SUSY @ LHC

The Challenge

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What comes beyond the SM?

SUSY =
main stream
and main
expectation
at TeV scale

LHC = ultimate
TeV scale
machine to
discover new
physics

What is SUSY?

SUSY is boson-fermion symmetry

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

scalar chiral fermion majorana fermion vector gravitino graviton

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

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

These terms are forbidden in the SM

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

The Usual Particle : R = + 1

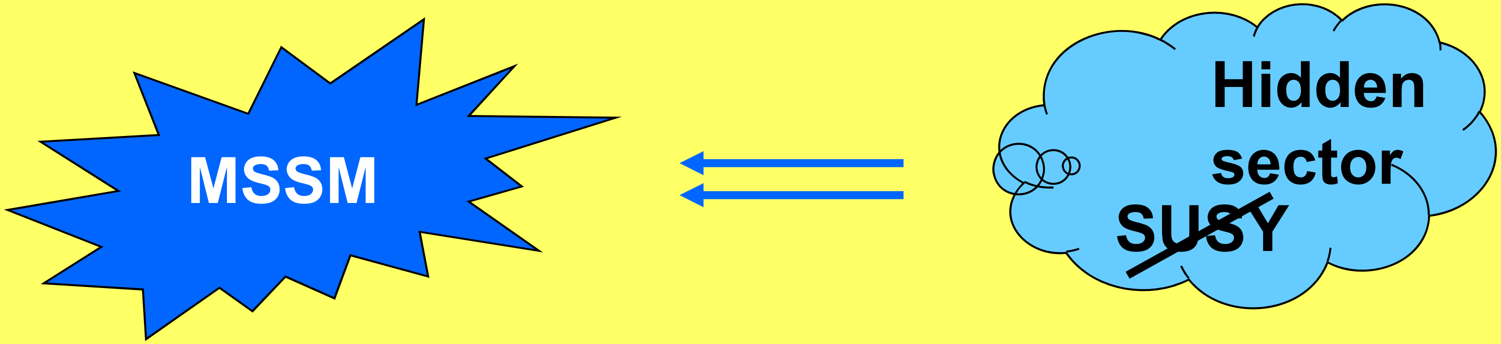
SUSY Particle : R = - 1

B - Baryon Number

L - Lepton Number

S - Spin

MSSM Parameter Space

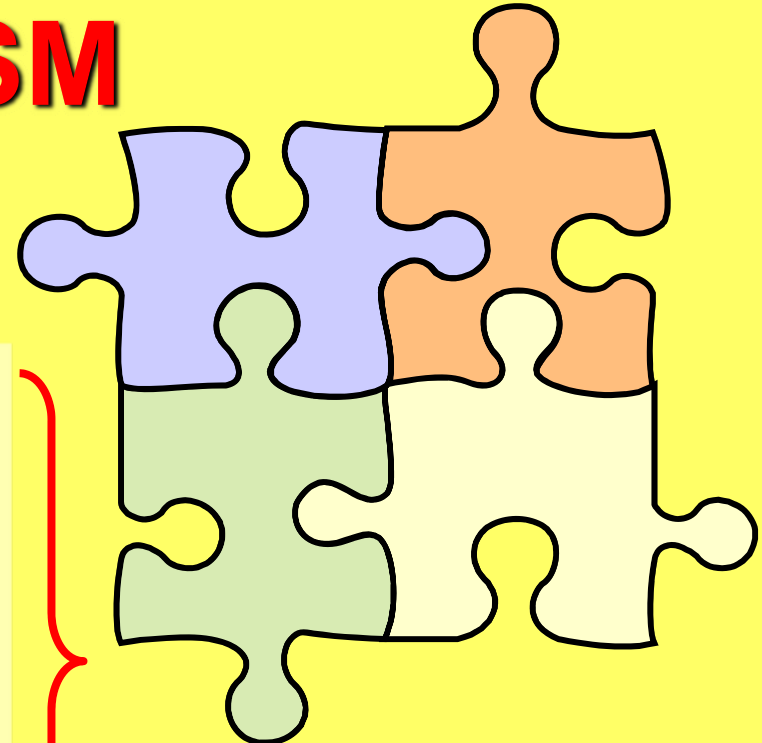


$$-L_{Soft} = A\{y_t Q_L H_2 U_R + y_b Q_L H_1 D_R + y_L L_L H_1 E_R\} + B\mu H_1 H_2 + m_0^2 \sum_i |\varphi_i|^2 + \tfrac{1}{2} M_{1/2} \sum_\alpha \tilde{\lambda}_\alpha \tilde{\lambda}_\alpha$$

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

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

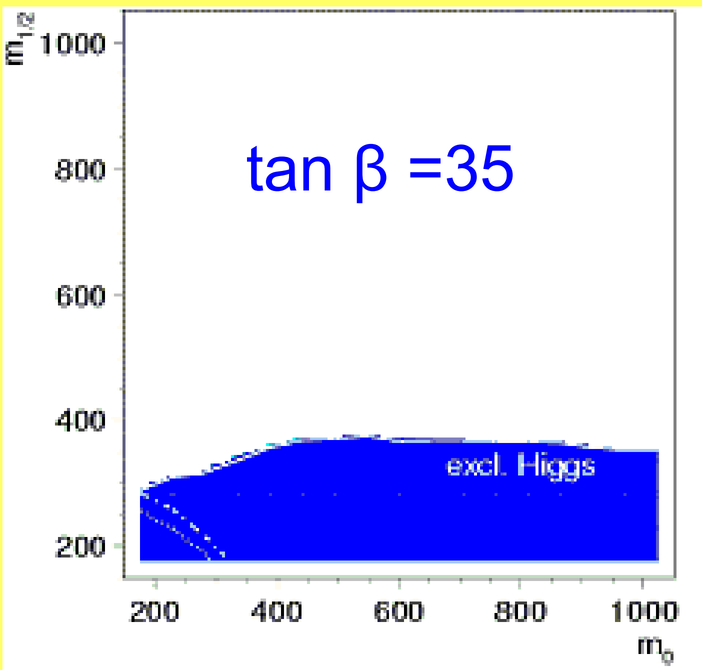
$$100 \text{ GeV} \le m_0, M_{1/2}, \mu \le 2 \text{ TeV}$$
$$-3m_0 \le A_0 \le 3m_0,\ 1 \le \tan\beta \le 70$$

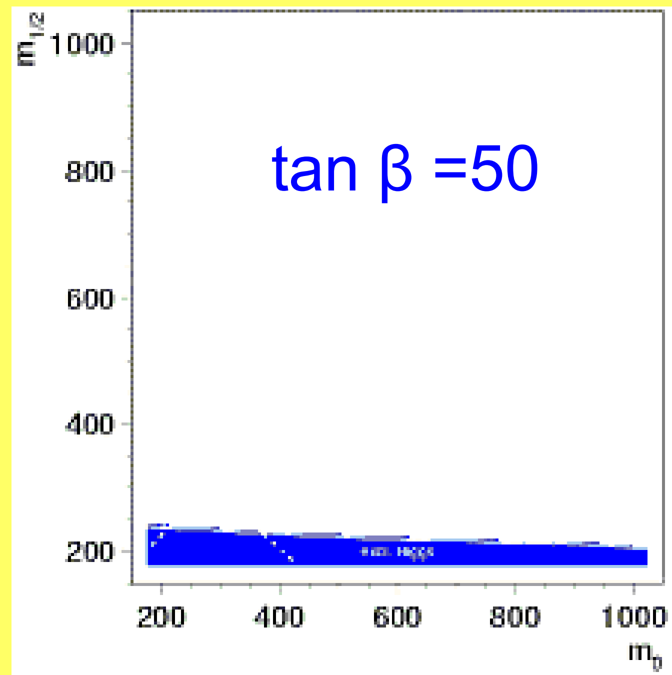
Constrained MSSM (Choice of constraints)

Experimental lower limits on Higgs and superparticle masses

Regions excluded by Higgs experimental limits provided by LEP2

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

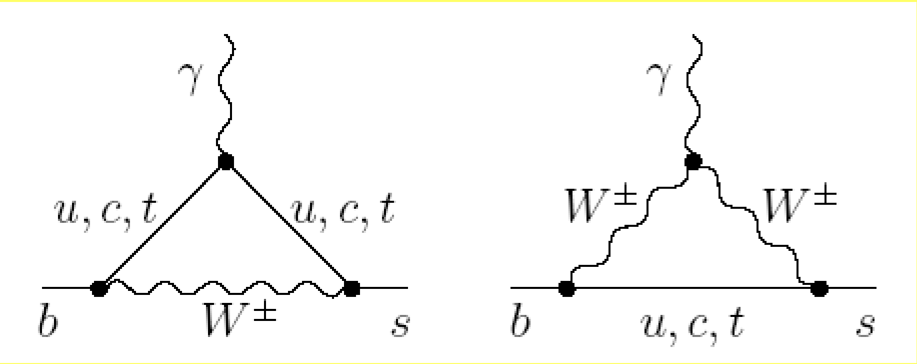


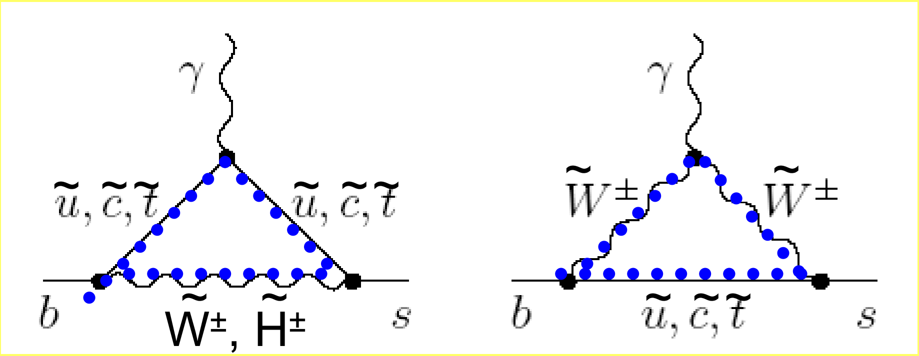


B->s γ decay rate

Standard Model

MSSM

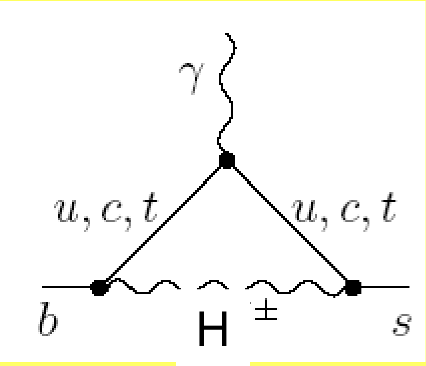




SM: $\mathcal{B}(B \to X_s\gamma) = (3.28 \pm 0.33) \times 10^{-4}$.

MSSM

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



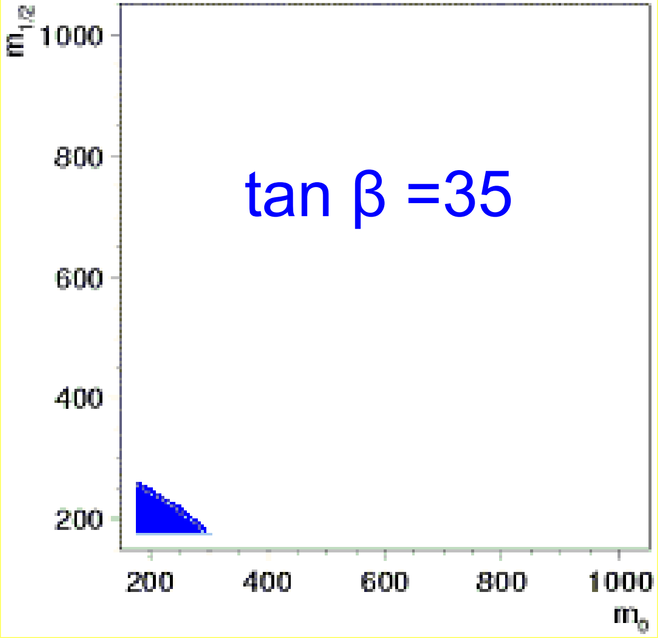
Experiment $B(B \to X_s\gamma) = (3.43 \pm 0.36) \cdot 10^{-4}$

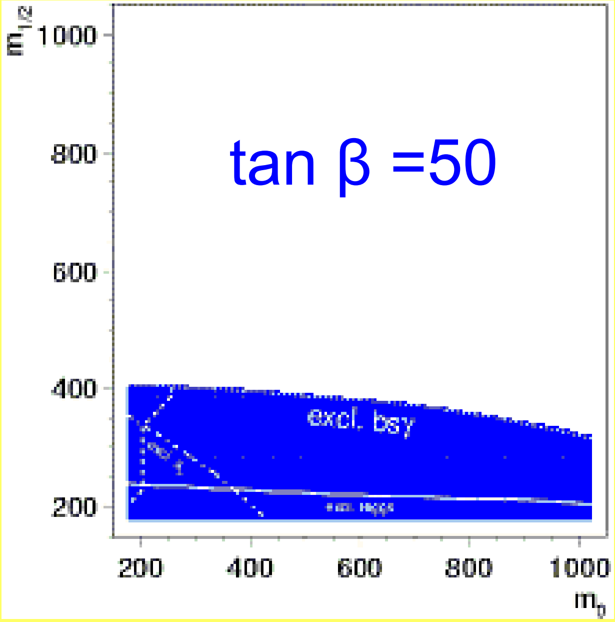
Constrained MSSM (Choice of constraints)

Data on rare processes branching ratios

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

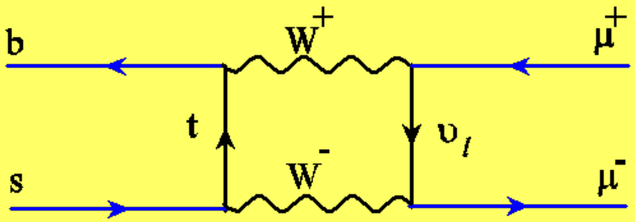
Regions excluded by experimental limits (for large tanβ)

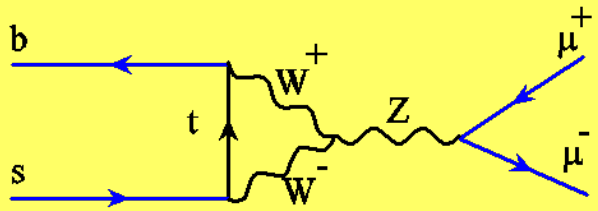




Rare Decay Bs → μ+ μ-

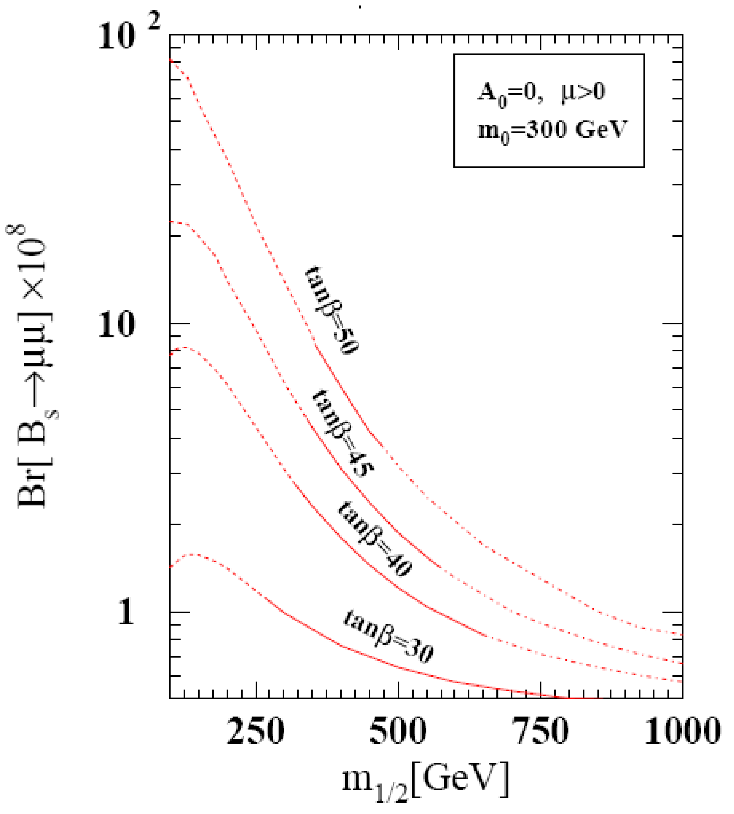
SM



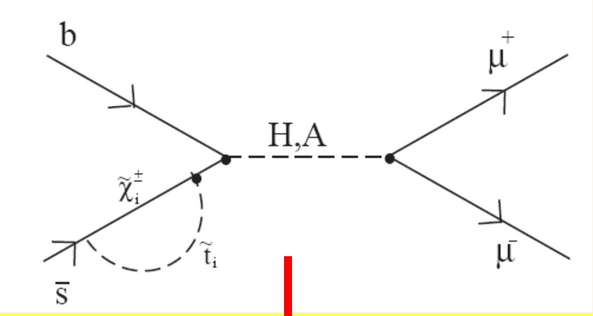


SM: Br=3.5·10^{-9}

Ex: <4.5· 10^{-8}



Main SYSY contribution



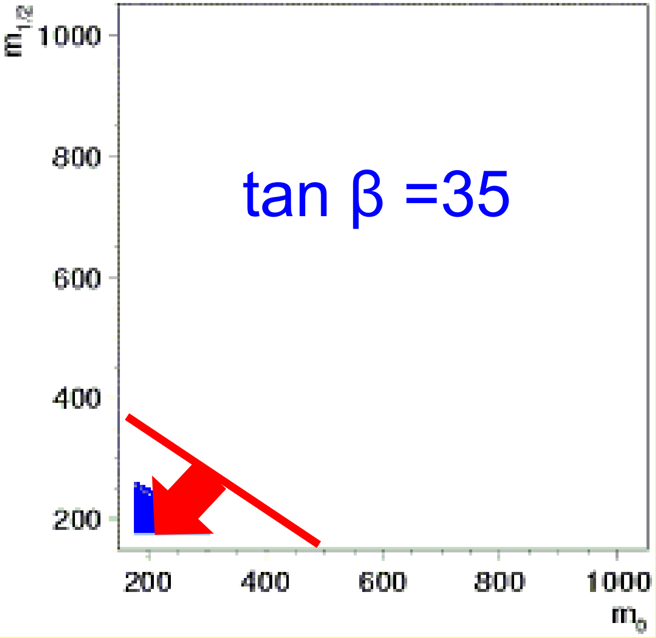
$$Br[B_s \to \mu^+\mu^-] \sim \left| \frac{G_F\alpha}{\sqrt{2}\pi} V_{tb}V_{ts}^* \left(\frac{\tan^3\beta}{4\sin^2\theta_W}\right)\left(\frac{m_b m_\mu m_t \mu}{M_W^2 M_A^2}\right)\frac{\sin 2\theta_{\tilde{t}}}{2}\left(\frac{m_{\tilde{t}_1}^2 \log\left[\frac{m_{\tilde{t}_1}^2}{\mu^2}\right]}{\mu^2 -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

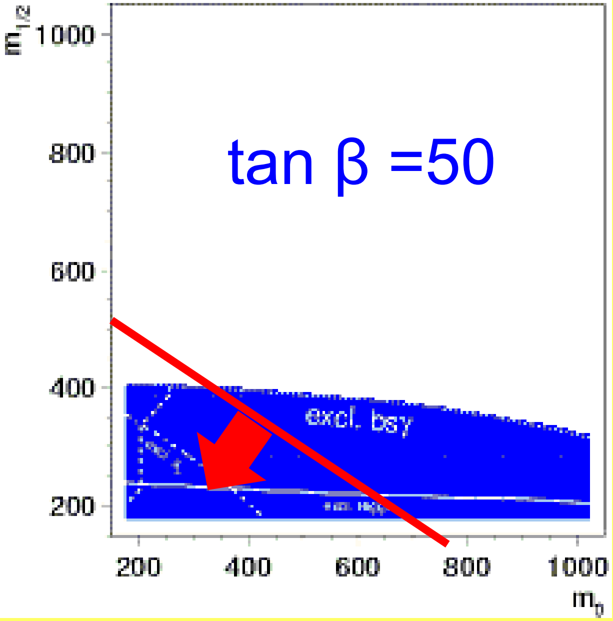
Constrained MSSM (Choice of constraints)

Data on rare processes branching ratios

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

Regions excluded by experimental limits (for large tanβ)



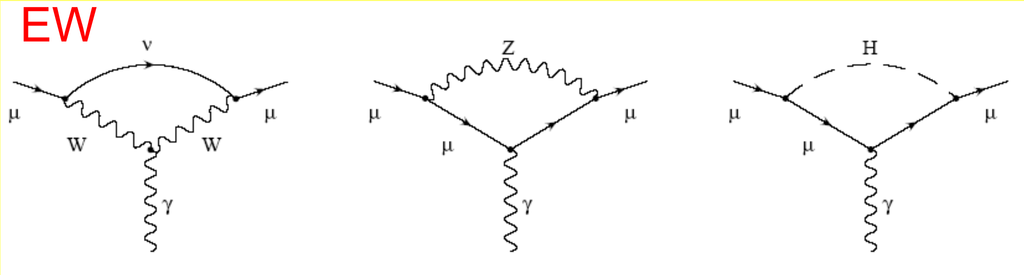


Anomalous magnetic moment

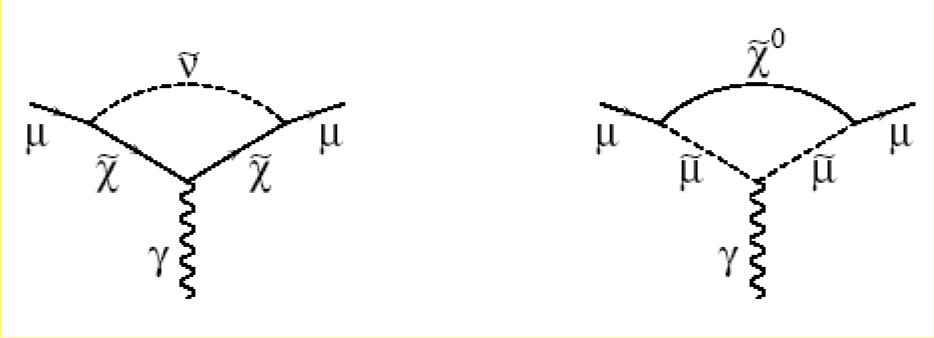
$$a_\mu^{exp} = 11\,659\,202\,(14)(6)\cdot 10^{-10}$$
$$a_\mu^{SM} = 11\,659\,159.6\,(6.7)\cdot 10^{-10}$$

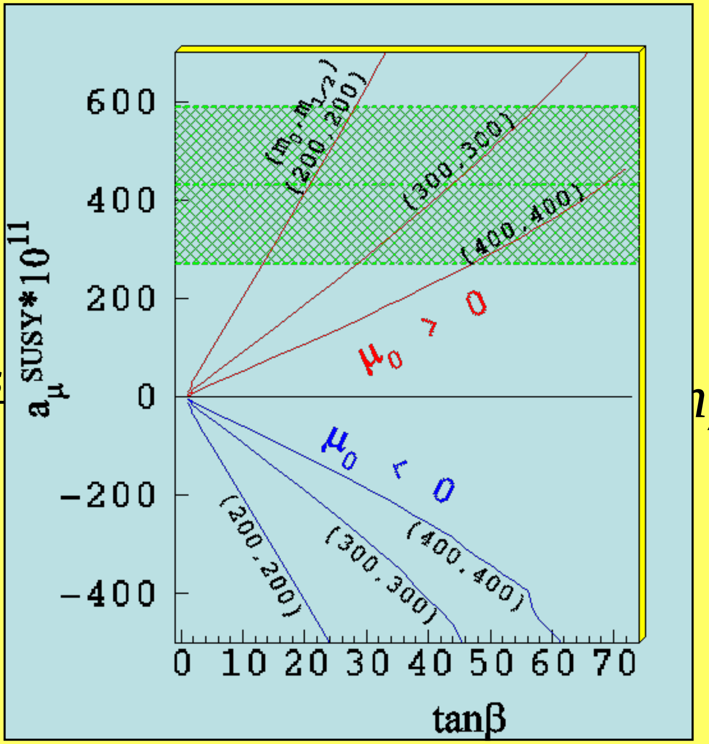
$$a_\mu^{exp} - a_\mu^{SM} = (\,27\pm10\,)\cdot 10^{-10}$$

$$a_\mu^{QED} = 11\,658\,470.56\,(0.29)\cdot 10^{-10}$$
$$a_\mu^{weak} = 15.1\,(0.4)\cdot 10^{-10}$$
$$a_\mu^{hadr} = 673.9\,(6.7)\cdot 10^{-10}$$



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



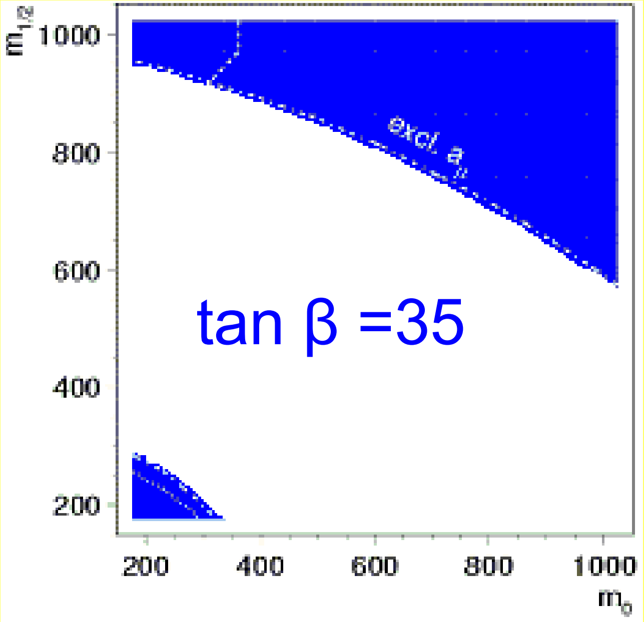


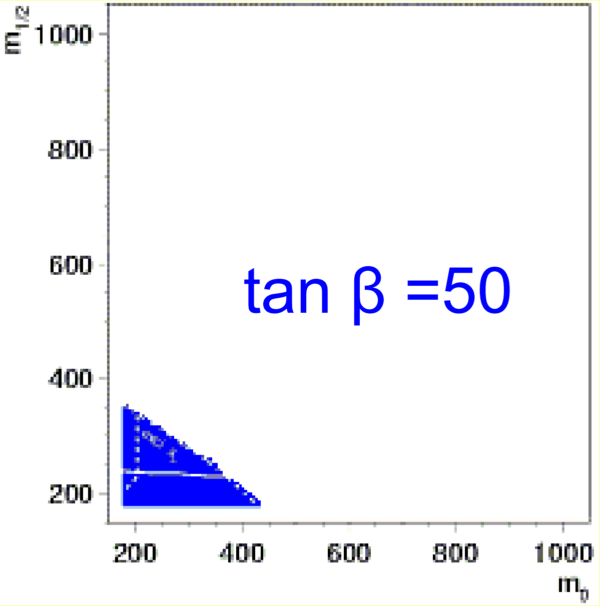
Constrained MSSM (Choice of constraints)

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



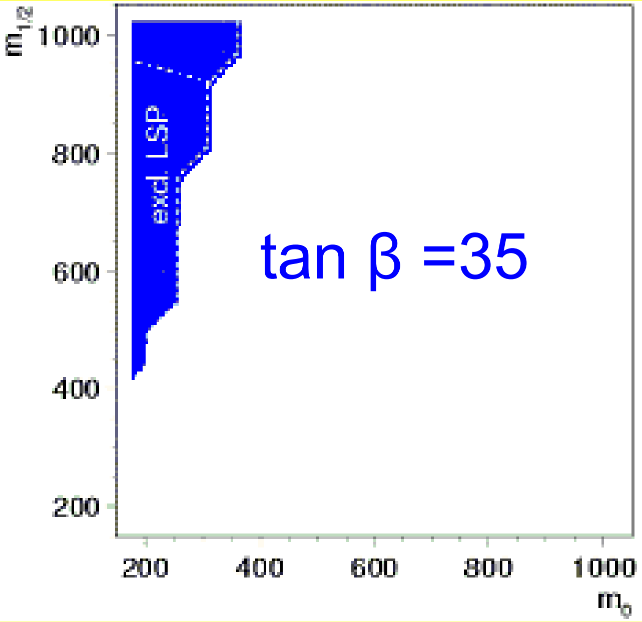


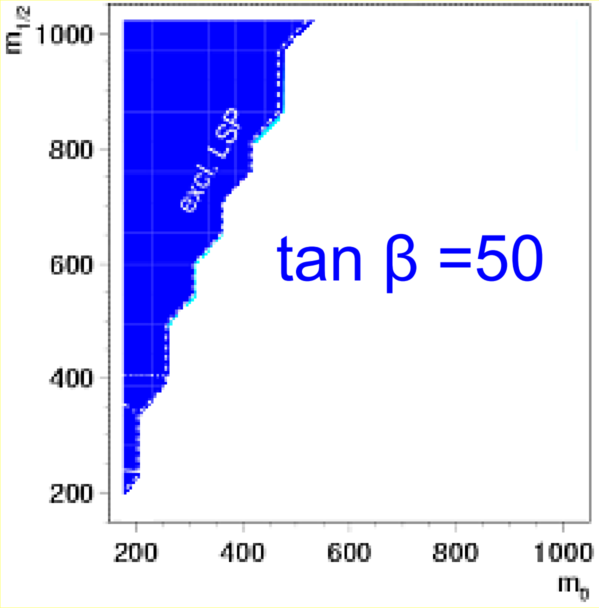
Constrained MSSM (Choice of constraints)

The lightest supersymmetric particle (LSP) is neutral.

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

Regions excluded by LSP constraint

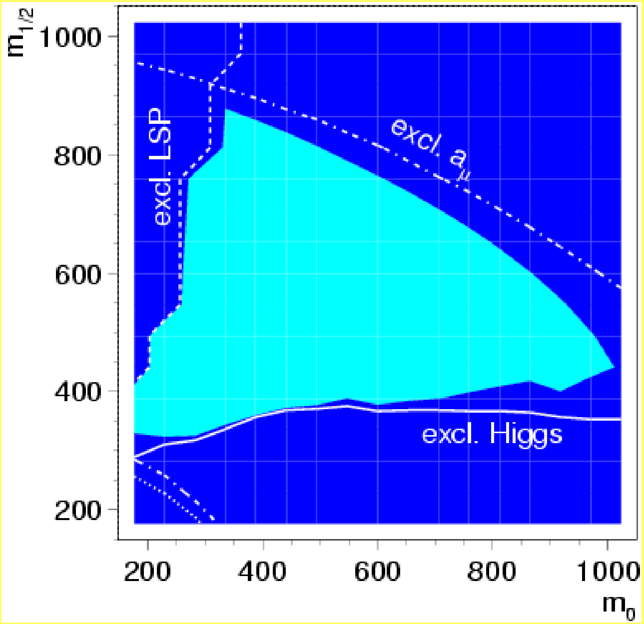




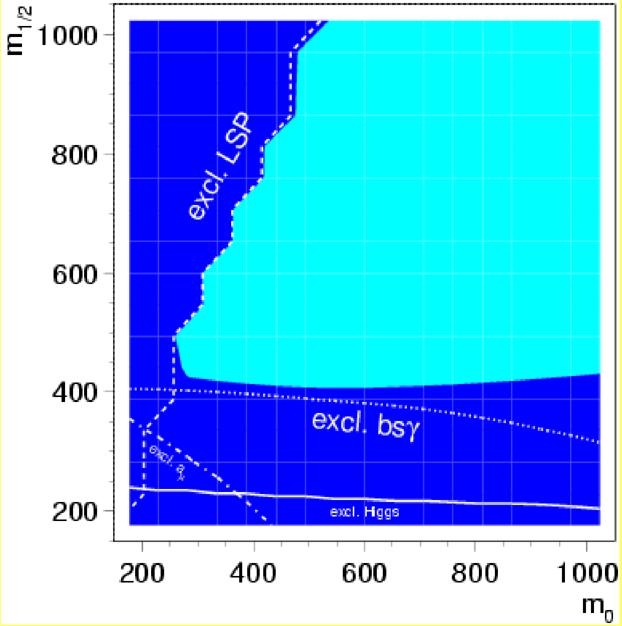
Favoured regions of parameter space

Pre-WMAP allowed regions in the parameter space.

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



tan β =35

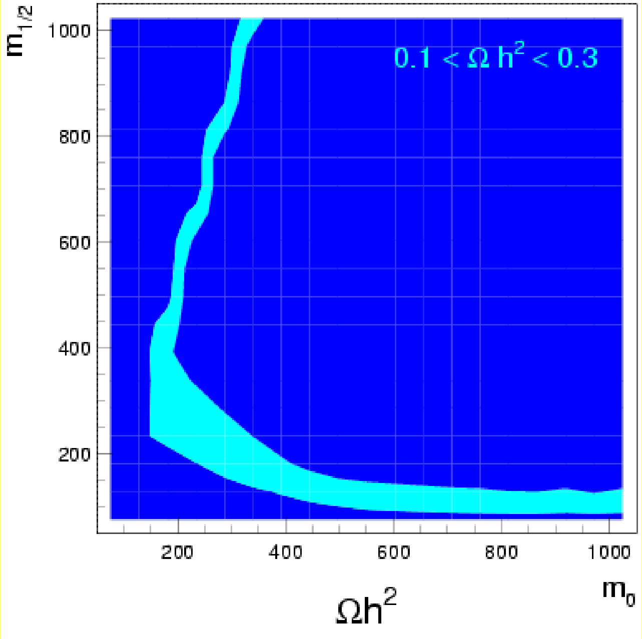


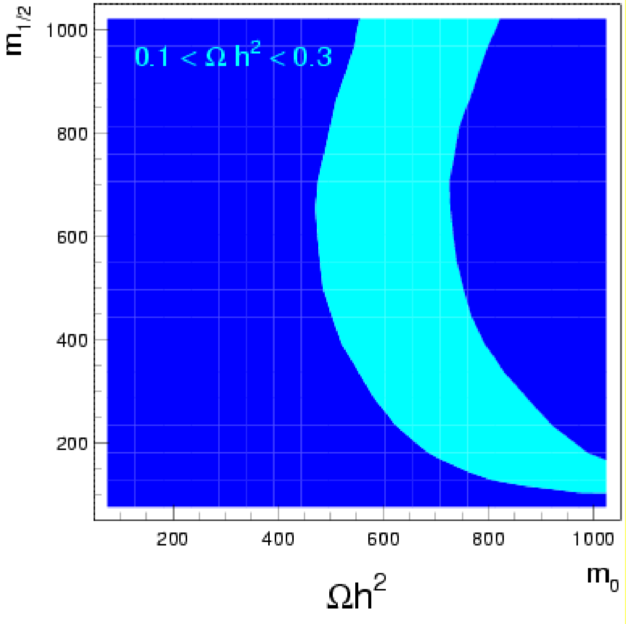
tan β =50

Favoured regions of parameter space

Pre-WMAP dark matter constraint

$0.1 < \Omega h^2 < 0.3$

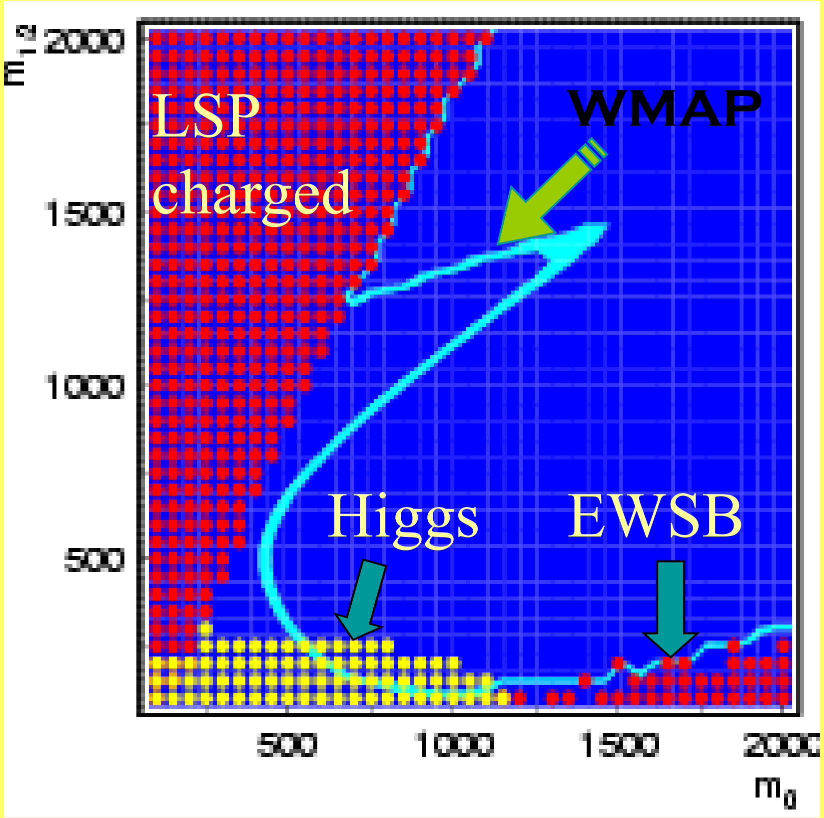




tan β =35

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

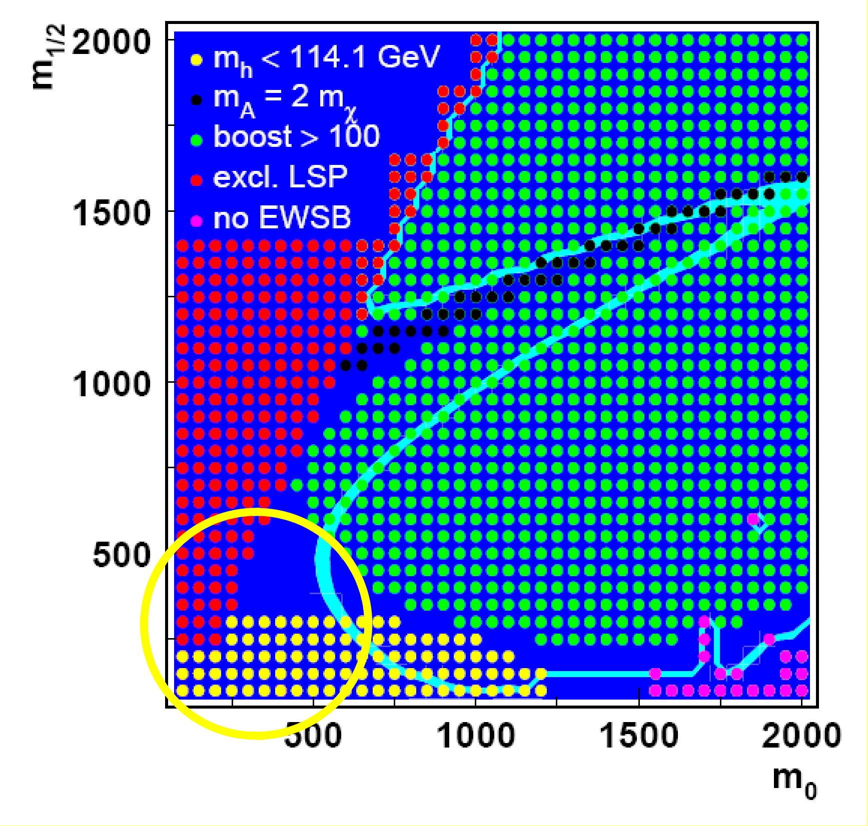
Favoured regions of parameter space

<u>Bulk region</u>

The region is characterized by low m_0 and low $m_{1/2}$ thus leading to <u>light</u> superpartners

Typical processes: annihilation of neutralinos through t-channel slepton and/or squark exchange:

$$\chi\chi \rightarrow f\bar{f} \quad \Rightarrow DM$$



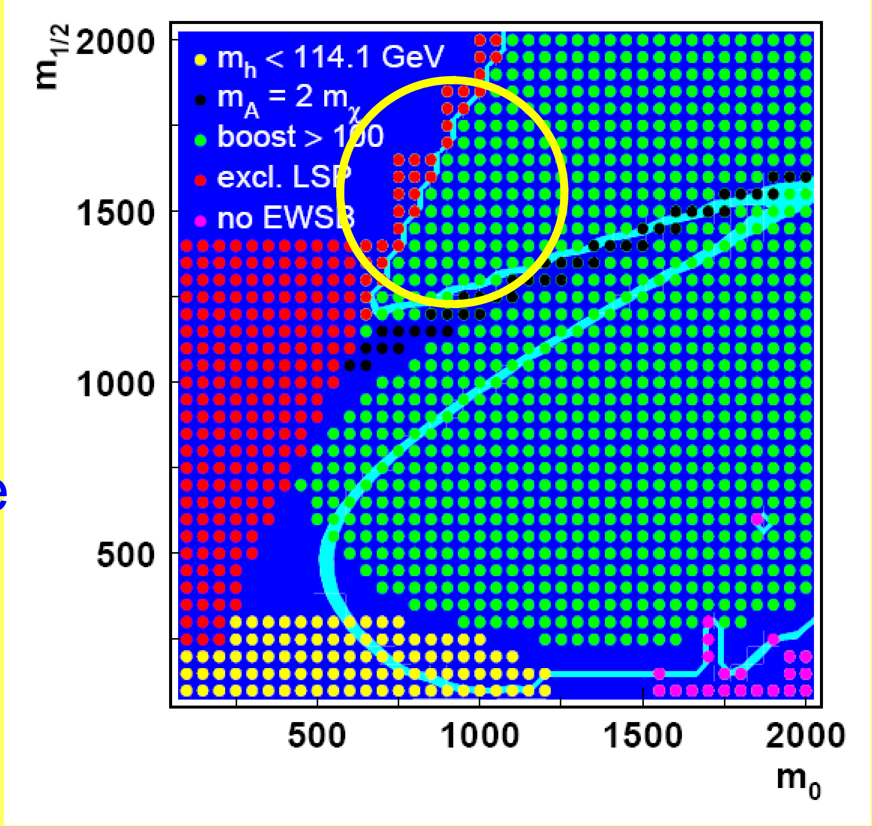
The bulk region is practically excluded by LEP2

Favoured regions of parameter space

$\tilde{\chi}^0 \tilde{\tau}$ -coannihilation region

The region is characterized by low m_0 but large $m_{1/2}$

Masses of tau-slepton and neutralino are almost degenerate



Typical processes: neutralino-stau co-annililation:

$$\chi\tilde{\tau} \rightarrow \tau^* \rightarrow \tau\gamma$$

Possibility of long-lived heavy charged staus flying through the detector or decaying at a distance !

Favoured regions of parameter space

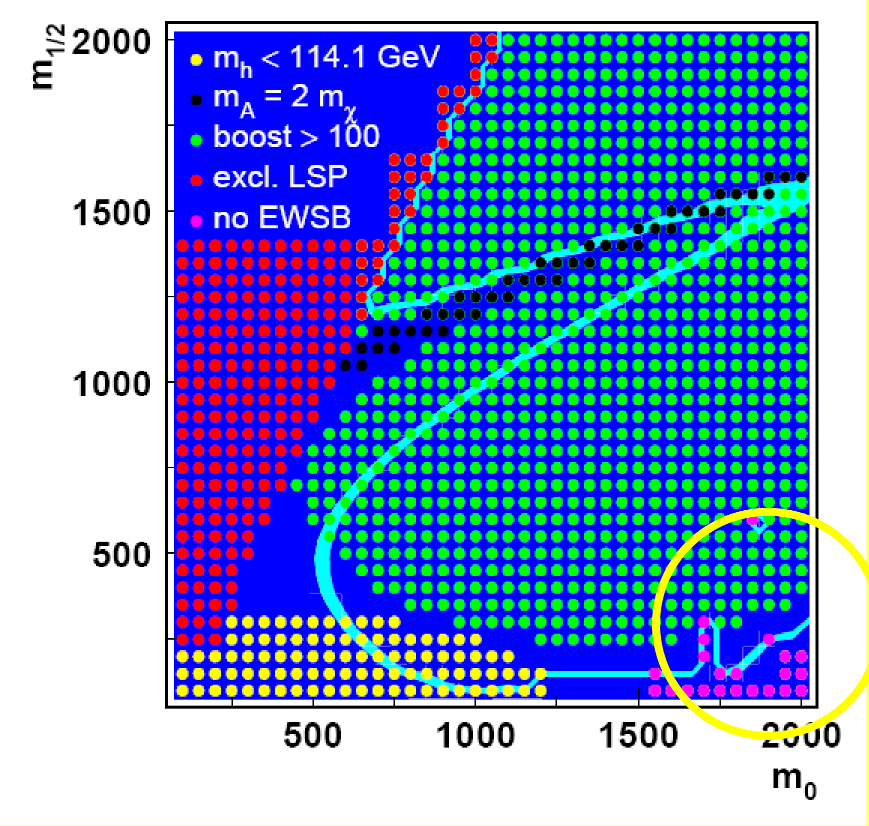
<u>Focus point region</u>

The region is characterized by large m_0 and low $m_{1/2}$

At the boundary of REWSB excluded region neutralino is almost higgsino
Possible long-lived chrginos

Splitting of heavy squarks and sleptons from light gauginos

Typical processes: annihilation of neutralinos to gauge bosons and/or quarks : $\chi\chi \rightarrow WW, ZZ, q\bar{q}$



Favoured regions of parameter space

A-annihilation funnel region

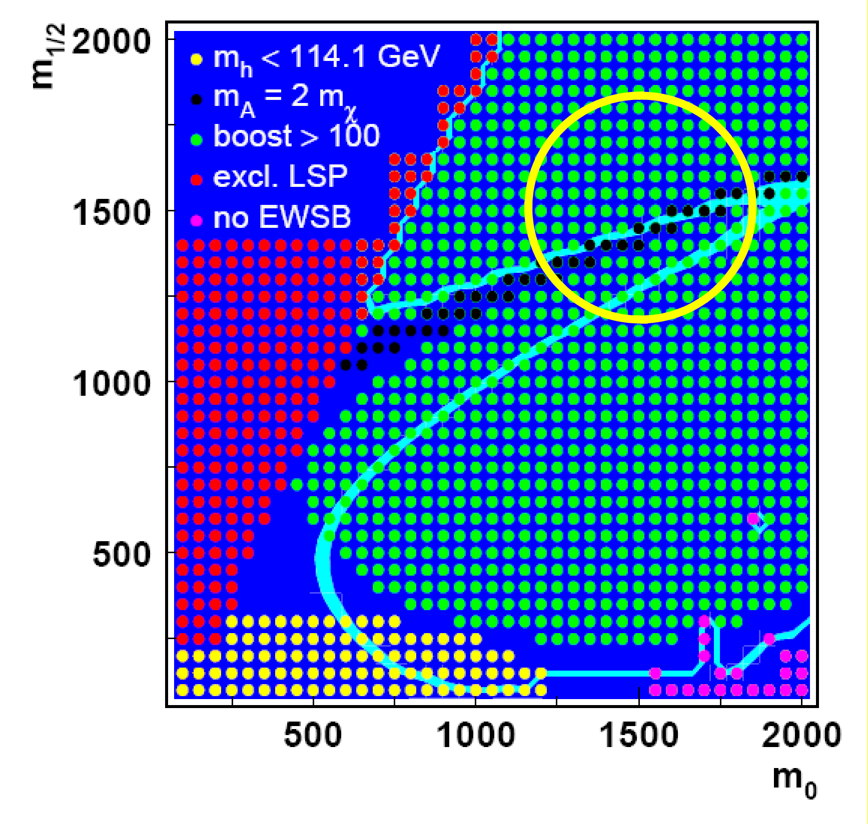
The region where

$$m_A \approx 2m_\chi$$

Typical processes:
resonance annihilation of neutralinos to fermion pairs through exchange of heavy Higgses *A* (and/or *H*):

$$\chi\chi \to A(H) \to f\bar{f}$$

The region requires large tan β and leads to heavy sparticles



Favoured regions of parameter space

EGRET region

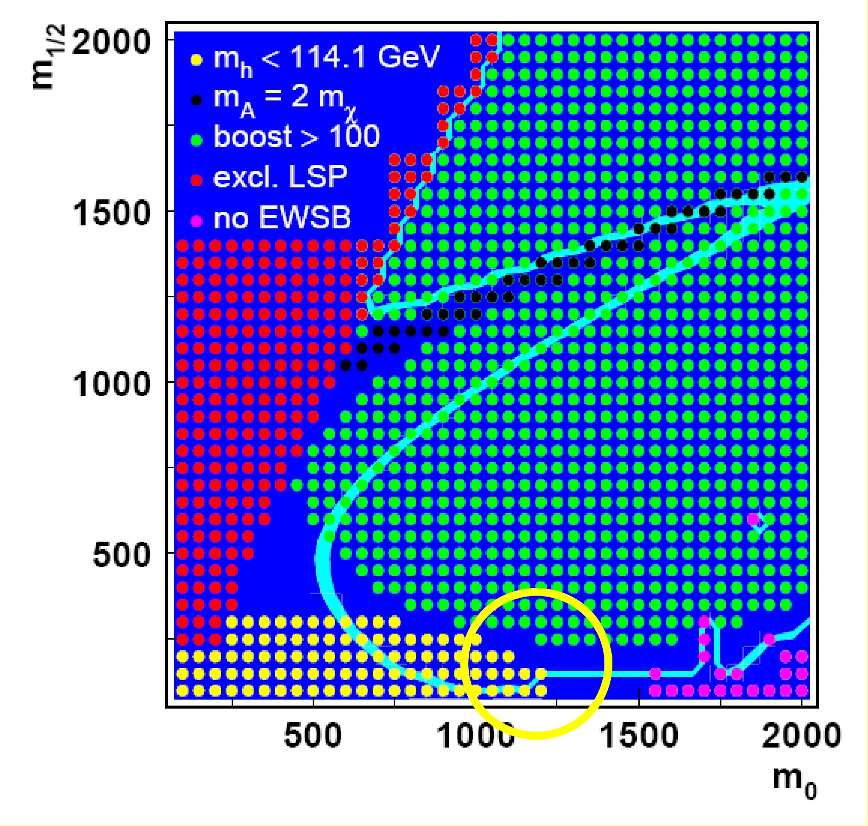
The region is compatible with diffuse gamma ray flux from the DM annihilation

It corresponds to the best fit values of parameters

tan β= 51

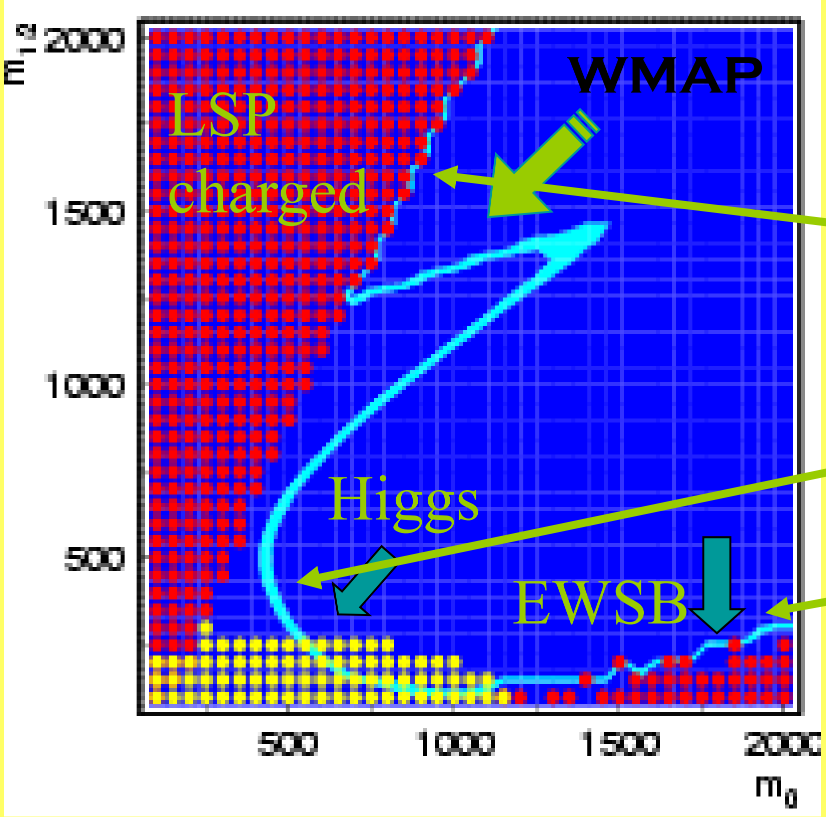
m0 = 1400 GeV

m1/2 = 180 GeV



SUSY DM: $m_{\chi^0} \approx 65\ \text{GeV}$ ⇒ $m_{\chi^\pm} \approx 115\ \text{GeV}$

Долгоживущие суперчастицы



Причина по которой частицы могут жить долго – вырождение по массе с LSP

Долгоживущие $\tilde{\tau}^{\pm}$

Долгоживущие $\tilde{t}^{\pm}$

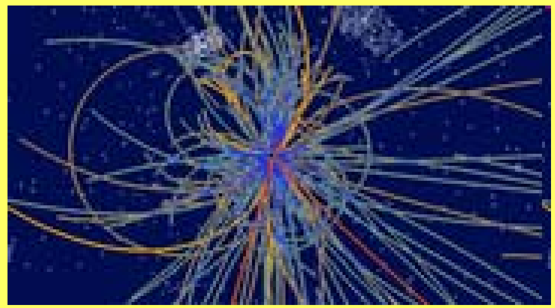
Долгоживущие $\tilde{\chi}_2^0, \tilde{\chi}_1^{\pm}$

Время жизни > 10^{-10} сек, M ~ 100 ГэВ
Распад с образованием вторичной вершины или пролёт сквозь детектор

Пространство параметров МССМ

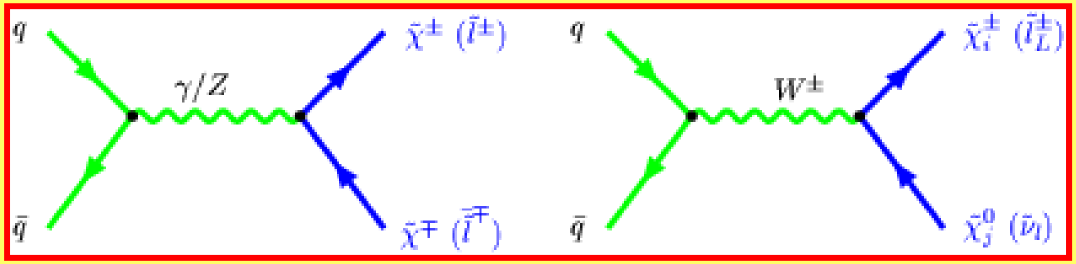
<u>Требует тонкой подстройки параметров</u>

Search for Superpartners @ Colliders

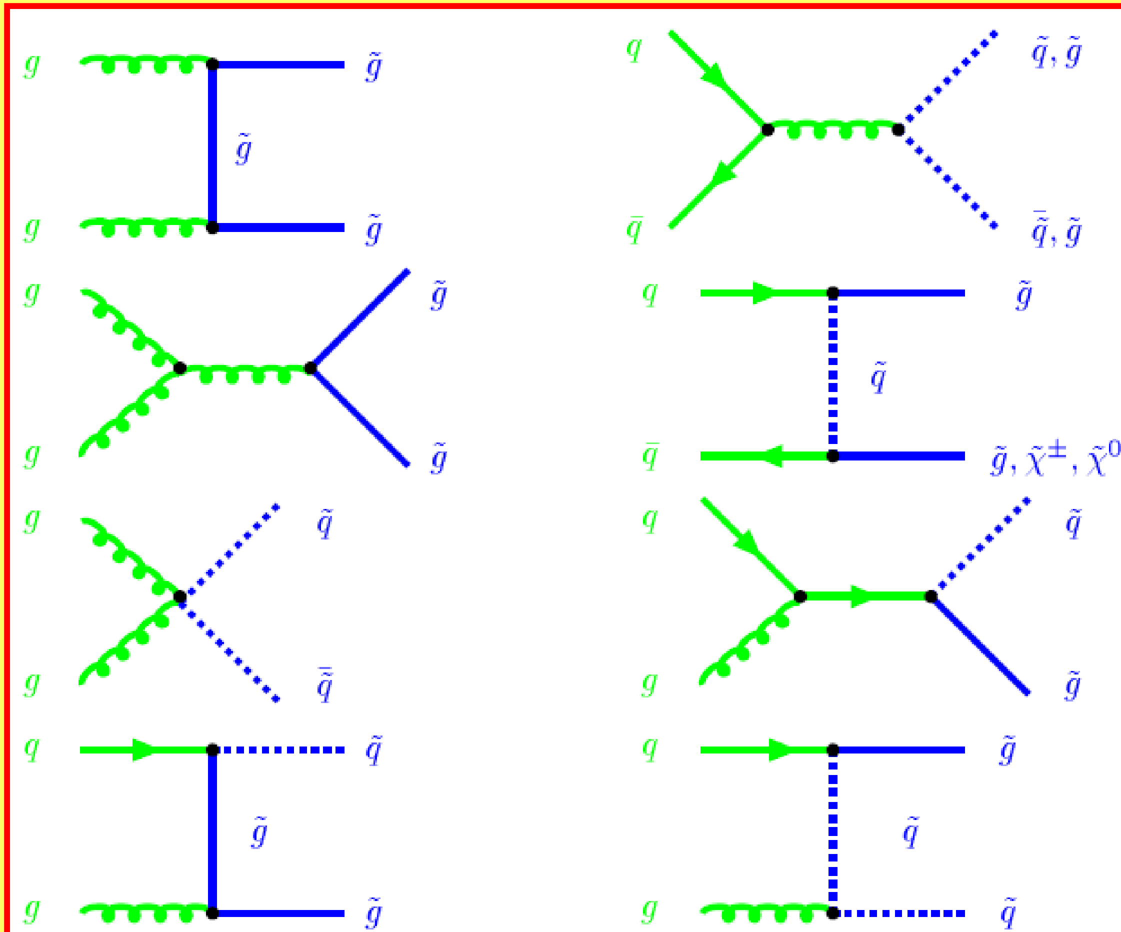


Superpartners Production at LHC

Annihilation



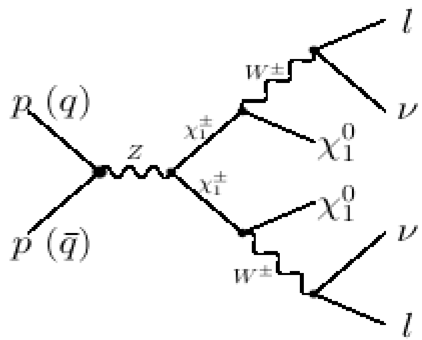
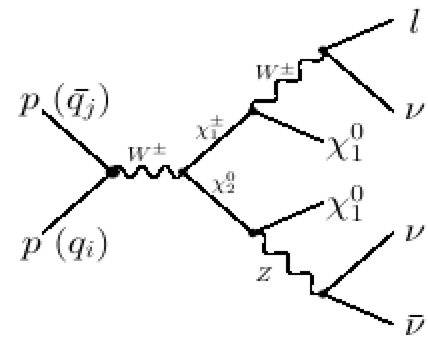
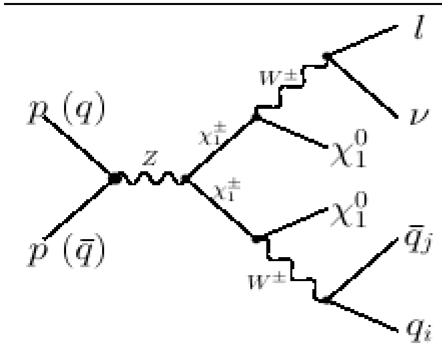
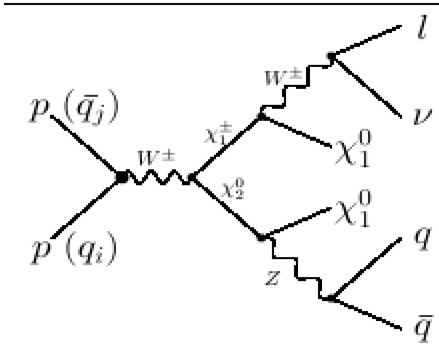
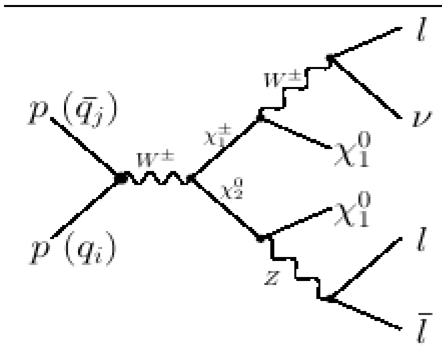
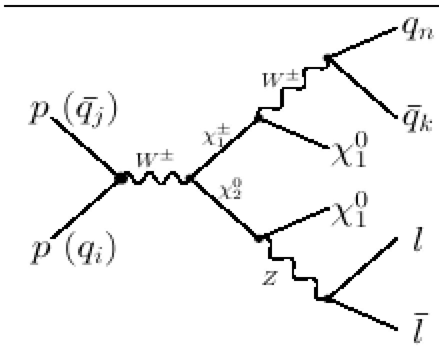
Quark- gluon Fusion



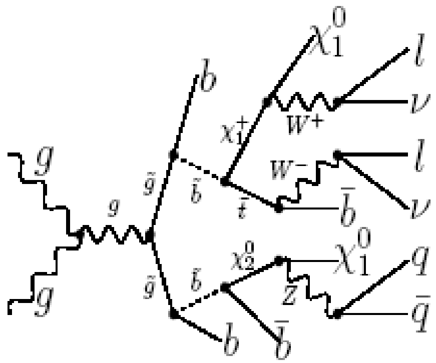
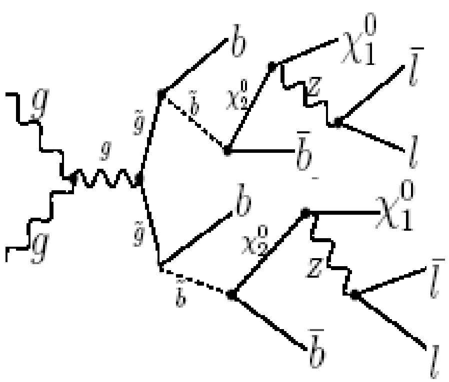
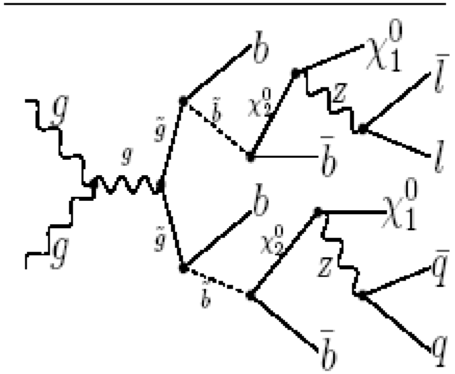
SUSY Signatures at LHC

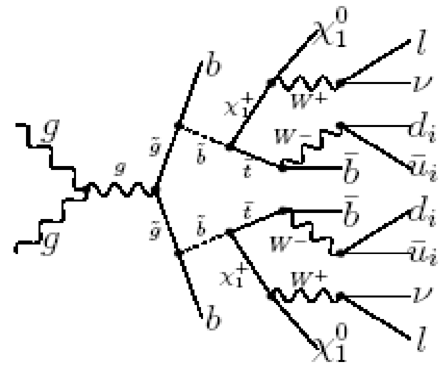
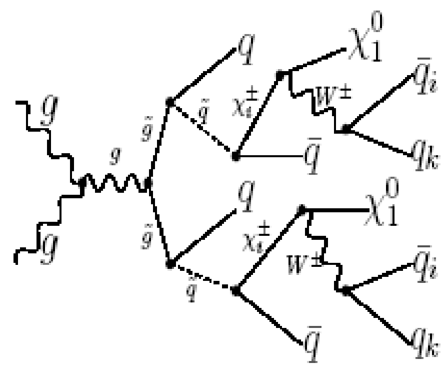
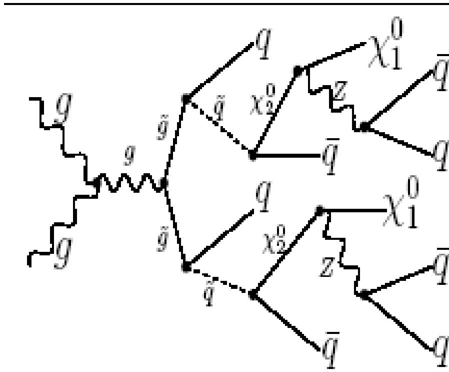
Production	Key Decay Modes	Signatures
• $\tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{g}\tilde{q}$	$\left.\begin{array}{l}\tilde{g} \to q\bar{q}\tilde{\chi}_1^0 \\ \quad q\bar{q}'\tilde{\chi}_1^\pm \\ \quad g\tilde{\chi}_1^0\end{array}\right\} m_{\tilde{q}} > m_{\tilde{g}}$ $\left.\begin{array}{l}\tilde{q} \to q\tilde{\chi}_i^0 \\ \tilde{q} \to q'\tilde{\chi}_i^\pm\end{array}\right\} m_{\tilde{g}} > m_{\tilde{q}}$	$\not{E}_T$ + multijets (+leptons)
• $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$	$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 l^\pm \nu,\ \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 ll$ $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 q\bar{q}', \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 ll,$	Trilepton + $\not{E}_T$ Dilepton + jet + $\not{E}_T$
• $\tilde{\chi}_1^+\tilde{\chi}_1^-$ • $\tilde{\chi}_i^0\tilde{\chi}_i^0$	$\tilde{\chi}_1^+ \to l\tilde{\chi}_1^0 l^\pm \nu$ $\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 X, \tilde{\chi}_i^0 \to \tilde{\chi}_1^0 X'$	Dilepton + $\not{E}_T$ $\not{E}_T$ + Dilepton + (jets) + (leptons)
• $\tilde{t}_1\tilde{t}_1$	$\tilde{t}_1 \to c\tilde{\chi}_1^0$ $\tilde{t}_1 \to b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 l^\pm \nu, \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 q\bar{q}'$ $\tilde{t}_1 \to b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 l^\pm \nu, \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 l^\pm \nu$	2 acollinear jets + $\not{E}_T$ single lepton + $\not{E}_T$ + $b's$ Dilepton + $\not{E}_T$ + $b's$
• $\tilde{l}\tilde{l}, \tilde{l}\tilde{\nu}, \tilde{\nu}\tilde{\nu}$	$\tilde{l}^\pm \to l \pm \tilde{\chi}_i^0, \tilde{l}^\pm \to \nu_l \tilde{\chi}_i^\pm$ $\tilde{\nu} \to \nu\tilde{\chi}_1^0$	Dilepton + $\not{E}_T$ Single lepton + $\not{E}_T$ + $(jets)$ $\not{E}_T$

Cascade Processes (weak int's)

process	final states	process	final states
	2ℓ 2ν $\not{E}_T$		ℓ 3ν $\not{E}_T$
	1ℓ $2j$ ν $\not{E}_T$		ℓ ν $2j$ $\not{E}_T$
	3ℓ ν $\not{E}_T$		2ℓ $2j$ $\not{E}_T$

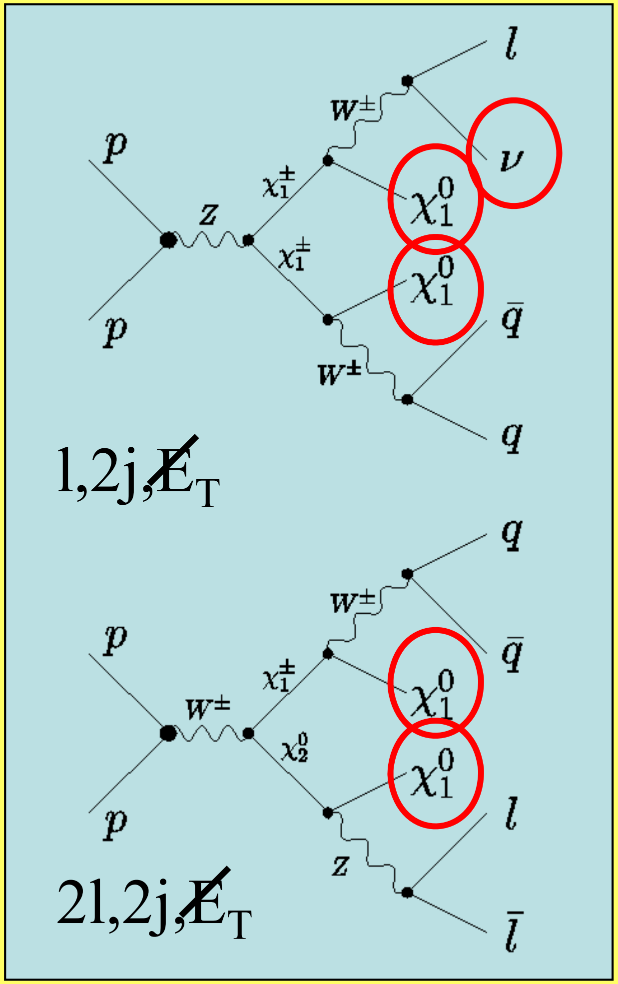
Cascade Processes (strong int's)

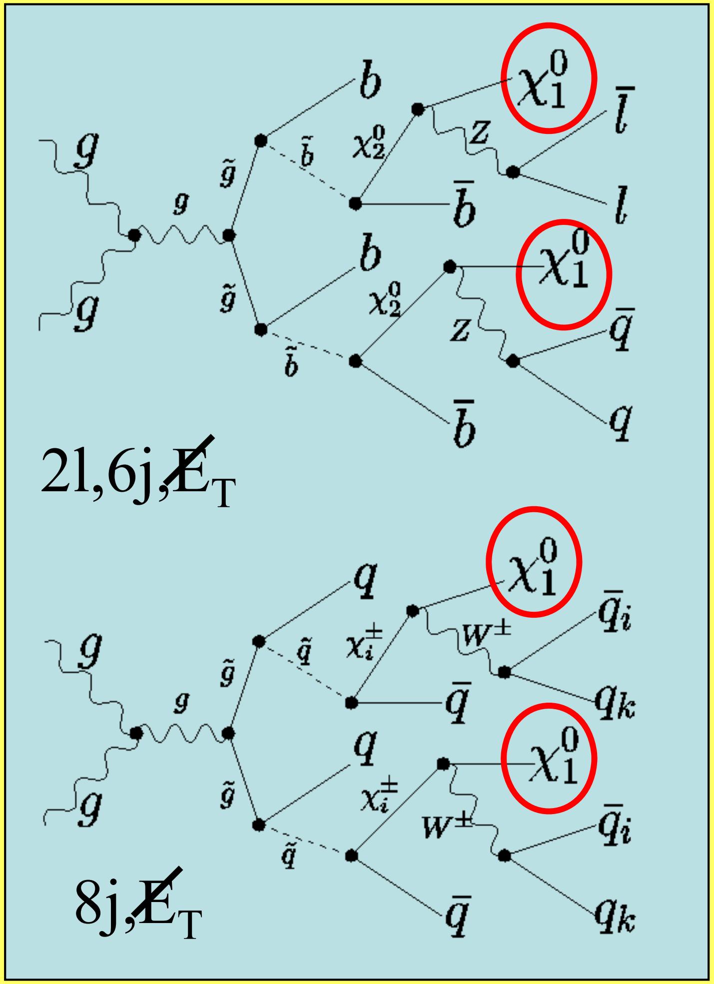
process	final states
	2ℓ 2ν $6j$ $\not{E}_T$
	4l 4j $\not{E}_T$
	2ℓ $6j$ $\not{E}_T$

process	final states
	2ℓ 2ν $8j$ $\not{E}_T$
	$8j$ $\not{E}_T$
	$8j$ $\not{E}_T$

Creation and decay of superpartners in cascade processes @ LHC

weak ints



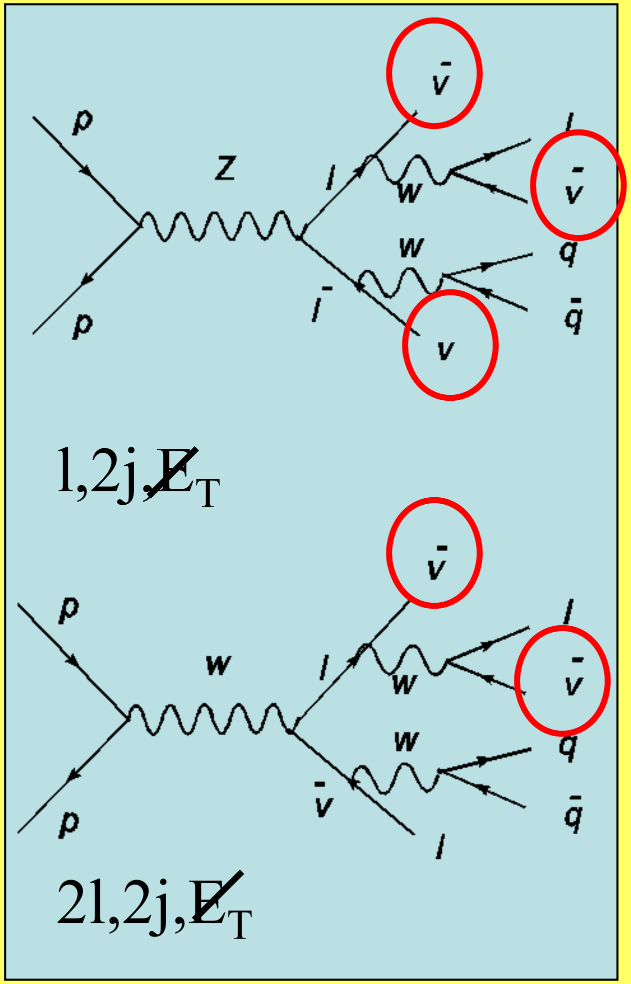


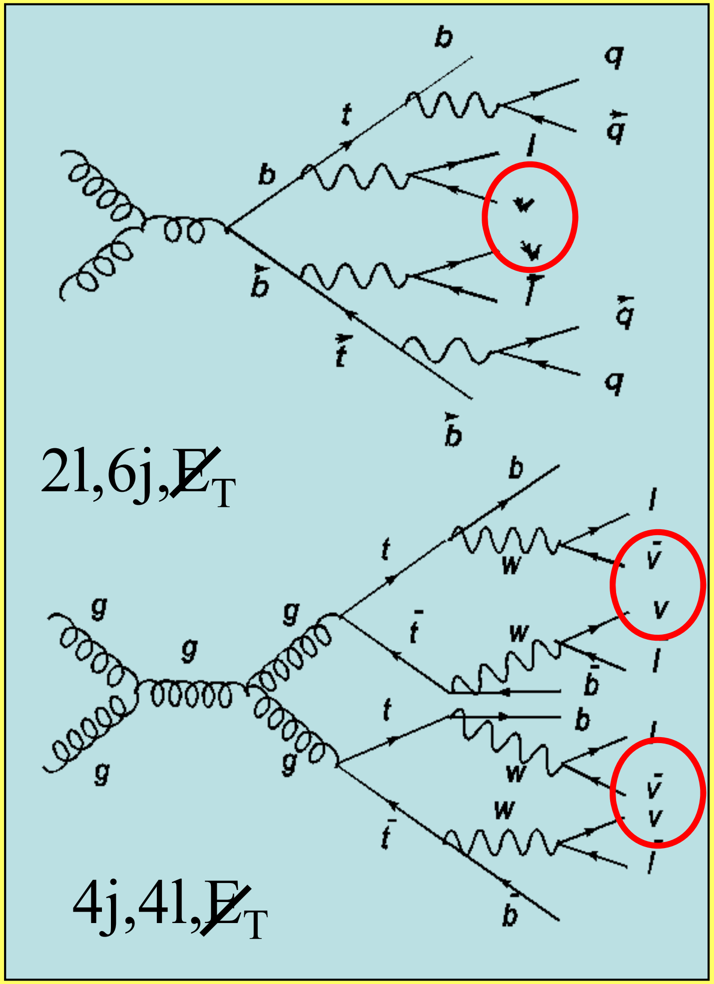
Strong ints

Typical SUSY signature: Missing energy and transverse momentum

Background Processes in the SM for superpartner production

weak int-s

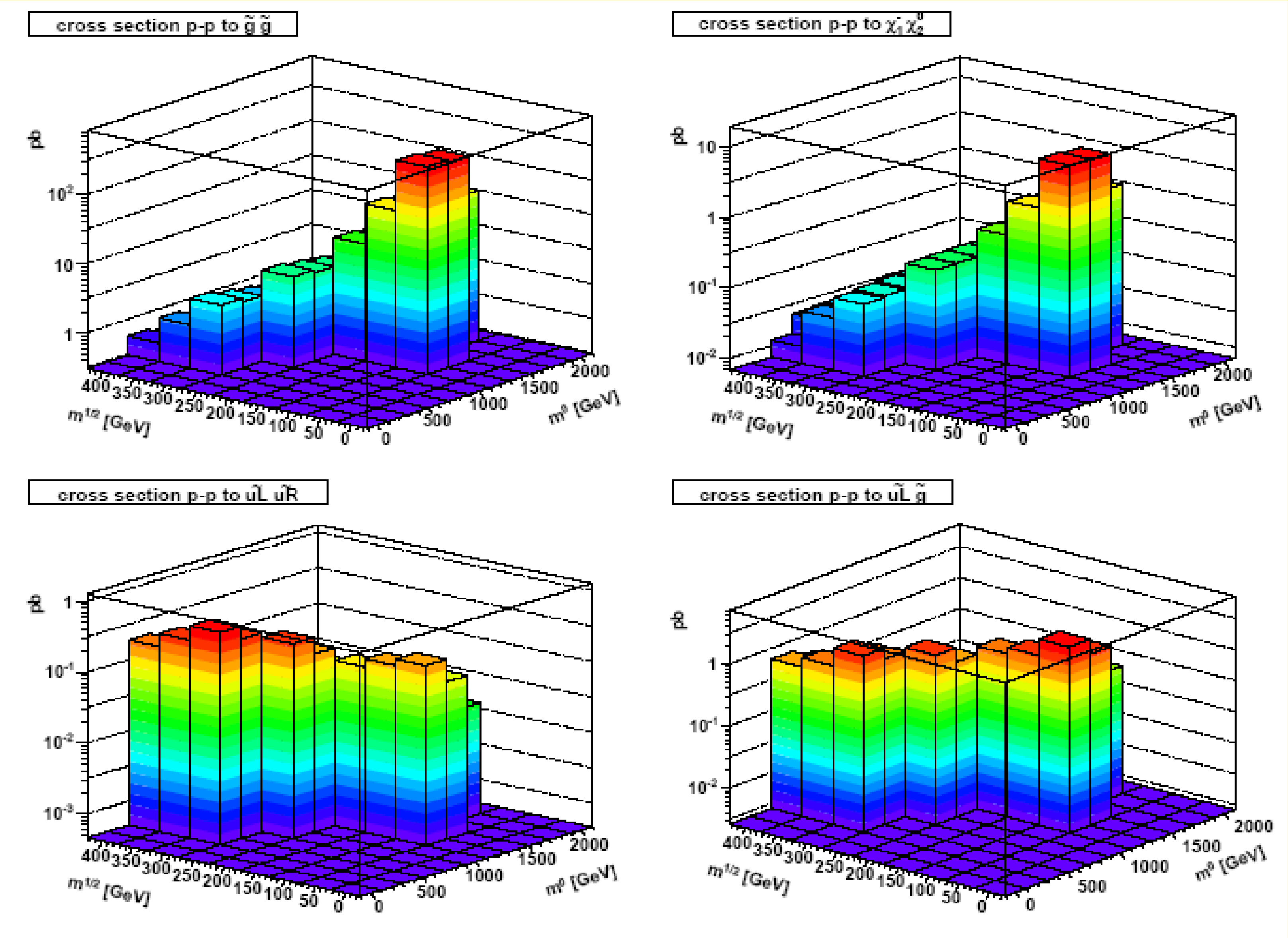




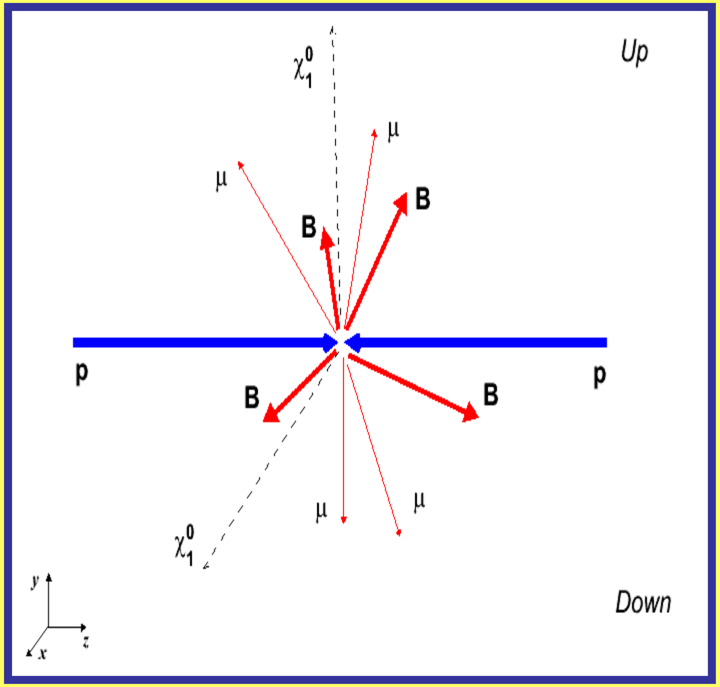
Strong int-s

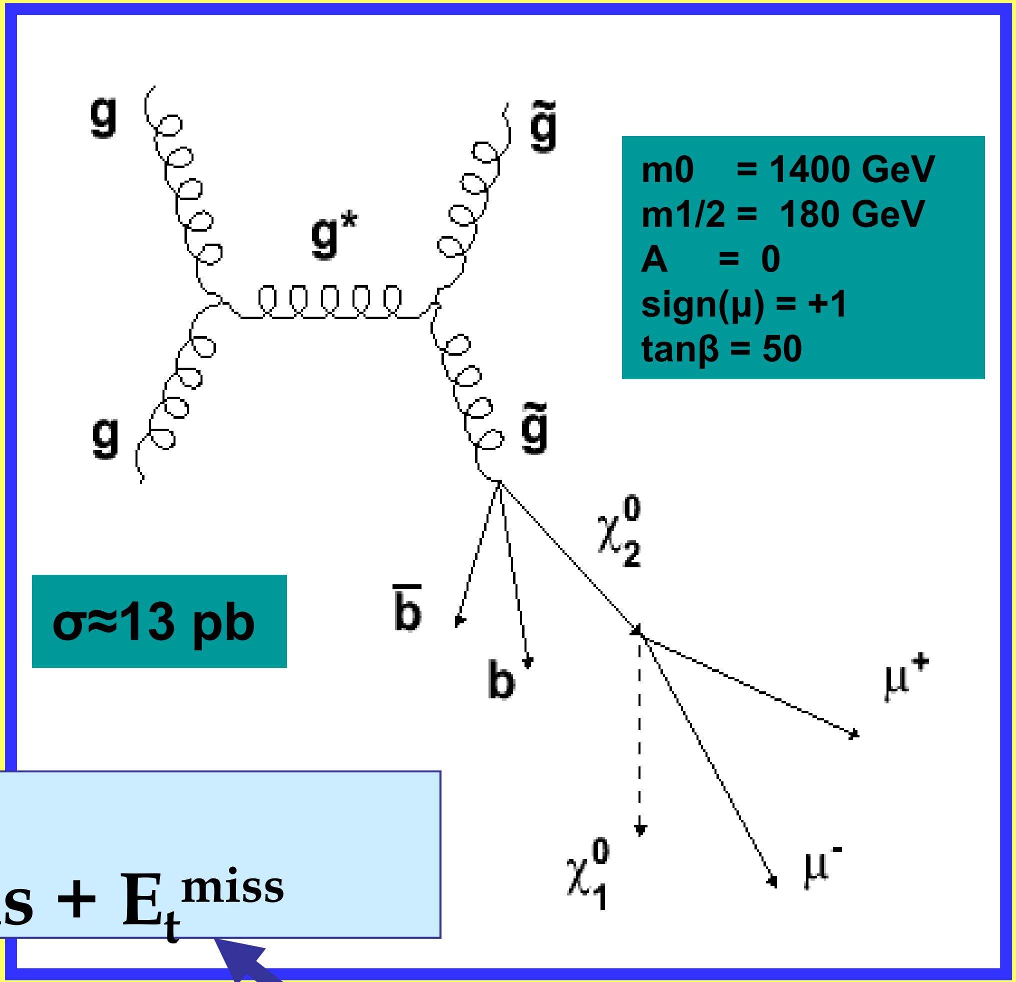
The x-section typically are smaller than for SUSY prodution

Cross-Sections at LHC



SUSY PRODUCTION AT LHC



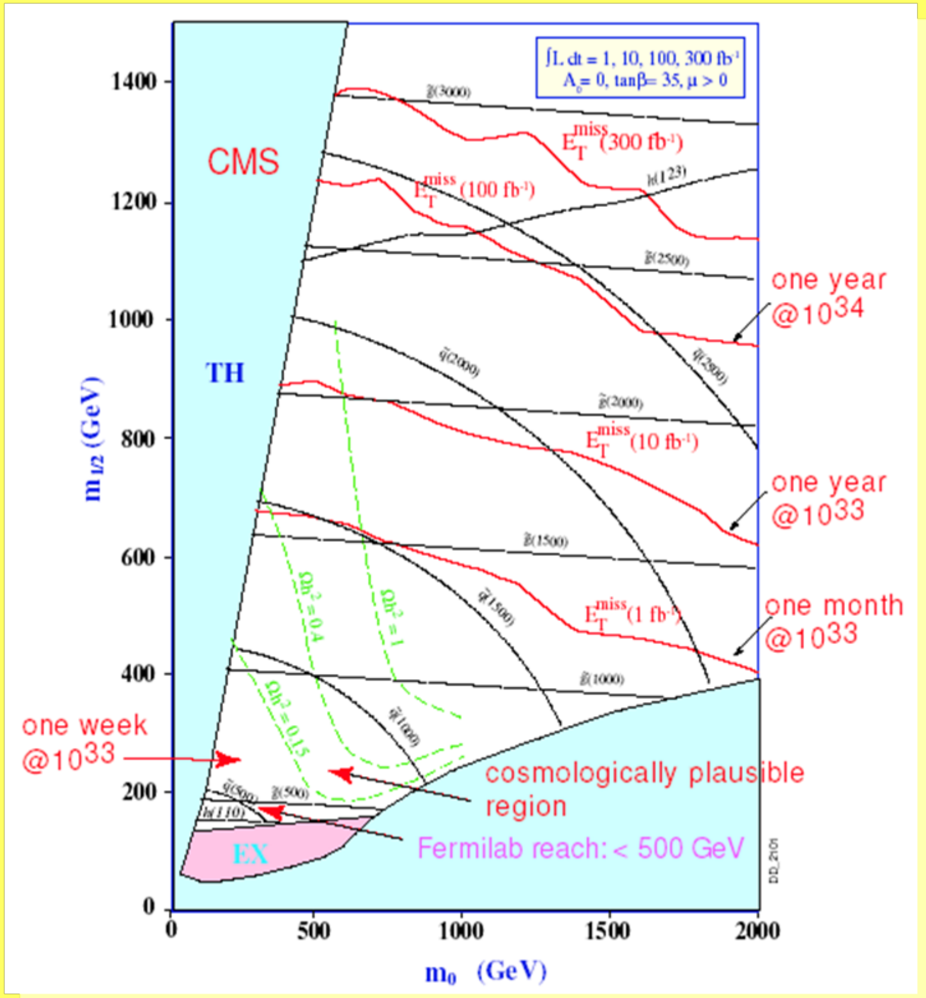


SIGNATURE:

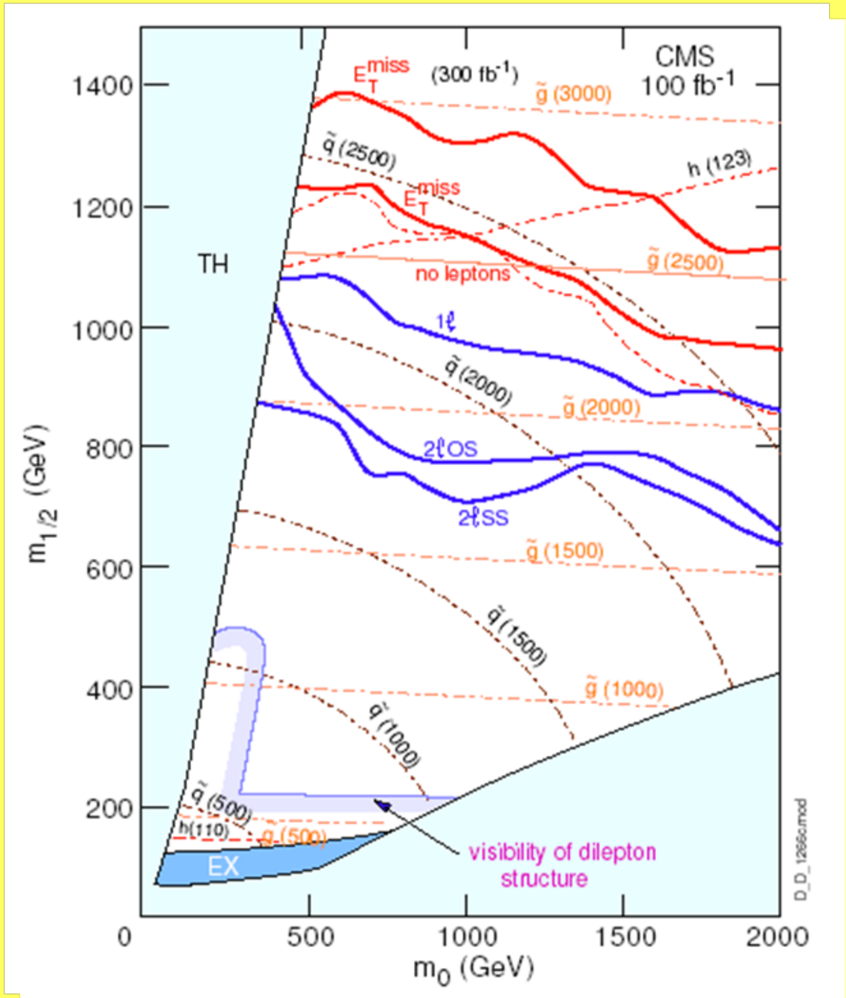
4 b-jets + 4 muons + E_t^{miss}

LARGE!

SUSY Searches at LHC

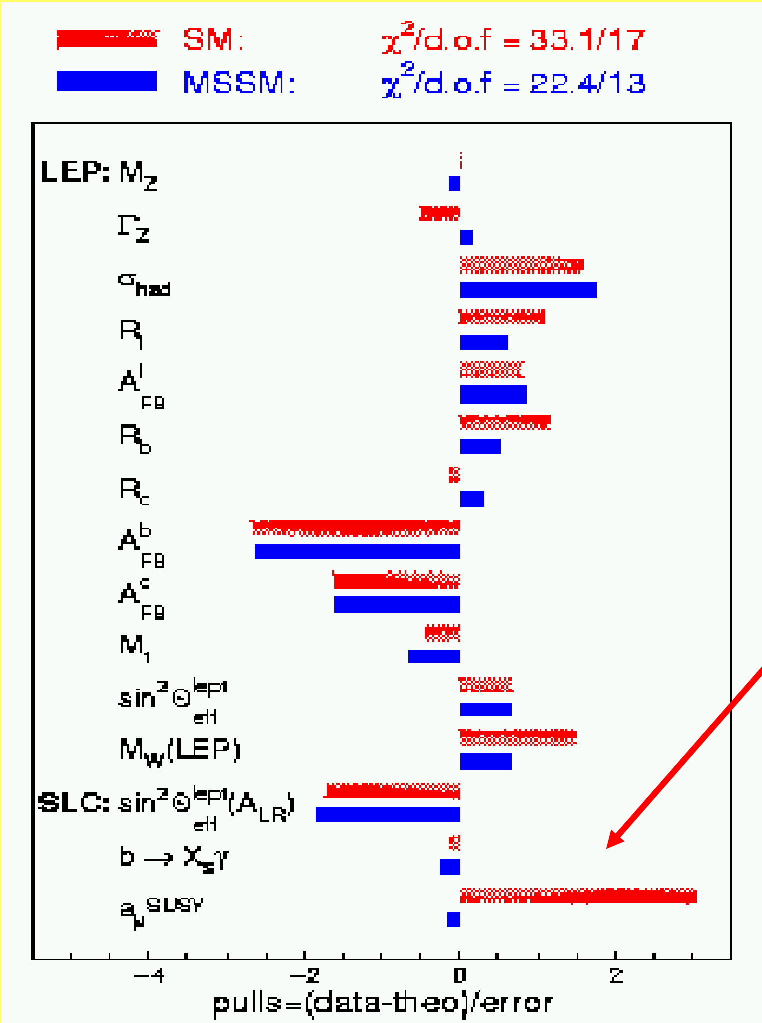


5 σ reach in jets + $\not{E}_T$ channel



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

MSSM versus SM



Global fit to precision EW data

- MSSM is as good as SM

- B->sγ
- a_μ

MSSM is better than SM

- Ω_{DM}

Is NOT described by SM, but is naturally described by MSSM

SUSY: Pros and Cons

Pro :

- Provides natural framework for unification with gravity
- Leads to gauge coupling unification (GUT)
- Solves the hierarchy problem
- Is a solid quantum field theory
- Provides natural candidate for the WIMP cold DM
- Predicts new particles and thus generates new job positions

Contra : Does not shed new light on the problem of

- Quark and lepton mass spectrum
- Quark and lepton mixing angles
- the origin of CP violation
- Number of flavours
- Baryon assymetry of the Universe

Doubles the number of particles

Conclusions

- LHC has potential for major discoveries already in the first year of operation (1 day of LHC at 10^{33} = 10 years of previous machines)
- SUSY might be discovered "quickly", light Higgs more difficult
- Machine luminosity performance is crucial in the first year
- However: lot of data and time is needed in the beginning to
  -- commission the detectors
  -- reach the performance
  -- understand the SM physics at $\sqrt{s}$=14 TeV