Supersymmetry:
Motivation, Models and Signatures
Lecture 1

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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, SuperSpace, Superfields and SUSY Lagrangian

  The Minimal Supersymmetric extension of the Standard Model

  Soft Supersymmetry Breaking [Prof. Chako's Lectures]

  Higgs and Super-particles Spectra

- Phenomenology:

  SUSY signals at Colliders

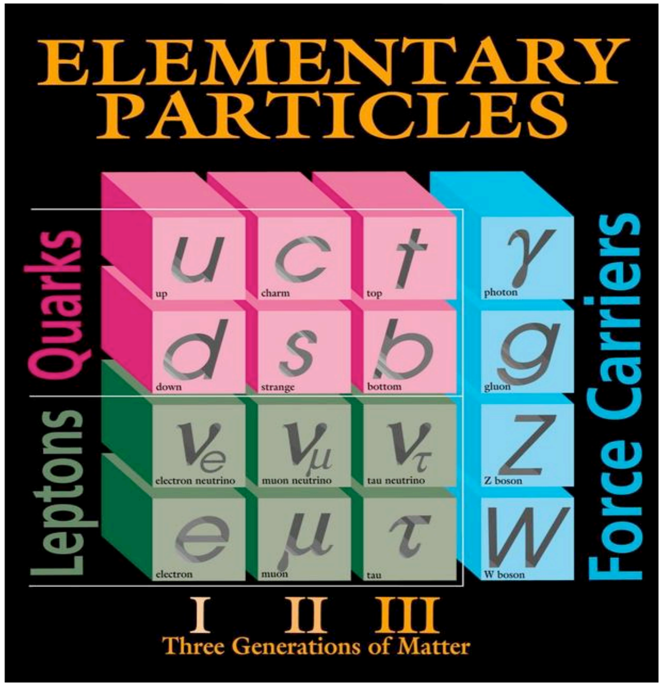
  The Search for SUSY Dark Matter

  The interplay among Higgs, B physics and Dark Matter Searches

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 :

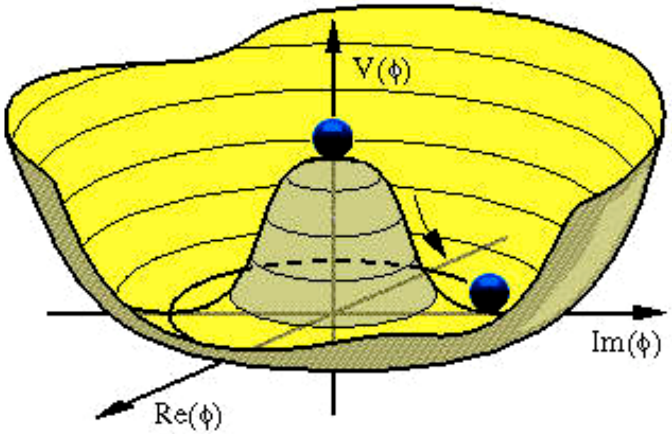
3 families of quarks and leptons with the same quantum numbers under the gauge groups

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

Crucial Problem: The gauge symmetries of the model do not allow the generation of mass for the fundamental particles !

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

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

2012-2013: an amazing time for HEP:

"The" Standard Model Scalar Boson, or not ....

CMS: $m_h \sim 125.8$ GeV (in ZZ); $m_h = 124.9.$ GeV (in $\gamma\gamma$)

ATLAS: $m_h = 124.3$ GeV (in ZZ); $m_h = 126.8$ GeV (in $\gamma\gamma$)

Observation with a significance > 5 σ

In the ZZ channel

$\mu = 1.7^{+0.5}_{-0.4}$ ATLAS $\quad \mu = 0.91^{+0.3}_{-0.24}$ CMS

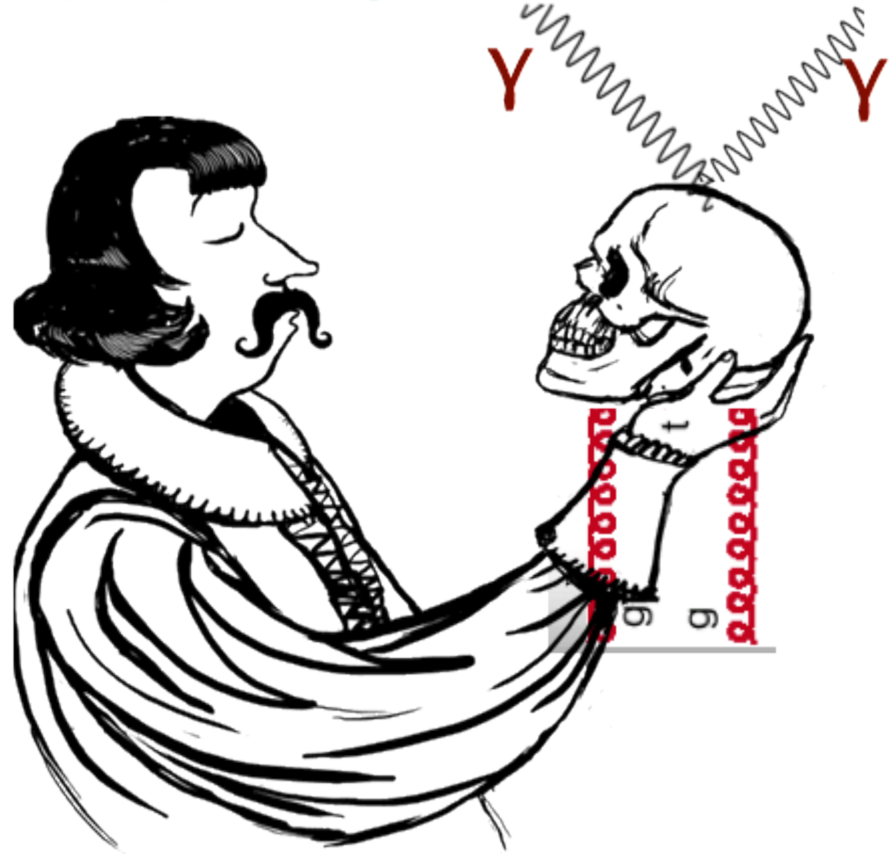
In the WW channel ($m_h \sim 125$ GeV)

$\mu = 1.5 \pm 0.6$ ATLAS $\quad \mu = 0.76 \pm 0.21$ CMS

In the $\gamma\gamma$ channel

$\mu = 1.65 \pm 0.24^{+0.25}_{-0.18}$ ATLAS

$\mu = 1.1 \pm 0.31$ CMS



The Discovery of a Scalar boson like particle puts the final piece of the Standard Model in place

and marks the birth of the hierarchy problem: one of the main motivations for physics beyond the SM

The SM works beautifully,
no compelling hints for deviations

But many questions remain unanswered:

Dynamical Origin of electroweak symmetry breaking

Origin of generations and structure of Yukawa interactions

Matter-antimatter asymmetry

Unification of forces

Neutrino masses

Dark matter and dark energy

Hence, the "prejudice" (the hope) that there must be "New Physics"

The Generation of big hierarchy of scales:
- The hierarchy problem of the SM Higgs sector -

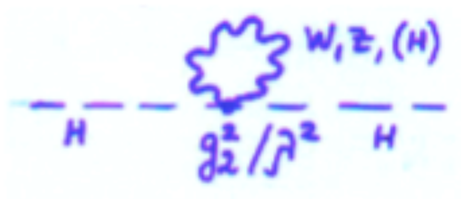
Why v $\ll$ M_{Pl}?

Quantum Corrections to the Higgs mass parameter diverge quadratically with the scale at which the SM is superseded by New Physics

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

to explain v $\approx O(m_W)$

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

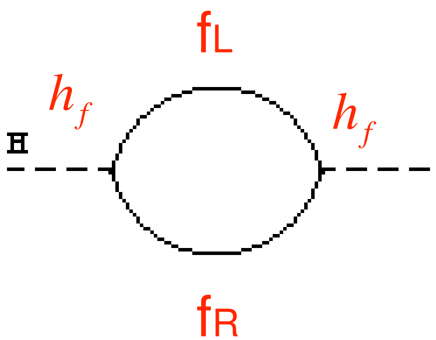


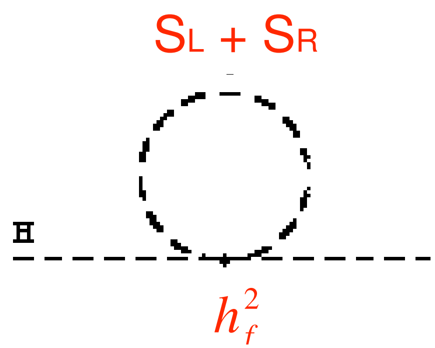
Quantum Corrections to the Higgs Mass Parameter

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

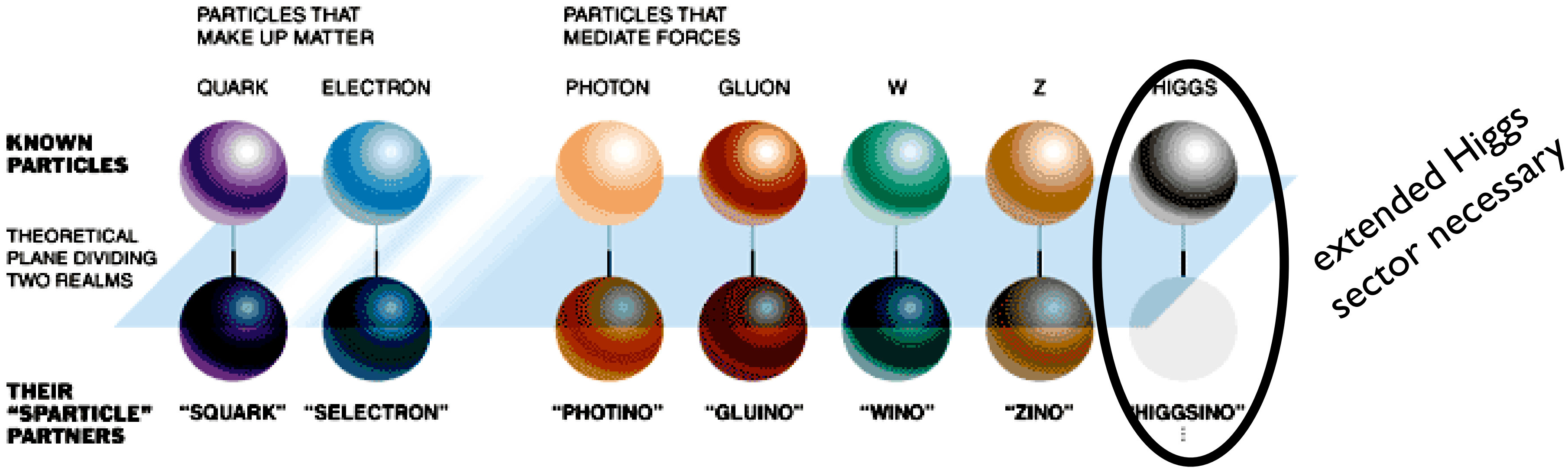
Automatic cancellation of loop corrections to the Higgs mass parameter

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 possible solutions to the baryon asymmetry of the universe.

Supersymmetry Generators

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

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:

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

$$\text{where } \sigma^\mu = (I, \vec\sigma), \quad \bar\sigma^\mu = (I, -\vec\sigma), \text{ and } \sigma^i \text{ are Pauli Matrices}$$

$$P^\mu = (H, \vec p) \text{ is the generator of spacetime translations: part of the SUSY algebra}$$

Two spinors may contract to form a Lorentz invariant:

$$\psi.\chi = \psi^\alpha \chi_\alpha = \psi^\alpha \epsilon_{\alpha\beta} \chi^\beta \qquad \bar\psi.\bar\chi = \bar\psi_{\dot\alpha} \bar\chi^{\dot\alpha} = \bar\psi_{\dot\alpha} \epsilon^{\dot\alpha\dot\beta} \bar\chi_{\dot\beta}$$

Hamiltonian of Supersymmetric Theories

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

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

- Two things may be concluded from here. First, the Hamiltonian operator is semidefinite positive.

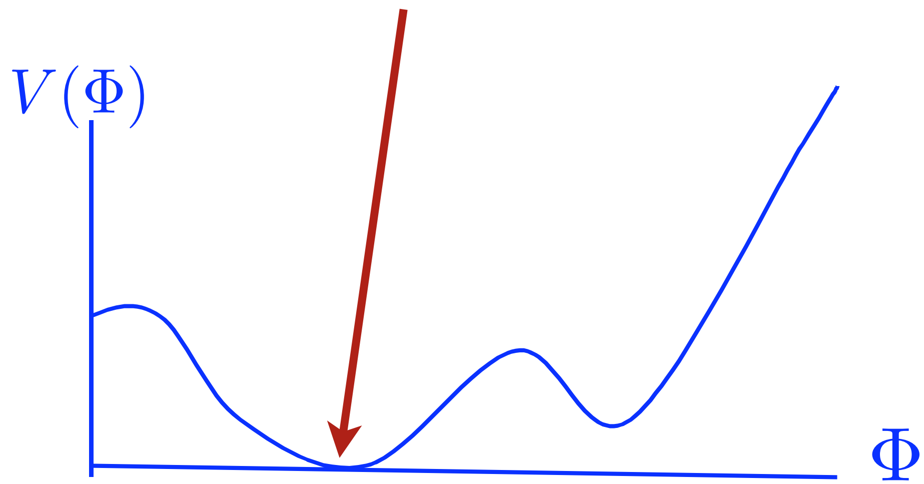
- $$< \ H \ > = \ E \geq 0$$

- Second, if the theory is supersymmetric, then the vacuum state should be annihilated by supersymmetric charges

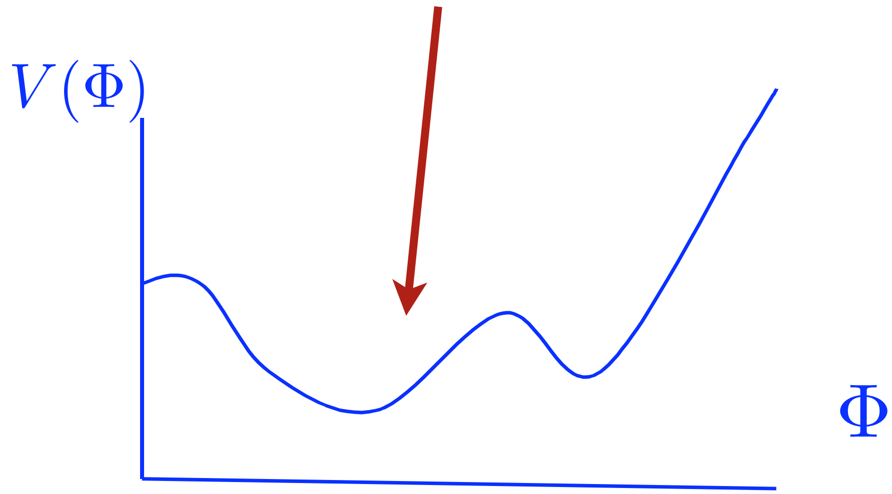
$$Q_\alpha|0>=0, \qquad Q^\dagger_{\dot\alpha}|0>=0 \qquad \Longrightarrow \qquad <0|H|0>=0$$

- So, the vacuum state energy is zero ! The vacuum energy is the order parameter for Supersymmetry breaking.

Preservation of SUSY



Spontaneous breakdown 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

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.

Four-component vs. two-component Weyl fermions

* A Dirac spinor is a four component object whose components are

$$\psi_D = \begin{pmatrix} \chi_\alpha \\ \bar{\psi}^{\dot{\alpha}} \end{pmatrix}$$

the hermitian conjugate of a L.H. Weyl fermion is a R.H. one $(\chi_\alpha)^\dagger = \chi^\dagger_{\dot{\alpha}} \equiv \bar{\chi}_{\dot{\alpha}}$

$$\psi_D^C = \begin{pmatrix} \psi_\alpha \\ \bar{\chi}^{\dot{\alpha}} \end{pmatrix}$$

where: $\psi^C = C\bar{\psi}^T = -i\gamma^2\psi^*$

* A Majorana spinor is a four component object whose components are

$$\psi_M = \begin{pmatrix} \chi_\alpha \\ \bar{\chi}^{\dot{\alpha}} \end{pmatrix} \qquad \psi_M^C = \psi_M$$

* Gamma Matrices (in Weyl representation)

$$\gamma^\mu = \begin{pmatrix} 0 & \sigma^\mu \\ \bar{\sigma}^\mu & 0 \end{pmatrix} \qquad \gamma^5 = \begin{pmatrix} -I & 0 \\ 0 & I \end{pmatrix}$$

$$\sigma^\mu = I, \vec{\sigma} \qquad \bar{\sigma}^\mu = I, -\vec{\sigma}$$

* Observe that $P_L\,\psi_D = \begin{pmatrix} \chi_\alpha \\ 0 \end{pmatrix}$ $\quad P_R\,\psi_D = \begin{pmatrix} 0 \\ \bar{\chi}^{\dot{\alpha}} \end{pmatrix}$

* Usual Dirac contractions may then be expressed in terms of two components contractions

$$\bar{\psi}_D \psi_D = \psi\chi + h.c. \qquad \text{with } \bar{\psi}_D = (\psi^\alpha \quad \bar{\chi}_{\dot{\alpha}}) \quad \psi_D = \begin{pmatrix} \chi_\alpha \\ \bar{\psi}^{\dot{\alpha}} \end{pmatrix}$$

The antisymmetric tensor $\varepsilon^{\alpha\beta} = - \varepsilon_{\alpha\beta} = i\sigma_2$ is used to define the invariant scalar product of Weyl spinors or to lower and raise indices:

$$\chi_\alpha = \epsilon_{\alpha\beta}\chi^\beta \quad \chi^\alpha = \epsilon^{\alpha\beta}\chi_\beta \qquad \bar{\chi}_{\dot{\alpha}} = \epsilon_{\dot{\alpha}\dot{\beta}}\bar{\chi}^{\dot{\beta}} \quad \bar{\chi}^{\dot{\alpha}} = \epsilon^{\dot{\alpha}\dot{\beta}}\bar{\chi}_{\dot{\beta}}$$

Convention: repeated spinor indices contracted ${}^{\alpha}{}_{\alpha}$ or ${}_{\dot{\alpha}}{}^{\dot{\alpha}}$ can be omitted

In particular: $\bar{\psi}_D\gamma^\mu\psi_D = \psi\sigma^\mu\bar{\psi} + \bar{\chi}\bar{\sigma}^\mu\chi = -\bar{\psi}\bar{\sigma}^\mu\psi + \bar{\chi}\bar{\sigma}^\mu\chi$

Observe that Majorana particles lead to vanishing vector currents
Hence, they must be neutral under electromagnetic interactions

Chiral currents, instead, do not vanish for Majorana fermions

$$\bar{\psi}_D\gamma^\mu\gamma_5\psi_D = \psi\sigma^\mu\bar{\psi} - \bar{\chi}\bar{\sigma}^\mu\chi = -\bar{\psi}\bar{\sigma}^\mu\psi - \bar{\chi}\bar{\sigma}^\mu\chi$$

They may couple to the Z boson

Other relations may be found in the literature

Superspace

The existence of a generator superalgebra is connected to the existence of a supergroup whose elements are obtained via exponential of the generators times some arbitrary parameters

- Apart from the ordinary coordinates x^μ, one introduces new anticommuting spinor coordinates θ^α and $\bar{\theta}_{\dot{\alpha}}$; $[\theta] = [\bar{\theta}] =$ -1/2.
- One can also define derivatives (similar to $P_\mu = -i\partial_\mu$)

$$\{\theta_\alpha, \theta_\beta\} = 0; \qquad \theta\theta\theta = 0; \qquad [\theta Q, \bar{\theta}\bar{Q}] = 2\theta\bar{\theta}\sigma^\mu P_\mu$$

$$\{\partial_\alpha, \partial_\beta\} = 0 \nwarrow \quad \partial_\alpha = \frac{\partial}{\partial\theta^\alpha}; \qquad \partial_\alpha\theta^\beta = \delta_\alpha^\beta; \qquad \partial_\alpha(\theta^\beta\theta_\beta) = 2\theta_\alpha$$

A general group element of the graded Lie Group is given by:

$$S(x, \theta, \bar{\theta}) = \exp[i(\theta Q + \bar{\theta}\bar{Q} + X^{\alpha\dot{\alpha}}P_{\alpha\dot{\alpha}}/2)]$$

Any cuadrivector V_μ can be associated to a matrix $V_{\alpha\dot{\alpha}}$ such that

$$V_{\alpha\dot{\alpha}} = V_\mu\sigma^\mu_{\alpha\dot{\alpha}} = V^\mu\sigma_{\mu\alpha\dot{\alpha}} \qquad \det V_{\alpha\dot{\alpha}} = V^{0^2} - \vec{V}^2 = V_\mu V^\mu$$

$$P_\mu\sigma^\mu_{\alpha\dot{\alpha}} = P_{\alpha\dot{\alpha}} \qquad X_\mu\sigma^\mu_{\alpha\dot{\alpha}} = X_{\alpha\dot{\alpha}} \qquad X^{\alpha\dot{\alpha}}P_{\alpha\dot{\alpha}} = 2X^\mu P_\mu$$

Differential representation of SUSY generators

- Supersymmetry is a particular translation in superspace characterized by a Grassmann parameter ς

- Considering a Taylor expansion

$$\exp^{\xi^{\alpha\dot{\alpha}}\partial_{\alpha\dot{\alpha}}} f(x) = f(x^{\alpha\dot{\alpha}} + \xi^{\alpha\dot{\alpha}})$$

$$\exp^{\zeta^{\alpha}\partial_{\alpha}} f(\theta) = f(\theta^{\alpha} + \zeta^{\alpha}) \qquad \exp^{\bar{\zeta}^{\dot{\alpha}}\partial_{\dot{\alpha}}} f(\bar{\theta}) = f(\bar{\theta}^{\dot{\alpha}} + \zeta^{\dot{\alpha}})$$

one can see that acting on superfields the generators can be given as derivative operators

$$P_{\alpha\dot{\alpha}} = -i\partial_{\alpha\dot{\alpha}} = -i\partial_{\mu}\sigma^{\mu}_{\alpha\dot{\alpha}} \qquad (\partial_{\alpha\dot{\alpha}} = 2\partial/\partial x^{\alpha\dot{\alpha}})$$

$$Q_{\alpha} = -i\partial_{\alpha} - \bar{\theta}^{\dot{\alpha}}\partial_{\alpha\dot{\alpha}} \qquad \bar{Q}_{\dot{\alpha}} = i\partial_{\dot{\alpha}} + \theta^{\alpha}\partial_{\alpha\dot{\alpha}}$$

One can check that these differential generators fulfill the SUSY algebra

Superspace allows to represent fermion and boson fields by the same superfield, by fields in superspace

Chiral Superfields

The superfields defined by $\Phi(z) = S(z)\Phi(0) = \Phi(x,\theta,\bar{\theta})$ are not an irreducible basis

One can define differential operators

$$D_\alpha = \partial_\alpha + i\bar{\theta}^{\dot{\alpha}}\partial_{\alpha\dot{\alpha}} \qquad \bar{D}_{\dot{\alpha}} = -\bar{\partial}_{\dot{\alpha}} - i\theta^\alpha\sigma^\mu_{\alpha\dot{\alpha}}\partial_\mu$$

Given that $\{\bar{D}_{\dot{\alpha}}, Q_\beta\} = 0 \quad \{\bar{D}_{\dot{\alpha}}, \bar{Q}_{\dot{\beta}}\} = 0 \quad [\bar{D}_{\dot{\alpha}}, P_{\beta\dot{\beta}}] = 0$

it is easy to show that $D_\alpha, \ \bar{D}_{\dot{\alpha}}$ commute with SUSY transf. $[\bar{D}, \exp^{i(\zeta Q + \bar{\zeta}\bar{Q})}] = 0$

A Chiral Superfield fulfills $\bar{D}_{\dot{\alpha}}\Phi = 0$

An anti-chiral superfield fulfills $D_\alpha\Phi = 0$

anti-chiral fields are the hermitian conjugate of chiral fields, enough to concentrate on chiral fields

If a superfield is chiral, since $\bar{D}$ commutes with SUSY transformation, hence the SUSY transformation is also chiral

$$S\bar{D}_{\dot{\alpha}}\Phi = \bar{D}_{\dot{\alpha}}S\Phi = 0$$

Chiral Superfields form the basis of an irreducible representation of SUSY

Chiral Superfields (cont'd)

To fulfill $\bar{D}_{\dot{\alpha}}\Phi = (-\bar{\partial}_{\dot{\alpha}} - i\theta^{\alpha}\sigma^{\mu}_{\alpha\dot{\alpha}}\partial_{\mu})\Phi = 0$

implies that the chiral superfield must depend on $\bar{\theta}$, x in a specific way

$$y^{\mu} = x^{\mu} - i\bar{\theta}^{\dot{\alpha}}\sigma^{\mu}_{\alpha\dot{\alpha}}\theta^{\alpha} \qquad \bar{D}_{\dot{\alpha}}y^{\mu} = 0$$

Hence a generic Chiral Superfield can be written staring from its value at $\bar{\theta} = 0$

$$\phi(x,\theta,\bar{\theta}) = \phi(x^{\mu} - i\bar{\theta}^{\dot{\alpha}}\sigma^{\mu}_{\alpha\dot{\alpha}}\theta^{\alpha},\theta) = \exp^{i\theta\sigma^{\mu}\bar{\theta}\partial_{\mu}}\phi(x,\theta,0)$$

$$\text{with} \quad \phi(x,\theta,\bar{\theta}=0) = A(x) + \sqrt{2}\Psi(x) + \theta^2 F(x)$$

- A, ψ and F are the scalar, fermion and auxiliary components.
- Under supersymmetric transformations, the components of chiral fields transform like

$$\delta A = \sqrt{2}\xi\psi, \qquad \delta F = -i\sqrt{2}\bar{\xi}\bar{\sigma}^{\mu}\partial_{\mu}\psi$$

$$\delta\psi = -i\sqrt{2}\sigma^{\mu}\bar{\xi}\partial_{\mu}A + \sqrt{2}\xi F$$

The F component of a Chiral Superfield transforms like a total derivative => good for SUSY $\mathcal{L}$

Properties of Chiral Superfields:

- The product of two superfields is another superfield.
- For instance, the F-component of the product of two superfields Φ_1 and Φ_2 is obtained by collecting all the terms in θ^2, and is equal to

$$[\Phi_1 \Phi_2]_F = A_1 F_2 + A_2 F_1 - \psi_1 \psi_2 \qquad 3)$$

- For a generic Polynomial function of several fields $P(\Phi_i)$, the result is

$$[P(\Phi)]_F = (\partial_{A_i} P(A)) F_i - \frac{1}{2} \left(\partial^2_{A_i A_j} P(A) \right) \psi_i \psi_j$$

- Finally, a single chiral field has dimensionality $[A] = [\Phi] = 1$, $[\psi] = 3/2$ and $[F] = 2$. For $P(A)$, $[P(\Phi)]_F = [P(\Phi)] + 1 \quad ([\theta] = [\bar{\theta}] = -1/2)$.

$\downarrow$

As we will see P(Φ) most generic polynomial, gauge invariant, of dimension 3 will be good to build SUSY $\mathcal{L}$

Expansion of a Chiral Superfield

* In the above, we only used the form of the chiral superfield at $\bar{\theta} = 0$

However, for many applications the full expression of the chiral superfield is necessary:

$$\Phi(x, \theta, \bar{\theta}) = \exp(-i\partial_\mu \theta \sigma^\mu \bar{\theta})\ \Phi(x, \theta, \bar{\theta} = 0)$$

$$\downarrow$$

$$\Phi(x, \theta, \bar{\theta}) = A(x) + i\partial^\mu A(x)\theta\sigma_\mu\bar{\theta} - \frac{1}{4}\partial^2 A(x)\theta^2\bar{\theta}^2$$

$$+\sqrt{2}\,\theta\psi(x) + i\frac{\theta^2}{2}\partial^\mu\psi(x)\sigma_\mu\bar{\theta} + F(x)\theta^2$$

Important to construct the SUSY Lagrangian considering the $\theta^2\bar{\theta}^2$ component of the general superfield formed by the product $\bar{\phi}\phi$

Vector Superfields

* Vector Superfields are generic hermitian fields. The minimal irreducible representations may be obtained by: (in Wess Zumino Gauge)

$$V_{WZ}(x,\theta,\bar\theta) = (\theta\sigma^\mu\bar\theta)\, V_\mu + i\theta^2\bar\theta\bar\lambda - i\bar\theta^2\theta\lambda + \frac{1}{2}\theta^2\bar\theta^2 D$$

$$V_{WZ}^2 = \frac{1}{2}\theta^2\bar\theta^2 V_\mu V^\mu$$

$$V_{WZ}^3 = 0$$

* Vector Superfields contain a regular gauge vector field V_μ, its fermionic superpartner λ and an auxiliary scalar field D

Under supersymmetric transformations the components transform like:

$$\delta V_\mu^a = -\bar\xi\bar\sigma_\mu\lambda^a - \bar\lambda^a\bar\sigma_\mu\xi \qquad \delta\lambda_\alpha^a = -\frac{i}{2}(\sigma^\mu\bar\sigma^\nu\xi)_\alpha F_{\mu\nu}^a + \xi_\alpha D^a$$

$$\delta D^a = i(\bar\xi\bar\sigma^\mu\nabla_\mu\lambda^a - \nabla_\mu\bar\lambda^a\bar\sigma^\mu\xi) \qquad \text{with } \nabla_\mu = \partial_\mu + ig\, V_\mu^a\, T^a$$

The D component of a vector field transforms as a total derivative

- $D = [V] + 2$; $[V_\mu] = [V] + 1$; $[\lambda] = [V] + 3/2$. If V_μ describes a physical gauge field, then $[V] = 0$.

Superfield Strength

- Similarly to $F_{\mu\nu}$ in the regular case, there is a field that contains the field strength. It is a chiral field, derived from V ($W = -\bar{D}\bar{D}DV/4$), and it is given by

$$W^\alpha(x,\theta,\bar{\theta}=0) = -i\lambda^\alpha + (\theta\sigma_{\mu\nu})^\alpha F^{\mu\nu} + \theta^\alpha D - \theta^2 \left(\bar{\sigma}^\mu \mathcal{D}_\mu \bar{\lambda}\right)^\alpha$$

W_α is chiral:

$$\bar{D}_{\dot{\alpha}} W_\alpha = 0 \text{ since } \{\bar{D}_{\dot{\alpha}} \bar{D}_{\dot{\beta}}\} = 0 => \bar{D}^2_{\dot{1}} = 0 = \bar{D}^2_{\dot{2}}$$

and gauge invariant (ok to work in WZ gauge)

hence the F component of $W^\alpha W_\alpha$ is good for SUSY $\mathcal{L}$

$W_\alpha[y,\theta]$ and $W_\alpha[x,\theta]$ differ in a total derivative,

hence one can consider $W_\alpha[x,\theta]_F$ for $\mathcal{L}$

$$\mathcal{L}_{gauge} = \frac{1}{4}[W_\alpha W^\alpha]_F + h.c \;\; = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{D^2}{2} + i\lambda\sigma^\mu\partial_\mu\bar{\lambda}$$

Gauge transformations

- Under gauge transformations, superfields transform like

$$\Phi \rightarrow \exp(-ig\Lambda)\Phi, \qquad W_\alpha \rightarrow \exp(-ig\Lambda)W_\alpha \exp(ig\Lambda)$$
$$\exp(gV) \rightarrow \exp(-ig\bar{\Lambda}) \exp(gV) \exp(ig\Lambda)$$

where Λ is a chiral field of dimension 0.

In the case of a non abelian gauge superfield, transformation laws can be generalized with Λ being a matrix: $\Lambda_{ij} = T_{ij}^a \Lambda_a$

The gauge superfield $V_{ij} = T_{ij}^a V_a$ has non trivial transformation in the field components but still can be considered in the WZ gauge

The SUSY field strength can be generalized in the non-Abelian case:

$$W_\alpha = -\frac{1}{4}\bar{D}\bar{D} \exp^{-V} D_\alpha \exp^V$$

Towards a SUSY Lagrangian

The aim $\longrightarrow$ construct a Lagrangian invariant under supersymmetric and gauge transformations

The variation $\delta\mathcal{L}$ should be a total derivative such that the action $\mathcal{S} = \int d^4x \;\; \mathcal{L}$ is invariant

Recall: The F-component of a chiral field (or products of chiral fields)
& The D-component of a vector field
transform under SUSY like a total derivative

If renormalizability is imposed, the dimension of all terms in the Lagrangian:

$$[\mathcal{L}_{int}] \leq 4$$

On the other hand the dimensions of the chiral and vector fields are:

$$[\Phi] = 1, \qquad [W_\alpha] = 3/2, \qquad [V] = 0.$$

and one should remember that $[V]_D = [V] + 2; \; [\Phi]_F = [\Phi] + 1.$

The Supersymmetric Lagrangian

- Once the above machinery is introduced, the total Lagrangian takes a particular simple form. The total Lagrangian is given by

$$\begin{aligned}\mathcal{L}_{\mathrm{SUSY}} &= \frac{1}{4g^2}\left(Tr[W^\alpha W_\alpha]_F + h.c.\right) + \sum_i \left(\bar{\Phi}\exp(gV)\Phi\right)_D \\ &+ \left([P(\Phi)]_F + h.c.\right)\end{aligned} \tag{26}$$

where $P(\Phi)$ is the most generic dimension-three, gauge invariant, polynomial function of the chiral fields Φ, and it is called Superpotential. It has the general expression

$$P(\Phi) = c_i\Phi_i + \frac{m_{ij}}{2}\Phi_i\Phi_j + \frac{\lambda_{ijk}}{3!}\Phi_i\Phi_k\Phi_k \tag{27}$$

- The D-terms of V^a and the F term of Φ_i do not receive any derivative contribution: Auxiliary fields that can be integrated out by equation of motion.

Supersymmetry: Motivation, Models and Signatures

Lecture 2

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São Paulo International Schools on Theoretical Physics

School on Particle Physics in the LHC Era
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The Supersymmetric Lagrangian

- Once the above machinery is introduced, the total Lagrangian takes a particular simple form. The total Lagrangian is given by

$$\begin{aligned}\mathcal{L}_{\mathrm{SUSY}} &= \frac{1}{4g^2}(Tr[W^\alpha W_\alpha]_F + h.c.) + \sum_i \left(\bar{\Phi}\exp(gV)\Phi\right)_D \\ &+ \left([P(\Phi)]_F + h.c.\right) \end{aligned} \tag{26}$$

where $P(\Phi)$ is the most generic dimension-three, gauge invariant, polynomial function of the chiral fields Φ, and it is called Superpotential. It has the general expression

$$P(\Phi) = c_i\Phi_i + \frac{m_{ij}}{2}\Phi_i\Phi_j + \frac{\lambda_{ijk}}{3!}\Phi_i\Phi_k\Phi_k \tag{27}$$

- The D-terms of V^a and the F term of Φ_i do not receive any derivative contribution: Auxiliary fields that can be integrated out by equation of motion.

SUSY Lagrangian in term of component fields

It contains the usual kinetic terms for boson and fermion fields, generalized Yukawa interactions, and novel interactions between gauginos and the scalar and fermion components of the chiral superfields

The last term is a scalar potential term that depends only on the auxiliary fields

SM fermion superpartners + Higgs

SM fermions + Higgsinos

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

Gauginos

Yukawa interactions

Novel gaugino-scalar-fermion interaction

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

with the non-abelian covariant derivatives:

$$D_\mu A/\psi = (\partial_\mu + i g V_\mu^a T^a) A/\psi \qquad\qquad D_\mu \lambda^a = \partial_\mu \lambda^a - g f_{abc} V_\mu^b \lambda^c$$

Notation bookkeeping

- All standard matter fermion fields are described by their left-handed components (using the charge conjugates for right-handed fields) ψ_i
- All standard matter fermion superpartners are described the scalar fields A_i. There is one complex scalar for each chiral Weyl fermion
- Gauge bosons are inside covariant derivatives and in the $G_{\mu\nu}$ terms.
- Gauginos, the superpartners of the gauge bosons are described by the fermion fields λ_a. There is one Weyl fermion for each massless gauge boson.
- Higgs bosons and their superpartners are described as regular chiral fields. Their only distinction is that their scalar components acquire a v.e.v. and, as we will see, they are the only scalars with positive R-Parity.

Scalar Potential

$$V(F_i, F_i^*, D^a) = \sum_i F_i^* F_i + \frac{1}{2} \sum_a (D^a)^2$$

where the auxiliary fields may be obtained from their equation of motion, as a function of the scalar components of the chiral fields:

$$F_i^* = -\frac{\partial P(A)}{\partial A_i}, \qquad D^a = -g \sum_i (A_i^* T^a A_i)$$

Quartic couplings governed by gauge couplings, crucial for Higgs sector

The scalar potential is positive definite - This is not a surprise-

From the SUSY algebra one has:

$$H = \frac{1}{4} \sum_{\alpha=1}^{2} (Q_\alpha^\dagger Q_\alpha + Q_\alpha Q_\alpha^\dagger)$$

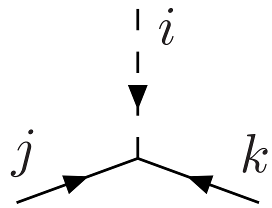
- If for a physical state the energy is zero, this is the ground state.
- Supersymmetry is broken if the vacuum energy is non-zero !

Couplings

Recall 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

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

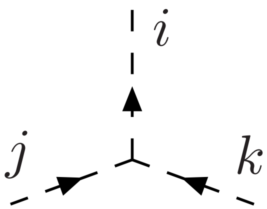


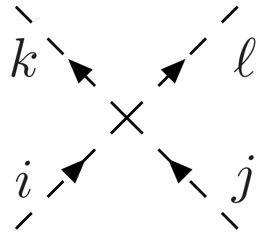
also m_{ij} Ψ_i Ψ_j (mass term)

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

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

also m_{ik}^* m_{kj} $A_i^* A_j$ (mass term)





if <A> non zero (mass terms)

The superpotential parameters determine all non-gauge interactions

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

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

- Similarly, the gaugino-scalar fermion interactions coming from

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

are governed by the gauge couplings

No new Couplings!

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

Structure of Supersymmetric Theories

- The Standard Model is based on a Gauge Theory.
- A supersymmetric extension of the Standard Model has then to follow the rules of Supersymmetric Gauge Theories.
- These theories are based on two set of fields:
  - Chiral fields, that contain left handed components of the fermion fields and their superpartners.
  - Vector fields, containing the vector gauge bosons and their superpartners.
- Right-handed fermions are contained on chiral fields by means of their charge conjugate representation

$$(\psi_R)^C = -i\gamma^2 P_R \psi^* \qquad \text{with } \psi^C = i\gamma_2\psi^* \qquad \gamma_2 = \begin{pmatrix} 0 & \sigma_2 \\ -\sigma_2 & 0 \end{pmatrix}$$

$$P_L(\psi_R)^C = (\psi_R)^C$$

- Higgs fields are described by chiral fields, with fermion superpartners
- The equality of fermion and boson couplings are essential for the cancellation of all quadratic divergences, at all oders in perturbation theory.

Types of supermultiplets

Chiral (or "Scalar" or "Matter" or "Wess-Zumino") supermultiplet:

1 two-component Weyl fermion, helicity $\pm\frac{1}{2}$. $(n_F = 2)$

2 real spin-0 scalars = 1 complex scalar. $(n_B = 2)$

The Standard Model quarks, leptons and Higgs bosons must fit into these.

Gauge (or "Vector") supermultiplet:

1 two-component Weyl fermion gaugino, helicity $\pm\frac{1}{2}$. $(n_F = 2)$

1 real spin-1 massless gauge vector boson. $(n_B = 2)$

The Standard Model $\gamma, Z, W^{\pm}, g$ must fit into these.

The SUSY extension of the Standard Model (MSSM)

- Apart from the superpotential $P[\Phi]$, all other properties are directly determined by the gauge interactions of the theory.
- To construct the superpotential, one should remember that chiral fields contain only left-handed fields, and right-handed fields should be represented by their charge conjugates.(this means by left handed fields as well)
- SM right-handed fields are singlet under $SU(2)$. Their complex conjugates have opposite hypercharge to the standard one.
- There is one chiral superfield for each chiral fermion of the Standard Model.
- In total, there are 15 chiral fields per generation, including the six left-handed quarks, the six right-handed quarks, the two left-handed leptons and the right-handed charged leptons.

The Minimal Supersymmetric Standard Model

Chiral Supermultiplets

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

The superpartners of the SM particles are written with a ~
Scalar Superpartners are generically called **s**quarks and **s**leptons
short for scalar quarks and scalar leptons

$$\phi_{e_L} = \tilde{e}_L + \sqrt{2}\theta\psi^e_L + \theta^2 F_{e_L} \qquad \phi_{e_R} = \tilde{e}^*_R + \sqrt{2}\theta((\psi^e_R)^C)_L + \theta^2 F^*_{e_R}$$

Gauge Supermultiplets

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	$\widetilde{W}^{\pm}\quad \widetilde{W}^0$	$W^{\pm}\quad W^0$	$(\ \mathbf{1},\ \mathbf{3}\ ,\ 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\ \mathbf{1},\ \mathbf{1}\ ,\ 0)$

The spin-$1/2$ **gauginos** transform as the adjoint representation of the gauge group. Each gaugino carries a $\widetilde{\ }$. The color-octet superpartner of the gluon is called the **gluino**. The $SU(2)_L$ gauginos are called **winos**, and the $U(1)_Y$ gaugino is called the **bino**.

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 Sector

- 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,

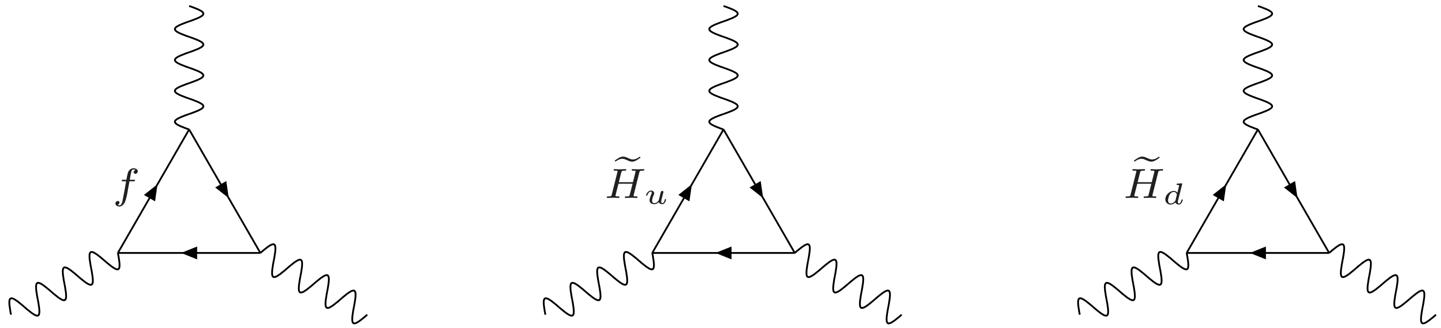
$$\begin{aligned} \sum_{quarks} Y_i &= 0; \qquad \sum_{left} Y_i = 0; \\ \sum_i Y_i^3 &= 0; \qquad \sum_i Y_i = 0 \end{aligned}$$

)

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

Solution: two Higgs Supermultiplets with opposite hypercharges

1) Anomaly Cancellation



$$\sum_{\text{SM fermions}} Y_f^3 = 0 \quad + 2\left(\frac{1}{2}\right)^3 \quad + 2\left(-\frac{1}{2}\right)^3 \quad = 0$$

This anomaly cancellation occurs if and only if **both** $\widetilde{H}_u$ and $\widetilde{H}_d$ higgsinos are present. Otherwise, the electroweak gauge symmetry would not be allowed!

2) Quark and Lepton masses

Only the H_u Higgs scalar can give masses to charge $+2/3$ quarks (top).

Only the H_d Higgs scalar can give masses to charge $-1/3$ quarks (bottom) and the charged leptons. We will show this later.

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	$(H_u^+\ \ H_u^0)$	$(\widetilde{H}_u^+\ \ \widetilde{H}_u^0)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ +\frac{1}{2})$
	H_d	$(H_d^0\ \ H_d^-)$	$(\widetilde{H}_d^0\ \ \widetilde{H}_d^-)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$

- 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

$$H_1 \equiv H_d \qquad H_2 \equiv H_u$$

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

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

<u>Interesting to observe:</u>

The quantum numbers of H₁ are the same as those of the lepton superfield L.
One can add terms in the superpotential replacing H₁ by L

Dangerous Baryon and Lepton Number Violating Interactions

- General superpotential contains, apart from the Yukawa couplings of the Higgs to lepton and quark fields, new couplings:

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

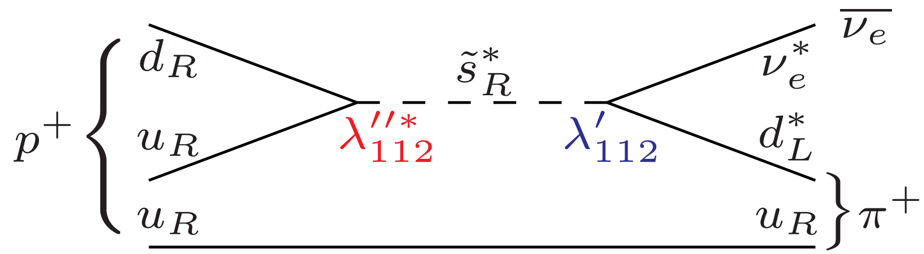
- Assigning every lepton chiral (antichiral) superfield lepton number 1 (-1) and every quark chiral (antichiral) superfield baryon number 1/3 (-1/3) one obtains :
  - Interactions in $P[\Phi]$ conserve baryon and lepton number.
  - Interactions in $P[\Phi]_{\text{new}}$ violate either baryon or lepton number.
- One of the most dangerous consequences of these new interaction is to induce proton decay, unless couplings are very small and/or sfermions are very heavy.

Proton Decay

In P_{new} there are two type of couplings which violate either

lepton number $(\Delta L = 1)$ or baryon number $(\Delta B = 1)$.

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:



One cannot require B and L conservation since they are already known to be violated at the quantum number 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 an 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.

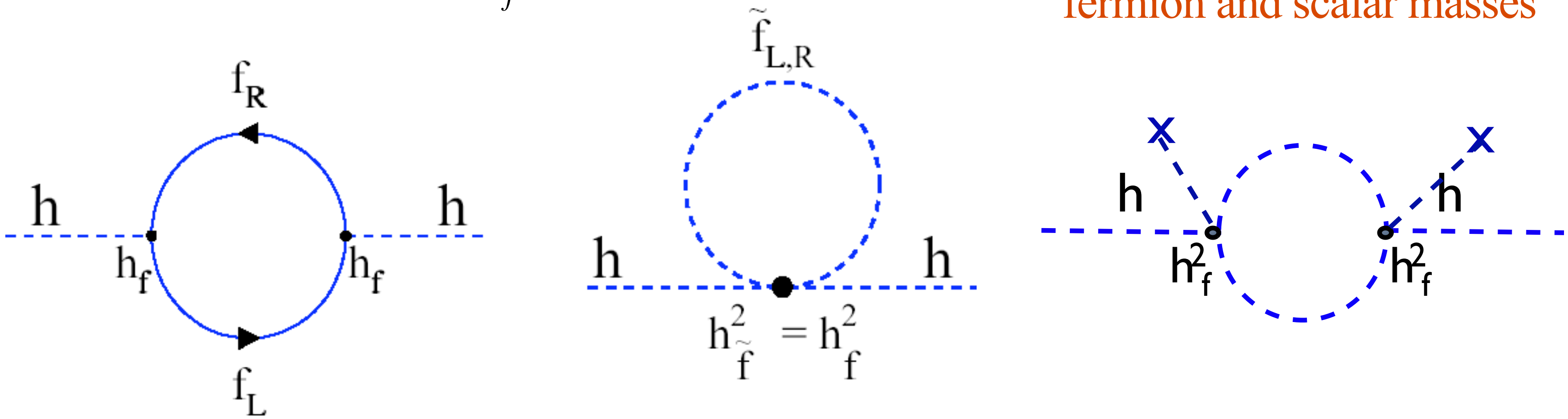
SUSY must be broken in nature

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

The breakdown of SUSY must be "SOFT"
this means it does not change the dimensionless terms in the lagrangian

If SUSY is realized in nature, why have we seen none of the SUSY particles while we have already seen all the SM particles?

Standard Model quark, leptons and gauge boson masses are protected by chiral and gauge symmetries
==> they acquire mass through EWSB, hence their masses are at most of order v~ 175 GeV

SUSY particles can acquire gauge invariant masses, same as SM Higgs
==> this explains why it is possible that we have not seen SUSY particles at high energy colliders yet

One can probe that after adding
Gaugino masses, Squark and Slepton squared mass terms, and trilinear and bilinear terms proportional to the scalar parts of the superpotential,
the cancellation of quadratic divergences is not spoiled

The Soft SUSY-breaking Lagrangian for the MSSM

$$\mathcal{L}_{soft} = -\frac{1}{2}(M_3\tilde{g}\tilde{g} + M_2\tilde{W}\tilde{W} + M_1\tilde{B}\tilde{B})$$

Mi for i=1,2,3 are the gluino, wino and bino mass terms

$$-m_Q^2\tilde{Q}^\dagger\tilde{Q} - m_U^2\tilde{U}^\dagger\tilde{U} - m_D^2\tilde{D}^\dagger\tilde{D} - m_L^2\tilde{L}^\dagger\tilde{L} - m_E^2\tilde{E}^\dagger\tilde{E}$$

$$-m_{H_1}^2 H_1^* H_1 - m_{H_2}^2 H_2^* H_2 - (\mu B H_1 H_2 + cc.)$$

$$-(A_u h_u \tilde{U}\tilde{Q}H_2 + A_d h_d \tilde{D}\tilde{Q}H_1 + A_l h_l \tilde{E}\tilde{L}H_1) + c.c.$$

$a_i = A_i\, h_i$ are trilinear terms proportional to the Yukawa couplings (complex 3x3 matrices in family space)

induce L-R mixing in the sfermion sector once the Higgs acquire v.e.v. (mixing proportional to fermion masses: relevant for 3rd generation)

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

$m_Q^2, m_U^2, m_D^2, m_L^2, m_E^2,$ are 3x3 complex hermitian matrices in family space

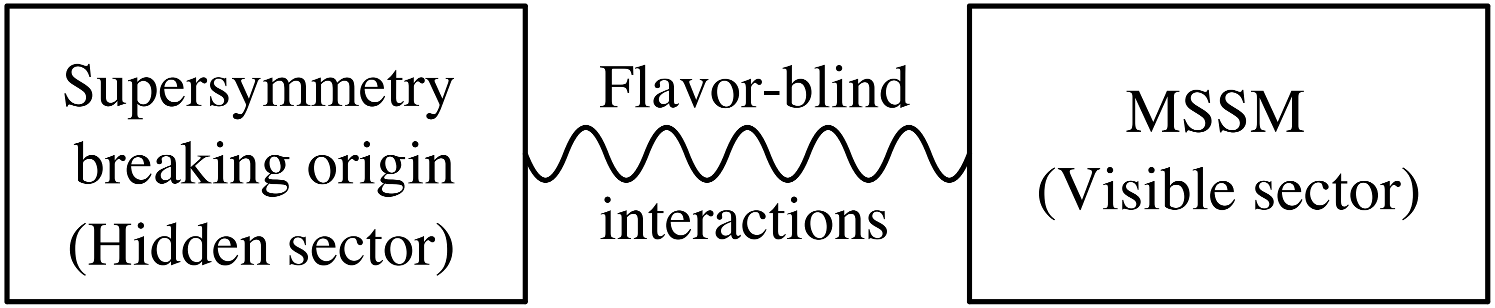
MSSM: 105 new parameters not present in the SM

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

Gaugino/Higgsino Mixing

- Just like the gauge boson mixes with the Goldstone modes of the theory after spontaneous breakdown of the gauge symmetry, gauginos mix with the Higgsinos. of equal charge

- Mixing comes from the interaction $\sqrt{2} g A_i^* T_a \psi_i \lambda^a$, when one takes $A_i \equiv H_i$, and $\lambda^a \equiv \tilde{W}^a$, $\tilde{B}$, and $\psi_i = \tilde{H}_i$.

- Charged Winos, $\tilde{W}_1 \pm i\tilde{W}_2$, mix with the charged components of the Higgsinos $\tilde{H}_{1,2}$. The mass eigenstates are called charginos $\tilde{\chi}^{\pm}$.

- Neutral Winos and Binos, $\tilde{B}$, $\tilde{W}_3$ mix with the neutral components of the Higgsinos. The mass eigenstates are called neutralinos, $\tilde{\chi}^0$.

- Charginos form two Dirac massive fields. Neutralinos give four massive Majorana states.

Charginos

Consider the chargino Lagrangian in terms of Weyl spinors, in the Wino- Higgsino basis, with $\tilde{W}^{\pm} = \left(\tilde{W}^1 \pm i\tilde{W}^2\right)/\sqrt{2}$

$$\mathcal{L}_{charginos} = -(\tilde{W}^- \tilde{H}_1^-) \begin{pmatrix} M_2 & g_2 v_2 \\ g_2 v_1 & \mu \end{pmatrix} \begin{pmatrix} \tilde{W}^+ \\ \tilde{H}_2^+ \end{pmatrix} + h.c.$$

M_2 is the soft SUSY breaking gaugino mass term, μ is the Higgsino mass parameter which comes from the superpotential, and the off diagonal terms come from the gaugino-Higgs Higgsino mixing and are always < M_Z

Defining: $\psi_j^+ \to (\tilde{W}^+,\ \tilde{H}_2^+)$ and $\psi_j^- \to (\tilde{W}^-, \tilde{H}_1^-)$

Chargino Mass Matrix is diagonalized by two unitary matrices V, U such that:

$$M_{\tilde{\chi}^{\pm}}^{Diag} = V^* M_{\tilde{\chi}^{\pm}} U^{-1}$$

The chargino mass eigenstates are: $\tilde{\chi}_i^+ = U_{ij}\psi_j^+ \qquad \tilde{\chi}_i^- = V_{ij}\psi_j^-$

One can always write two mass eigenstates, Dirac, charged fermions:

$$\psi^{Dirac}_{\tilde{\chi}_1^\pm} = \begin{pmatrix} \tilde{\chi}_1^+ \\ (\tilde{\chi}_1^-)^C \end{pmatrix} \qquad \psi^{Dirac}_{\tilde{\chi}_2^\pm} = \begin{pmatrix} \tilde{\chi}_2^+ \\ (\tilde{\chi}_2^-)^C \end{pmatrix} \qquad (\tilde{\chi}_1^-)^C_i = i\epsilon_{ij}\tilde{\chi}^+_{1j}$$

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.

Neutralinos

Consider the neutralino Lagrangian in terms of Weyl spinors, in the Bino-Wino-neutral Higgsino basis, with

$$\mathcal{L}_{neutralinos} = -\frac{1}{2}(\psi^0)^T M_{\tilde{\chi}^0}\psi^0 + h.c.$$

Defining: $\psi_j^0 \to (i\tilde{B}^0,\ i\tilde{W}^0,\ \tilde{H}_1^0,\ \tilde{H}_2^0)$

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -g_1 v_1/\sqrt{2} & g_1 v_2/\sqrt{2} \\ 0 & M_2 & g_2 v_1/\sqrt{2} & -g_2 v_2/\sqrt{2} \\ -g_1 v_1/\sqrt{2} & g_2 v_1/\sqrt{2} & 0 & -\mu \\ g_1 v_2/\sqrt{2} & -g_2 v_2/\sqrt{2} & -\mu & 0 \end{pmatrix}$$

Neutralino Mass Matrix diagonalized by a unitary matrix Z

$$\to M_{\tilde{\chi}^0}^{Diag} = Z^* M_{\tilde{\chi}^0} Z^{-1}$$

The neutralino mass eigenstates are: $\tilde{\chi}_i^0 = Z_{ij}\psi_j^0$

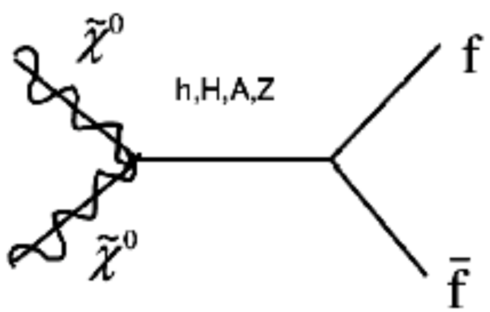
They form 4 Majorana mass eigenstates: $\psi_{\tilde{\chi}_i^0}^M = \begin{pmatrix} \tilde{\chi}_i^0 \\ (\tilde{\chi}_i^0)^* \end{pmatrix}$

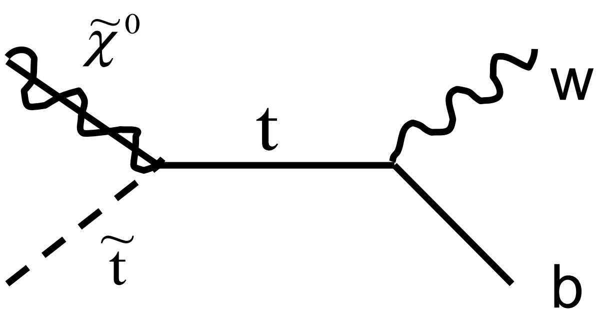
Neutralino Spectrum

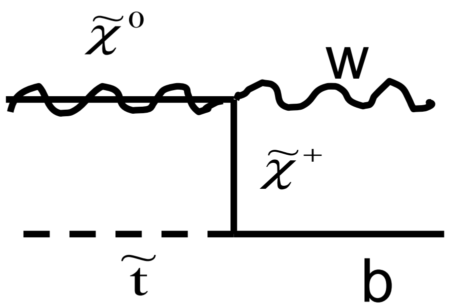
- The eigenstates are four Majorana particles.
- If the theory proceeds from a GUT, there is a relation between M_2 and M_1, $M_2 \simeq \alpha_2(M_Z)/\alpha_1(M_Z) M_1 \simeq 2M_1$.
- So, if μ is large, the lightest neutralino is a Bino (superpartner of the hypercharge gauge boson) and its interactions are governed by g_1.
- This tends to be a good dark matter candidate.

$\Omega_{CDM} \sim 1 / \int_0^{x_F} \langle \sigma_A v \rangle \, dx \qquad x \equiv \frac{M}{T} \qquad \boxed{0.089 < \Omega_{CDM} h^2 < 0.131 \quad \text{WMAP at 3 } \sigma}$

Many processes contribute to the $\tilde{\chi}_1^0 \, \tilde{\chi}_1^0$ annihilation cross section: $\langle \sigma_A v \rangle$







Gluinos

The gluino is an $SU(3)_C$ color octet fermion, so it does not have the right quantum numbers to mix with any other state. Therefore, at tree-level, its mass is the same as the corresponding parameter in the soft SUSY-breaking Lagrangian:

$$\boxed{M_{\tilde{g}} = M_3}$$

However, quantum corrections can be quite large, because it is a color octet.

This correction can be of order 5% to 25%, depending on the squark masses!
It tends to **increase** the gluino mass, compared to the tree-level prediction.

Squarks and Leptons

To treat these in complete generality, we would have to take into account arbitrary mixing. So the mass eigenstates would be obtained by diagonalizing:

- a 6×6 (mass)^2 matrix for up-type squarks ($\widetilde{u}_L, \widetilde{c}_L, \widetilde{t}_L, \widetilde{u}_R, \widetilde{c}_R, \widetilde{t}_R$),
- a 6×6 (mass)^2 matrix for down-type squarks ($\widetilde{d}_L, \widetilde{s}_L, \widetilde{b}_L, \widetilde{d}_R, \widetilde{s}_R, \widetilde{b}_R$),
- a 6×6 (mass)^2 matrix for charged sleptons ($\widetilde{e}_L, \widetilde{\mu}_L, \widetilde{\tau}_L, \widetilde{e}_R, \widetilde{\mu}_R, \widetilde{\tau}_R$),
- a 3×3 matrix for sneutrinos ($\widetilde{\nu}_e, \widetilde{\nu}_\mu, \widetilde{\nu}_\tau$)

If we assume that soft SUSY breaking parameters are flavor blind:

The first- and second-family squarks and sleptons have negligible Yukawa couplings, so they end up in 7 very nearly degenerate, unmixed pairs $(\widetilde{e}_R, \widetilde{\mu}_R)$, $(\widetilde{\nu}_e, \widetilde{\nu}_\mu)$, $(\widetilde{e}_L, \widetilde{\mu}_L)$, $(\widetilde{u}_R, \widetilde{c}_R)$, $(\widetilde{d}_R, \widetilde{s}_R)$, $(\widetilde{u}_L, \widetilde{c}_L)$, $(\widetilde{d}_L, \widetilde{s}_L)$.

Stop Sector

$\tilde{t}_L, \tilde{t}_R$ Mixing effects relevant due to large Yukawa coupling
lightest mass eigenstate $\tilde{t}_1$ may be the lightest visible sparticle

$$M_{\tilde{t}}^2 = \begin{pmatrix} m_{Q_3}^2 + m_t^2 + D_{\tilde{t}_L} & m_t(A_t - \mu/\tan\beta) \\ m_t(A_t - \mu/\tan\beta) & m_{U_3}^2 + m_t^2 + D_{\tilde{t}_R} \end{pmatrix} \equiv \begin{pmatrix} m_{\tilde{t}_L}^2 & m_{\tilde{t}_L R}^2 \\ m_{\tilde{t}_L R}^2 & m_{\tilde{t}_R}^2 \end{pmatrix}$$

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

The mass eigenstates are given by

$$\tilde{t}_1 = \cos\theta_{\tilde{t}}\tilde{t}_L + \sin\theta_{\tilde{t}}\tilde{t}_R$$
$$\tilde{t}_2 = -\sin\theta_{\tilde{t}}\tilde{t}_L + \cos\theta_{\tilde{t}}\tilde{t}_R$$

$$\tan 2\theta_{\tilde{t}} = \frac{2m_{\tilde{t}_{LR}}^2}{m_{\tilde{t}_L}^2 - m_{\tilde{t}_R}^2}$$

With masses:

$$m_{\tilde{t}_{1,2}}^2 = \frac{m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2}{2} \pm \sqrt{\left(\frac{m_{\tilde{t}_L}^2 - m_{\tilde{t}_R}^2}{2}\right)^2 + |m_{\tilde{t}_{LR}^2}^2|^2}$$

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

Supersymmetry:
Motivation, Models and Signatures

Lecture 3

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South American Institute for Fundamental Research
São Paulo International Schools on Theoretical Physics

School on Particle Physics in the LHC Era
April 1 - 12, 2013
Campus of IFT - UNESP - São Paulo, Brazil

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	$\widetilde{g}$	" "

What about the Higgs in Supersymmetry?

- **Minimal** Higgs Sector: Two Higgs doublets
- One Higgs doublet couples to up quarks, the other to down quarks/leptons only: $\longrightarrow$ **Higgs interactions flavor diagonal if SUSY preserved**

- Quartic Higgs couplings determined by SUSY as a function of the gauge couplings

  -- lightest (SM-like) Higgs strongly correlated to Z mass (naturally light!)

  -- other Higgs bosons can be as heavy as the SUSY breaking scale

- Important quantum corrections to the lightest Higgs mass due to incomplete cancellation of top and stop contributions in the loops

  -- also contributions from sbottoms and staus for large tan beta --

The Higgs Scalar potential derived from:

$$V[H_i] = \left|\frac{\partial P}{\partial H_i}\right|^2 + \frac{1}{2}\sum_a \left(H_i^* T_{ij}^a H_j\right)^2 + V_{soft}$$

V_{soft} includes the soft SUSY breaking effects.

$$V(H_1, H_2) = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 + m_3^2 (H_1^T i\tau_2 H_2 + h.c.) +$$
$$\frac{\lambda_1}{2}\left(H_1^\dagger H_1\right)^2 + \frac{\lambda_2}{2}\left(H_2^\dagger H_2\right)^2 + \lambda_3\left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + \lambda_4\left|(H_1^T i\tau_2 H_2)\right|^2$$

where $m_i^2 = m_{H_i}^2 + |\mu|^2$ and $m_{12}^2 \equiv m_3^2 = \mu\mathrm{B}$

Soft SUSY breaking terms

With: $H_1 = \begin{pmatrix} \mathrm{v}_1 + (H_1^0 + iA_1)/\sqrt{2} \\ H_1^- \end{pmatrix}$ $H_2 = \begin{pmatrix} H_2^+ \\ \mathrm{v}_2 + (H_2^0 + iA_2)/\sqrt{2} \end{pmatrix}$

$Q = T_3 + Y/2$ hence

$Y(H_1) = -1$; $Y(H_2) = 1$

and $\tan\beta = \frac{v_2}{v_1}$

At tree level:

Quartic couplings given as a function of gauge couplings

$$\lambda_1 = \lambda_2 = \frac{g_1^2 + g_2^2}{4}, \qquad \lambda_3 = \frac{g_2^2 - g_1^2}{4}, \qquad \lambda_4 = -\frac{g_2^2}{2}$$

The above effective potential is valid at the scale of the SUSY particle masses

At low energies the quartic couplings evolve with their Renormalization Group (RG) equations

Neutral Higgs potential

Analyzing first the neutral part of V[H_i]

$$V[H_1^0, H_2^0] = m_1^2|H_1^0|^2 + m_2^2|H_2^0|^2 - m_3^2\left(H_1^0 H_2^0 + H_1^{0^*} H_2^{0^*}\right)$$

$$+\frac{g_1^2 + g_2^2}{8}\left(|H_2^0|^2 - |H_1^0|^2\right)^2$$

Using the minimization conditions $\partial V/\partial H_i^0|_{<H_i^0>=v_i} = 0$

$$\tan^2\beta = \frac{\mathrm{v}_2^2}{\mathrm{v}_1^2} = \frac{m_1^2 + M_Z^2/2}{m_2^2 + M_Z^2/2} \qquad \sin 2\beta = \frac{2m_3^2}{m_1^2 + m_2^2}$$

Expanding V[H^0_i] in terms of $H_i^0 = \mathrm{v}_i + (H_i^0 + iA_i)/\sqrt{2} \quad i = 1, 2$

One can obtained the scalar and pseudoscalar mass matrices ==>

Tree Level Mass Predictions

$$V[A_i] \to (A_1 \quad A_2) \begin{bmatrix} m_1^2 + \frac{M_Z^2}{2}\cos 2\beta & m_3^2 \\ m_3^2 & m_1^2 - \frac{M_Z^2}{2}\cos 2\beta \end{bmatrix} \begin{pmatrix} A_1 \\ A_2 \end{pmatrix}$$

Using the minimization conditions

$$\Rightarrow \det M_A^2 = 0 \qquad\qquad \mathrm{Tr}[\mathrm{M_A^2}] = \mathrm{m_1^2 + m_2^2}$$

CP-odd neutral Higgs Sector:

One Goldstone boson with zero mass (eaten by Z boson)

One physical state: $A = \cos\beta A_2 + \sin\beta A_1$

Soft SUSY breaking Higgs mass parameters

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

CP-even neutral Higgs Sector:

$$V[H_i^0] \to \begin{pmatrix} H_1^0 & H_2^0 \end{pmatrix} \begin{bmatrix} M_Z^2 \cos^2\beta + m_A^2 \sin^2\beta & -(M_Z^2 + m_A^2)\cos\beta\sin\beta \\ -(M_Z^2 + m_A^2)\cos\beta\sin\beta & M_Z^2 \sin^2\beta + m_A^2\cos^2\beta \end{bmatrix} \begin{pmatrix} H_1^0 \\ H_2^0 \end{pmatrix}$$

Two physical states:

$$h = \cos\alpha H_2^0 - \sin\alpha H_1^0$$
$$H = \sin\alpha H_2^0 + \cos\alpha H_1^0$$

$$m_{h,H}^2 = \frac{m_A^2 + M_Z^2}{2} \pm \frac{\sqrt{(m_A^2 + M_Z^2)^2 - 4M_Z^2 m_A^2 \cos^2 2\beta}}{2}$$

Charged Higgs Sector: (Similar to CP-odd Higgs sector)

One Goldstone boson with zero mass $\Rightarrow \det M_{H_\pm}^2 = 0$

One physical state: $H^\pm = \cos\beta H_2^\pm + \sin\beta H_1^\pm$

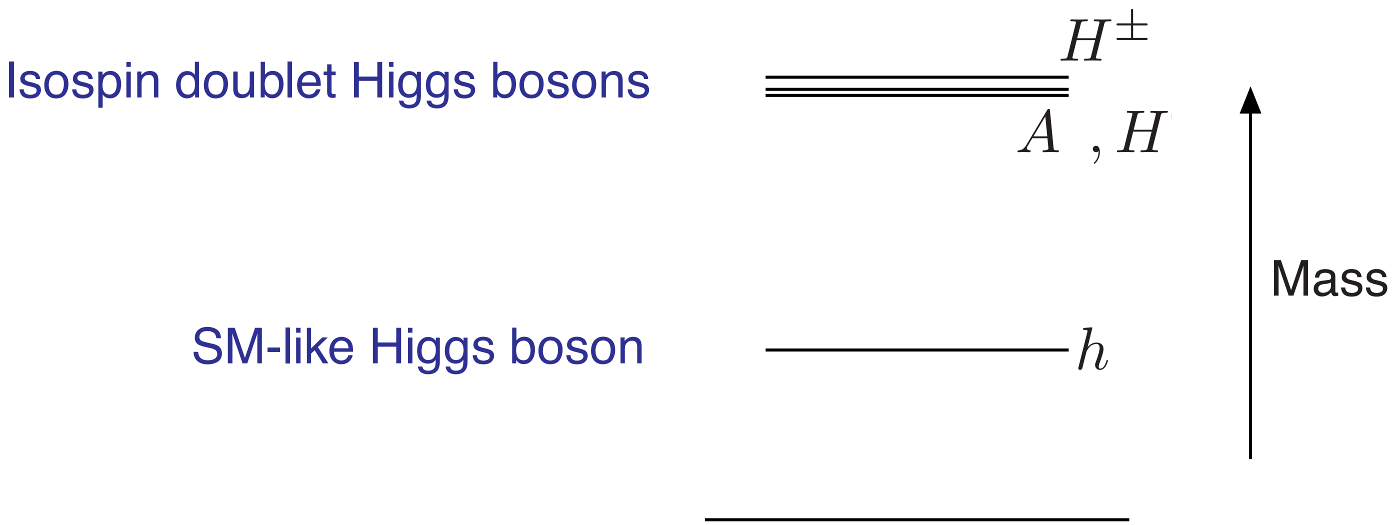
$$\mathrm{Tr}[\mathrm{M}_{\mathrm{H}^\pm}^2] = \mathrm{m}_\mathrm{A}^2 + \mathrm{m}_\mathrm{W}^2 = \mathrm{m}_{\mathrm{H}^\pm}^2$$

All tree-level masses given as a function of $\tan\beta,\ m_A$ and gauge couplings

The decoupling limit for the Higgs bosons

If $m_A \gg m_Z$, then: $m_h^2 = M_Z^2 \cos^2 2\beta$

- h has the same couplings as would a Standard Model Higgs boson of the same mass
- $\alpha \approx \beta - \pi/2$
- A, H, $H^{\pm}$ form an isospin doublet, and are much heavier than h



MSSM Higgs couplings to gauge bosons and fermions

<u>At tree level</u>: 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

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

(tanb enhanced)

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

Normalized to SM couplings

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

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

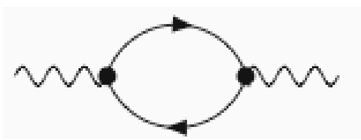
$$\text{such that } < \phi > = \mathrm{v}$$

while the orthogonal combination contains the other Higgs bosons

Quantum Corrections $\longleftrightarrow$ Evolution of Higgs quartic couplings below the SUSY breaking scale

Parameters that one measures at low energies (large distances) are not the fundamental ones, and they are modified by quantum corrections

Example: consider a charge in the vacuum, it polarizes the vacuum by inducing production of virtual particles/antiparticles that screen the charge



Same with couplings and masses: RG equations allow to relate fundamental parameters to those at low energies

Large $\tan\beta$ Limit

Given that $m_t = h_t v_2$ and $m_b = h_b v_1$

$$\downarrow$$

v_2 large keeps h_t perturbative

- If one makes h_b large, of the order of h_t, $\tan\beta$ is about 50
- For this limit to happen $m_3^2 \simeq 0$.
- Then, the doublet H_2 contains the Goldstone modes and the "physical" SM-like Higgs boson, while H_1 contains a scalar, a pseudoscalar and a charged Higgs boson.
- Physical Higgs mass ($m_2^2 = -M_Z^2/2$)

$$m_h^2 = 2\lambda_2 v^2 = M_Z^2$$

Radiative Corrections to the MSSM Higgs Masses

Important corrections due to incomplete cancellation of particles and sparticle effects.
Mainly top & stop loops and sbottom loops for tanb > 10

- The RG evolution of λ_2 is given by with $t = log(M_{SUSY}^2/Q^2)$.

$$\frac{d\lambda_2}{dt} \simeq -\frac{3}{8\pi^2}\left[\lambda_2^2 + \lambda_2 h_t^2 - h_t^4\right]$$

$M_{SUSY} \sim m_Q \sim m_U$

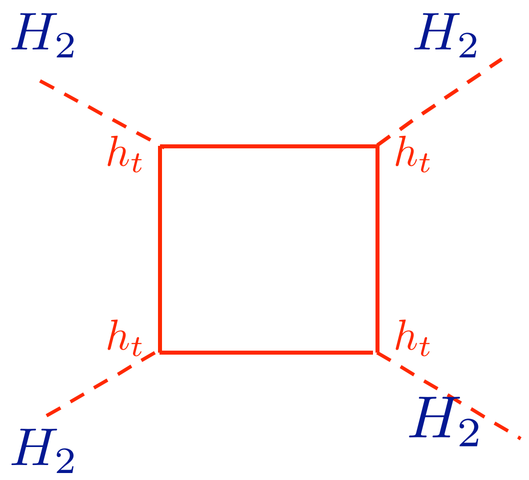
- For large values of $\tan\beta = v_2/v_1$, the Higgs H_2 is the only one associated with electroweak symmetry breaking.
- The Higgs boson mass is approximately given by $m_h^2 = 2\lambda_2 v^2$

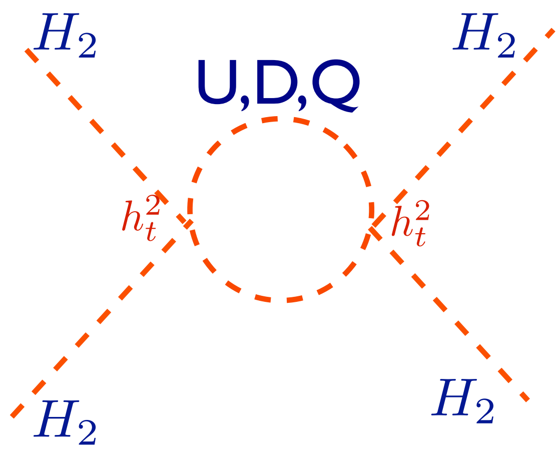
$$m_h^2 \simeq M_Z^2 + \frac{3m_t^4}{4\pi^2 v^2}\left[\log\left(\frac{M_{SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12 M_{SUSY}^2}\right)\right]$$

$M_{SUSY}^2 \rightarrow$ averaged stop squared mass $\quad X_t = A_t - \mu/\tan\beta \rightarrow$ stop mixing parameter

Log terms from RG evolution and A_t terms from threshold effects at M_{SUSY}

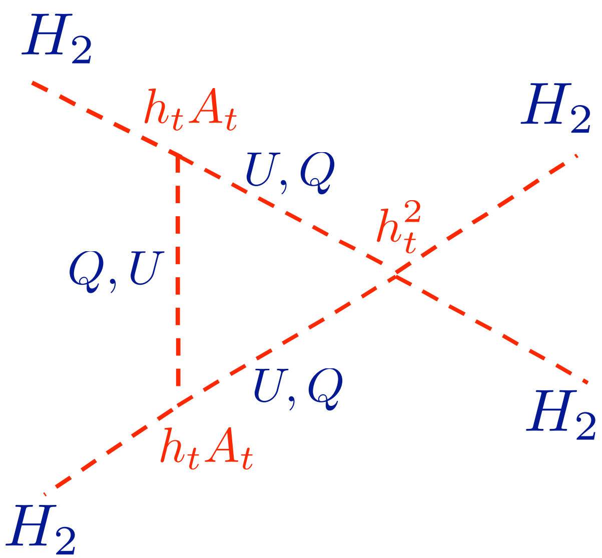
Top and Stop contributions to Higgs quartic couplings

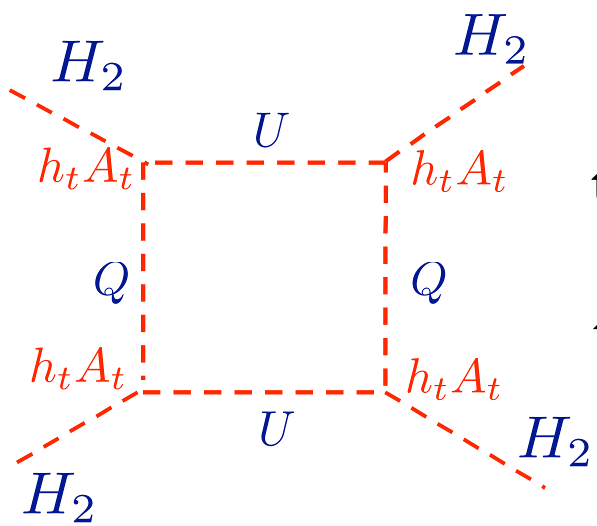




These diagrams provide the dominant logarithmic contributions below the stop mass scale.
If both masses were equal the log will vanish

Stop Threshold contributions to Higgs quartic coupling



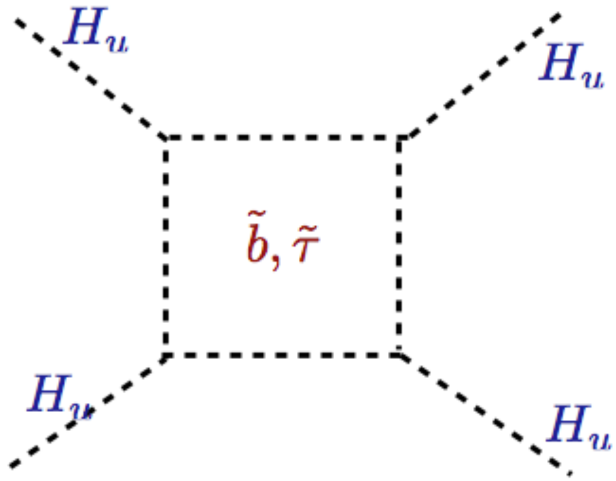


These diagrams provide the threshold corrections after decoupling of the top quarks superpartners

Additional effects at large tan beta from sbottoms:

$$\Delta m_h^2 \simeq - \frac{h_b^4 v^2}{16\pi^2} \frac{\mu^4}{M_{\rm SUSY}^4}$$

with $h_b \simeq \dfrac{m_b}{v\cos\beta(1+\tan\beta\Delta h_b)}$



receiving one loop corrections that depend on the sign of $\mu M_{\tilde{g}}$

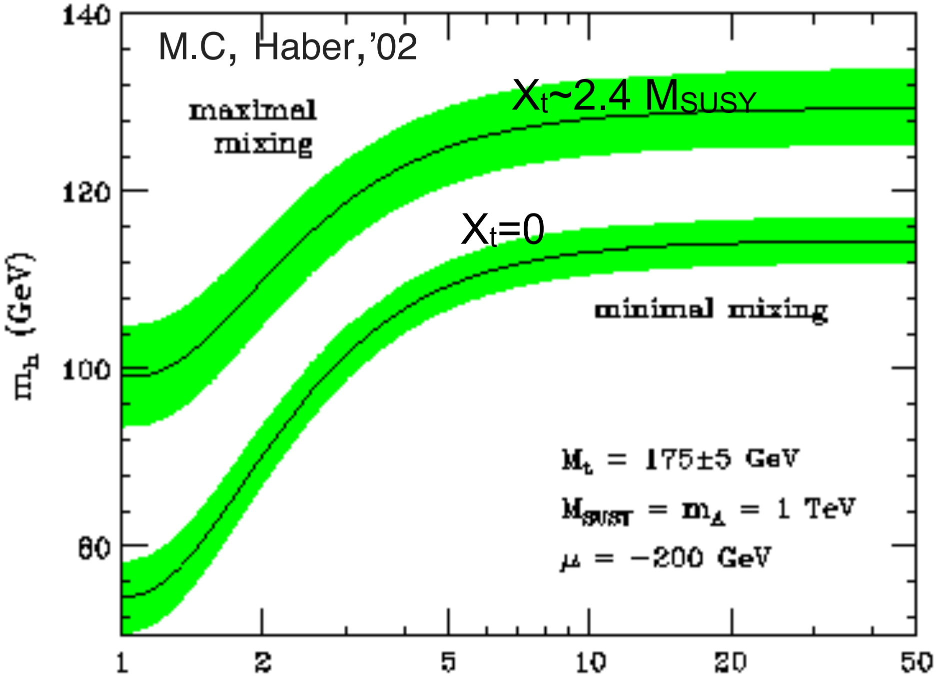
and staus: $\Delta m_h^2 \simeq - \dfrac{h_\tau^4 v^2}{48\pi^2} \dfrac{\mu^4}{M_{\tilde{\tau}}^4}$

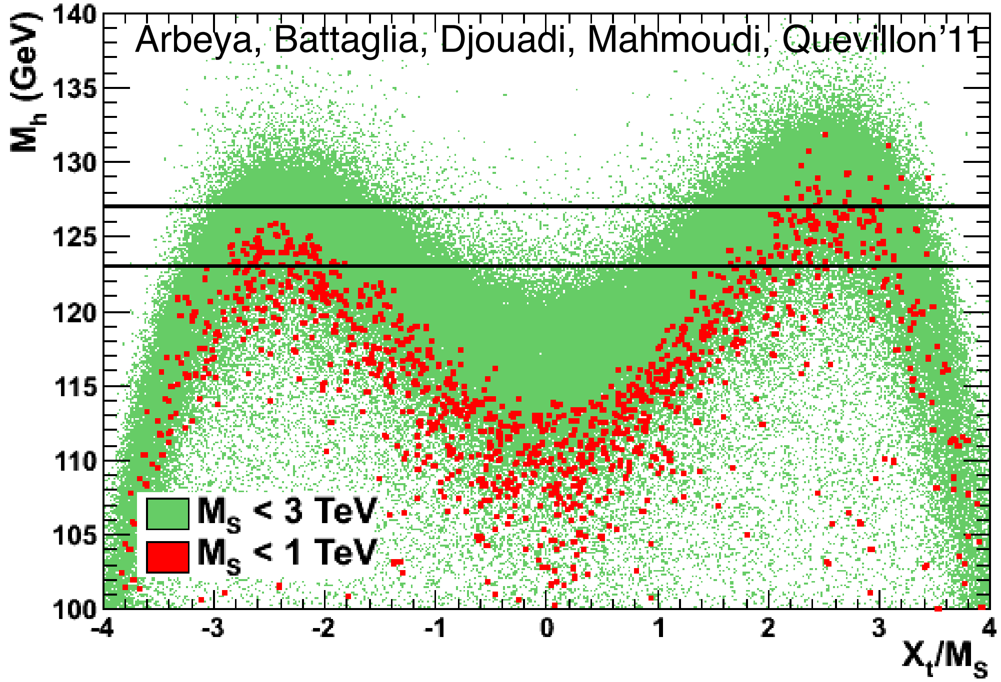
with $h_\tau \simeq \dfrac{m_\tau}{v\cos\beta(1+\tan\beta\Delta h_\tau)}$ Dep. on the sign of μM_2

Both corrections give negative contributions to the Higgs mass hence smaller values of μ and positive values of μM_2 and $\mu M_{\tilde{g}}$ enhance the value of the Higgs mass

Maximal effect: lower m_h by several GeV

SM-like MSSM Scalar Boson Mass:





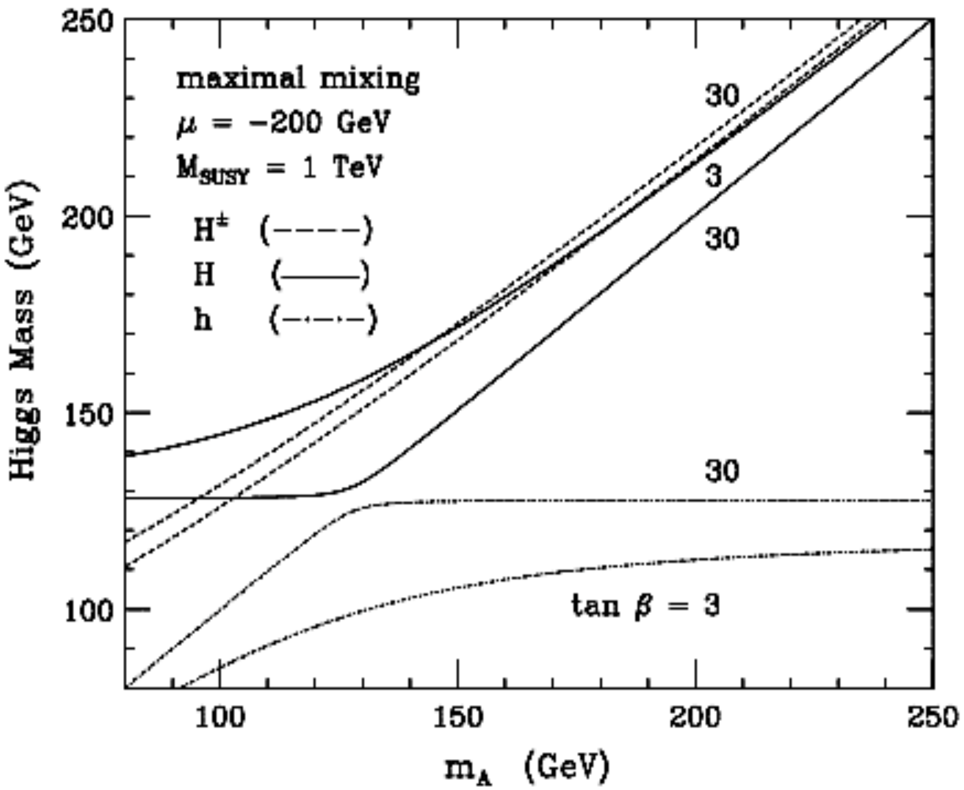
For moderate to large values of tan beta and large non-standard Scalar boson masses

$$\boxed{m_h^2 \cong M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{1}{2}\tilde{X}_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right]}$$

$$t = \log(M_{SUSY}^2 / m_t^2) \qquad \tilde{X}_t = \frac{2X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12 M_{SUSY}^2}\right) \qquad \underline{X_t = A_t - \mu/\tan\beta} \rightarrow \text{LR stop mixing}$$

$$\boxed{m_h \leq 130 \text{ GeV}}$$ (for sparticles of ~ 1 TeV)

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 $m_h^{max} \lesssim 135$ 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

Radiative corrections to the Higgs couplings

I) Important effects through radiative corrections to the CP-even Mass matrix

can have relevant effects in the production and decay rates

$$\mathcal{M}_H^2 = \begin{bmatrix} m_A^2 \sin^2\beta + M_Z^2 \cos^2\beta & -(m_A^2 + M_Z^2)\sin\beta\cos\beta + \mathrm{Loop}_{12} \\ -(m_A^2 + M_Z^2)\sin\beta\cos\beta + \mathrm{Loop}_{12} & m_A^2 \cos^2\beta + M_Z^2 \sin^2\beta + \mathrm{Loop}_{22} \end{bmatrix}$$

$$\mathrm{Loop}_{12} = \frac{m_t^4}{16\pi^2 v^2 \sin^2\beta} \frac{\mu \bar{A}_t}{M_{\mathrm{SUSY}}^2} \left[\frac{A_t \bar{A}_t}{M_{\mathrm{SUSY}}^2} - 6\right] + \frac{h_b^4 v^2}{16\pi^2} \sin^2\beta \frac{\mu^3 A_b}{M_{\mathrm{SUSY}}^4} + \frac{h_\tau^4 v^2}{48\pi^2} \sin^2\beta \frac{\mu^3 A_\tau}{M_{\tilde{\tau}}^4}$$

Radiative corrections to the CP-even mass matrix
affect the mixing angle alpha
that governs couplings of Higgs to fermions

$$\sin\alpha\cos\alpha = M_{12}^2 / \sqrt{\left(\mathrm{Tr}\, M^2\right)^2 - 4 \det M^2}$$

Normalized to SM ones

$$g_{hu\bar{u},Hu\bar{u},Au\bar{u}} \to \cos\alpha/\sin\beta, \quad \sin\alpha/\sin\beta, \quad 1/\tan\beta$$

$$g_{hb\bar{b},Hb\bar{b},Ab\bar{b}} \to -\sin\alpha/\cos\beta, \quad \cos\alpha/\cos\beta, \quad \tan\beta$$ (same for leptons)

If off diagonal elements **suppressed/enhanced**: same occurs for sinα or cosα

==> **suppression/enhancement** of SM-like Higgs coupling to bb and ττ

leads to enhancement/suppression of BR(h/H to WW/ZZ/γγ) for $m_{h/H}$ < 135 GeV

2) Important vertex corrections to Higgs-fermion Yukawa couplings through loops of SUSY particles

relevant for large $\tan\beta \geq 20$,

and can induce important flavor changing neutral and charged current effects

Recall:

In the SM, in the mass eigenstate basis, the Higgs interactions are flavor diagonal

Two Higgs doublet Models:

Yukawa interactions ==> $\bar{d}_{R,i}(\hat{h}^{ij}_{d,1}\ \phi_1^* + \hat{h}^{ij}_{d,2}\ \phi_2^*)\ d_{L,j}$

$\phi_1 = \epsilon_{ij} H_1^* \quad \phi_2 = H_2$

Different v.e.v.'s ==> $\hat{m}^{ij}_d = \hat{h}^{ij}_{d,1} v_1 + \hat{h}^{ij}_{d,2} v_2$

Diagonalization of the mass matrix will not give diagonal Yukawa couplings

==> will induce large, usually unacceptable FCNC in the Higgs sector

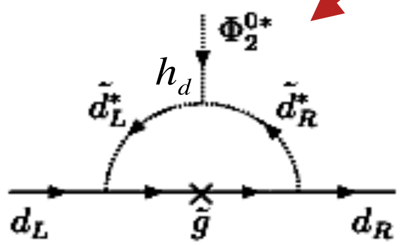
Solution: Each Higgs doublet couples only to one type of quarks

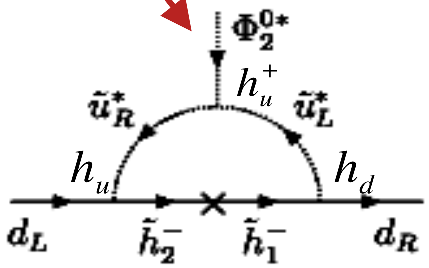
==> SUSY at tree level

After radiative corrections: ==> both Higgs doublets couple to the up and down /lepton sectors

The neutral Higgs sector: radiative corrections induce FCNC

$$-L_{eff.} = \bar{d}_R^0 \hat{h}_d \left[\phi_1^{0^*} + \phi_2^{0^*} \left(\hat{\varepsilon}_0 + \hat{\varepsilon}_Y \hat{h}_u^+ \hat{h}_u \right) \right] d_L^o + \phi_2^0 \bar{u}_R^0 \hat{h}_u u_L^0 + h.c.$$





ε loop factors intimately connected to the structure of the squark mass matrices.

- **<u>In terms of the quark mass eigenstates</u>**

$$-L_{eff} = \frac{1}{v_2} \left(\tan\beta \, \Phi_1^{0^*} - \Phi_2^{0^*} \right) \bar{d}_R M_d \left[V_{CKM}^+ R^{-1} V_{CKM} \right] d_L + \ldots$$

and $R = 1 + \varepsilon_0 \tan\beta + \varepsilon_Y \tan\beta |h_u|^2$ ➔ R diagonal with $R^{33} \equiv 1 + \Delta_b$

Dependence on SUSY parameters ➞ $\varepsilon_0^i \approx \dfrac{2\alpha_s}{3\pi} \dfrac{\mu^* M_{\tilde{g}}^*}{\max\left[m_{\tilde{d}_1^i}^2, m_{\tilde{d}_2^i}^2, M_{\tilde{g}}^2 \right]}$ $\quad \varepsilon_Y \approx \dfrac{\mu^* A_t^*}{16\pi^2 \max\left[m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2, \mu^2 \right]}$

Higgs Physics strongly connected to flavor physics and to the ~~SUSY~~ mechanism.

Flavor Conserving Higgs-fermion couplings

Looking at large $\tan\beta$ and $V_{CKM}^{33} = 1$

$$-L_{eff} \approx \frac{1}{\mathrm{v}_2} \tan\beta \, \Phi_1^{0*} \, \bar{\mathrm{d}}_R M_d \frac{1}{R^{33}} \mathrm{d}_L + h.\,c. = \frac{\mathrm{m_b} \tan\beta}{(1+\Delta_b)\mathrm{v}} \phi_1^{0*} \bar{\mathrm{d}}_R \mathrm{d}_L + h.c.$$

$$R^{33} = 1 + (\varepsilon_0^3 + \varepsilon_Y h_t^2) \tan\beta \equiv 1 + \Delta_b$$

In terms of the Higgs mass eigenstates:

$$\boxed{\begin{aligned} \phi_1^0 &= -\sin\alpha\, \mathrm{h} + \cos\alpha\, \mathrm{H} + \mathrm{i} \sin\beta \;\, \mathrm{A} \\ \phi_2^0 &= \cos\alpha\, \mathrm{h} + \sin\alpha\, \mathrm{H} \;-\; \mathrm{i} \cos\beta \;\, \mathrm{A} \end{aligned}}$$

and at large $\tan\beta$, $m_A > m_h^{\max}$:

$\cos\alpha \approx \sin\beta;\;\; \sin\alpha \approx -\cos\beta$

$$\boxed{H + iA \cong \sin\beta \;\; \phi_1^0 - \cos\beta \; \phi_2^0}$$

$$\longrightarrow \quad \boxed{g_{Abb} \cong g_{Hbb} \cong \frac{m_b \tan\beta}{(1+\Delta_b)\mathrm{v}}}$$

$$|\Delta_\tau| << |\Delta_b| \Rightarrow \boxed{g_{A\tau\tau} \cong g_{H\tau\tau} \cong m_\tau \tan\beta / \mathrm{v}} \longrightarrow$$

destroy basic relation

$$g_{A/H\ \mathrm{bb}} / g_{A/H\ \tau\tau} \propto m_b / m_\tau$$

In general, Higgs -third generation fermion couplings

$$\mathcal{L}_{\rm int} \quad = \quad - \sum_{q=t,b,\tau} \left[g_{hq\bar{q}} hq\bar{q} + g_{Hq\bar{q}} Hq\bar{q} - i g_{Aq\bar{q}} A\bar{q}\gamma_5 q \right] + \left[\bar{b} g_{H^- t\bar{b}} t H^- + {\rm h.c.} \right] .$$

$$\boxed{g_{H^- t\bar{b}} \quad \simeq \quad \left\{ \frac{m_t}{v} \cot\beta \left[1 - \frac{1}{1+\Delta_t} \frac{\Delta h_t}{h_t} \tan\beta \right] P_R + \frac{m_b}{v} \tan\beta \left[\frac{1}{(1+\Delta_b)} \right] P_L \right\}}$$

those involving bottom quarks

$$g_{h\, b\bar{b}} \simeq \frac{-\sin\alpha\, m_b}{v\ \cos\beta(1+\Delta_b)} \left(1 - \Delta_b / \tan\alpha \tan\beta\right)$$

$$g_{H\, b\bar{b}} \simeq \frac{\cos\alpha\, m_b}{v\ \cos\beta(1+\Delta_b)} \left(1 - \Delta_b \tan\alpha / \tan\beta\right)$$

$$g_{A\, b\bar{b}} \simeq \frac{m_b}{v(1+\Delta_b)}\ \tan\beta$$

- strong suppression of coupling of **hbb coupling if**

$\tan\alpha \simeq \Delta_b / \tan\beta \quad \longrightarrow g_{h\, b\bar{b}} \simeq 0 \quad ; \; g_{h\,\tau\tau} \simeq -\frac{m_\tau}{v} \Delta_b$ (similar for H)

$\Longrightarrow$ main decay modes of SM-like MSSM Higgs: $b\bar{b} \sim 80\%$ $\quad \tau^+\tau^- \sim 7-8\%$

drastically changed $\Longrightarrow$ other decay modes enhanced

$\Longrightarrow$ Higgs phenomenology at colliders revisited!!

Given the Discovery of a SM-like Scalar boson particle with mass ~ 125 GeV

- Do we still expect SUSY (some type of low energy SUSY) ?
- If yes, what does it imply for SUSY models?

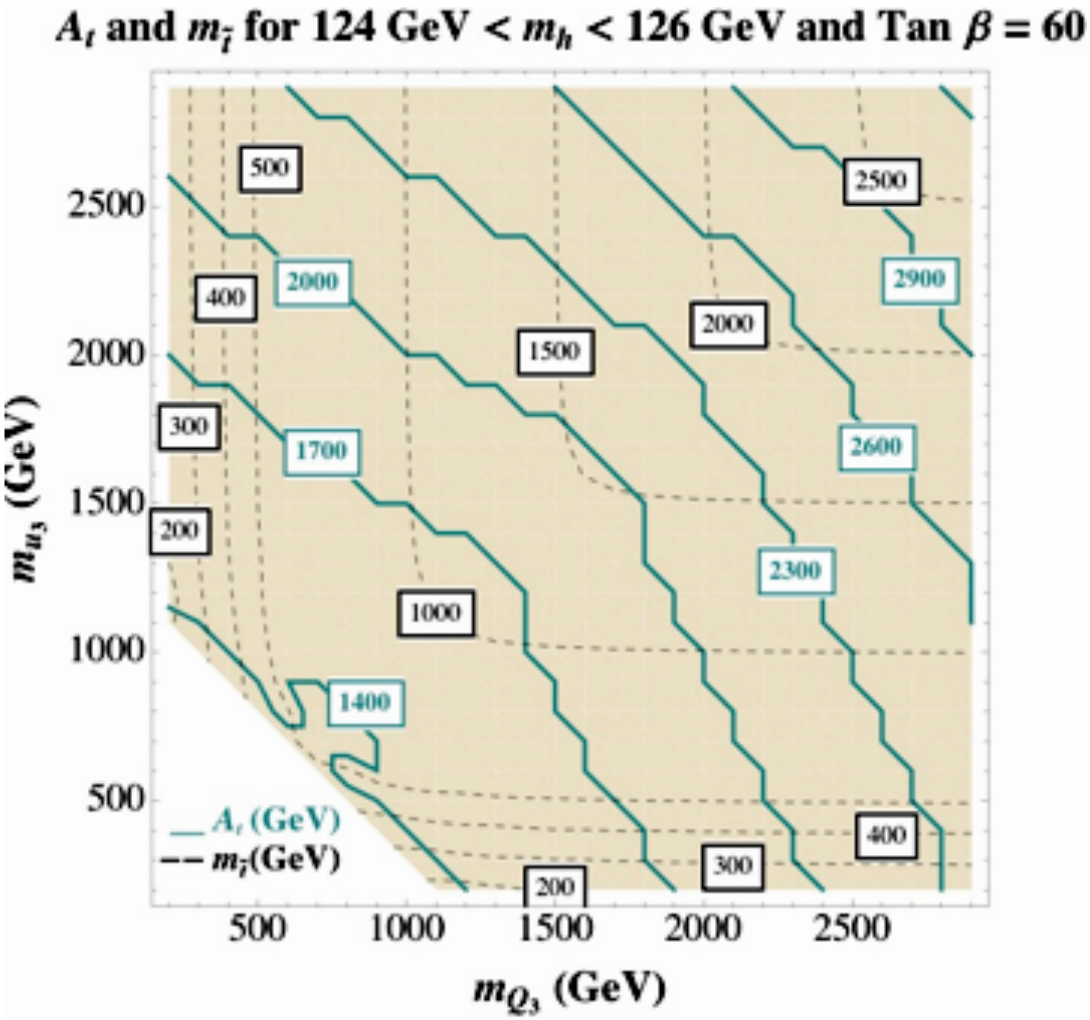
large mixing in the stop sector
or
new matter or gauge superfields

Both alternatives have important implications for the Higgs production and decay rates

They also have implications for the flavor-Higgs connection within assumption of MFV at the SUSY breaking scale

DM constraints less strongly correlated since predictions depend strongly on gaugino soft masses, not very relevant for Higgs rad. corrections.

Soft supersymmetry Breaking Parameters in the MSSM



Large stop sector mixing
A_t > 1 TeV

No lower bound on the lightest stop
One stop can be light and the other heavy
or
in the case of similar stop soft masses.
both stops can be below 1TeV

Large mixing also constrains
SUSY breaking model building

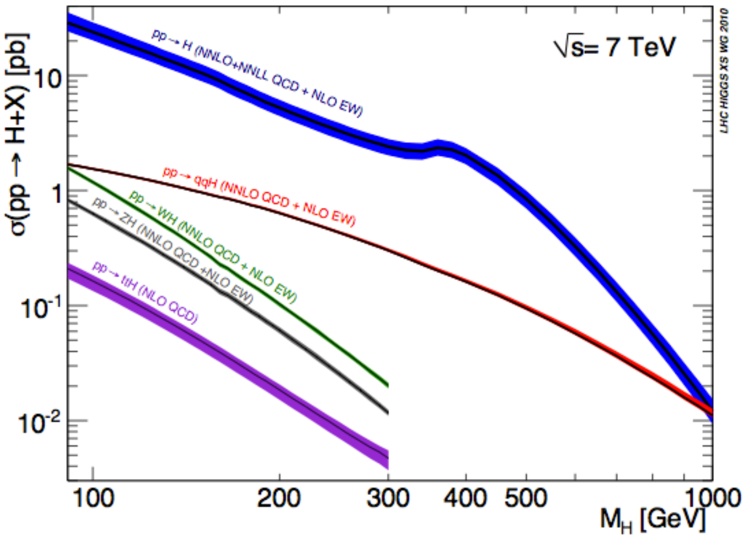
M. C., S. Gori, N. Shah, C. Wagner '11
+L.T.Wang '12

Similar results from
Arbey, Battaglia, Djouadi, Mahmoudi, Quevillon '11
Draper Meade, Reece, Shih'11
Shirman et al.

Can departures from the SM in the production/decay rates at the LHC disentangle among different SUSY spectra?

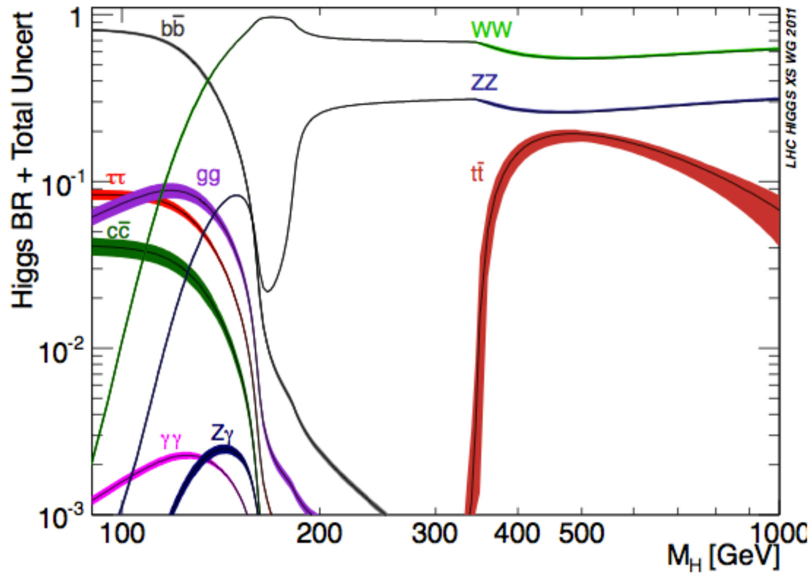
The event rates: $$B\sigma(p\bar{p} \to h \to X_{\rm SM}) \equiv \sigma(p\bar{p} \to h)\frac{\Gamma(h \to X_{\rm SM})}{\Gamma_{\rm total}}$$

- All three quantities may be affected by new physics.
- If one partial width is modified, the total width is modified as well, modifying all BR's.



Main production channel:
Gluon Fusion

Main/first search modes:
decay into γγ/ZZ/WW



How much can we perturb the gluon production mode?

Is it possible to change WW and ZZ decay rates independently?

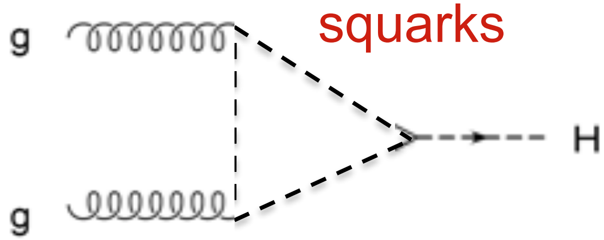
Can we vary the Higgs rate into di-photons independently from the rate into WW/ZZ?

Can we change the ratio of b-pair to tau pair decay rates?

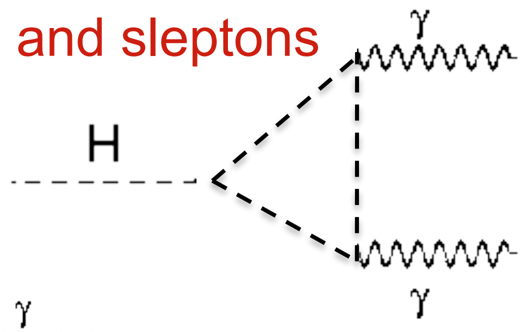
Possible departures in the production and decay rates at the LHC

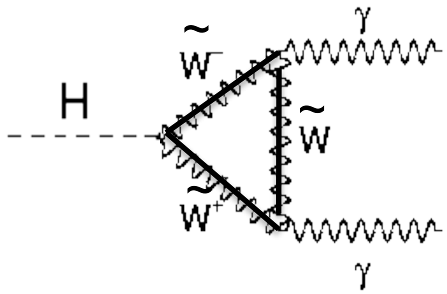
- Through SUSY particle effects in loop induced processes

squarks



squarks and sleptons





charginos

❖ Through enhancement/suppression of the Hbb and H$\tau\tau$ coupling strength via mixing in the scalar boson sector :
This affects in similar manner BR's into all other particles

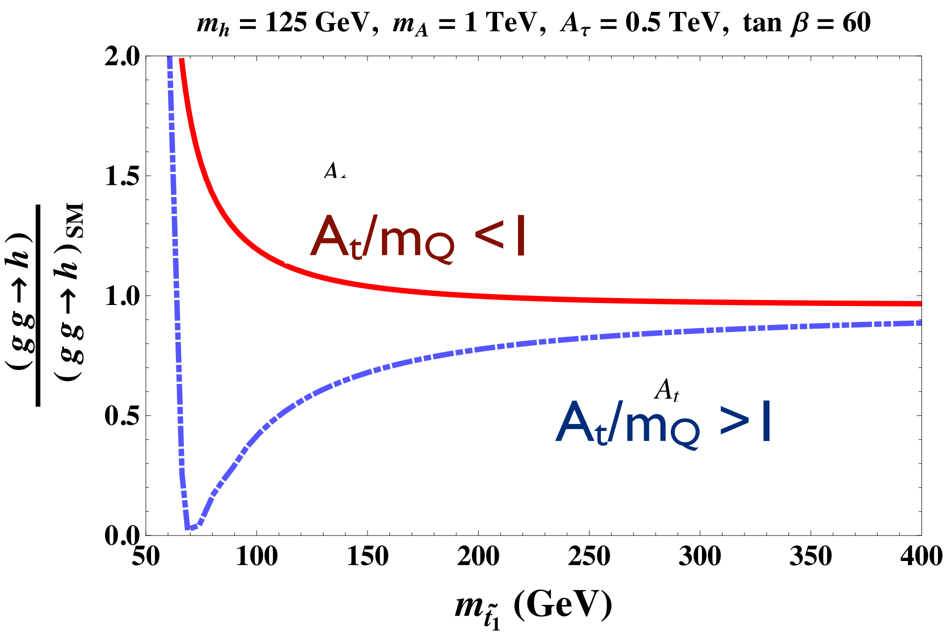
❖ Through vertex corrections to Yukawa couplings: different for bottoms and taus
This destroys the SM relation BR($h \rightarrow bb$)/BR($h \rightarrow \tau\tau$) ~ m_b^2/m_τ^2

❖ Through decays to new particles (including invisible decays)
This affects in similar manner BR's to all SM particles

Gluon Fusion in the MSSM

Light stops can increase the gluon fusion rate, but for large stop mixing X_t as required for m_h~125 GeV mostly leads to moderate suppression

[light sbottoms lead to suppression for large tanβ]



M.C.,Gori, Shah, Wagner, Wang

See also Dermisek, Low'07.

Natural SUSY fit: Espinosa, Grojean, Saenz, Trotta '12

$$\delta A^{\tilde{t}}_{\gamma\gamma,gg} \propto \frac{m_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\left[m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 - X_t^2\right]$$

Ellis, Gaillard, Nanopoulos '76

Shifman, Vainshtein, Voloshin, Zakharov'79; MC. Low, Wagner'12

If one stop much heavier: $m_Q >> m_U$ and large tanβ

$$\delta A^{\tilde{t}}_{\gamma\gamma,gg} \propto \frac{m_t^2}{m_{\tilde{t}_1}^2}\left[1 - \frac{A_t^2}{m_Q^2}\right]$$

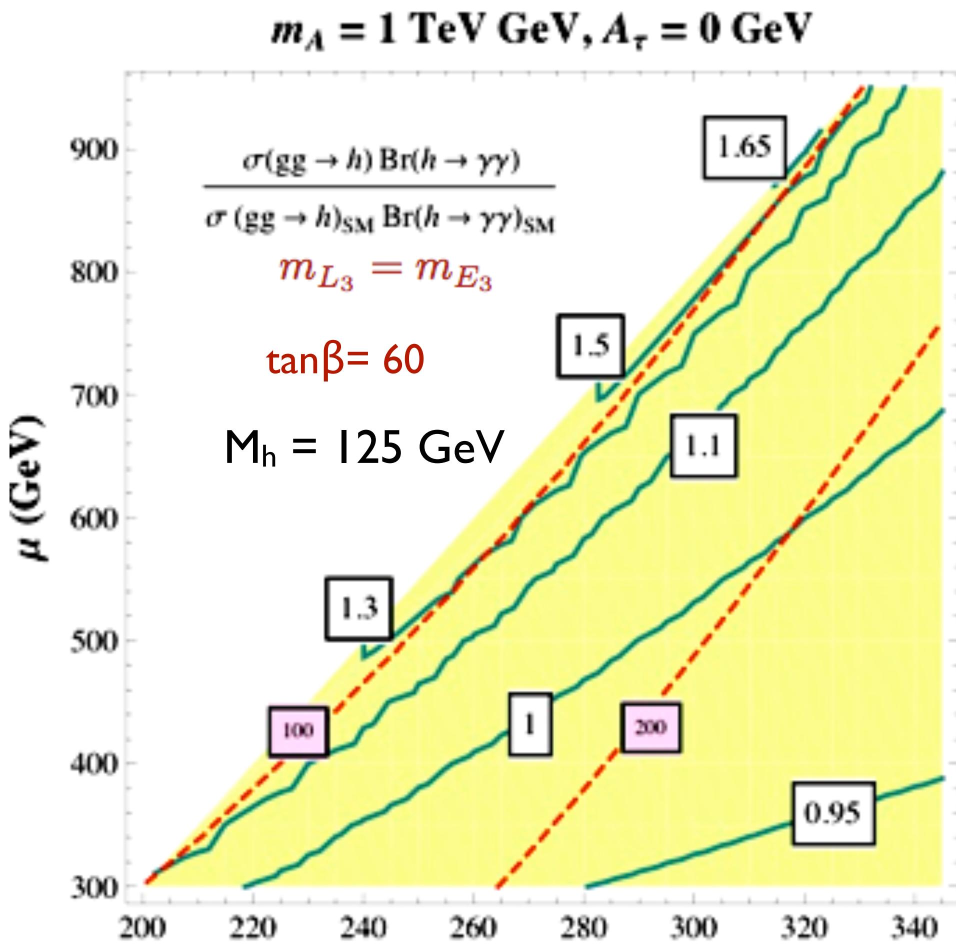
$$\frac{\sigma(gg \to h)BR(h \to \gamma\gamma)}{\sigma(gg \to h)_{SM}BR(h \to \gamma\gamma)_{SM}} < (>)1$$

Squark effects in gluon fusion overcome opposite effects in di-photon decay rate:

$$\text{If } \frac{\sigma(\text{gg} \to \text{h})}{\sigma(\text{gg} \to \text{h})_{\text{SM}}} < (>)1$$

Higgs Production in the di-photon channel in the MSSM

Charged scalar particles with no color charge can change di-photon rate without modification of the gluon production process



M. C, S. Gori, N. Shah, C. Wagner,'11 +L.T.Wang'12

$$\mathcal{M}^2_{\tilde{\tau}} \simeq \begin{bmatrix} m^2_{L_3} + m^2_\tau + D_L & h_\tau v(A_\tau \cos\beta - \mu \sin\beta) \\ h_\tau v(A_\tau \cos\beta - \mu \sin\beta) & m^2_{E_3} + m^2_\tau + D_R \end{bmatrix}$$

$$\delta A_{h\gamma\gamma} \propto -\frac{m_\tau^2}{m^2_{\tilde{\tau}_1} m^2_{\tilde{\tau}_2}}(m^2_{\tilde{\tau}_1} + m^2_{\tilde{\tau}_2} - \chi^2_\tau)$$

Light staus with large mixing

[sizeable μ and tan beta]:

➔ enhancement of the

Higgs to di-photon decay rate

- up to 50 % with SM-like ZZ/WW -

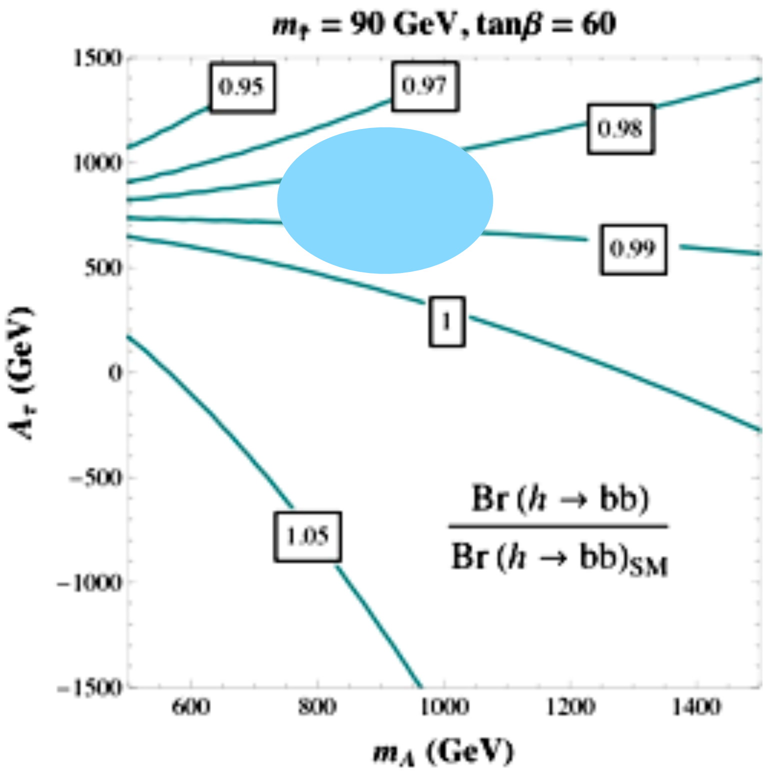
For a generic discussion of modified γγ and Zγ widths by new charged particles, see M. C. ,Low and C. Wagner'12; for specific connection with light staus: Giudice, Paradisi,Strumia'12

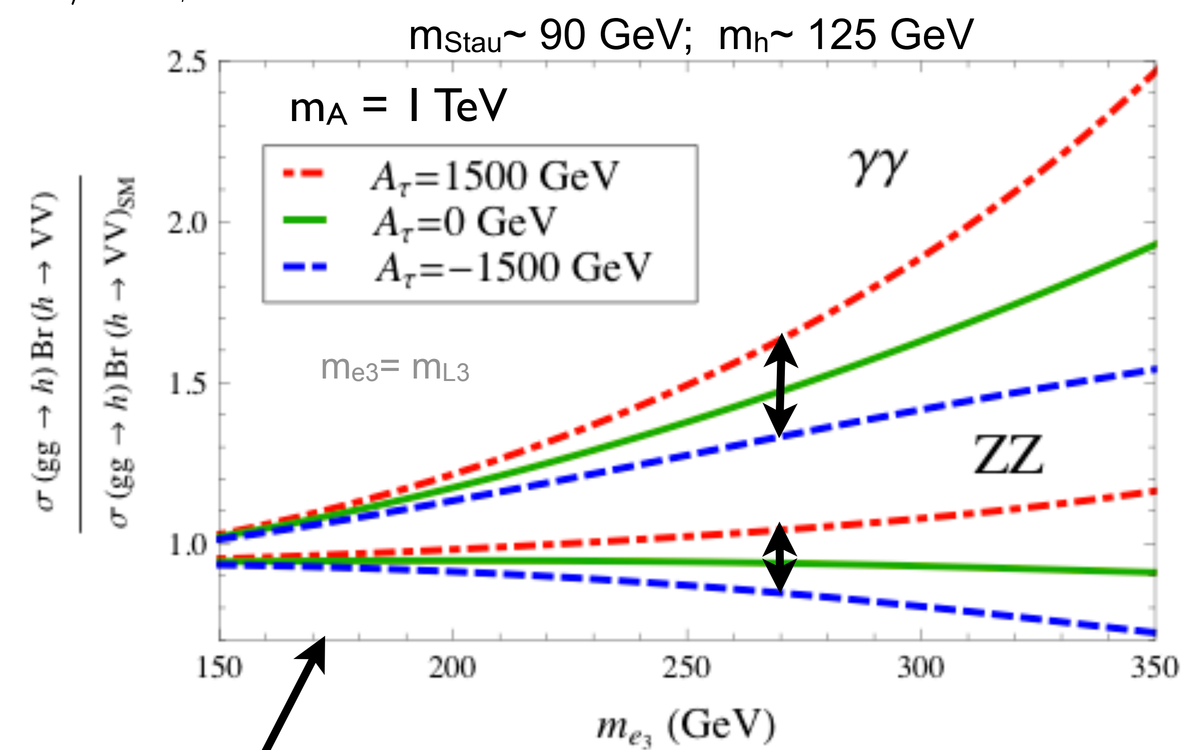
MSSM scan: Benbrik, Gomez Bock, Heinemeyer, Stal, Weigein, Zeune'12

Additional modifications of the Higgs rates into gauge bosons via stau induced mixing effects in the Higgs sector

Important A_τ induced radiative corrections to the mixing angle α

$$g_{h\bar{b}b,h\tau^+\tau^-} \propto -\sin\alpha/\cos\beta$$





Values of the soft parameters larger than ~ 250 GeV tend to lead to vacuum stability problems

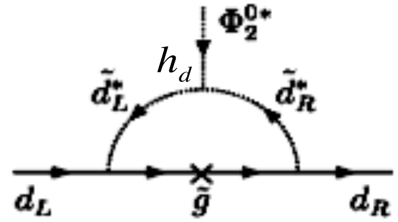
M. C. Gori, Shah, Wagner,'11 + Wang'12

Small variations in BR [H to bb] induce significant variations in the other Higgs BR's

Similar results for example within pMSSM/MSSM fits: Arbey, Battagllia, Djouadi,Mahmoudi '12
Benbrik, Gomez Bock, Heinemeyer, Stal, Weiglein, Zeune'12

After SUSY breaking all fermions couple to both Higgs Doublets

$$g_{hbb,h\tau\tau} = -h_{b,\tau} \sin\alpha + \Delta h_{b,\tau} \cos\alpha$$



can change the relative strength of Higgs decays to b and tau pairs

Modification of the tree level relation between $h_{b,\tau}$ and $m_{b,\tau}$

$$m_{b,\tau} \simeq \frac{h_{b,\tau} v}{\sqrt{2}} \cos\beta \left(1 + \frac{\Delta_{h_{b,\tau}}}{h_{b,\tau}} \tan\beta\right)$$

$\Delta_{b,\tau}$

$$g_{hbb,h\tau\tau} = -\frac{m_{b,\tau} \sin\alpha}{v \cos\beta (1 + \Delta_{b,\tau})} \left[1 - \frac{\Delta_{b,\tau}}{\tan\beta \tan\alpha}\right]$$

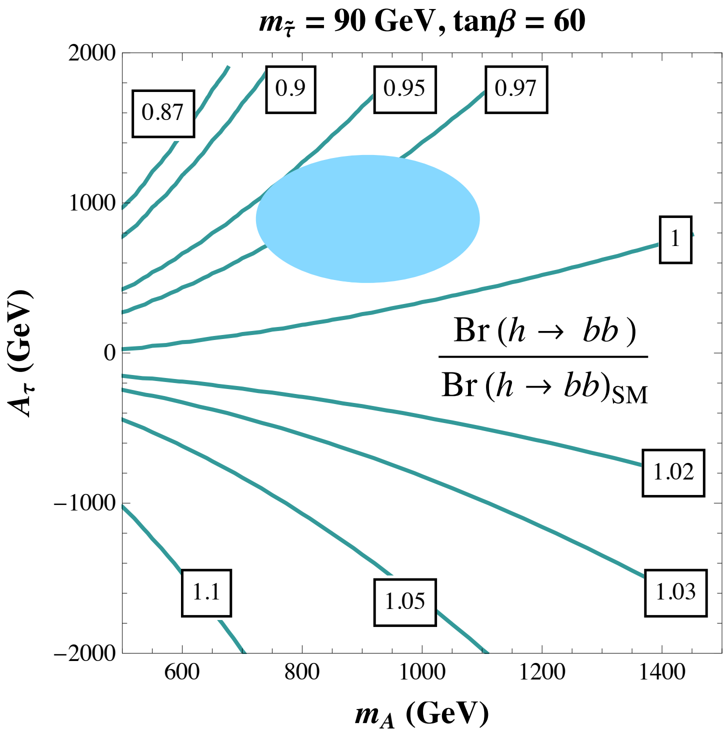
$\boxed{\text{destroy basic relation } g_{h,H,Abb}/g_{h,H,A\,\tau\tau} \propto m_b/m_\tau}$

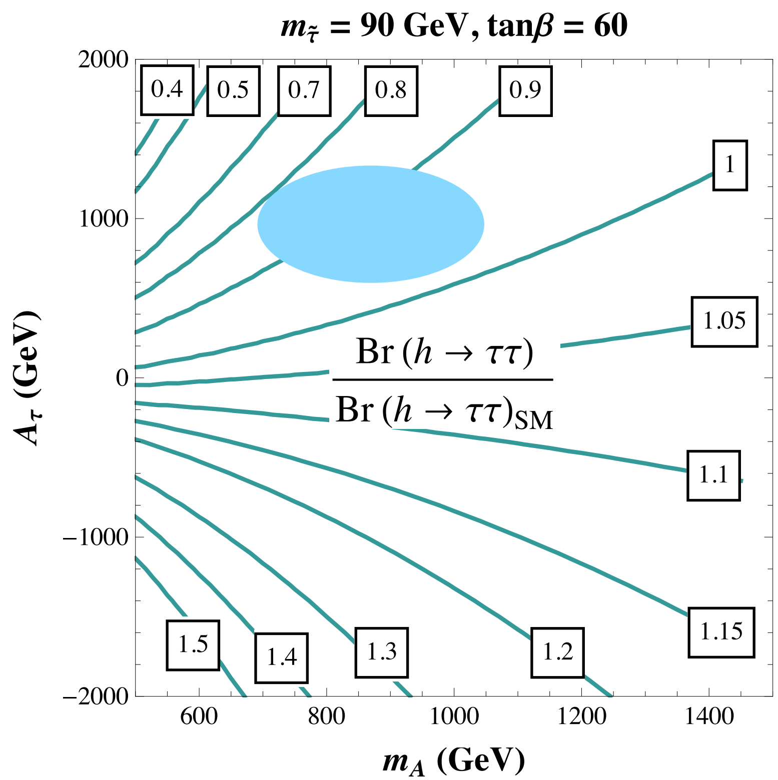
M.C. Mrenna, Wagner '98
Haber,Herrero, Logan, Penaranda, Rigolin, Temes '00

Radiative corrections ==> main decay modes of the SM-like MSSM Higgs into b- and tau-pairs can be drastically changed

Suppression of the h to taus to h to b's ratio

due to different radiative SUSY corrections to higgs-fermion couplings



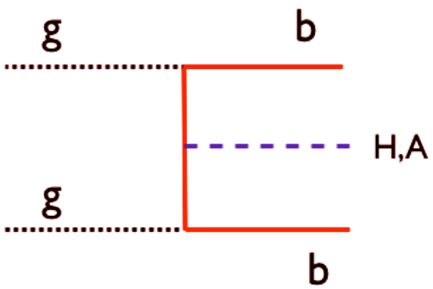


Suppression of di-tau rate
not larger than 10%
due to metastability constraints

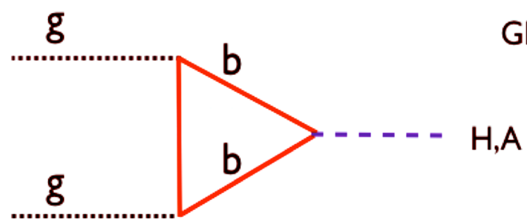
M. C., Gori, Shah, Wagner, Wang'12

Non-Standard Higgs Production at the Tevatron and LHC

- Important effects on couplings to b quarks and tau-leptons



Associated Production



Gluon Fusion

$$\rightarrow g_{bbA/H} \approx \frac{m_b \tan\beta}{\left(1+\Delta_b\right)v}$$

- Considering value of running bottom mass and 3 quark colors

$$BR(A \rightarrow b\bar{b}) \cong \frac{9}{9+\left(1+\Delta_b\right)^2} \Rightarrow \boxed{\sigma\left(b\bar{b}A\right) \times BR\left(A \rightarrow b\bar{b}\right) \cong \sigma\left(b\bar{b}A\right)_{SM} \times \frac{\tan\beta^2}{\left(1+\Delta_b\right)^2} \times \frac{9}{\left(1+\Delta_b\right)^2+9}}$$

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

There is a strong dependence on the SUSY parameters in the bb search channel.
This dependence is much weaker in the tau-tau channel

MSSM Higgs Boson Searches at colliders

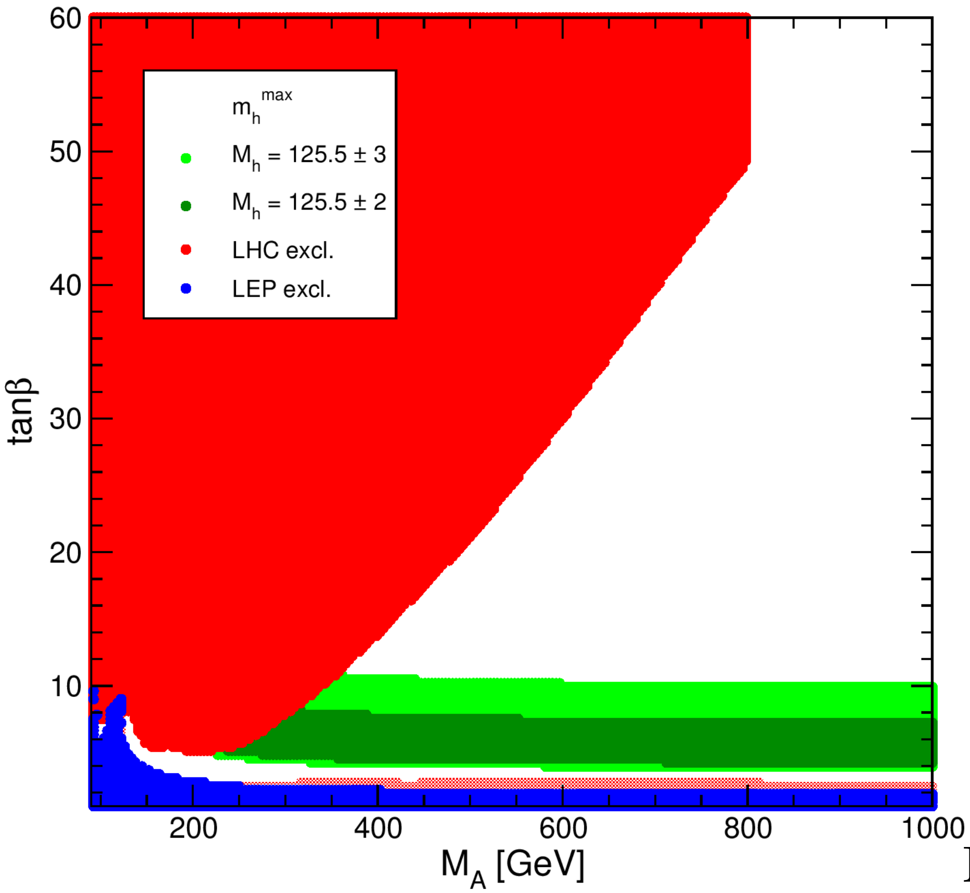
1) Discovery of a SM-like Higgs responsible for EWSB
must have SM-like couplings to W-Z gauge bosons
and most probably SM-like couplings to the top-quark

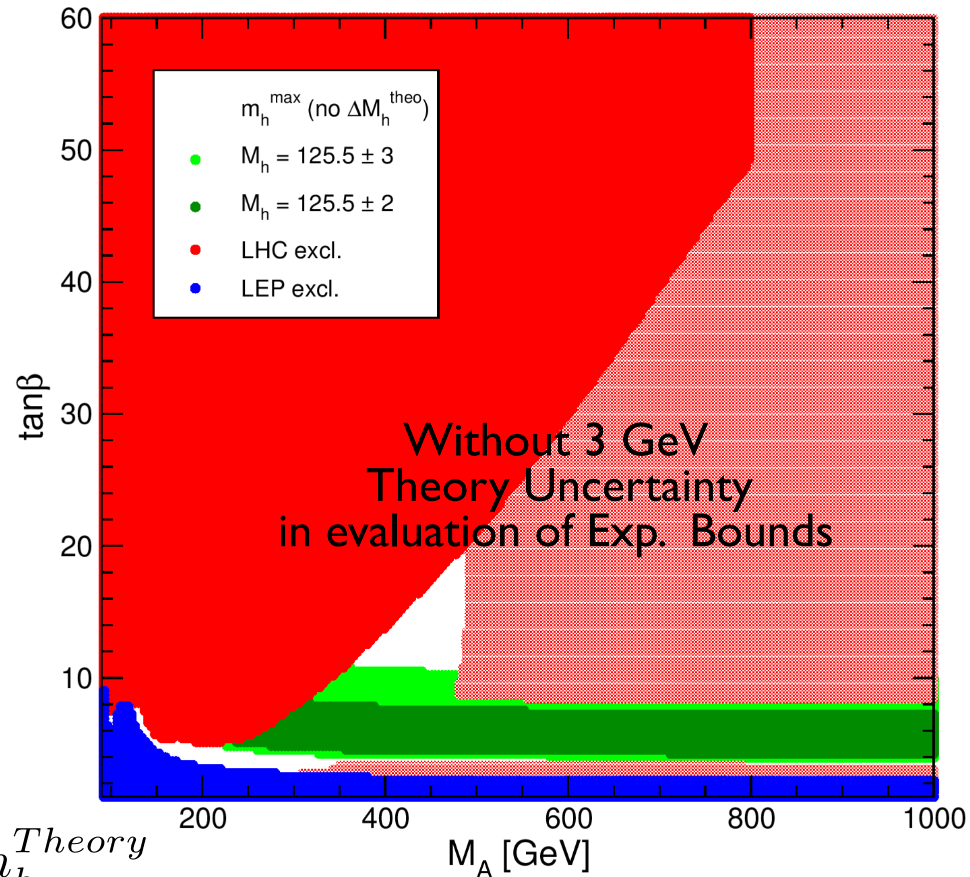
2) Search for the non-SM-like neutral Higgs bosons A and H
they have $\tan\beta$ enhanced couplings to the bottom quarks

Benchmark Scenarios for the Search of MSSM Scalar Bosons

with 125.5 GeV signal interpreted as h (or H)

m_h^{max} scenario (updated with M_{gluino} = 1.5 TeV, m_t = 173.2 GeV)





No Δm_h^{Theory}

Green region favored by LHC observation

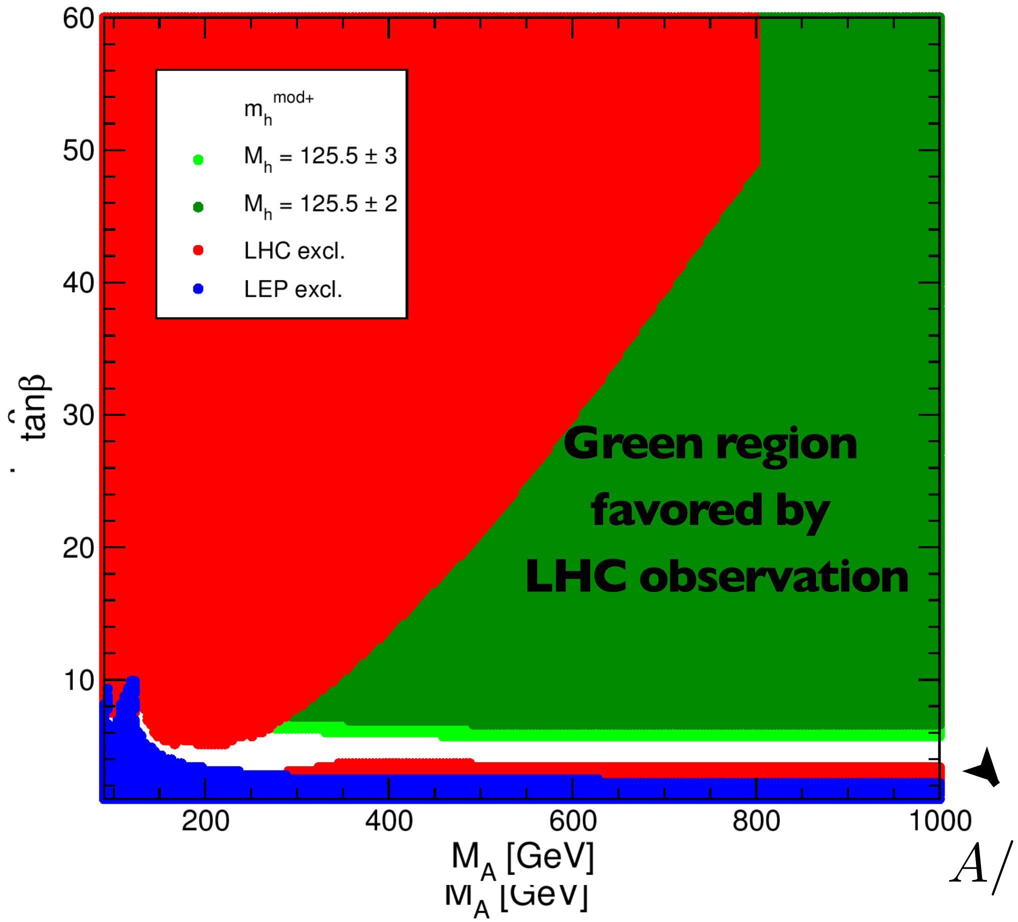
Lower bound on tanβ, M_A and M_{H+}
(slightly relaxed if M_{SUSY} ~ 2TeV)

M.C., Heinemeyer, Stal, Wagner, Weiglein '13

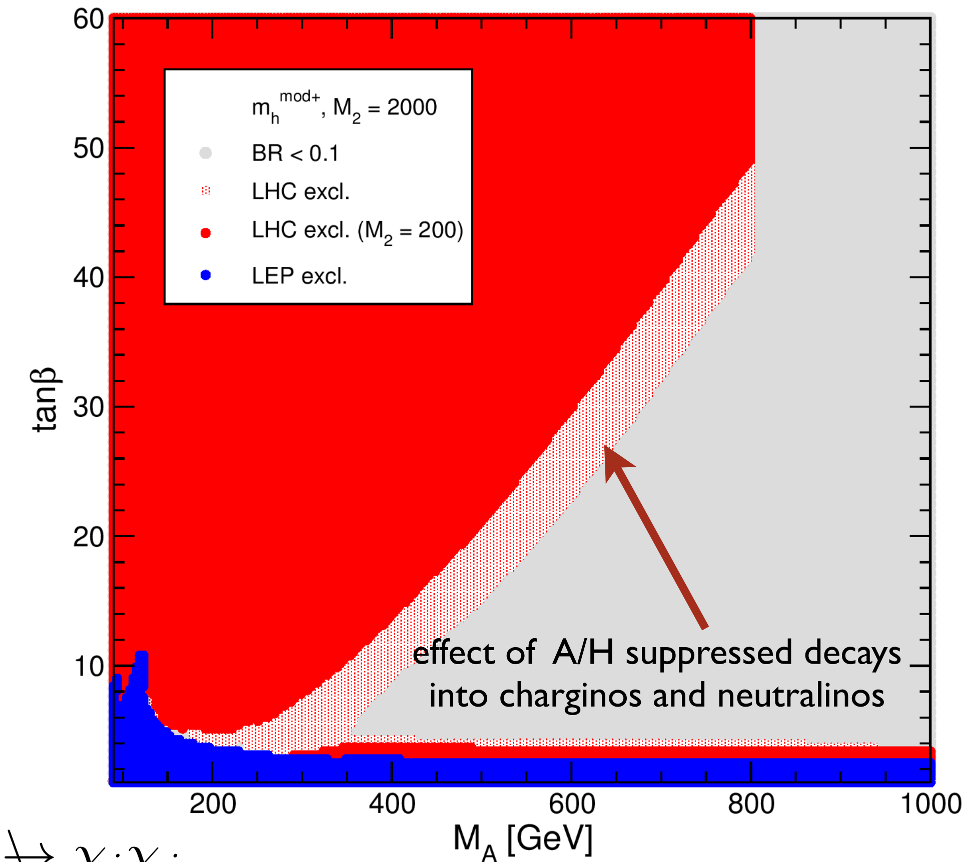
Benchmark Scenarios for the Search of MSSM Scalar Bosons

with 125.5 GeV signal interpreted as h (or H)

m_h^{mod} scenario (moderate stop mixing scenario)



$A/H \not\to \chi_i \chi_j$



M.C., Heinemeyer, Stal, Wagner, Weiglein '13

Additional Benchmark Scenarios:

Light stops, Light staus, τ-phobic and SM-like H with m_H ~125 GeV with interesting phenomenology for the MSSM scalar boson sector

Many Minimal SUSY models can produce m_h=125 GEV

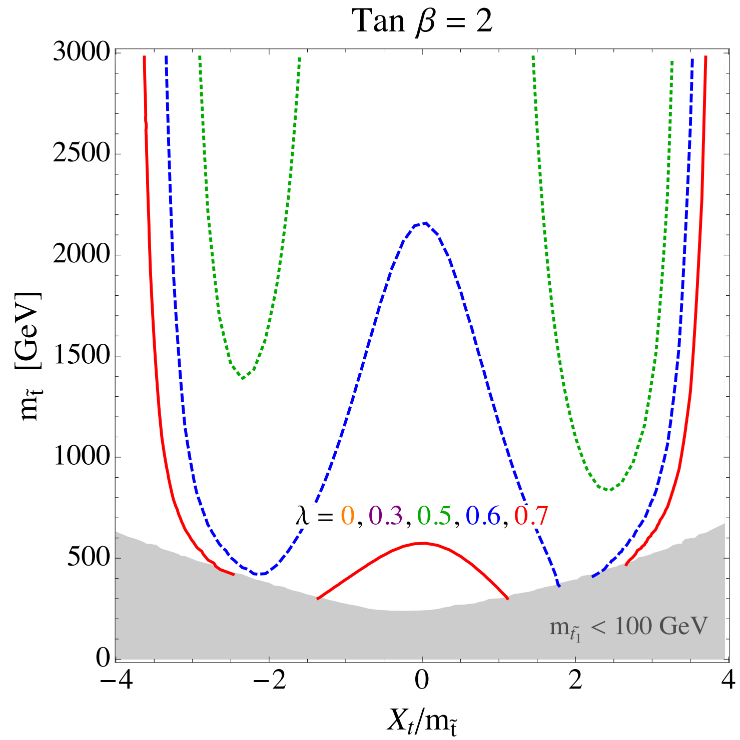
Extra singlet S with extra parameter λ

$$W \supset \lambda S H_u H_d + \hat{\mu}\, H_u H_d + \frac{M}{2} S^2 + \frac{\kappa}{3}\hat{S}^3 + \ldots$$

$$m_h^2 \;=\; M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \text{ rad. corrections}$$

SM + singlet limit

$$\mathcal{M}^2 \;=\; \begin{pmatrix} \lambda^2 v^2 \sin^2 2\beta + M_Z^2 \cos^2 2\beta & \lambda v(\mu, M_S, A_\lambda) \\ \lambda v(\mu, M_S, A_\lambda) & m_S^2 \end{pmatrix}$$



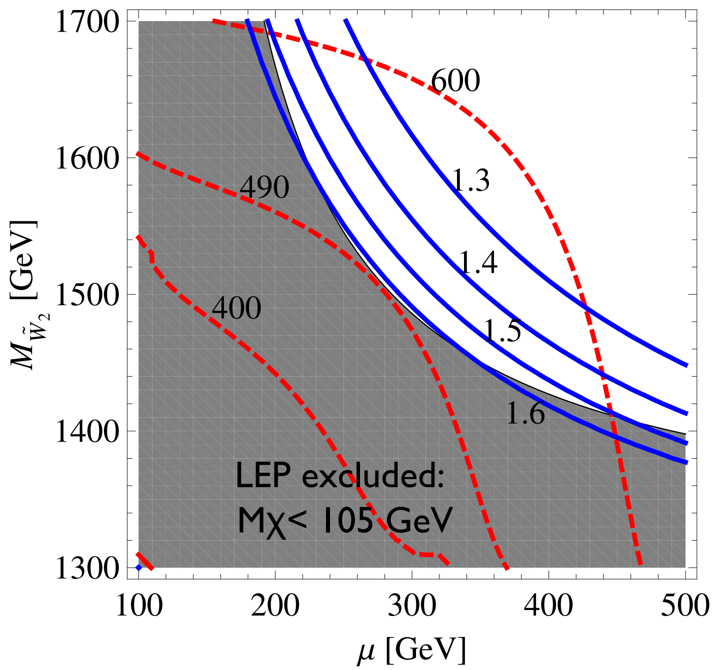
Hall, Pinner, Ruderman'11

NMSSM :At low tan beta, trade requirement on large stop mixing by sizeable trilinear Higgs-Higgs singlet coupling λ → more freedom on gluon fusion production

- **Higgs mixing effects can be also triggered by extra new parameter λ**
- Higgs-Singlet mixing ==> wide range of ZZ/WW and Diphoton rates
- Light staus cannot enhance the di-photon rate (at low tanβ stau mixing is negligible)
- Light chargino at low tanβ can contribute to enhance the di-photon rate

Ellwanger' 12; Benbrik, Bock, Heinemeyer, Stal, Weiglein,Zeune'12; Gunion, Jiang, Kraml '12

Extensions with extra gauge groups: 125 GeV Higgs mass from D terms plus chargino contribution to the quartic (plus usual top-stop)



SU(2) x SU(2) Extension of the weak interactions

Third generation and Higgs charged under strongly coupled SU(2)

Enhancement of γγ rate from new (strong) charginos (~60% max. to avoid too large Higgs mass)

Huo, Lee, Thalapillil, Wagner'12

Models with mixtures of singlets, W' Z', triplets:

look at specific models

or consider an EFT approach if new physics beyond direct reach

Dine, Seiberg, Thomas; Antoniadis, Dudas, Ghilencea, Tziveloglou
M.C, Kong, Ponton, Zurita

Split SUSY: (no extra light scalars below 100-1000 TeV)

→ diphoton rate constrained to be about the SM value

Arkani Hamed et al. '12

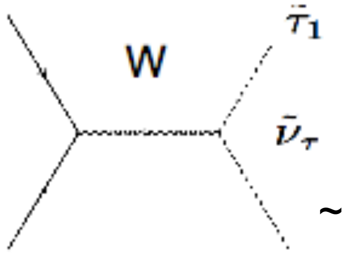
How are m$_h$~125 GeV SUSY scenarios constrained by data?

--- Third generation direct particle searches (**stau, stops**, sbottoms, charginos)

more experimental efforts needed in these direction

- LHC looks for staus produced through SUSY cascade decays
- LHC looks at long-lived staus
- Interesting channel to look for:

M. C., Gori, Shah, Wagner, Wang



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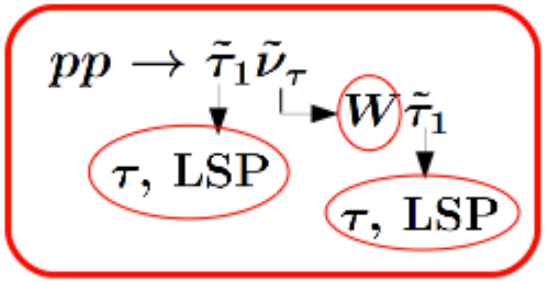


signature:
Lepton, 2 taus, missing energy

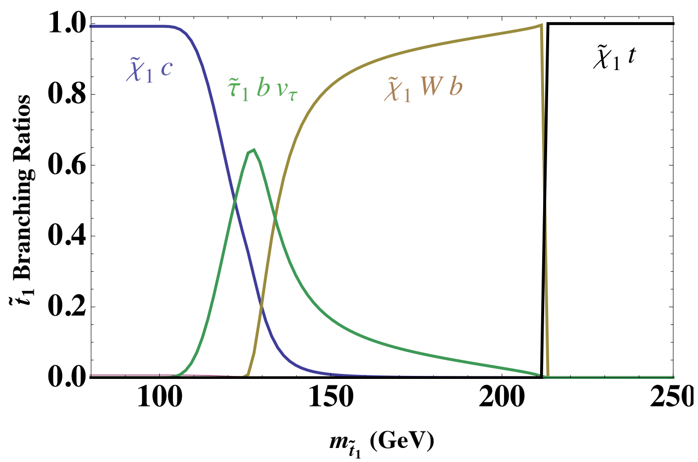
Physical background: Wγ*, WZ*Final
Fake background: W+jets

Estimation at the parton level shows promising results at 8 TeV LHC

- In principle also $pp \to \tilde{\tau}_1 \tilde{\tau}_1 \to (\tau\, \mathrm{LSP})(\tau\, \mathrm{LSP})$ can be interesting, but more challenging

- Another interesting possibility: Staus in “light” Stop decays

$$\tilde{t}_1 \to b\tilde{\chi}^+ \to b\tilde{\tau}\nu$$



How are m_h~125 GeV SUSY scenarios constrained by data?

-- Direct searches of other SUSY Higgs particles

more comprehensive searches/decay modes need to be considered

Example:

-- Strong constraints in MSSM on m_A-tan beta from A/H to $\tau\tau$, however, change of analysis/results if other channels open up; A/H to charginos/staus/...

-- NMSSM; many possible Higgs decay chains H_i to A A

-- other extensions with different relations among Higgs masses
The channels A/H to hh and H+ to hW+ replaced by h/H to AA and H+ to AW+ in BMSSM

-- spectra with quasi degenerate Higgs bosons?

- How to disentangle between SUSY Higgs vs 2HDM's in the absence of obvious SUSY partner effects?

CP-violation in the Higgs sector:

MSSM: Upper bound on Higgs mass same as in the CP conserving case
Similar requirement on the SUSY parameters
harder to achieve enhanced di-photon rate (?)

Other extensions: CP violation at tree level

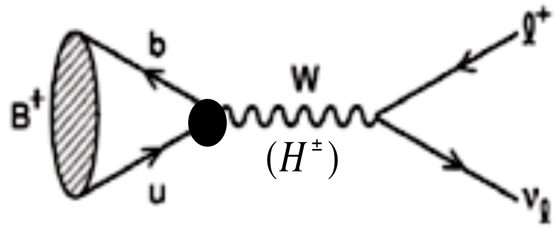
Strong bounds on CP phases from EDM's

Interplay between collider and EDM's/MDM's data
(only in model dependent scenarios) ?

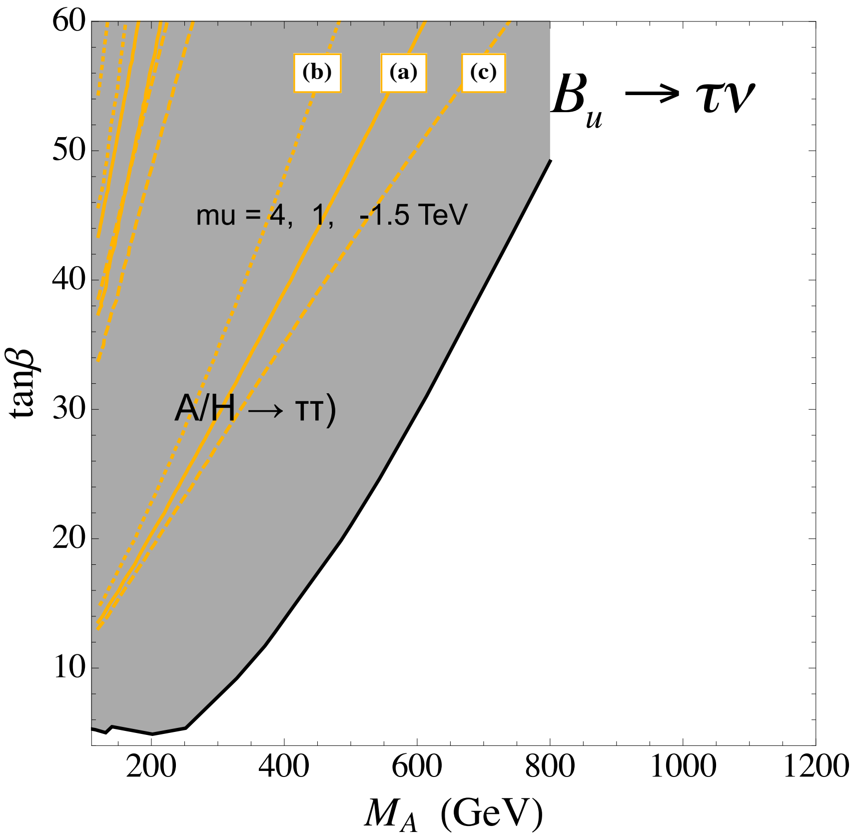
The Higgs discovery and
the Higgs-flavor connection in the MFV MSSM

M_h ~ 125 GeV and flavor in the MSSM

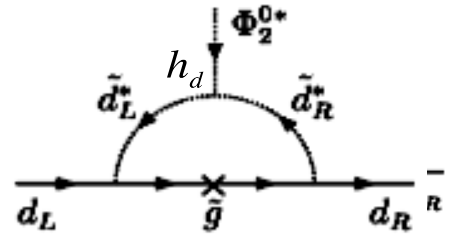
- $B_u \to \tau\nu$ **transition** MSSM charged Higgs & SM contributions interfere destructively



$$R_{B_u \to \tau\nu} = \frac{\mathrm{BR}(B_u \to \tau\nu)^{MSSM}}{\mathrm{BR}(B_u \to \tau\nu)^{SM}} = \left[1 - \left(\frac{m_B^2}{m_{H^\pm}^2}\right)\frac{\tan\beta^2}{(1+\varepsilon_0^3 \tan\beta)}\right]^2$$



$$\varepsilon_0^i \approx \frac{2\alpha_s}{3\pi}\frac{\mu^* M_{\tilde{g}}^*}{\max\left[m^2_{\tilde{d}_1^i}, m^2_{\tilde{d}_2^i}, M^2_{\tilde{g}}\right]}$$



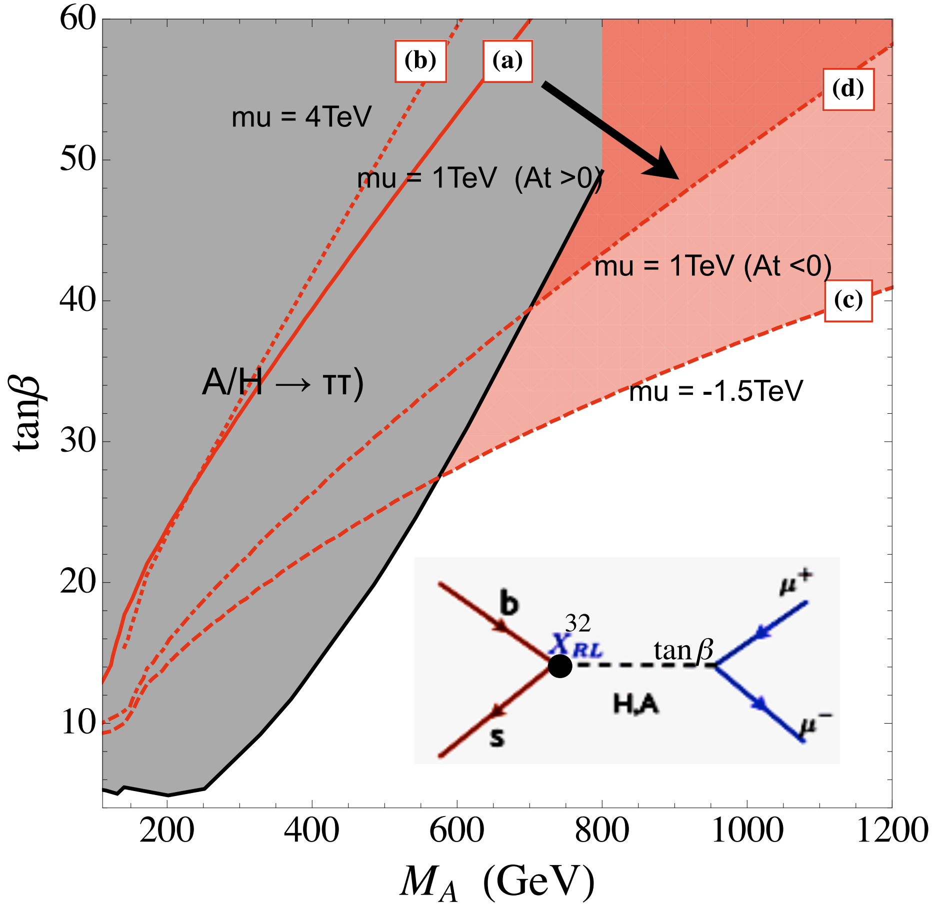
Independent on stop mixing
Almost independent of
SUSY breaking scale
it became less powerful than direct
Heavy Higgs searches for large tanβ

Altmannshofer, MC, Shah,Yu ’12.

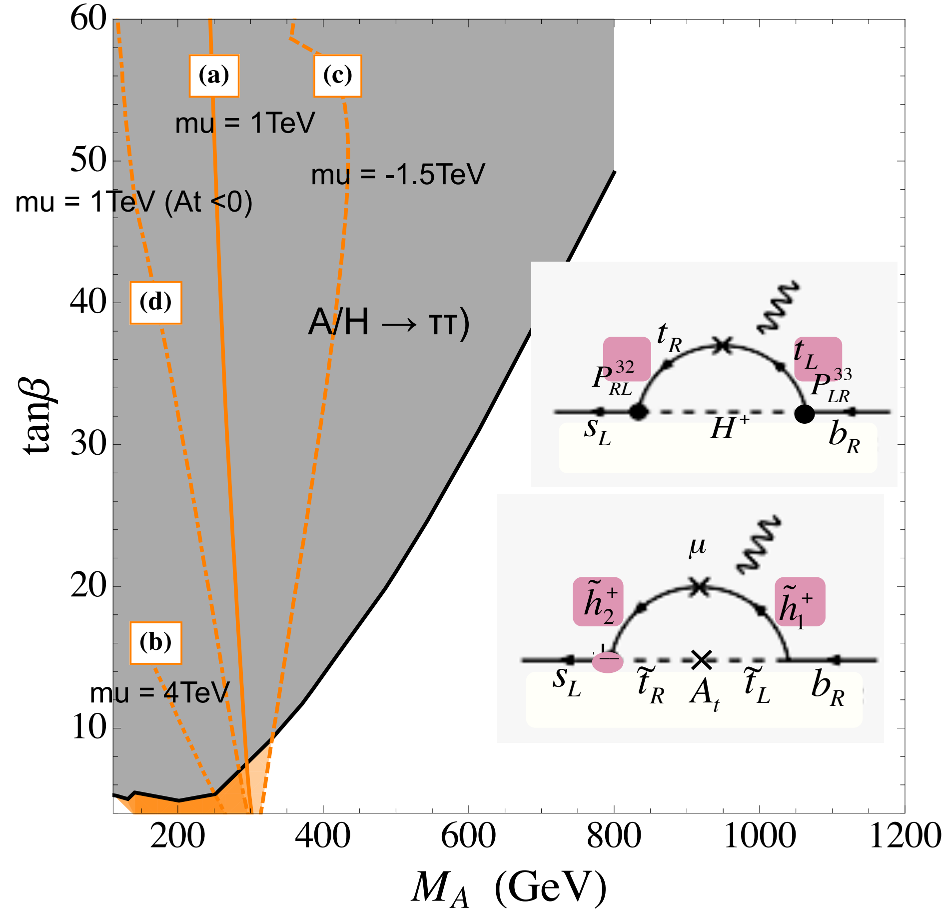
M_h ~125 GeV and Higgs-flavor connection in the MFV MSSM

Altmannshofer, MC, Shah,Yu '12

Bounds from $B_s \to \mu^+\mu^-$



Bounds from $B_s \to X_s \gamma$



SUSY effects intimately connected to the structure of the squark mass matrices

Positive values of A_t less constraining for sizeable m_A and large tan beta

Low Energy Supersymmetry

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

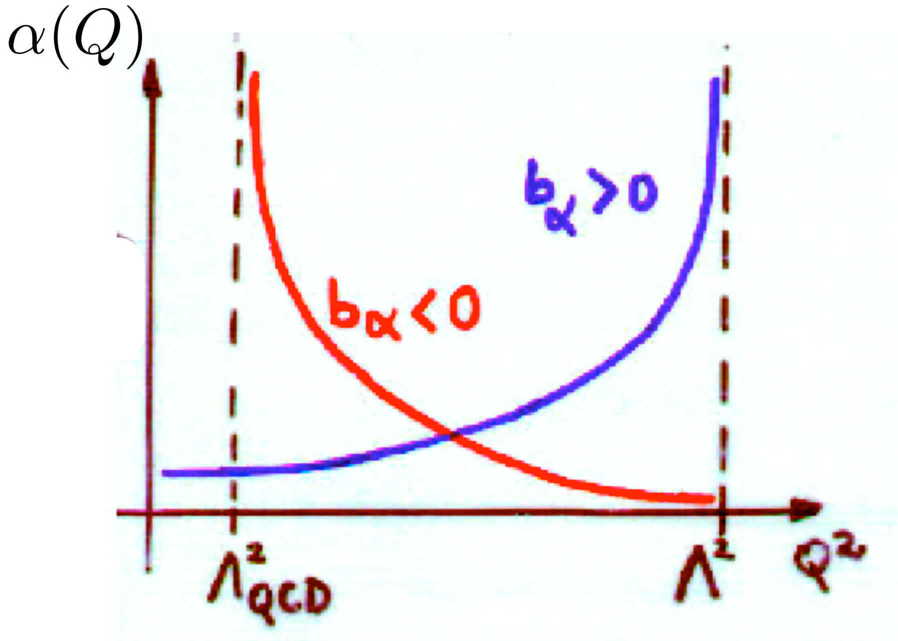
Unification of Gauge Couplings

Renormalization group evolution $\longrightarrow$ 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

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

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

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

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

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

<u>Instead, in the MSSM</u>

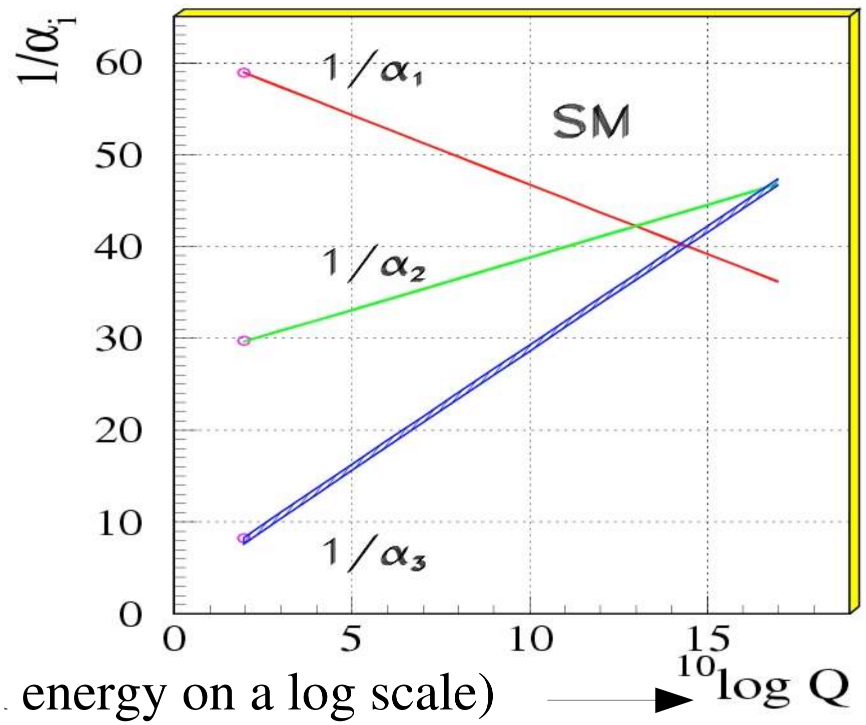
$$\left(\frac{b_3 - b_2}{b_2 - b_1}\right)^{MSSM} = \frac{5}{7} \quad \rightarrow \frac{1}{\alpha_3(M_Z)} \approx 8.5!!$$

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

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

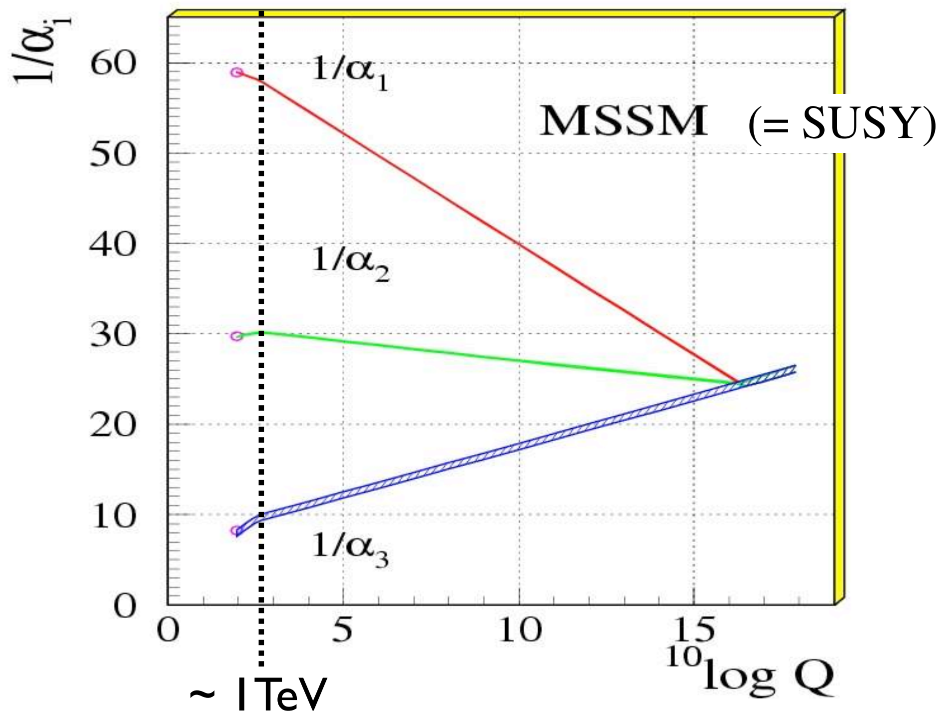
SUSY particles at the TeV scale allow Unification of Gauge Couplings

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:

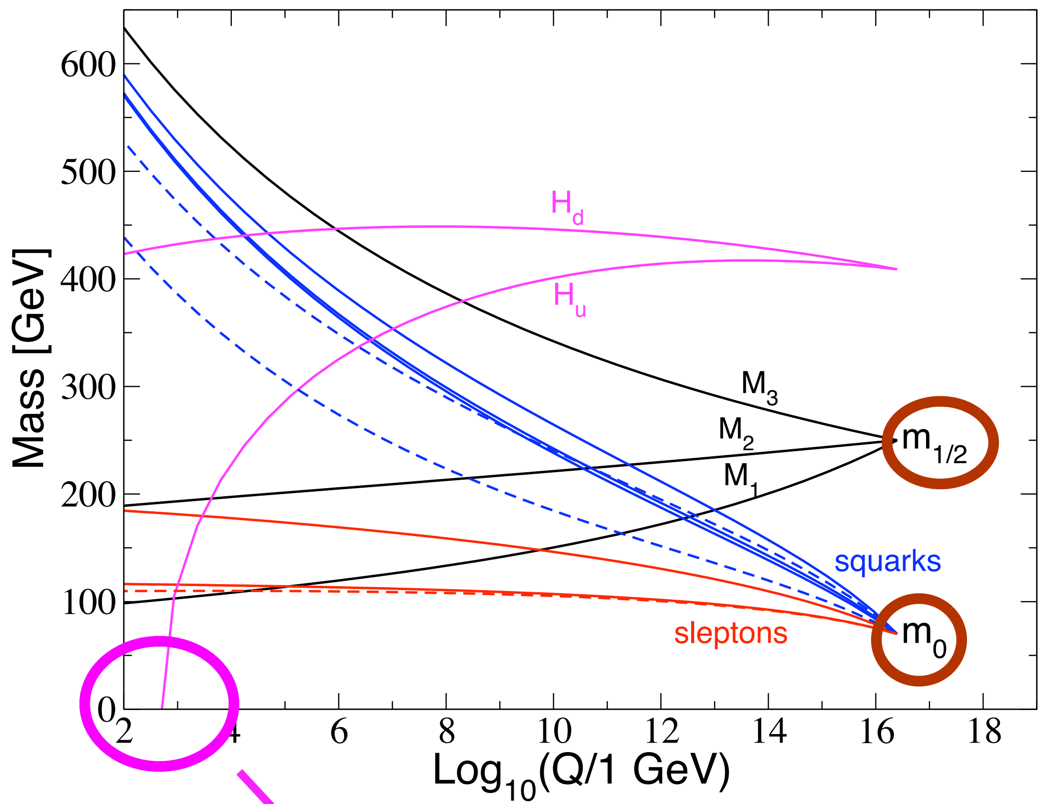
Renormalization group running of the soft SUSY breaking parameters starting with common values m_0 and $M_{1/2}$ for sfermion and guagino masses, respectively

Gaugino masses M_1, M_2, M_3

Slepton masses (dashed=stau)

Squark masses (dashed=stop)

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



Electroweak symmetry breaking occurs because $m_{H_u}^2 + \mu^2$ 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

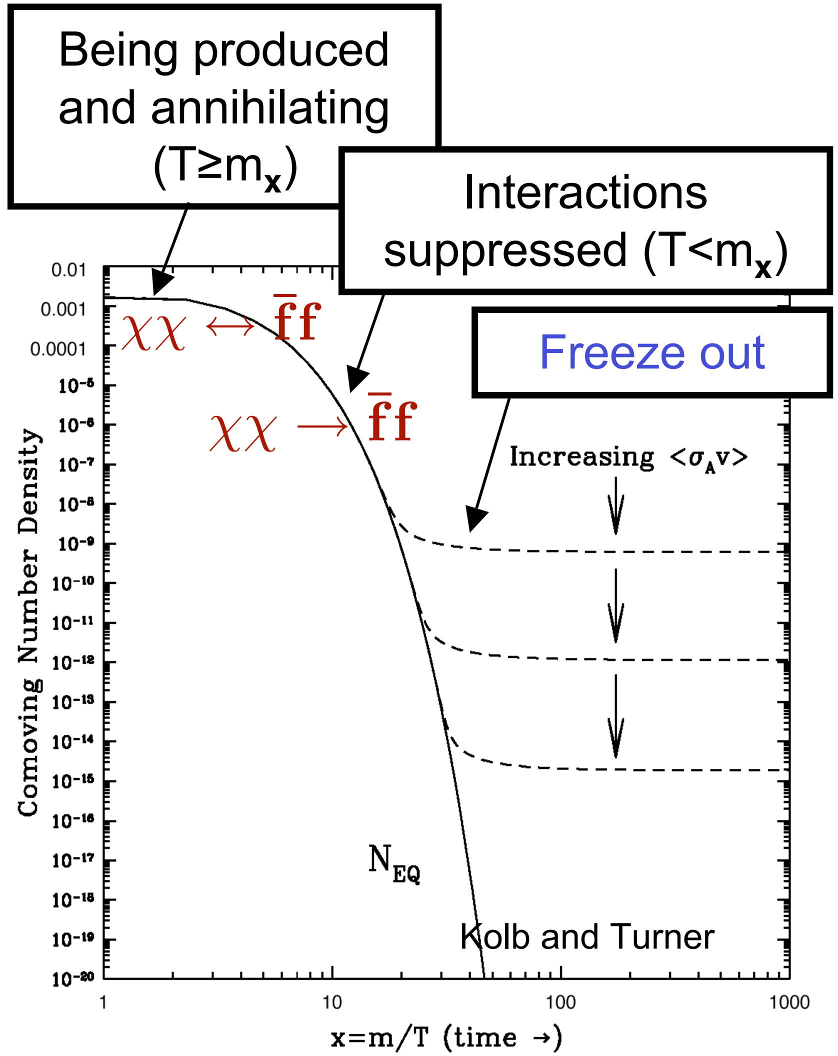
- Heavy particle initially in thermal equilibrium
- Annihilation stops when number density drops

$$H > \Gamma_A \approx n_\chi < \sigma_A \mathrm{v} >$$

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

- Leaves a relic abundance:

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



If m_x and σ_A determined by electroweak physics,

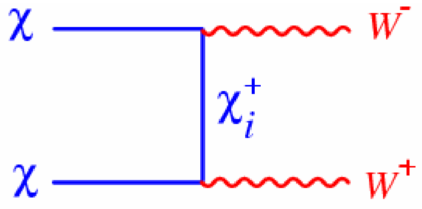
$\sigma_A \approx k\alpha_W^2 / m_X^2 \approx$ a few pb then Ω_{DM} h^2~0.1 for m_x~0.1-1 TeV

Remarkable agreement with WMAP-SDSS → $\Omega_{DM} h^2 = 0.104 \pm 0.009$

Dark Matter density strongly restricts viable models:

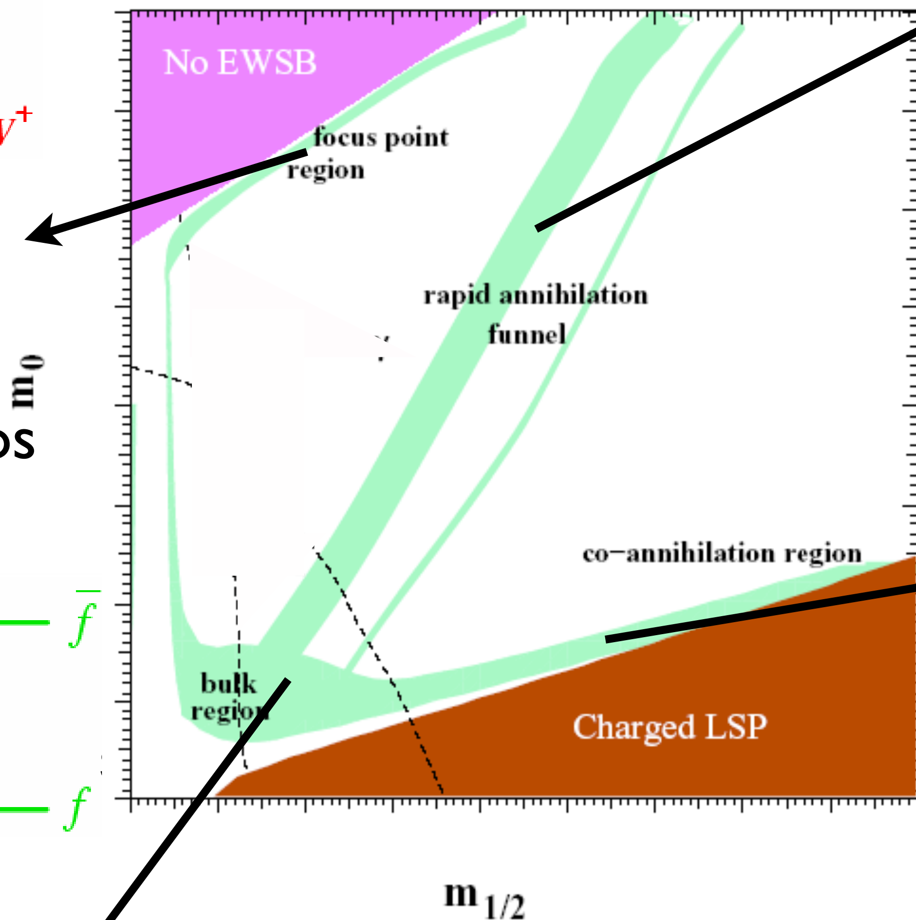
-- CMSSM example --

Only green regions allowed



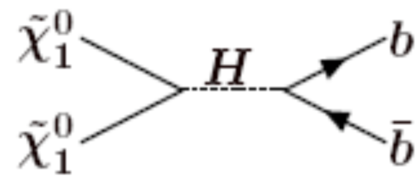
Focus point region

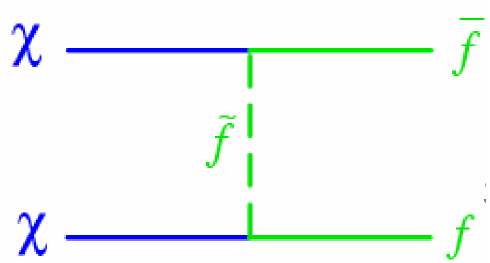
mixed neutralinos



Funnel region

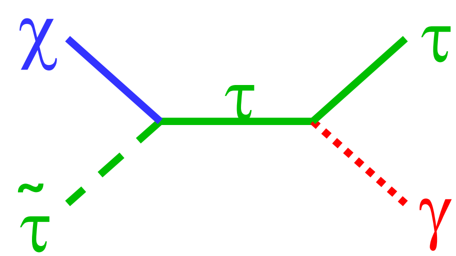
$$m_H \approx 2m_\chi$$





Co-annihilation region

degenerate LSP and stau



Bulk region

light sfermions

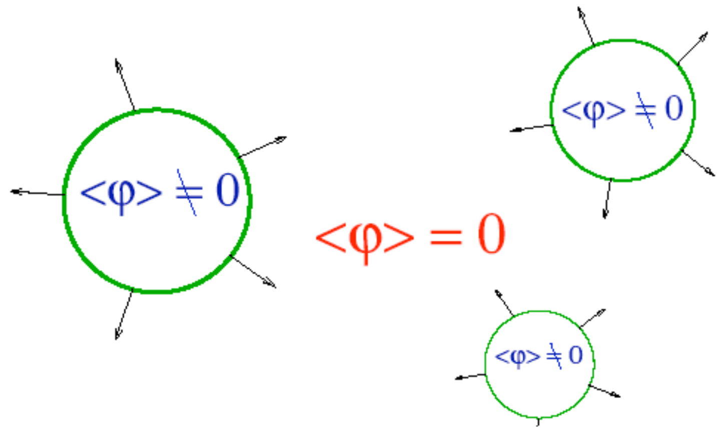
Baryon Asymmetry Preservation at the Electroweak Phase Transition

Kuzmin, Rubakov and Shaposhnikov, '85-'87
Cohen, Kaplan and Nelson '93 Riotto, Trodden'99
M.C, Quiros, Riotto, Vilja, Wagner, Moreno,Seco97-02

- Start with B=L=0 at T>Tc

- CP violating phases create chiral baryon-antibaryon asymmetry in the symmetric phase. Sphaleron processes create net baryon asymmetry.

- Net Baryon Number diffuse in the broken phase



If $n_B \neq 0$ generated at Tc

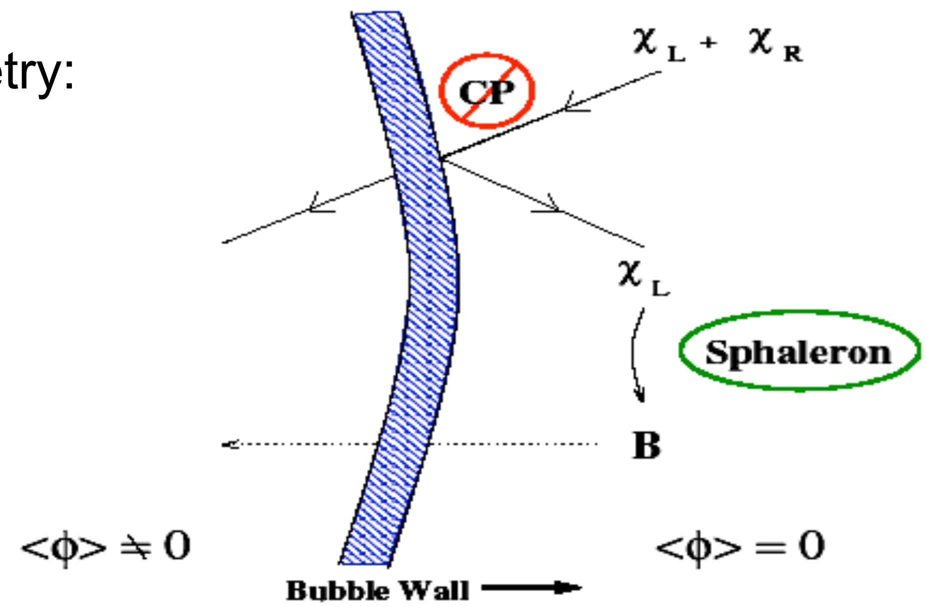
$$\frac{n_B}{s} = \frac{n_B(T_c)}{s} \exp\left(-\frac{10^{16}}{T_c(\mathrm{GeV})} \exp\left(-\frac{E_{sph}(T_c)}{T_c}\right)\right)$$

To preserve the generated baryon asymmetry:
strong first order phase transition:

$$v(T_c)/T_c > 1$$

Shaposhnikov '86-'88

Baryon number violating processes out of equilibrium in the broken phase

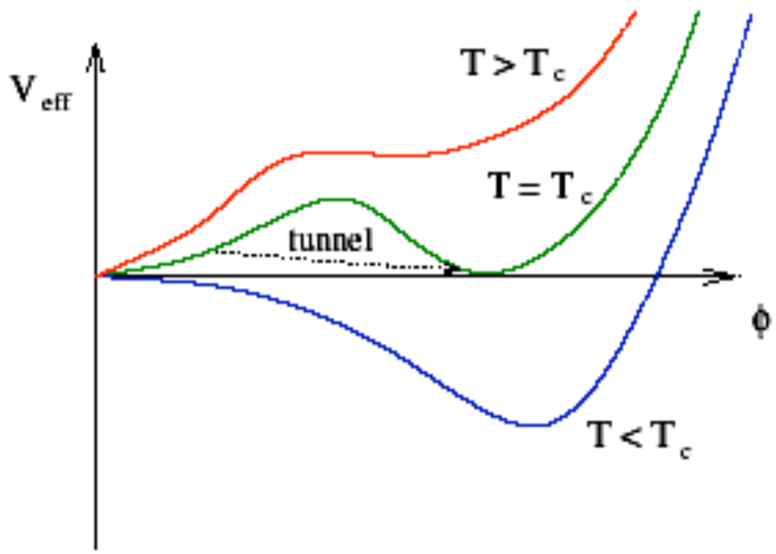


Finite Temperature Higgs Potential

$$V = D(T^2 - T_0^2)H^2 + E_{SM} T\, H^3 + \lambda(T)\, H^4$$

- D term is responsible for the phenomenon of symmetry restoration
- E term receives contributions proportional to the sum of the cube of all light boson particle masses

$$\text{and} \quad \frac{v(T_c)}{T_c} \approx \frac{E}{\lambda} \quad , \quad \text{with} \quad \lambda \propto \frac{m_H^2}{v^2}$$



Since in the SM the only bosons are the gauge bosons and the quartic coupling is proportional to the square of the Higgs mass

$$\boxed{\frac{v(T_c)}{T_c} > 1 \quad \text{implies} \quad m_H < 40 \text{ GeV} \;\Rightarrow\; \text{ruled out by LEP}}$$

- **Independent Problem: not enough CP violation**

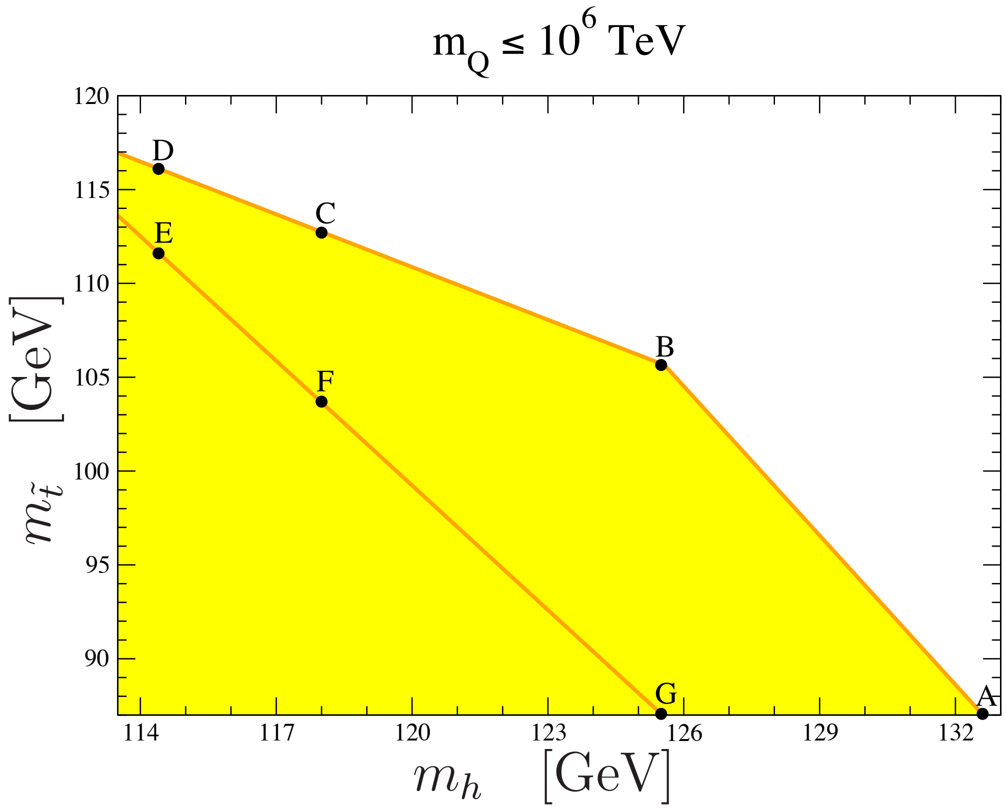
Farrar and Shaposhnikov, Gavela et al., Huet and Satter

Electroweak Baryogenesis in the SM is ruled out

Electroweak Baryogenesis in the MSSM : is it possible?

New bosonic degrees of freedom: superpartners of the top quark, with strong coupling to the Higgs $\Rightarrow E_{SUSY} \approx 8\, E_{SM}$

Sufficiently strong first-order phase transition to preserve the generated baryon asymmetry



The window with $\langle\phi(T_n)\rangle/T_n \gtrsim 1$

for a gluino mass $M_3 = 700$ GeV

Point	A	B	C	D	E	F	G
$\vert A_t/m_Q \vert$	0.5	0	0	0	0.3	0.4	0.7
$\tan\beta$	15	15	2.0	1.5	1.0	1.0	1.0

Invisible Higgs decay into neutralinos must be open to compensate for enhanced gluon fusion rate for light stop

CP violation in the Higgsino/Gaugino sector needed to generate the baryon asymmetry

Conclusions:

The Higgs discovery is of paramount importance

but

We need more precise measurements of Higgs properties

and/or

direct observation of new physics

to further advance in our understanding of EWSB