# BEYOND THE STANDARD MODEL

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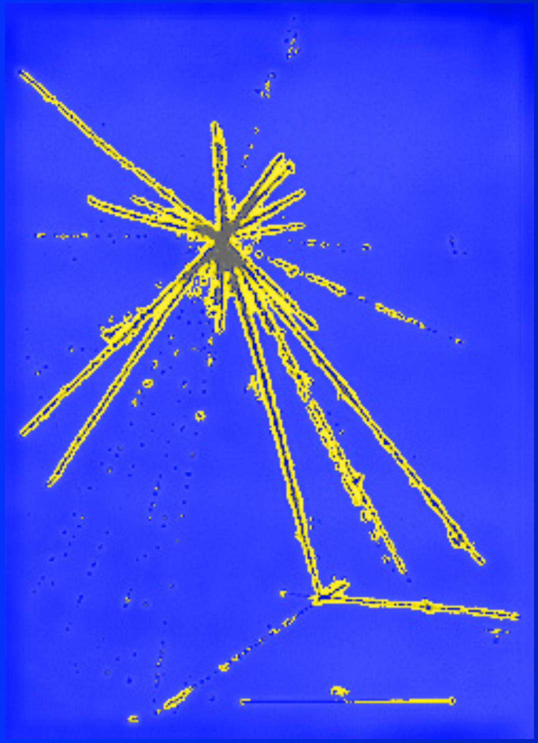
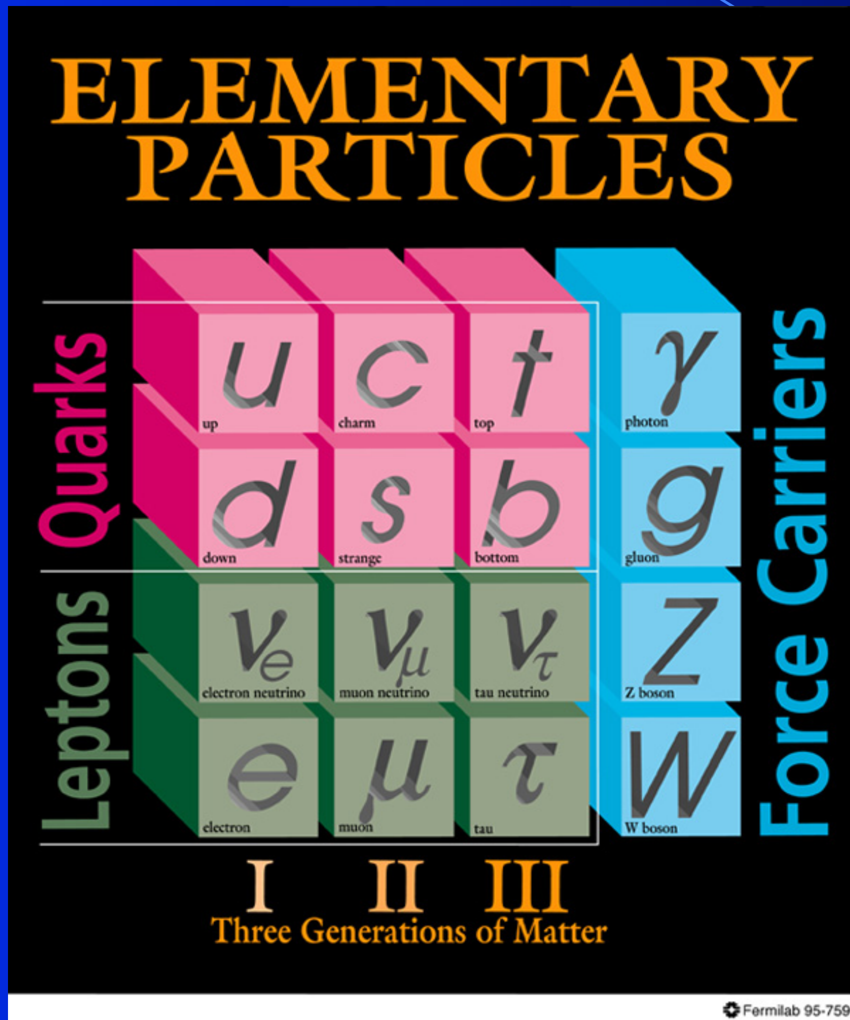


## Outline

1. What is SUSY
2. Motivation of SUSY
3. Basics of SUSY
4. The MSSM
5. Constrained MSSM
6. SUSY searches

# The Standard Model

Particles




H

The Higgs boson

## Forces

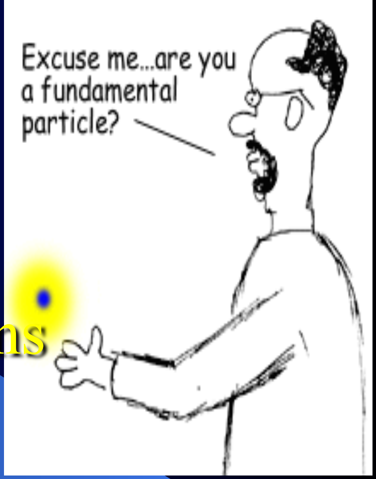
Electromagnetic

Strong

Weak

Gravity

# The SM and Beyond



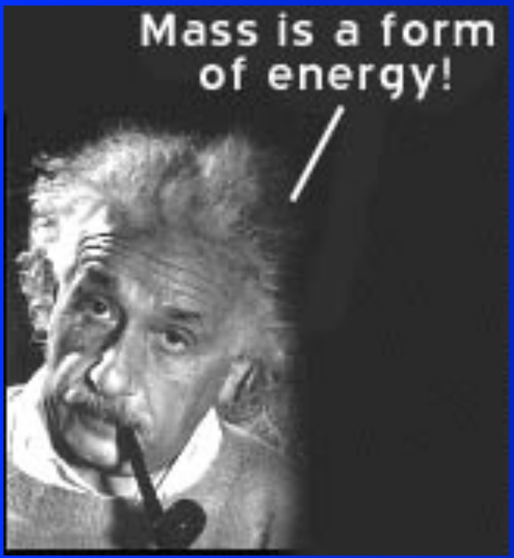

The problems of the SM:

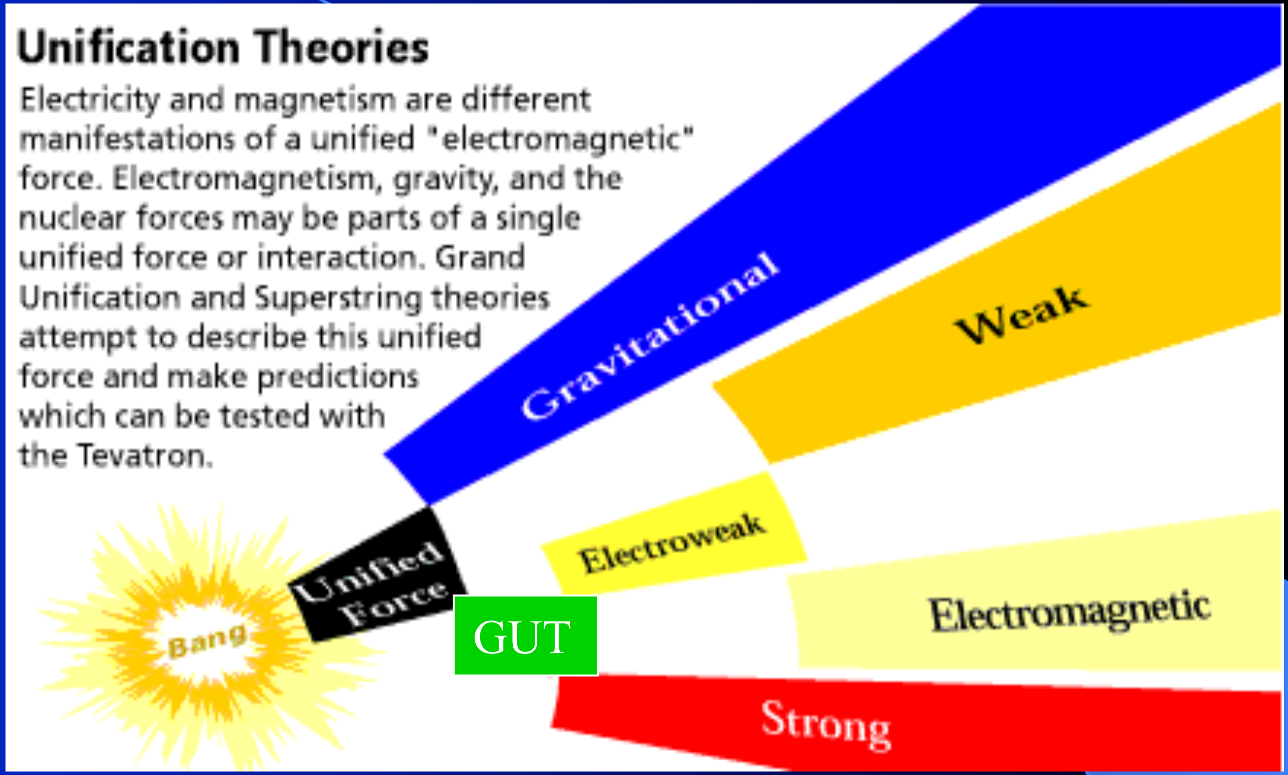
- Inconsistency at high energies due to Landau pole
- Large number of free parameters
- Formal unification of strong and electroweak interactions
- Still unclear mechanism of EW symmetry breaking
- CP-violation is not understood
- Flavour mixing and the number of generations is arbitrary
- The origin of the mass spectrum is unclear

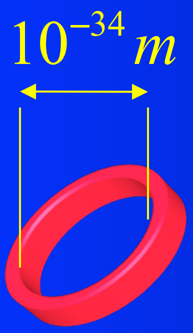
The ways beyond the SM:

- The SAME fields with NEW interactions ⇒ GUT, SUSY, String
- NEW fields with NEW interactions ⇒ Compositeness, Technicolour, preons

# Grand Unified Theories

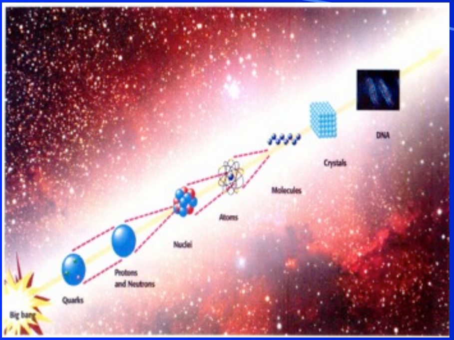


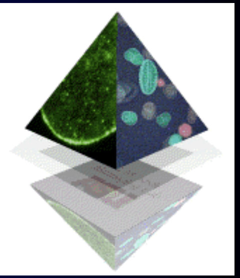




D=10

- Unification of strong, weak and electromagnetic interactions within Grand Unified Theories is the new step in unification of all forces of Nature
- Creation of a unified theory of everything based on string paradigm seems to be possible




# What is SUSY



- **Supersymmetry** is a boson-fermion symmetry that is aimed to unify all forces in Nature including gravity within a singe framework

$$Q\,|\,boson> = |\,fermion> \qquad Q\,|\,fermion> = |\,boson>$$

$$[b,b]=0, \quad \{f,f\}=0 \quad \Rightarrow$$

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

- Modern views on supersymmetry in particle physics are based on string paradigm, though low energy manifestations of SUSY can be found (?) at modern colliders and in non-accelerator experiments

# Motivation of SUSY in Particle Physics

- 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.

*Supertranslation*

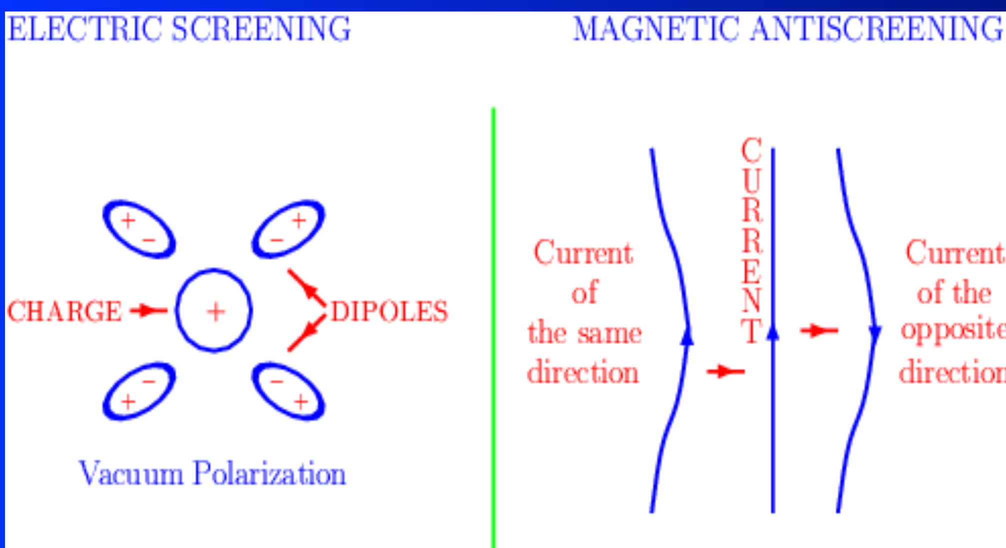
$$x_\mu \rightarrow x_\mu + i\theta\sigma_\mu\bar\xi - i\xi\sigma_\mu\bar\theta,$$
$$\theta \rightarrow \theta + \xi,$$
$$\bar\theta \rightarrow \bar\theta + \bar\xi$$

Local translation =
general relativity !

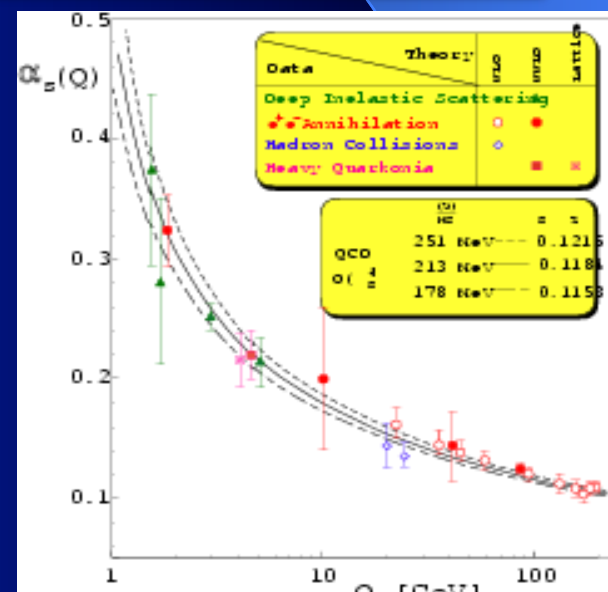
# Motivation of SUSY in Particle Physics

- 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* |
| $g_3$ | $g_2$ | $g_1$ | $\Rightarrow$ | $g_{GUT}$ |




$$\alpha_i = \alpha_i\left(\frac{Q^2}{\Lambda^2}\right) = \alpha_i(\text{distance})$$




Running of the strong coupling

# Motivation of SUSY

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

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

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

Input

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

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

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

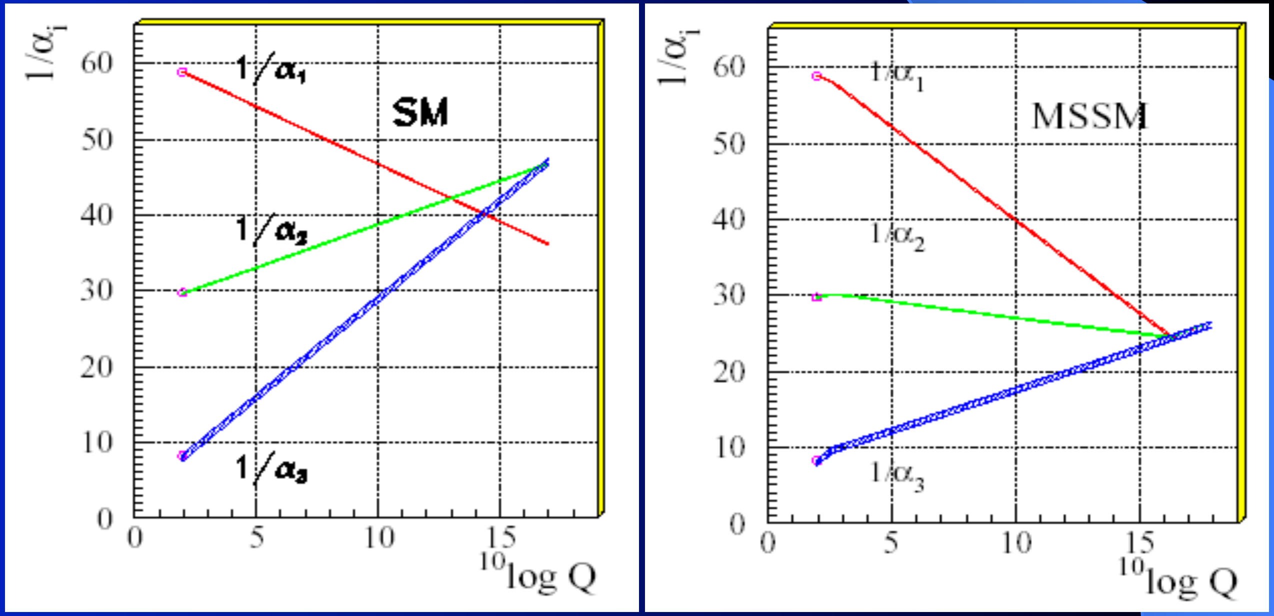
Output

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

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

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

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




SUSY yields unification!

# Motivation of SUSY

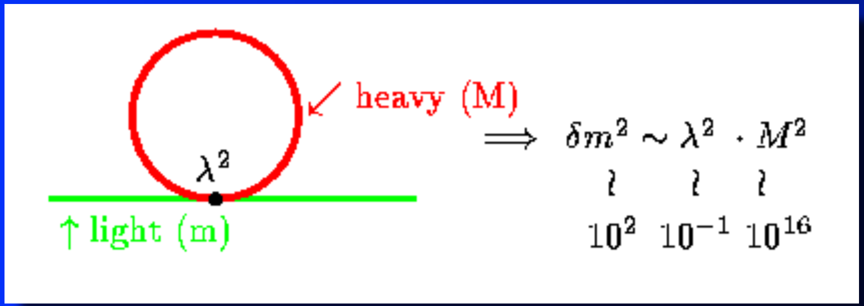
- Solution of the Hierarchy Problem

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

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

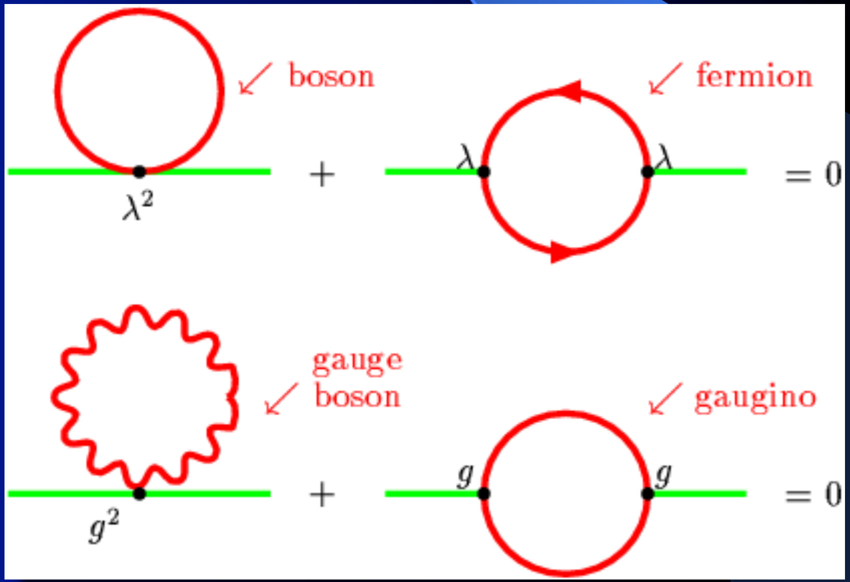
$$\frac{m_H}{m_\Sigma} \sim 10^{-14} \ll 1$$

Destruction of the hierarchy by radiative corrections




SUSY may also explain the origin of the hierarchy due to radiative mechanism

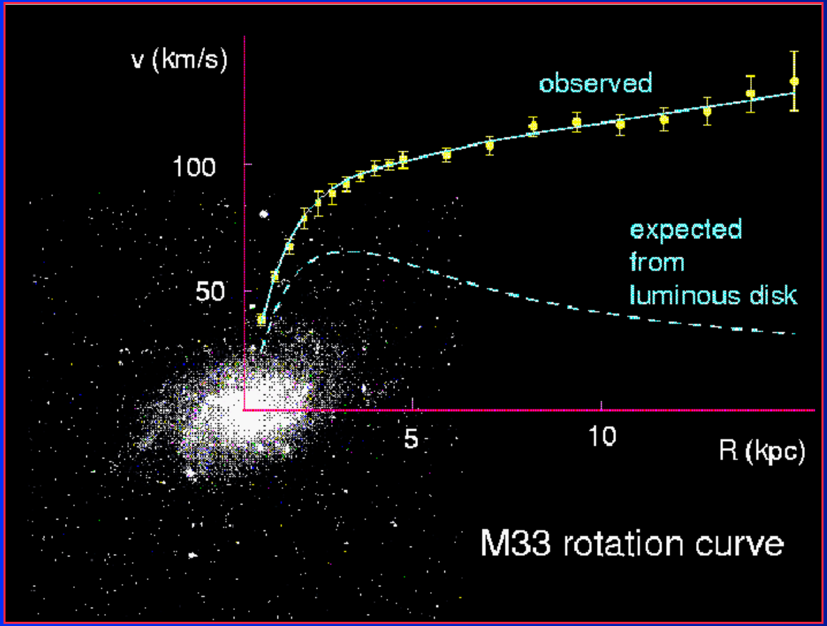
Cancellation of quadratic terms



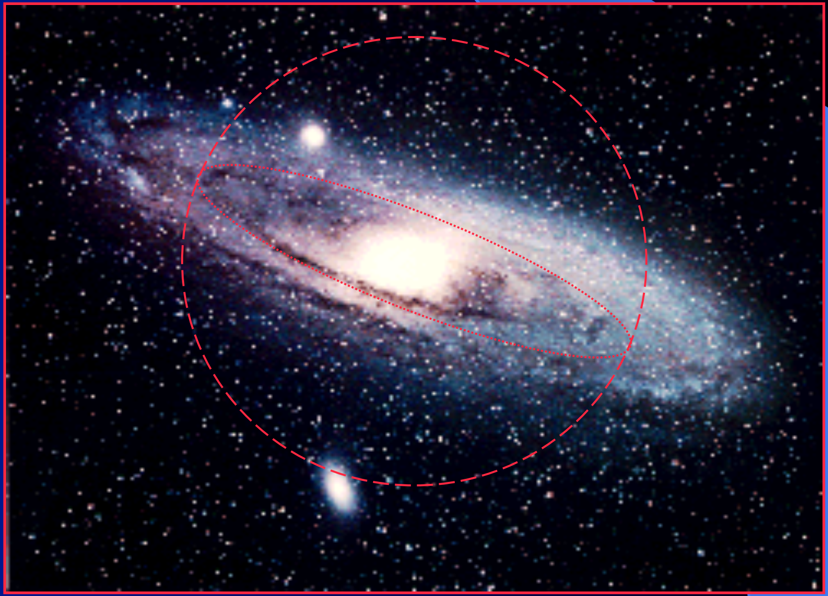

$$\sum_{bosons} m^2 = \sum_{fermions} m^2$$

# Motivation of SUSY

- Dark Matter in the Universe



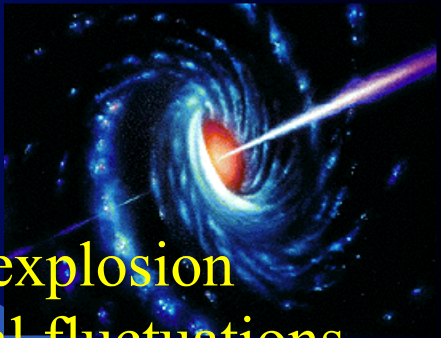

The flat rotation curves of spiral galaxies provide the most direct evidence for the existence of large amount of the dark matter.



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

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

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

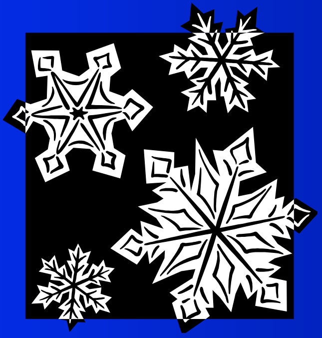
$$\Omega_{DarkMatter} \approx 23 \pm 4\%$$

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

- Supernova Ia explosion
- CMBR thermal fluctuations

(news from WMAP )

Dark Matter in the Universe:



Hot DM (not favoured by galaxy formation)

Cold DM (rotation curves of Galaxies) ← SUSY

# Supersymmetry

$(Super)\ Algebra$

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

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

$$[B_r, B_s] = iC^t_{rs}B_t,\ \ [B_r, P_\mu] = [B_r, M_{\mu\sigma}] = 0,$$

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

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

$$[Q^i_\alpha, B_r] = (b_r)^i_j Q^j_\alpha,\ [\bar{Q}^i_{\dot\alpha}, B_r] = -\bar{Q}^j_{\dot\alpha}(b_r)^i_j,$$

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

$$\{Q^i_\alpha, Q^j_\beta\} = 2\varepsilon_{\alpha\beta}Z^{ij},\ Z^{ij} = Z^\dagger_{ij}, Z_{ij} = a^r_{ij}b_r,$$

$$\{\bar{Q}^i_{\dot\alpha}, \bar{Q}^j_{\dot\beta}\} = -2\varepsilon_{\dot\alpha\dot\beta}Z^{ij},\ [Z_{ij}, anything] = 0,$$

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

*Superspace*

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

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

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

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

# Basics of SUSY

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

(Energy → $E$, helicity → $\lambda$)

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

| 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 | $\bar{Q}_1 \bar{Q}_2 ... \bar{Q}_N \|E,\lambda> = \|E,\lambda+N/2>$ | $\binom{N}{N} = 1$ |

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 |

$(\varphi, \psi)$ — scalar, spinor

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

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

$(\lambda, A_\mu)$ — spinor, vector

Members of a supermultiplet are called **superpartners**

Extended SUSY multiplets

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 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

# Minimal Supersymmetric Standard Model (MSSM)

- SUSY: # of fermions = # of bosons N=1 SUSY: $(\varphi, \psi)$ $(\lambda, A_\mu)$
- 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)

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

↑ ↑ ↑ ↑ ↑ ↑ ↑ ↑

colour $u_L$ $d_L$ $u_R$ $d_R$ $\nu_L$ $e_L$ $e_R$

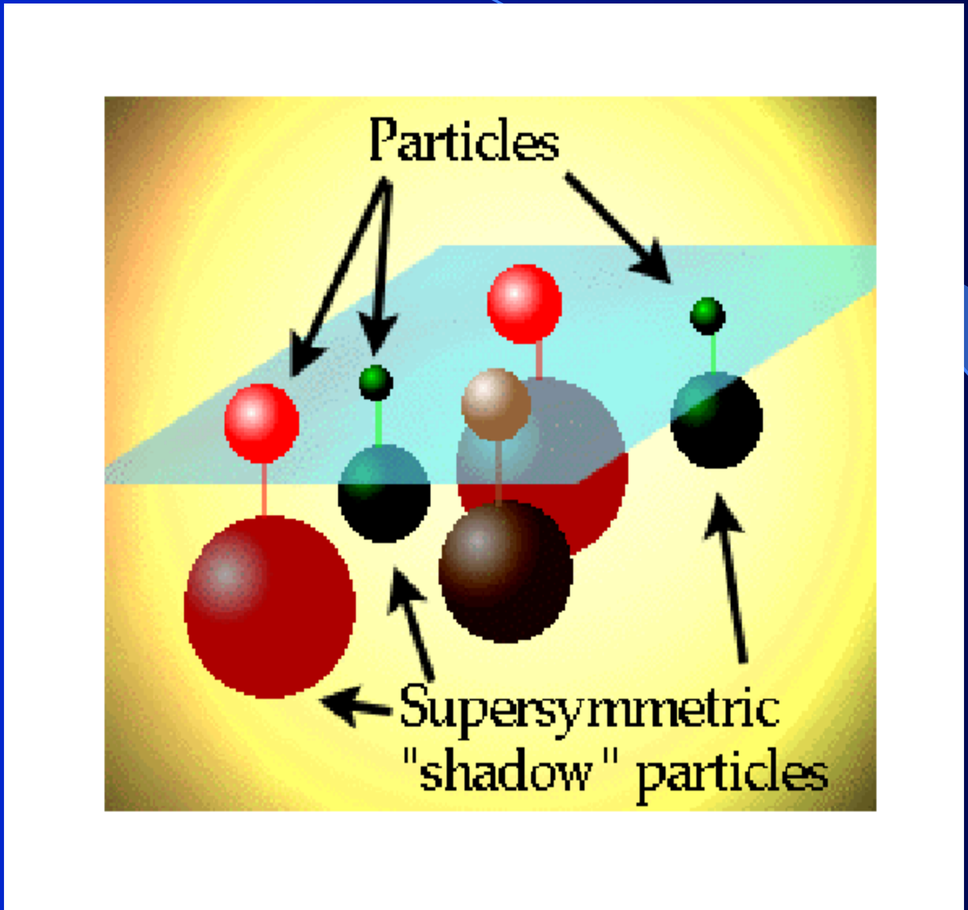
Higgsinos

-1+1=0

# Particle Content of the MSSM

| *Superfield* | *Bosons* | *Fermions* | $SU_c(3)$ | $SU_L(2)$ | $U_Y(1)$ |
|---|---|---|---|---|---|
| *Gauge* | | | | | |
| $G^a$ | *gluon* $\mathrm{g}^a$ | *gluino* $\tilde{\mathrm{g}}^a$ | 8 | 1 | 0 |
| $V^k$ | *Weak* $\mathrm{W}^k(W^\pm, Z)$ | *wino, zino* $\tilde{w}^k(\tilde{w}^\pm, \tilde{z})$ | 1 | 3 | 0 |
| $V'$ | *Hypercharge* $\mathrm{B}(\gamma)$ | *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 |

# SUSY Shadow World




One half is observed!

One half is NOT observed!

# 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

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

These terms are forbidden in the SM

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

The Usual Particle : R = + 1

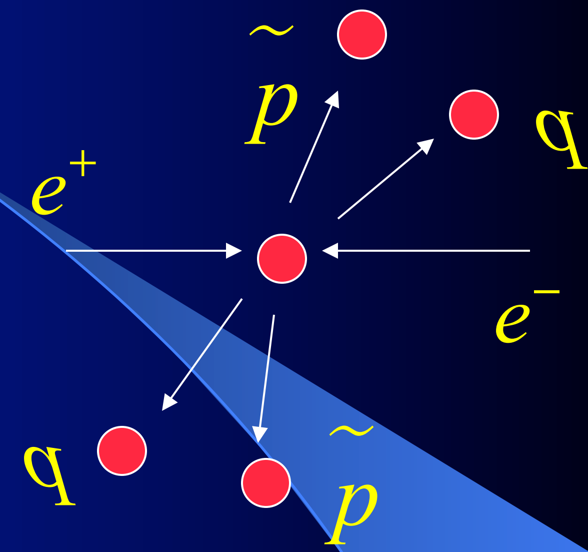
SUSY Particle : R = - 1

B - Baryon Number

L - Lepton Number

S - Spin

# R-parity Conservation



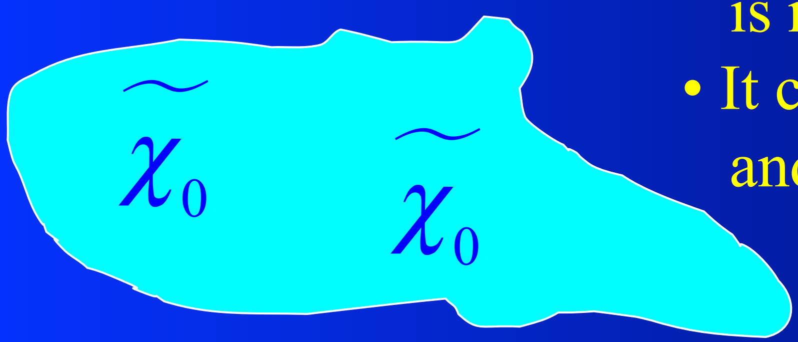

The consequences:

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

⇓

Physical output:

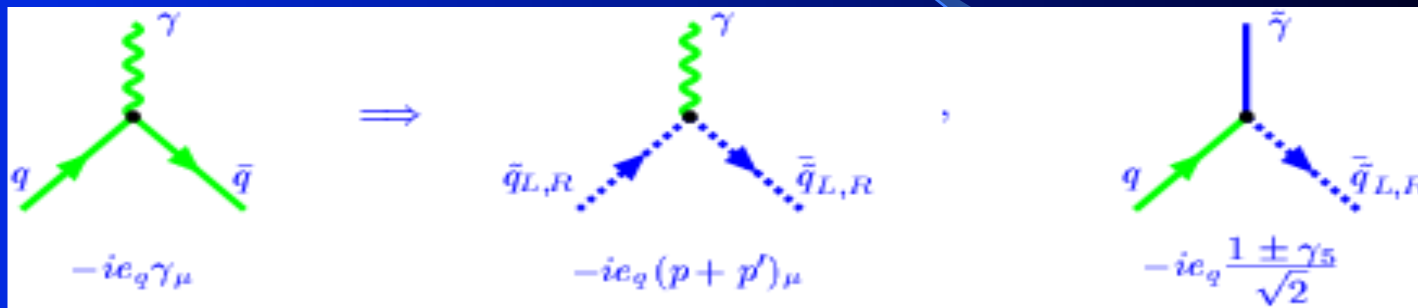
- The lightest superparticle (LSP) should be neutral - the best candidate is neutralino (photino or higgsino) $\tilde{\chi}_0$
- It can survive from the Big Bang and form the Dark matter in the Universe

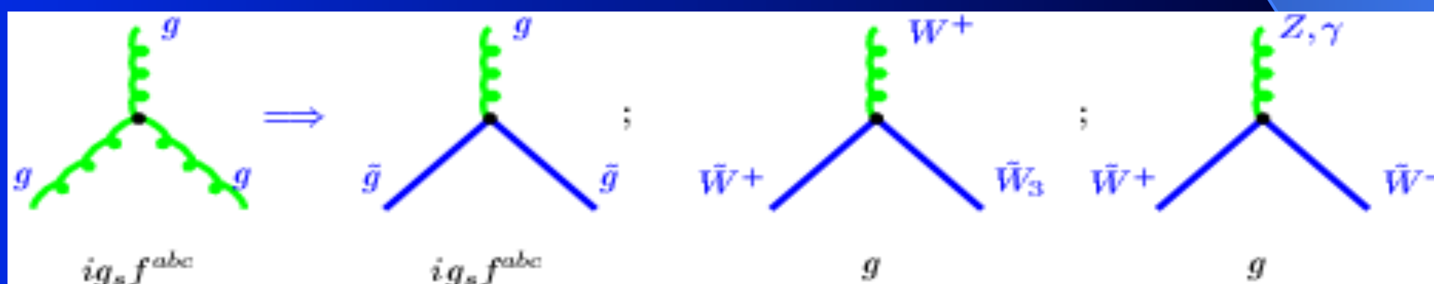


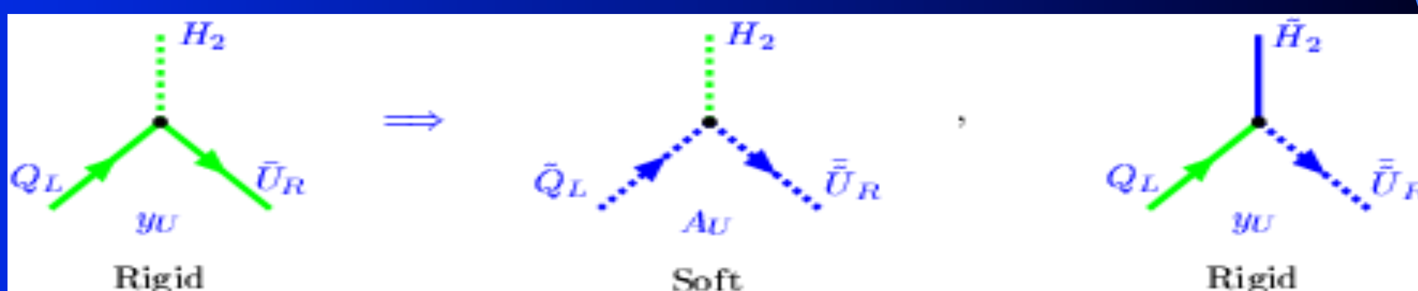
# Interactions in the MSSM

**SM** → **MSSM**

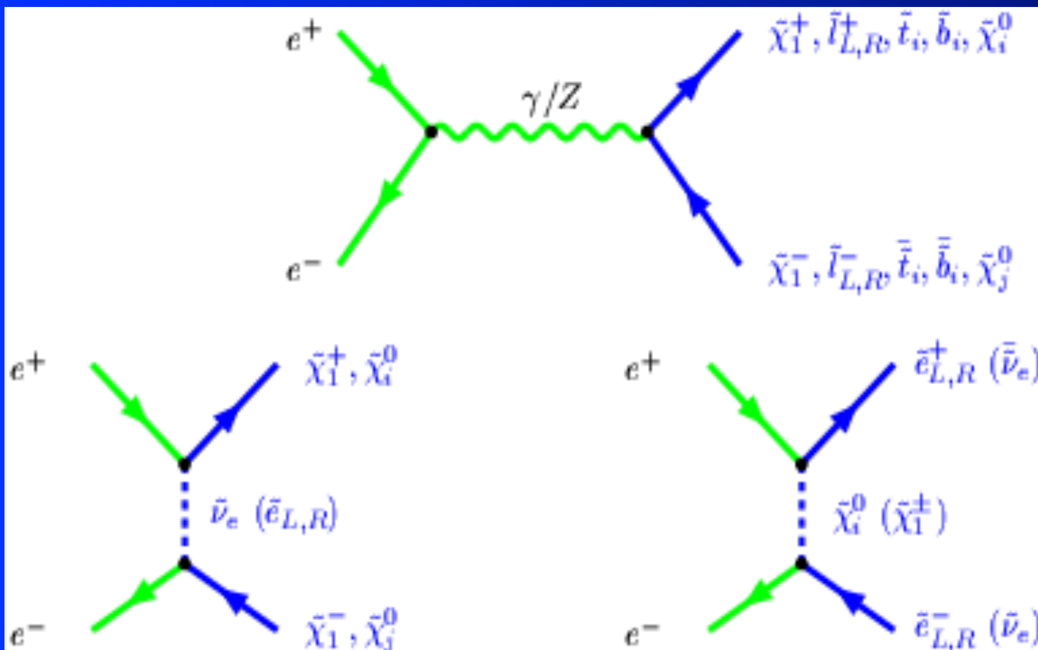
Vertices



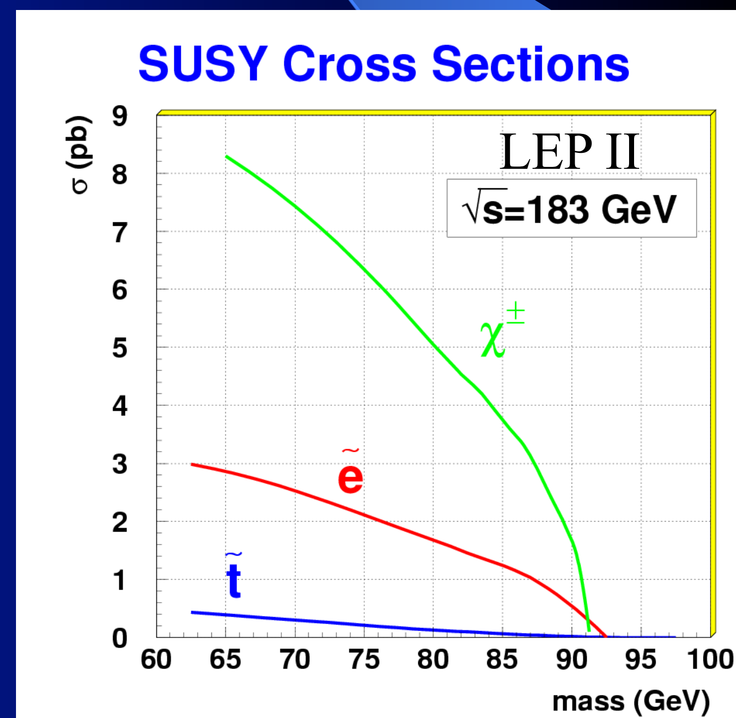



# Creation of Superpartners at $e^+e^-$ colliders



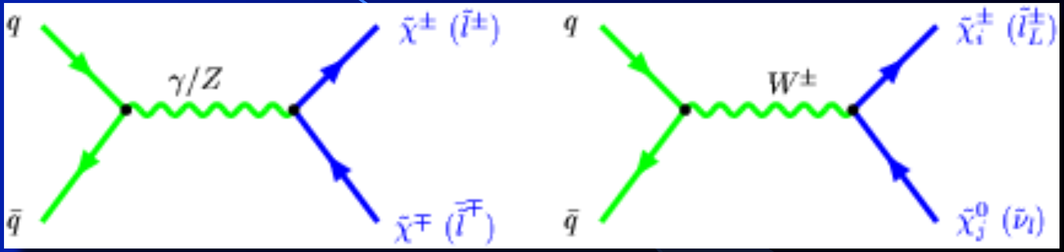

$$m_{\text{sparticle}}^{\max} \leq \frac{\sqrt{s}}{2}$$



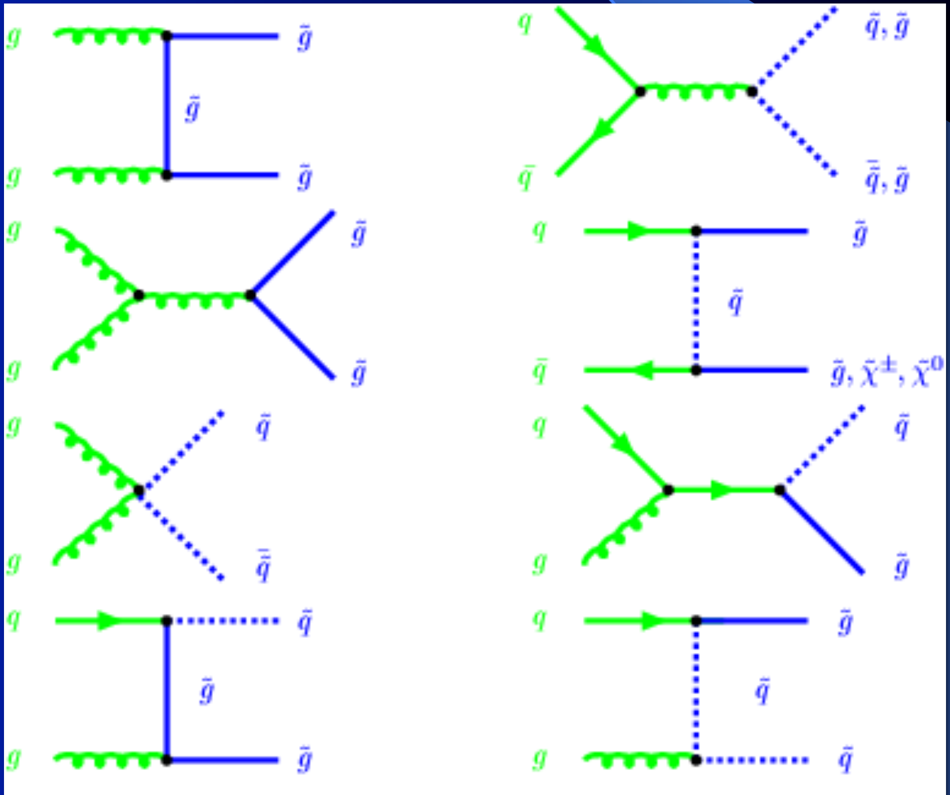

Experimental signature:
missing energy and transverse momentum

# SUSY Production at Hadron Colliders

Annihilation channel

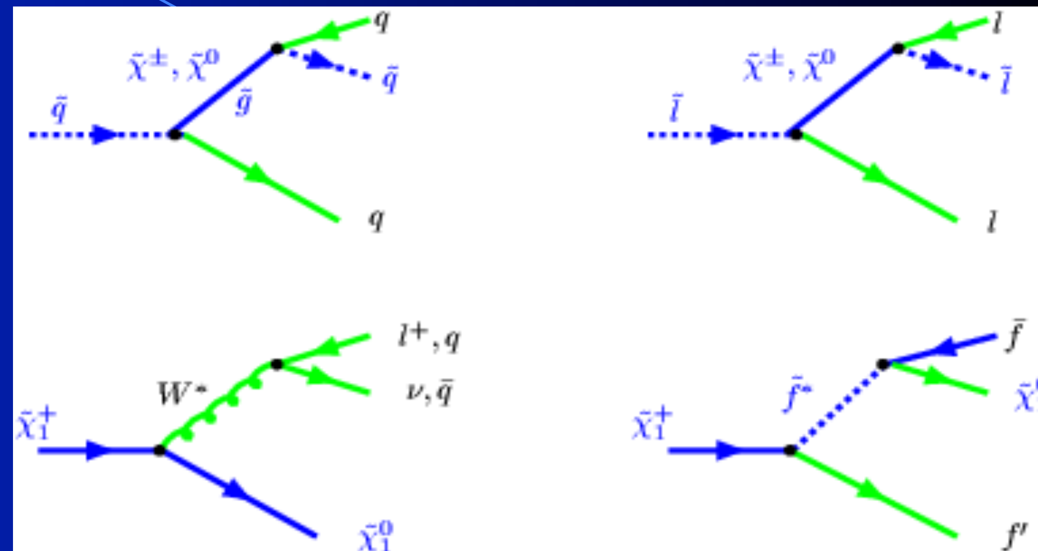



Gluon fusion, qq scattering and qg scattering channels




No new data so far due to insufficient luminosity at the Tevatron

# 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 jets $+ \not{E}_T$

$\gamma + \not{E}_T$

$\not{E}_T$

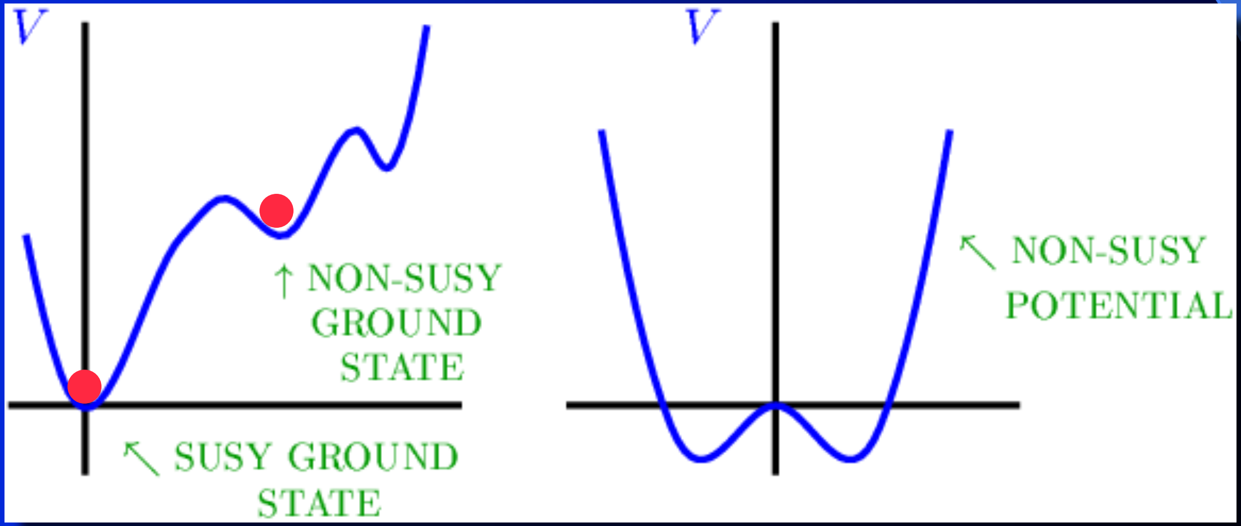
# Spontaneous Breaking of SUSY

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 $Q_\alpha|0> \neq 0$



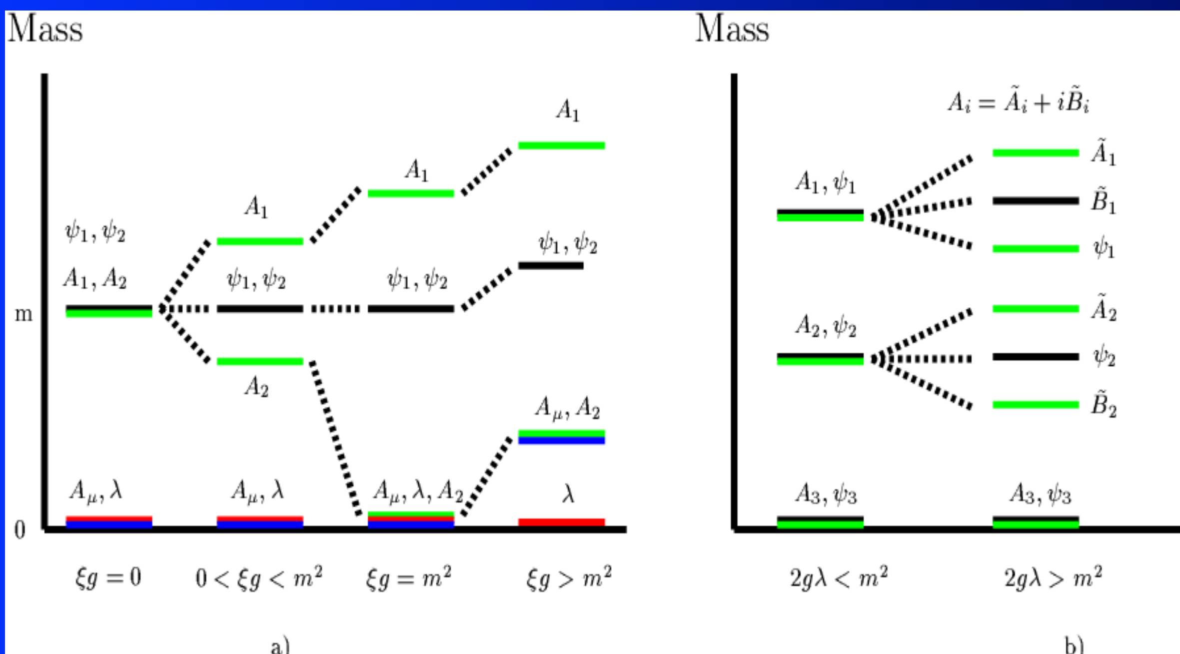
# Mechanism of SUSY Breaking

- 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

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



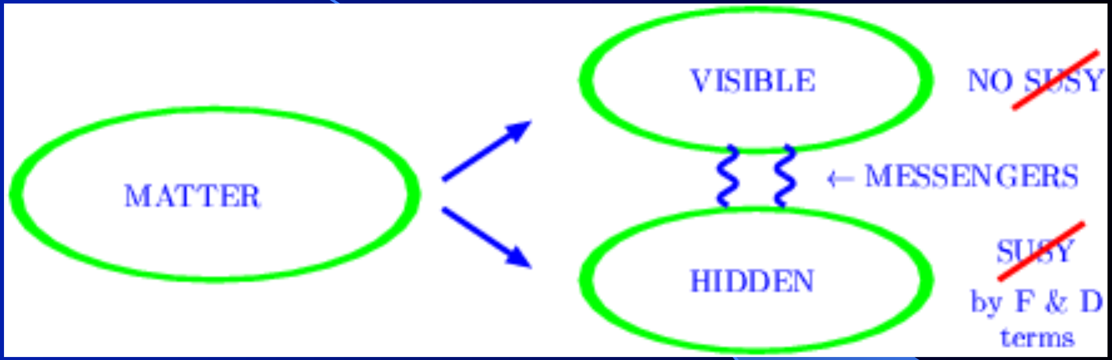

D-term F-term

$$F_1^* = mA_2 + 2gA_1A_2$$
$$F_2^* = mA_1$$
$$F_3^* = \lambda + gA_1^2$$
$$\Rightarrow \quad \langle F_i \rangle \neq 0$$

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

# Soft SUSY Breaking

Hidden sector scenario:




four scenarios:

1. Gravity mediation
2. Gauge mediation
3. Anomaly mediation
4. Gaugino mediation

<u>SUGRA</u> S-dilaton, T-moduli $< F_T > \neq 0, < F_S > \neq 0$

$$M_{\not{S}USY} \sim \frac{< F_T >}{M_{PL}} + \frac{< F_S >}{M_{PL}} \sim m_{3/2} \leftarrow$$ gravitino mass $\sim 1$ TeV

$$L_{soft} = -\sum_i m_i^2 |A_i|^2 - \sum_i M_i(\lambda_i\lambda_i + \bar{\lambda}_i\bar{\lambda}_i) - \mathrm{B}W^{(2)}(A) - \mathrm{A}W^{(3)}(A)$$

$$m_i^2 \sim \mathrm{B} \sim m_{3/2}^2, \; M_i \sim \mathrm{A} \sim m_{3/2}$$

# Soft SUSY Breaking Cont'd

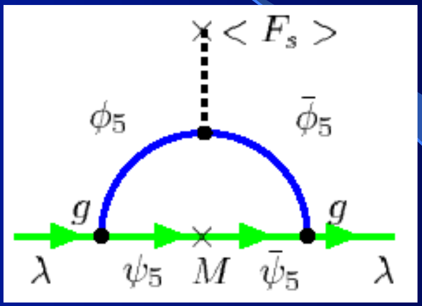
<u>Gauge mediation</u>

Scalar singlet S $\quad < S >= M \quad < F_S > \neq 0$

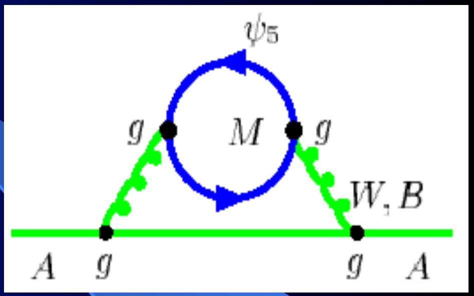
Messenger Φ $\quad W \sim S\Phi^{+}\Phi$

$$m_{\tilde{G}} \sim \frac{< F_S >}{M_{PL}} \frac{M}{M_{PL}} \sim 10^{-14} \frac{M}{[GeV]}$$

gravitino mass




gaugino




squark

- LSP=gravitino

$$M_i \sim c_i N \frac{\alpha_i}{4\pi} \frac{< F_S >}{M} \qquad m_i^2 \sim \left( \frac{< F_S >}{M_{PL}} \right)^2 N \left( \frac{\alpha_i}{4\pi} \right)^2$$

<u>Anomaly mediation</u>

Results from conformal anomaly = β function

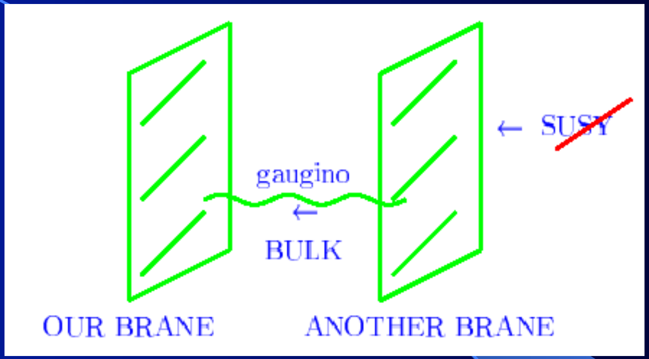
$$M_i \sim b_i \frac{\alpha_i(\Lambda)}{4\pi} \frac{< F_{T,S} >}{M_{PL}} \sim b_i \alpha_i m_{3/2}$$

$$m_i^2 \sim b_i^2 \alpha_i^2 m_{3/2}^2$$

- $M_1 : M_2 : M_3 = b_1 : b_2 : b_3$
- LSP=slepton

# Soft SUSY Breaking Cont'd

<u>Gaugino mediation</u>




All scenarios produce
soft SUSY breaking terms

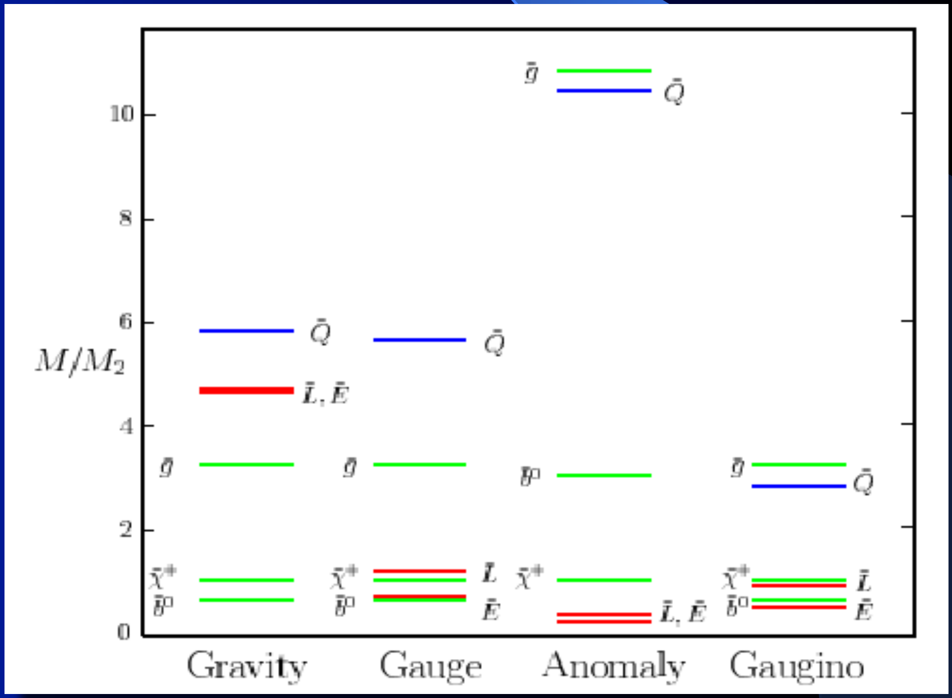
Soft = operators of dimension ≤ 4

<u>Net result of SUSY breaking</u>

$$-L_{Soft} = \sum_i m_{0i}^2 |A_i|^2 + \sum_\alpha M_i \widetilde{\lambda}_i \widetilde{\lambda}_i$$

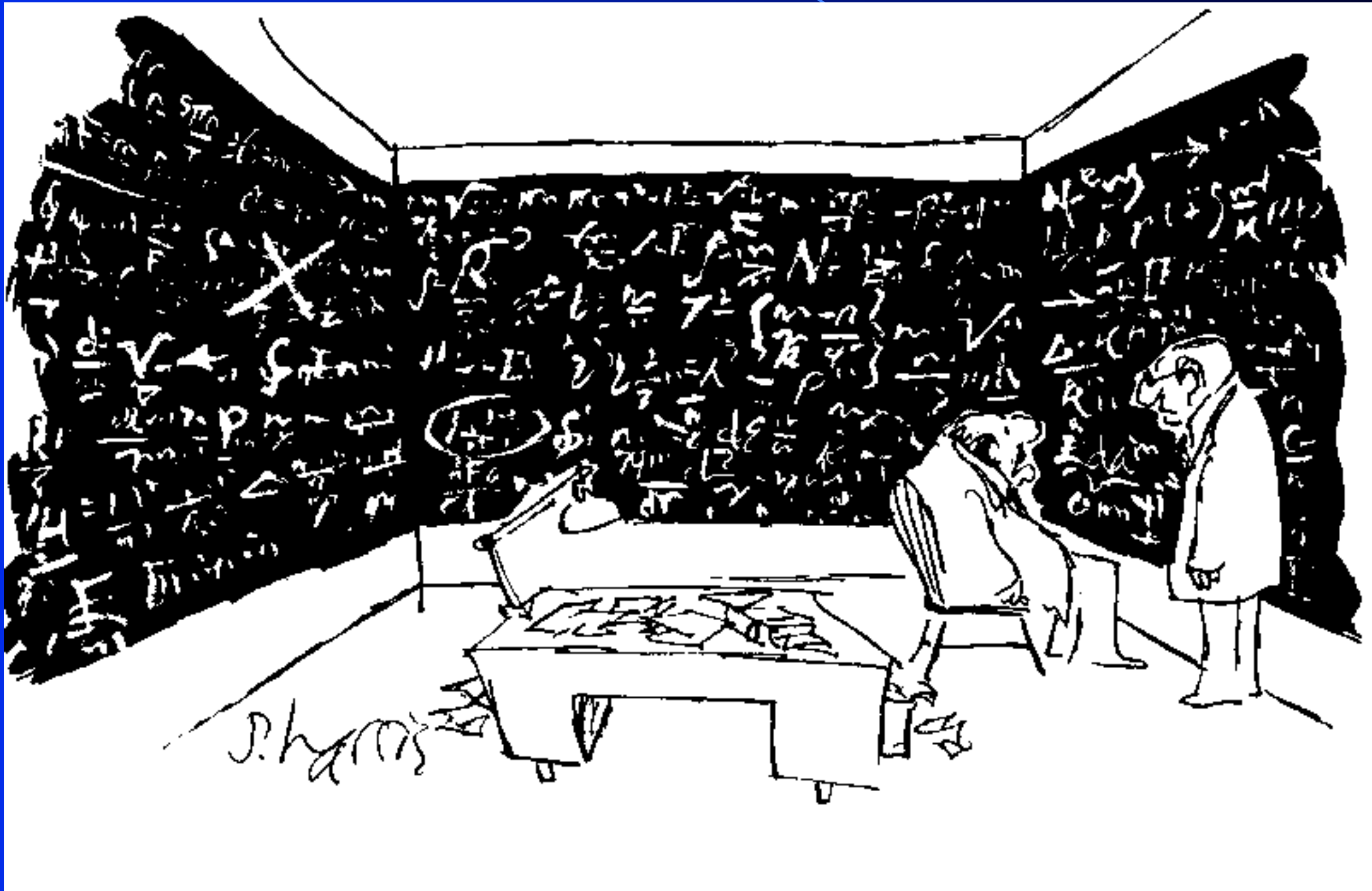
$$+ \sum_{ijk} \mathrm{A}_{ijk} A_i A_j A_k + \sum_{ij} \mathrm{B}_{ij} A_i A_j$$

scalar fileds gauginos




SUSY spectra for various mediation mechanisms

# We like elegant solutions




"Whatever happened to *elegant* solutions?"

# Parameter Space of the MSSM

- Three gauge coupligs $\alpha_i$, i=1,2,3
- Three (four) Yukawa matrices $y^k_{ab},\ k = U, D, L, (E)$
- The Higgs mixing parameter $\mu$
- Soft SUSY breaking terms

<u>SUGRA</u> Universality hypothesis: soft terms are universal and repeat the Yukawa potential

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

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

versus $m$ and $\lambda$ 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

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

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

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

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

$$\tilde{m}_{tL}^2 = \tilde{m}_Q^2 + m_t^2 + \tfrac{1}{6}(4M_W^2 - M_Z^2)\cos 2\beta,$$
$$\tilde{m}_{tR}^2 = \tilde{m}_U^2 + m_t^2 - \tfrac{2}{3}(M_W^2 - M_Z^2)\cos 2\beta,$$
$$\tilde{m}_{bL}^2 = \tilde{m}_Q^2 + m_b^2 - \tfrac{1}{6}(2M_W^2 + M_Z^2)\cos 2\beta,$$
$$\tilde{m}_{bR}^2 = \tilde{m}_D^2 + m_b^2 + \tfrac{1}{3}(M_W^2 - M_Z^2)\cos 2\beta,$$

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

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

# SUSY Higgs Bosons

**SM**

4=2+2=3+1

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

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

**MSSM**

8=4+4=3+5

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

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

| | |
|---|---|
| $G^0 = -\cos\beta P_1 + \sin\beta P_2$ | *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

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

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 !

# 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

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

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

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

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

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

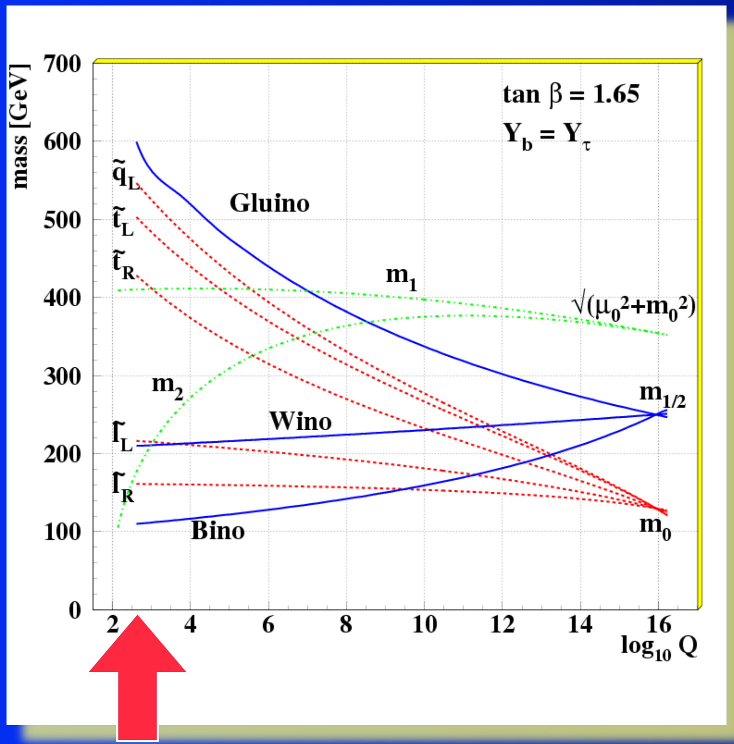
$$\dot{\tilde{m}}_{H_1}^2 = -[3\tilde{\alpha}_2 M_2^2 + \tfrac{3}{5}\tilde{\alpha}_1 M_1^2 - 3Y_b(\Sigma_b + A_b^2) - Y_\tau(\Sigma_\tau + A_\tau^2)]$$

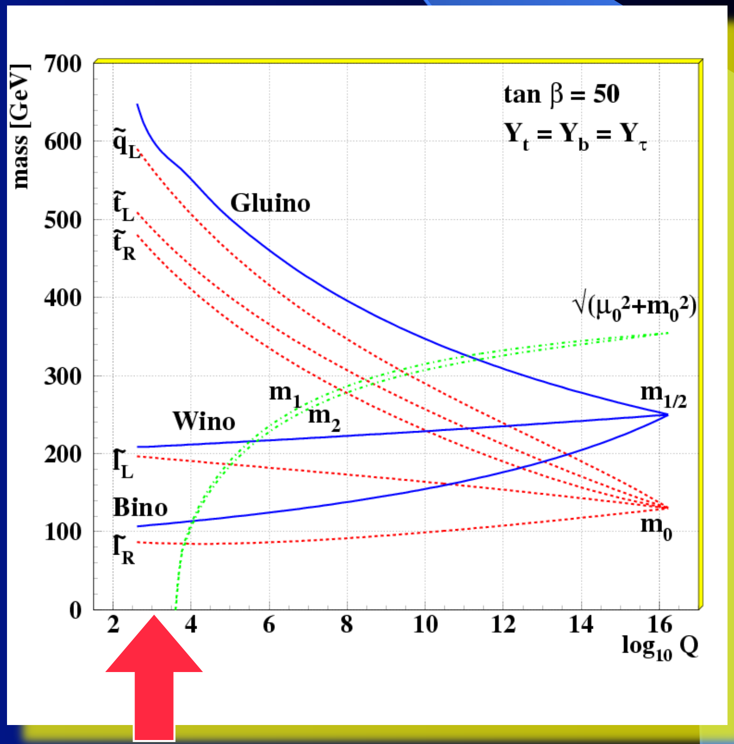
$$\dot{\tilde{m}}_{H_2}^2 = -[3\tilde{\alpha}_2 M_2^2 + \tfrac{3}{5}\tilde{\alpha}_1 M_1^2 - 3Y_t(\Sigma_t + A_t^2)]$$

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

# 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>



# The Higgs Bosons Masses

CP-odd neutral Higgs A $\quad m_A^2 = m_1^2 + m_2^2 \quad M_W^2 = \frac{g^2}{2} v^2$

CP-even charged Higgses $H_\pm$ $\quad m_{H^\pm}^2 = m_A^2 + M_W^2 \quad M_Z^2 = \frac{g^2 + g'^2}{2} v^2$

CP-even neutral Higgses h,H

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

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

➡ 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 Lightest Superparticle

| | | property | signature |
|---|---|---|---|
| • Gravity mediation | $\mathrm{LSP} = \tilde{\chi}_1^0$ | stable | jets/leptons $+ \not{E}_T$ |
| • Gauge mediation | $\mathrm{LSP} = \tilde{G}$ | stable | $\not{E}_T$ |
| | $\mathrm{NLSP} = \tilde{\chi}_1^0$ | $\tilde{\chi}_1^0 \to \gamma\tilde{G}, h\tilde{G}, Z\tilde{G}$ | photons/jets $+ \not{E}_T$ |
| | $\mathrm{NLSP} = \tilde{l}_R$ | $\tilde{l}_R \to \tau\tilde{G}$ | lepton $+ \not{E}_T$ |
| • Anomaly mediation | $\mathrm{LSP} = \tilde{\chi}_1^0$ | stable | lepton $+ \not{E}_T$ |
| | $\mathrm{LSP} = \tilde{\nu}_L$ | stable | |

• R-parity violation LSP is unstable ➔ SM particles

• Modern limit $M_{LSP} \geq 40$ GeV

Rare decays
Neutrinoless double β decay

# 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

Allowed region in the parameter space of the MSSM

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

Parameter space:

$$100\ Gev < m_0, M_{1/2}, \mu < 2\ Tev$$
$$-3m_0 < A_0 < 3m_0,\ 1 < \tan\beta < 70$$

# SUSY Fits

$$\chi^2 = \sum_{i=1}^{3} \frac{(\alpha_i^{-1}(M_Z) - \alpha_{MSSMi}^{-1}(M_Z))^2}{\sigma_i^2}$$

$$+ \frac{(M_Z - 91.18)^2}{\sigma_Z^2} + \frac{(M_t - 174)^2}{\sigma_t^2}$$

$$+ \frac{(M_b - 4.94)^2}{\sigma_b^2} + \frac{(M_\tau - 1.7771)^2}{\sigma_\tau^2}$$

$$+ \frac{(\mathrm{Br}(b \to s\gamma) - 3.14 \times 10^{-4})^2}{\sigma^2(b \to s\gamma)}$$

$$+ \frac{(\Omega h^2 - 1)^2}{\sigma_\Omega^2} \quad (\text{for } \Omega h^2 > 1)$$

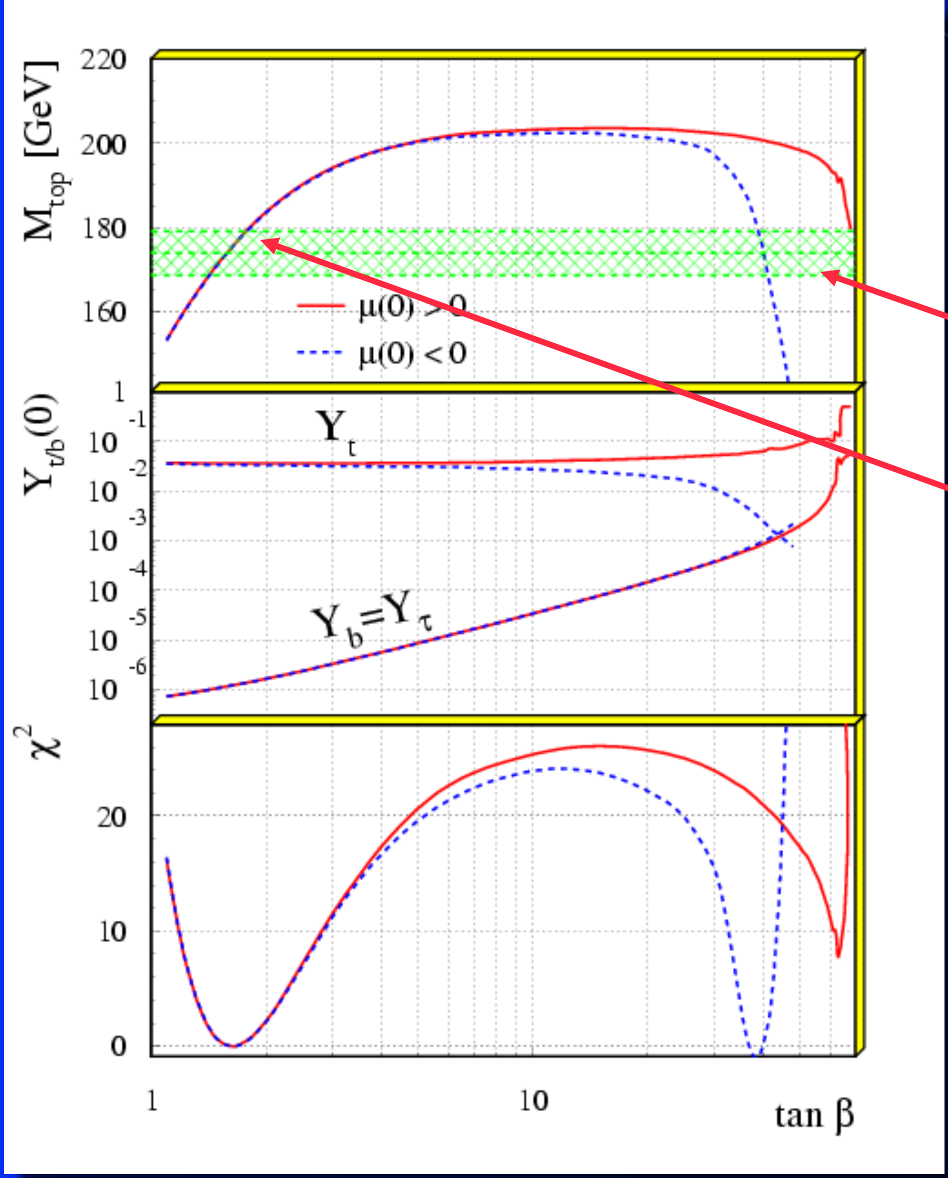
$$+ \frac{(\tilde{M} - \tilde{M}_{exp})^2}{\sigma_{\tilde{M}}^2} \quad (\text{for } \tilde{M} < \tilde{M}_{exp})$$

$$+ \frac{(\tilde{m}_{LSP} - \tilde{m}_\chi)^2}{\sigma_{LSP}^2} \quad (\text{for } \tilde{m}_{LSP} \text{ charged})$$

Minimize $\chi^2$

| Exp.input data | Fit low tanβ | Parameters high tanβ |
|---|---|---|
| $\alpha_1, \alpha_2, \alpha_3$ | $M_{GUT}, \alpha_{GUT}$ | $M_{GUT}, \alpha_{GUT}$ |
| $m_t$ | $Y_t^0, Y_b^0 = Y_\tau^0$ | $Y_t^0 = Y_b^0 = Y_\tau^0$ |
| $m_b$ | $m_0, m_{1/2}$ | $m_0, m_{1/2}$ |
| $m_\tau$ | $\tan\beta$ | $\tan\beta$ |
| $M_Z$ | $\mu$ | $\mu$ |
| $b \to s\gamma$ | $(A_0)$ | $A_0$ |
| $\tau_{Universe}$ | | |

# Low and High tanβ Solutions




Requirements:

- EWSB
- bτ unification

Low tanβ solution

High tanβ solution

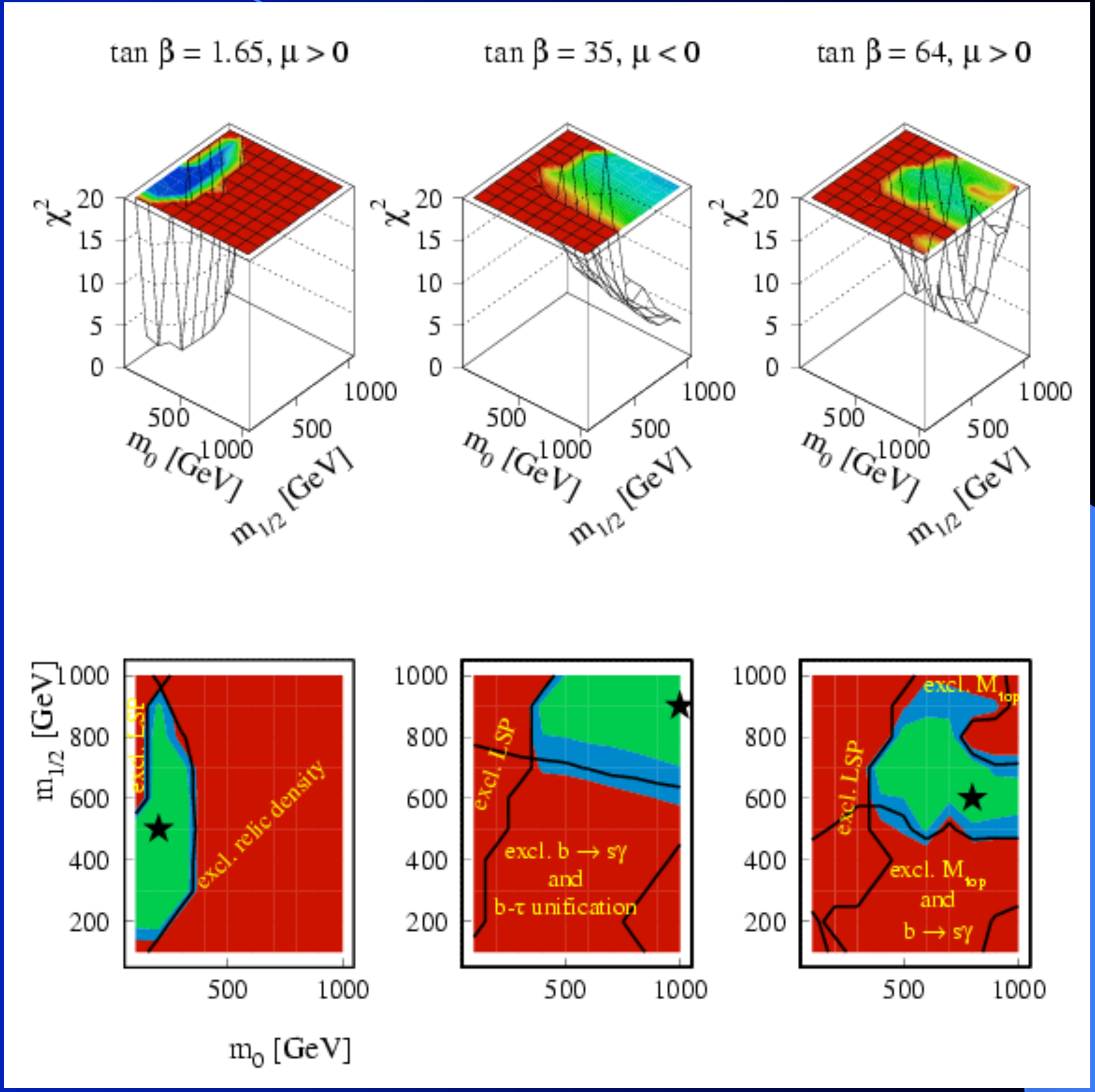
- bτ unification is the consequence of GUT
- Non working for the light generations

# Allowed Regions in Parameter Space

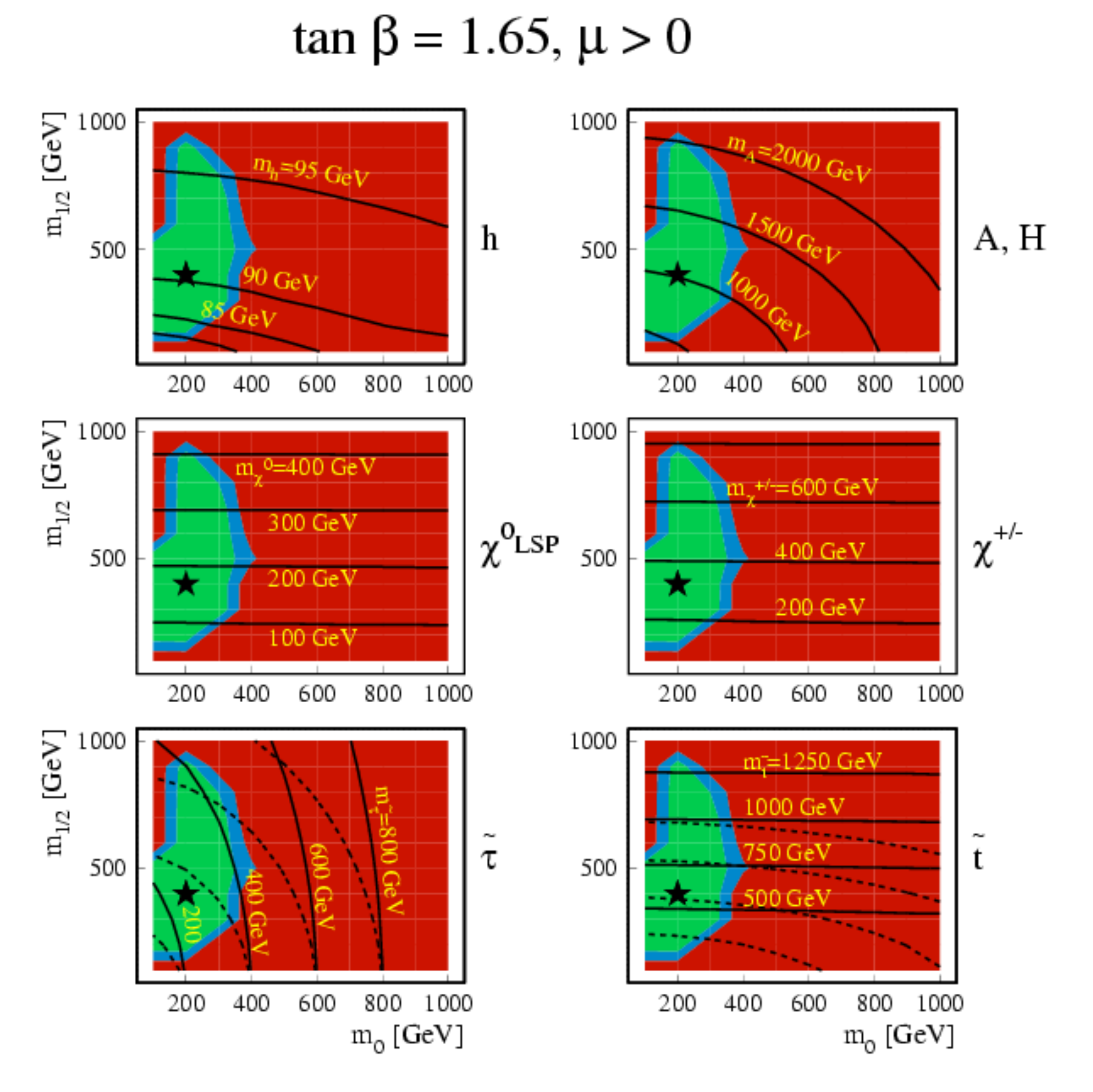
All the requirements are fulfilled simultaneously !

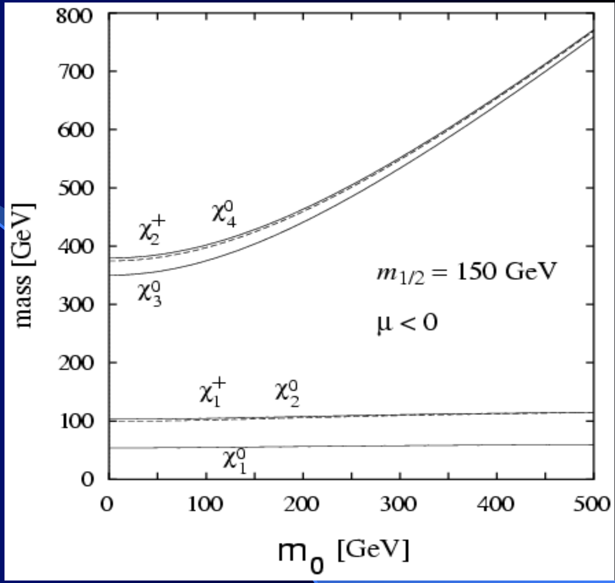
- μ is defined from the EWSB
- $A_0 = 0$

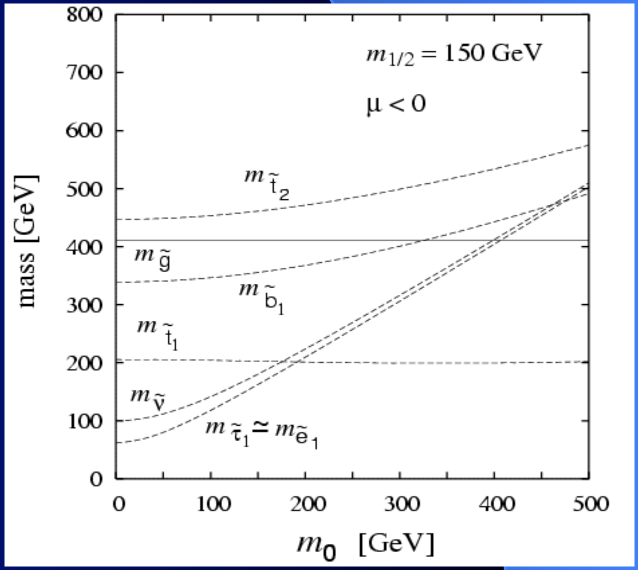
★ - is the best fit value



# Masses of Superpartners



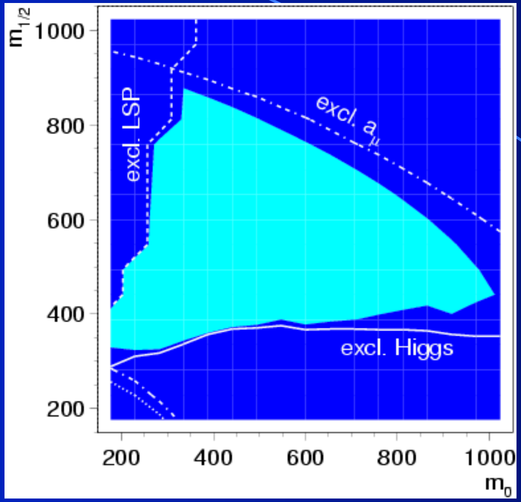
# Allowed regions of parameter space

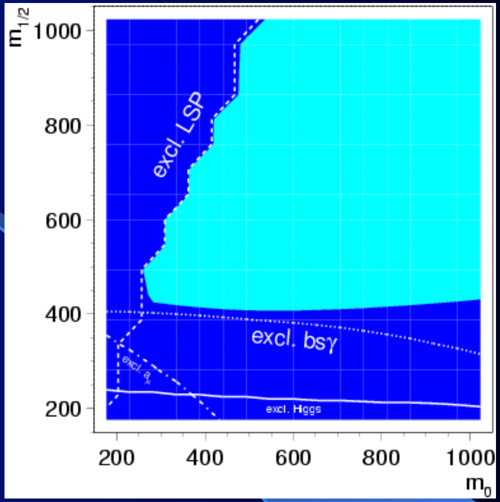
- $\tan\beta > 4$

From the Higgs searches

- $\mu > 0$

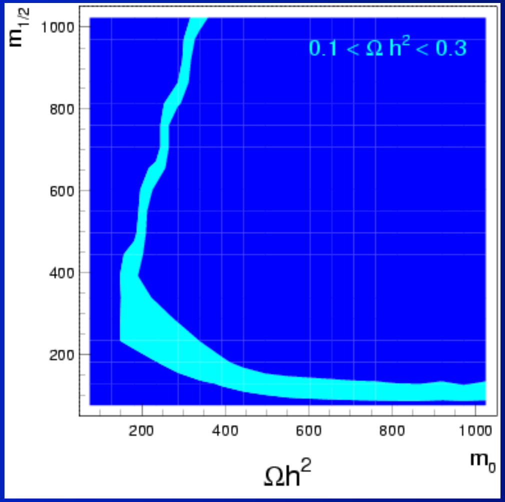
From $a_\mu$ measurement

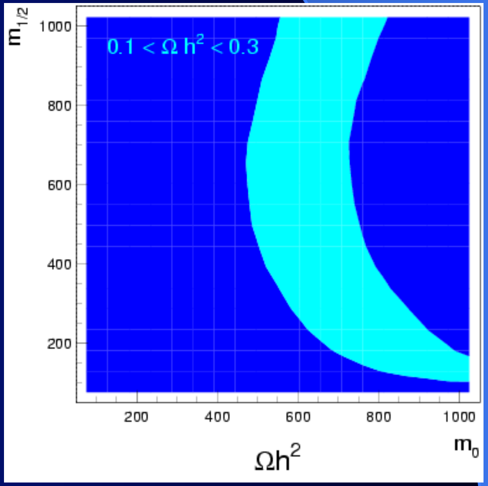



Fit to all constraints

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

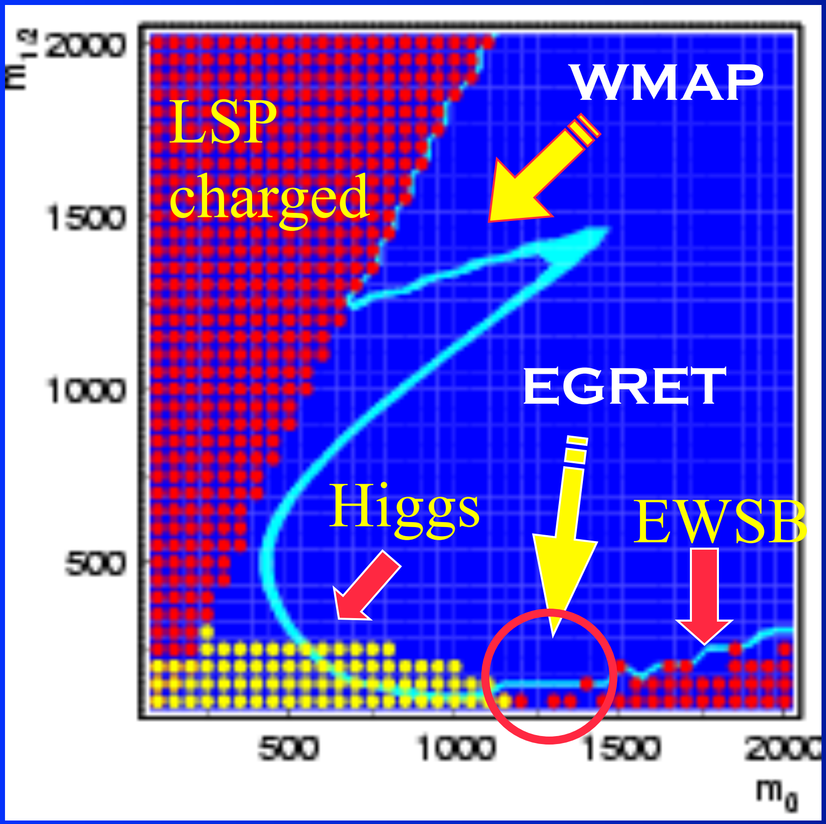


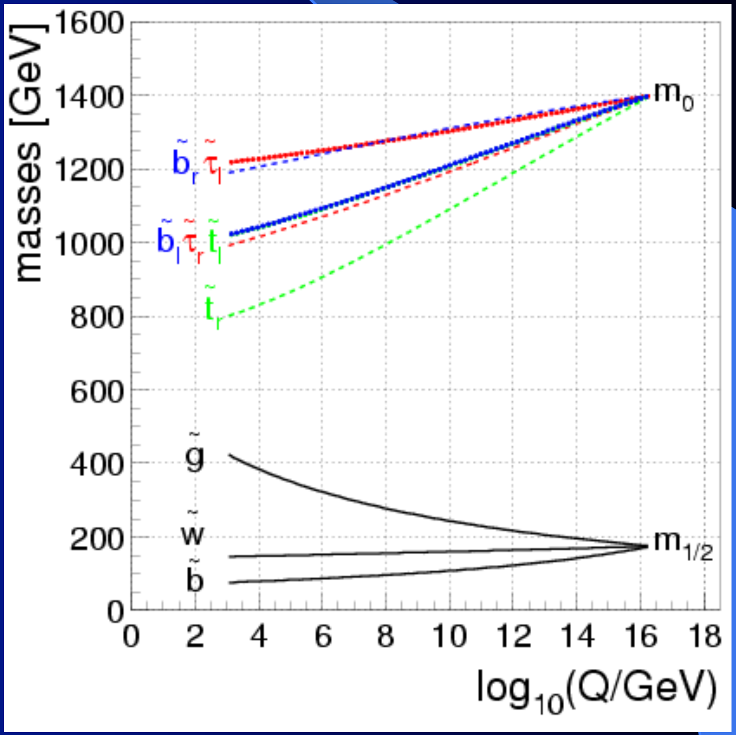

$\tan\beta = 35$ Fit to Dark Matter constraint $\tan\beta = 50$

# Allowed regions after WMAP

Fit to Dark Matter constraint




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 has direct influence on phenomenology and SUSY searches

$m_\chi$ : $50 \div 100$ GeV

# Mass Spectrum in CMSSM

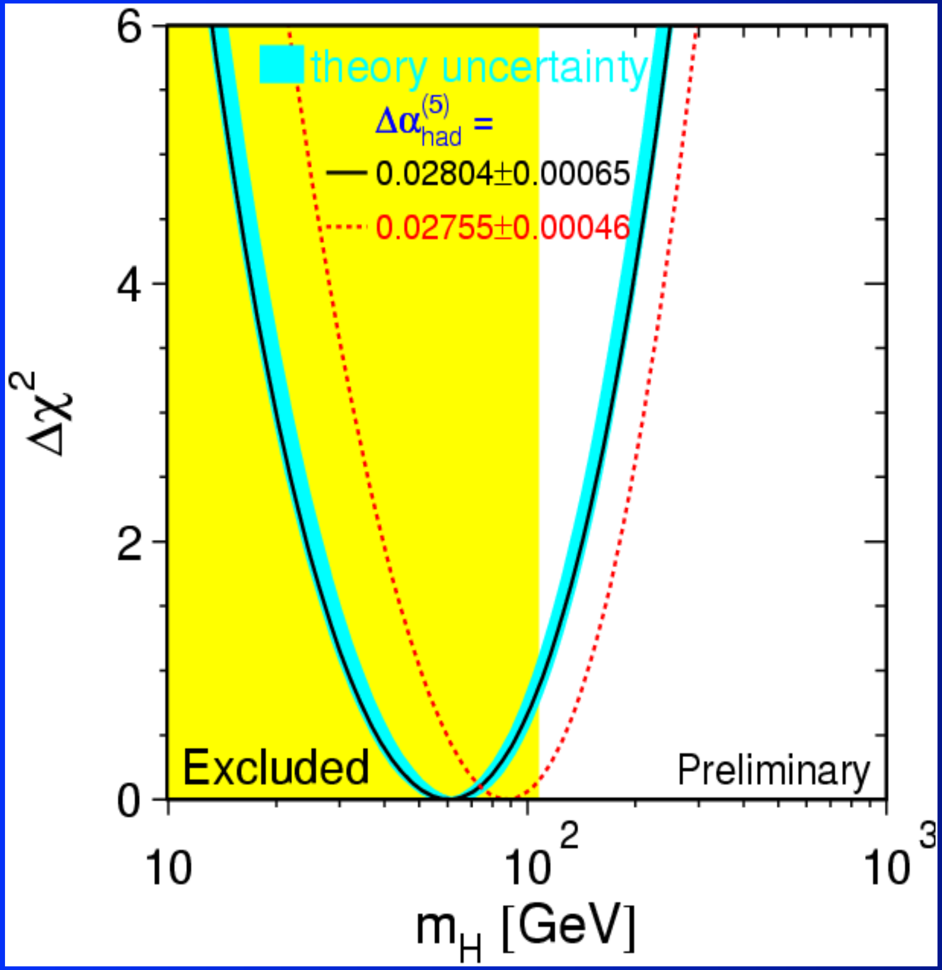
## Fitted SUSY Parameters

| 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 |

# The Higgs Mass Limit

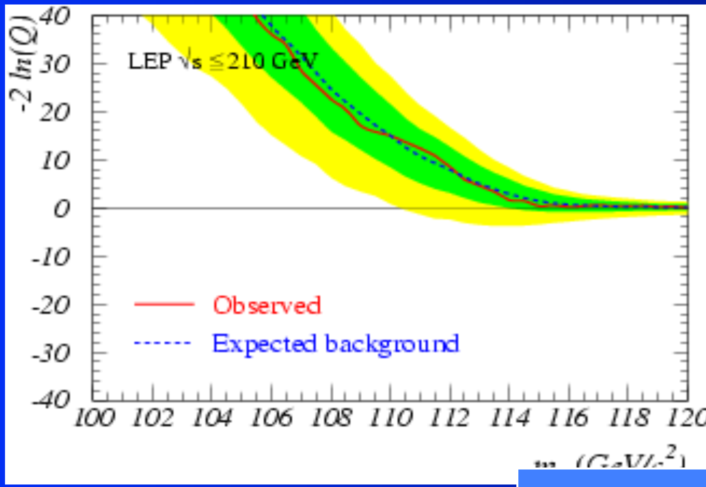


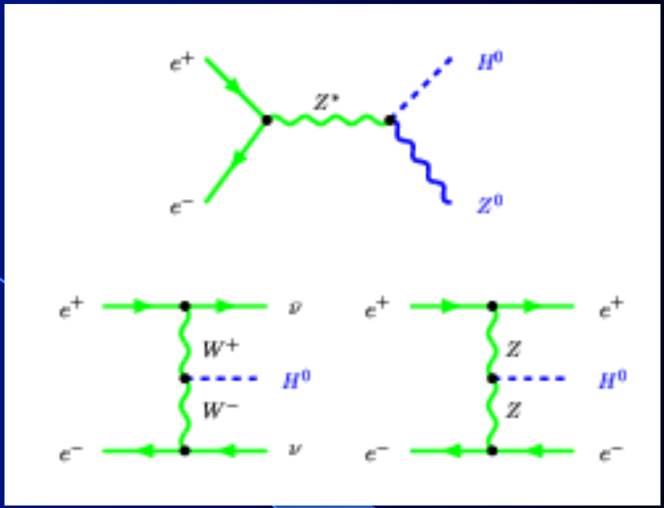

- Indirect limit from radiative corrections
- Direct limit from Higgs non-observation at LEP II (CERN)

113 < $m_H$ < 200 GeV

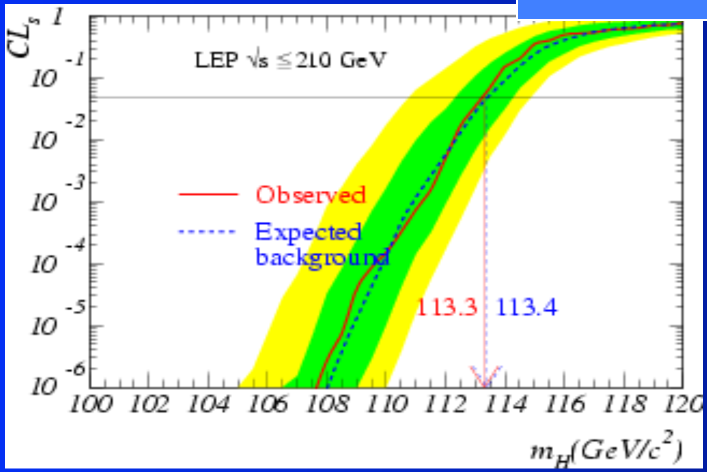
At 95 % C.L.

# Higgs Searches

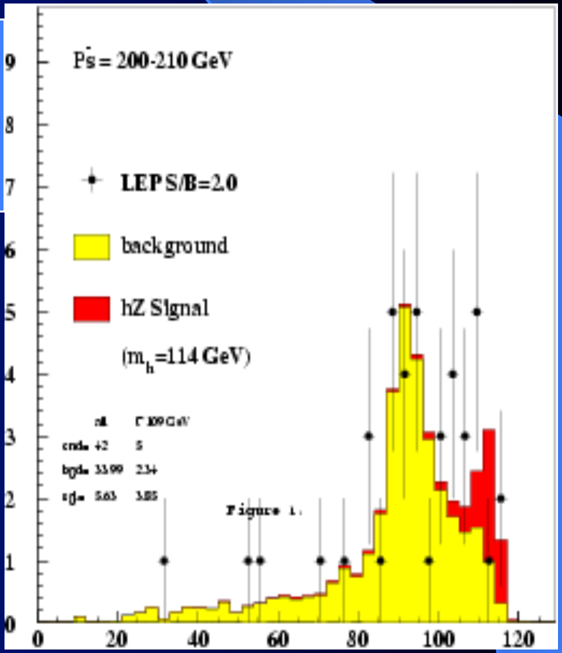


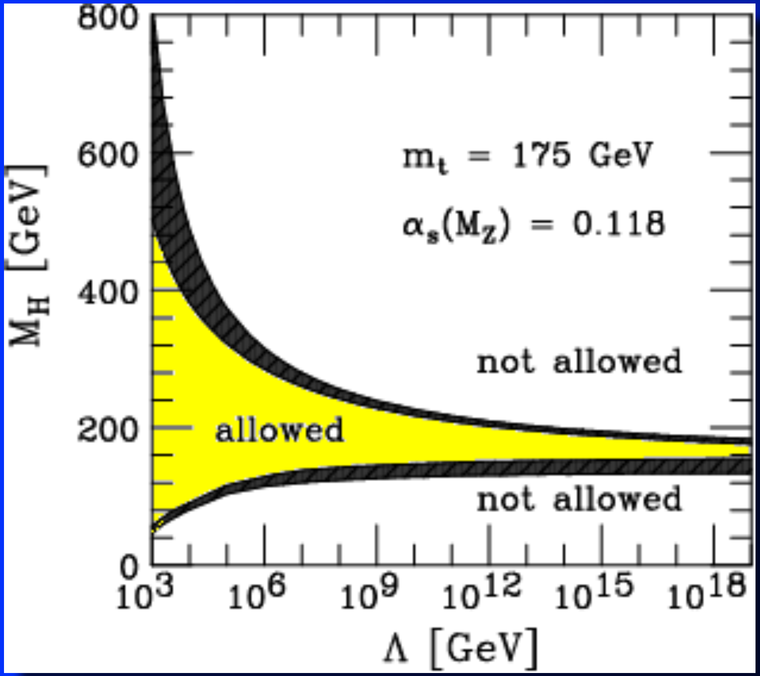

mH ≥ 113.4 GeV at 95 % C.L.




114 -115 GeV Event

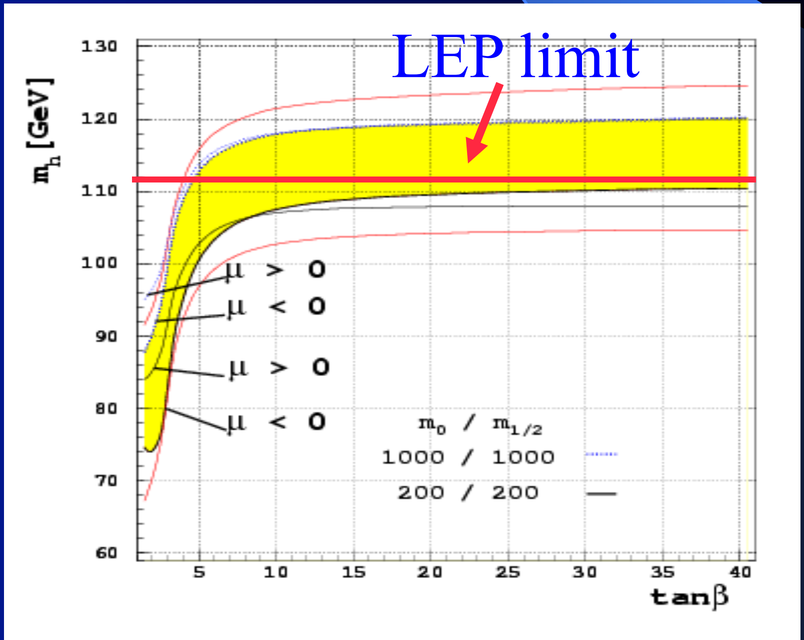


# The Higgs Mass Limit (Theory)




- The SM Higgs

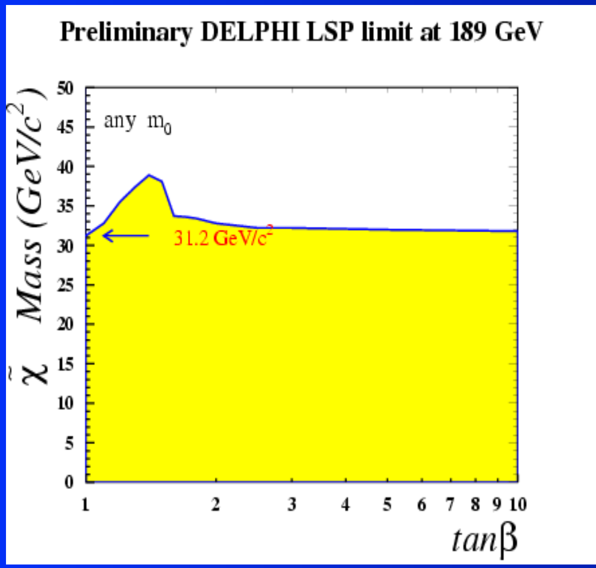
$m_H \geq 134$ GeV

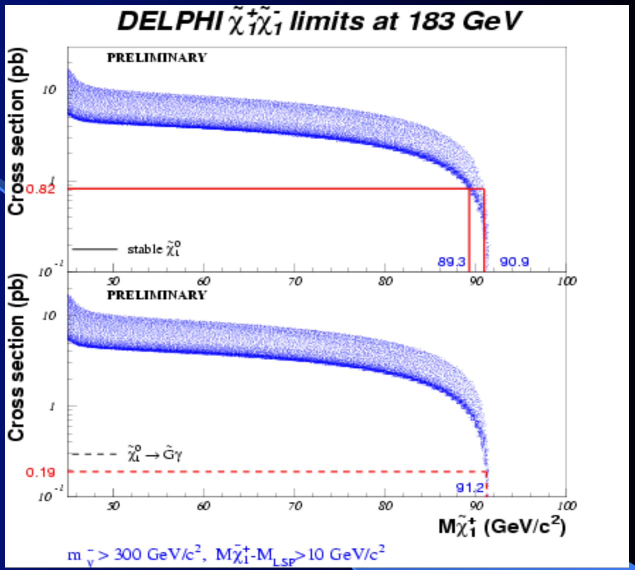



SUSY Higgs

$m_H \leq 130$ GeV

# SUSY Searches at LEP



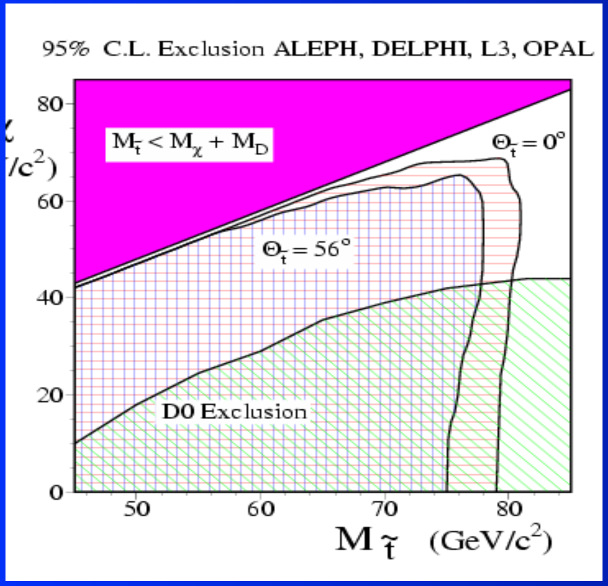



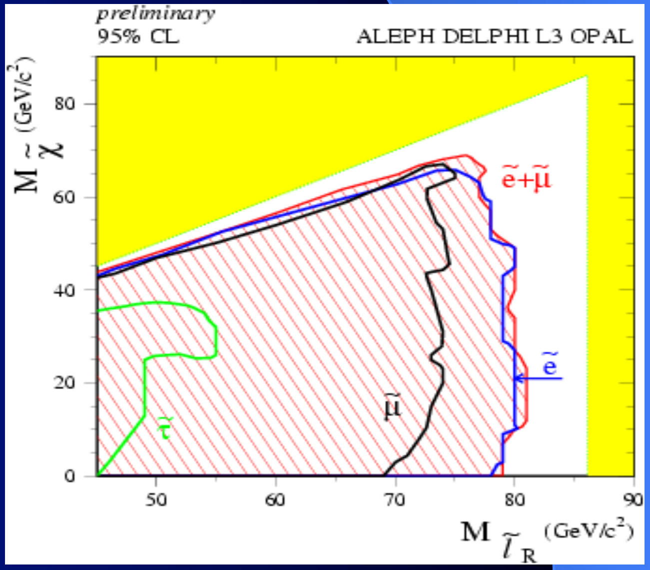

neutralinos

$\tilde{M}\chi 0 \geq$ 45 GeV

charginos

$\tilde{m}\chi + \geq$ 104 GeV



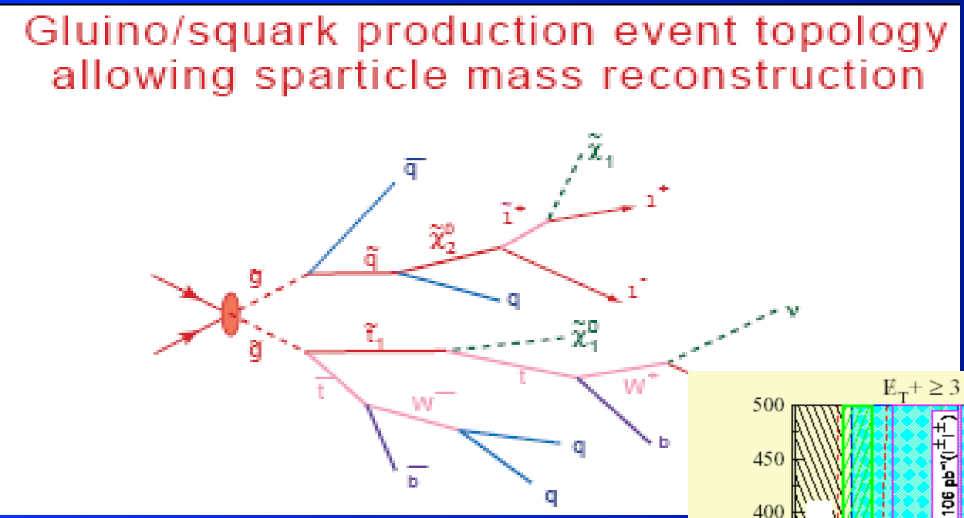

squarks

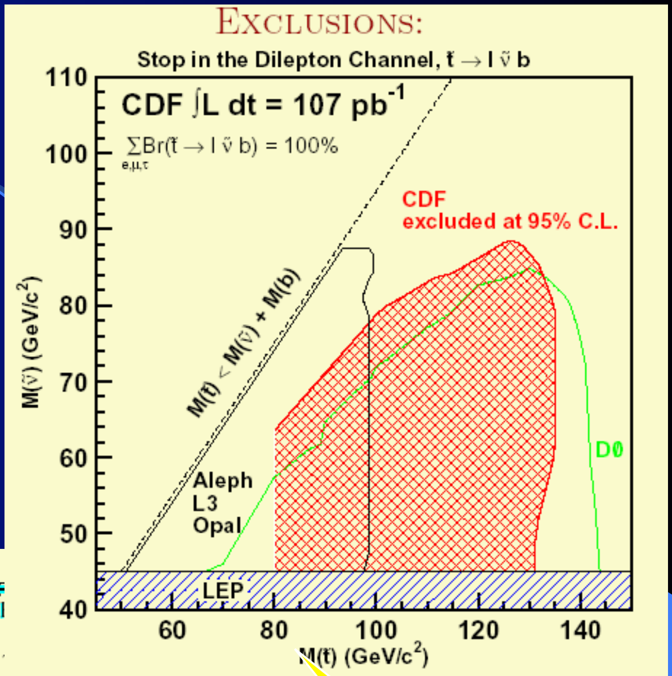
sleptons

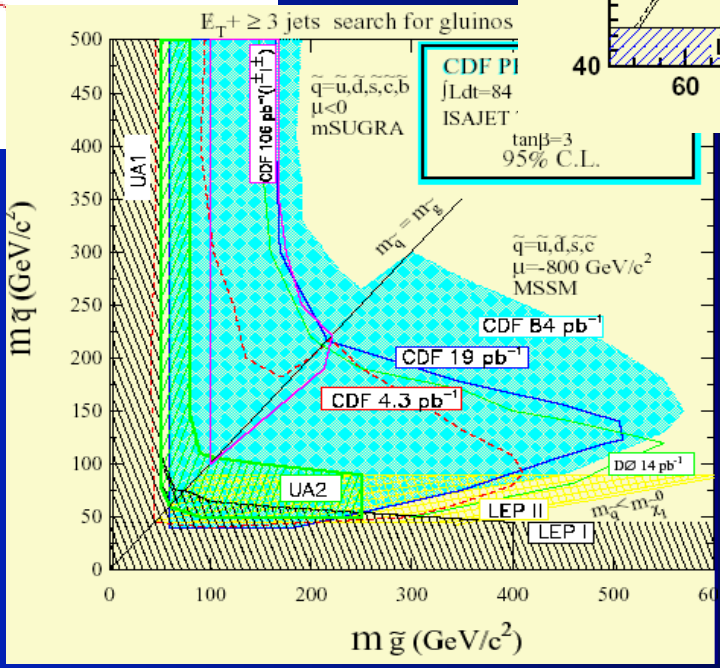
$\tilde{m}_l \geq$ 104 GeV

# SUSY Searches at Tevatron

Cascade production of superpatrners in hadron collisions




Dilepton Channel

3 jet channel

Exclusion:
World's Best Limits

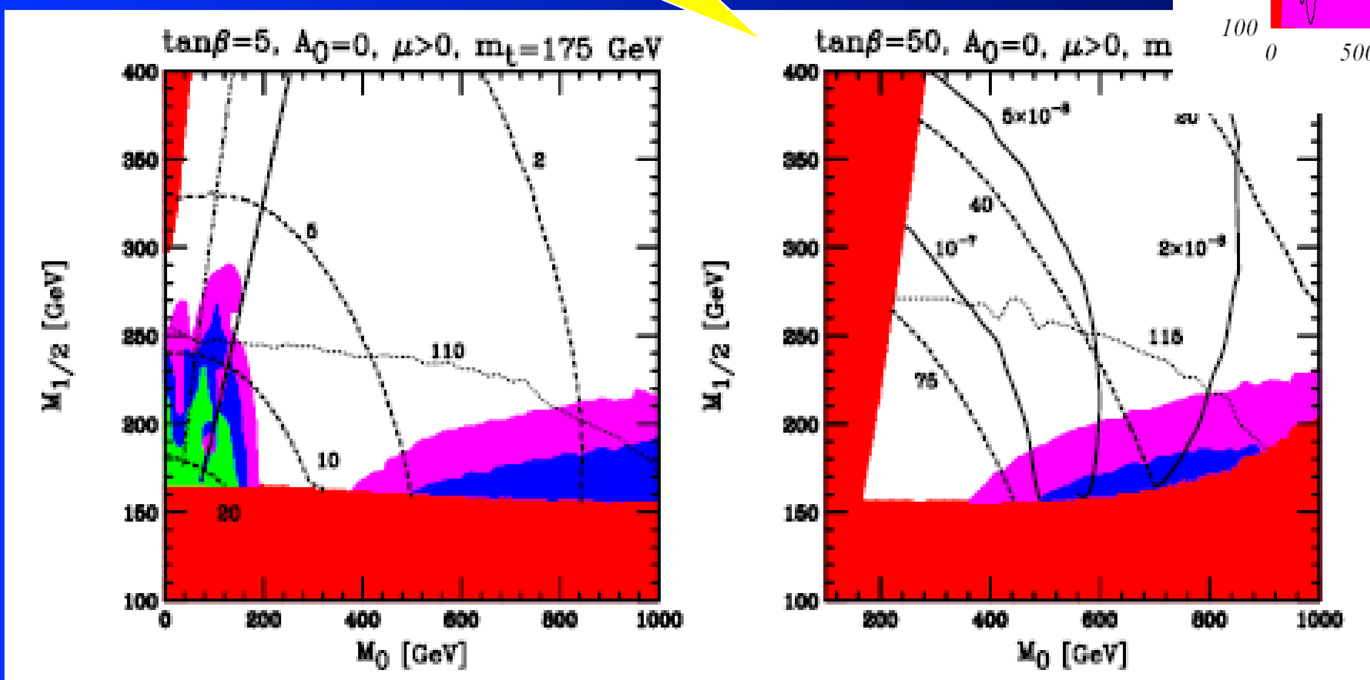
$M\tilde{q} \geq$ 300 GeV

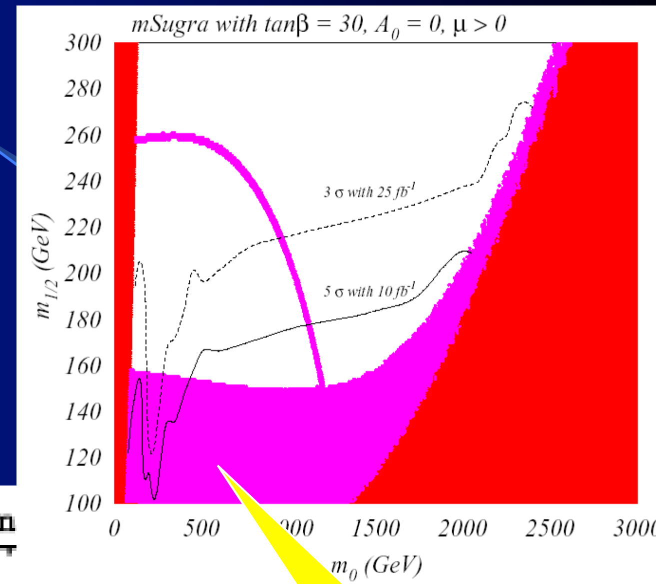
$m\tilde{g} \geq$ 195 GeV

# SUSY Searches at Tevatron

The reach of Tevatron in lepton channels in $m_0/m_{1/2}$ plane

Trilepton events reach at $2\ fb^{-1}$, $10\ fb^{-1}$, $30\ fb^{-1}$



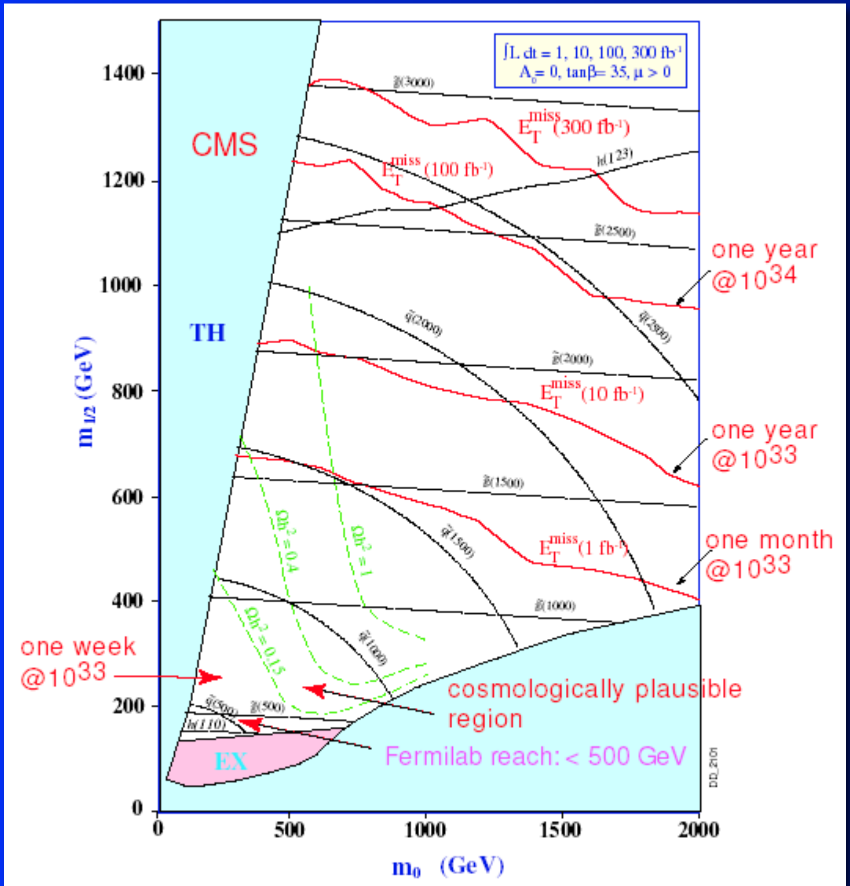

Dimuon Channel at $10\ fb^{-1}$, $25\ fb^{-1}$

# Tevatron Discovery Reach

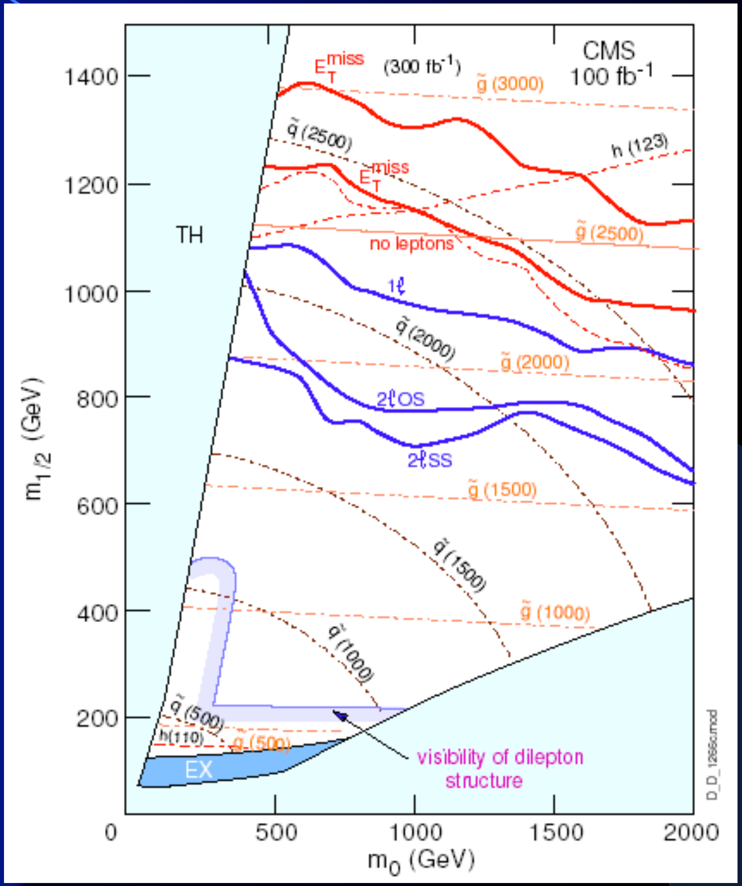
| Decay ($Br = 100\%$) | Subsequent Decay | Final State of $\tilde{b}_1\bar{\tilde{b}}_1$ or $\tilde{t}_1\bar{\tilde{t}}_1$ | Discovery Reach in $M_{\tilde{t}_1}$ or $M_{\tilde{b}_1}$ @20 fb$^{-1}$ | (Run I) |
|---|---|---|---|---|
| $\tilde{b}_1 \to b\tilde{\chi}_1^0$ | | $bb\not{E}_T$ | 260 GeV/$c^2$ | (146 GeV/$c^2$ [26]) |
| $\tilde{t}_1 \to c\tilde{\chi}_1^0$ | | $cc\not{E}_T$ | 220 GeV/$c^2$ | (116 GeV/$c^2$ [26]) |
| $\tilde{t}_1 \to bl\tilde{\nu}$ | $\tilde{\nu} \to \nu\tilde{\chi}_1^0$ | $\ell^+\ell^- b\not{E}_T$ | 240 GeV/$c^2$ | (140 GeV/$c^2$ [28]) |
| $\tilde{t}_1 \to bl\nu\tilde{\chi}_1^0$ | | $\ell^+\ell^- b\not{E}_T$ | - | (129 GeV/$c^2$ [28]) |
| $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$ | $\tilde{\chi}_1^\pm \to W^{(*)}\tilde{\chi}_1^0$ | $\ell bj\not{E}_T$ and $\ell^+\ell^- j\not{E}_T$ | 210 GeV/$c^2$ | (-) |
| $\tilde{t}_1 \to bW\tilde{\chi}_1^0$ | | $\ell bj\not{E}_T$ | 190 GeV/$c^2$ | (-) |

| NLSP | Decay Mode | $c\tau$ | Prod. | Key Final State(s) | Discovery Reach @30 fb$^{-1}$ |
|---|---|---|---|---|---|
| Bino $\tilde{\chi}_1^0$ | $\gamma + \tilde{G}$ | p | all | $\gamma\gamma\not{E}_T + X$ | 340 GeV/$c^2$ ($\tilde{\chi}_1^\pm$) |
| | | d | all | $\gamma_d jj\not{E}_T$ or $\gamma\gamma\not{E}_T + X$ | 300 GeV/$c^2$ ($\tilde{\chi}_1^\pm$) ($c\tau = 50$ cm) |
| Higgsino $\tilde{\chi}_1^0$ | $(h, Z, \gamma) + \tilde{G}$ | p | all | $(hh, h\gamma, hZ, Z\gamma, ZZ, \gamma\gamma)\not{E}_T + X$ | 220 GeV/$c^2$ ($\tilde{\chi}_1^\pm$) |
| | | d | all | $\delta_{ip} < 0$ for $h \to bb$, $Z \to \ell^+\ell^-$ | – |
| | | d | all | $\gamma_d + X$ | – |
| $\tilde{\tau}$ | $\tau + \tilde{G}$ | p | all | $\ell\ell\ell j\not{E}_T$, $\ell^\pm\ell^\pm jj\not{E}_T$, $\tau_h\tau_h\not{E}_T$ | 230 GeV/$c^2$ ($\tilde{\chi}_1^\pm$) 120 GeV/$c^2$ ($\tilde{\tau}_1$) |
| | | ll | all | $\mu(dE/dx) + \ell\ell(M_{\ell\ell} > 150$ GeV/$c^2)$ | 420 GeV/$c^2$ ($\tilde{\chi}_1^\pm$) 210 GeV/$c^2$ ($\tilde{\tau}$) |
| | | ll | all | $\mu(dE/dx) + X$ | 180 GeV/$c^2$ ($\tilde{\tau}$) |
| | | ll | all | $\mu(dE/dx$+TOF$) + X$ | 210 GeV/$c^2$ ($\tilde{\tau}$) |
| $\tilde{t}_1$ | $(c, bW) + \tilde{G}$ | p | $\tilde{t}_1\bar{\tilde{t}}_1$ | $cc\not{E}_T$ or $\ell + jets + \not{E}_T$ | 175 GeV/$c^2$ ($\tilde{t}_1$) |

# SUSY Searches at LHC

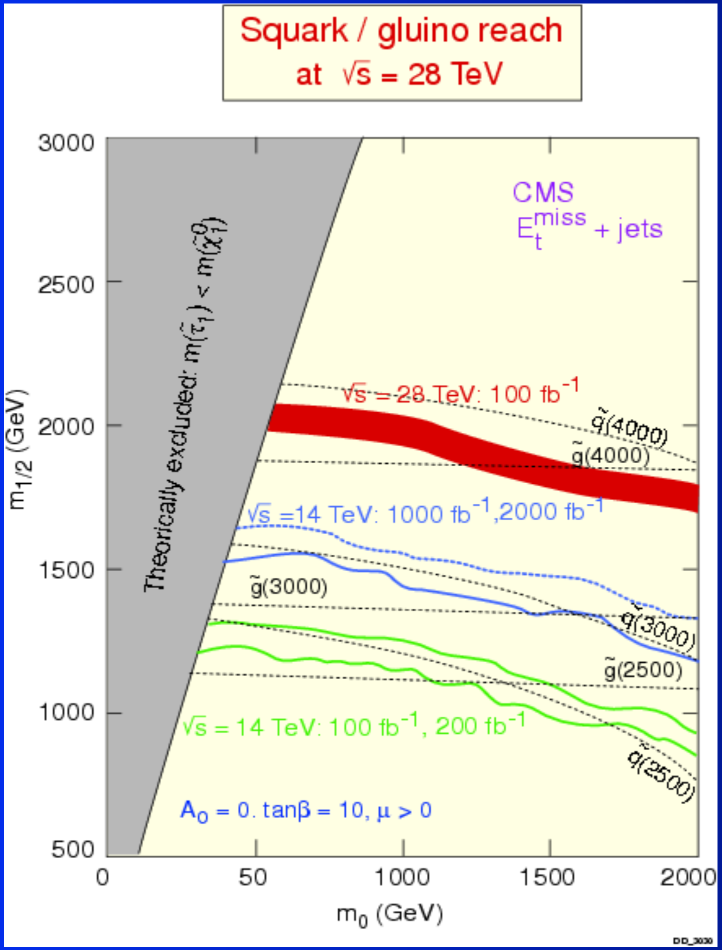


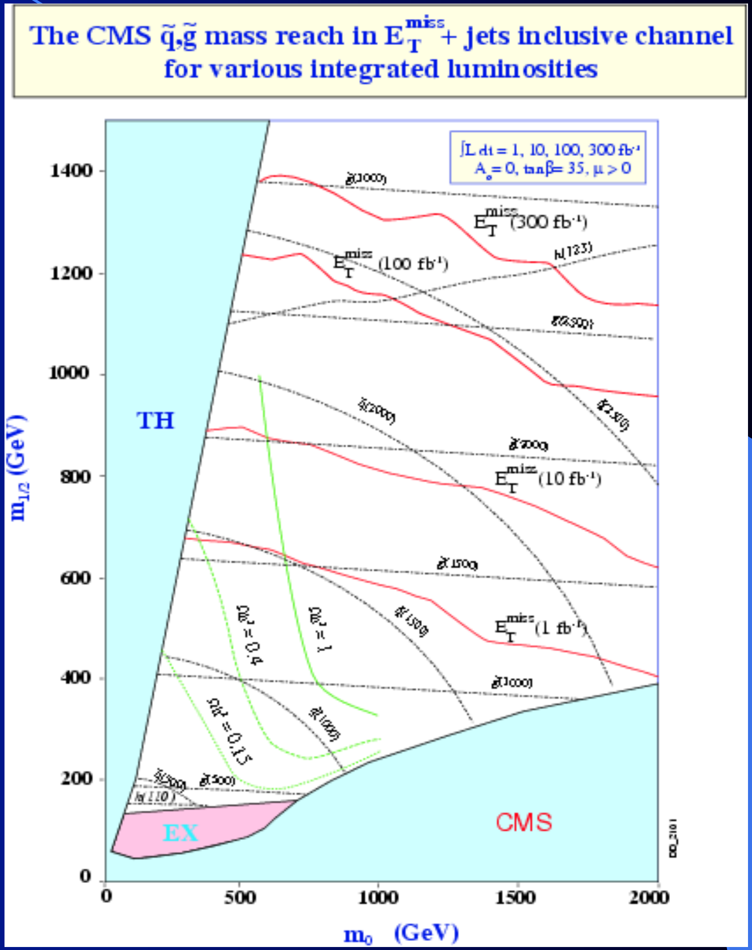

5 σ reach in jets + $\not{E}_T$ channel




Reach limits for various channels at 100 fb$^{-1}$

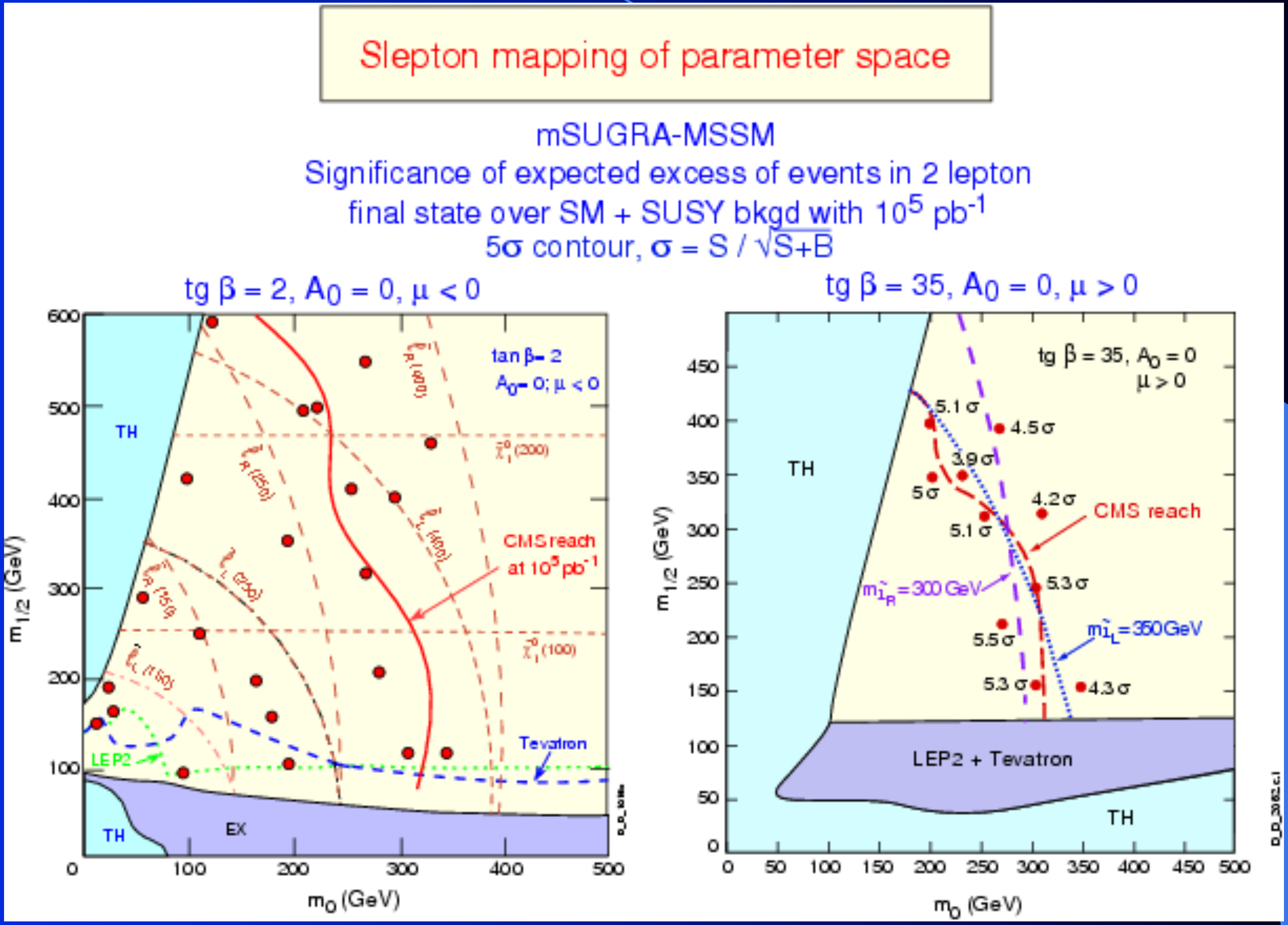
# SUSY Searches at LHC




Squark and gluino reaches at various luminocities

# SUSY Searches at LHC



# 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


# What comes beyond the Standard Model ?