Basics of SUSY

phenomenology

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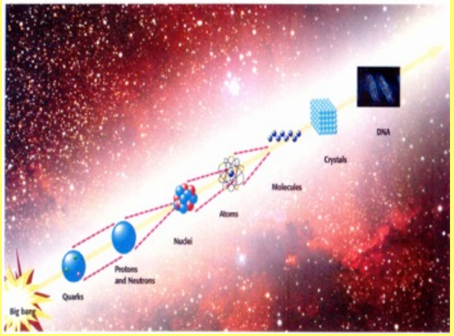
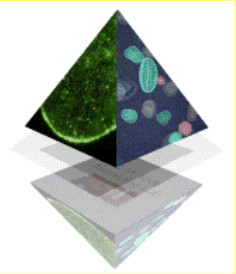


What is SUSY?



- **Supersymmetry** is a boson-fermion sy... y that is aimed to unify all forces in N... ...ing gravity within a singe fram...

$Q\,|\,boson>=|\,fe$ ... $on>$

$[b,b]$ ... $2\delta^{ij}(\sigma^{\mu})_{\alpha\dot{\beta}}P_{\mu}$

First papers in 1971-1972

No evidence in particle physics yet

- Moder... ...ry in particle physics are based... ...gin, though low energy manifestat... ...SY can be found (?) at modern colliders and ...n non-accelerator experiments

Motivation of SUSY in Particle Physics

- Unification with Gravity
- Unification with Gravity
- Unification of gauge couplings
- Solution of the hierarchy problem
- Dark matter in the Universe
- Superstrings

$$spin\ 2 \rightarrow spin\ 3/2 \rightarrow spin\ 1 \rightarrow spin\ 1/2 \rightarrow spin\ 0$$

Unification of matter (fermions) with forces (bosons) naturally arises
from an attempt to unify gravity with the other interactions

$$\{Q^i_\alpha, \bar{Q}^j_{\dot\beta}\} = 2\delta^{ij}(\sigma^\mu)_{\alpha\dot\beta} P_\mu \quad \Rightarrow \quad \{\delta_\varepsilon, \bar\delta_{\bar\varepsilon}\} = 2(\varepsilon\sigma^\mu\bar\varepsilon)P_\mu$$

$\varepsilon = \varepsilon(x)$ local coordinate transformation.

Local translation =
general relativity !

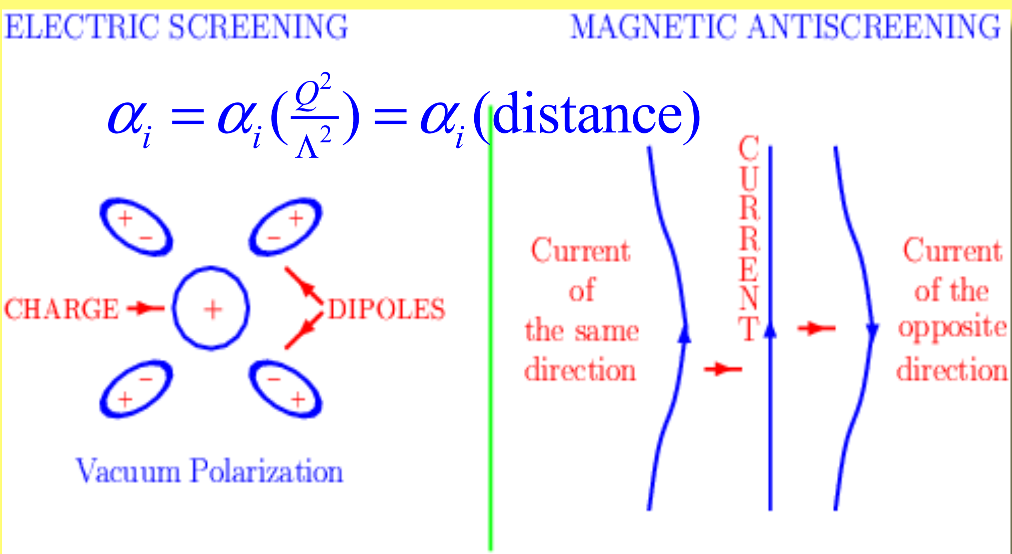
Supertranslation

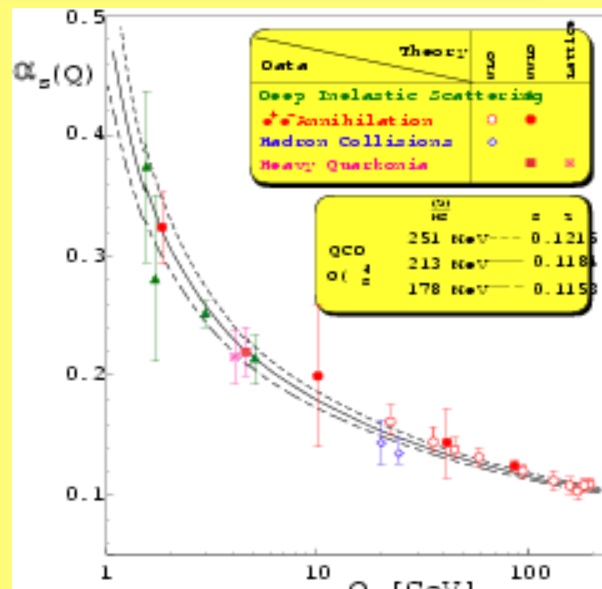
$$x_\mu \rightarrow x_\mu + i\theta\sigma_\mu\bar\xi - i\xi\sigma_\mu\bar\theta,$$
$$\theta \rightarrow \theta + \xi,$$
$$\bar\theta \rightarrow \bar\theta + \bar\xi$$

Motivation of SUSY in Particle Physics

- Unification of gauge couplings

	Low Energy		$\Rightarrow$	*High Energy*
$SU_c(3)$	$SU_L(2)$	$U_Y(1)$	$\Rightarrow$	G_{GUT} (or G^n + symm)
gluons	W, Z	*photon*	$\Rightarrow$	*gauge bosons*
quarks	*leptons*		$\Rightarrow$	*fermions*
g_3	g_2	g_1	$\Rightarrow$	g_{GUT}





Running of the strong coupling

Motivation of SUSY

RG Equations

$$\frac{d\tilde{\alpha}_i}{dt} = b_i \tilde{\alpha}_i^2, \quad \tilde{\alpha}_i = \alpha_i / 4\pi = g_i^2 / 16\pi^2, \quad t=\log(Q^2/\mu^2)$$

$$SM: \quad b_i = \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = \begin{pmatrix} 0 \\ -22/3 \\ -11 \end{pmatrix} + N_{Fam} \begin{pmatrix} 4/3 \\ 4/3 \\ 4/3 \end{pmatrix} + N_{Higgs} \begin{pmatrix} 1/10 \\ 1/6 \\ 0 \end{pmatrix}$$

$$MSSM: \quad b_i = \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = \begin{pmatrix} 0 \\ -6 \\ -9 \end{pmatrix} + N_{Fam} \begin{pmatrix} 2 \\ 2 \\ 2 \end{pmatrix} + N_{Higgs} \begin{pmatrix} 3/10 \\ 1/2 \\ 0 \end{pmatrix}$$

Unification of the Coupling Constants
in the SM and in the MSSM

Amaldi, de Boer, Fuerstenau'91

Input

$$\alpha^{-1}(M_Z) = 128.978 \pm 0.027$$

$$\sin^2 \theta_{\overline{MS}} = 0.23146 \pm 0.00017$$

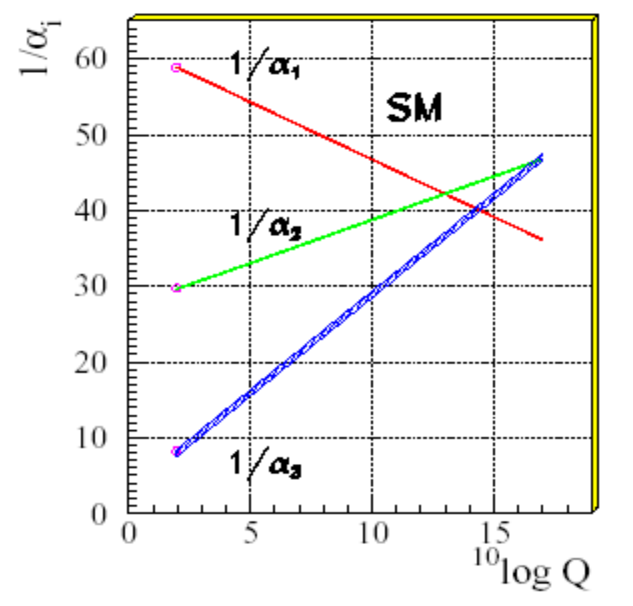
$$\alpha_s(M_Z) = 0.1184 \pm 0.0031$$

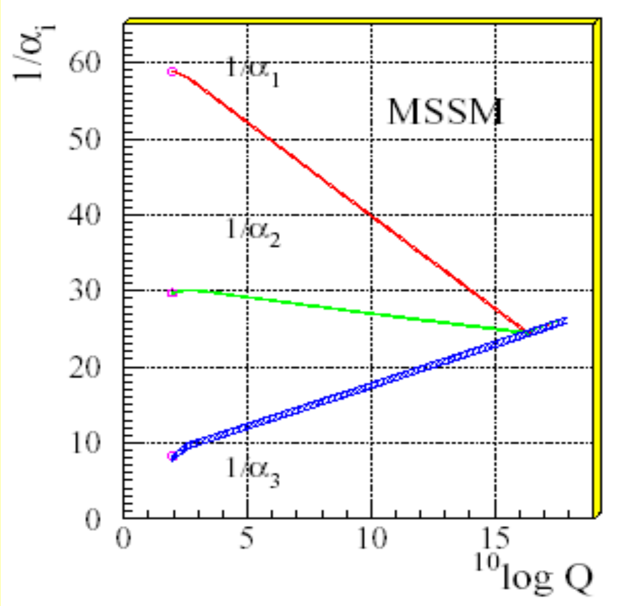
Output

$$M_{SUSY} = 10^{3.4\pm0.9\pm0.4} \text{ GeV}$$

$$M_{GUT} = 10^{15.8\pm0.3\pm0.1} \text{ GeV}$$

$$\alpha_{GUT}^{-1} = 26.3 \pm 1.9 \pm 1.0$$





SUSY yields unification!

Motivation of SUSY

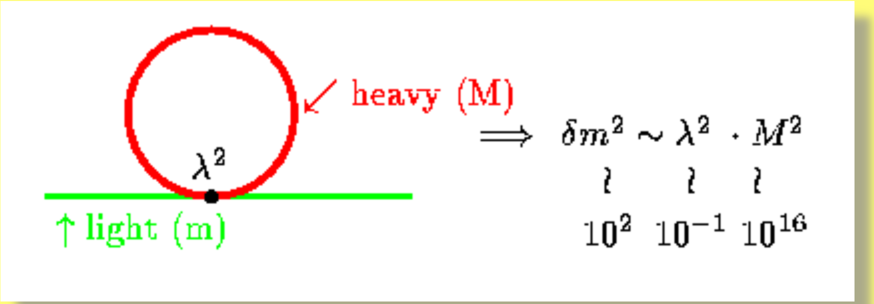
- Solution of the Hierarchy Problem

$$m_H \sim v \sim 10^2 \text{ GeV}$$

$$m_\Sigma \sim V \sim 10^{16} \text{ GeV}$$

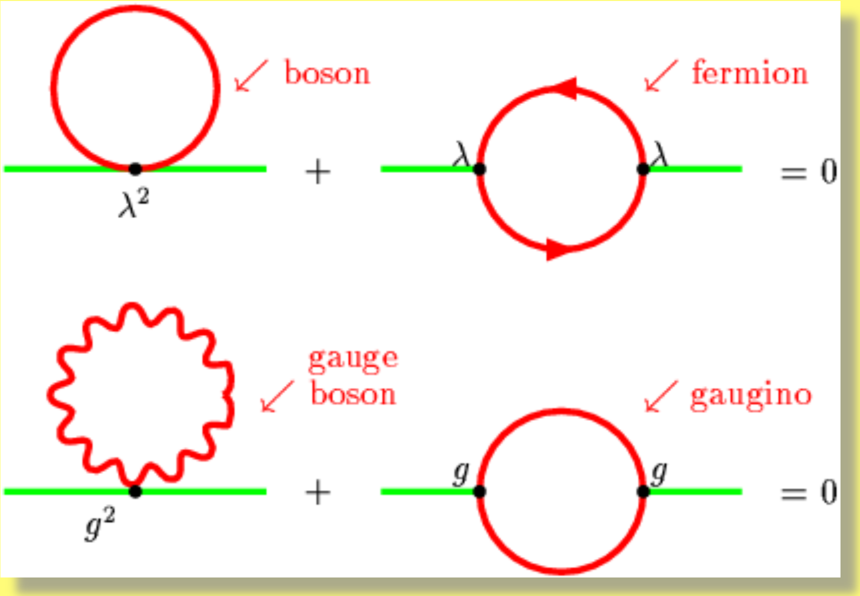
$$\frac{m_H}{m_\Sigma} \sim 10^{-14} \ll 1$$

Destruction of the hierarchy by radiative corrections



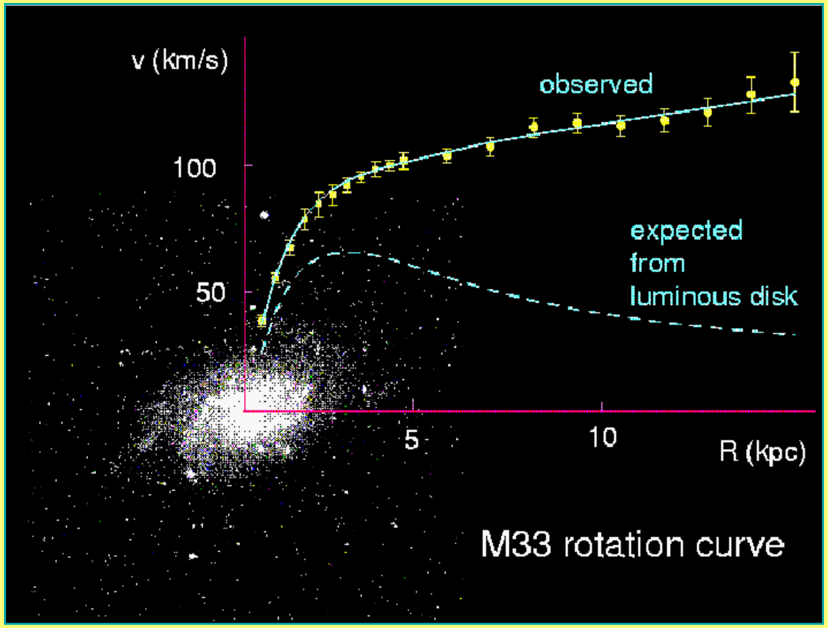
$$\sum_{bosons} m^2 = \sum_{fermions} m^2$$

Cancellation of quadratic terms



Motivation of SUSY

- Dark Matter in the Universe



The flat rotation curves of spiral galaxies provide the most direct evidence for the existence of large amount of the dark matter.

Spiral galaxies consist of a central bulge and a very thin disc, and surrounded by an approximately spherical halo of dark matter

SUSY provides a candidate for the Dark matter – a stable neutral particle

Cosmological Constraints

New precise cosmological data

$$\Omega h^2 = 1 \quad \Longleftrightarrow \quad \rho = \rho_{crit}$$

$$\Omega_{vacuum} \approx 73\%$$

$$\Omega_{DarkMatter} \approx 23 \pm 4\%$$

$$\Omega_{Baryon} \approx 4\%$$

- Supernova Ia explosion
- CMBR thermal fluctuations

Dark Matter in the Universe:

→ Hot DM (not favoured by galaxy formation)

→ Cold DM (rotation curves of Galaxies) ← SUSY

Superalgebra

$(Super)\ Algebra$

Lorentz Algebra

$$[P_\mu, P_\nu] = 0,\ [P_\mu, M_{\rho\sigma}] = i(g_{\mu\rho}P_\sigma - g_{\mu\sigma}P_\rho),$$

$$[M_{\mu\nu}, M_{\rho\sigma}] = i(g_{\nu\rho}M_{\mu\sigma} - g_{\nu\sigma}M_{\mu\rho} - g_{\mu\rho}M_{\nu\sigma} + g_{\mu\sigma}M_{\nu\rho}),$$

SUSY Algebra

$$[Q^i_\alpha, P_\mu] = [\bar{Q}^i_{\dot{\alpha}}, P_\mu] = 0,$$

$$[Q^i_\alpha, M_{\mu\nu}] = \tfrac{1}{2}(\sigma_{\mu\nu})^\beta_\alpha Q^i_\beta,\ [\bar{Q}^i_{\dot{\alpha}}, M_{\mu\nu}] = -\tfrac{1}{2}\bar{Q}^i_{\dot{\beta}}(\bar{\sigma}_{\mu\nu})^{\dot{\beta}}_{\dot{\alpha}},$$

$$\{Q^i_\alpha, \bar{Q}^j_{\dot{\beta}}\} = 2\delta^{ij}(\sigma^\mu)_{\alpha\dot{\beta}}P_\mu$$

$$\alpha, \dot{\alpha}, \beta, \beta = 1,2;\ i,j = 1,2,\dots,N.$$

$Superspace$

$$x_\mu \to x_\mu, \theta_\alpha, \bar{\theta}_{\dot{\alpha}}$$

$\alpha, \dot{\alpha} = 1,2$

Grassmannian parameters

$$\vartheta^2_\alpha = 0,\ \bar{\vartheta}^2_{\dot{\alpha}} = 0$$

SUSY Generators

$$Q_\alpha = \frac{\partial}{\partial\vartheta_\alpha} - i\sigma^\mu_{\alpha\dot{\alpha}}\bar{\theta}^{\dot{\alpha}}\partial_\mu$$

$$\bar{Q}_{\dot{\alpha}} = -\frac{\partial}{\partial\bar{\vartheta}_{\dot{\alpha}}} + i\theta_\alpha\sigma^\mu_{\alpha\dot{\alpha}}\partial_\mu$$

$$Q^2_\alpha = 0,\ \bar{Q}^2_{\dot{\alpha}} = 0$$

This is the only possible graded Lie algebra that mixes integer and half-integer spins and changes statistics

Quantum States

Quantum states: Vacuum = $|E,\lambda>$ $\qquad Q|E,\lambda>=0$

Energy helicity

$$[Q^i_\alpha, P_\mu] = [\bar{Q}^i_{\dot\alpha}, P_\mu] = 0$$

State	Expression	# of states
vacuum	$\|E,\lambda>$	1
1-particle	$\bar{Q}_i\|E,\lambda>=\|E,\lambda+1/2>$	$\binom{N}{1}=N$
2-particle	$\bar{Q}_i\bar{Q}_j\|E,\lambda>=\|E,\lambda+1>$	$\binom{N}{2}=\frac{N(N-1)}{2}$
…	…	…
N-particle	$\bar{Q}_1\bar{Q}_2\ldots\bar{Q}_N\|E,\lambda>=\|E,\lambda+N/2>$	$\binom{N}{N}=1$

Total # of states: $\sum_{k=0}^{N}\binom{N}{k}=2^N=2^{N-1}bosons+2^{N-1}fermions$

SUSY Multiplets

Chiral multiplet $N=1,\ \lambda=0$

helicity	-1/2	0	1/2
# of states	1	2	1

scalar spinor

(φ, ψ)

Vector multiplet $N=1,\ \lambda=1/2$

helicity	-1	-1/2	1/2	1
# of states	1	1	1	1

(λ, A_μ)

spinor vector

Members of a supermultiplet are called **superpartners**

N=4	SUSY YM	helicity			-1	–1/2	0	1/2	1			
	λ = -1	# of states			1	4	6	4	1			
N=8	SUGRA	helicity	-2	–3/2	–1	–1/2	0	1/2	1	3/2	2
	λ = -2	# of states	1	8	28	56	70	56	28	8	1

$N \leq 4S$ ← spin

$N \leq 4$ For renormalizable theories (YM)

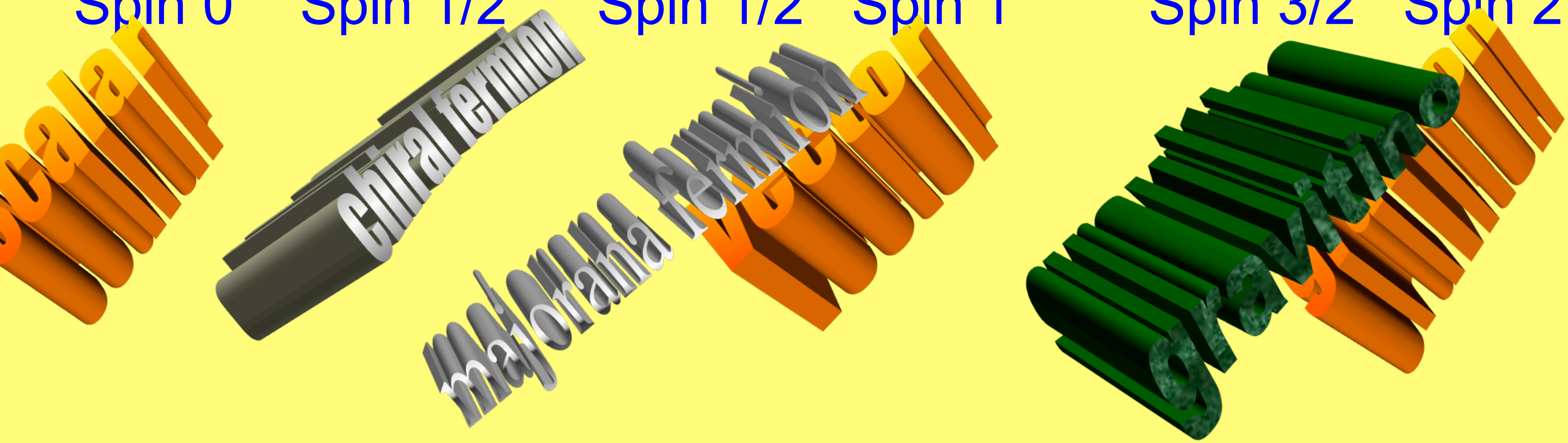
$N \leq 8$ For (super)gravity

Simplest (N=1) SUSY Multiplets

Bosons and Fermions come in pairs

$$(\varphi,\psi) \qquad (\lambda, A_\mu) \qquad (\tilde{g}, g)$$

Spin 0 Spin 1/2 Spin 1/2 Spin 1 Spin 3/2 Spin 2



SUSY Transformation

N=1 SUSY Chiral supermultiplet:

parameter of SUSY transformation (spinor)

spin=0 → $$\delta_\varepsilon A = \sqrt{2}\varepsilon\psi,$$

spin=1/2 → $$\delta_\varepsilon \psi = i\sqrt{2}\sigma^\mu \bar{\varepsilon}\partial_\mu A + \sqrt{2}\varepsilon F,$$

$$\delta_\varepsilon F = i\sqrt{2}\bar{\varepsilon}\sigma^\mu \partial_\mu \psi$$

Auxiliary field

(unphysical d.o.f. needed to close SYSY algebra)

SUSY multiplets ➡ Superfiled in Superspace

$$(y = x + i\theta\sigma\bar{\theta})$$

superfield

$$\Phi(y,\theta) = A(y) + \sqrt{2}\theta\psi(y) + \theta\theta F(y)$$

$$= A(x) + i\theta\sigma^\mu\bar{\theta}\partial_\mu A(x) + \tfrac{1}{4}\theta\theta\bar{\theta}\bar{\theta}\Box A(x)$$

$$+ \sqrt{2}\theta\psi(x) - i/\sqrt{2}\theta\theta\partial_\mu\psi(x)\sigma^\mu\bar{\theta} + \theta\theta F(x)$$

Expansion over grassmannian parameter

component fields

$$\theta^2 = \theta_1\theta_2, \quad \theta_1^2 = \theta_2^2 = 0!$$

Gauge superfields

Gauge superfield

$$V(x,\theta,\bar\theta) = C(x) + i\theta\chi(x) - i\bar\theta\bar\chi(x) + i\theta\theta M(x) - i\bar\theta\bar\theta M^+(x)$$
$$-\theta\sigma^\mu\bar\theta v_\mu(x) + i\theta\theta\bar\theta[\bar\lambda(x) + i\bar\sigma^\mu\partial_\mu\chi(x)] - i\bar\theta\bar\theta\theta[\lambda(x) + i\sigma^\mu\partial_\mu\bar\chi(x)]$$
$$+\tfrac{1}{2}\theta\theta\bar\theta\bar\theta[D(x) + \tfrac{1}{2}WC(x)]$$

Gauge transformation

$$V \to V + \Phi + \bar\Phi$$

$$C \to C + A + A^*$$
$$\chi \to \chi - i\sqrt{2}\psi$$
$$M \to M - 2iF$$
$$v_\mu \to v_\mu - i\partial_\mu(A - A^*)$$
$$\lambda \to \lambda$$
$$D \to D$$

Wess-Zumino gauge

$$C = \chi = M = 0$$

physical fields

Field strength tensor

$$W_\alpha = -\tfrac{1}{4}\bar D^2 e^V D_\alpha e^{-V}$$

Covariant derivatives

$$D_\alpha = \frac{\partial}{\partial\vartheta_\alpha} + i\sigma^\mu_{\alpha\dot\alpha}\bar\vartheta^{\dot\alpha}\partial_\mu$$
$$\bar D_{\dot\alpha} = -\frac{\partial}{\partial\bar\theta_\alpha} - i\theta_{\dot\alpha}\sigma^\mu_{\alpha\dot\alpha}\partial_\mu$$

$$W_\alpha = -i\lambda_\alpha + \theta_\alpha D - \tfrac{i}{2}(\sigma^\mu\bar\sigma^\nu\theta)_\alpha F_{\mu\nu} + \theta^2\sigma^\mu D_\mu\bar\lambda$$

How to write SUSY Lagrangians

1st step

Take your favorite Lagrangian written in terms of fields

2nd step

Replace $$Field\ (\varphi, \psi, A_\mu) \Rightarrow Superfield\ (\Phi, V)$$

3rd step

Replace

$$Action = \int d^4x\, L(x) \quad \Rightarrow \quad \int d^4x\, d^4\theta\, L(x, \theta, \bar{\theta})$$

Grassmannian integration in superspace $$\int d\theta_\alpha = 0, \ \int \theta_\beta d\theta_\alpha = \delta_{\alpha\beta}$$

SUSY Lagrangian (Matter)

Superfields

$$L = \int d^2\theta d^2\bar{\theta}\, \Phi_i^{+}\Phi_i + \int d^2\theta\, (\lambda_i\Phi_i + \tfrac{1}{2} m_{ij}\Phi_i\Phi_j + \tfrac{1}{3} y_{ijk}\Phi_i\Phi_j\Phi_k) + h.c.]$$

Kinetic term — Superpotential

Components

$$L = i\partial_\mu \bar{\psi}_i \bar{\sigma}^\mu \psi_i + A_i^* W A_i + F_i^* F_i$$ ← no derivatives

$$+ \, [\lambda_i F_i + m_{ij}(A_i F_j - \tfrac{1}{2}\psi_i\psi_j) + y_{ijk}(A_i A_j F_k - \psi_i\psi_j A_k) + h.c.]$$

Constraint $\dfrac{\delta L}{\delta F_k} = F_k^* + \lambda_k + m_{ik}A_i + y_{ijk}A_i A_j = 0$ → F_k

$$L = i\partial_\mu \bar{\psi}_i \bar{\sigma}^\mu \psi_i + A_i^* W A_i - \tfrac{1}{2} m_{ij}\psi_i\psi_j - \tfrac{1}{2} m_{ij}^* \bar{\psi}_i\bar{\psi}_j$$

$$- \, y_{ijk}\psi_i\psi_j A_k - y_{ijk}^* \bar{\psi}_i\bar{\psi}_j A_k^* - V(A_i, A_j)$$

$$V = F_k^* F_k$$

SUSY Lagrangians (gauge)

Gauge fields

$$L=\tfrac{1}{4}\int d^2\theta\ W^{\alpha}W_{\alpha}+\int d^2\bar{\theta}\ \overline{W}^{\dot{\alpha}}\overline{W}_{\dot{\alpha}}=\tfrac{1}{2}D^2-\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}-i\lambda\sigma^{\mu}D_{\mu}\bar{\lambda}$$

Gauge transformation

$$\Phi\to e^{-ig\Lambda}\Phi,\ \Phi^{+}\to\Phi^{+}e^{ig\Lambda^{+}},\ V\to V+i(\Lambda-\Lambda^{+})$$

Gauge invariant interaction with matter (covariant derivative)

$$\Phi^{+}\Phi\ \to\ \Phi^{+}e^{gV}\Phi$$

Gauge Invariant SUSY Lagrangian

Superfields

$$L_{SUSY\ YM} = \tfrac{1}{4}\int d^2\theta\ \mathrm{Tr}(W^\alpha W_\alpha) + \tfrac{1}{4}\int d^2\bar\theta\ \mathrm{Tr}(\overline{W}^\alpha \overline{W}_\alpha)$$
$$+\int d^2\theta d^2\bar\theta\ \overline{\Phi}_{ia}(e^{gV})^a_b \Phi^b_i + \int d^2\theta\ \mathrm{W}(\Phi_i) + \int d^2\bar\theta\ \overline{\mathrm{W}}(\overline{\Phi}_i)$$

Components

$$L_{SUSY\ YM} = -\tfrac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} - i\lambda^a\sigma^\mu D_\mu\bar\lambda^a + \tfrac{1}{2}\underline{D^a D^a}$$
$$+(\partial_\mu A_i - igv^a_\mu T^a A_i)^\dagger(\partial_\mu A_i - igv^a_\mu T^a A_i) - i\bar\psi_i\bar\sigma^\mu(\partial_\mu\psi_i - igv^a_\mu T^a\psi_i)$$
$$-\underline{D^a} gA_i^\dagger T^a A_i - i\sqrt{2}gA_i^\dagger T^a\lambda^a\psi_i + i\sqrt{2}g\bar\psi_i T^a\bar\lambda^a A_i + \underline{F_i^\dagger F_i}$$
$$+\frac{\partial \mathrm{W}}{\partial A_i}\underline{F_i} + \frac{\partial \overline{\mathrm{W}}}{\partial A_i^\dagger}\underline{F_i^\dagger} - \tfrac{1}{2}\frac{\partial^2 \mathrm{W}}{\partial A_i \partial A_j}\psi_i\psi_j - \tfrac{1}{2}\frac{\partial^2 \overline{\mathrm{W}}}{\partial A_i^\dagger \partial A_j^\dagger}\bar\psi_i\bar\psi_j$$

Potential

$$D^a = -gA_i^\dagger T^a A_i, \quad F_i = -\frac{\partial \mathrm{W}}{\partial A_i} \quad \rightarrow \quad \mathrm{V} = \tfrac{1}{2}D^a D^a + F_i^\dagger F_i$$

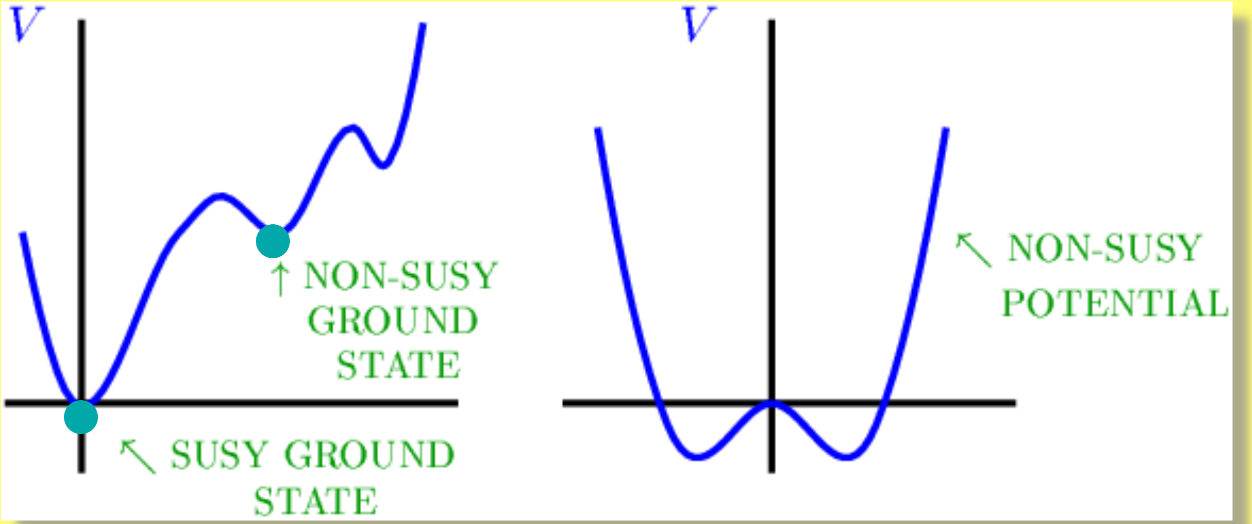
Spontaneous Breaking of SUSY

Energy $E = <0|H|0>$

$$\{Q^i_\alpha, \overline{Q}^j_{\dot\beta}\} = 2\delta^{ij}(\sigma^\mu)_{\alpha\dot\beta}P_\mu$$

$$E = \frac{1}{4}\sum_{\alpha=1,2} <0|\{Q^i_\alpha, \overline{Q}^j_\alpha\}|0> = \frac{1}{4}\sum_\alpha |Q_\alpha|0>|^2 \geq 0$$

$E = <0|H|0> \neq 0$ if and only if $Q_\alpha |0> \neq 0$



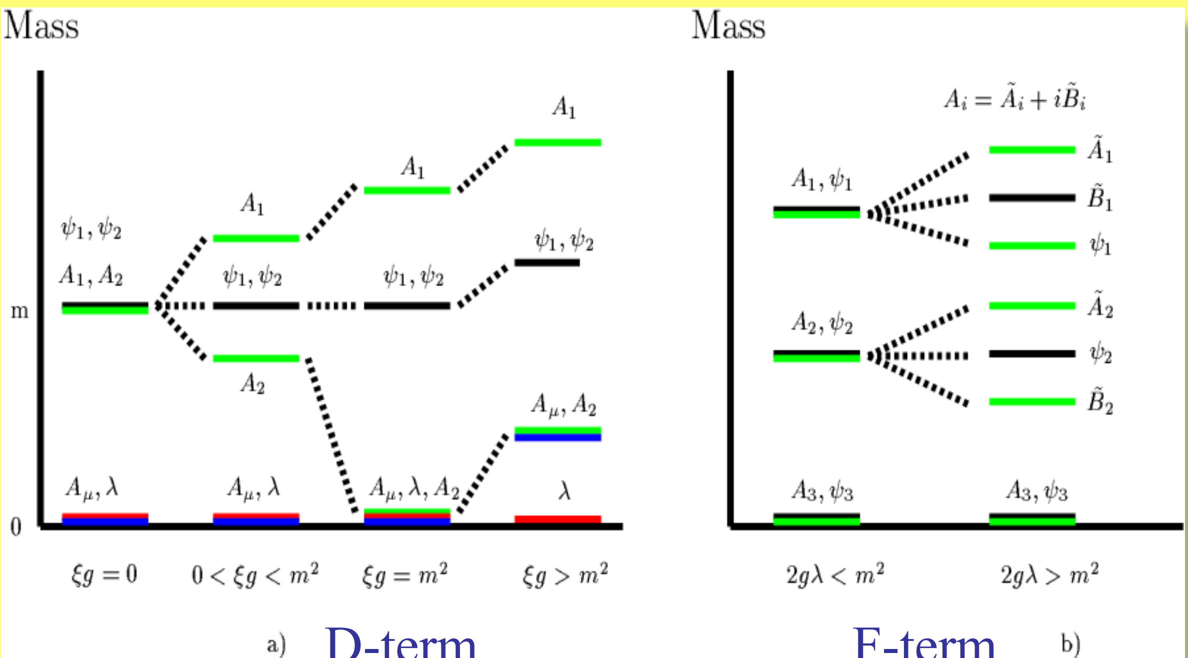
Mechanism of SUSY Breaking

- Fayet-Iliopoulos (D-term) mechanism (in Abelian theory)

$$\Delta L = \xi V|_{\theta\theta\bar{\theta}\bar{\theta}} = \xi \int d^4\theta \; V = \xi D \neq 0$$

- O'Raifertaigh (F-term) mechanism

$$W(\Phi) = \lambda\Phi_3 + m\Phi_1\Phi_2 + g\Phi_3\Phi_1^2$$



$$F_1^* = mA_2 + 2gA_1A_2$$

$$F_2^* = mA_1$$

$$F_3^* = \lambda + gA_1^2$$

$$\Longrightarrow \quad \langle F_i \rangle \neq 0$$

$$\sum_{bosons} m_i^2 = \sum_{fermions} m_i^2$$

Minimal Supersymmetric Standard Model (MSSM)

- SUSY: # of fermions = # of bosons   N=1 SUSY: (φ,ψ) (λ, A_μ)
- SM: 28 bosonic d.o.f. & 90 (96) fermionic d.o.f.

There are no particles in the SM that can be superpartners

SUSY associates known bosons with new fermions
and known fermions with new bosons

- Even number of the Higgs doublets – min = 2
Cancellation of axial anomalies (in each generation)

$$Tr\ Y^3 = 3(\tfrac{1}{27}+\tfrac{1}{27}-\tfrac{64}{27}+\tfrac{8}{27})-1-1+8=0$$

colour u_L d_L u_R d_R ν_L e_L e_R

Higgsinos

-1+1=0

Particle Content of the MSSM

Superfield	Bosons	Fermions	$SU_c(3)$	$SU_L(2)$	$U_Y(1)$
Gauge					
G^a	*gluon* g^a	*gluino* $\tilde{g}^a$	8	1	0
V^k	*Weak* $W^k(W^\pm, Z)$	*wino, zino* $\tilde{w}^k(\tilde{w}^\pm, \tilde{z})$	1	3	0
V'	*Hypercharge* $B(\gamma)$	*bino* $\tilde{b}(\tilde{\gamma})$	1	1	0
Matter					
L_i	sleptons $\tilde{L}_i = (\tilde{\nu}, \tilde{e})_L$	leptons $L_i = (\nu, e)_L$	1	2	-1
E_i	sleptons $\tilde{E}_i = \tilde{e}_R$	leptons $E_i = e_R$	1	1	2
Q_i	squarks $\tilde{Q}_i = (\tilde{u}, \tilde{d})_L$	quarks $Q_i = (u, d)_L$	3	2	$1/3$
U_i	squarks $\tilde{U}_i = \tilde{u}_R$	quarks $U_i = u_R^c$	3^*	1	$-4/3$
D_i	squarks $\tilde{D}_i = \tilde{d}_R$	quarks $D_i = d_R^c$	3^*	1	$2/3$
Higgs					
H_1	Higgses H_1	higgsinos $\tilde{H}_1$	1	2	-1
H_2	Higgses H_2	higgsinos $\tilde{H}_2$	1	2	1

The MSSM Lagrangian

$$L = L_{gauge} + L_{Yukawa} + L_{SoftBreaking}$$

The Yukawa Superpotential

Superfields

$$W_R = y_U Q_L H_2 U_R + y_D Q_L H_1 D_R + y_L L_L H_1 E_R + \mu H_1 H_2$$

Yukawa couplings

Higgs mixing term

$$W_{NR} = \lambda_L L_L L_L E_R + \lambda_L^{'} L_L Q_L D_R + \mu^{'} L_L H_2 + \lambda_B U_R D_R D_R$$

Violate: Lepton number Baryon number

These terms are forbidden in the SM

$$\lambda_L, \lambda_L^{'} < 10^{-6}, \quad \lambda_B < 10^{-9}$$

R-parity

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

The Usual Particle : R = + 1
SUSY Particle : R = - 1

B - Baryon Number
L - Lepton Number
S - Spin

The consequences:

- The superpartners are created in pairs
- The lightest superparticle is stable

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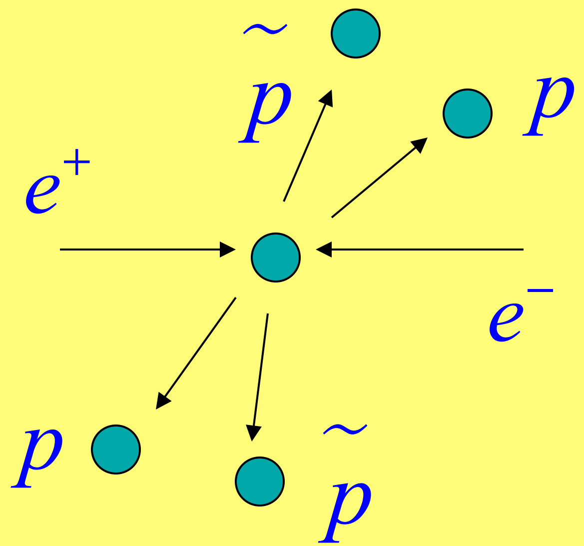
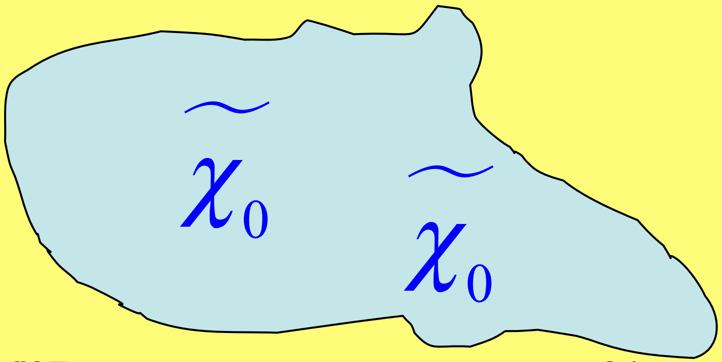


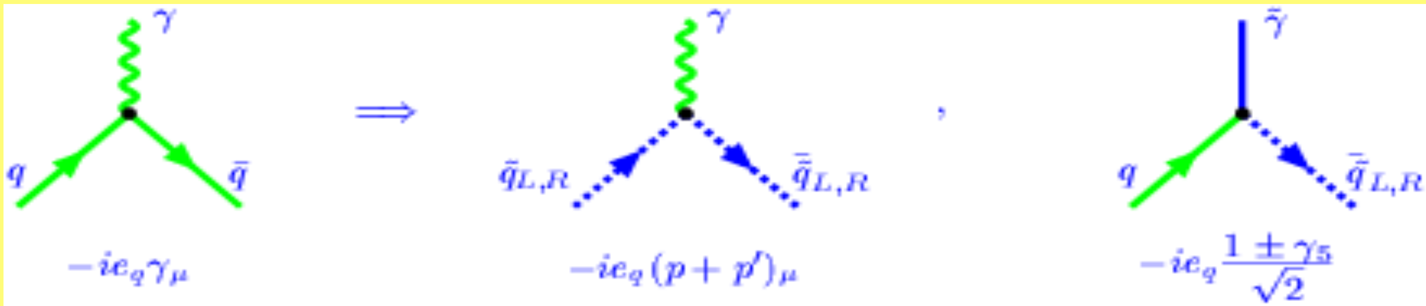
- The lightest superparticle (LSP) should be neutral - the best candidate is neutralino (photino or higgsino) $\tilde{\chi}_0$
- It can survive from the Big Bang and form the Dark matter in the Universe

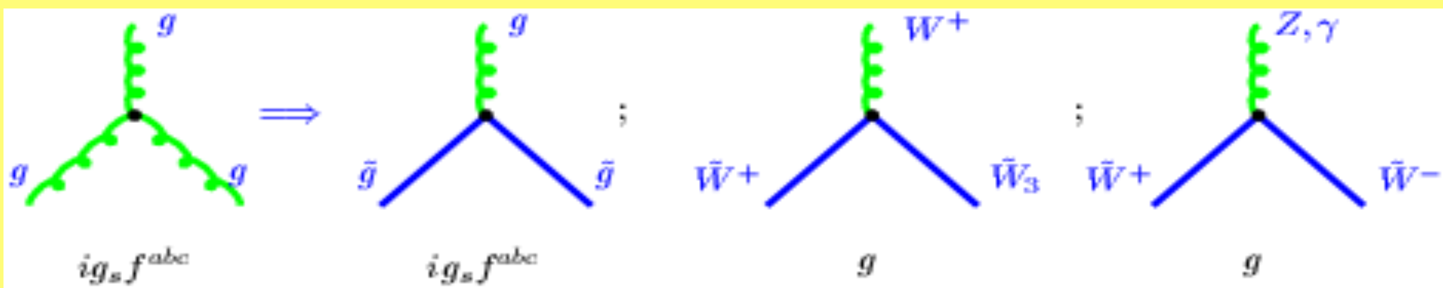


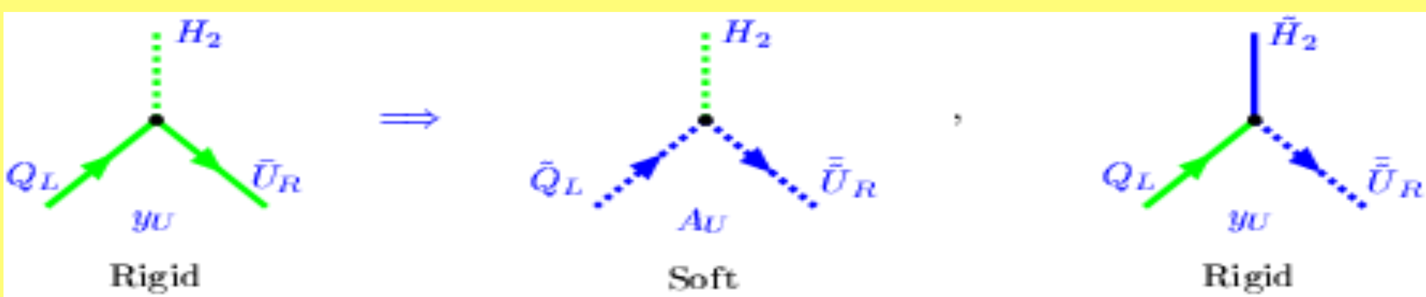
Interactions in the MSSM

SM → MSSM

Vertices

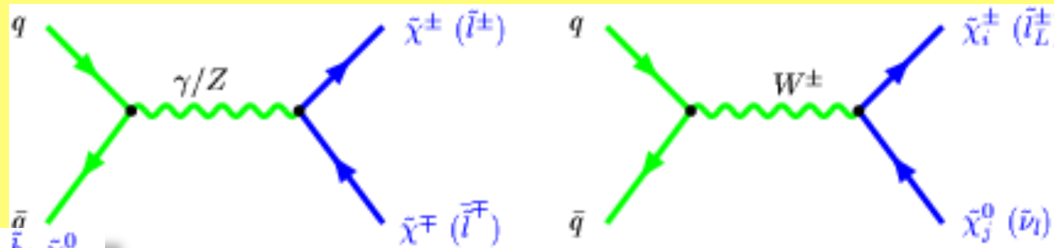


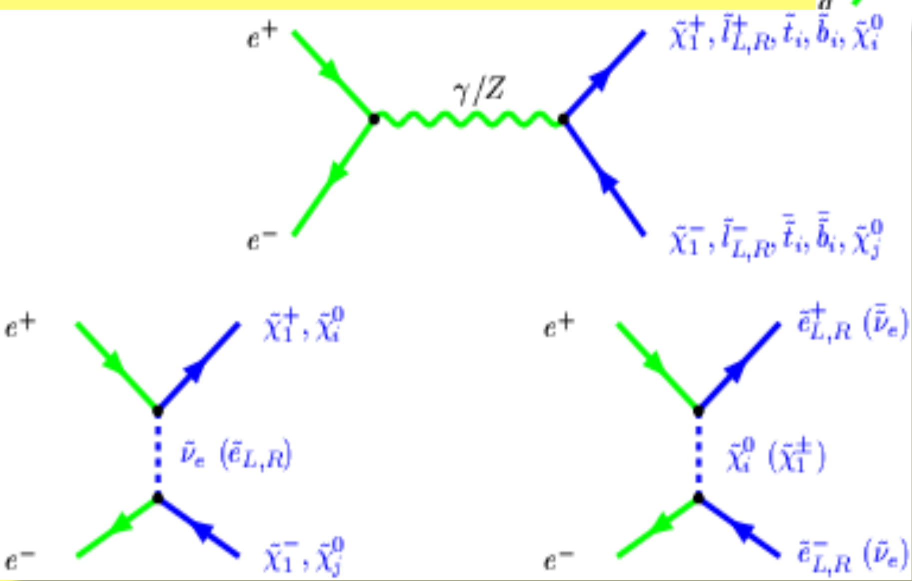


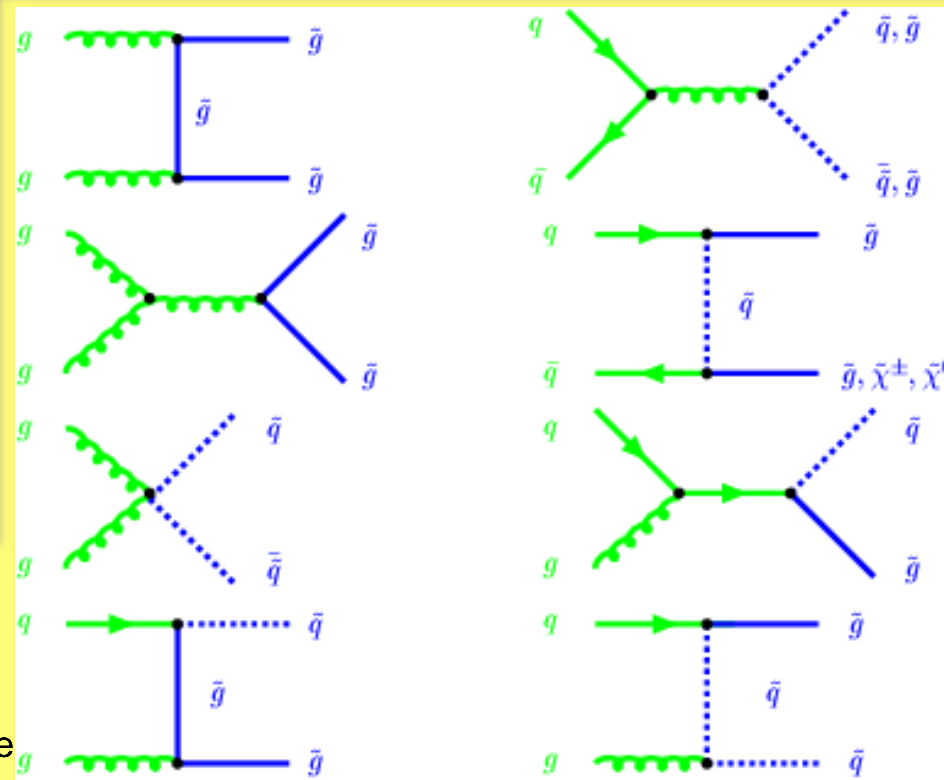


Creation of Superpartners at colliders

Annihilation channel

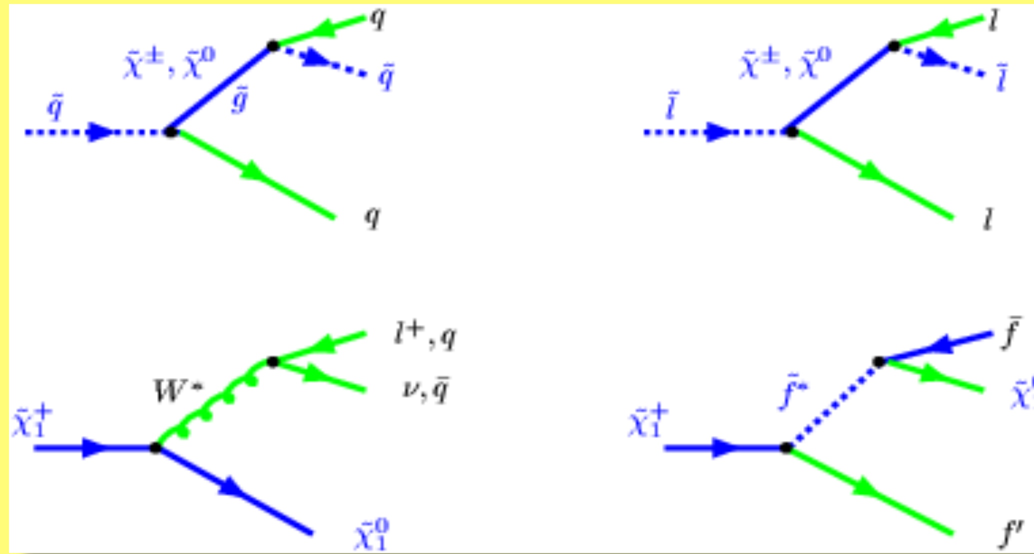






Gluon fusion, ee, qq scattering and qg scattering channels

Decay of Superpartners



squarks

$$\tilde{q}_{L,R} \to q + \tilde{\chi}_i^0$$

$$\tilde{q}_L \to q' + \tilde{\chi}_i^\pm$$

$$\tilde{q}_{L,R} \to q + \tilde{g}$$

sleptons

$$\tilde{l} \to l + \tilde{\chi}_i^0$$

$$\tilde{l}_L \to \nu_l + \tilde{\chi}_i^\pm$$

chargino

$$\tilde{\chi}_i^\pm \to e + \nu_e + \tilde{\chi}_i^0$$

$$\tilde{\chi}_i^\pm \to q + \bar{q}' + \tilde{\chi}_i^0$$

gluino

$$\tilde{g} \to q + \bar{q} + \tilde{\gamma}$$

$$\tilde{g} \to g + \tilde{\gamma}$$

neutralino

$$\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 + l^+ + l^-$$

$$\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 + q + \bar{q}'$$

$$\tilde{\chi}_i^0 \to \tilde{\chi}_1^\pm + l^\pm + \nu_l$$

$$\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 + \nu_l + \bar{\nu}_l$$

Final sates

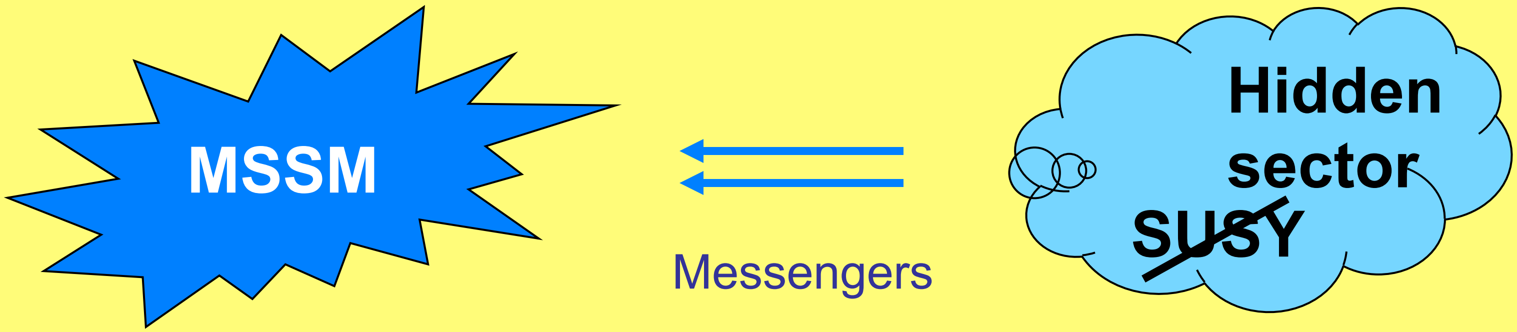
$$l^+ l^- + \not{E}_T$$

$$2 \text{ jets } + \not{E}_T$$

$$\gamma + \not{E}_T$$

$$\not{E}_T$$

Soft SUSY Breaking



Gravitons, gauge, gauginos, etc

Breaking via F and D terms in a hidden sector

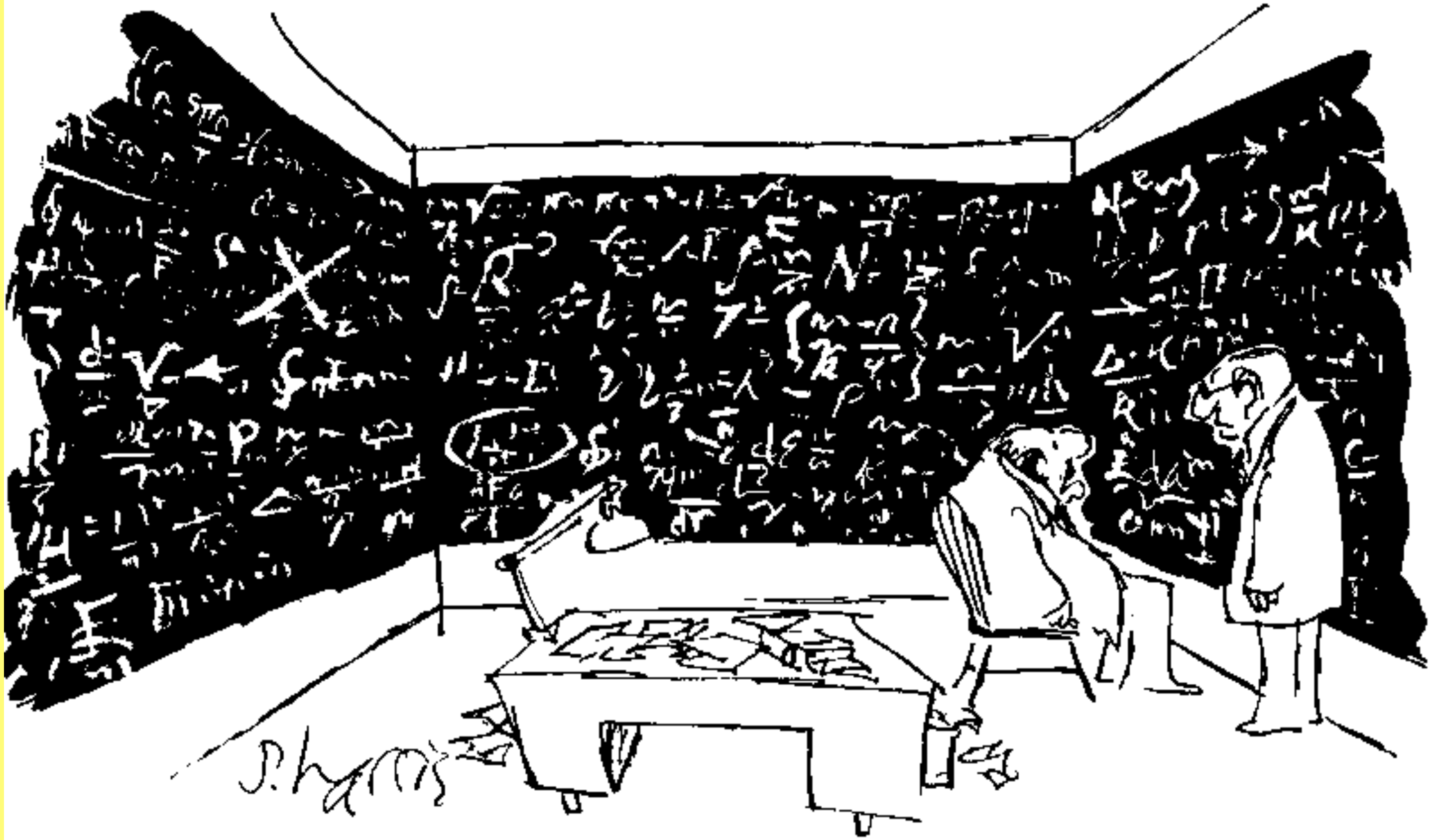
$$-L_{Soft} = \sum_{\alpha} M_i \tilde{\lambda}_i \tilde{\lambda}_i + \sum_i m_{0i}^2 \, | A_i |^2 + + \sum_{ijk} \mathrm{A}_{ijk} A_i A_j A_k + \sum_{ij} \mathrm{B}_{\mathrm{ij}} A_i A_j$$

gauginos

scalar fields

Over 100 of free parameters !

We like elegant solutions



"Whatever happened to *elegant* solutions?"

MSSM Parameter Space

- Three gauge couplings
- Three (four) Yukawa matrices
- The Higgs mixing parameter
- Soft SUSY breaking terms

mSUGRA Universality hypothesis (gravity is colour and flavour blind): Soft parameters are equal at Planck (GUT) scale

$$-L_{Soft} = A\{y_t Q_L H_2 U_R + y_b Q_L H_1 D_R + y_L L_L H_1 E_R\} + B\mu H_1 H_2 + m_0^2 \sum_i |\varphi_i|^2 + \tfrac{1}{2} M_{1/2} \sum_\alpha \tilde{\lambda}_\alpha \tilde{\lambda}_\alpha$$

Five universal soft parameters: $A,\ m_0,\ M_{1/2},\ B \leftrightarrow \tan\beta = v_2 / v_1$ and μ

versus m and λ in the SM

Mass Spectrum

$$L_{gaugino-Higgsino} = -\tfrac{1}{2} M_3 \bar{\lambda}_a \lambda_a - \tfrac{1}{2} \bar{\chi} M^{(0)} \chi - (\bar{\psi} M^{(c)} \psi + h.c.)$$

Chargino

$$\psi = \begin{pmatrix} \tilde{W}^+ \\ \tilde{H}^+ \end{pmatrix} \qquad M^{(c)} = \begin{pmatrix} M_2 & \sqrt{2} M_W \sin\beta \\ \sqrt{2} M_W \cos\beta & \mu \end{pmatrix} \Rightarrow \begin{pmatrix} \chi_1^+ \\ \chi_2^+ \end{pmatrix}$$

Neutralino

$$\chi_1^0,\ \chi_2^0,\ \chi_3^0,\ \chi_4^0$$

$$\chi = \begin{pmatrix} \tilde{B}^0 \\ \tilde{W}^3 \\ \tilde{H}_1^0 \\ \tilde{H}_2^0 \end{pmatrix} \quad M^{(0)} = \begin{pmatrix} M_1 & 0 & -M_Z \cos\beta \sin W & M_Z \sin\beta \sin W \\ 0 & M_2 & M_Z \cos\beta \cos W & -M_Z \sin\beta \cos W \\ -M_Z \cos\beta \sin W & M_Z \cos\beta \cos W & 0 & -\mu \\ M_Z \sin\beta \sin W & -M_Z \sin\beta \cos W & -\mu & 0 \end{pmatrix}$$

Squarks & Sleptons

Mass Spectrum

$$\tilde{m}_t^2 = \begin{pmatrix} \tilde{m}_{tL}^2 & m_t(A_t - \mu \cot\beta) \\ m_t(A_t - \mu\cot\beta) & \tilde{m}_{tR}^2 \end{pmatrix} \Rightarrow \begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix}$$

$$\tilde{m}_b^2 = \begin{pmatrix} \tilde{m}_{bL}^2 & m_b(A_b - \mu \tan\beta) \\ m_b(A_b - \mu\tan\beta) & \tilde{m}_{bR}^2 \end{pmatrix} \Rightarrow \begin{pmatrix} \tilde{b}_1 \\ \tilde{b}_2 \end{pmatrix}$$

$$\tilde{m}_{tL}^2 = \tilde{m}_Q^2 + m_t^2 + \tfrac{1}{6}(4M_W^2 - M_Z^2)\cos 2\beta,$$

$$\tilde{m}_{tR}^2 = \tilde{m}_U^2 + m_t^2 - \tfrac{2}{3}(M_W^2 - M_Z^2)\cos 2\beta,$$

$$\tilde{m}_{bL}^2 = \tilde{m}_Q^2 + m_b^2 - \tfrac{1}{6}(2M_W^2 + M_Z^2)\cos 2\beta,$$

$$\tilde{m}_{bR}^2 = \tilde{m}_D^2 + m_b^2 + \tfrac{1}{3}(M_W^2 - M_Z^2)\cos 2\beta,$$

$$\tilde{m}_{\tau L}^2 = \tilde{m}_L^2 + m_\tau^2 - \tfrac{1}{2}(2M_W^2 - M_Z^2)\cos 2\beta,$$

$$\tilde{m}_{\tau R}^2 = \tilde{m}_E^2 + m_\tau^2 + (M_W^2 - M_Z^2)\cos 2\beta.$$

$$\tilde{m}_\tau^2 = \begin{pmatrix} \tilde{m}_{\tau L}^2 & m_\tau(A_\tau - \mu \tan\beta) \\ m_\tau(A_\tau - \mu\tan\beta) & \tilde{m}_{\tau R}^2 \end{pmatrix} \Rightarrow \begin{pmatrix} \tilde{\tau}_1 \\ \tilde{\tau}_2 \end{pmatrix}$$

7

Renormalization Group Eqns

$$\tilde{\alpha}_i \equiv \frac{g_i^2}{16\pi^2} = \frac{\alpha_i}{4\pi}, \quad Y_k \equiv \frac{y_k^2}{16\pi^2}, \quad t = \log(M_{GUT}^2 / Q^2)$$

$$i = 1,2,3 \qquad k = U, D, L$$

The couplings

$$\dot{\tilde{\alpha}}_i = -b_i \tilde{\alpha}_i^2, \qquad b_i^{MSSM} = (\tfrac{33}{5}, 1, -3)$$

$$\dot{Y}_U = Y_U(\tfrac{16}{3}\tilde{\alpha}_3 + 3\tilde{\alpha}_2 + \tfrac{13}{15}\tilde{\alpha}_1 - 6Y_U - Y_D),$$

$$\dot{Y}_D = Y_D(\tfrac{16}{3}\tilde{\alpha}_3 + 3\tilde{\alpha}_2 + \tfrac{7}{15}\tilde{\alpha}_1 - Y_U - 6Y_D - Y_L),$$

$$\dot{Y}_L = Y_L(3\tilde{\alpha}_2 + \tfrac{9}{5}\tilde{\alpha}_1 - 3Y_D - 4Y_L),$$

$$\dot{M}_i = b_i \tilde{\alpha}_i M_i,$$

$$\dot{A}_U = -(\tfrac{16}{3}\tilde{\alpha}_3 M_3 + 3\tilde{\alpha}_2 M_2 + \tfrac{13}{15}\tilde{\alpha}_1 M_1) - 6Y_U A_U - Y_D A_D,$$

$$\dot{A}_D = -(\tfrac{16}{3}\tilde{\alpha}_3 M_3 + 3\tilde{\alpha}_2 M_2 + \tfrac{7}{15}\tilde{\alpha}_1 M_1) - Y_U A_U - 6Y_D A_D - Y_L A_L,$$

$$\dot{A}_L = -(3\tilde{\alpha}_2 M_2 + \tfrac{9}{5}\tilde{\alpha}_1 M_1) - 3Y_D A_D - 4Y_L A_L,$$

$$\dot{B} = -3(\tilde{\alpha}_2 M_2 + \tfrac{1}{5}\tilde{\alpha}_1 M_1) - 3Y_U A_U - 3Y_D A_D - Y_L A_L,$$

$$\dot{\mu} = -\mu^2(3\tilde{\alpha}_2 + \tfrac{3}{5}\tilde{\alpha}_1 - 3Y_U - 3Y_D - Y_L)$$

Soft Terms

RG Eqns for the Soft Masses

$$\dot{\tilde{m}}_Q^2 = -[\tfrac{16}{3}\tilde{\alpha}_3 M_3^2 + 3\tilde{\alpha}_2 M_2^2 + \tfrac{1}{15}\tilde{\alpha}_1 M_1^2 - Y_t(\Sigma_t + A_t^2) - Y_b(\Sigma_b + A_b^2)]$$

$$\dot{\tilde{m}}_U^2 = -[\tfrac{16}{3}\tilde{\alpha}_3 M_3^2 + \tfrac{16}{15}\tilde{\alpha}_1 M_1^2 - 2Y_t(\Sigma_t + A_t^2)]$$

$$\dot{\tilde{m}}_D^2 = -[\tfrac{16}{3}\tilde{\alpha}_3 M_3^2 + \tfrac{4}{15}\tilde{\alpha}_1 M_1^2 - 2Y_b(\Sigma_b + A_b^2)]$$

$$\dot{\tilde{m}}_L^2 = -[3\tilde{\alpha}_2 M_2^2 + \tfrac{3}{5}\tilde{\alpha}_1 M_1^2 - Y_\tau(\Sigma_\tau + A_\tau^2)]$$

$$\dot{\tilde{m}}_E^2 = -[\tfrac{12}{5}\tilde{\alpha}_1 M_1^2 - 2Y_\tau(\Sigma_\tau + A_\tau^2)]$$

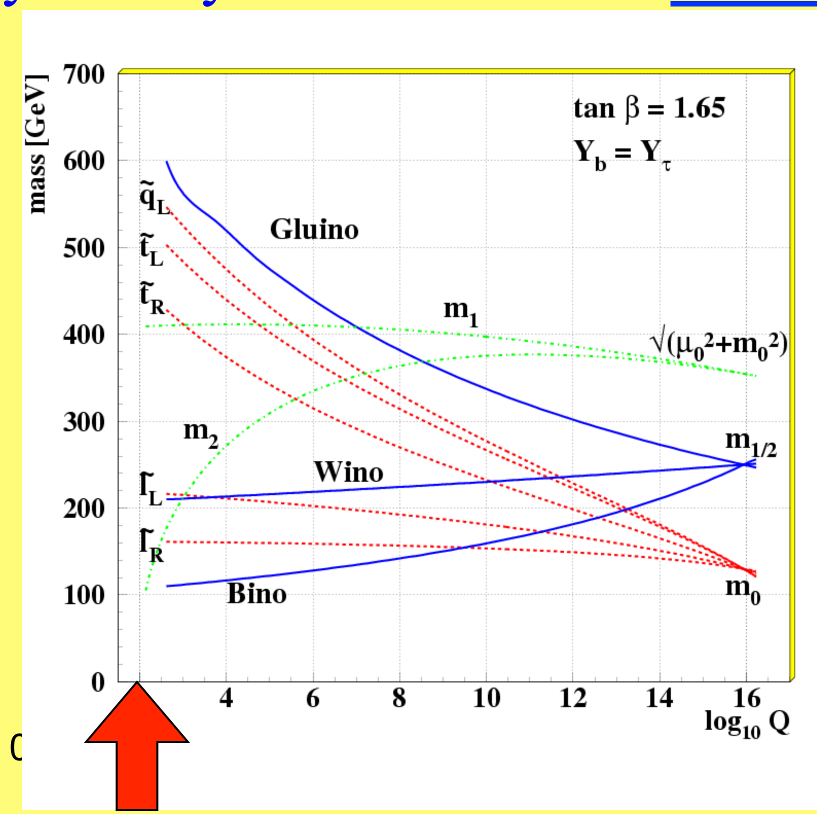
$$\dot{\tilde{m}}_{H_1}^2 = -[3\tilde{\alpha}_2 M_2^2 + \tfrac{3}{5}\tilde{\alpha}_1 M_1^2 - 3Y_b(\Sigma_b + A_b^2) - Y_\tau(\Sigma_\tau + A_\tau^2)]$$

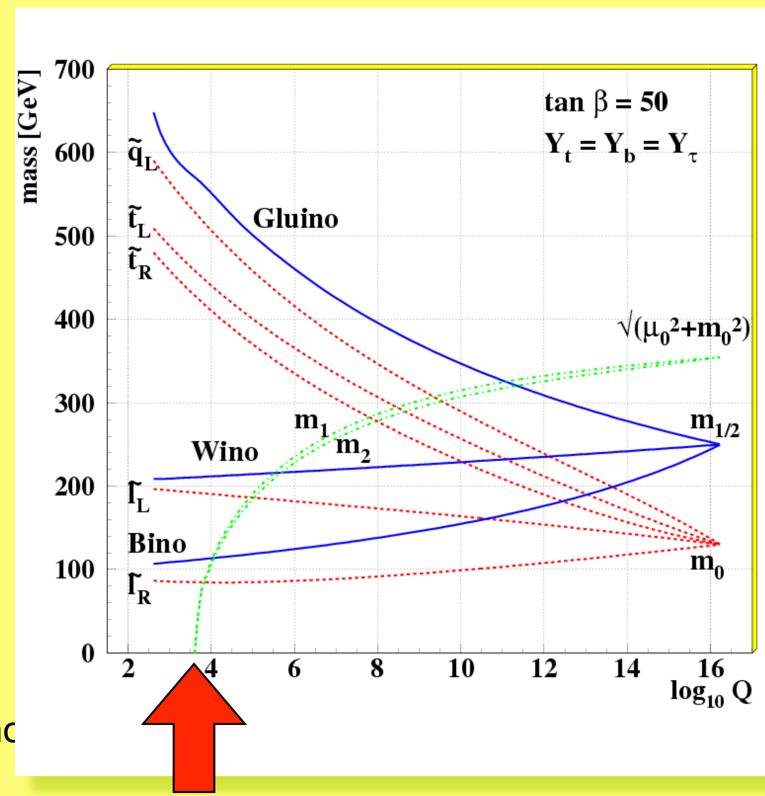
$$\dot{\tilde{m}}_{H_2}^2 = -[3\tilde{\alpha}_2 M_2^2 + \tfrac{3}{5}\tilde{\alpha}_1 M_1^2 - 3Y_t(\Sigma_t + A_t^2)]$$

$$\Sigma_t = m_Q^2 + m_U^2 + m_{H_2}^2,\ \Sigma_b = m_Q^2 + m_D^2 + m_{H_1}^2,\ \Sigma_\tau = m_L^2 + m_E^2 + m_{H_1}^2$$

Radiative EW Symmetry Breaking

Due to RG controlled running of the mass terms from the Higgs potential they may change sign and trigger the appearance of non-trivial minimum leading to spontaneous breaking of EW symmetry - this is called <u>Radiative EWSB</u>





SUSY Higgs Bosons

SM

$$H=\begin{pmatrix}H^0\\H^-\end{pmatrix}=\begin{pmatrix}v+\frac{S+iP}{\sqrt{2}}\\H^-\end{pmatrix}=\exp(i\frac{\vec{\xi}\vec{\sigma}}{2})\begin{pmatrix}v+\frac{S}{\sqrt{2}}\\0\end{pmatrix}$$

4=2+2=3+1

$$H\rightarrow H'=\exp(i\frac{\vec{\alpha}\vec{\sigma}}{2})H\xrightarrow{(\vec{\alpha}=-\vec{\xi})}H'=\begin{pmatrix}v+\frac{S}{\sqrt{2}}\\0\end{pmatrix}$$

MSSM

$$H_1=\begin{pmatrix}H_1^0\\H_1^-\end{pmatrix}=\begin{pmatrix}v_1+\frac{S_1+iP_1}{\sqrt{2}}\\H_1^-\end{pmatrix},\quad H_2=\begin{pmatrix}H_2^+\\H_2^0\end{pmatrix}=\begin{pmatrix}H_2^+\\v_2+\frac{S_2+iP_2}{\sqrt{2}}\end{pmatrix},$$

$v_1^2+v_2^2=v^2$, $v_2/v_1\equiv\tan\beta$

8=4+4=3+5

$G^0=-\cos\beta P_1+\sin\beta P_2$	*Goldstone boson* $\rightarrow Z_0$
$A=\sin\beta P_1+\cos\beta P_2$	*Neutral* $CP=-1$ *Higgs*
$G^+=-\cos\beta(H_1^-)^*+\sin\beta H_2^+$	*Goldstone boson* $\rightarrow W^+$
$H^+=\sin\beta(H_1^-)^*+\cos\beta H_2^+$	*Charged Higgs*
$h=-\sin\alpha S_1+\cos\alpha S_2$	SM *Higgs boson* $CP=1$
$H=\cos\alpha S_1+\sin\alpha S_2$	*Extra heavy Higgs boson*

$$\tan 2\alpha=\tan 2\beta\frac{m_A^2+m_Z^2}{m_A^2-m_Z^2}$$

The Higgs Potential

$$V_{tree}(H_1,H_2) = m_1^2 \mid H_1\mid^2 + m_2^2 \mid H_2 \mid^2 - m_3^2(H_1H_2 + h.c.)$$
$$+\frac{g^2+g'^2}{8}(\mid H_1\mid^2 - \mid H_2\mid^2)^2 + \frac{g^2}{2}\mid H_1^+ H_2\mid^2$$

At the GUT scale: $m_1^2 = m_2^2 = \mu_0^2 + m_0^2,\ m_3^2 = -B\mu_0$

Minimization

$$\frac{1}{2}\frac{\delta V}{\delta H_1} = m_1^2 v_1 - m_3^2 v_2 + \frac{g^2+g'^2}{4}(v_1^2 - v_2^2)v_1 = 0,$$
$$\frac{1}{2}\frac{\delta V}{\delta H_2} = m_2^2 v_2 - m_3^2 v_1 - \frac{g^2+g'^2}{4}(v_1^2 - v_2^2)v_2 = 0.$$
$$< H_1 > \equiv v_1 = v\cos\beta,\ \ < H_2 > \equiv v_2 = v\sin\beta,$$

Solution

$$v^2 = \frac{4(m_1^2 - m_2^2\tan^2\beta)}{(g^2+g'^2)(\tan^2\beta - 1)},$$
$$\sin 2\beta = \frac{2m_3^2}{m_1^2 + m_2^2}$$

At the GUT scale

$$v^2 = -\frac{4}{g^2+g'^2}m^2 < 0$$

No SSB in SUSY theory !

The Higgs Bosons Masses

CP-odd neutral Higgs A
CP-even charged Higgses $H^{\pm}$

CP-even neutral Higgses h,H

$$m_A^2 = m_1^2 + m_2^2$$
$$m_{H^\pm}^2 = m_A^2 + M_W^2$$

$$M_W^2 = \frac{g^2}{2} v^2$$
$$M_Z^2 = \frac{g^2 + g'^2}{2} v^2$$

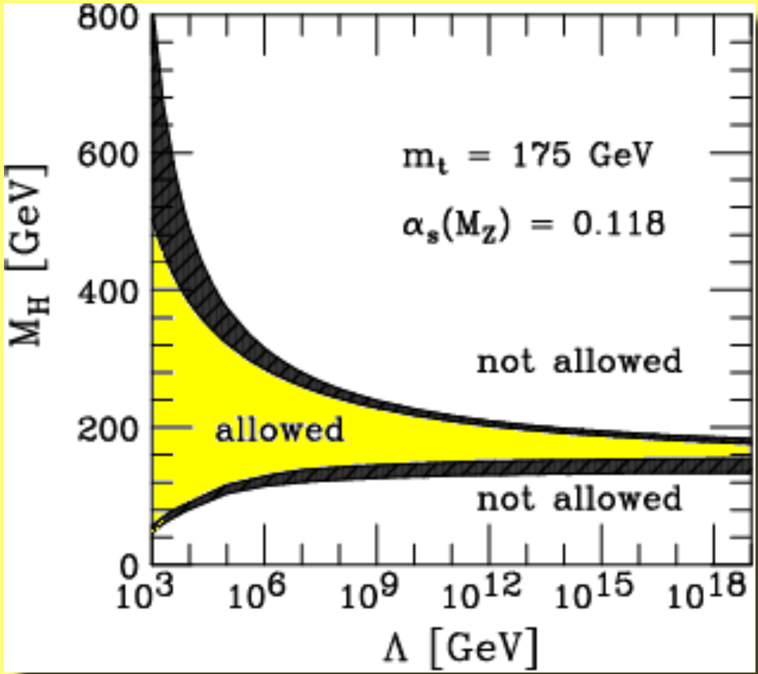
$$m_{h,H}^2 = \frac{1}{2}\left[m_A^2 + M_Z^2 \pm \sqrt{(m_A^2 + M_Z^2)^2 - 4 m_A^2 M_Z^2 \cos^2 2\beta}\right]$$

$$m_h \approx M_Z \,|\cos 2\beta|\; < \; M_Z \; !$$

➡ Radiative corrections

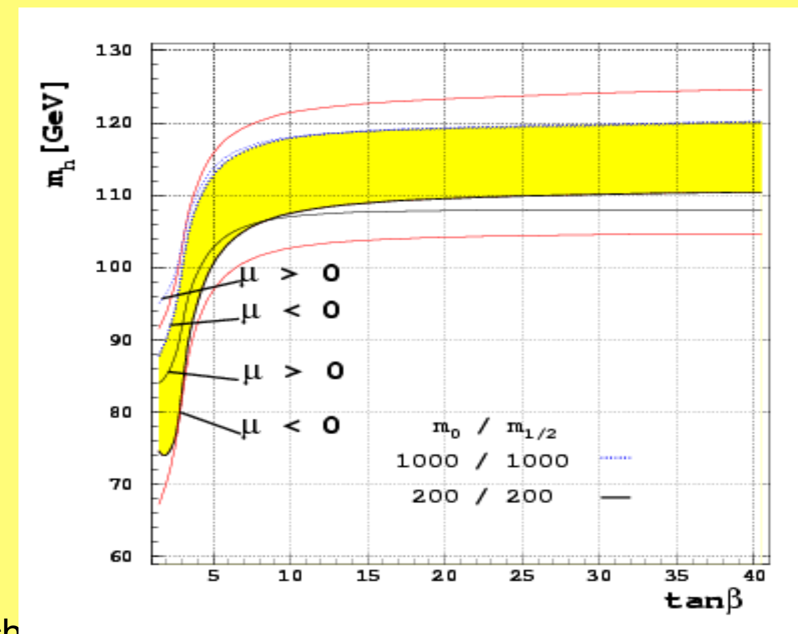
$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3 g^2 m_t^4}{16\pi^2 M_W^2} \log \frac{\tilde{m}_{t_1}^2 \tilde{m}_{t_2}^2}{m_t^4} + 2\ loops$$

The Higgs Mass Limit



- The SM Higgs

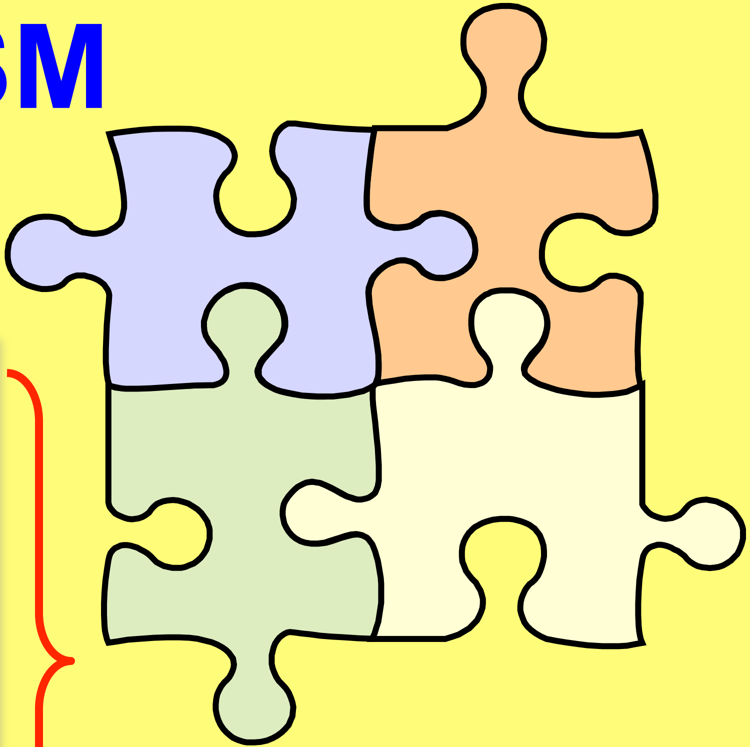
$m_H \geq 134$ GeV



SUSY Higgs

$m_H \leq 130$ GeV

Constrained MSSM



Requirements:

- Unification of the gauge couplings
- Radiative EW Symmetry Breaking
- Heavy quark and lepton masses
- Rare decays (b -> sγ)
- Anomalous magnetic moment of muon
- LSP is neutral
- Amount of the Dark Matter
- Experimental limits from direct search

$$A_0, m_0, M_{1/2}, \mu, \tan\beta$$

Allowed region
in the parameter
space of the MSSM

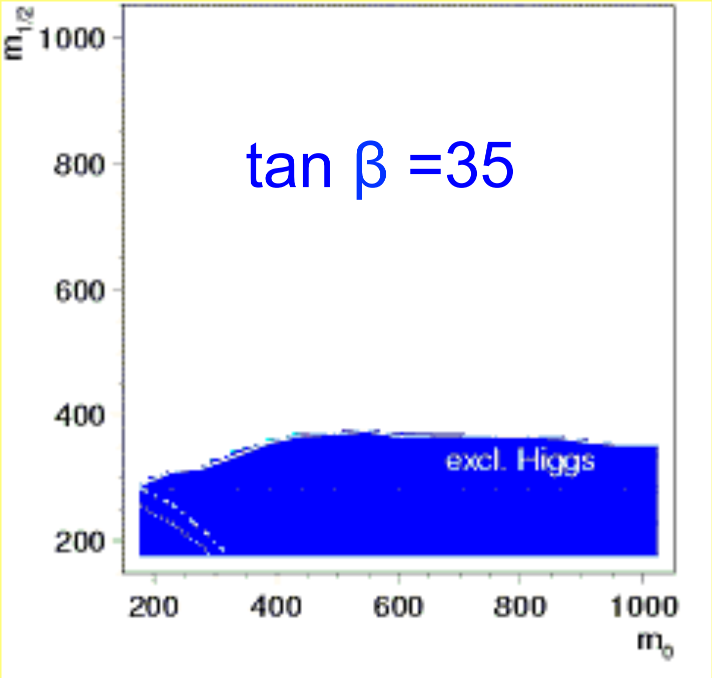
$$100\ \text{GeV} \le m_0, M_{1/2}, \mu \le 2\ \text{TeV}$$
$$-3m_0 \le A_0 \le 3m_0,\ 1 \le \tan\beta \le 70$$

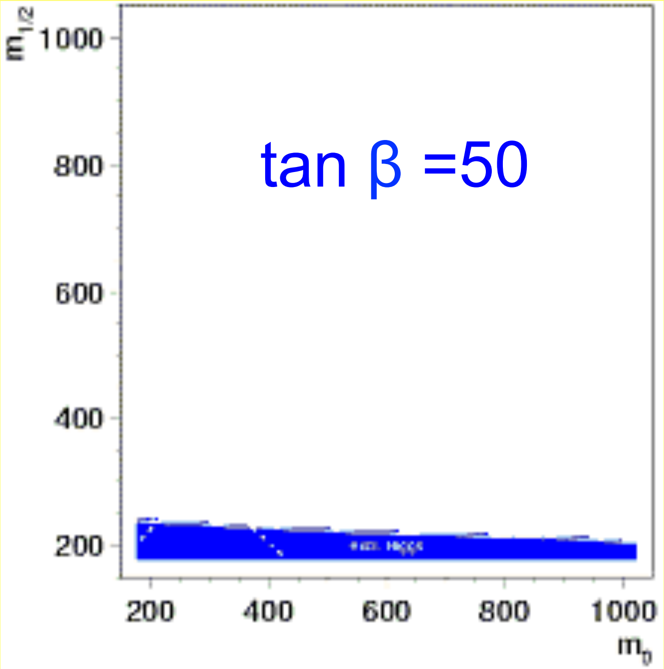
Constrained MSSM (Choice of constraints)

Experimental lower limits on Higgs and superparticle masses

Regions excluded by Higgs experimental limits provided by LEP2

$$m_{Higgs} \geq 114.3 \text{ GeV}$$



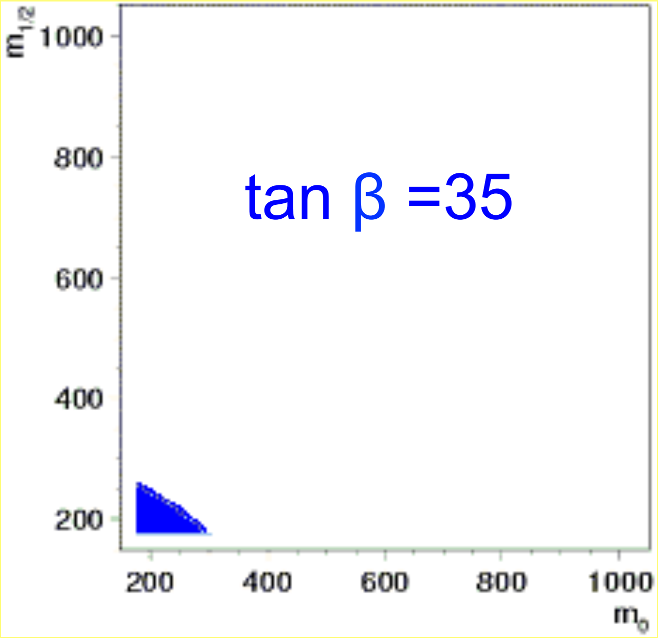


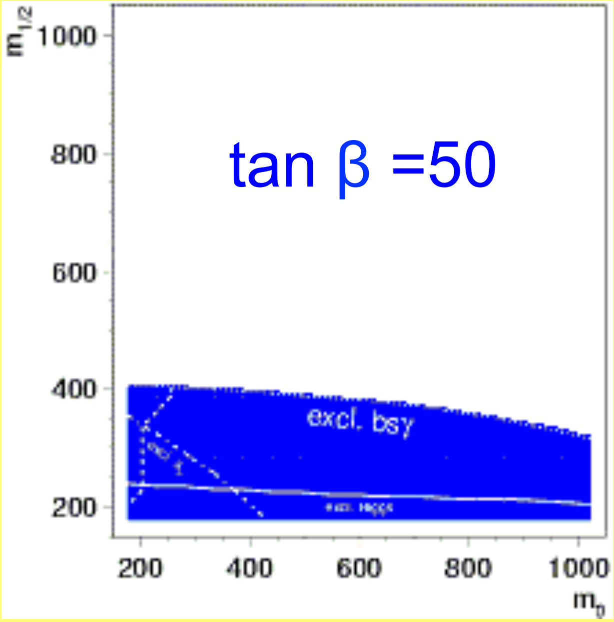
Constrained MSSM (Choice of constraints)

Data on rare processes branching ratios

$$B(B \to X_s \gamma) = (3.43 \pm 0.36) \cdot 10^{-4}$$

Regions excluded by experimental limits (for large tanβ)



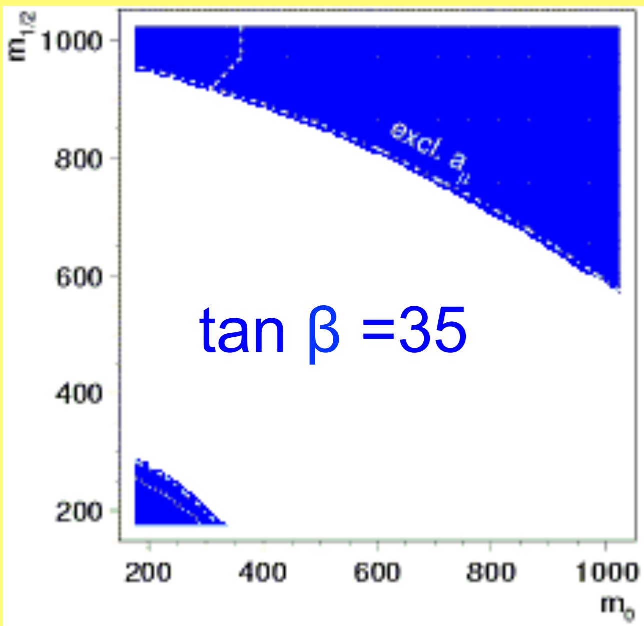


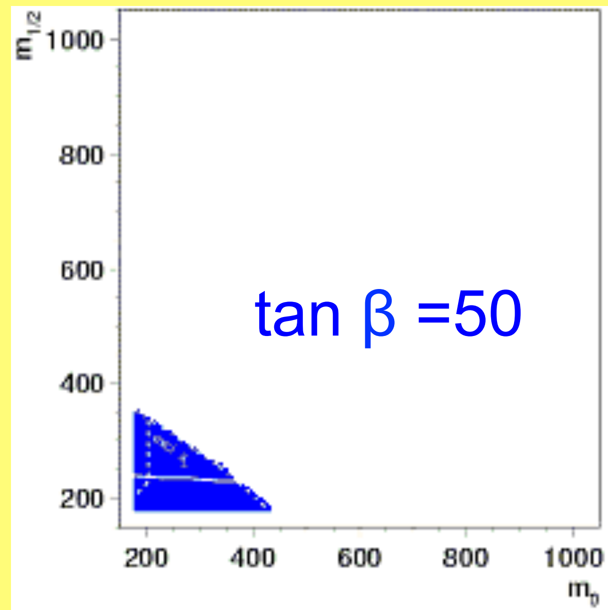
Constrained MSSM (Choice of constraints)

Muon anomalous magnetic moment

$$\Delta a_\mu = a_\mu^{\exp} - a_\mu^{th} = (27 \pm 10)\cdot 10^{-10}$$

Regions excluded by muon amm constraint



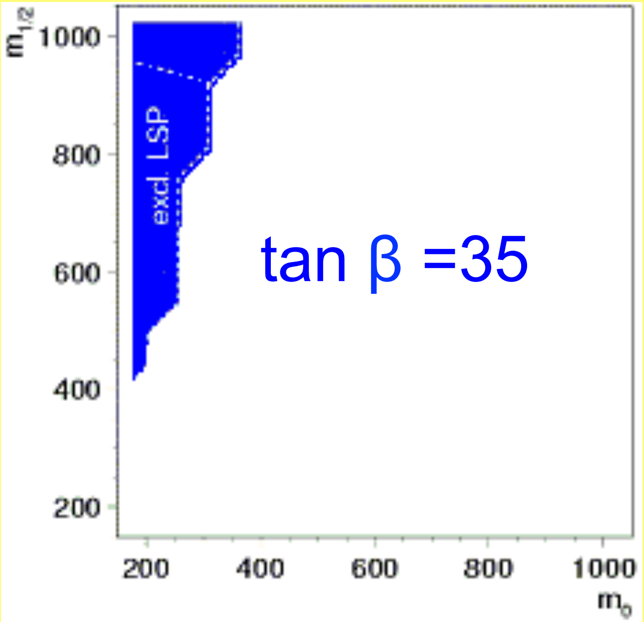


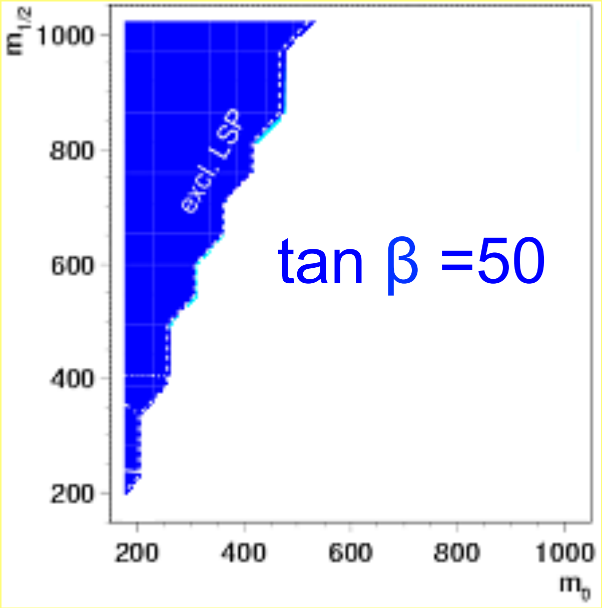
Constrained MSSM (Choice of constraints)

The lightest supersymmetric particle (LSP) is neutral.

This constraint is a consequence of *R*-parity conservation requirement

Regions excluded by LSP constraint

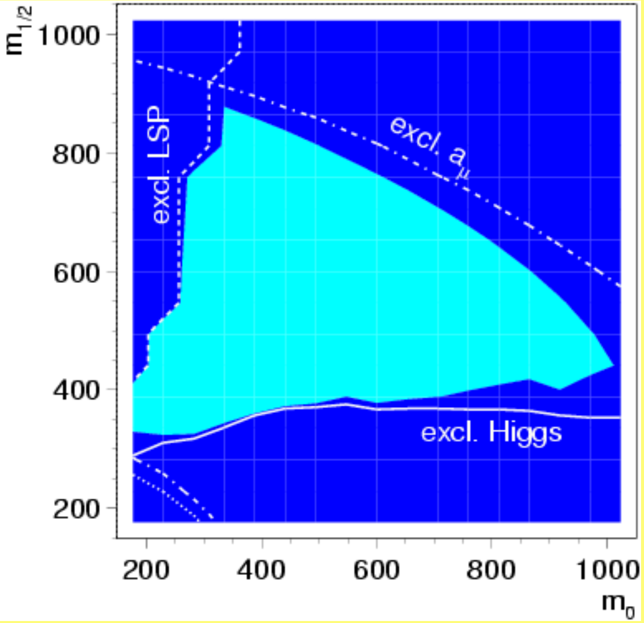




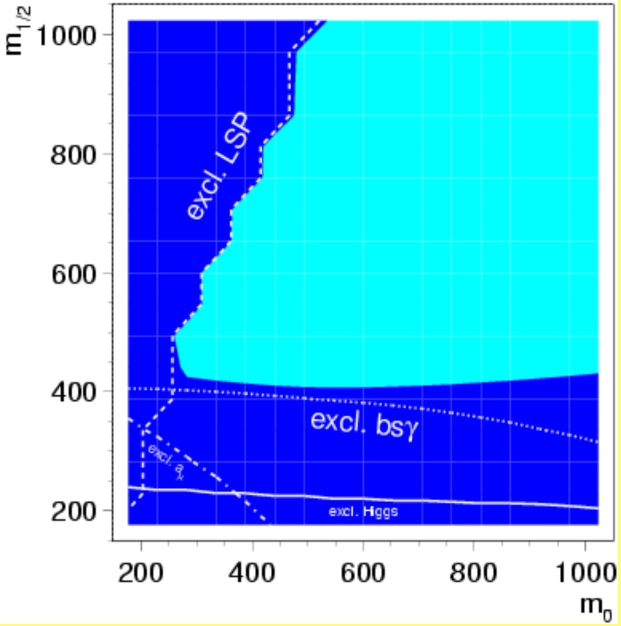
Favoured regions of parameter space

Pre-WMAP allowed regions in the parameter space.

From the Higgs searches tan β >4, from a_μ measurements μ >0

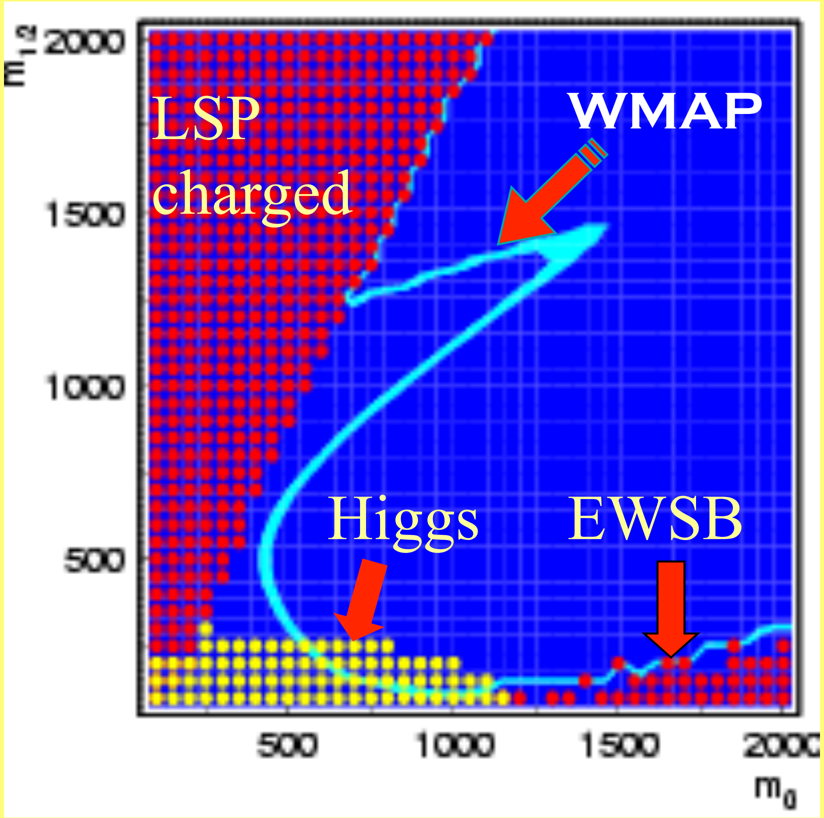


tan β =35



tan β =50

Allowed regions after WMAP



tan β =50

In allowed region one fulfills all the constraints simultaneously and has the suitable amount of the dark matter

Narrow allowed region enables one to predict the particle spectra and the main decay patterns

Phenomenology essentially depends on the region of parameter space and has direct influence on the strategy of SUSY searches

Mass Spectrum in CMSSM

(Sample)

Fitted SUSY Parameters

Symbol	Low tan β	High tan β
Tan β	1.71	35.0
m_0	200	600
$m_{1/2}$	500	400
μ(0)	1084	-558
A(0)	0	0
$1/\alpha_{GUT}$	24.8	24.8
M_{GUT}	$1.6 \cdot 10^{16}$	$1.6 \cdot 10^{16}$

SUSY Masses in GeV

Symbol	Low tan β	High tan β
$\tilde{\chi}_1^0(\tilde{B}), \tilde{\chi}_2^0(\tilde{W}^3)$	214, 413	170, 322
$\tilde{\chi}_3^0(\tilde{H}_1), \tilde{\chi}_4^0(\tilde{H}_2)$	1028, 1016	481, 498
$\tilde{\chi}_1^\pm(\tilde{W}^\pm), \tilde{\chi}_2^\pm(\tilde{H}^\pm)$	413, 1026	322, 499
$\tilde{g}$	1155	950
$\tilde{e}_L, \tilde{e}_R$	303, 270	663, 621
$\tilde{\nu}_L$	290	658
$\tilde{q}_L, \tilde{q}_R$	1028, 936	1040, 1010
$\tilde{\tau}_1, \tilde{\tau}_2$	279, 403	537, 634
$\tilde{b}_1, \tilde{b}_2$	953, 1010	835, 915
$\tilde{t}_1, \tilde{t}_2$	727, 1017	735, 906
h, H	95, 1344	119, 565
A, $H^\pm$	1340, 1344	565, 571

Superparticles

SParticle Data Group

The SPDG is an international collaboration that reviews Sparticle Physics and related areas of Astrophysics, and compiles/analyzes data on particle properties. SPDG products are distributed to 130,000 physicists, teachers, and other interested people. The **Review of Sparticle Physics** is the most cited publication in particle physics during the last twenty years. Plots of SPDG statistics are available.

Mirror sites: USA (LBNL) Brazil CERN Italy (Genova) Japan (KEK) Russia (Novosibirsk) Russia (Protvino) UK (Durham)

Review of Sparticle Physics Charts, Educational materials, Sparticle Adventure Information and Databases
US-HEPFOLK Sparticle Physics: Twenty Years of Discoveries Home Pages of major HEP labs

The Review of Sparticle Physics

C. Caso *et al*, The European Physical Journal **C103** (2018) 1 (2018 Authors)

- 2019 — **2019 Web update of Reviews, Tables, Plots** — **New November 2, 2019**
- 2019 — **2019 Web update of Sparticle Listings** — **New July 6, 2019**
- 2018 — **2018 Summary Tables and Conservation Laws**
- **2018 Reviews, Tables, Plots (incl. Intro. Text)** — **Superseded by 2019 Web Version**
- **2018 Sparticle Listings (published version)** — **Superseded by 2019 Web Version**

- Errata (last changed January 18, 2020)
- Archived WWW editions: 2017 2016 2015
- Descriptions of the Summary Tables, Reviews, Listings, etc.
- Ordering information and list of products
- 2018 Authors and Directory of Sparticle Data Group Authors, Associates, and Advisors
- Computer-readable files — masses, widths, cross-sections, etc., including Palm Pilot XXII files.
- Encoder tools (for SPDG collaborators)

Discovery of the new world of SUSY

Back to 60's

New discoveries every year