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

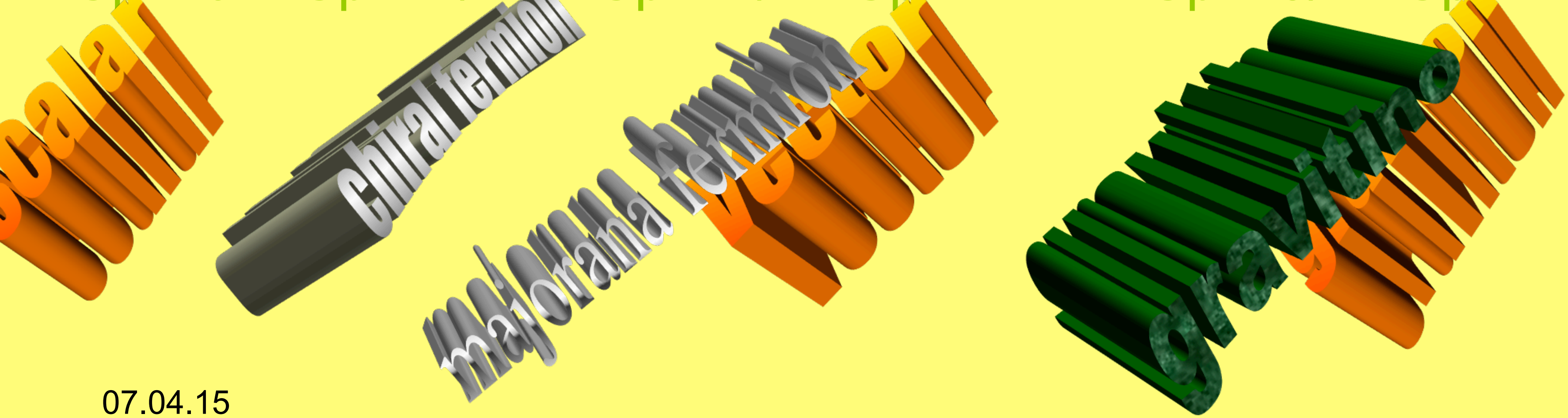
What is SUSY?

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



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	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

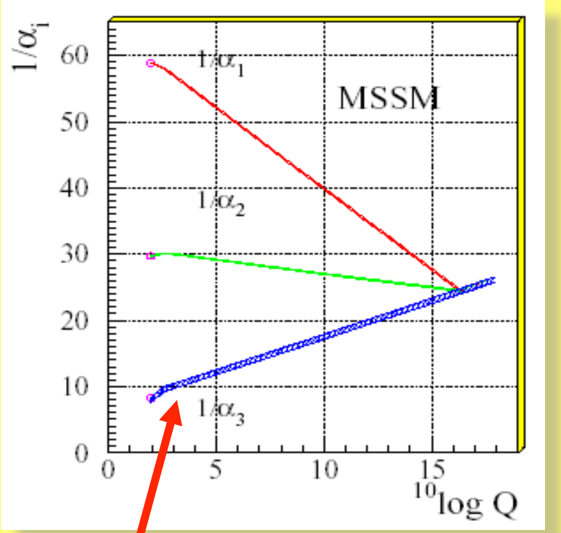
Why we like SUSY?

- Unification with gravity

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

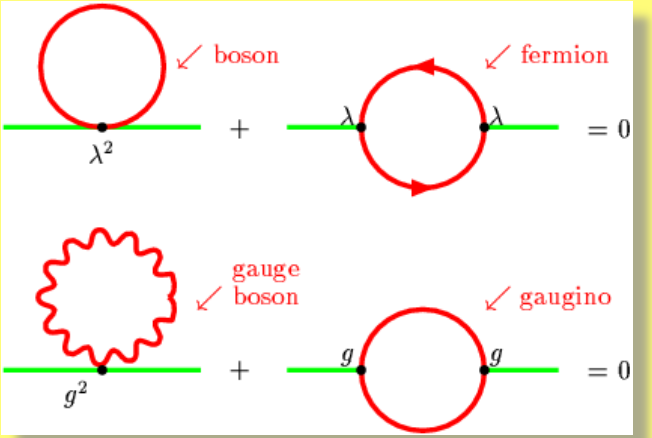
$$\varepsilon = \varepsilon(x) \text{ local coordinate transf. } \Rightarrow \text{ (super)gravity}$$

- Unification of the gauge couplings



M_{SUSY} ~ 1 TeV

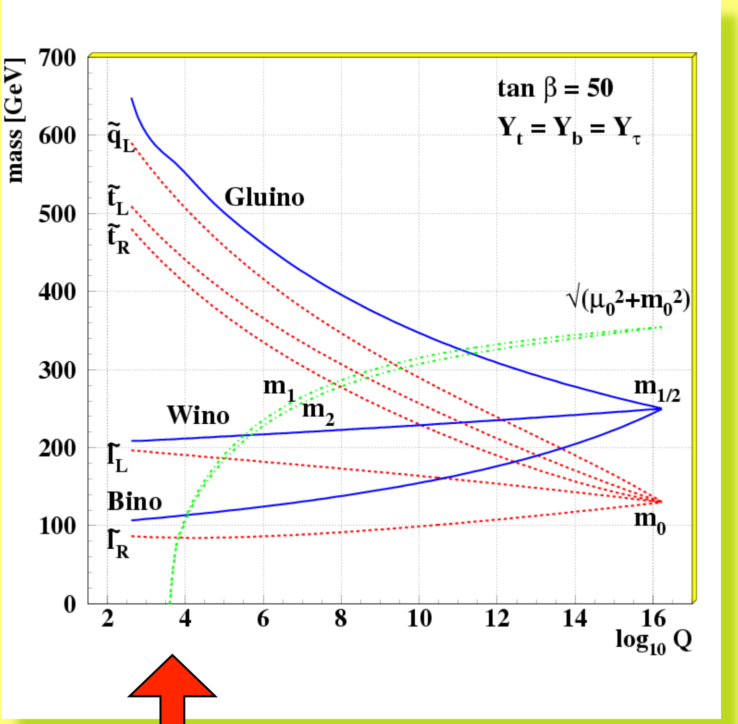
- Solution of the hierarchy problem



$M_{SUSY} = M_W/g$ ~ 1 TeV

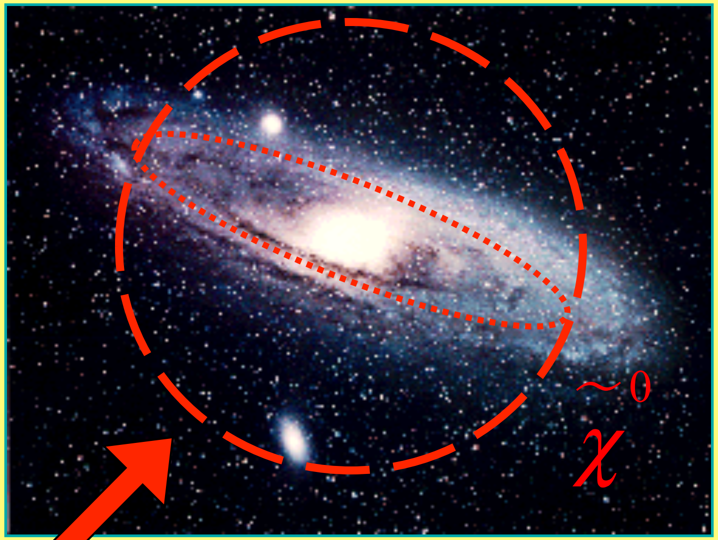
Why we like SUSY? Cont'd

- **Radiative EWSB**



M²<0

- **Dark Matter in the Universe**



SUSY Cold DM Halo

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

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

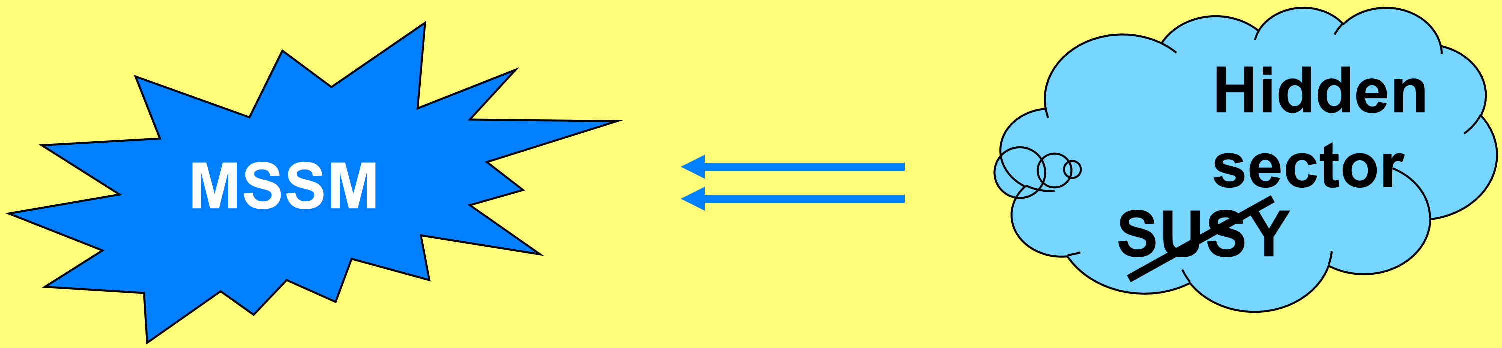
R-parity $R = (-)^{3(B-L)+2S}$

B - Baryon Number
L - Lepton Number
S - Spin

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

These terms are forbidden in the SM

MSSM Parameter Space

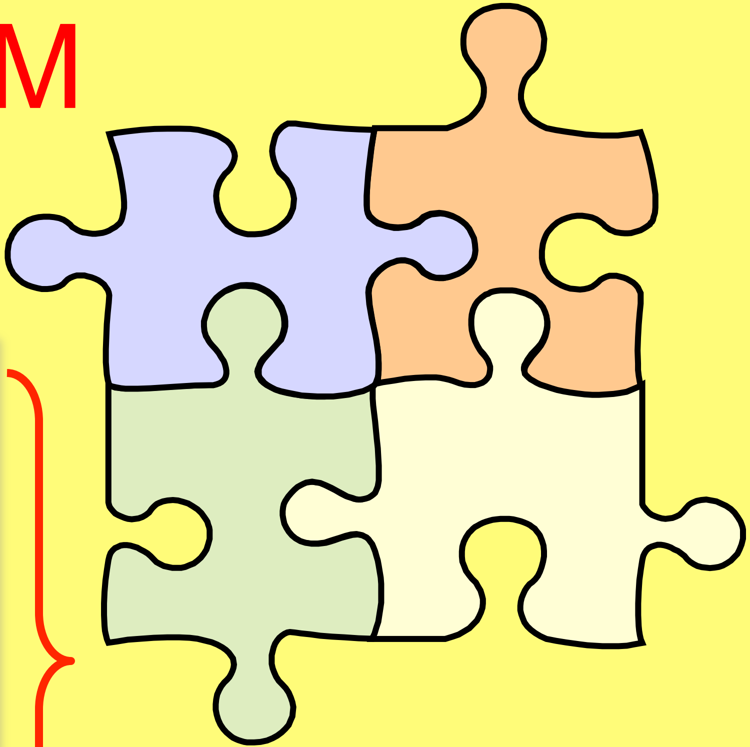


$$-L_{Soft} = A\{y_t Q_L H_2 U_R + y_b Q_L H_1 D_R + y_L L_L H_1 E_R\} + B\mu H_1 H_2 + m_0^2 \sum_i |\varphi_i|^2 + \tfrac{1}{2} M_{1/2} \sum_\alpha \tilde{\lambda}_\alpha \tilde{\lambda}_\alpha$$

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

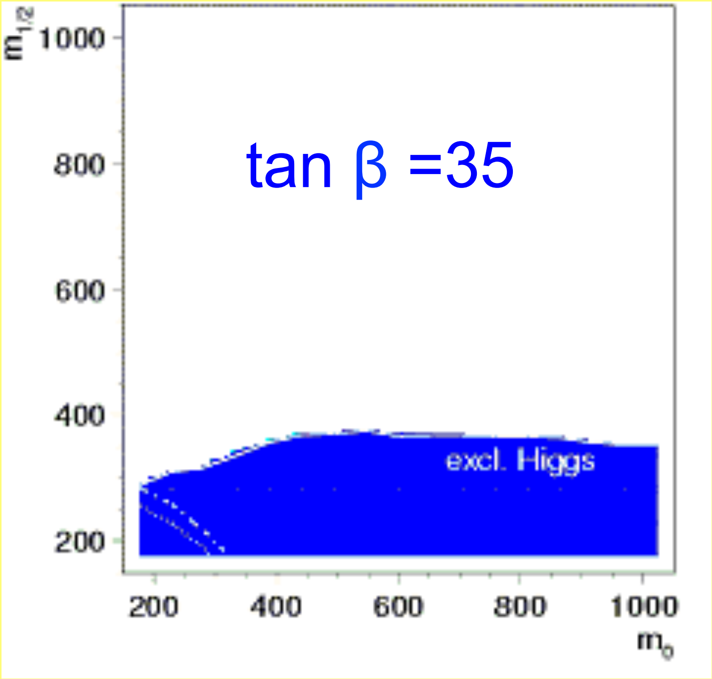
$$100 \text{ GeV} \leq m_0, M_{1/2}, \mu \leq 2 \text{ TeV}$$
$$-3m_0 \leq A_0 \leq 3m_0,\ 1 \leq \tan\beta \leq 70$$

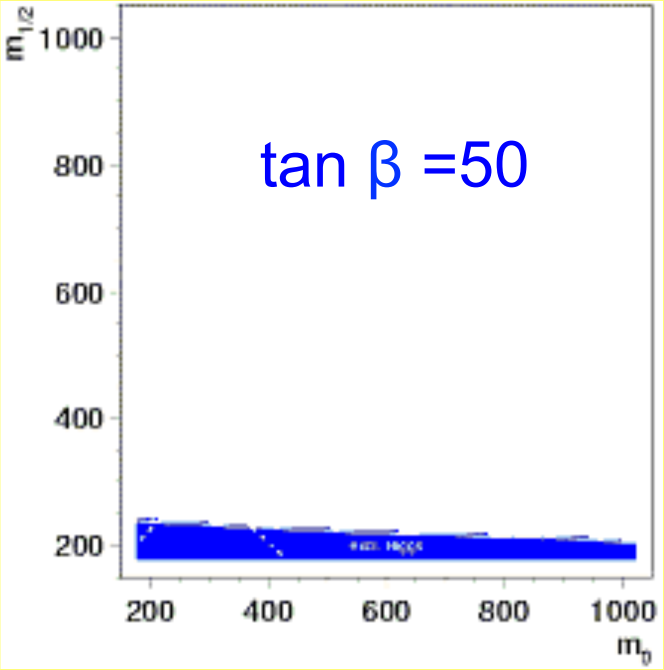
Constrained MSSM (Choice of constraints)

Experimental lower limits on Higgs and superparticle masses

Regions excluded by Higgs experimental limits provided by LEP2

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



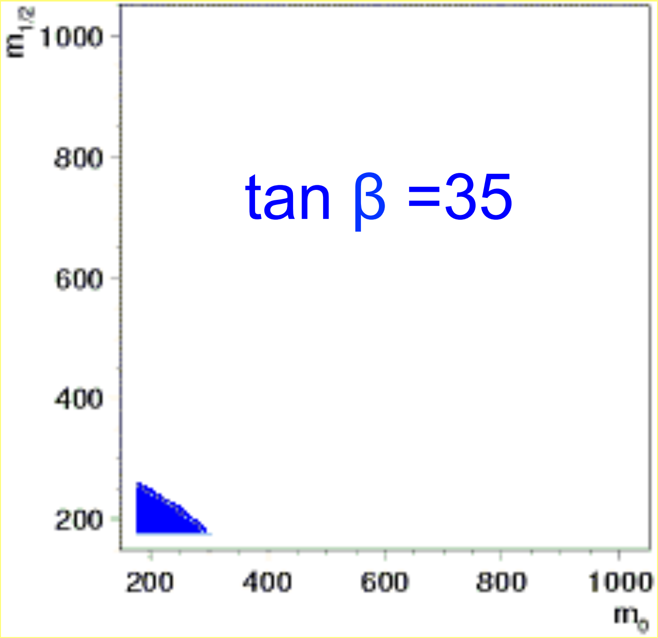


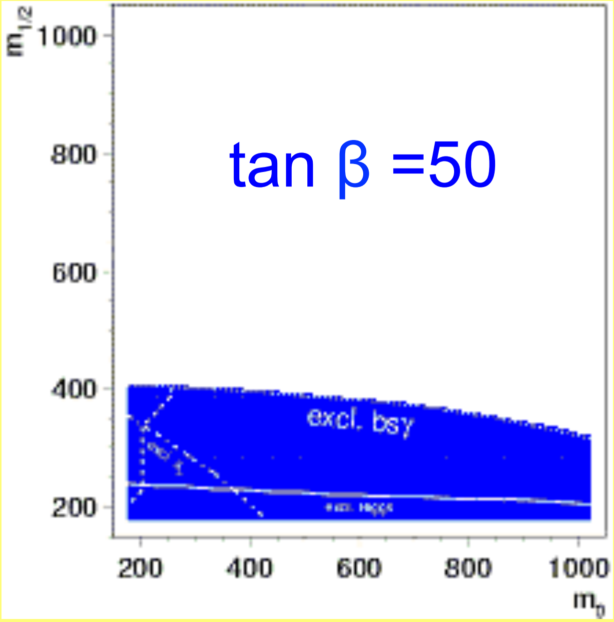
Constrained MSSM (Choice of constraints)

Data on rare processes branching ratios

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

Regions excluded by experimental limits (for large tanβ)



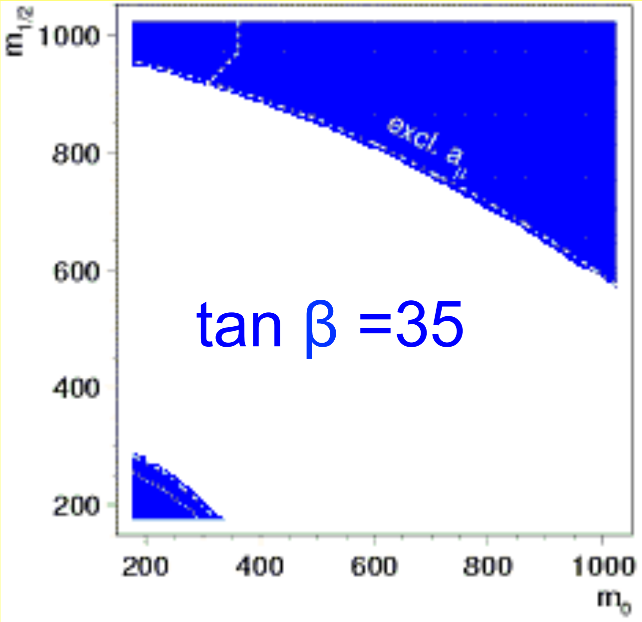


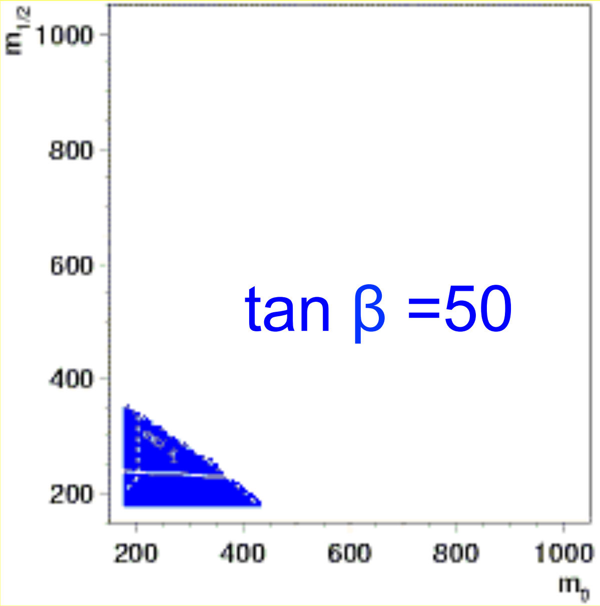
Constrained MSSM (Choice of constraints)

Muon anomalous magnetic moment

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

Regions excluded by muon amm constraint



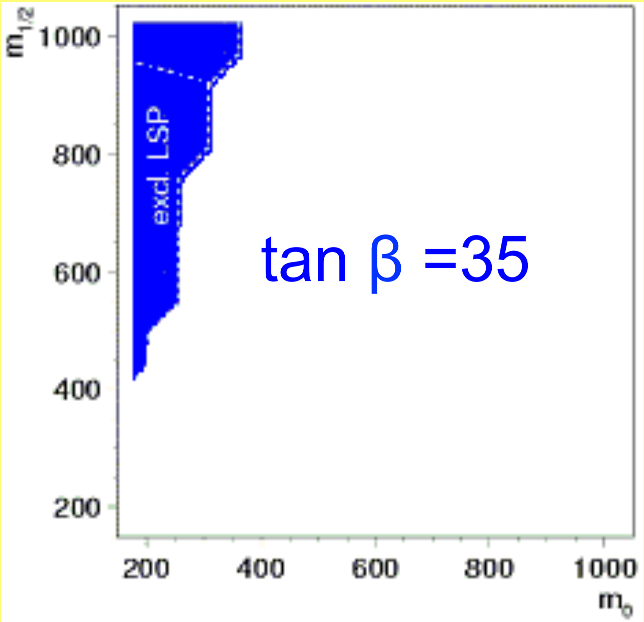


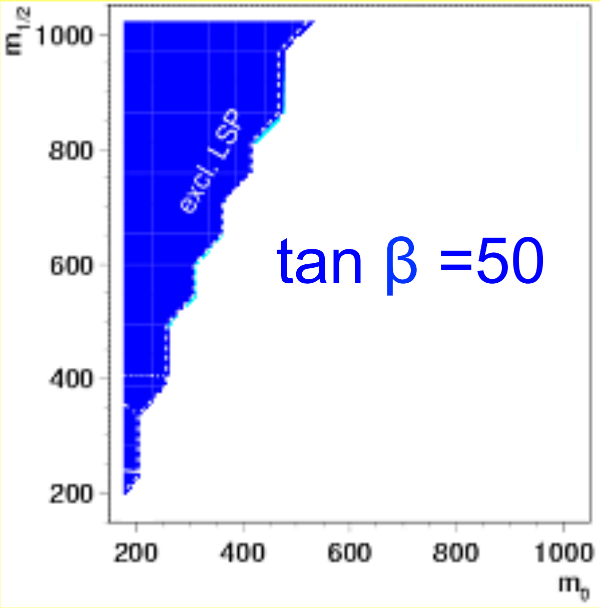
Constrained MSSM (Choice of constraints)

The lightest supersymmetric particle (LSP) is neutral.

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

Regions excluded by LSP constraint

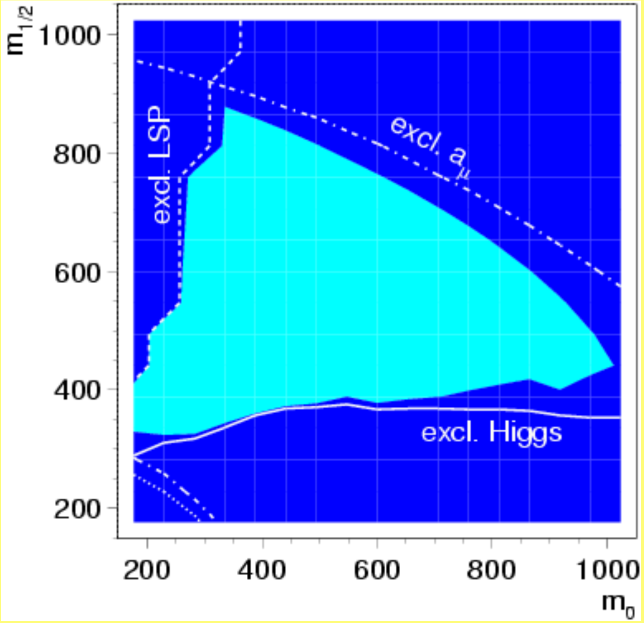




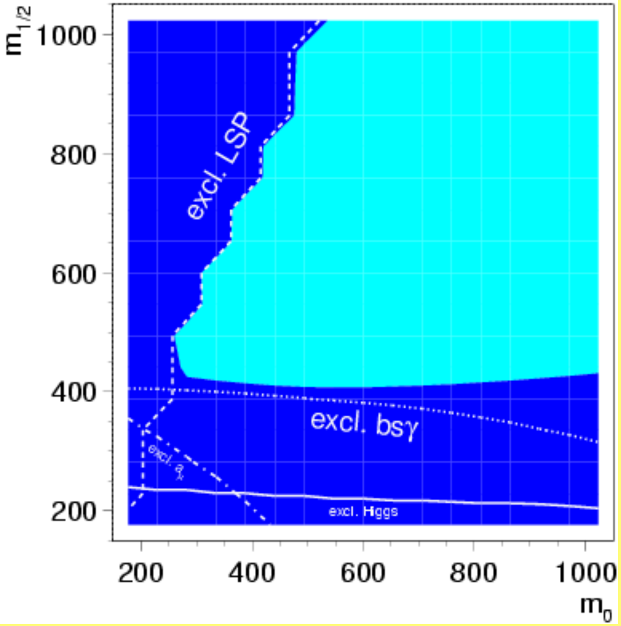
Favoured regions of parameter space

Pre-WMAP allowed regions in the parameter space.

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



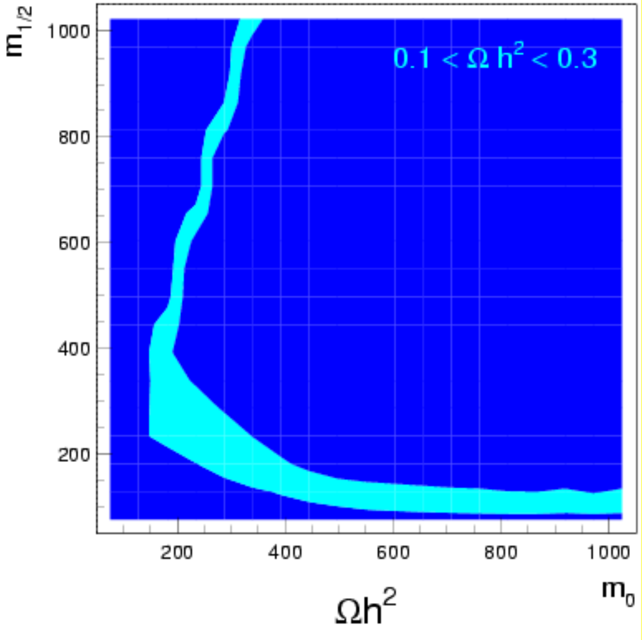
tan β =35

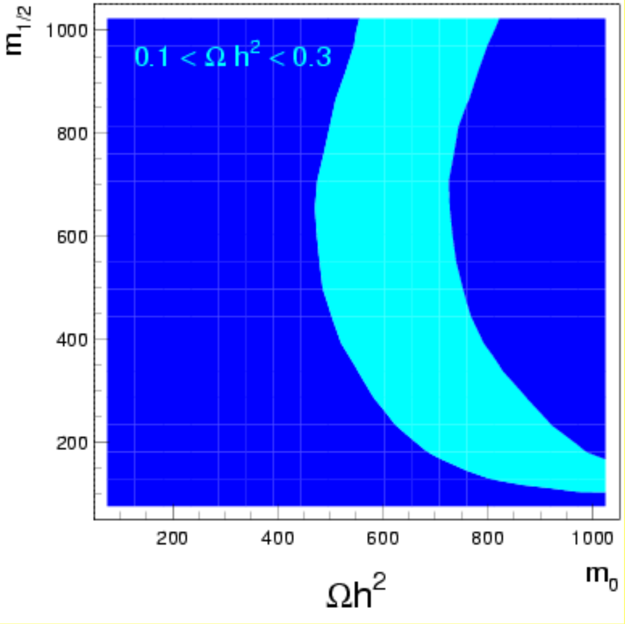


tan β =50

Favoured regions of parameter space

Pre-WMAP dark matter constraint
$0.1 < \Omega h^2 < 0.3$

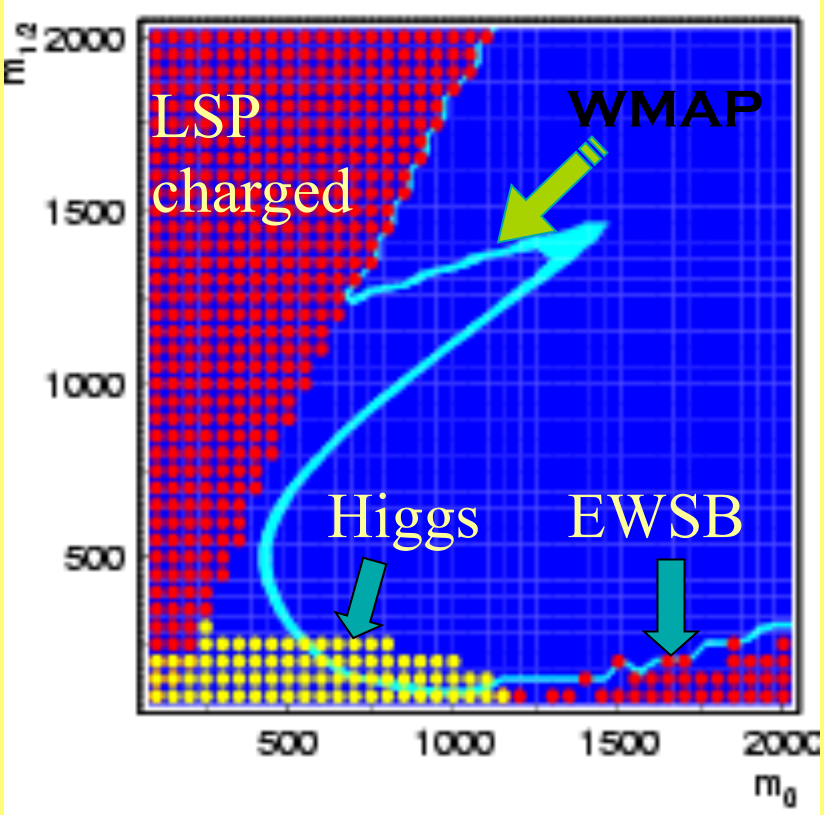




tan β =35

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

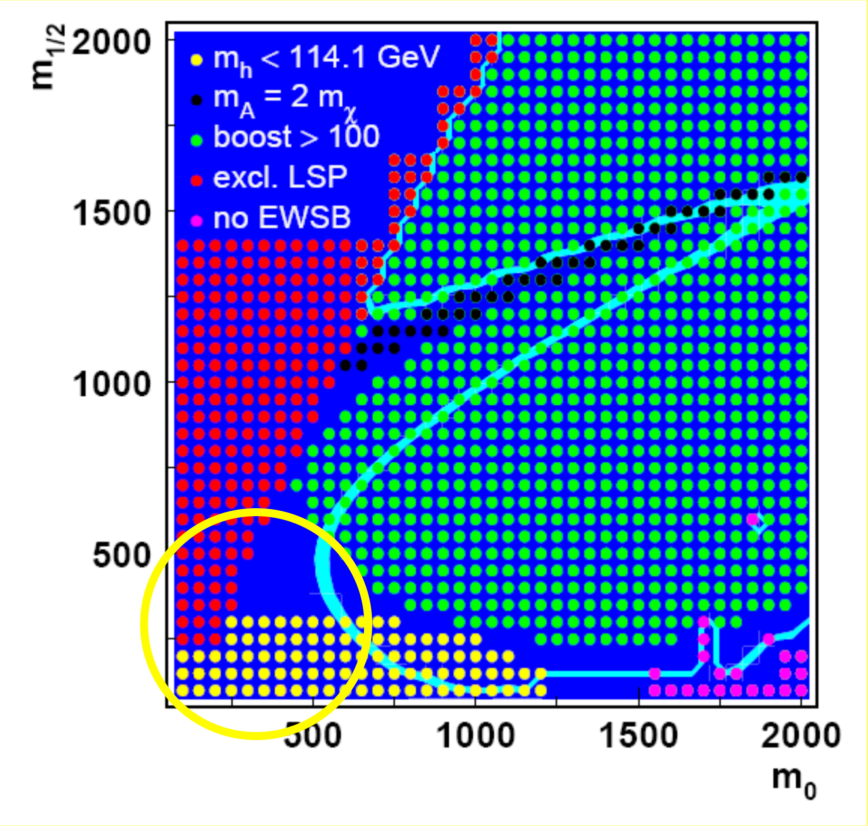
Narrow allowed region enables one to predict the particle spectra and the main decay patterns

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:

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

The bulk region is practically excluded by LEP2

Favoured regions of parameter space

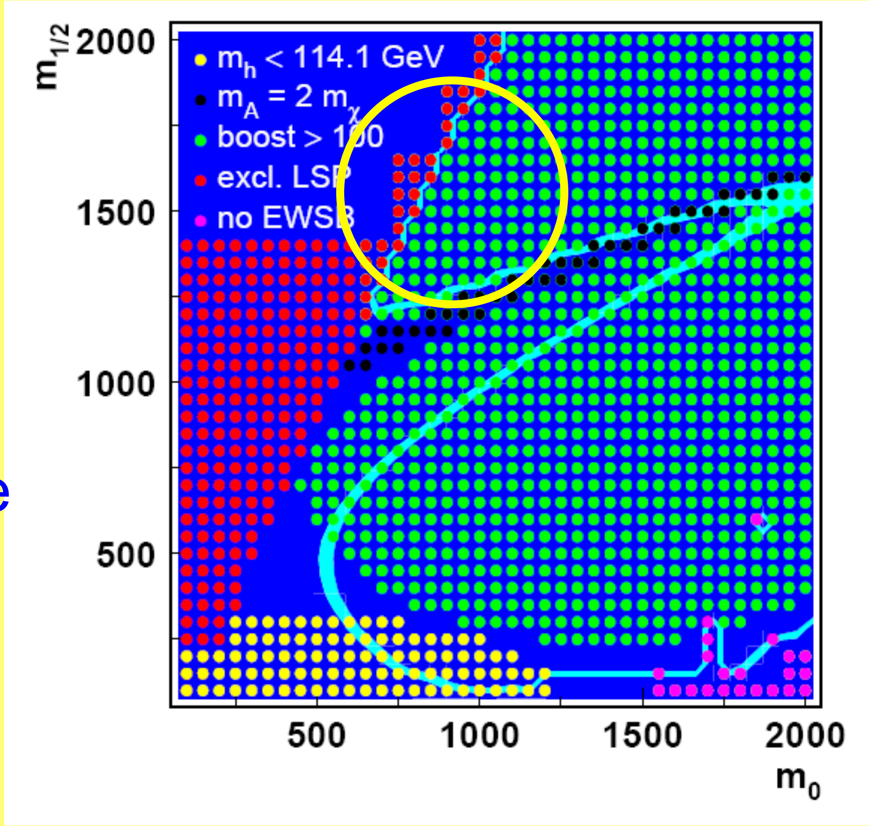
$\tilde{\chi}^0\tilde{\tau}$ -coannihilation region

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:

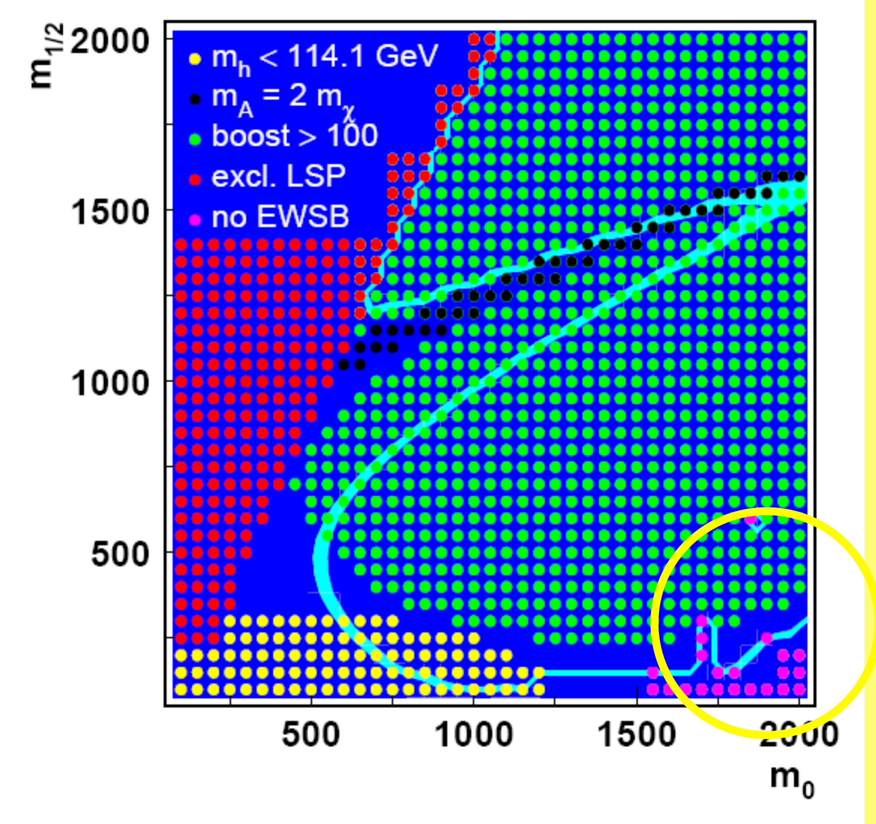
$$\chi\tilde{\tau} \rightarrow \tau^* \rightarrow \tau\gamma$$



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

Favoured regions of parameter space

Focus point region



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

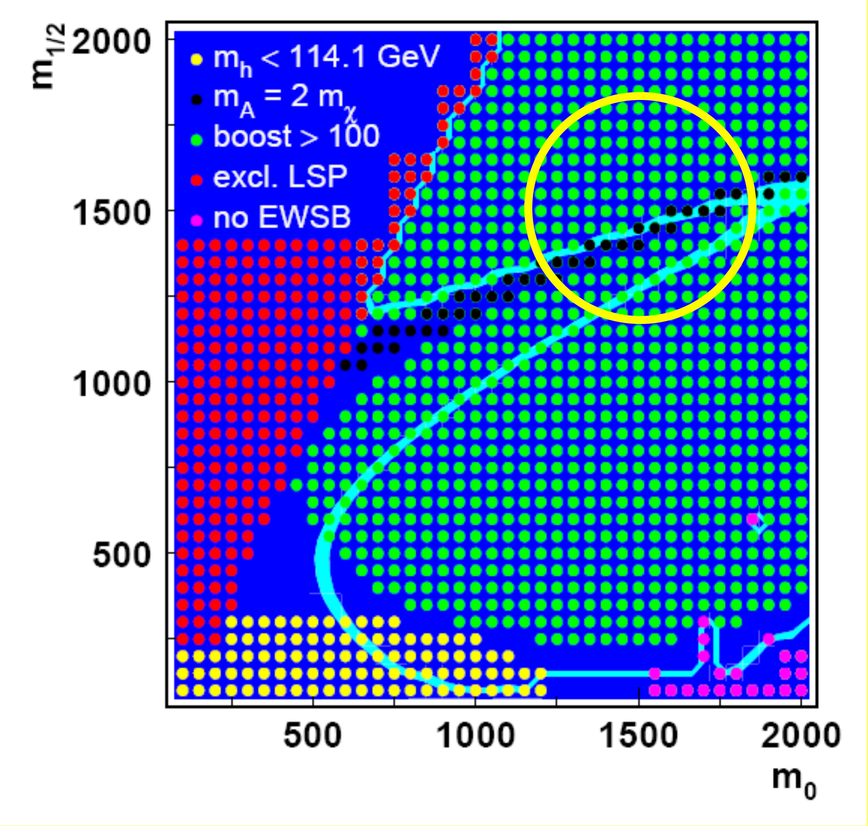
The region where

$$m_A \; ; \; 2m_\chi$$

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

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

The region requires large tan β and leads to heavy sparticles



Favoured regions of parameter space

EGRET region

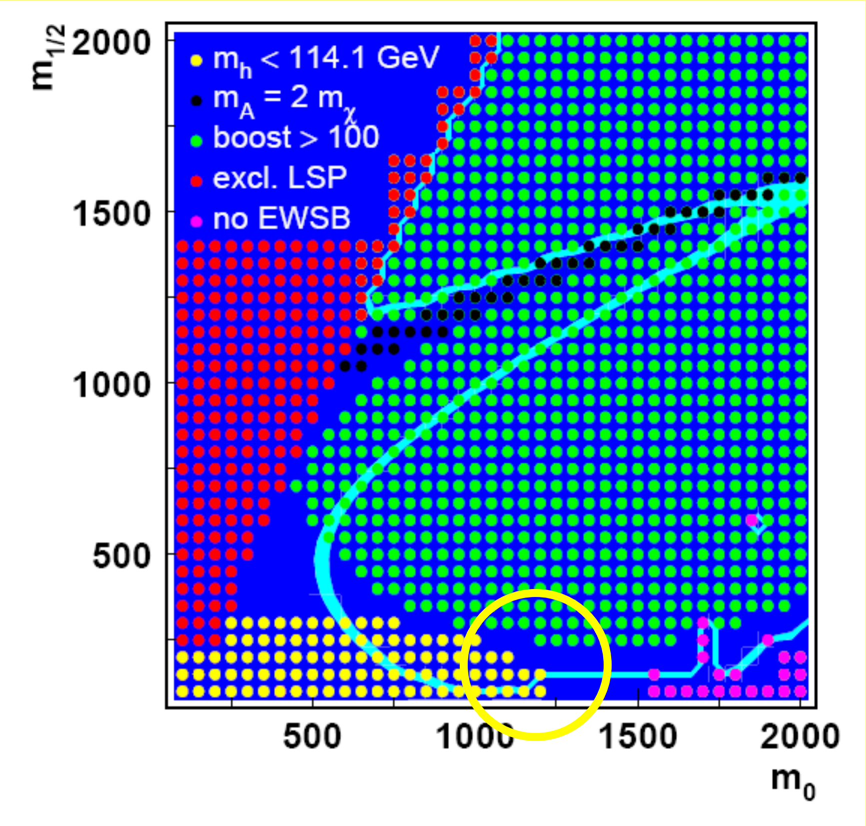
The region is compatible with diffuse gamma ray flux from the DM annihilation

It corresponds to the best fit values of parameters

tan β= 51

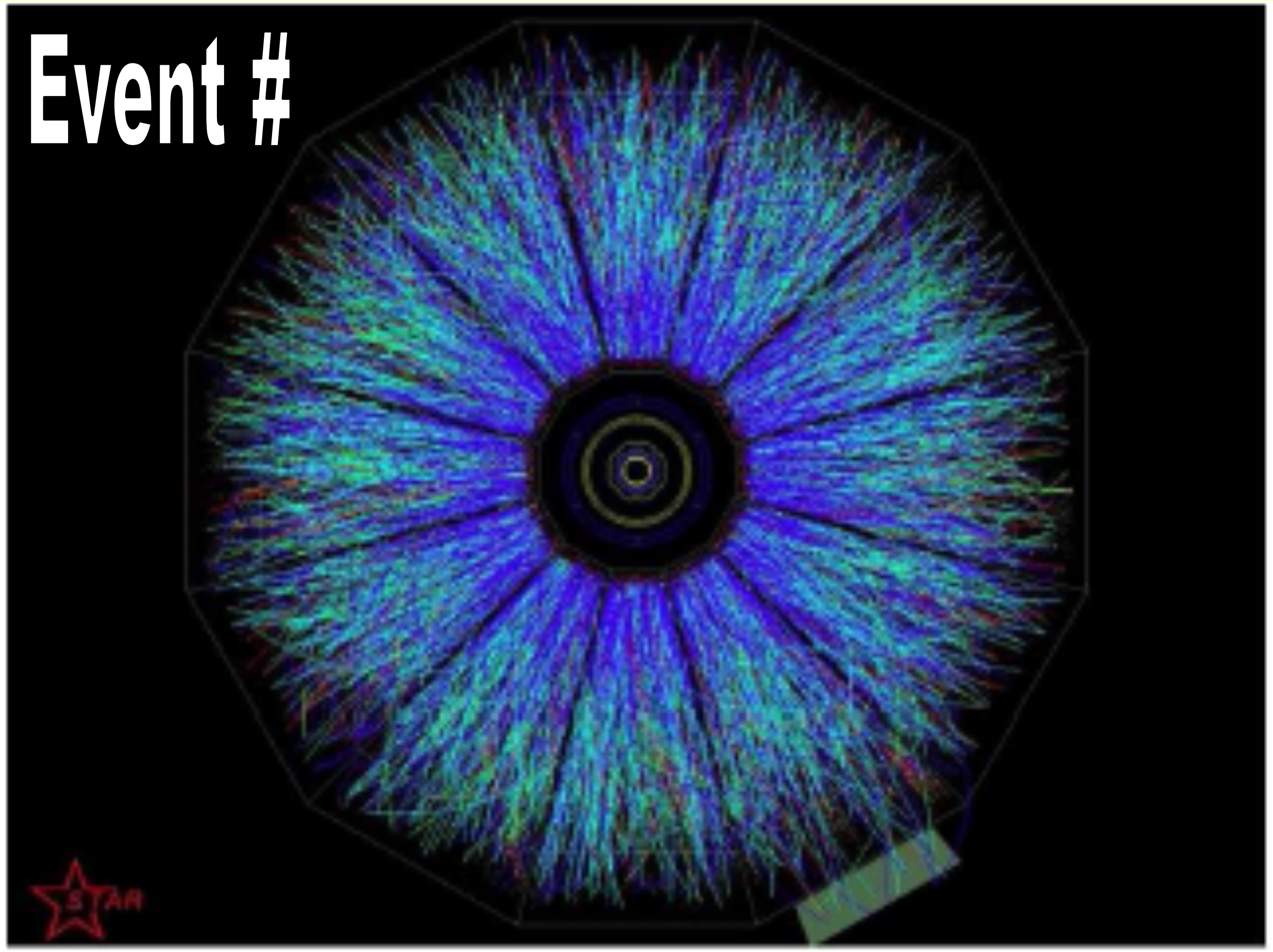
m0 = 1400 GeV

m1/2 = 180 GeV



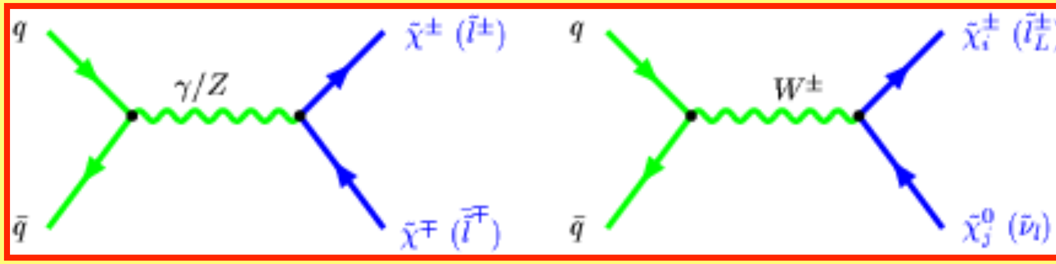
SUSY DM: $m_{\chi^0} \sim 65$ GeV → $m_{\chi^\pm} \sim 115$ GeV

Producing SUSY at Colliders

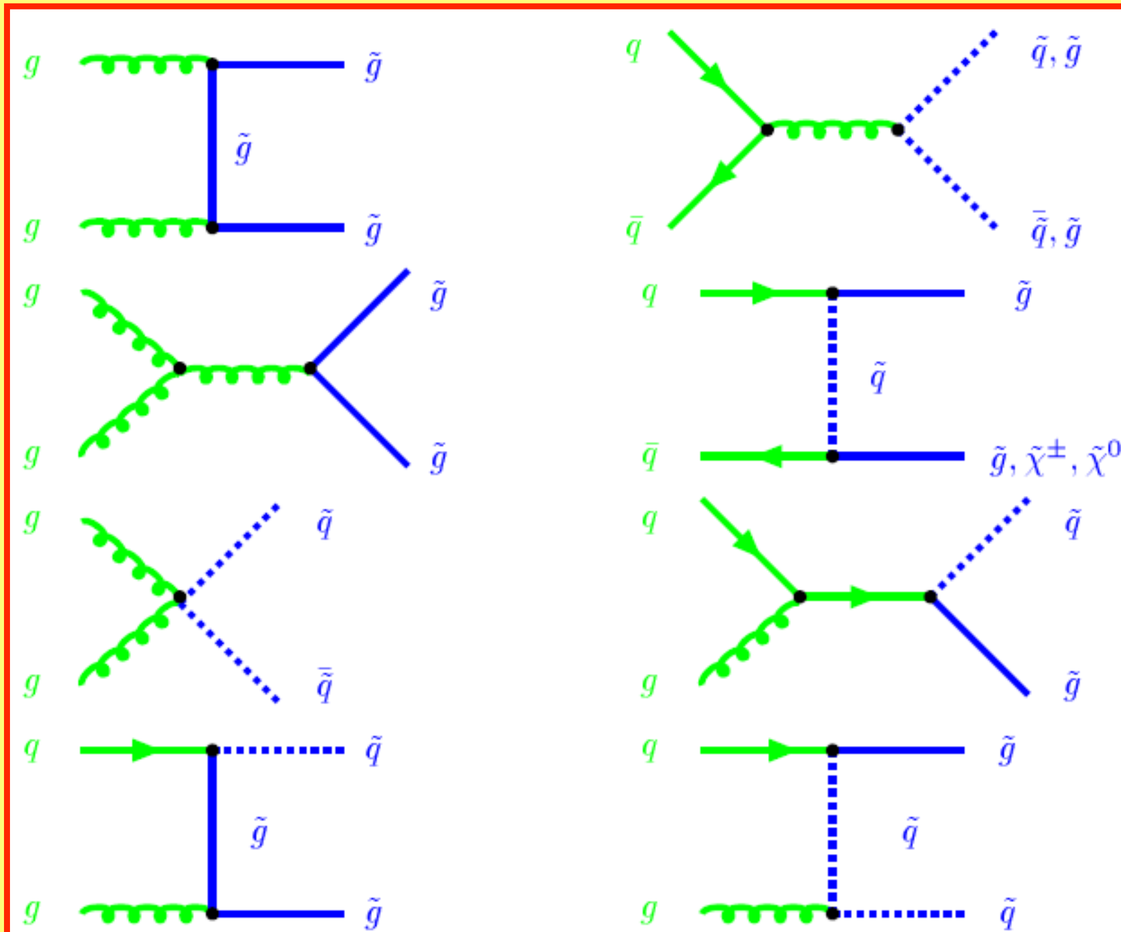


Superpartners Production at LHC

Annihilation



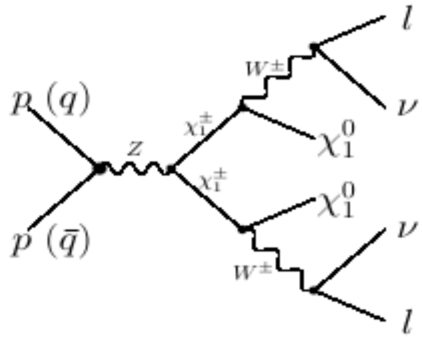
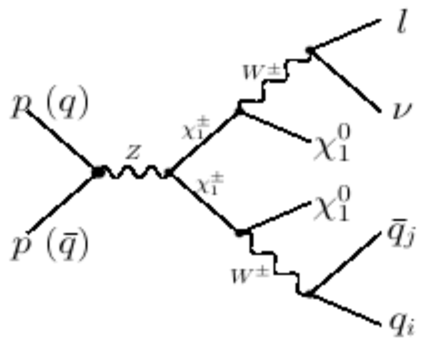
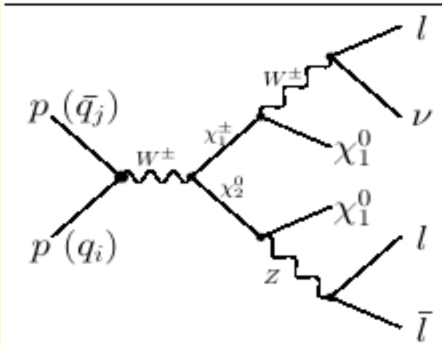
Quark- gluon Fusion

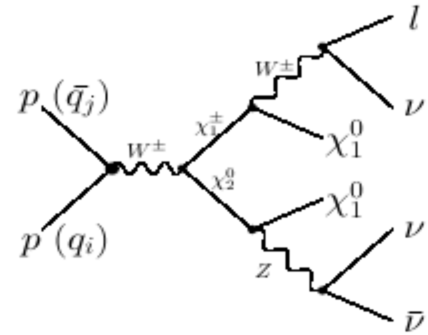
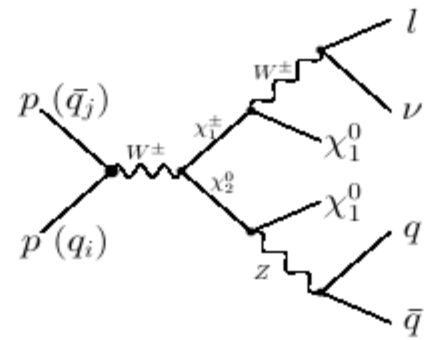
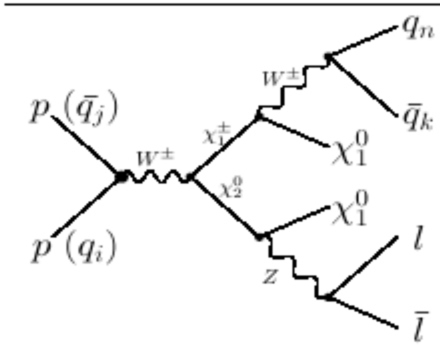


SUSY Signatures at LHC

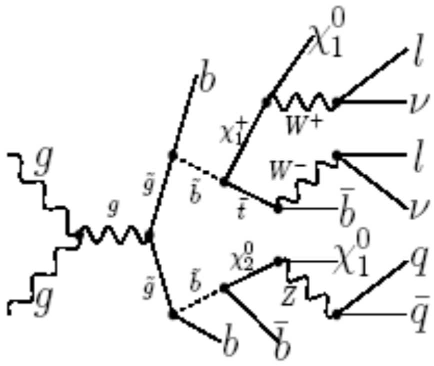
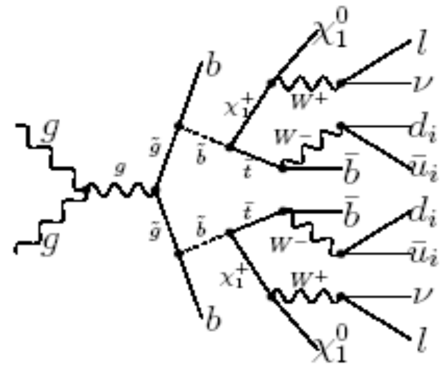
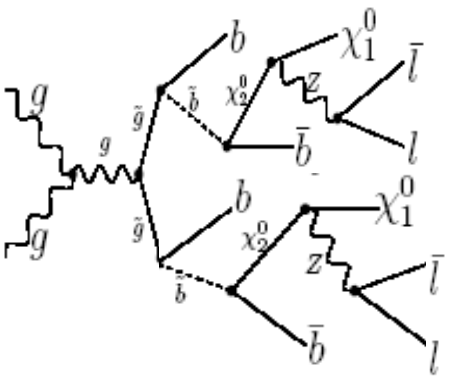
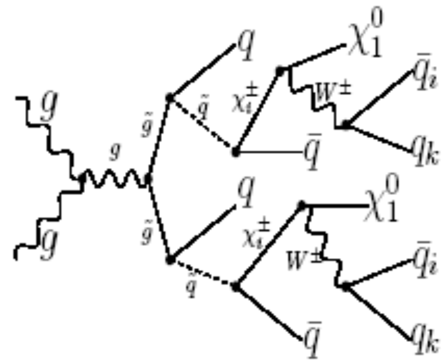
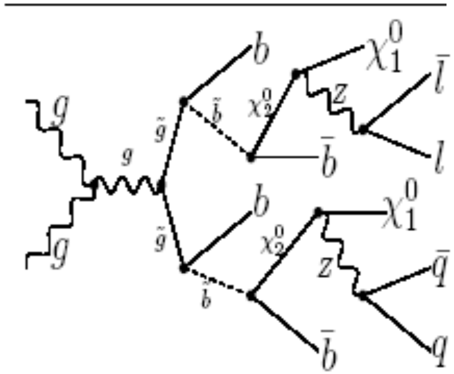
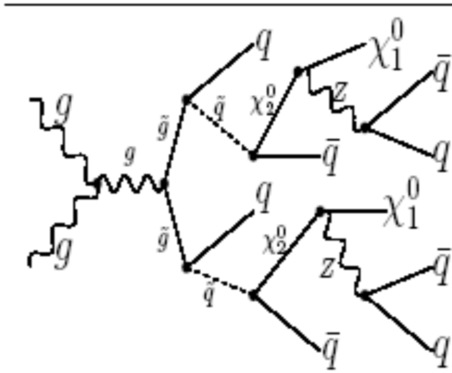
Production	Key Decay Modes	Signatures
• $\tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{g}\tilde{q}$	$\left.\begin{array}{l}\tilde{g} \to q\bar{q}\tilde{\chi}_1^0 \\ \quad q\bar{q}'\tilde{\chi}_1^\pm \\ \quad g\tilde{\chi}_1^0\end{array}\right\} m_{\tilde{q}} > m_{\tilde{g}}$ $\left.\begin{array}{l}\tilde{q} \to q\tilde{\chi}_i^0 \\ \tilde{q} \to q'\tilde{\chi}_i^\pm\end{array}\right\} m_{\tilde{g}} > m_{\tilde{q}}$	$\not{E}_T$ + 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)

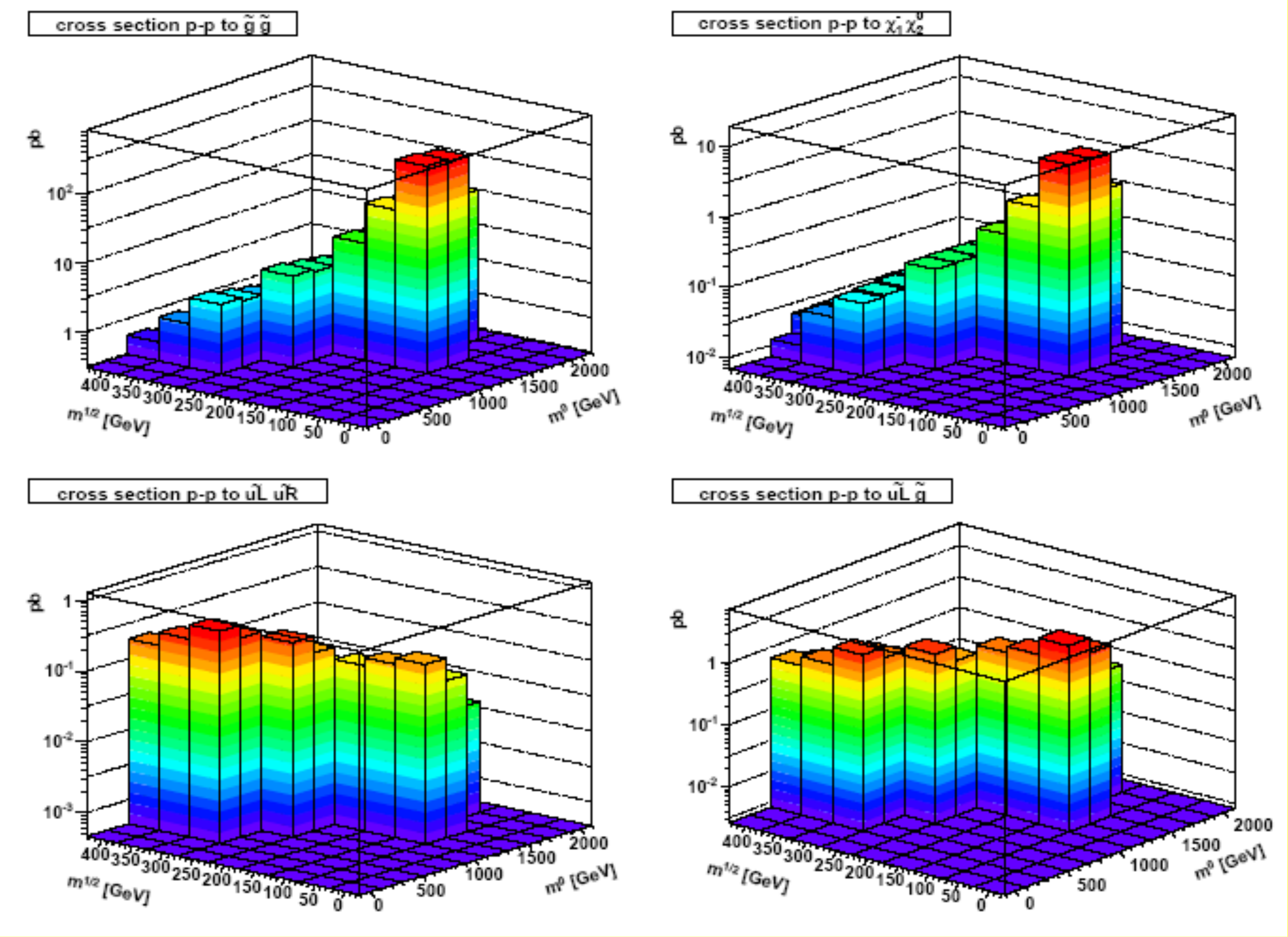
process	final states
	2ℓ 2ν $\not{E}_T$
	1ℓ $2j$ ν $\not{E}_T$
	3ℓ ν $\not{E}_T$

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

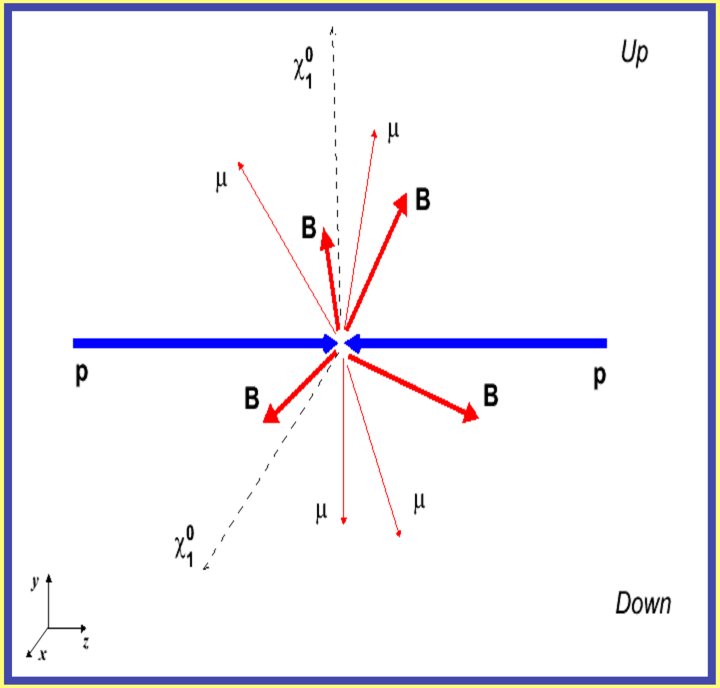
Cascade Processes (strong int's)

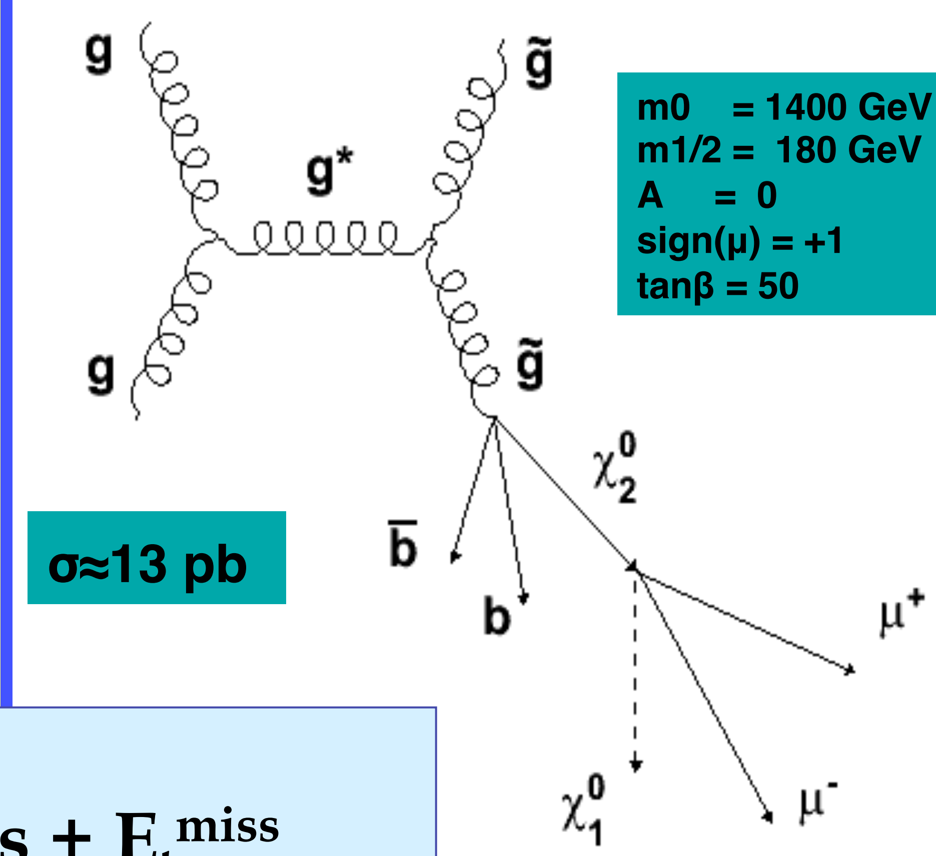
process	final states	process	final states
	2ℓ 2ν $6j$ $\not{E}_T$		2ℓ 2ν $8j$ $\not{E}_T$
	$4l$ $4j$ $\not{E}_T$		$8j$ $\not{E}_T$
	2ℓ $6j$ $\not{E}_T$		$8j$ $\not{E}_T$

Cross-Sections at LHC



SUSY PRODUCTION AT LHC





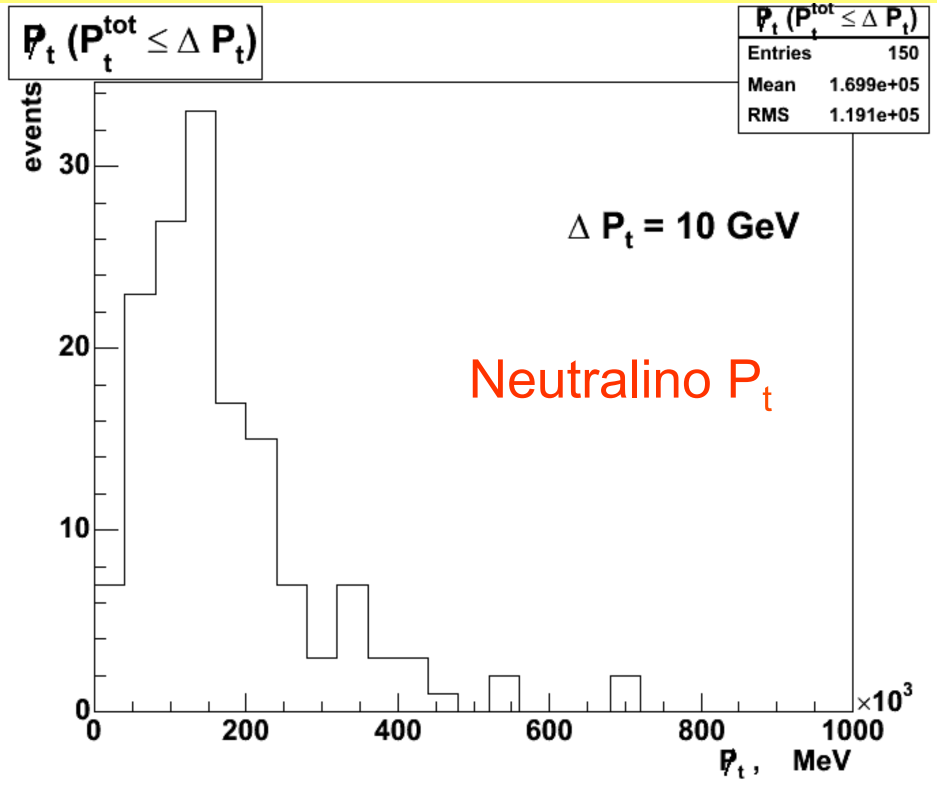
m0 = 1400 GeV
m1/2 = 180 GeV
A = 0
sign(μ) = +1
tanβ = 50

σ≈13 pb

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

LARGE!

SUSY $gg \to \tilde{g}\tilde{g}$ IN ATLAS

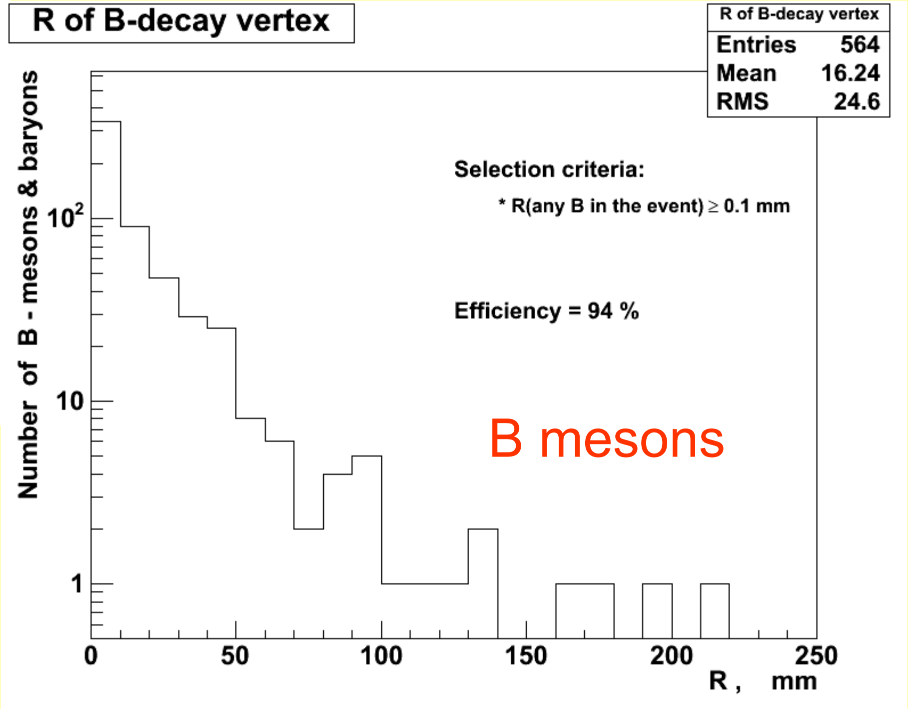


JINR(Dubna) ATLAS Group

V. Bednyakov, Y.Budagov, G. Khoriauli, J.Khubua

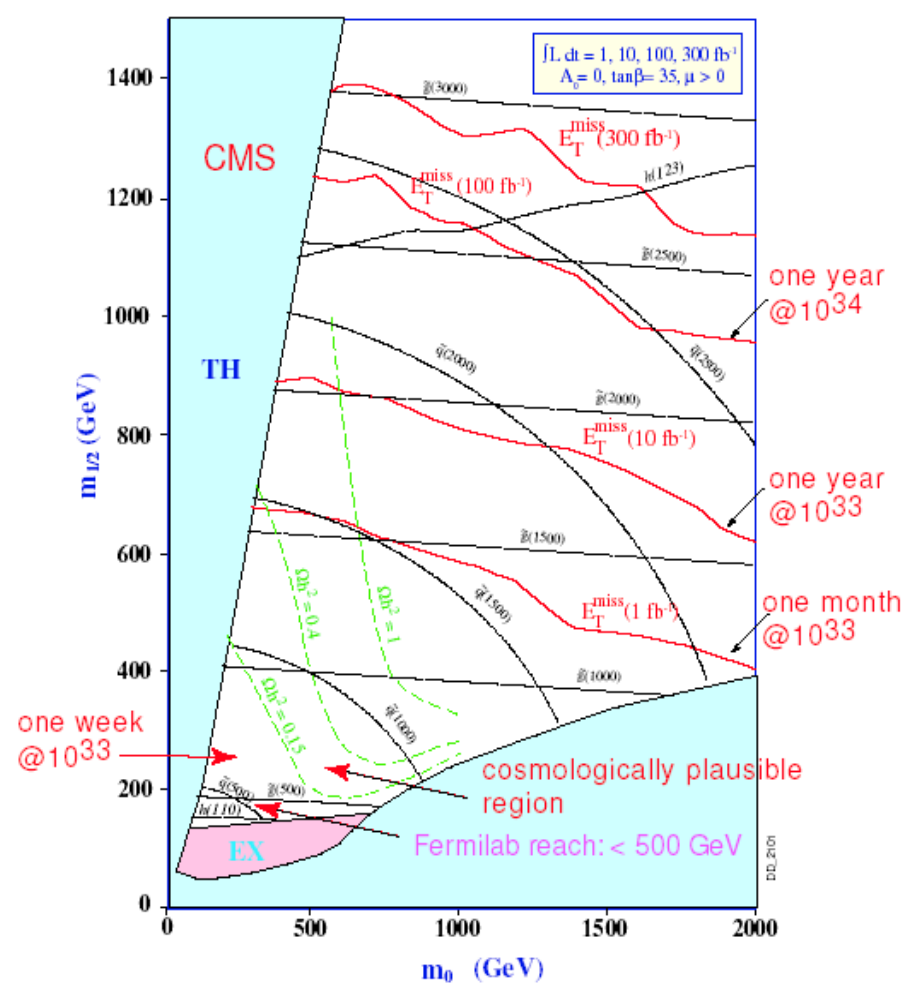
Pythia within ATHENA,

B-vertex taging

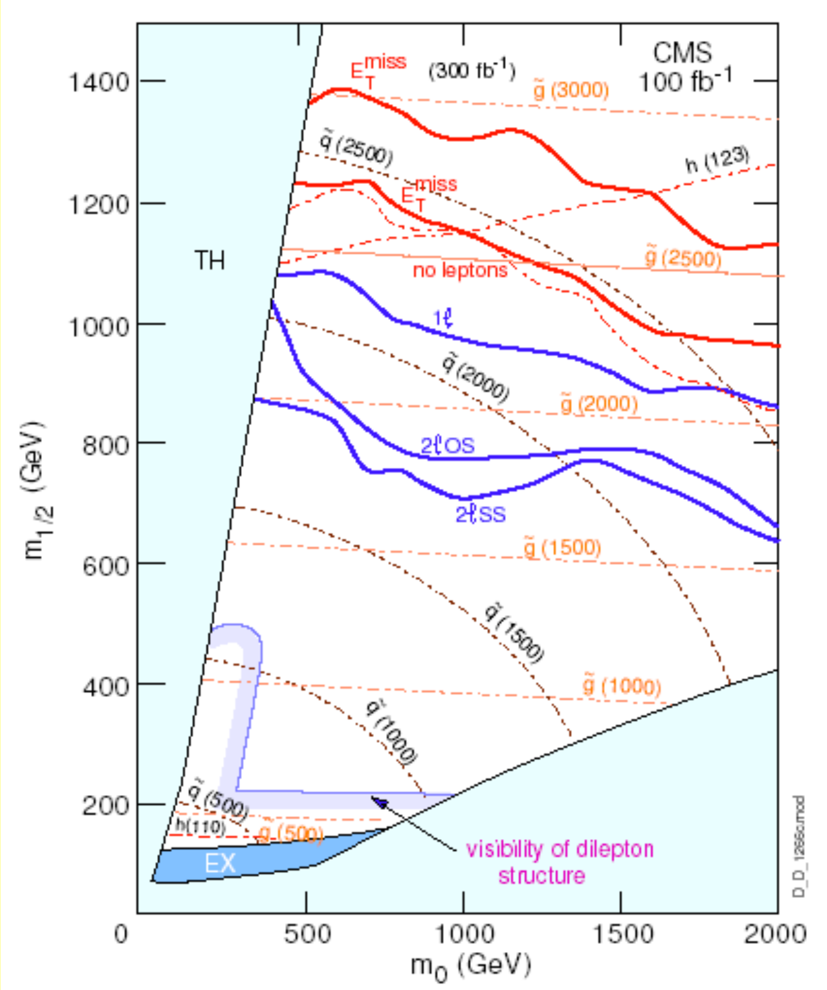


$$\Sigma P_t^{B,B,\mu,\mu}\text{(down)} - \Sigma P_t^{B,B,\mu,\mu}\text{(up)} = \not{P}_t \equiv \not{E}_t$$

SUSY Searches at LHC

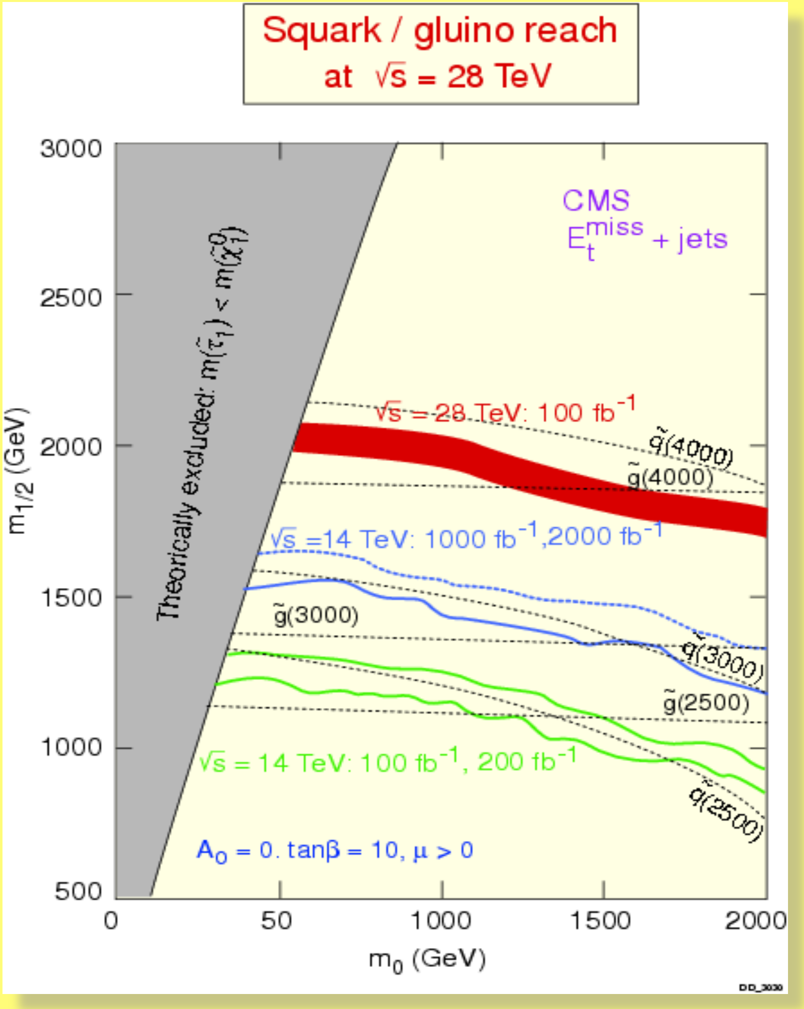


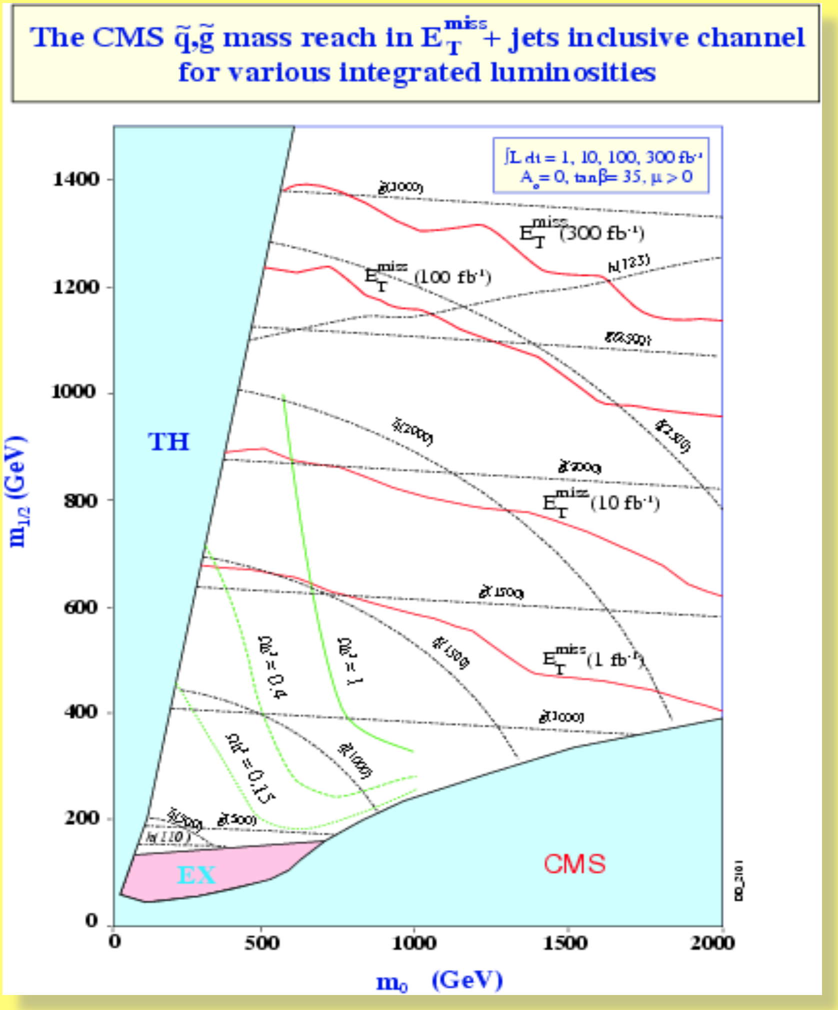
5 σ reach in jets + $\not{E}_T$ channel



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

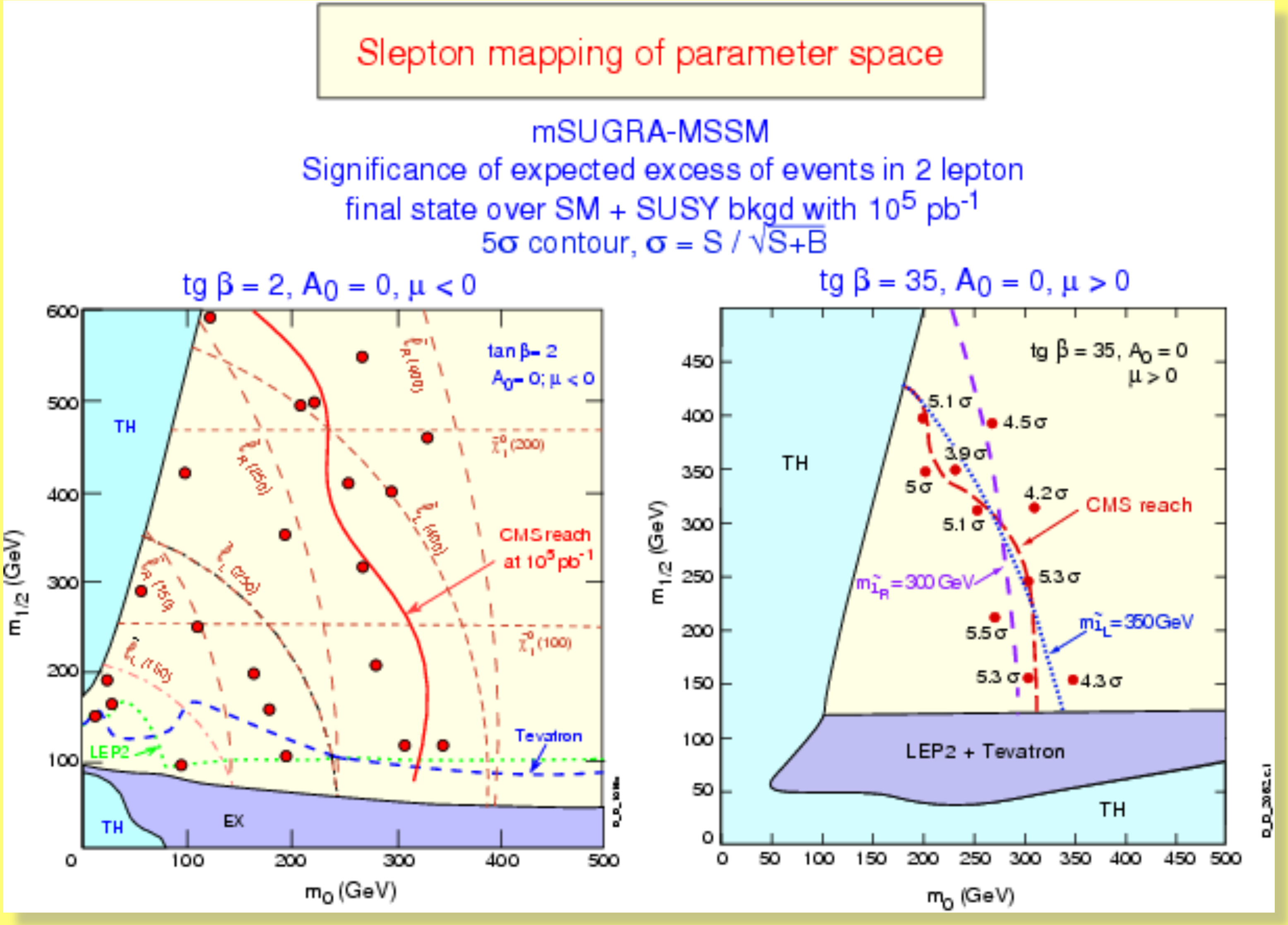
SUSY Searches at LHC





Squark and gluino reaches at various luminosities

SUSY Searches at LHC



SUSY Higgs Bosons

SM

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

4=2+2=3+1

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

MSSM

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

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

8=4+4=3+5

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

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

The Higgs Potential

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

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

Minimization

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

Solution

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

At the GUT scale

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

No SSB in SUSY theory !

The Higgs Bosons Masses

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

CP-even neutral Higgses h,H

$$m_A^2 = m_1^2 + m_2^2$$

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

$$M_W^2 = \frac{g^2}{2} v^2$$

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

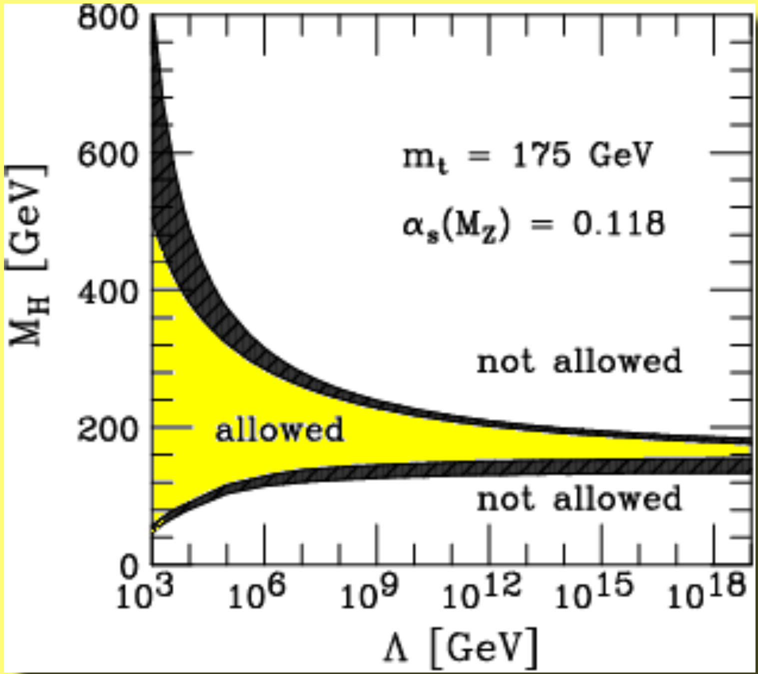
$$m_{h,H}^2 = \frac{1}{2}[m_A^2 + M_Z^2 \pm \sqrt{(m_A^2 + M_Z^2)^2 - 4 m_A^2 M_Z^2 \cos^2 2\beta}]$$

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

Radiative corrections

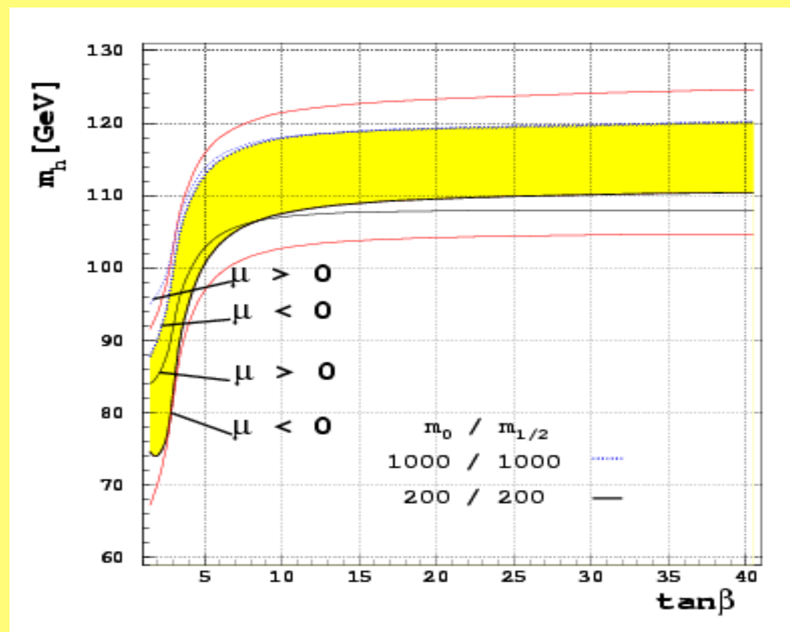
$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3 g^2 m_t^4}{16 \pi^2 M_W^2} \log \frac{\tilde{m}_{t_1}^2 \tilde{m}_{t_2}^2}{m_t^4} + 2 \; loops$$

The Higgs Mass Limit



- The SM Higgs

$m_H \geq 134$ GeV

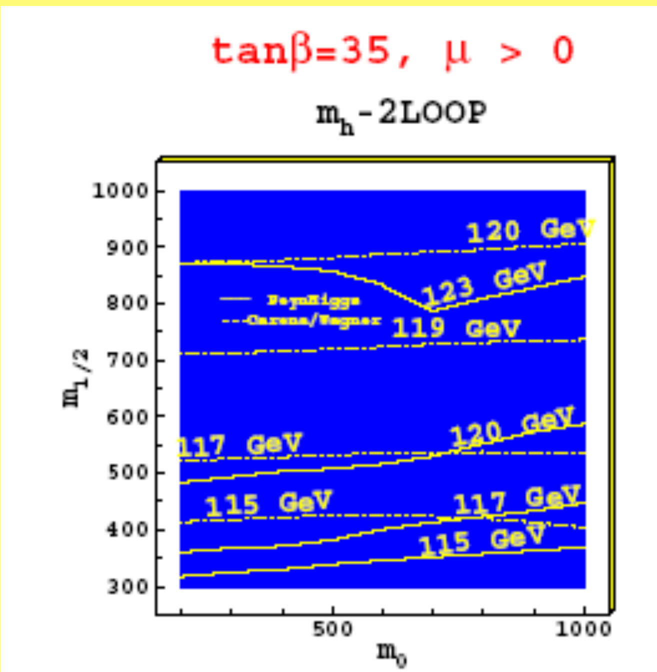


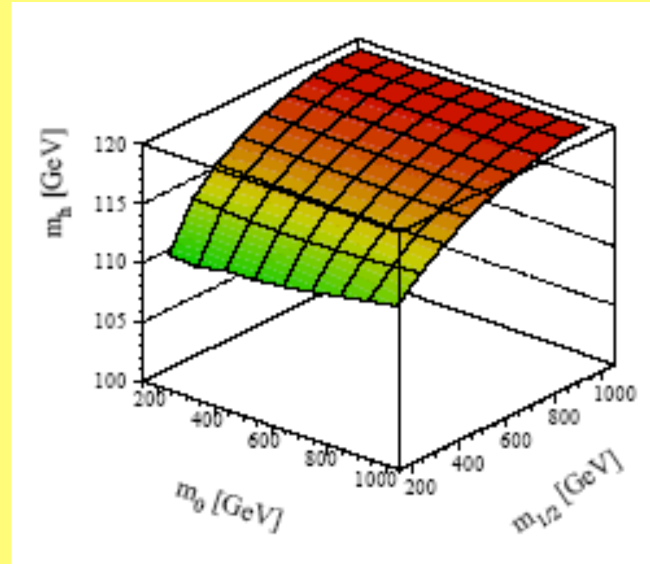
SUSY Higgs

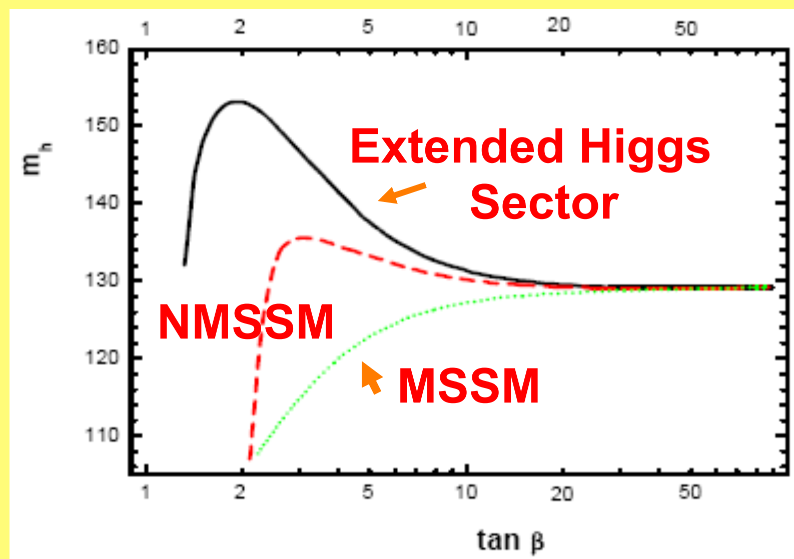
$m_H \leq 130$ GeV

The Higgs Mass Limit

The Higgs mass in the MSSM
with radiative corrections

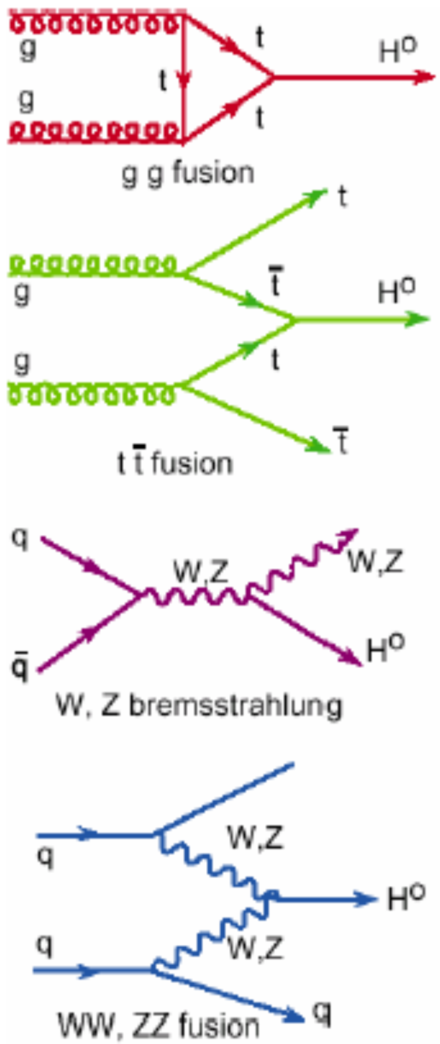


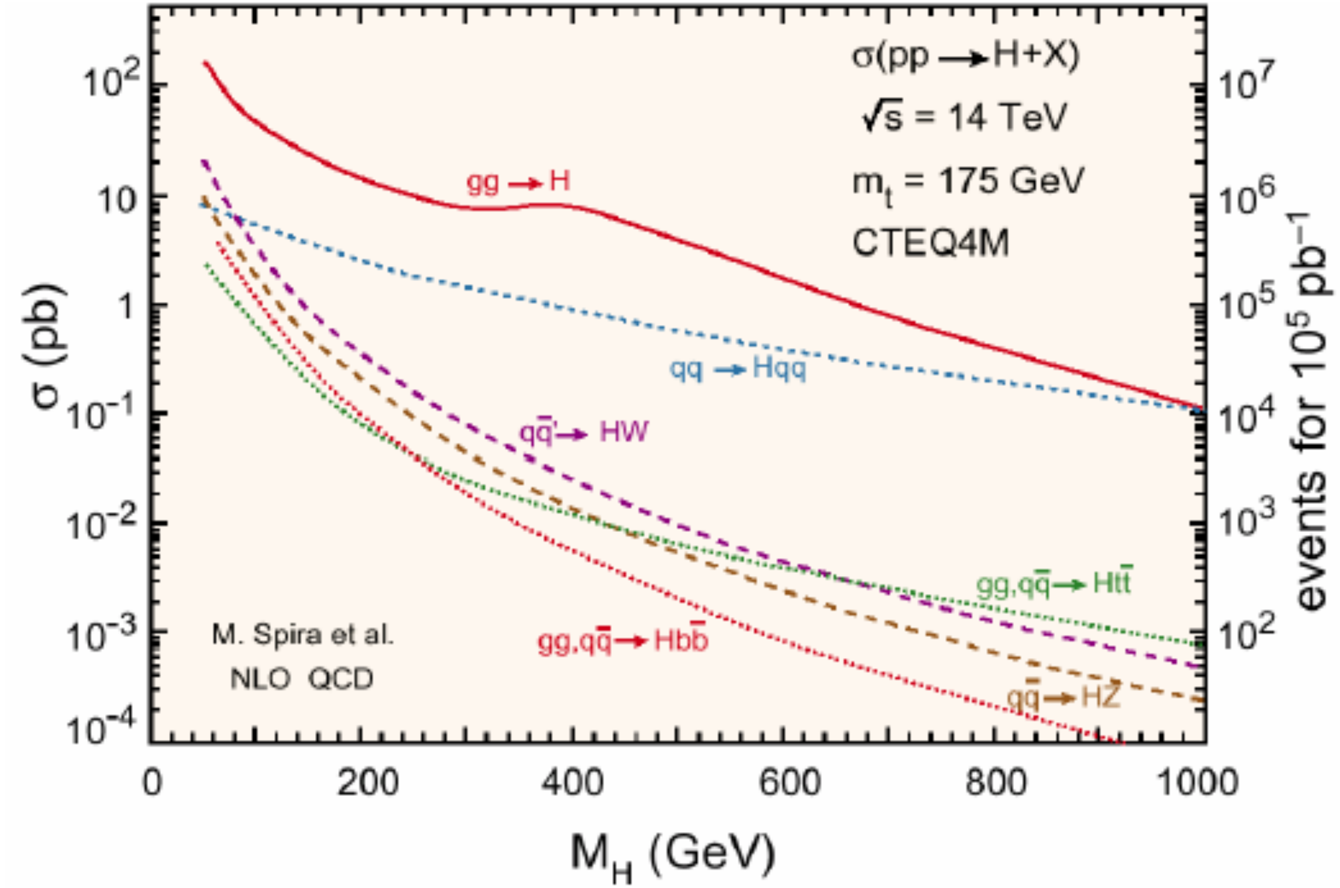




Search for SUSY Higgs

- Production mechanisms & cross section



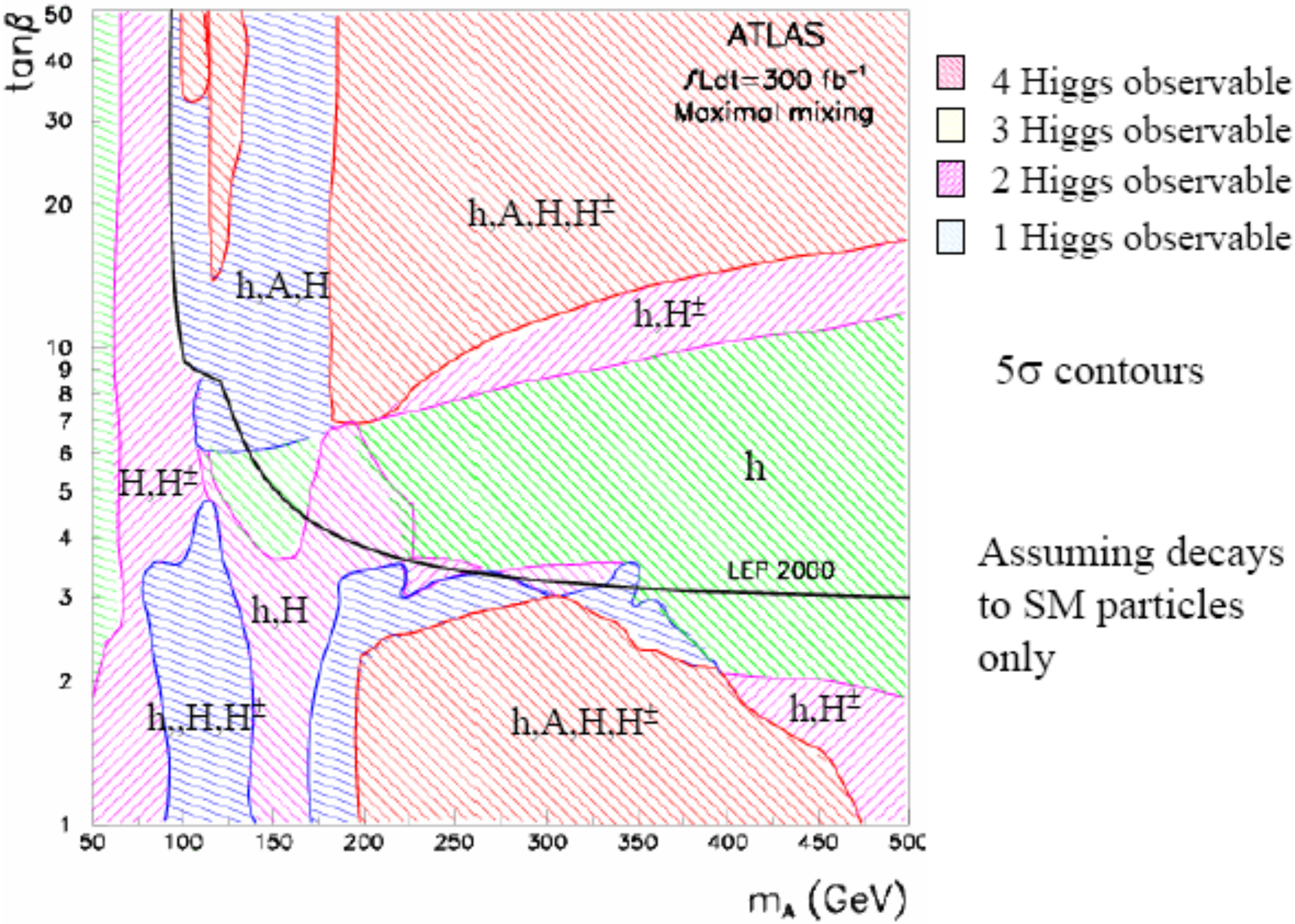


Higgs decay channels

- Channels currently being investigated:
  - H, $h \to \gamma\gamma$, $b\bar{b}$ ($H \to b\bar{b}$ in WH, $t\bar{t}H$) — (very) important and hopeful
  - $h \to \gamma\gamma$ in WH, $t\bar{t}h \to \ell\gamma\gamma$
  - h, H $\to ZZ^*$, $ZZ \to 4\ell$
  - h, H, A $\to \tau^+\tau^- \to (e/\mu)^+ + h^- + E_T^{miss}$
    $\to e^+ + \mu^- + E_T^{miss}$
    $\to h^+ + h^- + E_T^{miss}$
    } inclusively and in $b\bar{b}H_{SUSY}$
  - $H^+ \to \tau^+\nu$ from $t\bar{t}$
  - $H^+ \to \tau^+\nu$ and $H^+ \to t\bar{b}$ for $M_H > M_{top}$
  - $A \to Zh$ with $h \to b\bar{b}$; $A \to \gamma\gamma$
  - H, A $\to \tilde{\chi}^0_2\tilde{\chi}^0_2$, $\tilde{\chi}^0_i\tilde{\chi}^0_j$, $\tilde{\chi}^+_i\tilde{\chi}^-_j$
  - $H^+ \to \tilde{\chi}^+_2\tilde{\chi}^0_2$
    } promising
  - $qq \to qqH$ with $H \to \tau^+\tau^-$
  - $H \to \tau\tau$, in WH, $t\bar{t}H$

Observability of MSSM Higgses

MSSM Higgs bosons



5σ contours

Assuming decays to SM particles only

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