Collider Physics

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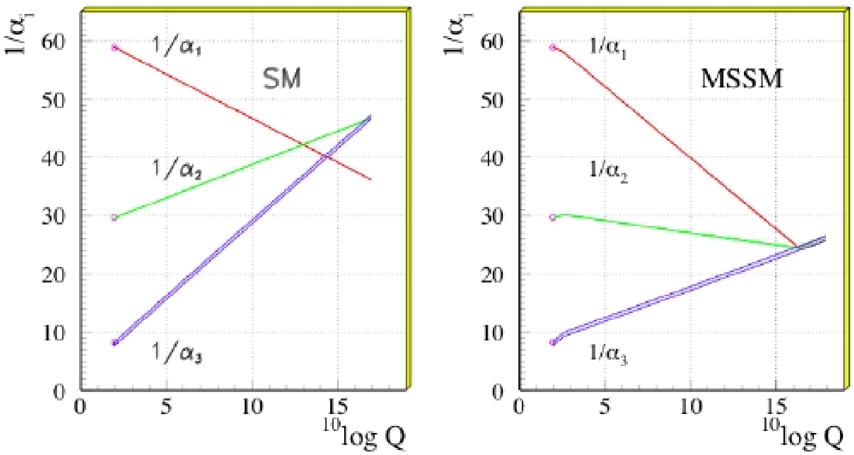
Third part: Beyond the SM searches

- I. SUSY searches at the LHC
- II. SUSY Higgses at the LHC
- III. Extra dimensions at the LHC

I. SUSY searches at the LHC

➪ SUSY has been extensively studied as a candidate for physics BSM:

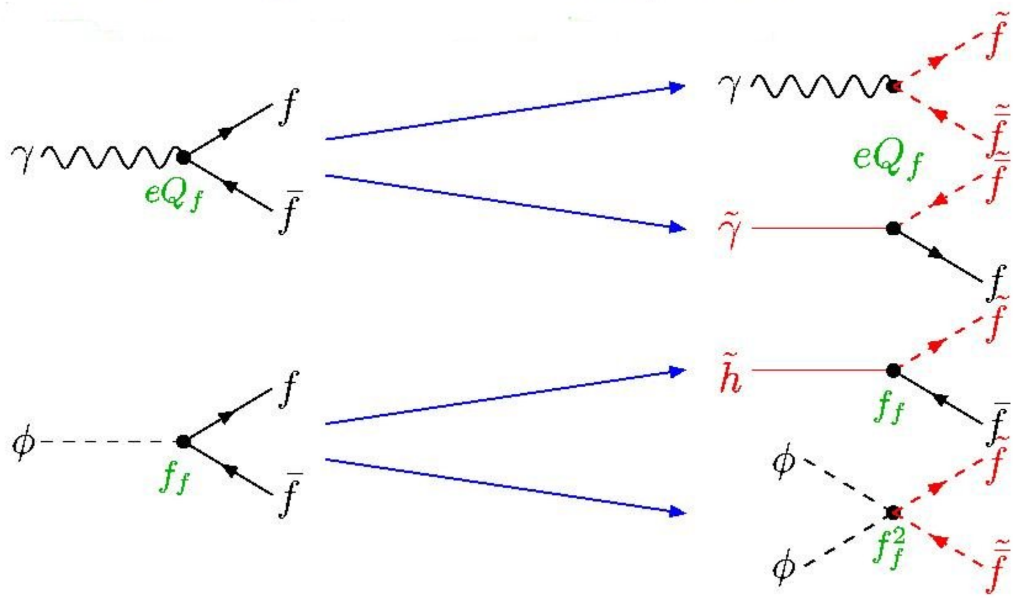
- the most general extension of the Poincaré group;
- SUSY can lead to coupling unification;
- Weak scale SUSY can solve the hierarchy problem;
- it is perturbative;
- SUSY has many signals $\Longrightarrow$ good work out



➩ In the minimal SUSY extension of the SM the new states are

particle name	symbol	spin
gluino	$\tilde{g}$	1/2
charginos	$\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^{\pm}$	1/2
neutralinos	$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$	1/2
sleptons	$\tilde{e}_L$, $\tilde{\nu}_{e_L}$, $\tilde{e}_R$	0
	$\tilde{\mu}_L$, $\tilde{\nu}_{\mu_L}$, $\tilde{\mu}_R$	0
	$\tilde{\tau}_1$,$\tilde{\tau}_2$, $\tilde{\nu}_{\tau_L}$	0
squarks	$\tilde{u}_L$, $\tilde{d}_L$, $\tilde{u}_R$,$\tilde{d}_R$	0
	$\tilde{c}_L$,$\tilde{s}_L$, $\tilde{c}_R$,$\tilde{s}_R$	0
	$\tilde{t}_1$, $\tilde{t}_2$, $\tilde{b}_1$,$\tilde{b}_2$	0
higgs	h, H, A, $H^{\pm}$	0

➪ Interactions are easy to "remember"



➪ Our goals

- measure the masses, decay widths, production cross sections, mixing angles, etc., of the new particles,
- prove that each particle can be associated to its superpartner with the expected spin and parity, gauge quantum numbers and couplings,
- reconstruct the low energy SUSY breaking parameters

➪ This will require more than one machine!

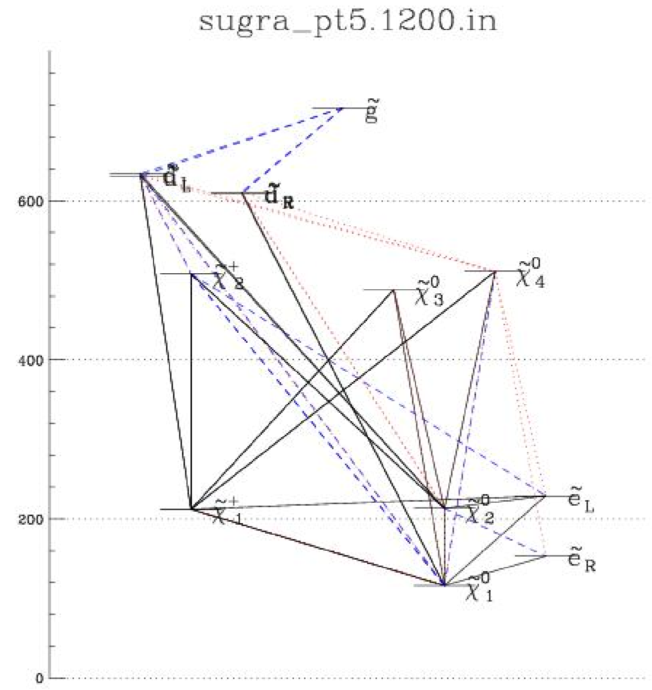
➪ To study the SUSY signals we need the spectrum, lifetimes and the decays

➪ This depends on the soft breaking terms and point in the parameter space

➪ General features

- complicated cascade decays
  many intermediate states

- typical signal for
  ($\mathbf{R = (-1)^{3B+L+2s}}$ conserved)
  - gluinos and squarks: jets
  - gauginos and sleptons: leptons
  - LSP: $\not{E}_T$

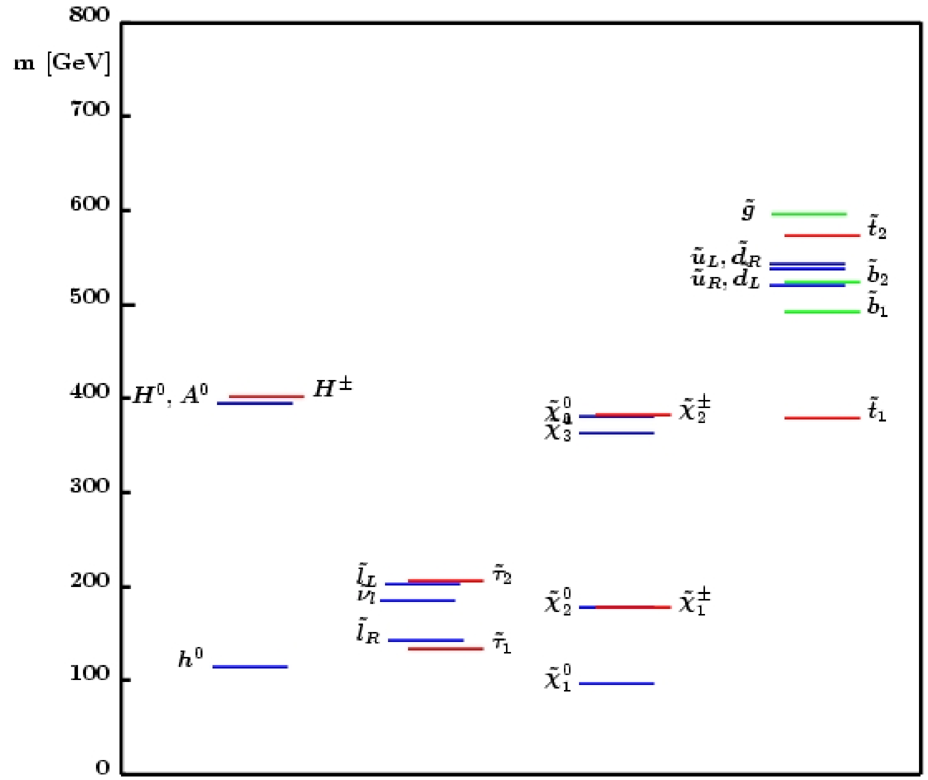


SPS1a

- SPS1a (MSUGRA)

$$m_0 = 100 \text{ GeV} ; \qquad m_{1/2} = 250 \text{ GeV} ;$$
$$A_0 = -100 \text{ GeV} ; \qquad \tan\beta = 10 ; \; \mu > 0$$

- SPS1a has a light spectrum



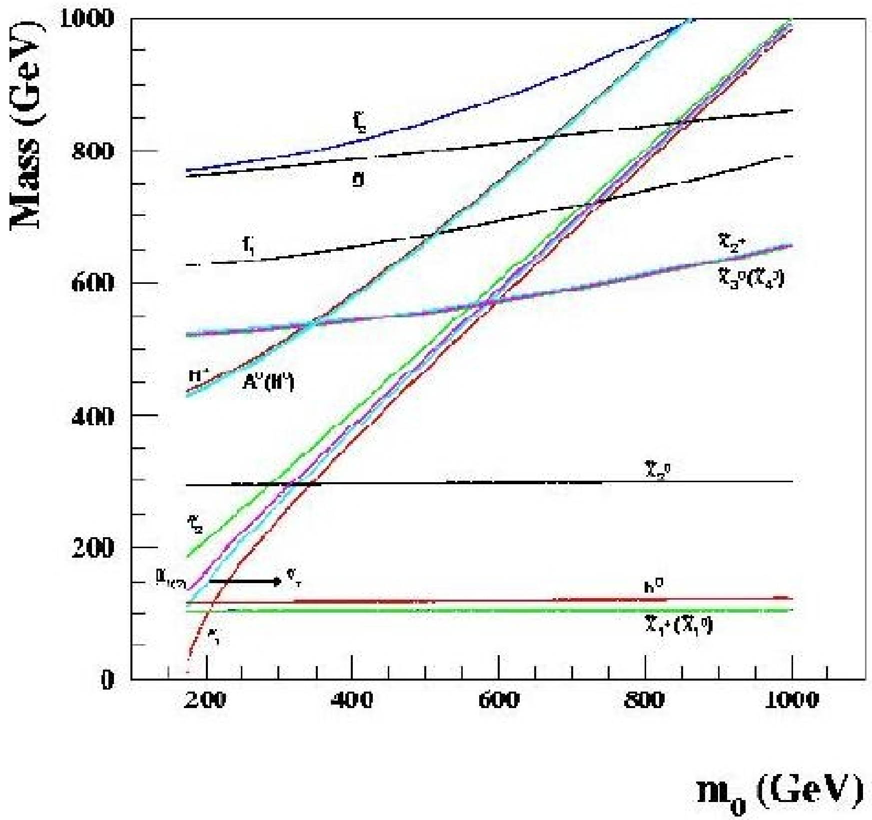
$\tilde{\ell}$	m [GeV]	decay	$\mathcal{B}$
$\tilde{e}_R$	143.0	$\tilde{\chi}_1^0 e^-$	1.000
$\tilde{e}_L$	202.1	$\tilde{\chi}_1^0 e^-$	0.490
		$\tilde{\chi}_2^0 e^-$	0.187
		$\tilde{\chi}_1^- \nu_e$	0.323
$\tilde{\nu}_e$	186.0	$\tilde{\chi}_1^0 \nu_e$	0.885
		$\tilde{\chi}_2^0 \nu_e$	0.031
		$\tilde{\chi}_1^+ e^-$	0.083
$\tilde{\mu}_R$	143.0	$\tilde{\chi}_1^0 \mu^-$	1.000
$\tilde{\mu}_L$	202.1	$\tilde{\chi}_1^0 \mu^-$	0.490
		$\tilde{\chi}_2^0 \mu^-$	0.187
		$\tilde{\chi}_1^- \nu_\mu$	0.323
$\tilde{\nu}_\mu$	186.0	$\tilde{\chi}_1^0 \nu_\mu$	0.885
		$\tilde{\chi}_2^0 \nu_\mu$	0.031
		$\tilde{\chi}_1^+ \mu^-$	0.083
$\tilde{\tau}_1$	133.2	$\tilde{\chi}_1^0 \tau^-$	1.000
$\tilde{\tau}_2$	206.1	$\tilde{\chi}_1^0 \tau^-$	0.526
		$\tilde{\chi}_2^0 \tau^-$	0.174
		$\tilde{\chi}_1^- \nu_\tau$	0.300
$\tilde{\nu}_\tau$	185.1	$\tilde{\chi}_1^0 \nu_\tau$	0.906
		$\tilde{\chi}_1^+ \tau^-$	0.067

$\tilde{\chi}$	m [GeV]	decay	$\mathcal{B}$
$\tilde{\chi}_1^0$	96.1		
$\tilde{\chi}_2^0$	176.8	$\tilde{e}_R^\pm e^\mp$	0.062
		$\tilde{\mu}_R^\pm \mu^\mp$	0.062
		$\tilde{\tau}_1^\pm \tau^\mp$	0.874
$\tilde{\chi}_3^0$	358.8	$\tilde{\chi}_1^\pm W^\mp$	0.596
		$\tilde{\chi}_1^0 Z^0$	0.108
		$\tilde{\chi}_2^0 Z^0$	0.215
$\tilde{\chi}_4^0$	377.8	$\tilde{\chi}_1^\pm W^\mp$	0.526
		$\tilde{\chi}_1^0 h^0$	0.064
		$\tilde{\chi}_2^0 h^0$	0.134

$\tilde{\chi}$	m [GeV]	decay	$\mathcal{B}$
$\tilde{\chi}_1^+$	176.4	$\tilde{\tau}_1^+ \nu_\tau$	0.979
$\tilde{\chi}_2^+$	378.2	$\tilde{\chi}_1^0 W^+$	0.064
		$\tilde{e}_L^+ \nu_e$	0.052
		$\tilde{\mu}_L^+ \nu_\mu$	0.052
		$\tilde{\tau}_2^+ \nu_\tau$	0.056
		$\tilde{\chi}_1^+ Z^0$	0.244
		$\tilde{\chi}_1^+ h^0$	0.170

BACK

AMSB spectrum

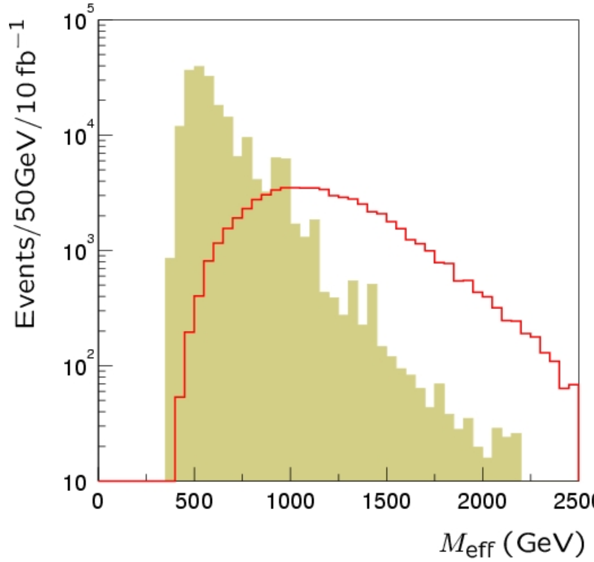


- A different boundary condition at the unification scale
- Defined by: $\mathbf{m_0}, \mathbf{m_{3/2}}, \tan\beta,$ sign(μ)

Inclusive SUSY search

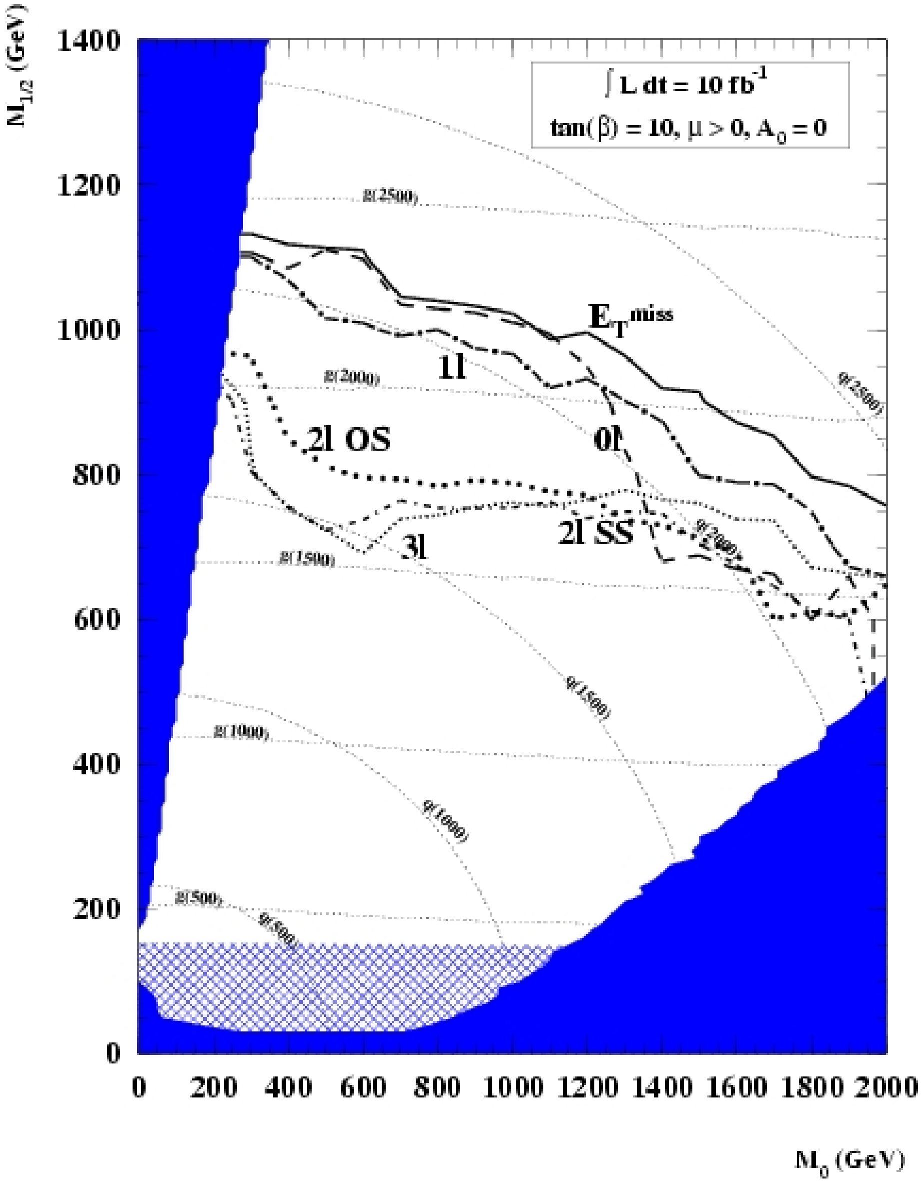
- LHC $\Longrightarrow$ jets and missing $\not{E}_T$
- $\sigma(\mathbf{1}\text{ TeV}) \simeq \mathcal{O}(\mathbf{10}\text{ pb})$
- define $\mathbf{M}_{\rm SUSY} = \min(\mathbf{m}_{\tilde{\mathbf{g}}}, \mathbf{m}_{\tilde{\mathbf{q}}})$

$$\mathbf{M}_{\rm eff} \equiv \sum_{j=1}^{4} \mathbf{p}_T^j + \not{E}_T \ \propto \mathbf{M}_{\rm SUSY}$$

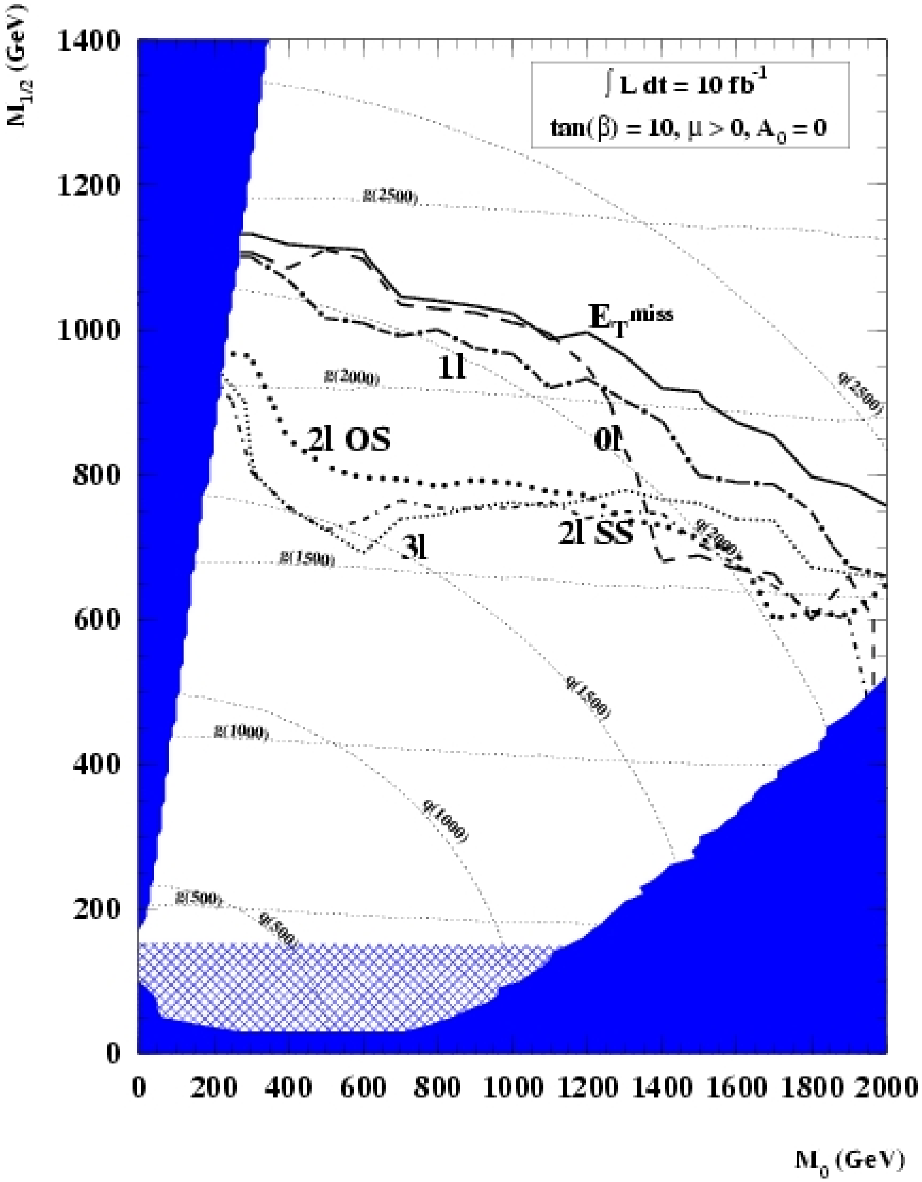


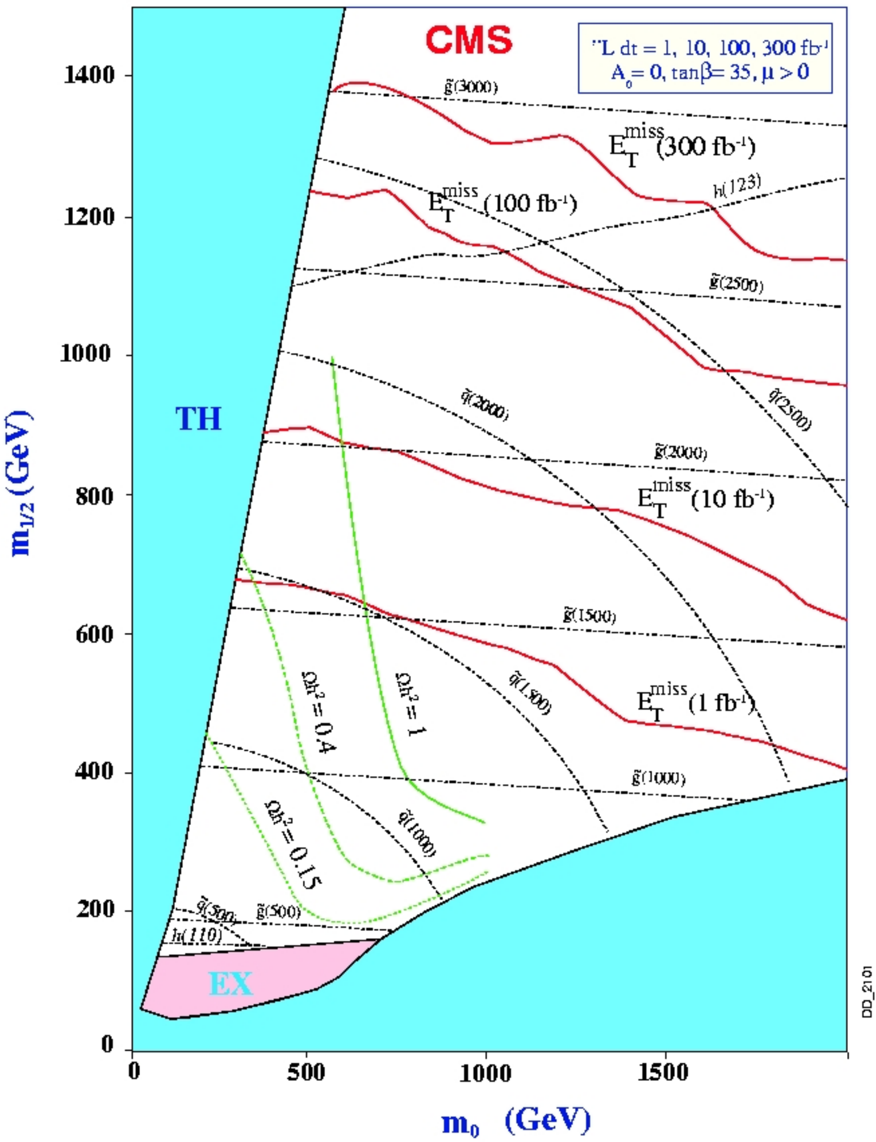
- Example: cuts to extract the jets $+\not{E}_T$ signal

- 4 jets with $\mathbf{p_T} > \mathbf{50}$ GeV (2 with $\mathbf{p_T} > \mathbf{100}$ GeV)
- $\not{E}_T > \max(\mathbf{0.2M_{\rm eff}}, \mathbf{100}\text{ GeV})$
- no lepton

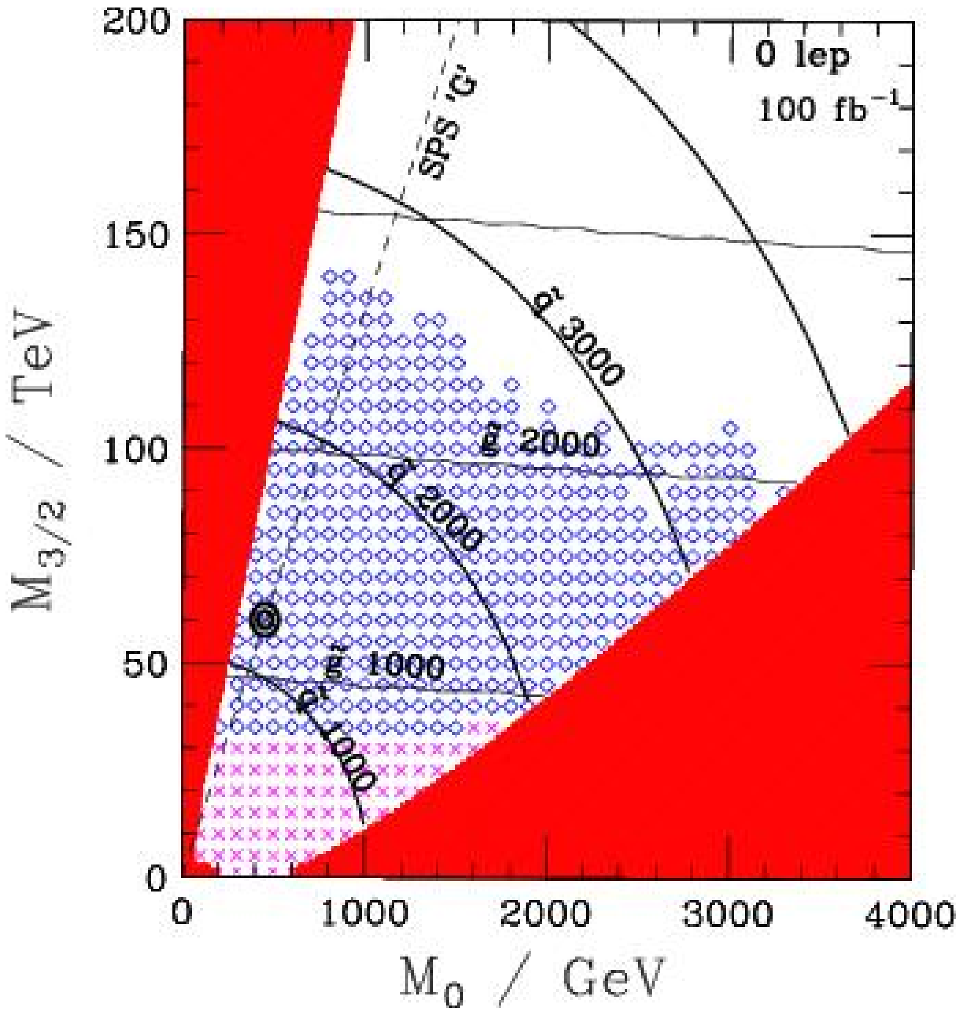


$\int L\,dt = 10\ fb^{-1}$
$\tan(\beta) = 10, \mu > 0, A_0 = 0$
E_T^{miss}
1l
0l
2l OS
2l SS
3l
g(2500)
g(2000)
g(1500)
g(1000)
g(500)
q(2500)
q(2000)
q(1500)
q(1000)
q(500)
$M_{1/2}$ (GeV)
M_0 (GeV)
0
200
400
600
800
1000
1200
1400
1600
1800
2000


∫ L dt = 10 fb^-1
tan(β) = 10, μ > 0, A0 = 0
ET miss
1l
0l
2l OS
2l SS
3l
M1/2 (GeV)
M0 (GeV)


CMS
∫L dt = 1, 10, 100, 300 fb-1
A0 = 0, tanβ= 35, μ > 0
TH
EX
ET miss (300 fb-1)
ET miss (100 fb-1)
ET miss (10 fb-1)
ET miss (1 fb-1)
Ωh² = 0.4
Ωh² = 1
Ωh² = 0.15
m1/2 (GeV)
m0 (GeV)
DD_2101

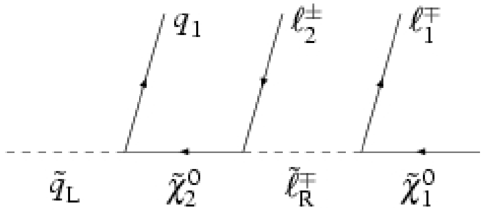
AMSB has reach similar do mSUGRA



Exclusive SUSY search

❈ Reconstruction is quite involved due to:

- long decay chains $\Longrightarrow$ huge combinatorics
- unknown boost of the subprocess CMS
- Undetectable LSP $\Longrightarrow$ not possible to reconstruct invariant masses event by event



❈ Measurement of SUSY masses $\Longrightarrow$ kinematic endpoints (SPS1a)

❈ Consider $\tilde{q}_L \to q\tilde{\chi}_2^0 \to q l_2^\pm \tilde{l}_R^\mp \to q l_2^\pm l_1^\mp \tilde{\chi}_1^0$

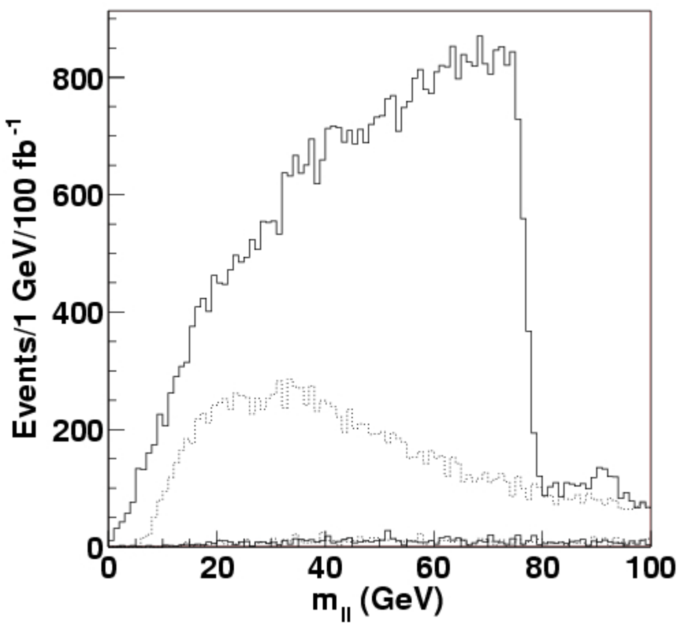
❈ m_{ll} has an edge due to $3 \to 2$ kinematics (Prove it!)

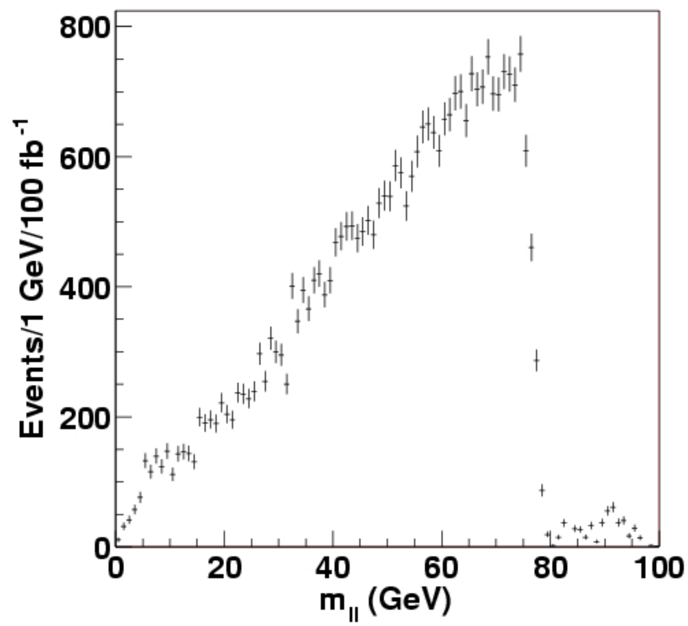
$$(m_{ll}^2)^{edge} = \frac{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2)(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{l}_R}^2}$$

❈ Cuts to isolate select this chain

- At least four jets: $p_{T,1} > 150$ GeV, $p_{T,2} > 100$ GeV, $p_{T,3} > 50$ GeV.
- $M_{eff} \equiv E_{T,miss} + p_{T,1} + p_{T,2} + p_{T,3} + p_{T,4} > 600$ GeV
- $E_{T,miss} > \max(100 \text{ GeV}, 0.2 M_{eff})$
- Two isolated Opposite–Sign Same–Flavour (OS-SF) leptons (not τ) $p_T(l) > 20$ GeV and $p_T(l) > 10$ GeV

- The edge is quite sharp





- Main background is from SUSY and can be subtracted from OSOF leptons

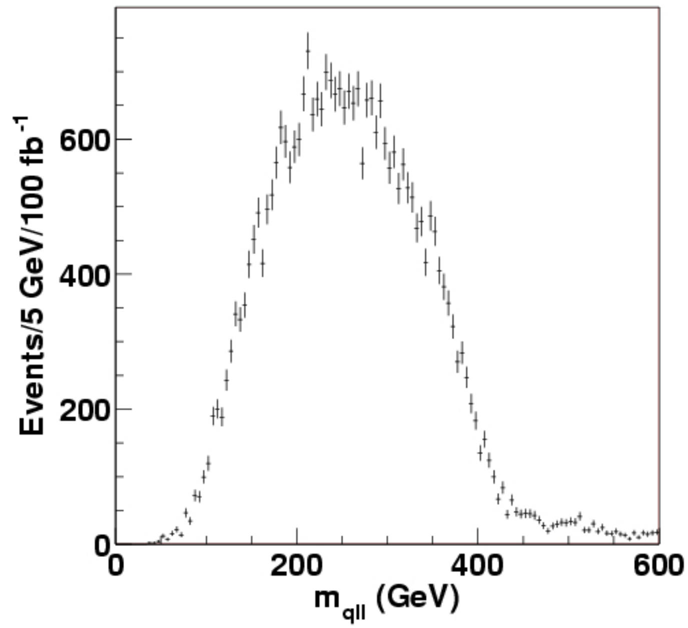
❄ Long decay chain $\Longrightarrow$ more edges available

$$(m^2_{qll})^{\rm edge} = \frac{(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{\chi}^0_1})}{m^2_{\tilde{\chi}^0_2}}$$

$$(m^2_{ql})^{\rm edge}_{\rm min} = \frac{(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R})}{m^2_{\tilde{\chi}^0_2}}$$

$$(m^2_{ql})^{\rm edge}_{\rm max} = \frac{(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1})}{m^2_{\tilde{l}_R}}$$

$$(m^2_{qll})^{\rm thres} = [(m^2_{\tilde{q}_L} + m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R}$$



- The masses can be obtained with a precision

	LHC
$\Delta m_{\tilde{\chi}_1^0}$	4.8
$\Delta m_{\tilde{l}_R}$	4.8
$\Delta m_{\tilde{\chi}_2^0}$	4.7
$\Delta m_{\tilde{q}_L}$	8.7
$\Delta m_{\tilde{b}_1}$	13.2

- Some information on the spin of SUSY particles can also be extracted

II. SUSY Higgses at the LHC

- SUSY requires more than one Higgs doublet

- In the minimal version one extra Higgs doublet must added

$$\mathbf{\Phi_1} = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} \quad , \quad \mathbf{\Phi_2} = \begin{pmatrix} \phi_2^0 \\ \phi_2^- \end{pmatrix}$$

- Quartic couplings are fixed by SUSY $\simeq$ gauge couplings

- Physical spectrum: 2 neutral CP-even states $(\mathbf{h},\ \mathbf{H})$, 1 neutral CP-odd $(\mathbf{A})$ and the charged $\mathbf{H}^\pm$

- The physical Higgs are mixtures of the initial doublets $\Longrightarrow$ couplings to other particles depend on mixing angles, *e.g.* $\mathbf{G_{hdd}} = -\mathbf{i}\frac{\mathbf{m_d}}{\mathbf{v}}\frac{\sin\alpha}{\cos\beta}$

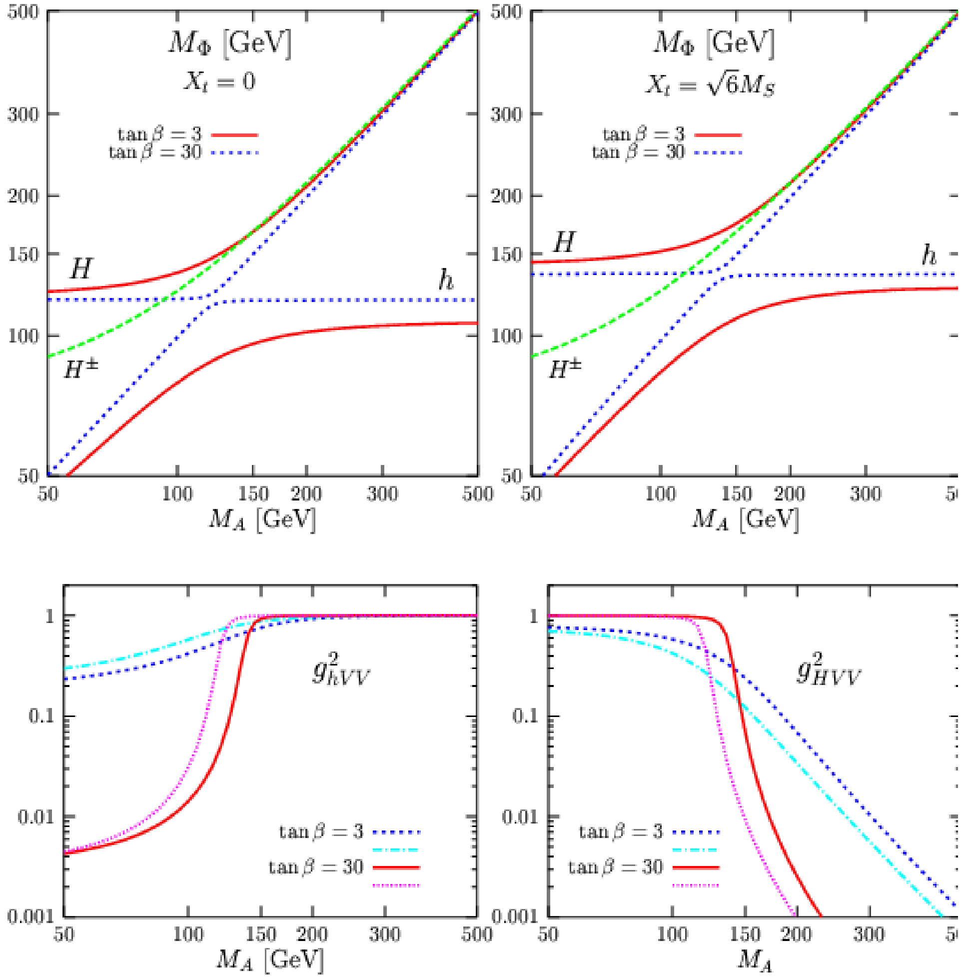
- At tree level there are only two independent parameters $\mathbf{M_A}$ and $\tan\beta$

$$\mathbf{M^2_{H^\pm} = M^2_A + M^2_W \quad ; \quad M^2_{H,h} = \frac{1}{2}\Big(M^2_A + M^2_Z \pm ((M^2_A + M^2_Z)^2 - 4M^2_Z M^2_A \cos^2 2\beta)}$$

Note that $\mathbf{M_h < M_Z}$

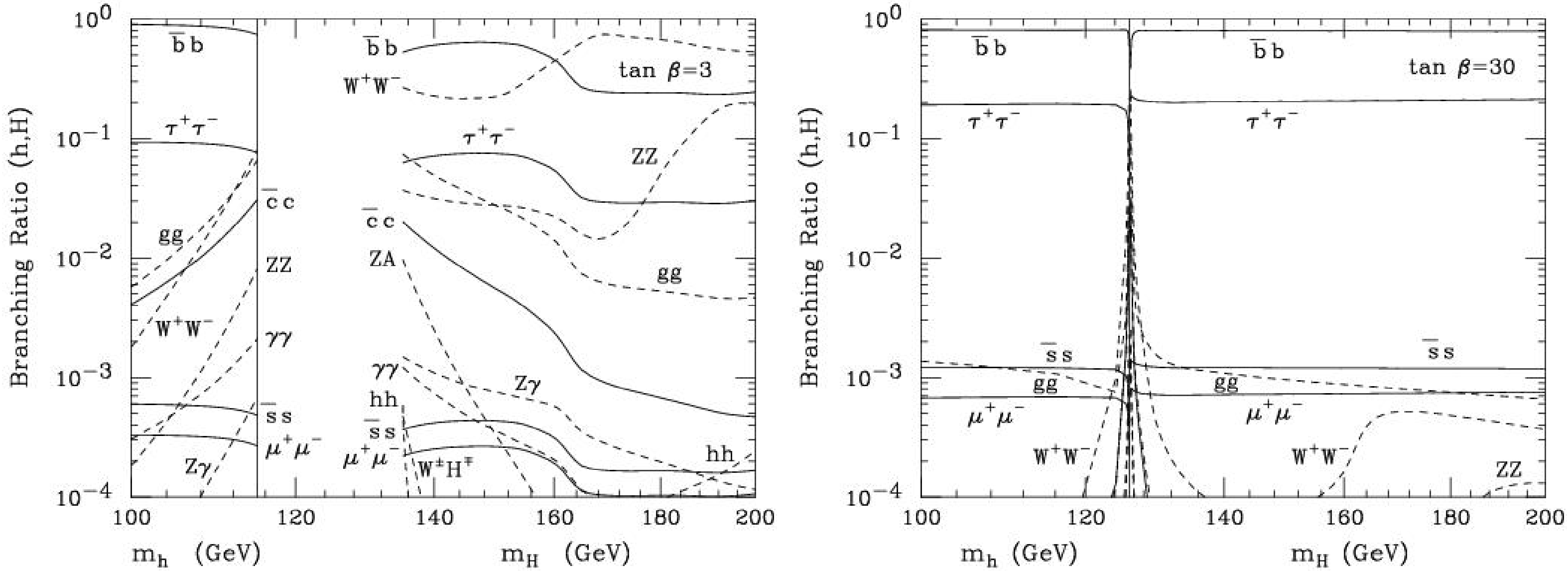
- Radiative correction help to evade this limit

$$\mathbf{\Delta M^2_h = \frac{3G_\mu}{\sqrt{2}\pi^2} m^4_t \log \frac{M^2_{\tilde{t}}}{m^2_t} \lesssim 140 \text{ GeV}}$$

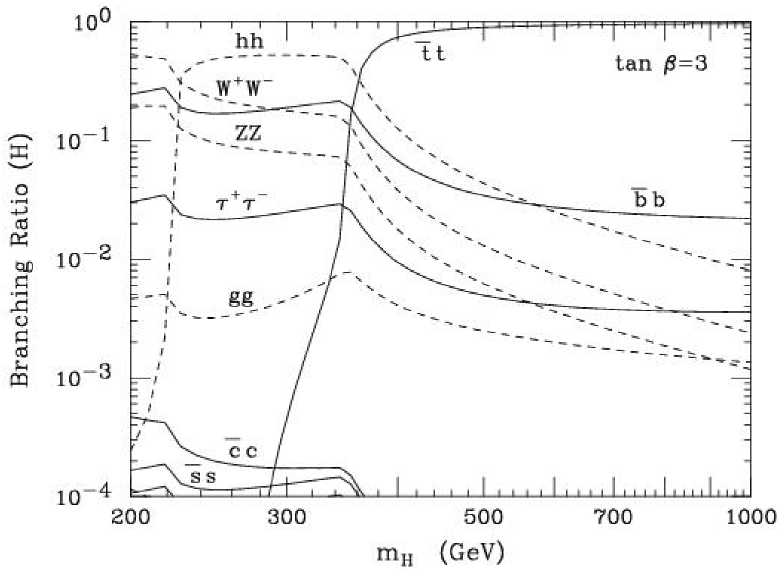


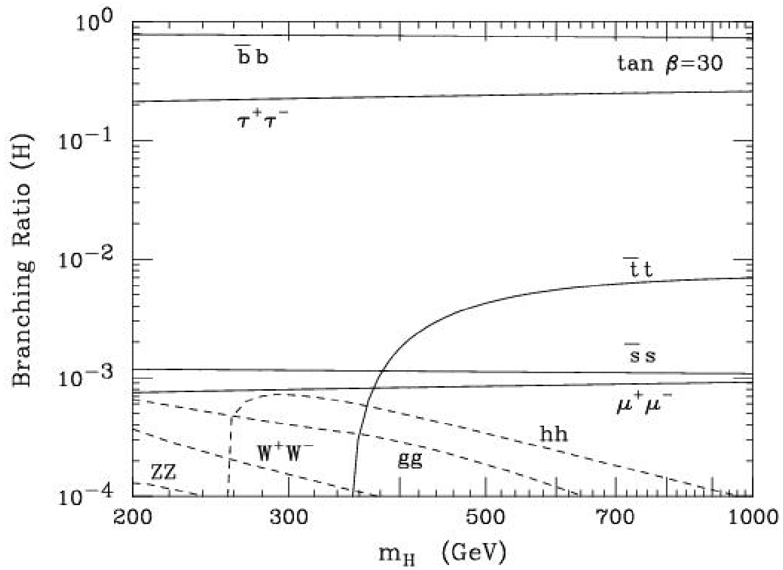
- One state similar to a light SM Higgs

✪ Branching ratios for heavy SUSY spectrum ($\tan\beta = \mathbf{3}$) and 30

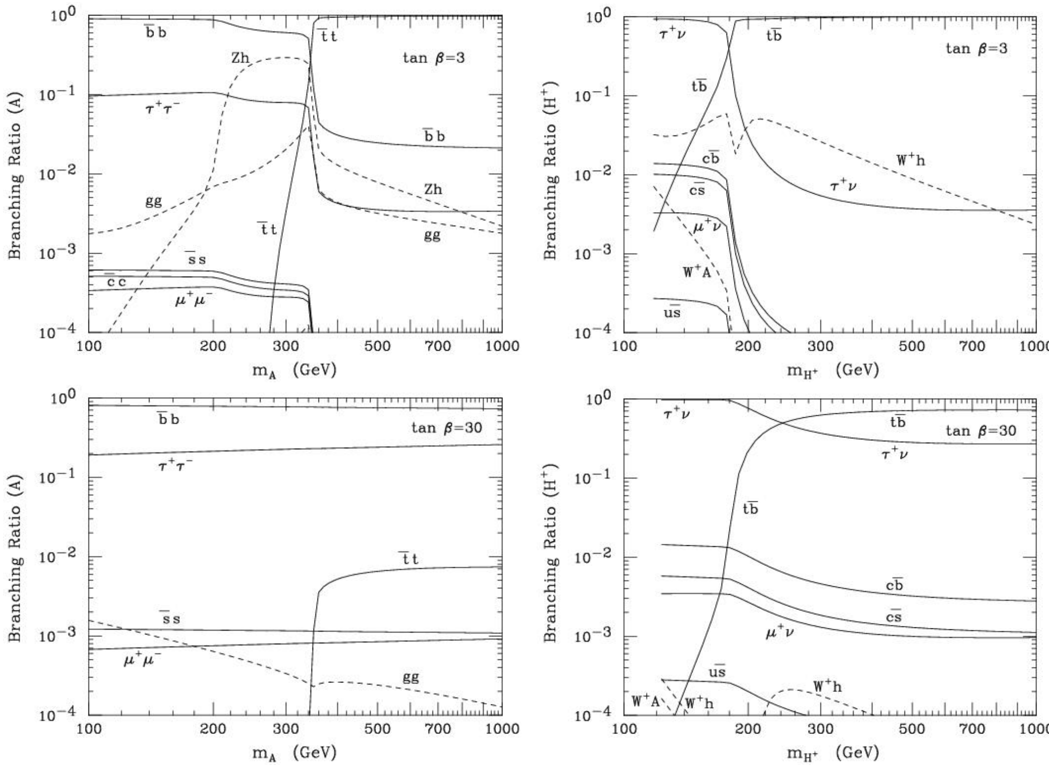


✪ Branching ratios for heavy SUSY spectrum ($\tan\beta = \mathbf{3}$) and 30



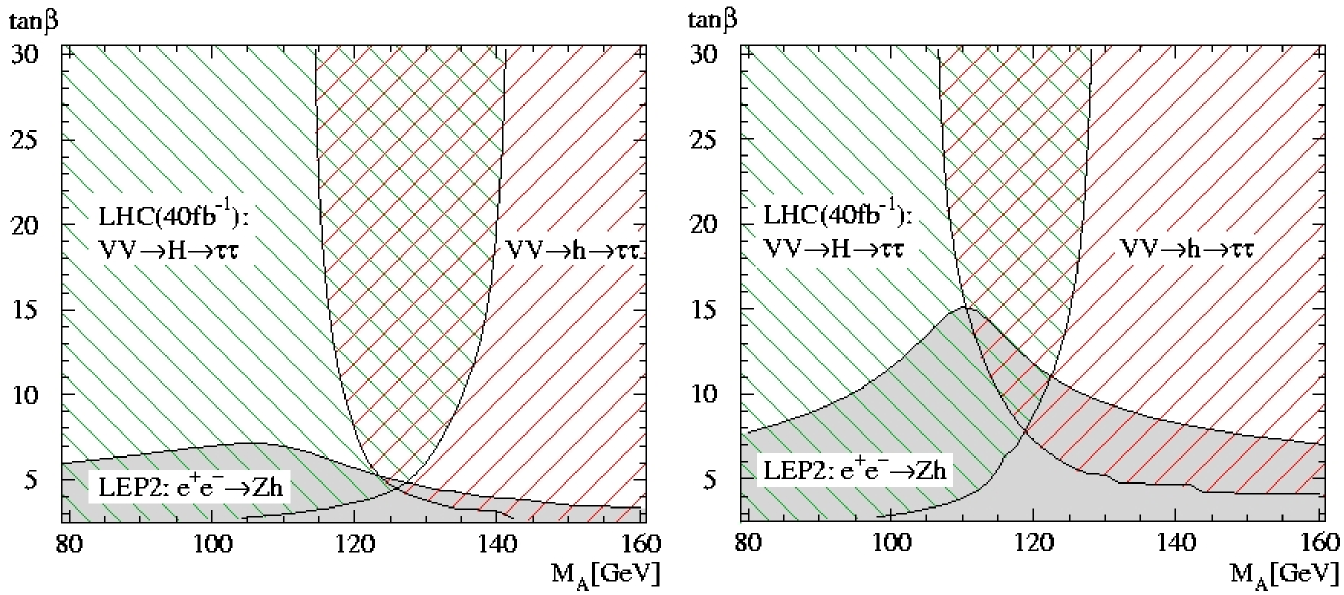


Branching ratios for heavy SUSY spectrum ($\tan\beta = \mathbf{3}\ (\mathbf{30})$)

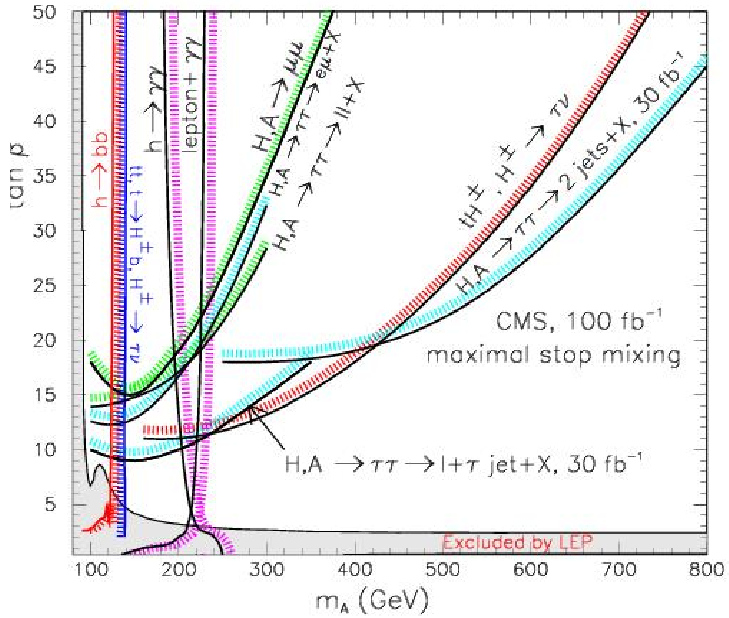


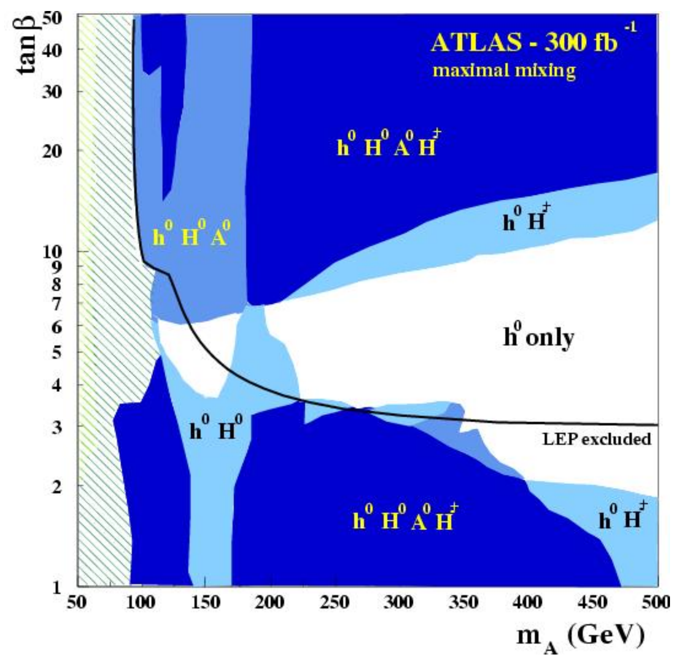
No-lose theorem

- for a neutral CP–even higgs at the LHC in WBF and $\mathbf{H}/\mathbf{h} \to \tau\tau$ (maximum/no mixing)



Like the branching ratios the importance of the different channels gets modified $\Longrightarrow$ the analysis has to be redone

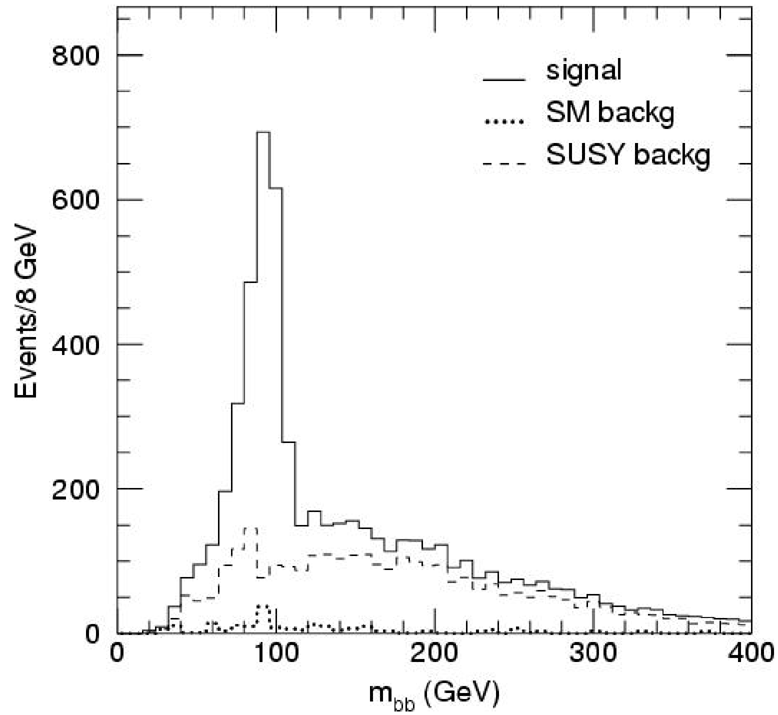




Higgs is decay chain

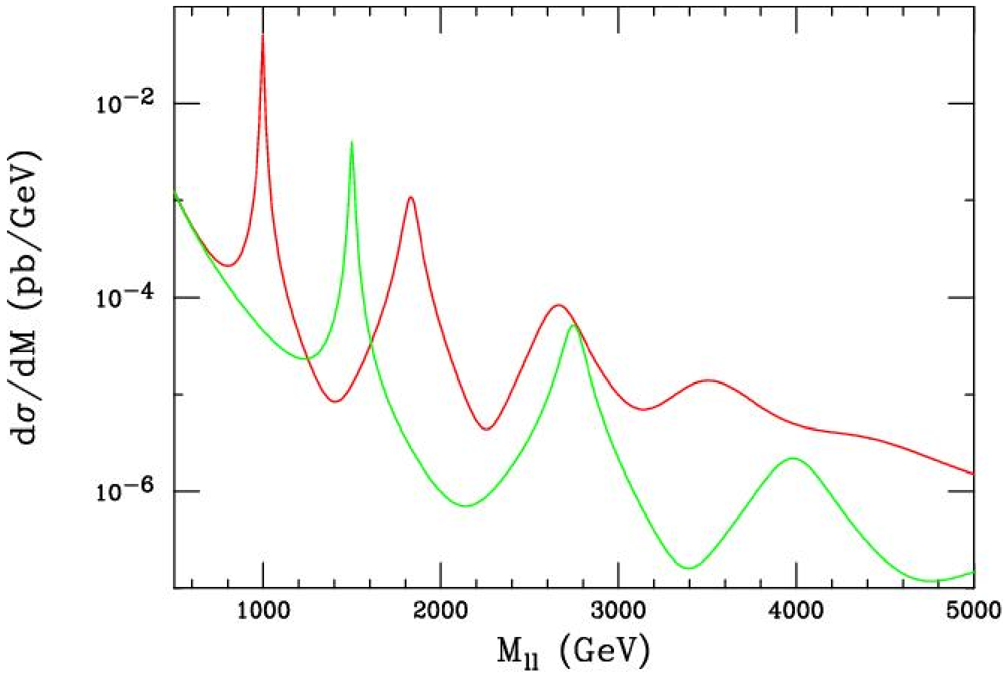
❈ Depending on the SUSY point, Higgs might be produced copiously in decay chains.

❈ For instance, $\tilde{\chi}_0^2 \to \mathbf{h}\tilde{\chi}_0^1$ versus $\tilde{\chi}_0^2 \to \ell^\pm \tilde{\ell}^\mp \tilde{\chi}_0^1$

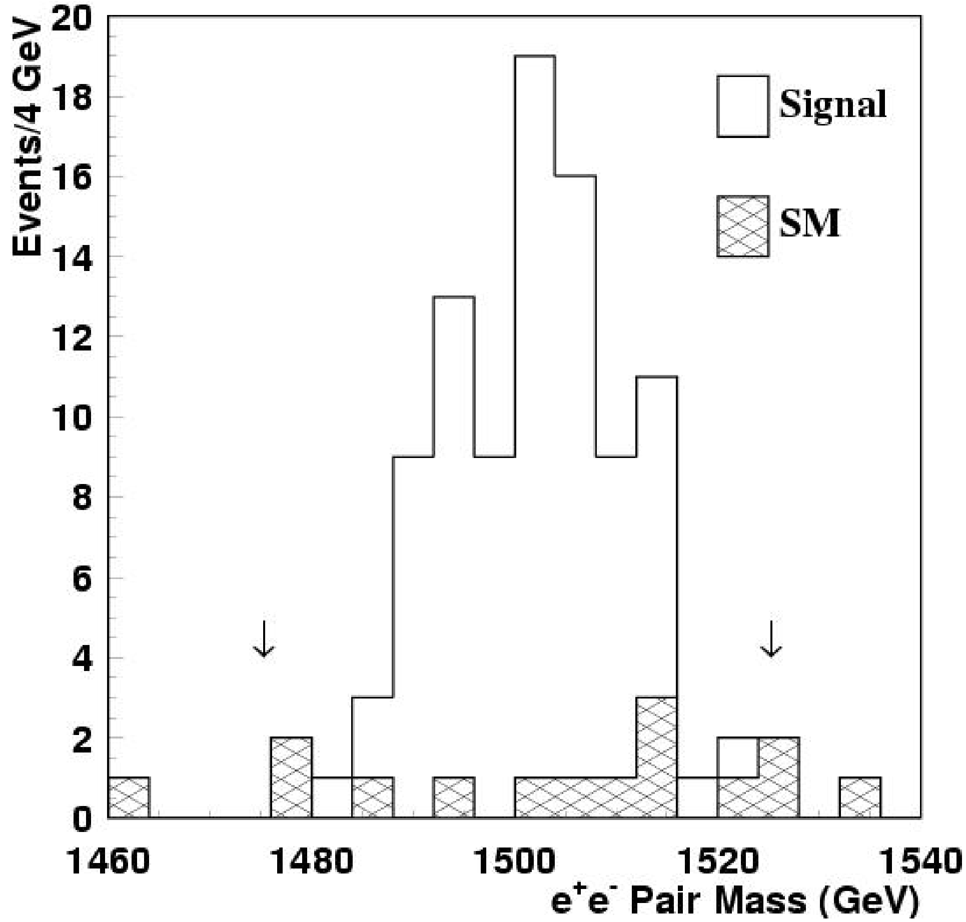


III. Extra dimensions at the LHC

- The signal is model dependent. Several searches are already under way
- Let's consider Randall-Sundrum model $\Longrightarrow$ new massive spin–2 particles
- There should be a series of resonances in $\mathbf{M}_{\ell\ell}$



- With mild cuts it is easy to extract the signal



- Can we probe the graviton spin?

- Just use the angular distribution: $\mathbf{1} + \cos^{\mathbf{2}}\theta^*$ for spin1, $\mathbf{1} - \cos^{\mathbf{4}}\theta^*$ ($gg \to G$) and $\mathbf{1} - \mathbf{3}\cos^{\mathbf{2}}\theta^* + \mathbf{4}\cos^{\mathbf{4}}\theta^*$ ($q\bar{q} \to G$)

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