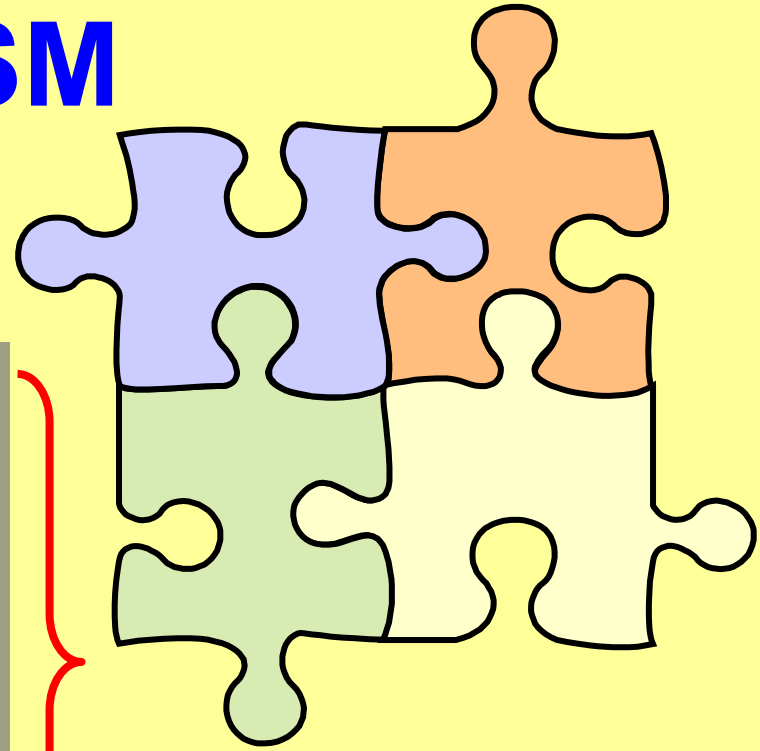


# Constrained MSSM

## Requirements:

- Unification of the gauge couplings
- Radiative EW Symmetry Breaking
- Heavy quark and lepton masses
- Rare decays ( $b \rightarrow s\gamma$ ,  $b \rightarrow \mu\mu$ )
- Anomalous magnetic moment of muon
- LSP is neutral
- Amount of the Dark Matter
- Experimental limits from direct search

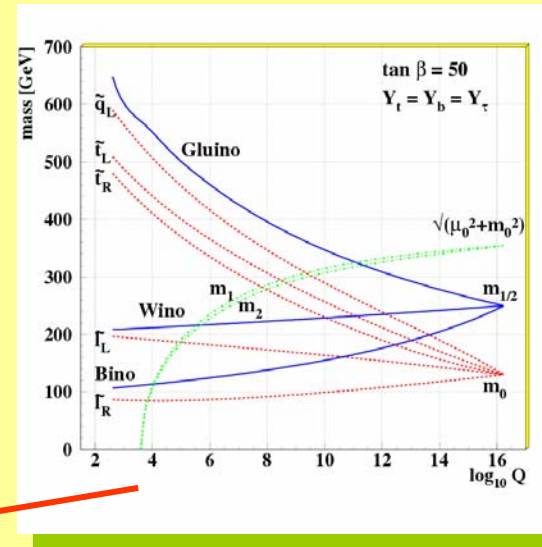
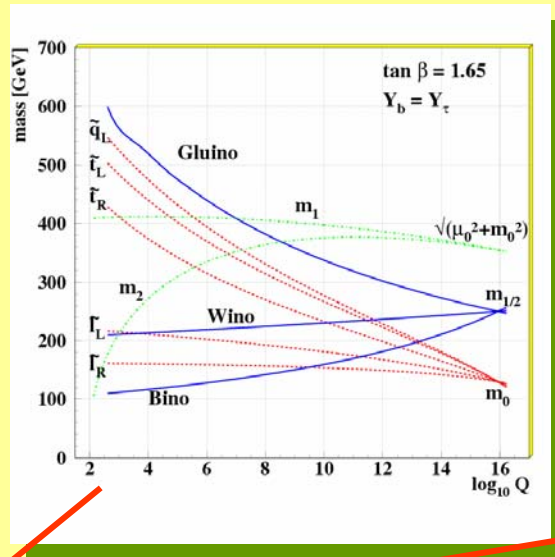


$A_0, m_0, M_{1/2}, \mu, \tan \beta$

Allowed region  
in the parameter  
space of the MSSM

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

# Radiative EW Symmetry Breaking



$$\frac{M_Z^2}{2} = -\mu^2 + \frac{m_{H_1}^2 - m_{H_2}^2 \tan^2 \beta}{\tan^2 \beta - 1}$$

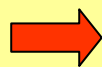


$\mu^2$

For given  $\tan \beta$   
 $m_0$  and  $m_{1/2}$

$m_{H_1} \sim m_{H_2} \sim m_0 \sim 1 \text{ TeV}$

Soft SUSY parameters



$\mu \sim 1 \text{ TeV}$

Hard SUSY parameter

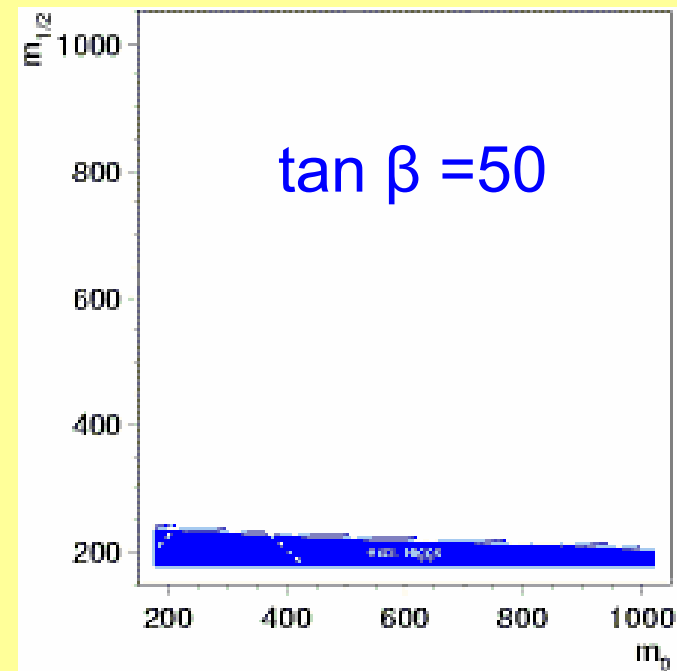
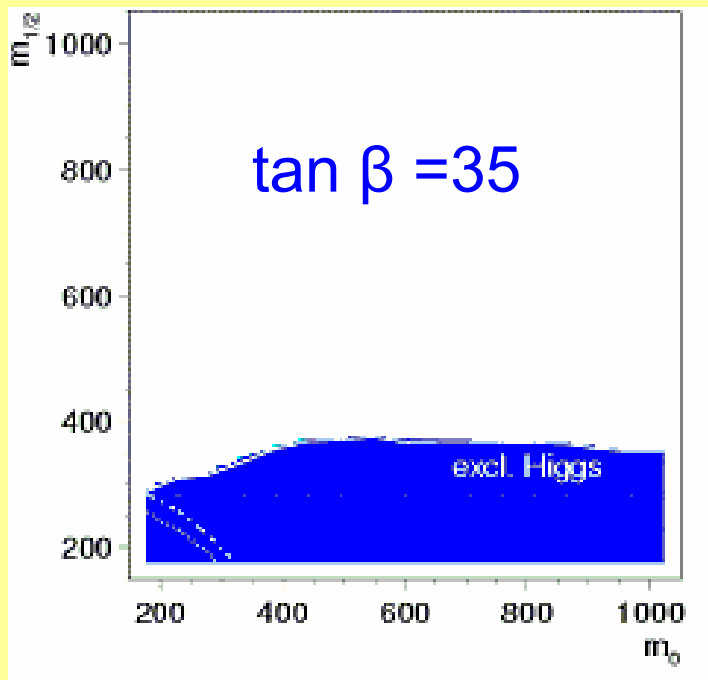
$\mu$  - problem

# Constrained MSSM (Choice of constraints)

Experimental lower limits on Higgs and superparticle masses

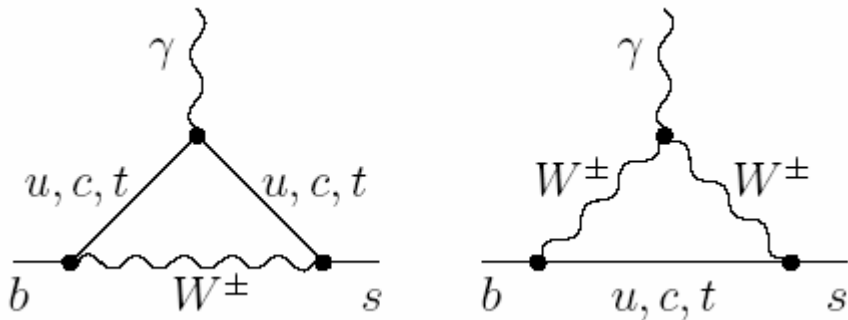
Regions excluded by Higgs experimental limits provided by LEP2

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

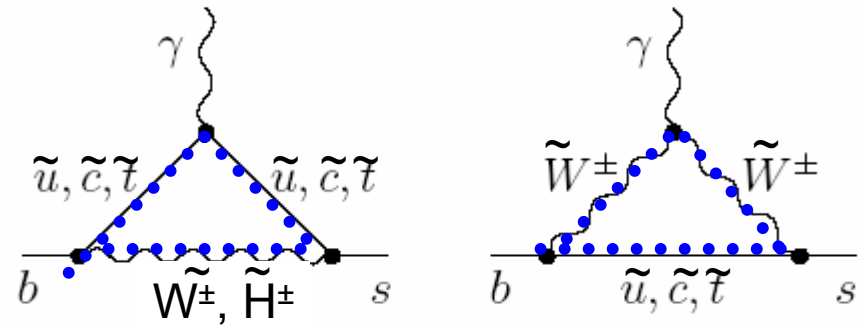


# B → s γ decay rate

## Standard Model



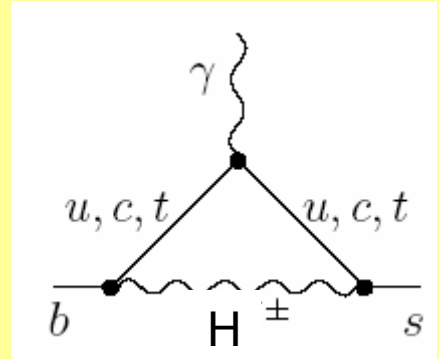
## MSSM



SM:  $\mathcal{B}(B \rightarrow X_s \gamma) = (3.28 \pm 0.33) \times 10^{-4}$ .

## MSSM

$$\mathcal{BR}(b \rightarrow s \gamma)|_{\chi^\pm} \propto \mu A_t \tan \beta f(m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\tilde{\chi}^+}) \frac{m_b}{v(1 + \Delta m_b)}$$



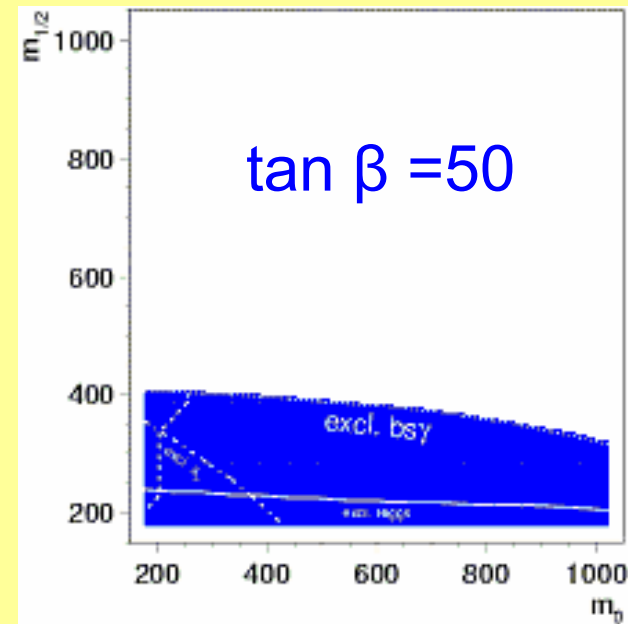
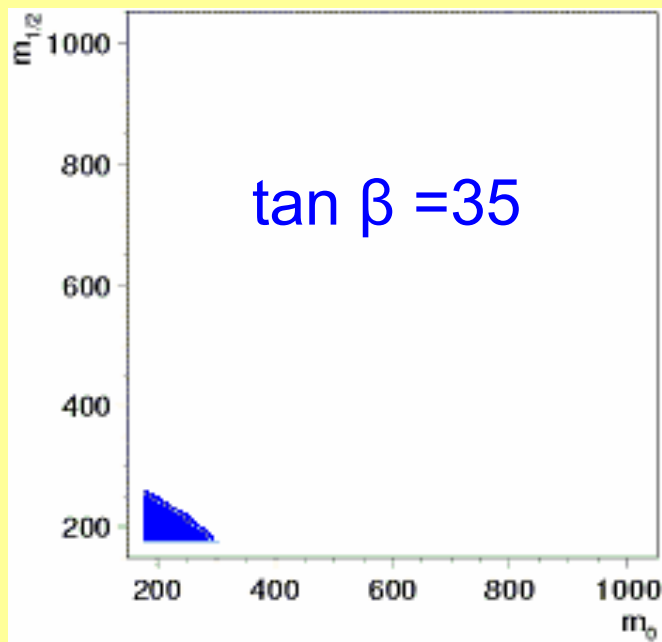
Experiment  $\mathcal{B}(B \rightarrow X_s \gamma) = (3.43 \pm 0.36) \cdot 10^{-4}$

# Constrained MSSM (Choice of constraints)

Data on rare processes branching ratios

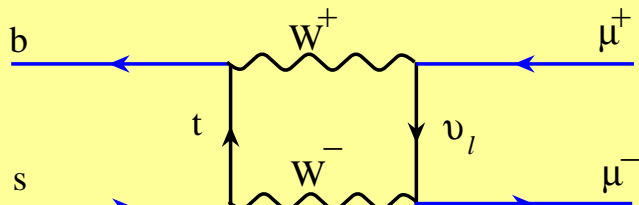
$$B(B \rightarrow X_s \gamma) = (3.43 \pm 0.36) \cdot 10^{-4}$$

Regions excluded by experimental limits (for large  $\tan\beta$ )



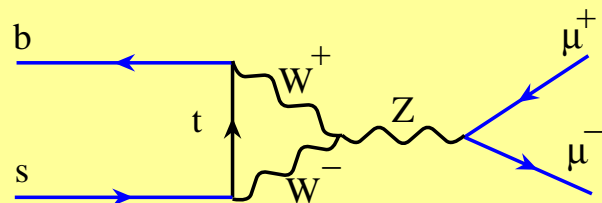
# Rare Decay $B_s \rightarrow \mu^+ \mu^-$

SM

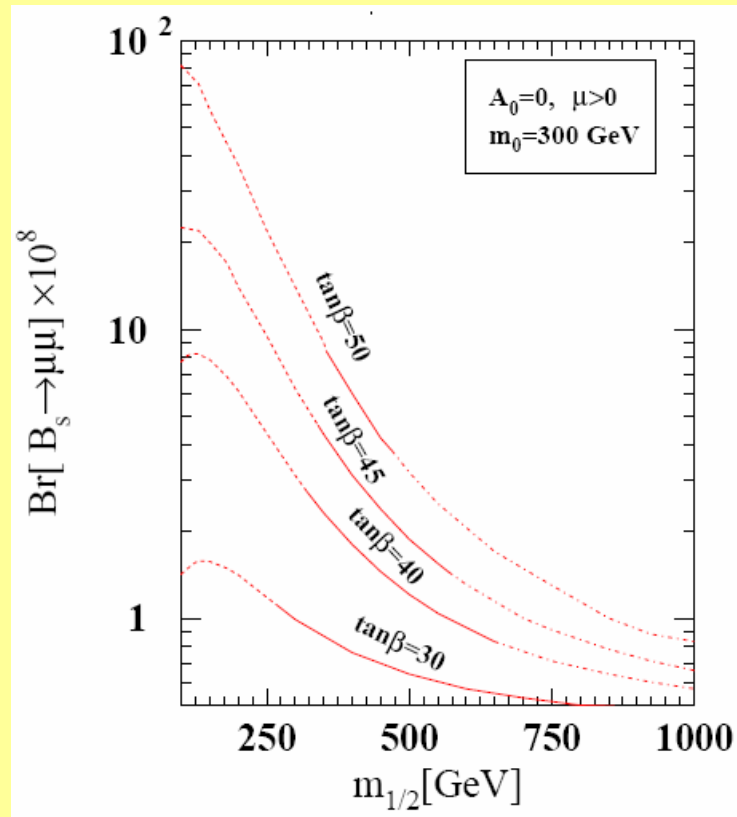
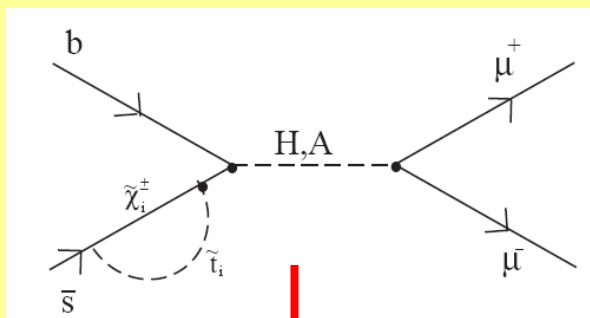


SM:  $\text{Br} = 3.5 \cdot 10^{-9}$

Ex:  $< 4.5 \cdot 10^{-8}$



Main SUSY contribution



$\text{Br}[B_s \rightarrow \mu^+ \mu^-]$

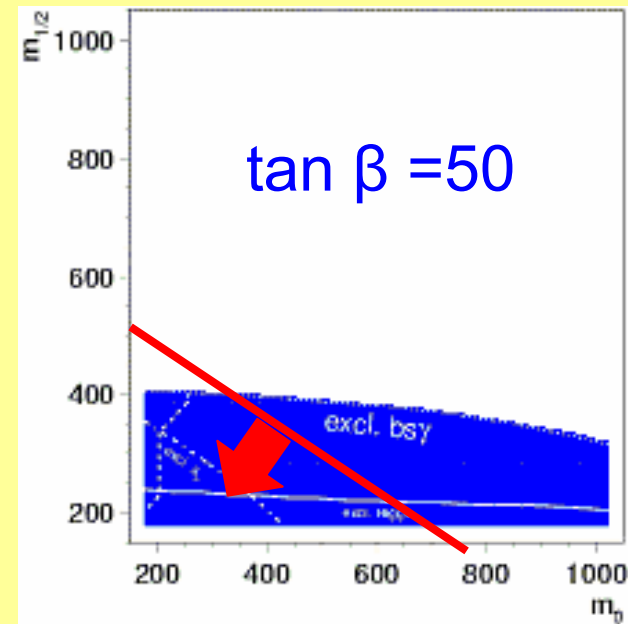
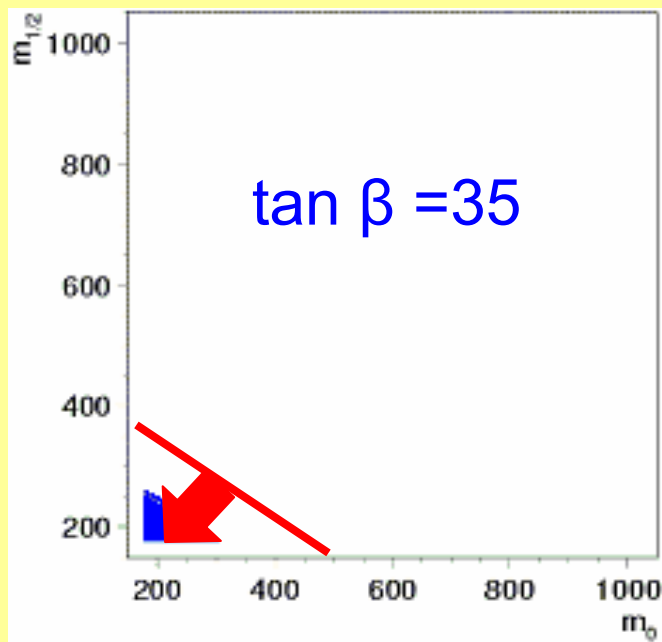
$$\sim \left| \frac{G_F \alpha}{\sqrt{2} \pi} V_{tb} V_{ts}^* \left( \frac{\tan^3 \beta}{4 \sin^2 \theta_W} \right) \left( \frac{m_b m_\mu m_t \mu}{M_W^2 M_A^2} \right) \frac{\sin 2\theta_{\tilde{t}}}{2} \left( \frac{m_{\tilde{t}_1}^2 \log \left[ \frac{m_{\tilde{t}_1}^2}{\mu^2} \right]}{\mu^2 - m_{\tilde{t}_1}^2} - \frac{m_{\tilde{t}_2}^2 \log \left[ \frac{m_{\tilde{t}_2}^2}{\mu^2} \right]}{\mu^2 - m_{\tilde{t}_2}^2} \right) \right|^2$$

# Constrained MSSM (Choice of constraints)

Data on rare processes branching ratios

$$B(Bs \rightarrow \mu^+ \mu^-) < 3.7 \cdot 10^{-7}$$

Regions excluded by experimental limits (for large  $\tan\beta$ )



# Anomalous magnetic moment

$$a_{\mu}^{exp} = 11\,659\,202(14)(6) \cdot 10^{-10}$$

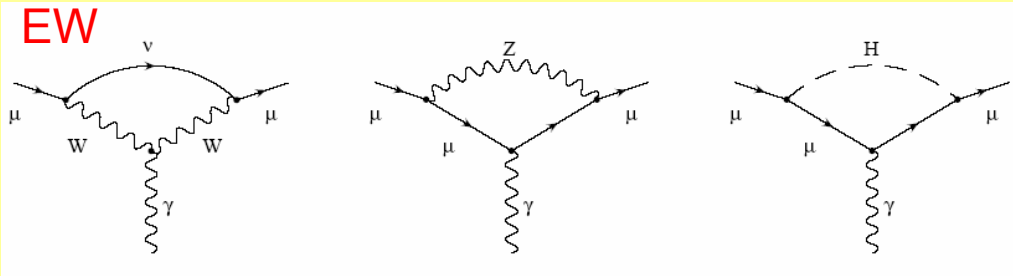
$$a_{\mu}^{SM} = 11\,659\,159.6(6.7) \cdot 10^{-10}$$

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

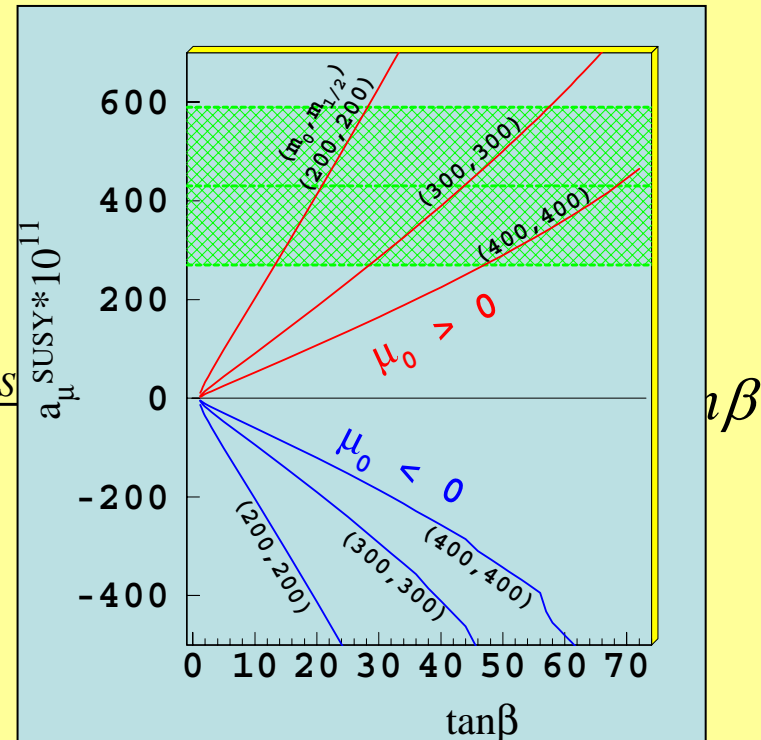
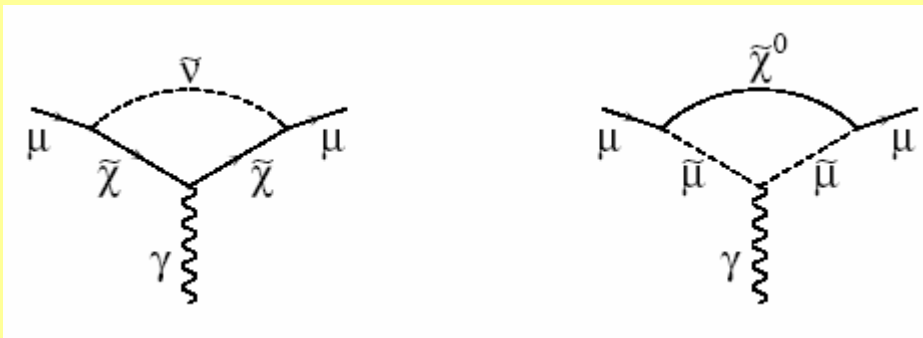
$$a_{\mu}^{QED} = 11\,658\,470.56(0.29) \cdot 10^{-10}$$

$$a_{\mu}^{weak} = 15.1(0.4) \cdot 10^{-10}$$

$$a_{\mu}^{hadr} = 673.9(6.7) \cdot 10^{-10}$$



$$|a_{\mu}^{SUSY}| \simeq \frac{\alpha(M_Z)}{8\pi \sin^2 \theta_W} \frac{m_{\mu}^2}{M_{SUSY}^2} \tan \beta \left(1 - \frac{4\alpha}{\pi} \log \frac{M_{SUSY}}{m_{\mu}}\right)$$



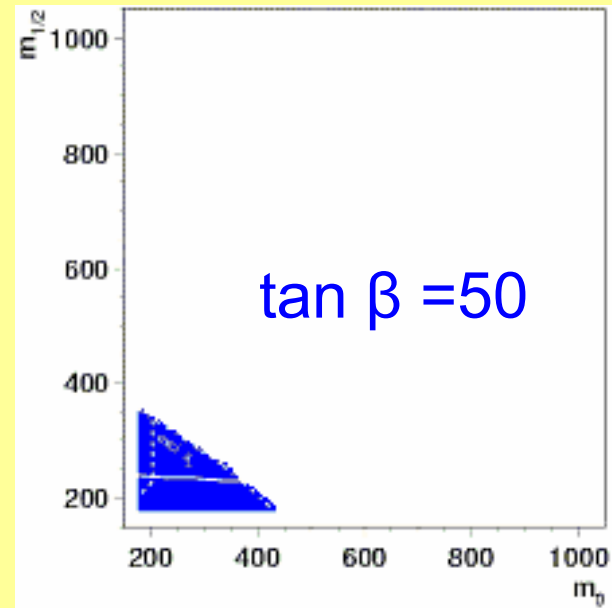
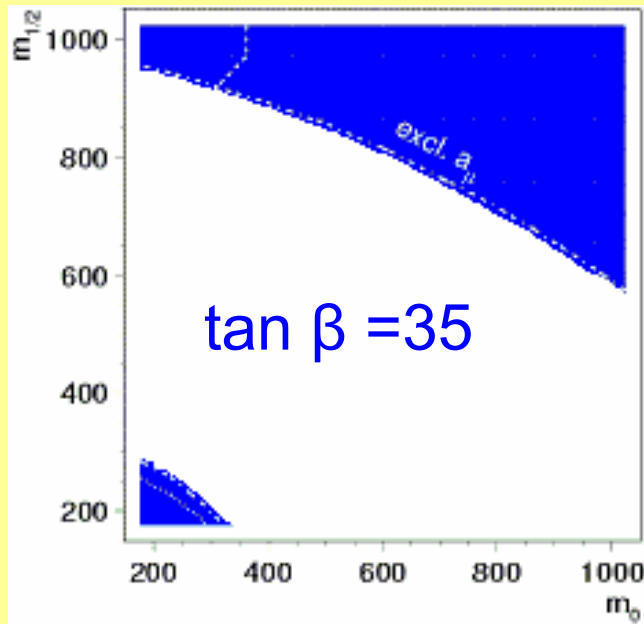


# Constrained MSSM (Choice of constraints)

Muon anomalous magnetic moment

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

Regions excluded by muon amm constraint

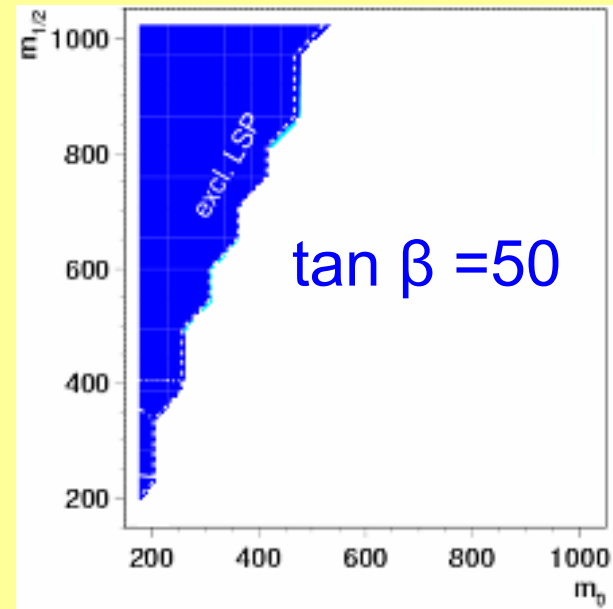
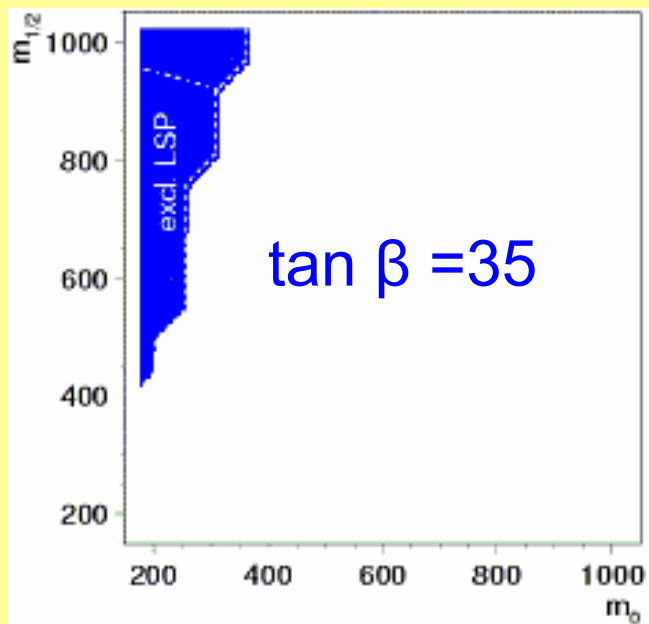


# Constrained MSSM (Choice of constraints)

The lightest supersymmetric particle (LSP) is neutral.

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

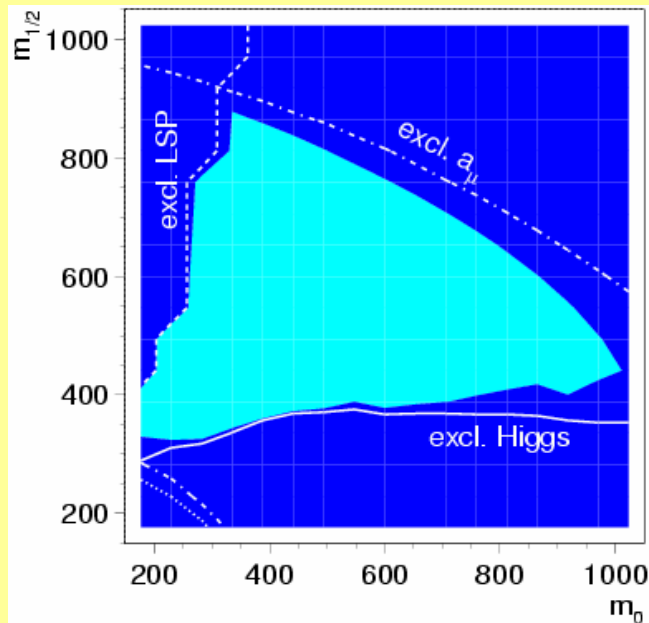
Regions excluded by LSP constraint



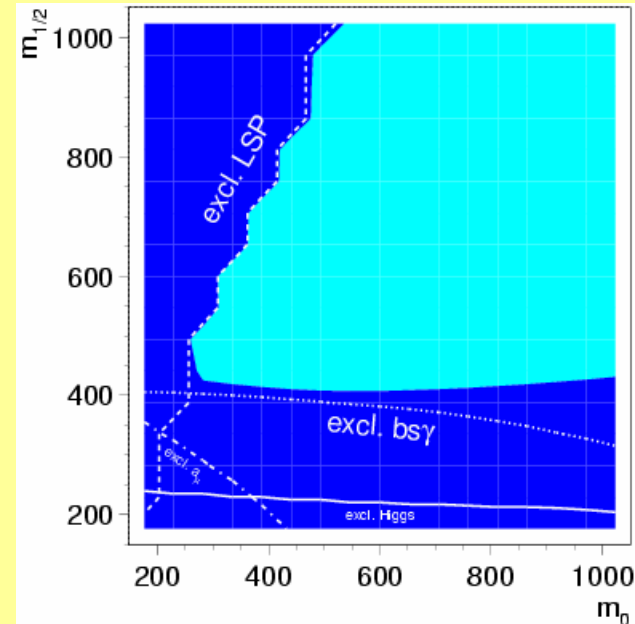
# Favoured regions of parameter space

Pre-WMAP allowed regions in the parameter space.

From the Higgs searches  $\tan \beta > 4$ , from  $a_\mu$  measurements  $\mu > 0$

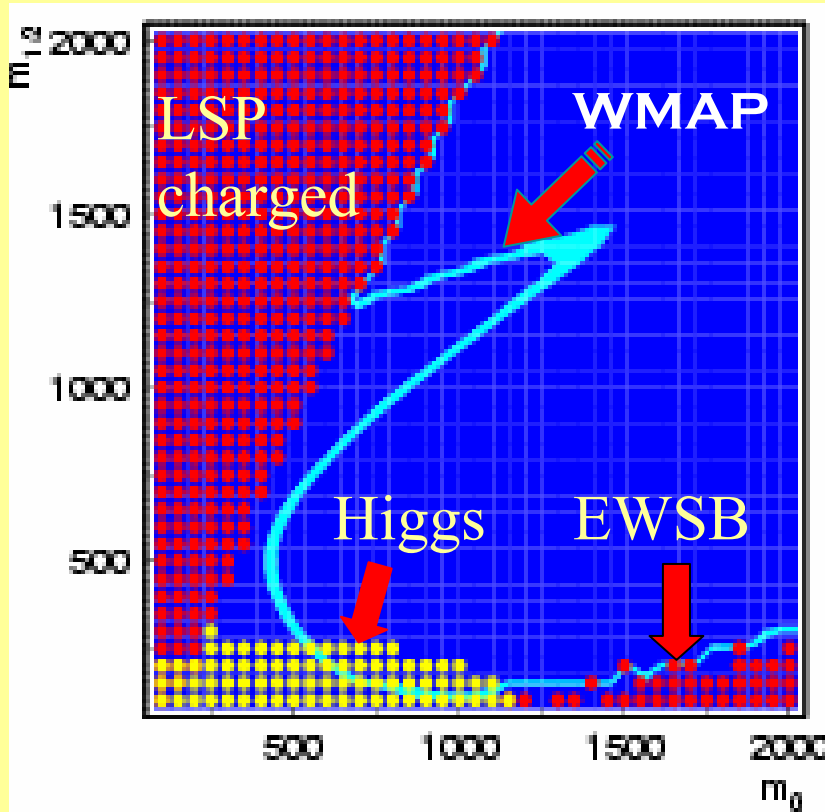


$\tan \beta = 35$



$\tan \beta = 50$

# Allowed regions after WMAP



$$\tan \beta = 50$$

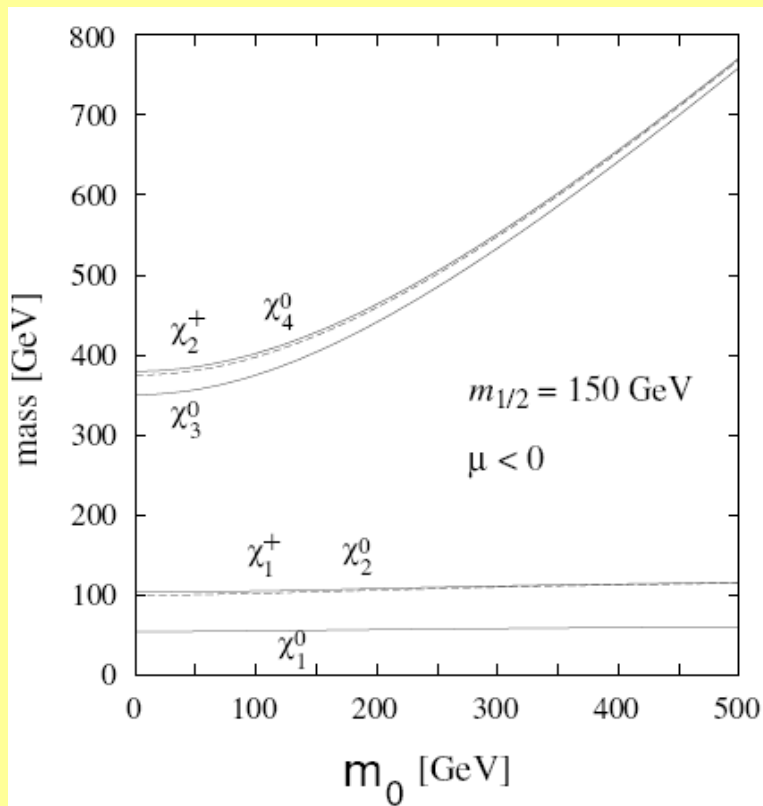
In allowed region one fulfills all the constraints simultaneously and has the suitable amount of the dark matter

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

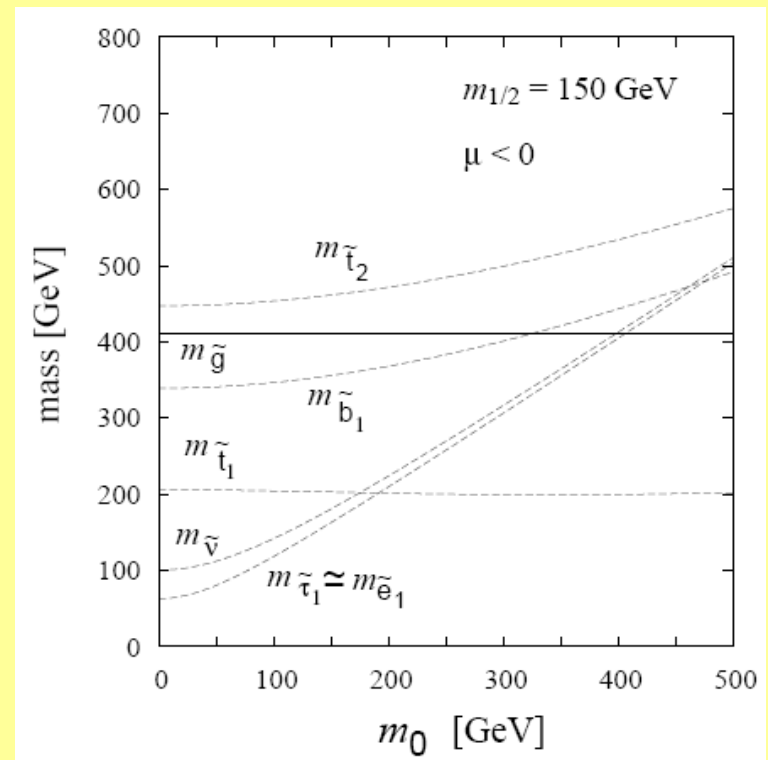
Phenomenology essentially depends on the region of parameter space and has direct influence on the strategy of SUSY searches

# SUSY Masses in MSSM

Gauginos+Higgsinos



Squarks and Sleptons



# Mass Spectrum in CMSSM

(Sample)

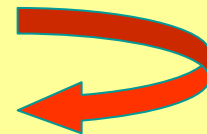
SUSY Masses in GeV

Fitted SUSY Parameters

Fitted SUSY Parameters			Symbol	Low tan $\beta$	High tan $\beta$
Symbol	Low tan $\beta$	High tan $\beta$	$\tilde{\chi}_1^0(\tilde{B}), \tilde{\chi}_2^0(\tilde{W}^3)$	214, 413	64, 113
tan $\beta$	1.71	52.2	$\tilde{\chi}_3^0(\tilde{H}_1), \tilde{\chi}_4^0(\tilde{H}_2)$	1028, 1016	194, 229
$m_0$	200	1500	$\tilde{\chi}_1^\pm(\tilde{W}^\pm), \tilde{\chi}_2^\pm(\tilde{H}^\pm)$	413, 1026	110, 130
$m_{1/2}$	500	170	$\tilde{g}$	1155	516
$\mu(0)$	1084	558	$\tilde{e}_L, \tilde{e}_R$	303, 270	1497, 1499
A(0)	0	0	$\tilde{\nu}_L$	290	1495
$1/\alpha_{\text{GUT}}$	24.8	24.8	$\tilde{q}_L, \tilde{q}_R$	1028, 936	1519, 1523
$M_{\text{GUT}}$	$1.6 \cdot 10^{16}$	$1.6 \cdot 10^{16}$	$\tilde{\tau}_1, \tilde{\tau}_2$	279, 403	1305, 1288
			$\tilde{b}_1, \tilde{b}_2$	953, 1010	1309, 1152
			$\tilde{t}_1, \tilde{t}_2$	727, 1017	906, 1046
			h, H	95 1344	115 372
			A, H $^\pm$	1340, 1344	372, 383

# The Lightest Superparticle

		<u>property</u>	<u>signature</u>
• <u>Gravity mediation</u>	LSP = $\tilde{\chi}_1^0$	stable	jets/leptons + $\cancel{E}_T$
• <u>Gauge mediation</u>	LSP = $\tilde{G}$	stable	$\cancel{E}_T$
	NLSP = $\begin{cases} \tilde{\chi}_1^0 \\ \tilde{l}_R \end{cases}$	$\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}, h \tilde{G}, Z \tilde{G}$ $\tilde{l}_R \rightarrow \tau \tilde{G}$	photons/jets + $\cancel{E}_T$ lepton + $\cancel{E}_T$
• <u>Anomaly mediation</u>	LSP = $\begin{cases} \tilde{\chi}_1^0 \\ \tilde{\nu}_L \end{cases}$	stable stable	lepton + $\cancel{E}_T$
• <u>R-parity violation</u>	LSP is unstable $\rightarrow$ SM particles		
• <u>Modern limit</u>	$M_{LSP} \geq 40 \text{ GeV}$		Rare decays Neutrinoless double $\beta$ decay



# SUSY Dark Matter

Neutralino = SUSY candidate for the cold Dark Matter  
 Neutralino = the Lightest Superparticle (LSP) = WIMP

$$\tilde{\chi}^0 = N_1 \tilde{\gamma} + N_2 \tilde{z} + N_3 \tilde{H}_1^0 + N_4 \tilde{H}_2^0$$

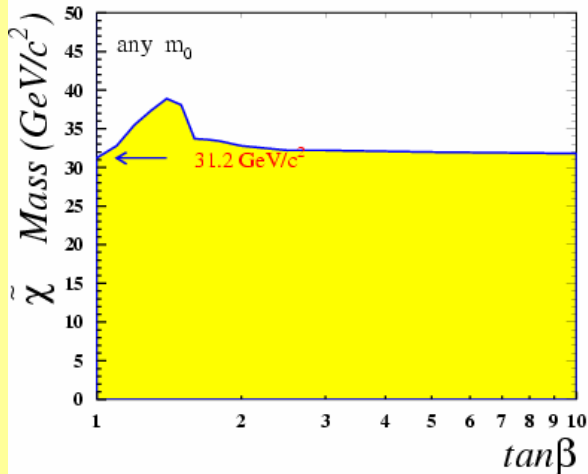
photino

zino

higgsino

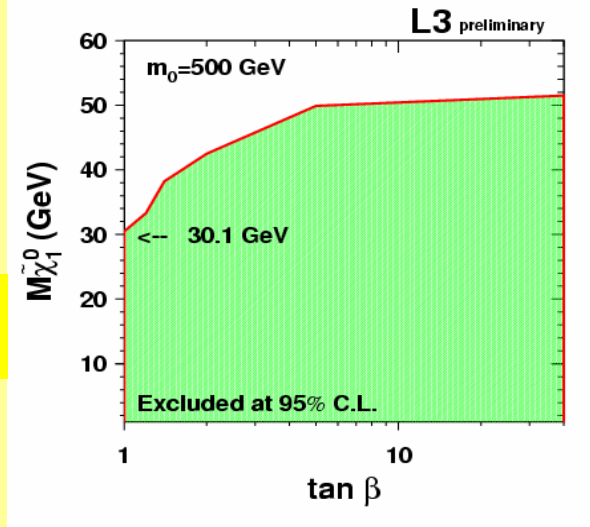
higgsino

Preliminary DELPHI LSP limit at 189 GeV



$$M_{\chi}^{\text{exp}} \geq 40 \text{ GeV}$$

$$M_{\chi}^{\text{theor}} = 40 \div 400 \text{ GeV}$$



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

$$R_p = +1, R_{\tilde{p}} = -1$$



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