SUPERSYMMETRIC EXTENSION OF THE STANDARD MODEL

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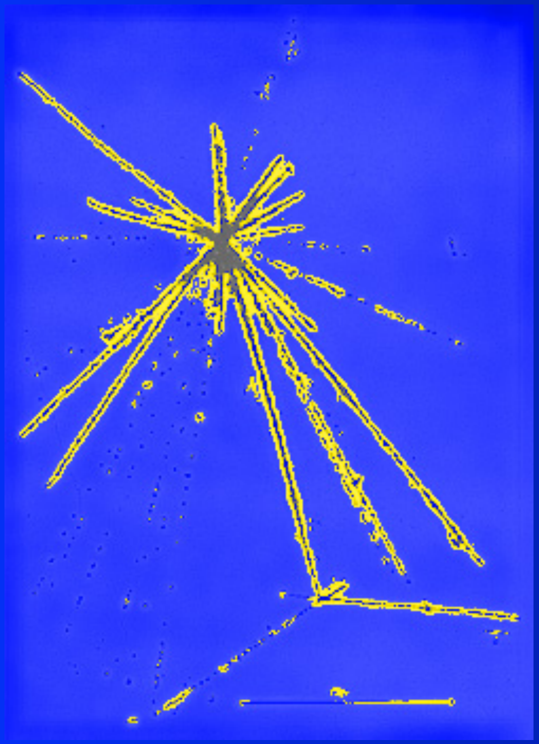
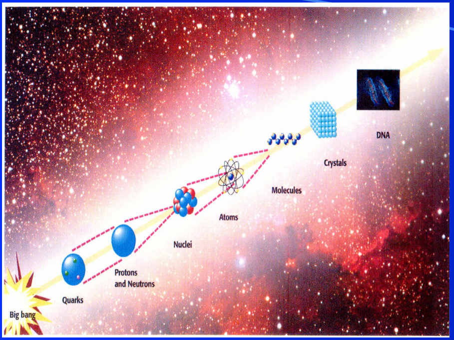
JINR / ITEP

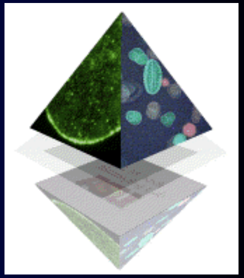


Outline

1. What is SUSY
2. Motivation of SUSY
3. The MSSM
4. SUSY Searches
5. SUSY in Astrophysics



What is SUSY



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

- 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

- The concepts of Quantum Field Theory allow SUSY without any restrictions

- There is no direct confirmation of SUSY but this does not stop theorists due to extreme beauty of SUSY models

Supersymmetry

$(Super)\ Algebra$

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

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

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

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

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

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

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

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

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

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

Superspace

$$x_\mu \to x_\mu, \vartheta, \bar\vartheta$$

Group Element

$$G(x, \vartheta, \bar\vartheta) = e^{i(-x^\mu P_\mu + \vartheta Q + \bar\vartheta\bar Q)}$$

Supertranslation

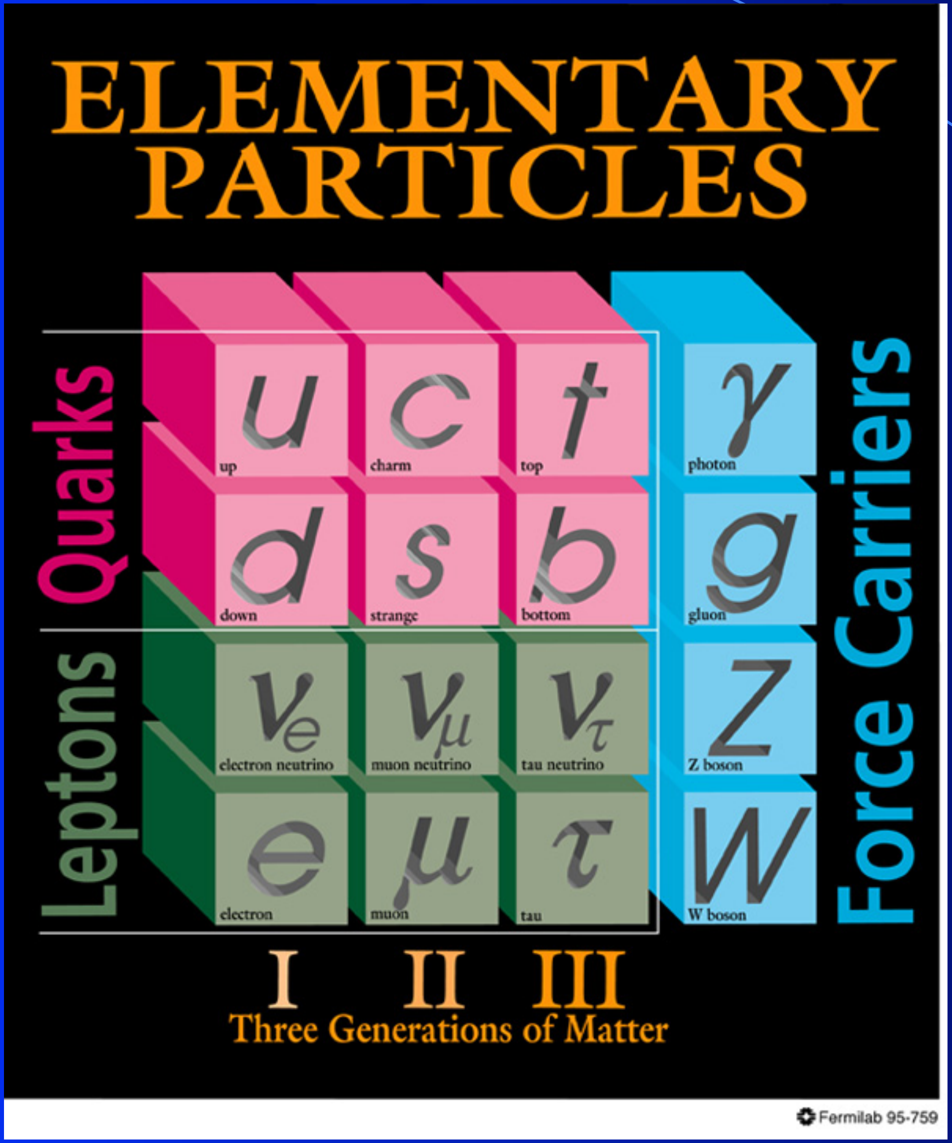
$$x_\mu \to x_\mu, \vartheta, \bar\vartheta$$

$$\vartheta \to \vartheta + \xi,$$

$$\bar\vartheta \to \bar\vartheta + \bar\xi$$

Local translation =
general relativity !

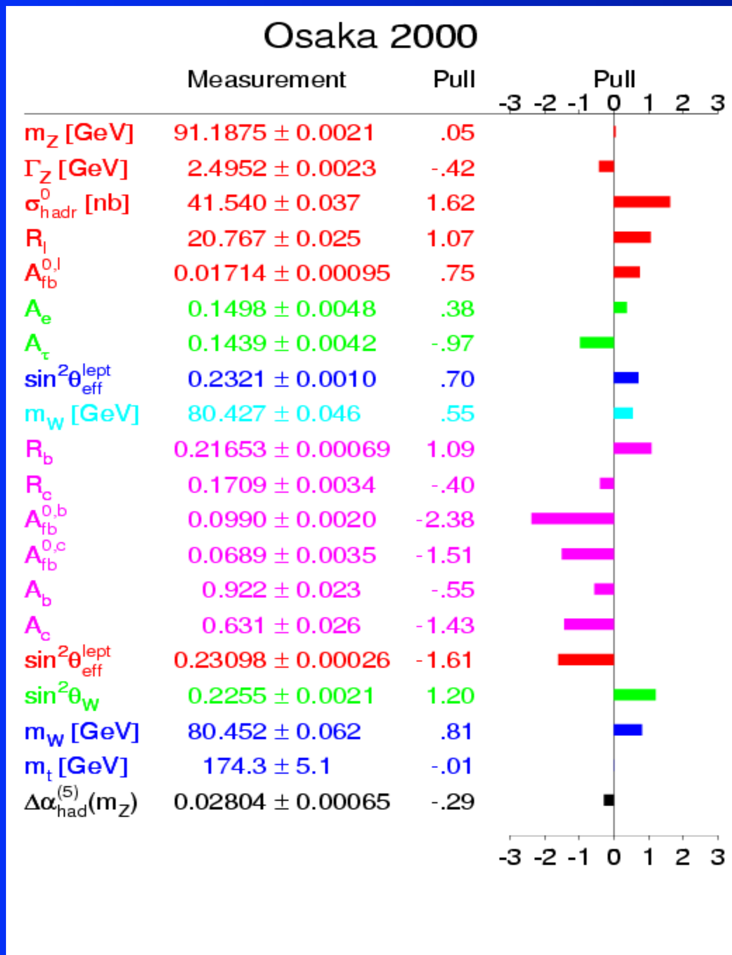
The Standard Model



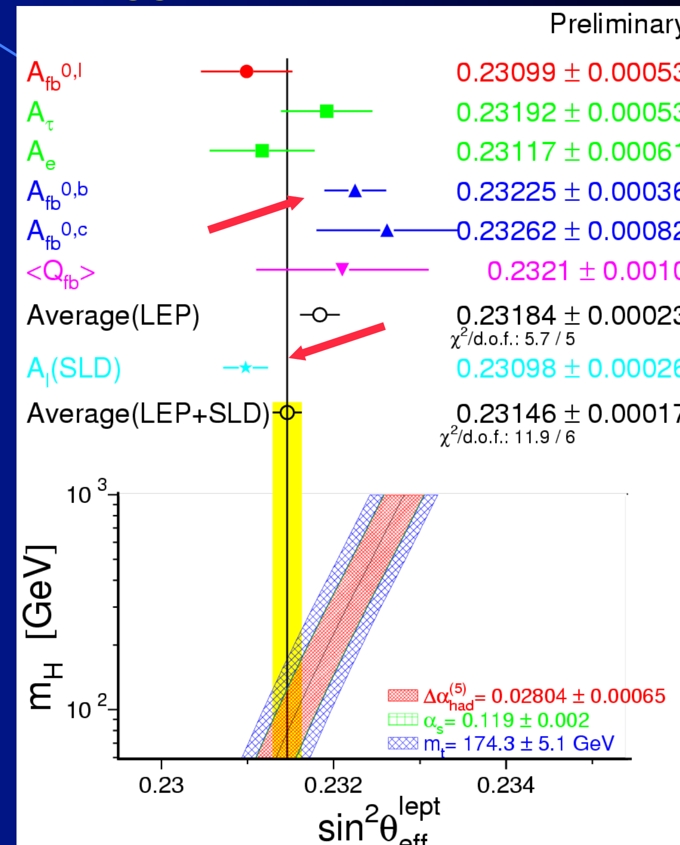
- Fits the experimental data very well
- Has too many free parameters and unexplained features
- The Higgs boson is still missing

Comparison with Experiment

Global Fit to Data



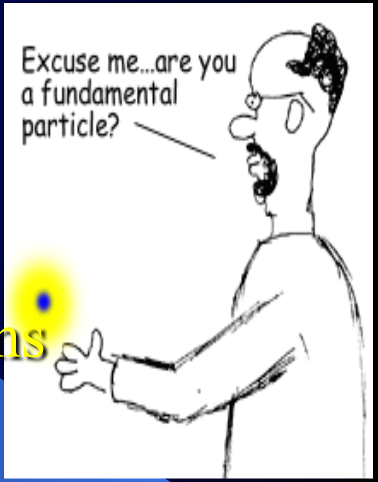
Higgs Mass Constraint



Remarkable agreement of ALL the data with the SM predictions - precision tests of radiative corrections and the SM

Though the values of sin θw extracted from different experiments are in good agreement, two most precise measurements from hadron and lepton asymmetries disagree by 3σ

The SM and Beyond



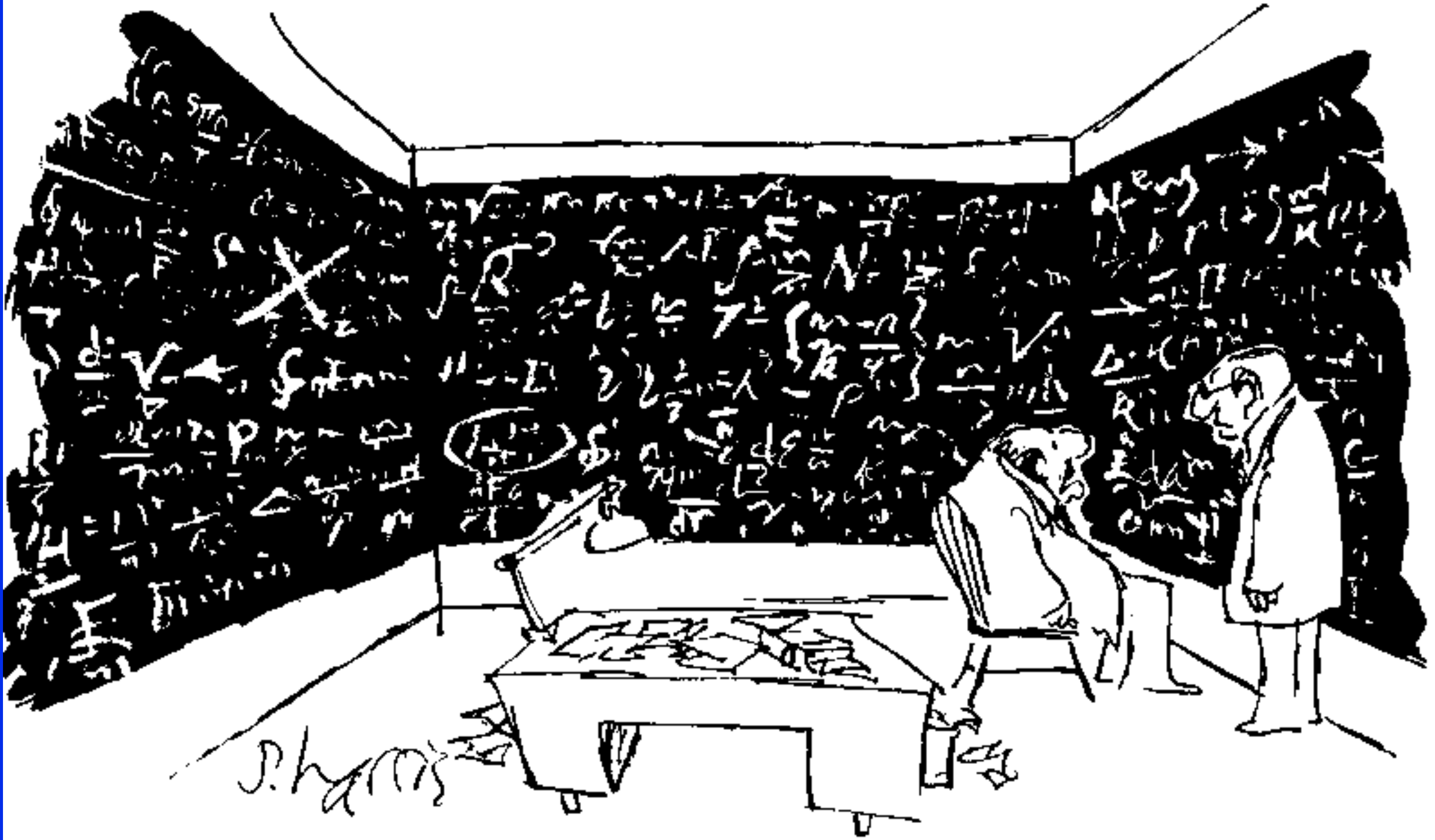
The problems of the SM:

- 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 in unclear

The way beyond the SM:

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

We like elegant solutions



"Whatever happened to *elegant* solutions?"

Motivation of SUSY in Particle Physics

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

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

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

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

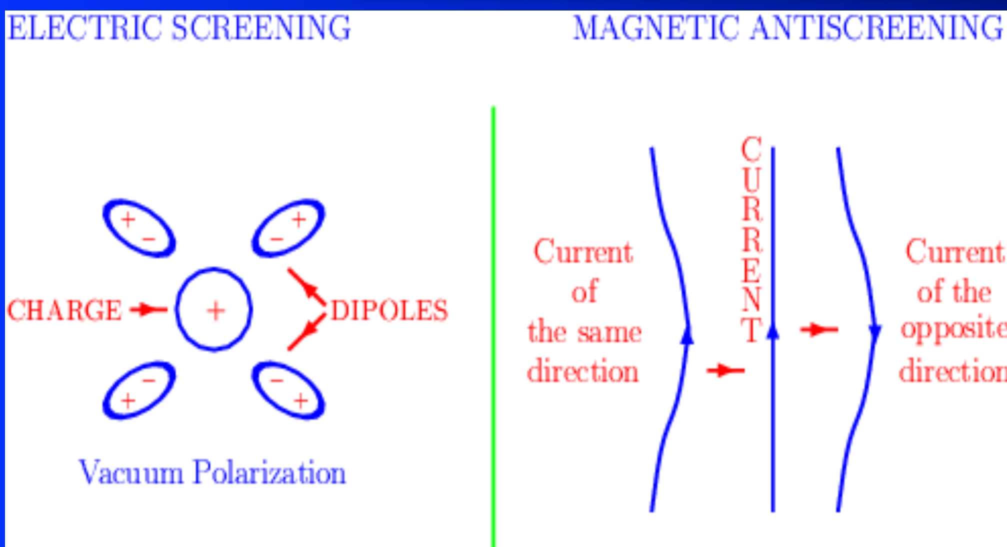
$$\{Q^i_\alpha, \bar{Q}^j_{\dot\beta}\} = 2\delta^{ij}(\sigma^\mu)_{\alpha\dot\beta} P_\mu \quad \Rightarrow \quad \{\delta_\varepsilon, \bar{\delta}_{\bar\varepsilon}\} = 2(\varepsilon\sigma^\mu\bar{\varepsilon})P_\mu$$

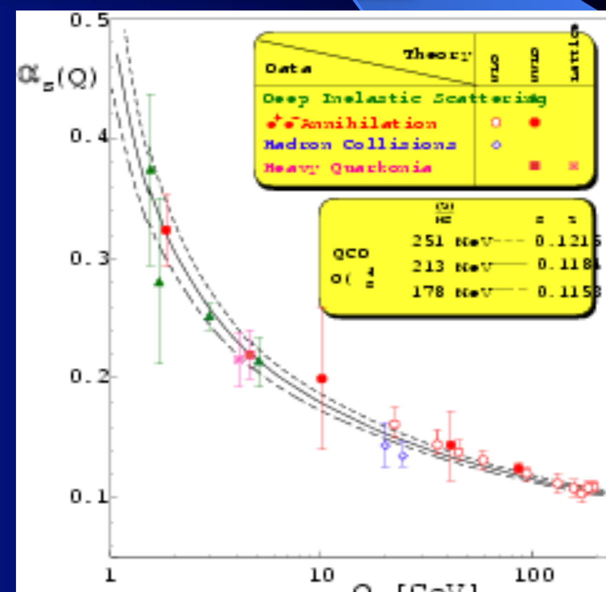
$$\varepsilon = \varepsilon(x) \ \text{ local coordinate transf.} \ \Rightarrow \ \text{(super)gravity}$$

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

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

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

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

Input

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

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

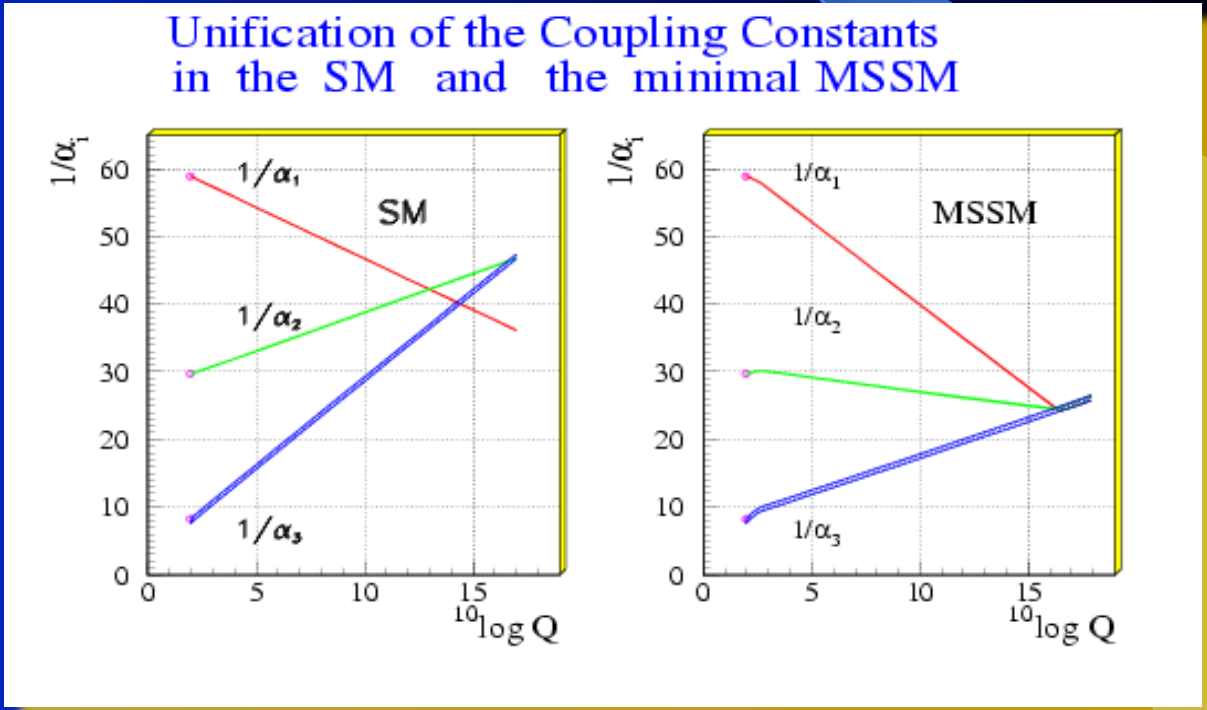
$$\alpha_s(M_Z) = 0.1184 \pm 0.0031$$

Output

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

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

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



SUSY yields unification!

Motivation of SUSY

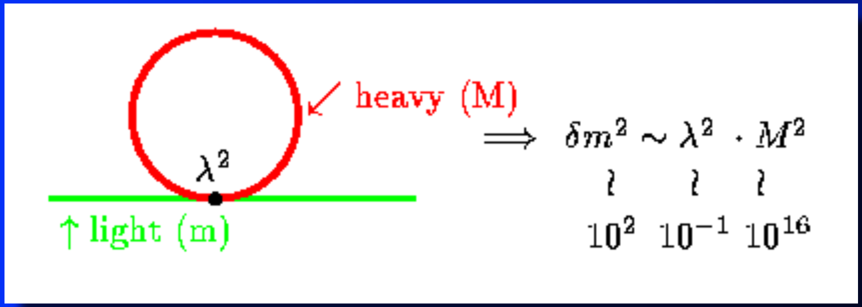
- Solution of the Hierarchy Problem

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

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

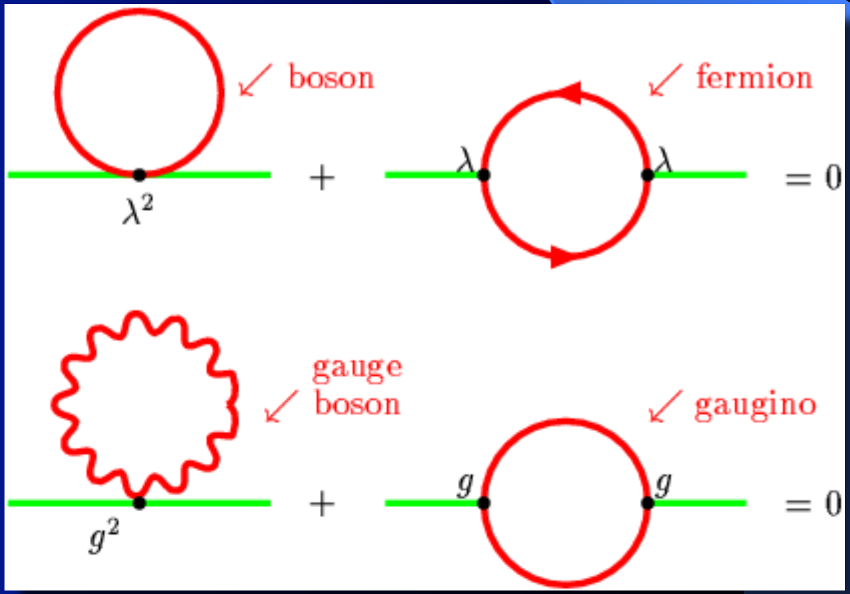
$$\frac{m_H}{m_\Sigma} \sim 10^{-14} \ll 1$$

Destruction of the hierarchy by Radiative corrections



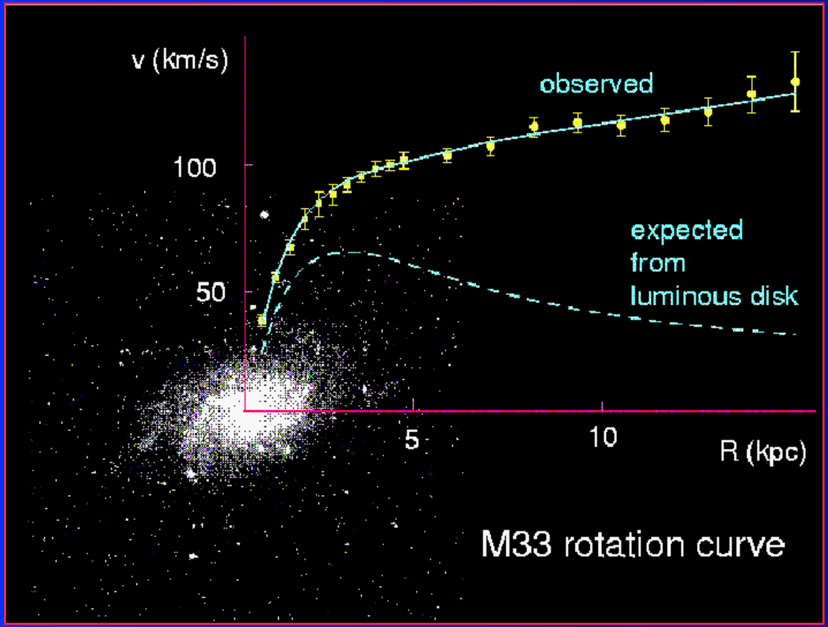
$$\sum_{bosons} m^2 = \sum_{fermions} m^2$$

Cancellation of quadratic terms

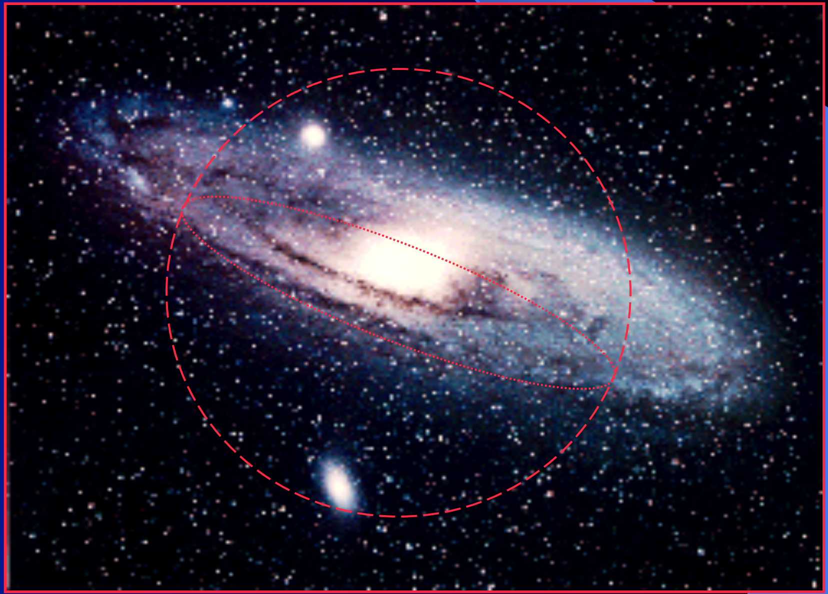


Motivation of SUSY

- 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.



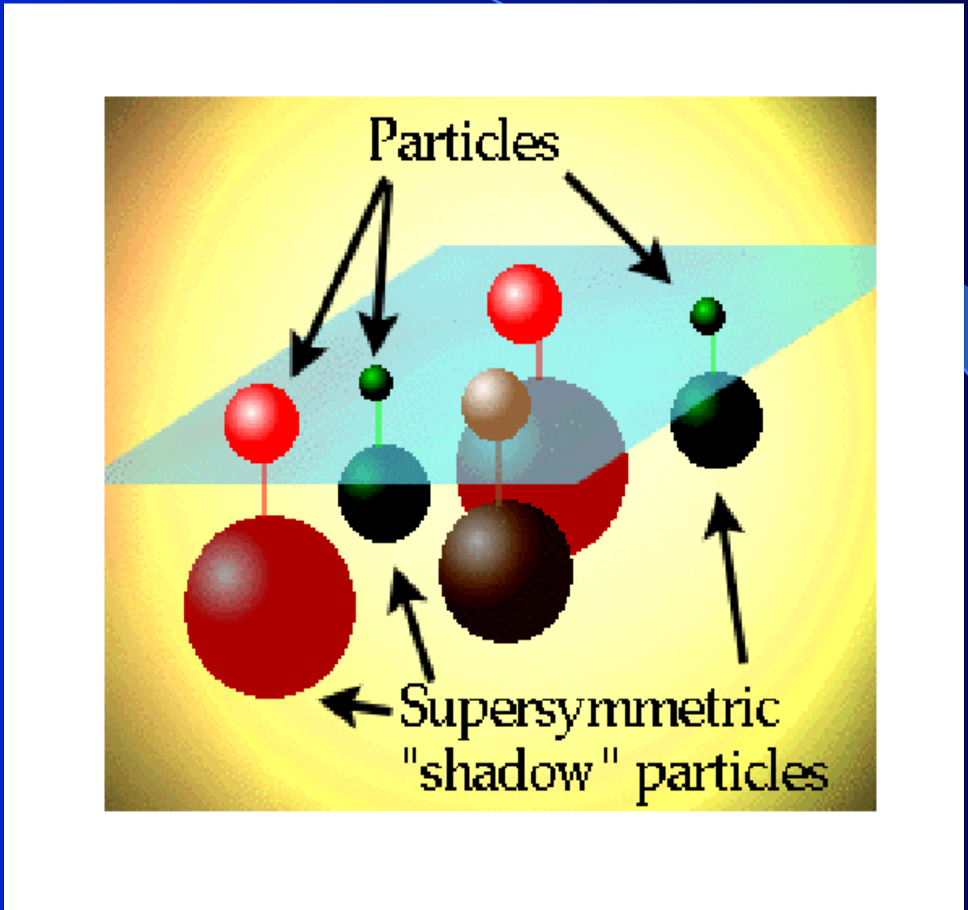
Spiral galaxies consist of a central bulge and a very thin disc, and surrounded by an approximately spherical halo of dark matter

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

Particle Content of the MSSM

Superfield	Bosons	Fermions	$SU_c(3)$	$SU_L(2)$	$U_Y(1)$
Gauge					
G^a	gluon g^a	gluino $\tilde{\mathrm{g}}^a$	8	0	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 $U_i = u_R$	3^*	1	$-4/3$
D_i	squarks $\tilde{D}_i = \tilde{d}_R$	quarks $D_i = d_R$	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!

SUSY Lagrangians

Superfields

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

Components

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

Potential

$$D^a = -g A^\dagger_i T^a A_i, \quad F_i = -\frac{\partial W}{\partial A_i} \quad \rightarrow \quad V = \tfrac{1}{2} D^a D^a + F^\dagger_i F_i$$

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

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

R-parity

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

The Usual Particle : R= + 1

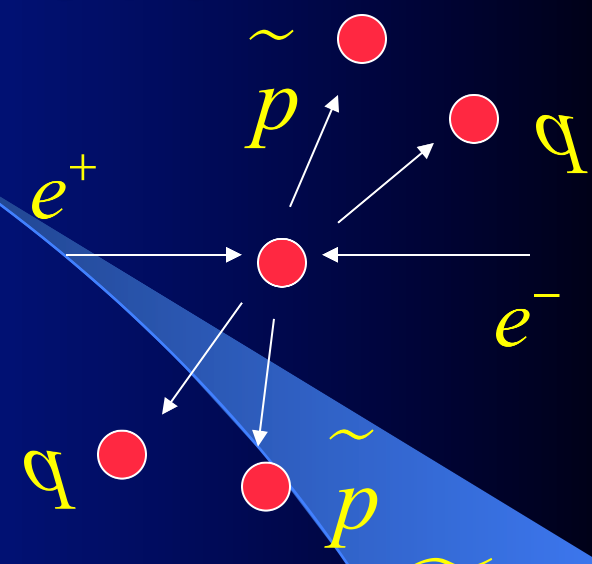
SUSY Particle : R= - 1

B-Bartion Number

L-Lepton Number

S-Spin

R-parity Conservation

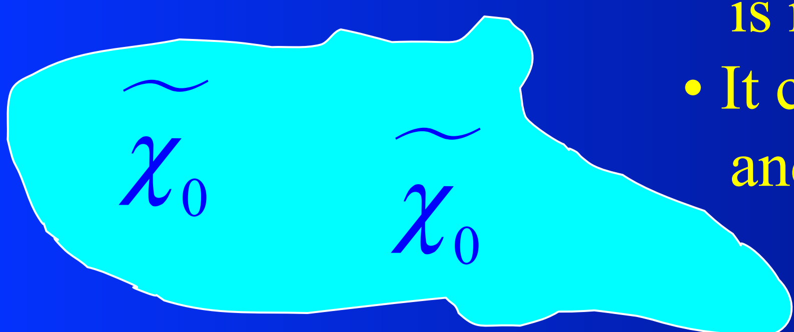


The consequences:

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

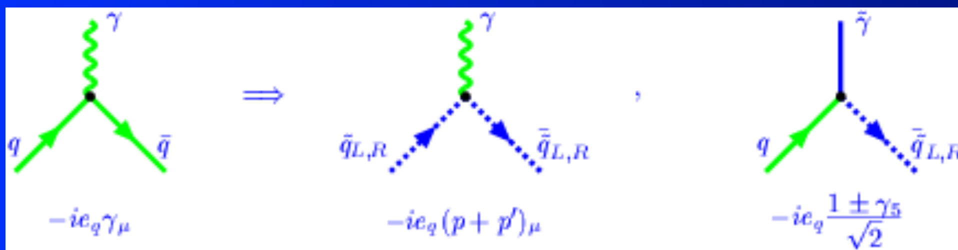
Physical output:

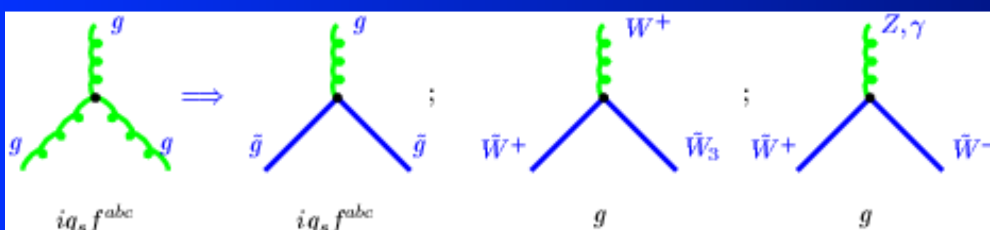
- The lightest superparticle (LSP) $\tilde{\chi}_0$ should be neutral - the best candidate is neutralino (photino or higgsino)
- It can survive from the Big Bang and form the Dark matter in the Universe

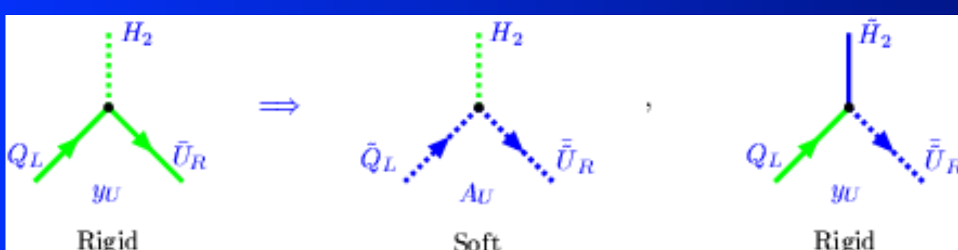


Interactions in the MSSM

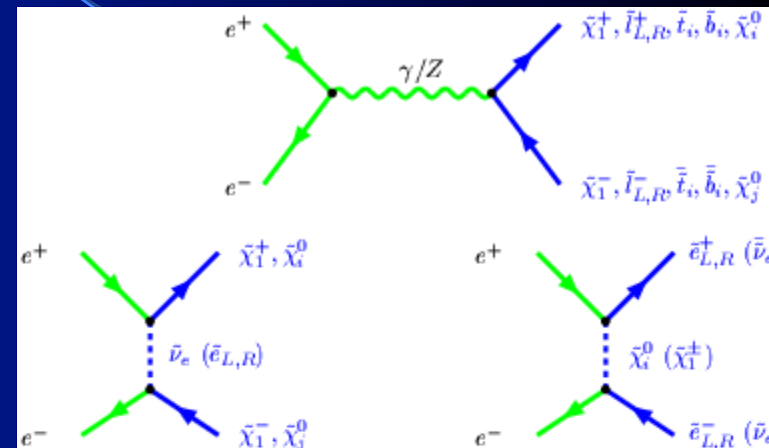
Interaction Vertices



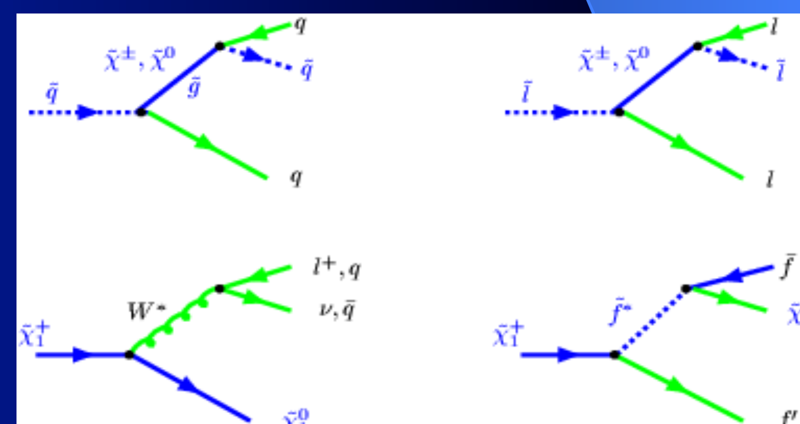




Creation of superpartners

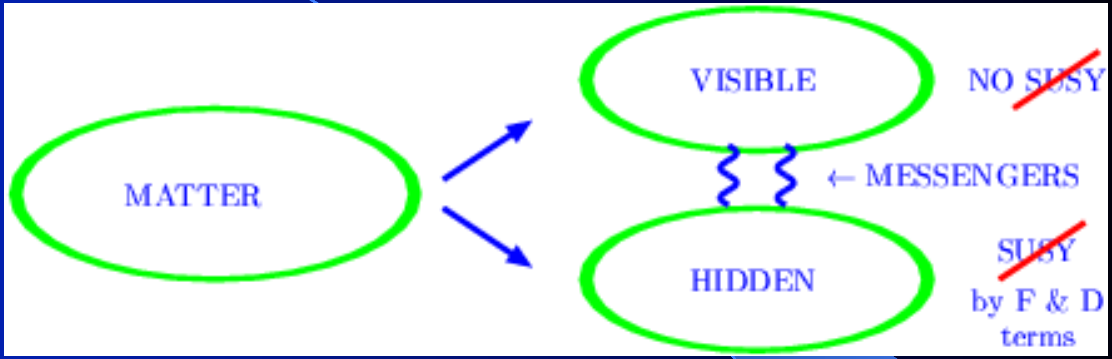


Decay of superpartners



Soft SUSY Breaking

Hidden Sector Scenario:



SUGRA

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

The Universal Soft Parameters: $A, B, m_0, M_{1/2}$ and μ

Versus m and λ in the SM

Mass Spectrum

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

Neutralino

$$M^{(0)} = \begin{pmatrix} M_1 & 0 & -M_Z \cos\beta \sin W & M_Z \sin\beta \sin W \\ 0 & M_2 & M_Z \cos\beta \cos W & -M_Z \sin\beta \cos W \\ -M_Z \cos\beta \sin W & M_Z \cos\beta \cos W & 0 & -\mu \\ M_Z \sin\beta \sin W & -M_Z \sin\beta \cos W & -\mu & 0 \end{pmatrix}$$

$$\chi = \begin{pmatrix} \tilde{B}^0 \\ \tilde{W}^3 \\ \tilde{H}_1^0 \\ \tilde{H}_2^0 \end{pmatrix}$$

Chargino

$$M^{(c)} = \begin{pmatrix} M_2 & \sqrt{2} M_W \sin\beta \\ \sqrt{2} M_W \cos\beta & \mu \end{pmatrix}$$

$$\psi = \begin{pmatrix} \tilde{W}^+ \\ \tilde{H}^+ \end{pmatrix}$$

Squarks & Sleptons

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

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

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

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

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

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

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

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

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

SUSY Higgs Bosons

SM

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

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

MSSM

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

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

$G^0 = -\cos\beta P_1 + \sin\beta P_2$	*Goldstone boson* $\to Z_0$
$A = \sin\beta P_1 + \cos\beta P_2$	*Neutral* $CP = -1$ *Higgs*
$G^+ = -\cos\beta (H_1^-)^* + \sin\beta H_2^+$	*Goldstone boson* $\to W^+$
$H^+ = \sin\beta (H_1^-)^* + \cos\beta H_2^+$	*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

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

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

Minimization

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

Solution

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

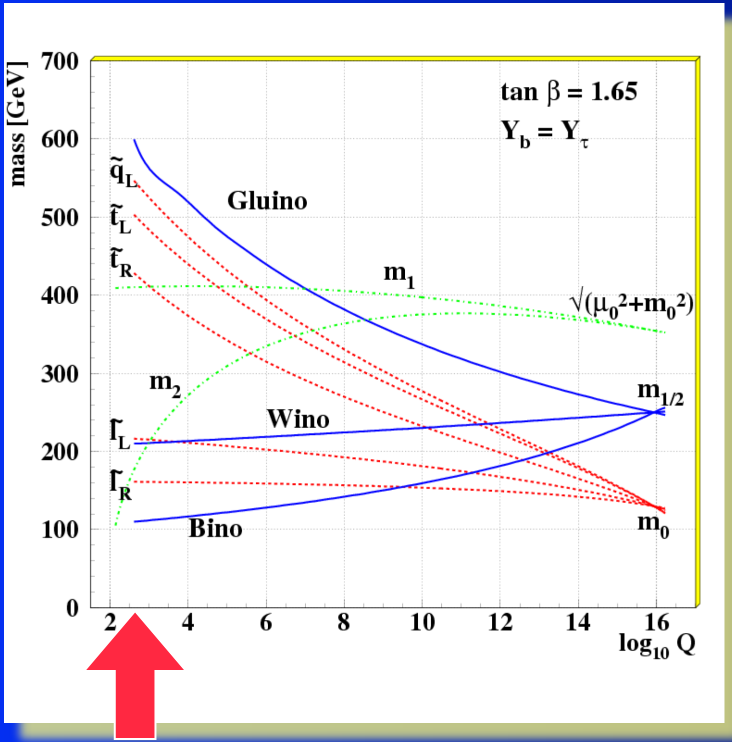
At the GUT scale

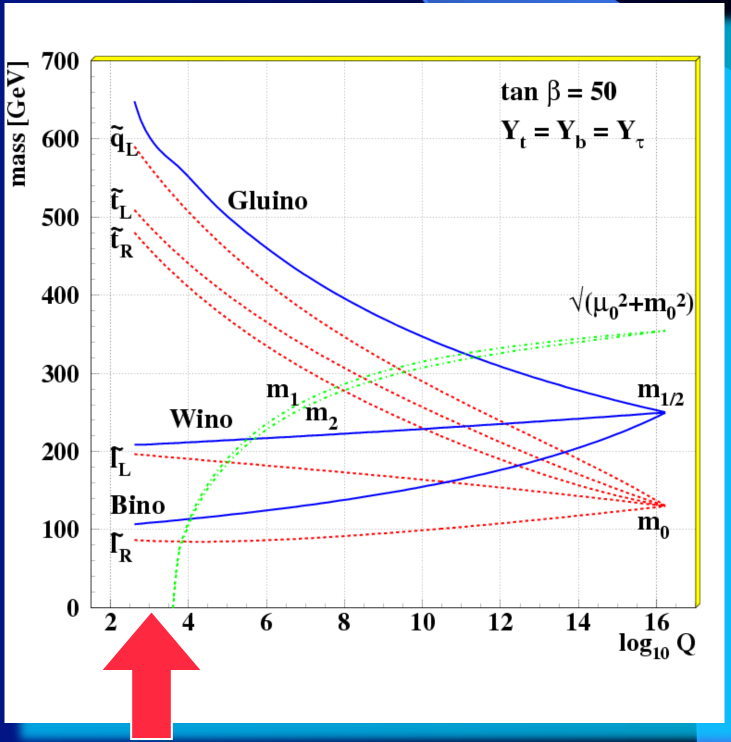
$$v^2=-\frac{4}{g^2+g'^2}m^2<0$$

No SSB in SUSY theory !

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 Radiative EWSB





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

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

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

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

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

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

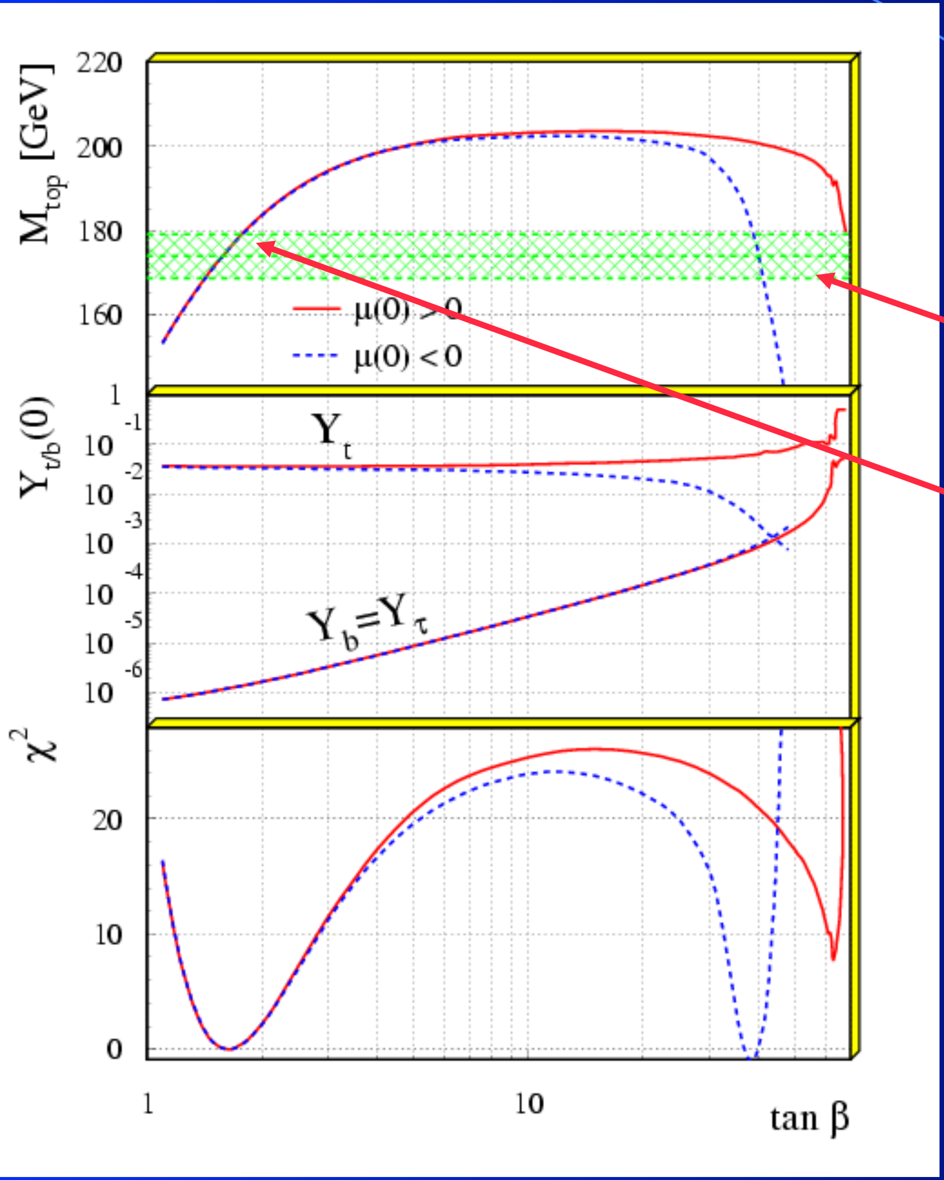
$$+ \frac{(\tilde{\mathrm{M}}\text{-}\tilde{\mathrm{M}}_{\mathrm{exp}})^2}{\sigma_{\tilde{\mathrm{M}}}^2} \quad (\text{for } \tilde{\mathrm{M}} < \tilde{\mathrm{M}}_{\mathrm{exp}})$$

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

Minimize χ^2

Exp.input data	Fit	Parameters
	low tan β	high tan β
$\alpha_1, \alpha_2, \alpha_3$	M_{GUT}, α_{GUT}	M_{GUT}, α_{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_τ	$\tan\beta$	$\tan\beta$
M_Z	μ	μ
$b \to s\gamma$	(A_0)	A_0
$\tau_{Universe}$		

Low and High tanβ Solutions



Requirements:
- EWSB
- bτ unification

Low tanβ solution

High tanβ solution

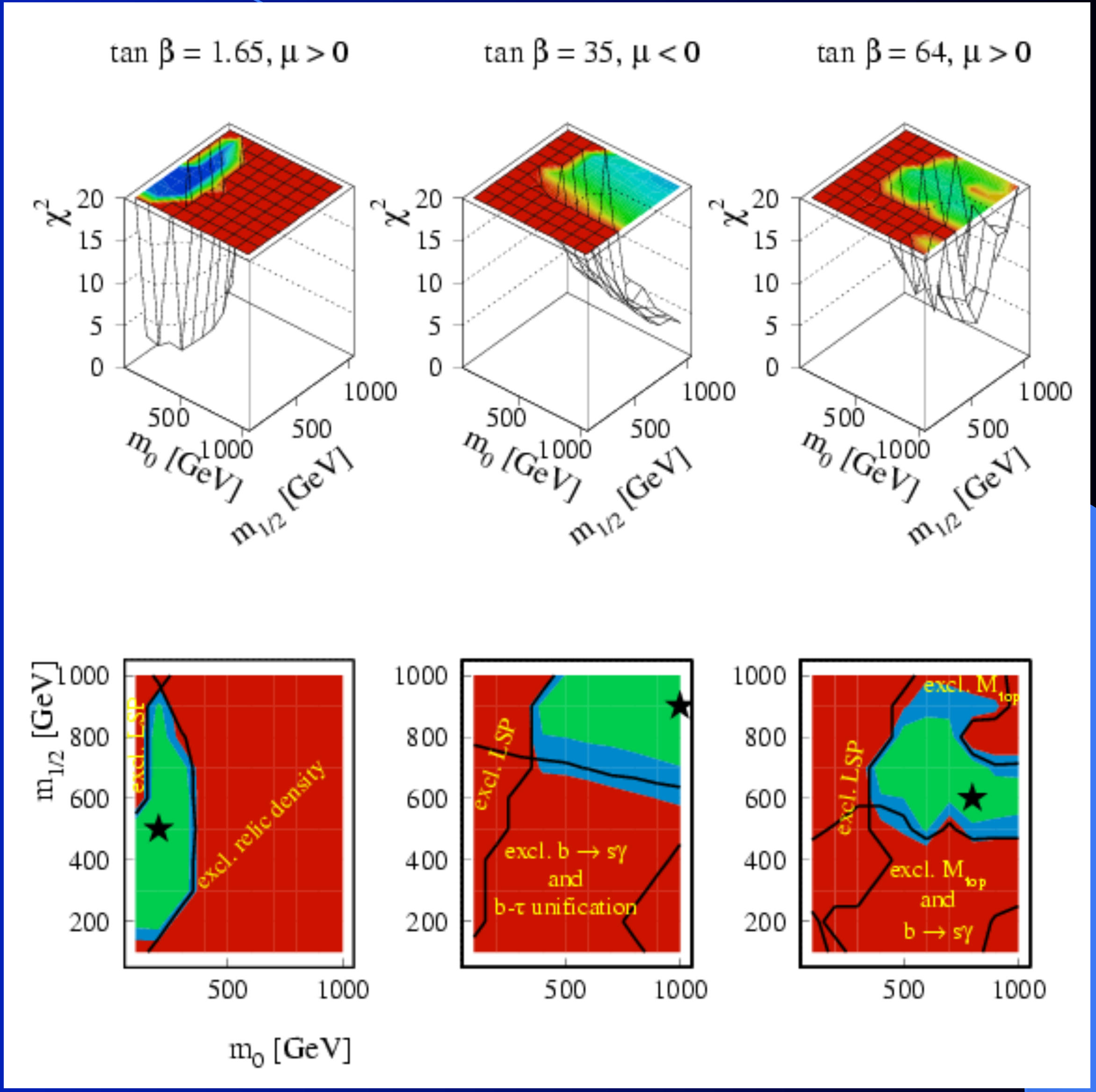
- bτ unification is the consequence of GUT
- Non working for the light generations

Allowed Regions in Parameter Space

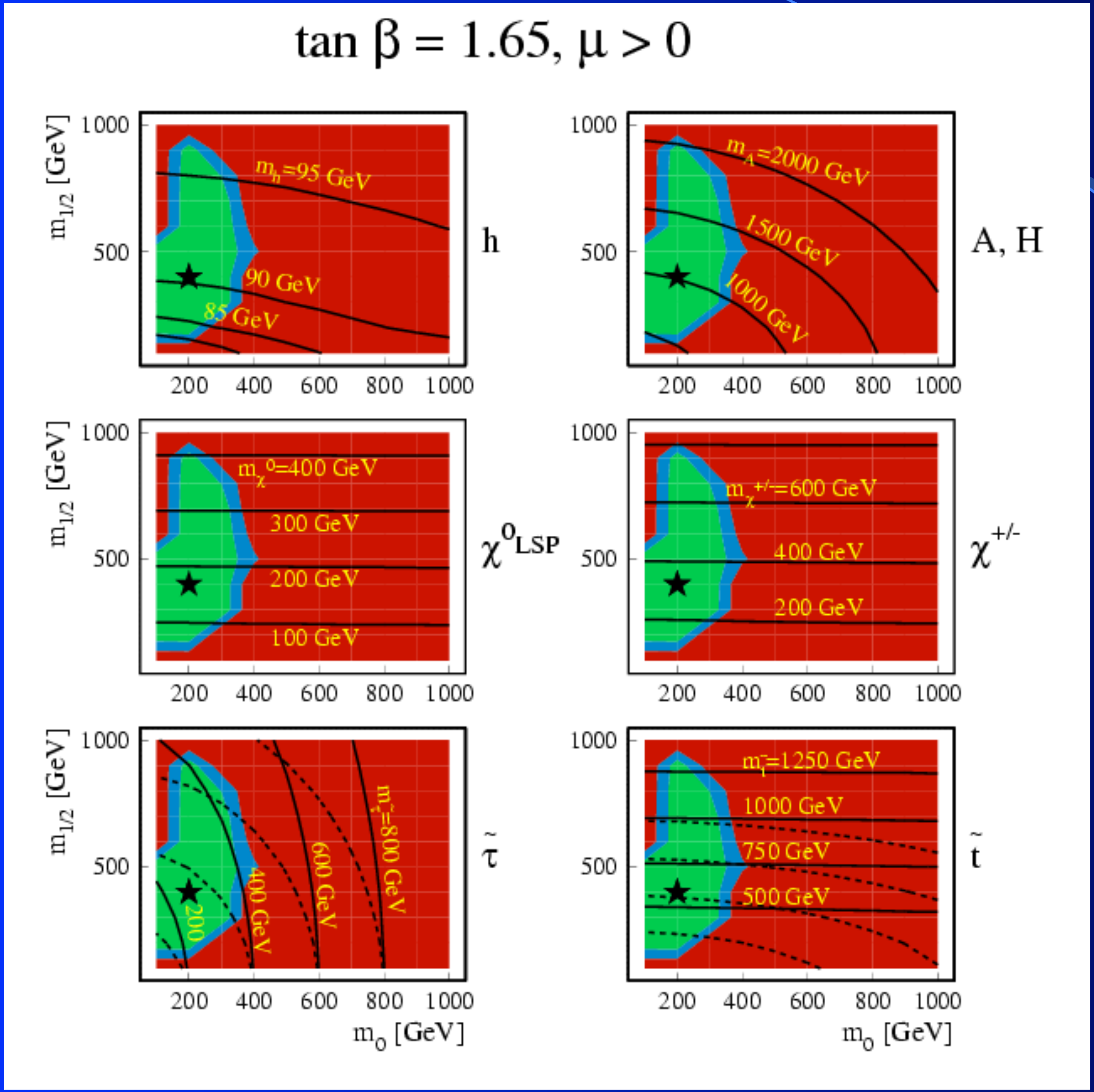
All the requirements are fulfilled simultaneously !

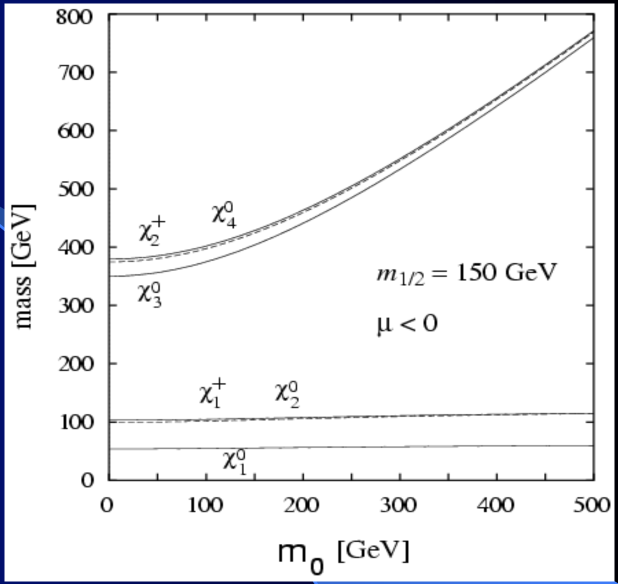
- μ is defined from the EWSB
- $A_0 = 0$

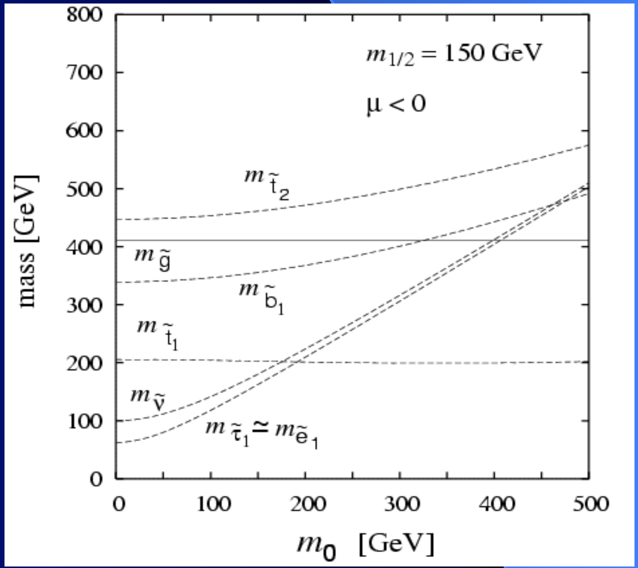
* - is the best fit value



Masses of Superpartners







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

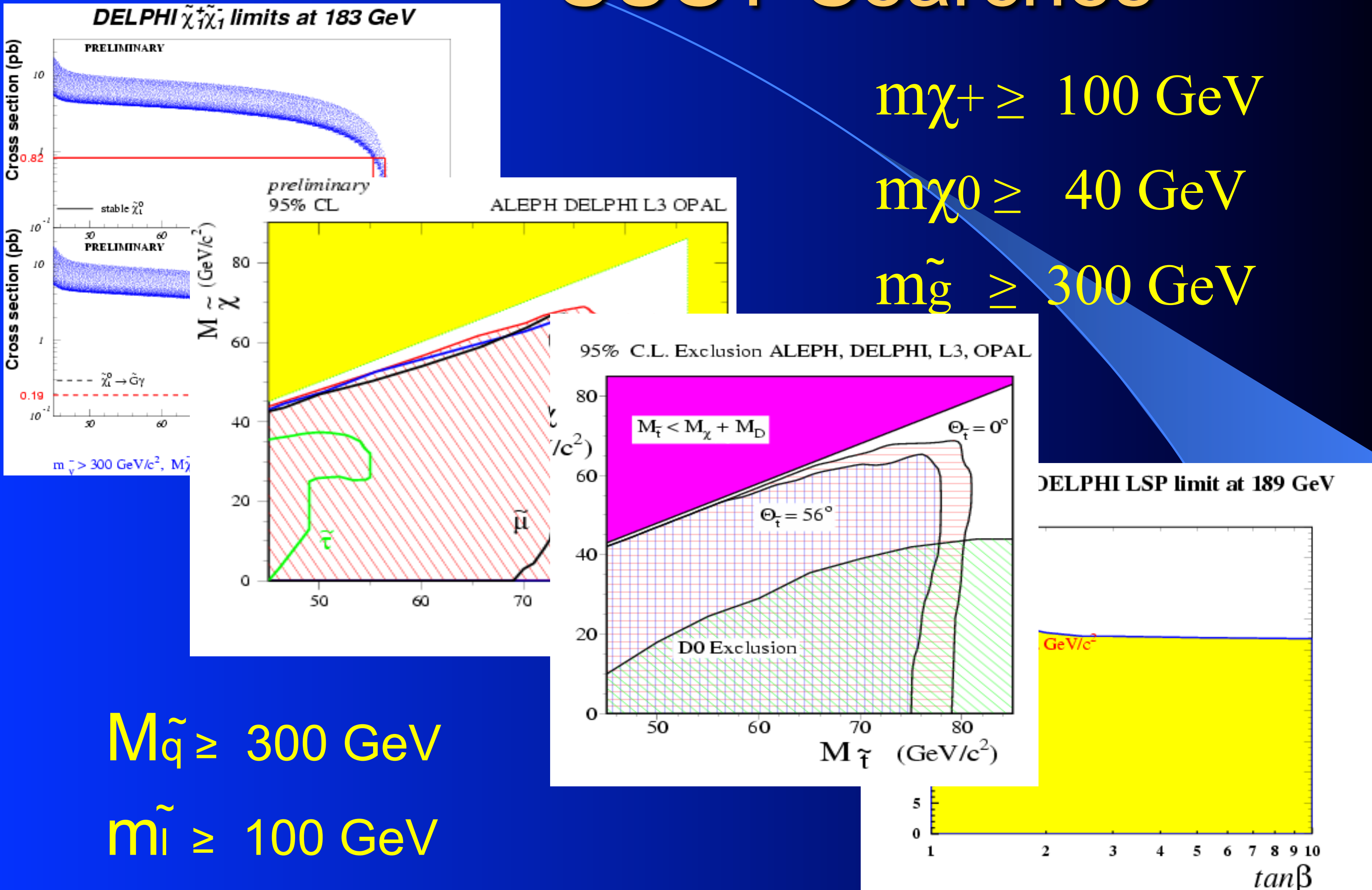
Symbol	Low tan β	High tan β
$\tilde{\chi}_1^0(\tilde{B}), \tilde{\chi}_2^0(\tilde{W}^3)$	214, 413	170, 322
$\tilde{\chi}_3^0(\tilde{H}_1), \tilde{\chi}_4^0(\tilde{H}_2)$	1028, 1016	481, 498
$\tilde{\chi}_1^\pm(\tilde{W}^\pm), \tilde{\chi}_2^\pm(\tilde{H}^\pm)$	413, 1026	322, 499
$\tilde{g}$	1155	950
$\tilde{e}_L, \tilde{e}_R$	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

SUSY Searches

$m_{\chi^+} \geq$ 100 GeV

$m_{\chi^0} \geq$ 40 GeV

$m_{\tilde{g}} \geq$ 300 GeV

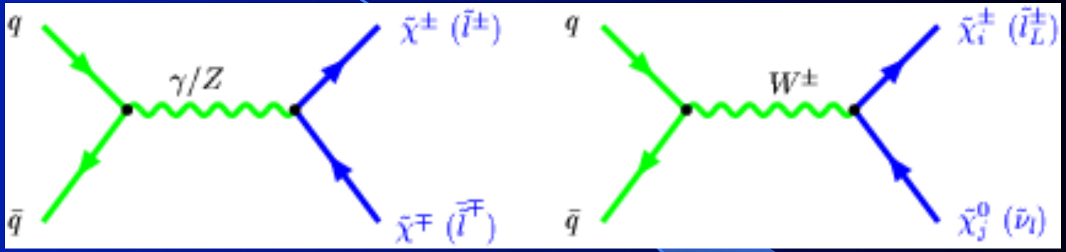


$M_{\tilde{q}} \geq$ 300 GeV

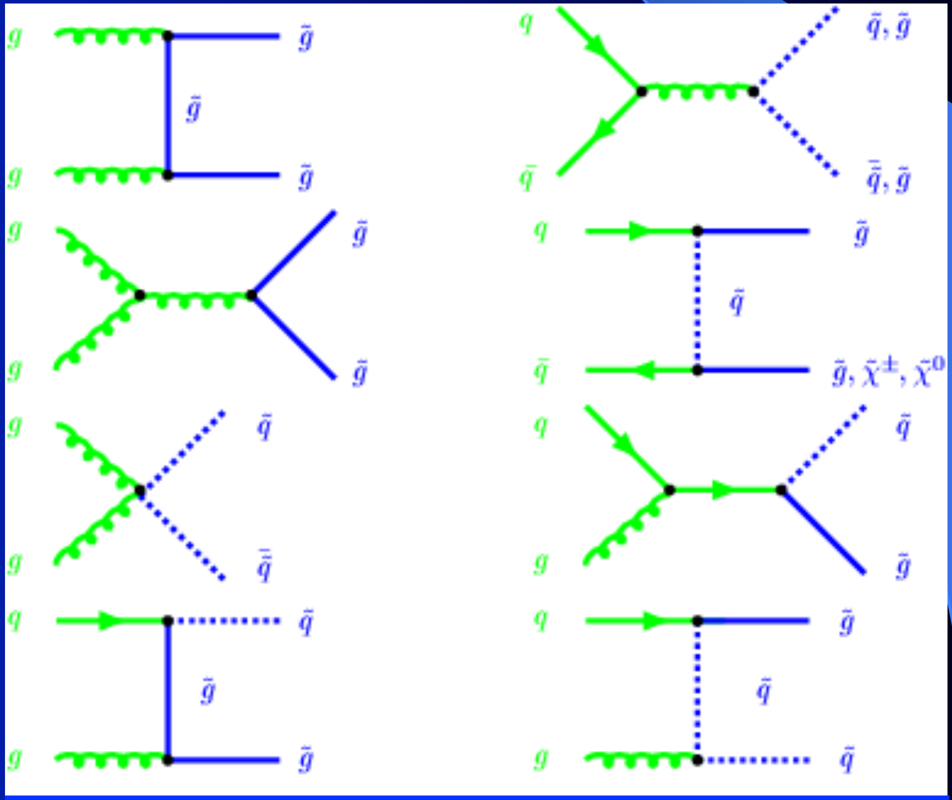
$m_{\tilde{l}} \geq$ 100 GeV

SUSY Production at Hadron Colliders

Annihilation channel

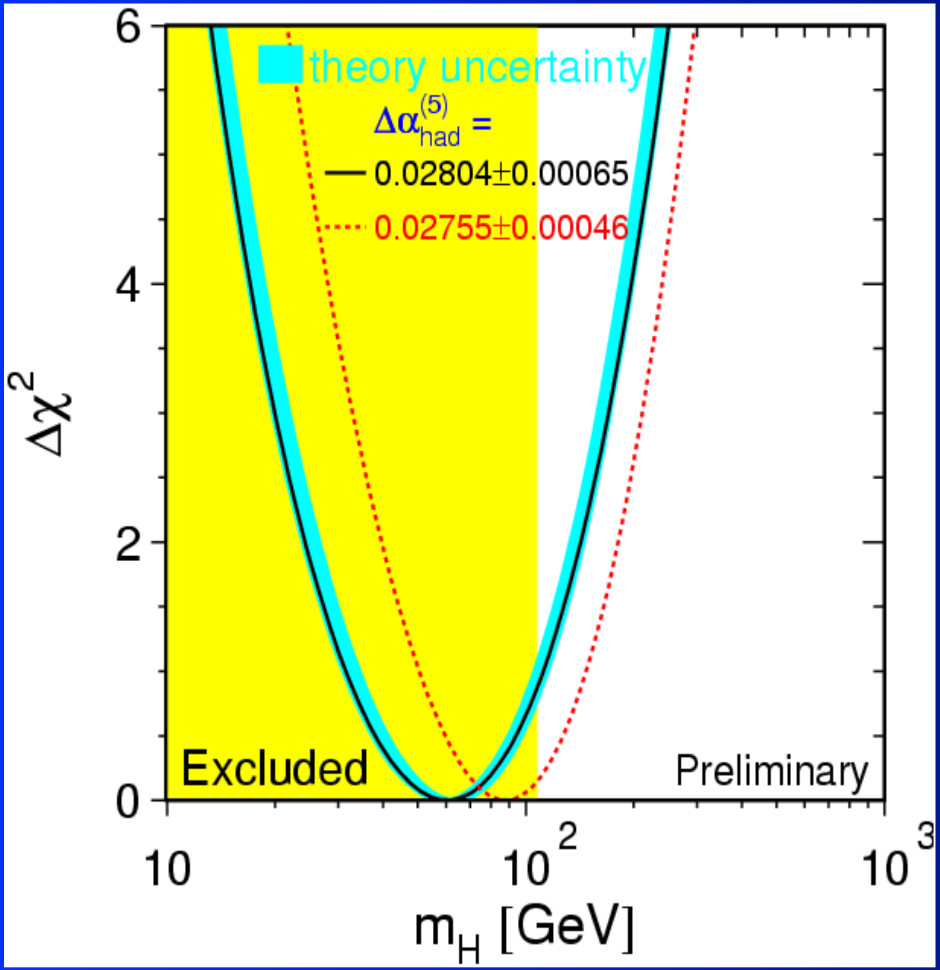


Gluon fusion, qq scattering and qg scattering channels



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

The Higgs Mass Limit

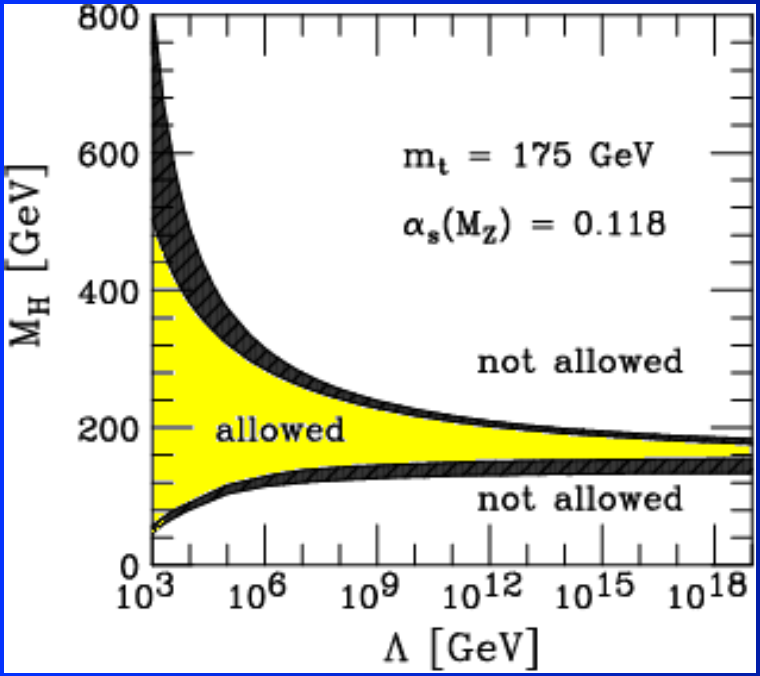


- Indirect limit from radiative corrections
- Direct limit from Higgs non-observation at LEP II (CERN)

$113 < m_H < 200$ GeV

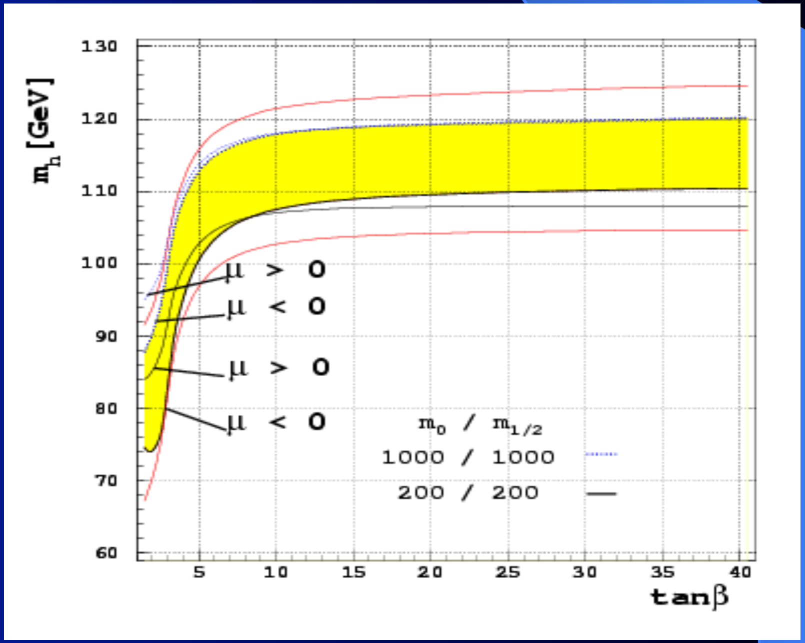
At 95 % C.L.

The Higgs Mass Limit (**Theory**)



- The SM Higgs

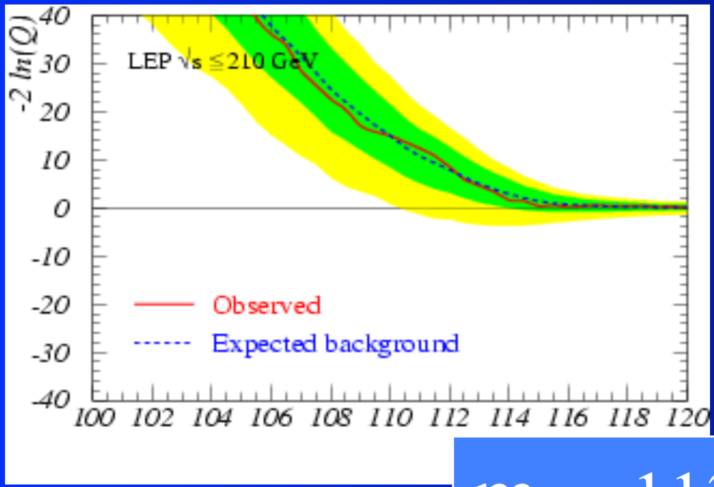
$m_H \geq 134$ GeV

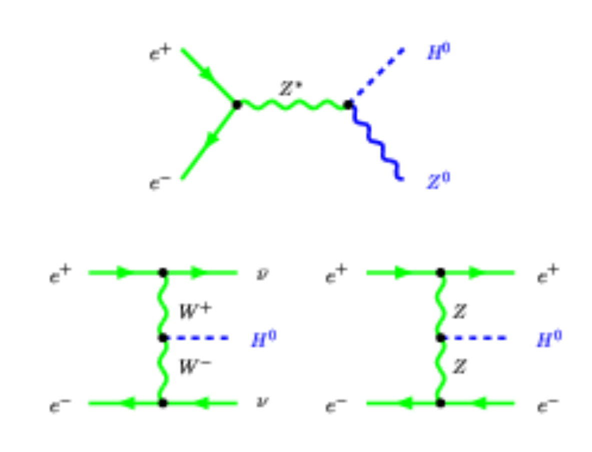


SUSY Higgs

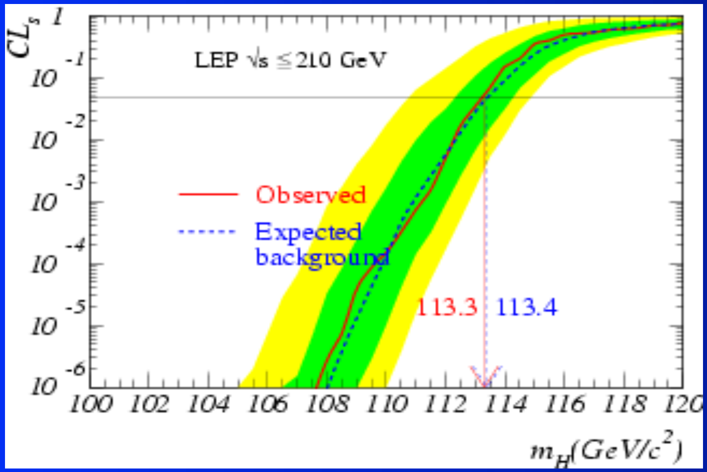
$m_H \leq 130$ GeV

Higgs Searches

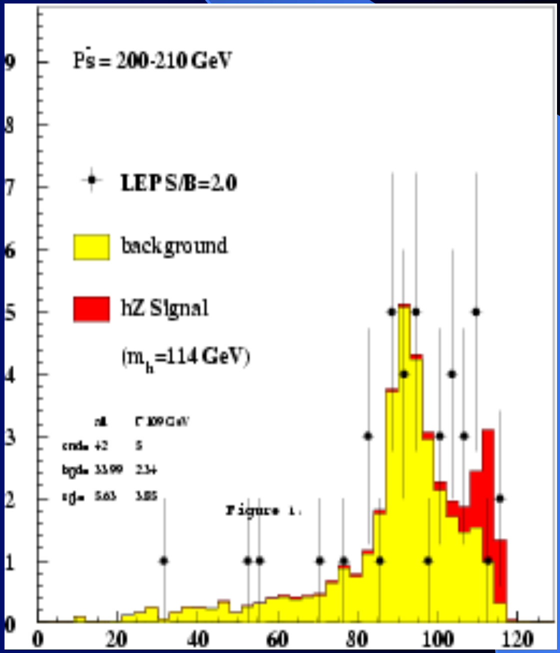




$m_H \geq 113.4$ GeV at 95 % C.L.



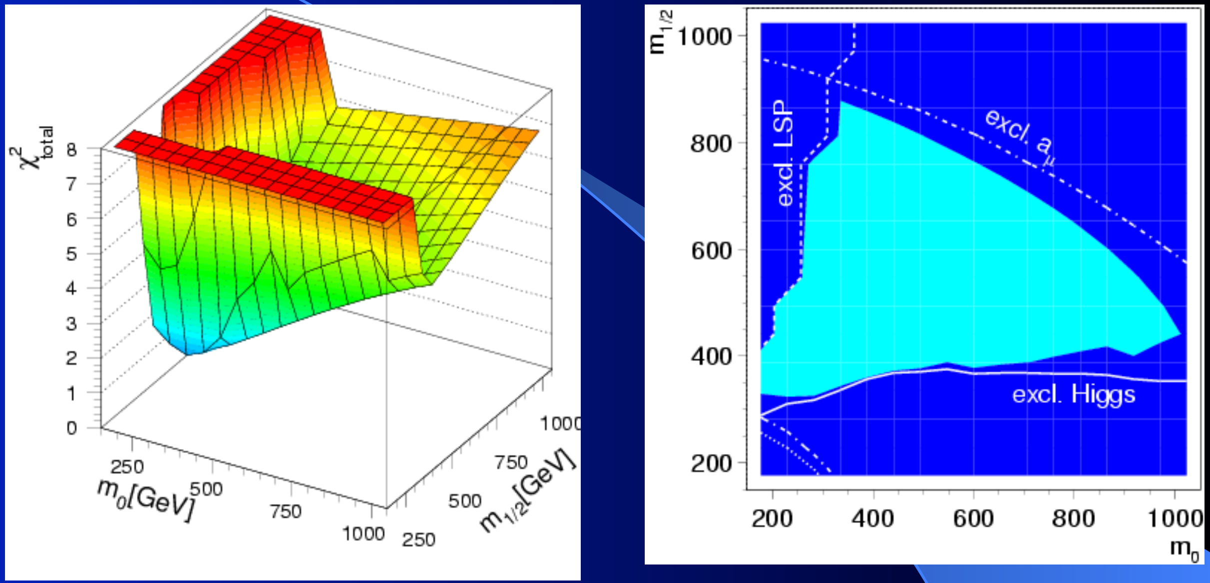
114 -115 GeV Event



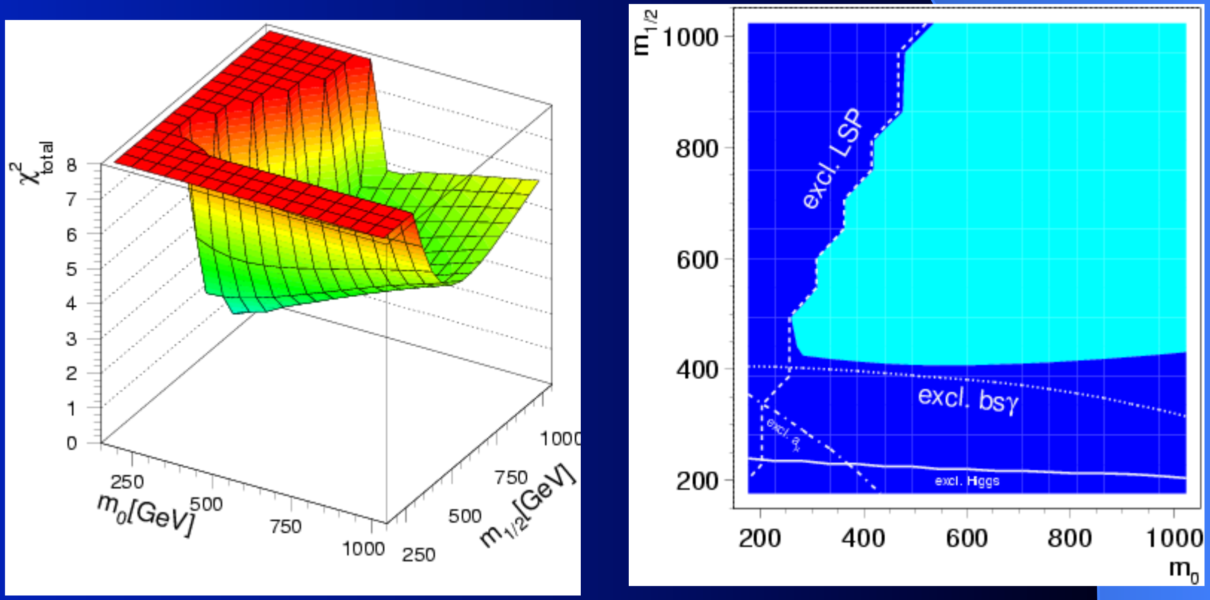
Allowed Regions Renewed

- $\tan\beta > 4$ from the Higgs limit at LEP
- $\mu > 0$ from a_μ

$\tan\beta = 35$



$\tan\beta = 50$



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

(recent news from WMAP)

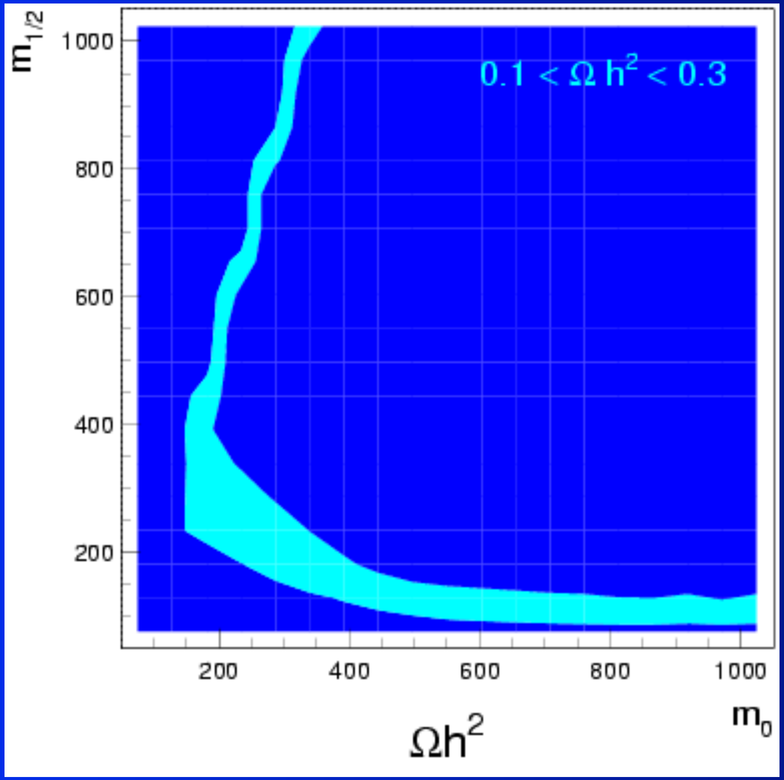
Dark Matter in the Universe:

Hot DM
(not favoured by
galaxy formation)

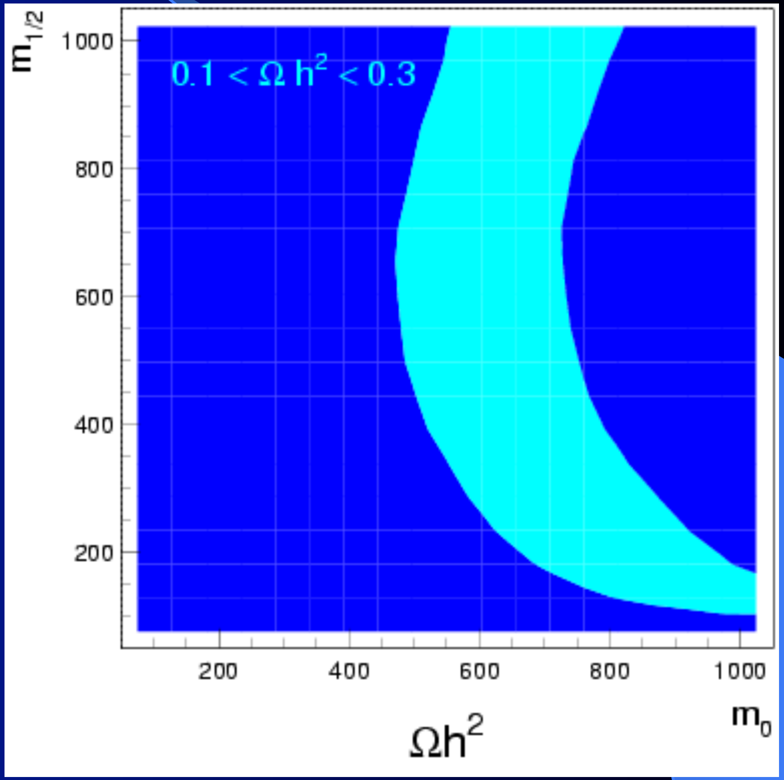
Cold DM
(rotation curves
of Galaxies)

SUSY Fits to Dark Matter

Results in severe constraints on parameter space



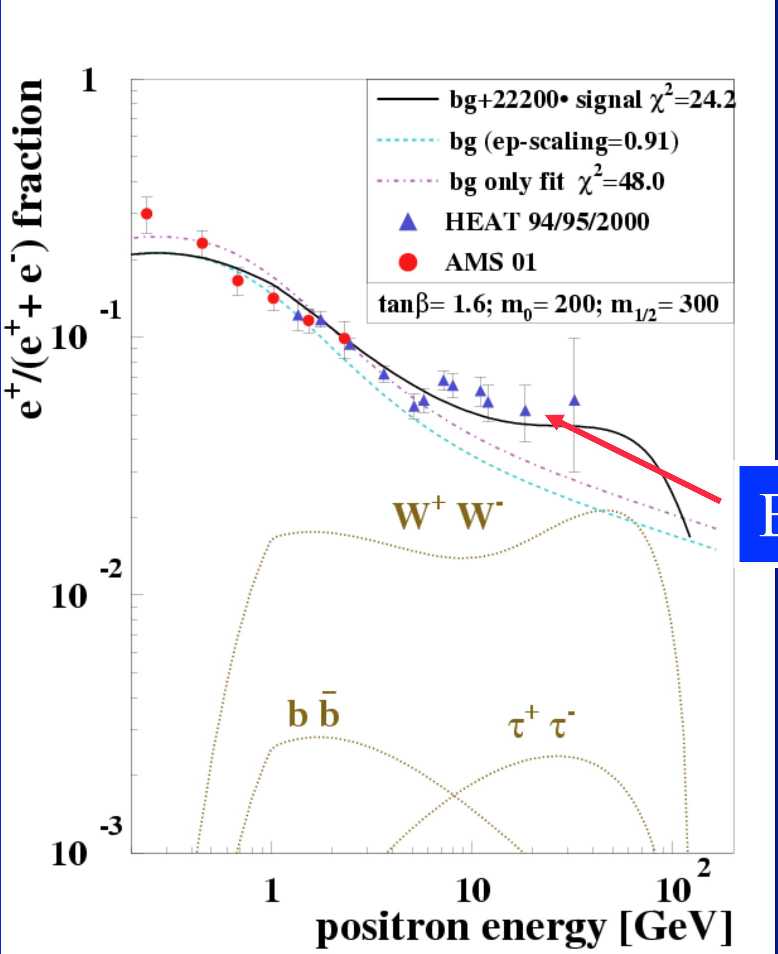
$\tan\beta = 35$



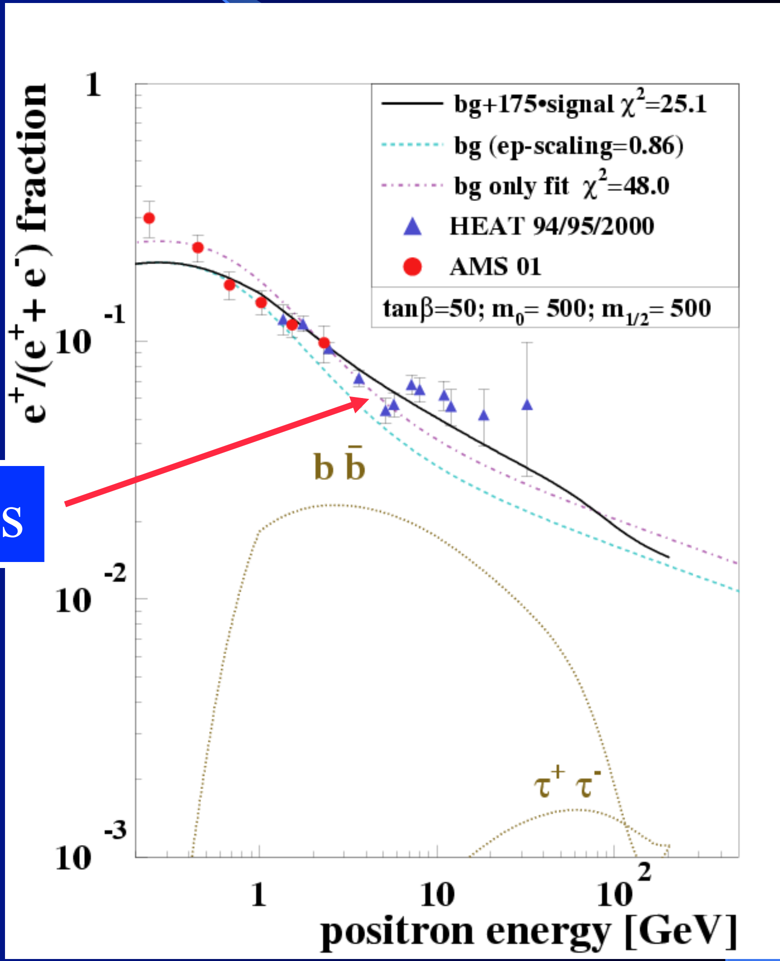
$\tan\beta = 50$

SUSY Search in Space

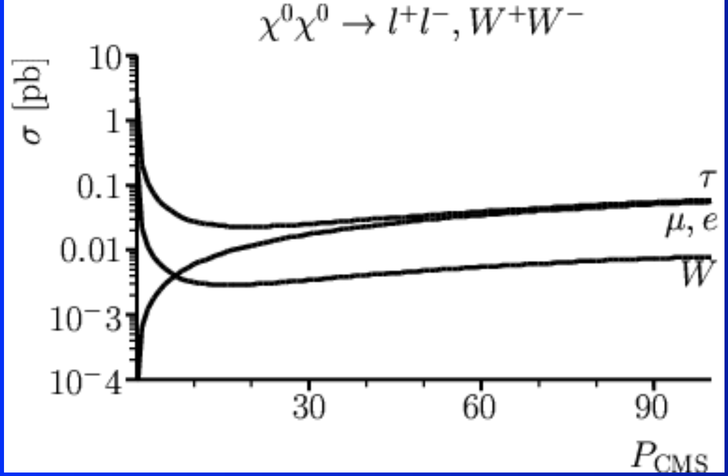
Cosmic ray spectrum at high energies

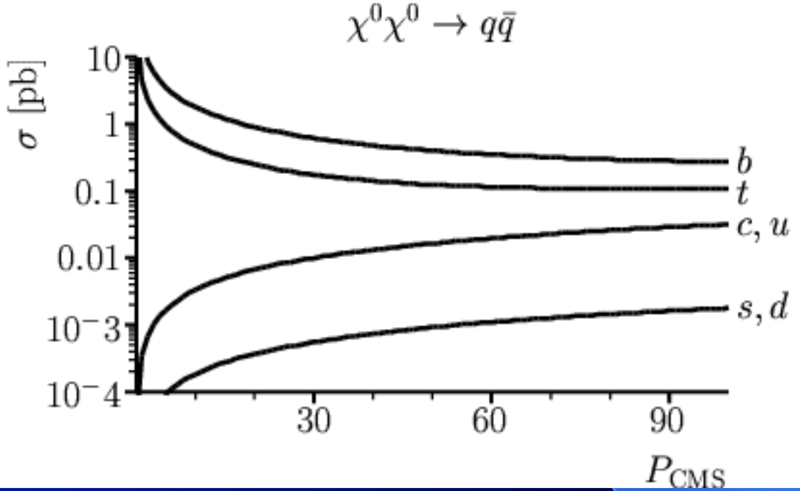


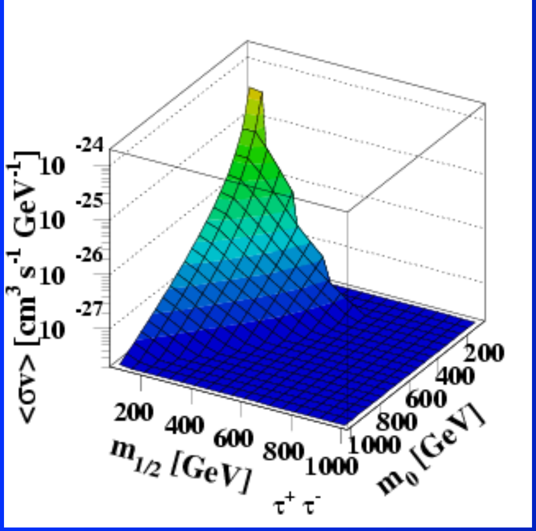
Excess

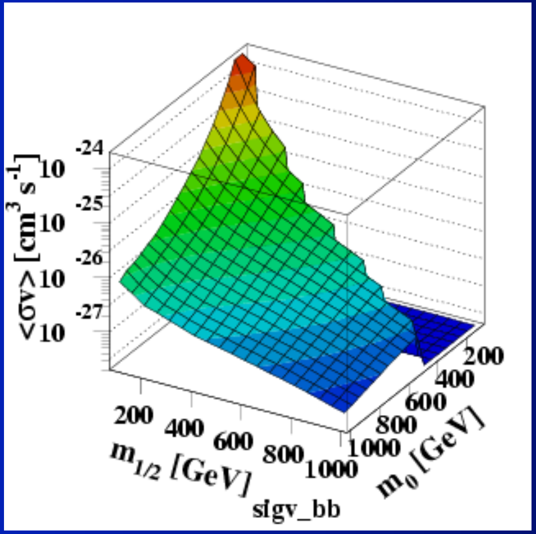


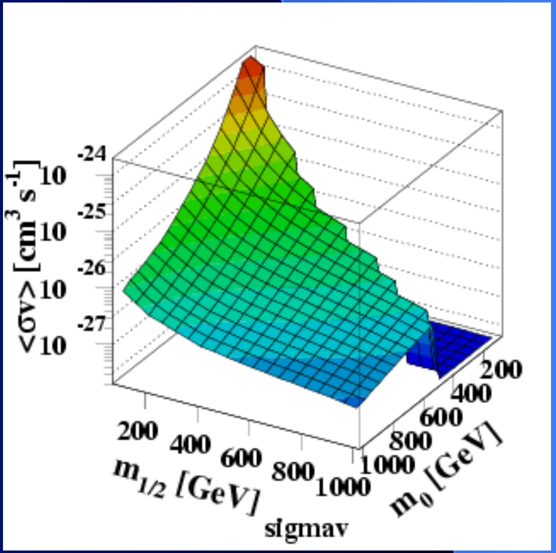
Positrons from Neutralinos of the Dark Matter



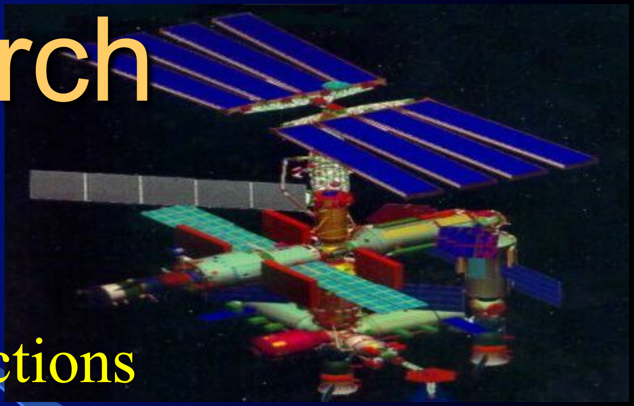




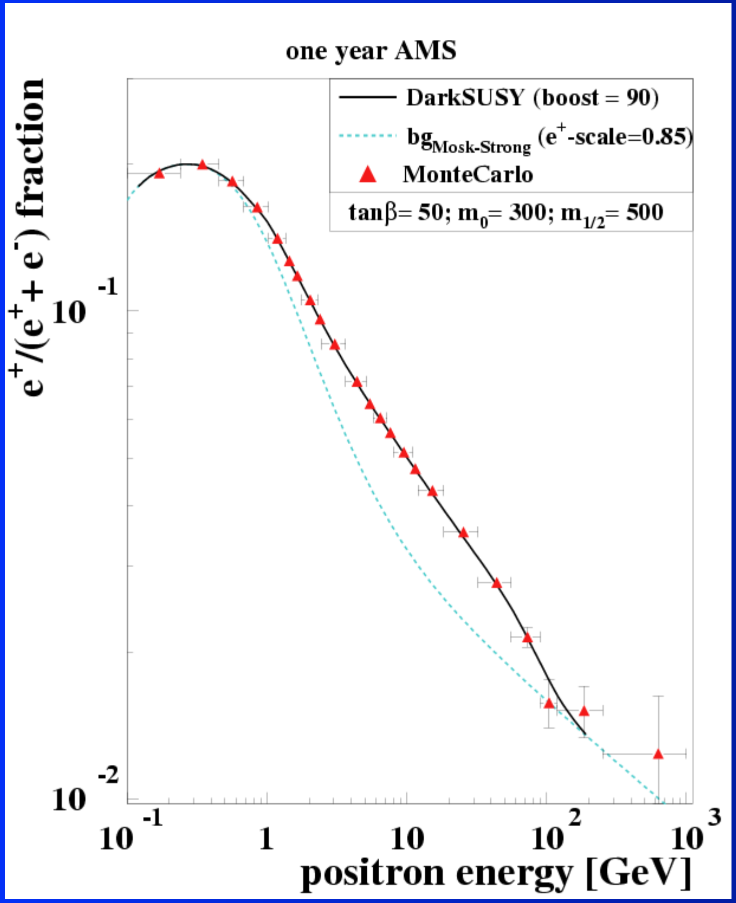


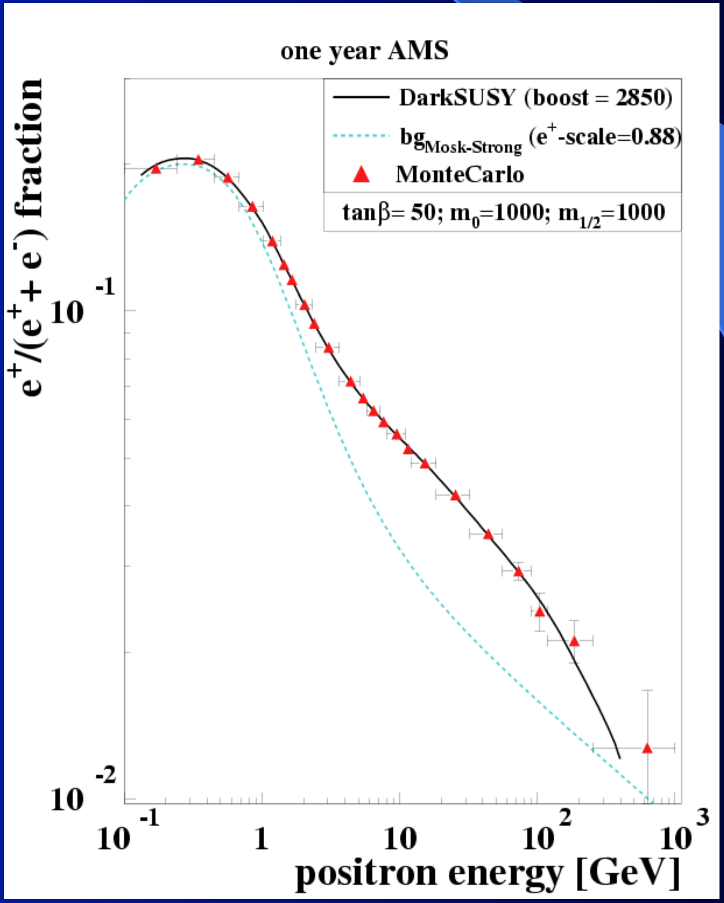


AMS – Antimatter Search in Space at ISS



Will be able to check SUSY Dark matter predictions





Superparticles

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