Long-lived superparticles at the LHC

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Long-lived next-to-lightest SUSY particles

- Favoured regions of the MSSM parameter space.
- Long-lived stau NLSP
- Long-lived stop NLSP
- Long-lived chargino NLSP
- Conclusions

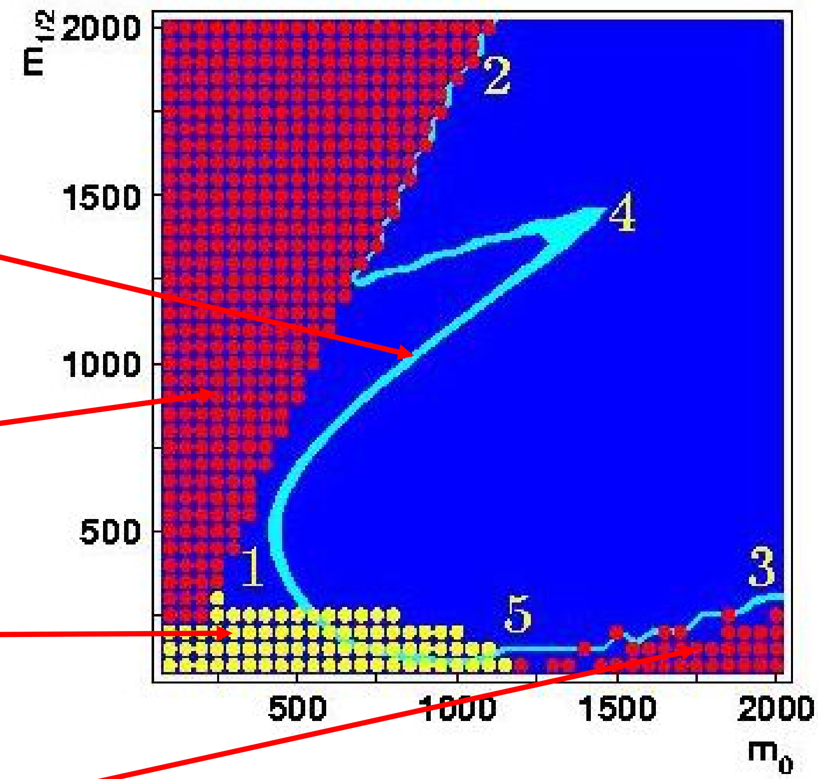
Minimal SUSY Standard Model (MSSM)

- Particle content of the Minimal Supersymmetric Standard Model:

	Superfield	Bosons		Fermions		$SU_c(3)$	$SU_L(2)$	$U_Y(1)$
Gauge	$\mathbf{G^a}$	gluon	g^a	gluino	$\tilde{g}^a$	8	1	0
	$\mathbf{V^k}$	Weak	W^k $(W^\pm, Z)$	wino, zino	$\tilde{w}^k$ $(\tilde{w}^\pm, \tilde{z})$	1	3	0
	$\mathbf{V'}$	Hypercharge	B (γ)	bino	$\tilde{b}(\tilde{\gamma})$	1	1	0
Matter	$\mathbf{L_i}$	sleptons	$\tilde{L}_i = (\tilde{\nu}, \tilde{e})_L$	leptons	$L_i = (\nu, e)_L$	1	2	-1
	$\mathbf{E_i}$		$\tilde{E}_i = \tilde{e}_R$		$E_i = e_R$	1	1	2
	$\mathbf{Q_i}$	squarks	$\tilde{Q}_i = (\tilde{u}, \tilde{d})_L$	quarks	$Q_i = (u, d)_L$	3	2	1/3
	$\mathbf{U_i}$		$\tilde{U}_i = \tilde{u}_R$		$U_i = u_R^c$	3*	1	$-4/3$
	$\mathbf{D_i}$		$\tilde{D}_i = \tilde{d}_R$		$D_i = d_R^c$	3*	1	2/3
Higgs	$\mathbf{H_1}$	Higgses	H_1 $(h, H, A, H^\pm)$	higgsinos	$\tilde{H}_1$ $(\tilde{h}_1, \tilde{h}_2, \tilde{h}^\pm)$	1	2	-1
	$\mathbf{H_2}$		H_2		$\tilde{H}_2$	1	2	1

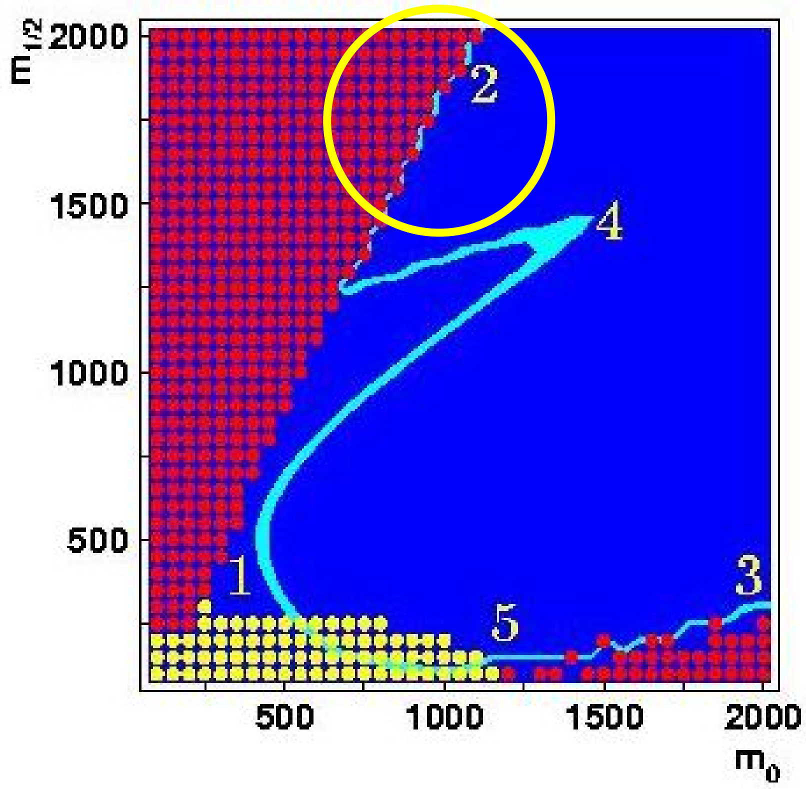
Favoured regions of parameter space

- WMAP data leave only very small allowed region as shown by the thin blue line which give acceptable neutralino relic density
- Excluded by LSP
- Excluded by Higgs searches at LEP2
- Excluded by REWSB



Favoured regions of parameter space

- Coannihilation region
- The region is characterized by low m_0 but large $m_{1/2}$
- Masses of tau-slepton and neutralino (which has a large gaugino component here) are almost degenerate
- Typical process: neutralino-stau coannihilation



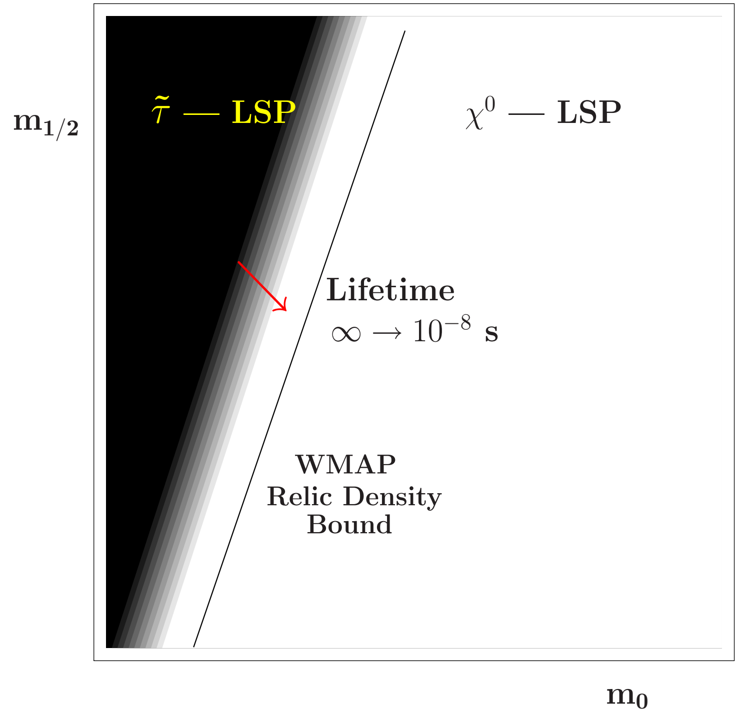
Favoured regions of parameter space

- Coannihilation region

- LSP constraint (in the dark triangle region stau is LSP, to the right – neutralino is LSP)

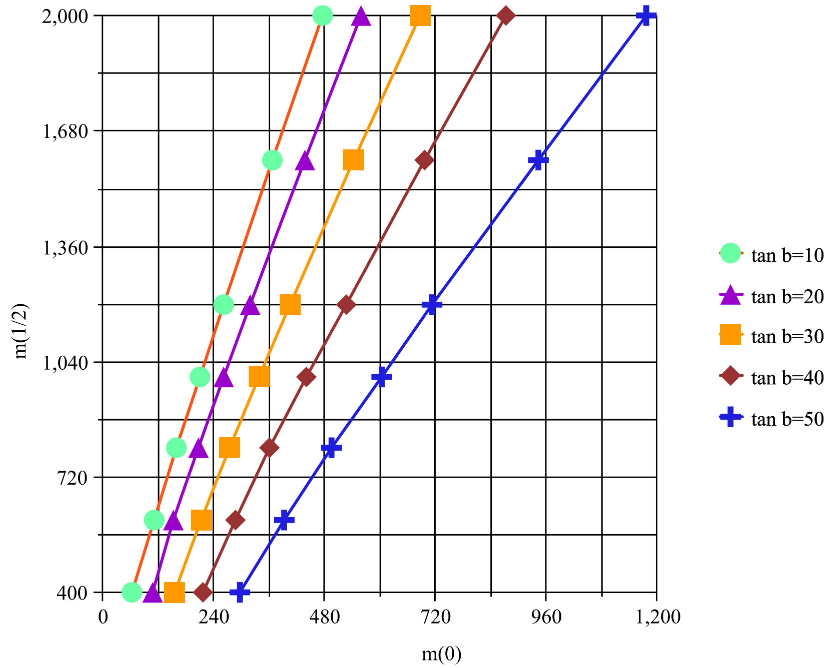
- At the boundary stau lifetime decreases from left to right

- Relic density constraint is satisfied



Favoured regions of parameter space

- Coannihilation region
- Boundary line of the LSP allowed region depends strongly on tan β
- The region consistent with WMAP is very narrow, however, changing tan β, one sweeps up a rather wide area.

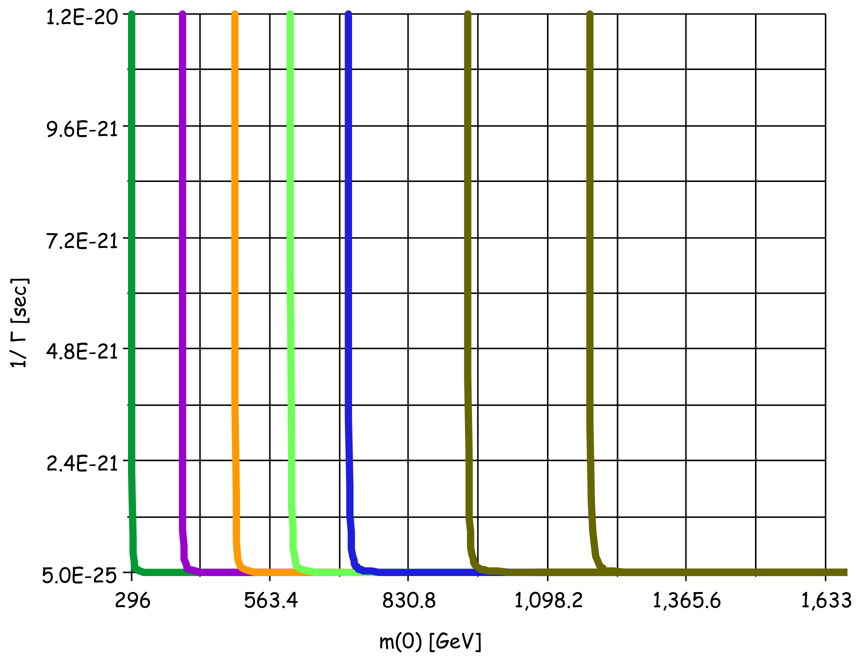


Stau lifetime

- When the stau is heavier than the neutralino, it decays.
- The only decay mode is

$$\widetilde{\tau} \longrightarrow \widetilde{\chi}_1^0 \tau.$$

- The lifetime crucially depends on the mass difference and decreases while departing from boundary line



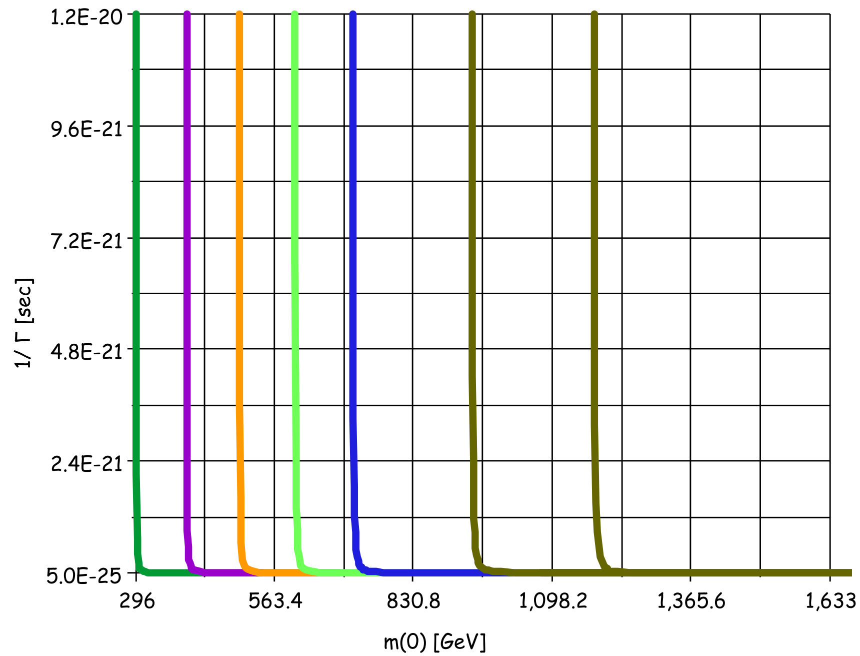
$$\Gamma(\tilde{\tau} \to \chi_1^0 \tau) = \frac{1}{2} \alpha_{em} \left(N_{11} - N_{12} \tan \theta_W \right)^2 m_{\tilde{\tau}} \left(1 - \frac{m^2_{\chi_1^0}}{m^2_{\tilde{\tau}}} \right)^2$$

Stau lifetime

- A small deviation from the border line results in immediate fall-down of the lifetime

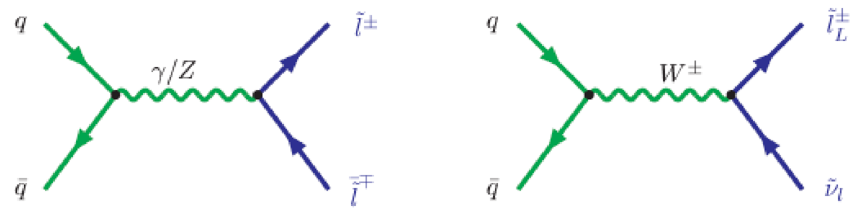
- To get lifetimes of the order of $10^{-10} – 10^{-12}$ sec so that a particle can go through the detector one has to be almost exactly at the border line.

- However, the border itself is not fixed, it moves with tan β



Stau production at LHC

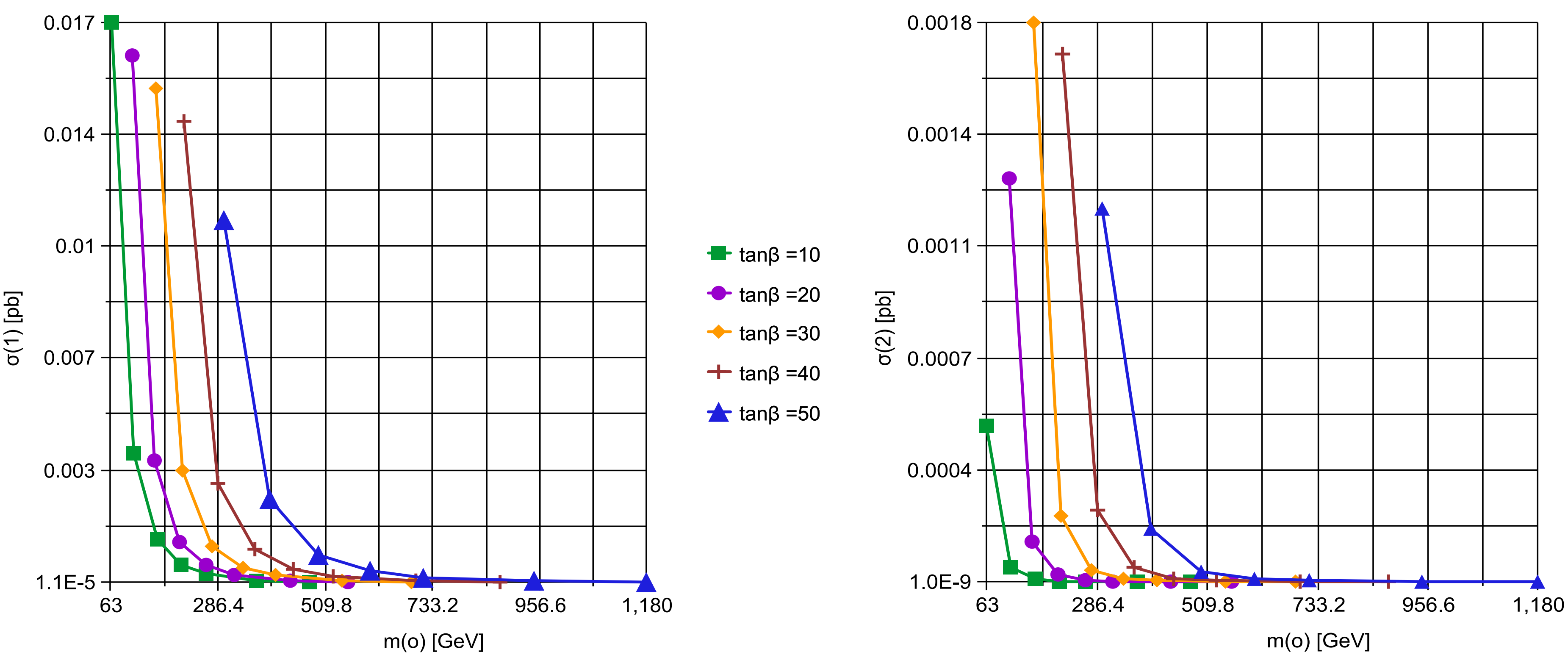
- Long-lived staus can be produced at LHC
- The main process is a quark-antiquark annihilation channel
- For small masses of stau production cross-sections are of order of few % of pb.



#	$\tan\beta = 10$	$\tan\beta = 20$	$\tan\beta = 30$	$\tan\beta = 40$	$\tan\beta = 50$
	$\tilde{m}_\tau$ σ_1, σ_2	$\tilde{m}_\tau$ σ_1, σ_2	$\tilde{m}_\tau$ σ_1, σ_2	$\tilde{m}_\tau$ σ_1, σ_2	$\tilde{m}_\tau$ σ_1, σ_2
1	160 1.7×10^{-2} 5.0×10^{-4}	160 1.6×10^{-2} 1.3×10^{-3}	161 1.5×10^{-2} 1.8×10^{-3}	161 1.4×10^{-2} 1.7×10^{-3}	162 1.1×10^{-2} 1.2×10^{-3}
2	245 3.9×10^{-3} 4.4×10^{-5}	245 3.7×10^{-3} 1.3×10^{-4}	246 3.4×10^{-3} 2.1×10^{-4}	247 3.0×10^{-3} 2.3×10^{-4}	247 2.5×10^{-3} 1.7×10^{-4}
3	332 1.3×10^{-3} 7.1×10^{-6}	332 1.2×10^{-3} 2.3×10^{-5}	332 1.1×10^{-3} 3.8×10^{-5}	333 1.0×10^{-3} 4.4×10^{-5}	334 8.3×10^{-4} 3.4×10^{-5}

Stau production at LHC

- Cross-sections for slepton production at LHC as functions of m_0 for different values of tan β for pair (left) and single (right) production



Light stops in the MSSM

- In case when *A* is large enough the squarks of the third generation, and first of all stop, become relatively light. This happens via the see-saw mechanism while diagonalizing the stop mass matrix

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

- The off-diagonal terms increase with *A* and give negative contribution to the lightest squark mass

$$\tilde{m}_{1,2}^2 = \frac{1}{2}\left(\tilde{m}_{tL}^2 + \tilde{m}_{tR}^2 \pm \sqrt{(\tilde{m}_{tL}^2 - \tilde{m}_{tR}^2)^2 + 4m_t^2(A_t - \mu\cot\beta)^2}\right)$$

- Hence, increasing |*A*| one can make the lightest stop as light as one likes it to be and even make it the LSP.

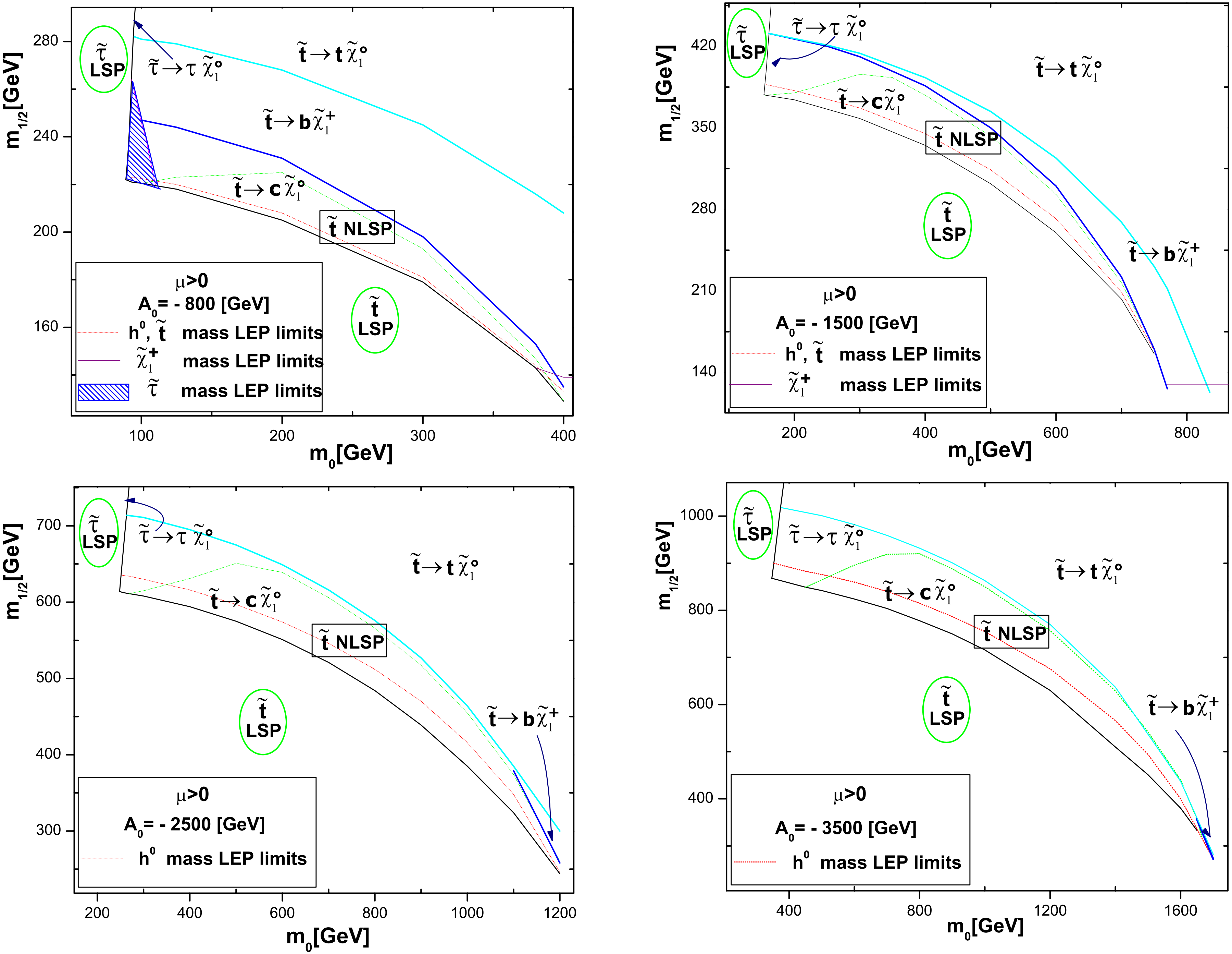
Light stops in the MSSM

- The situation is similar to that with stau for small m_0 and large $m_{1/2}$ when stau becomes the LSP.

- For squarks it takes place for low $m_{1/2}$ and low m_0. One actually gets the border line where stop becomes the LSP.

- The region with light stops exists only for large negative A, for small A it is completely ruled out by the LEP Higgs limit.

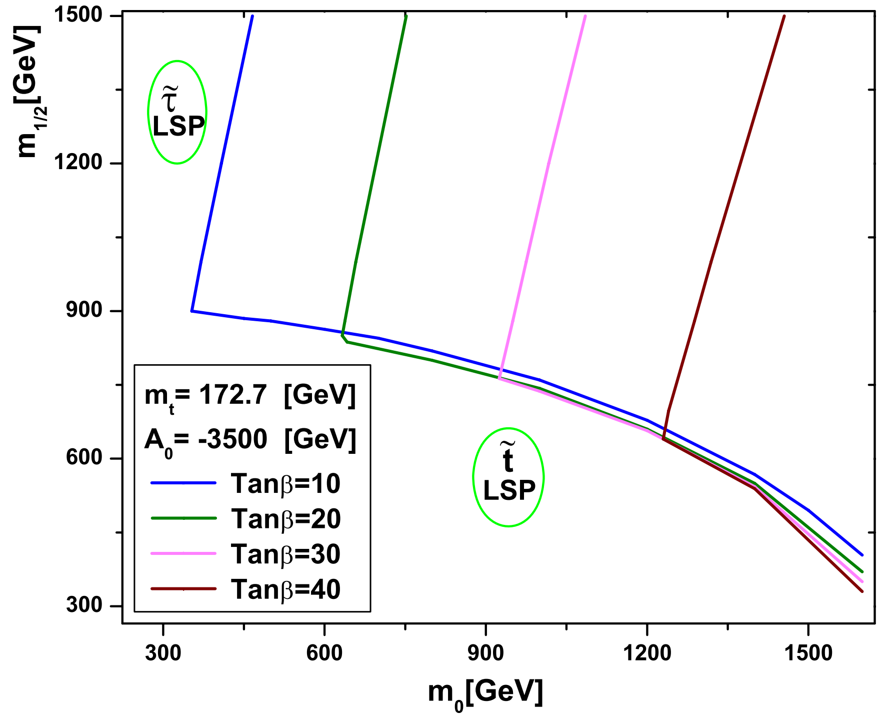
- In this region one gets not only the light stop, but also the light Higgs, since the radiative correction to the Higgs mass is proportional to the log of the stop mass. The stop mass boundary is close to the Higgs mass one and they may overlap for intermediate values of $\tan\beta$



m1/2[GeV]
m0[GeV]
τ̃ LSP
τ̃ → τ χ̃1°
t̃ → t χ̃1°
t̃ → b χ̃1+
t̃ → c χ̃1°
t̃ NLSP
t̃ LSP
μ>0
A0= - 800 [GeV]
h0, t̃ mass LEP limits
χ̃1+ mass LEP limits
τ̃ mass LEP limits
A0= - 1500 [GeV]
A0= - 2500 [GeV]
h0 mass LEP limits
A0= - 3500 [GeV]

Light stops in the MSSM

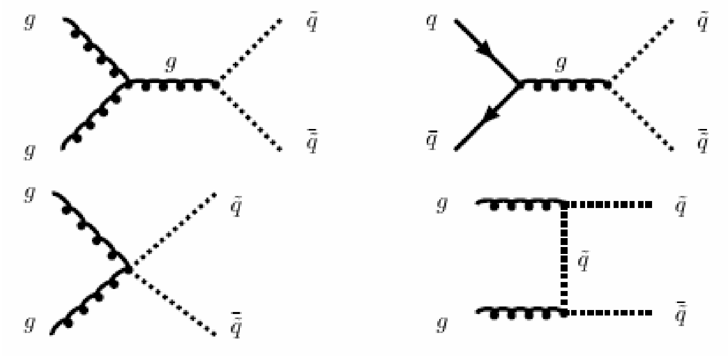
- When $|A|$ decreases the border line moves down and finally disappears. Increasing $|A|$ one gets larger forbidden area and the value of the stop mass at the border increases.

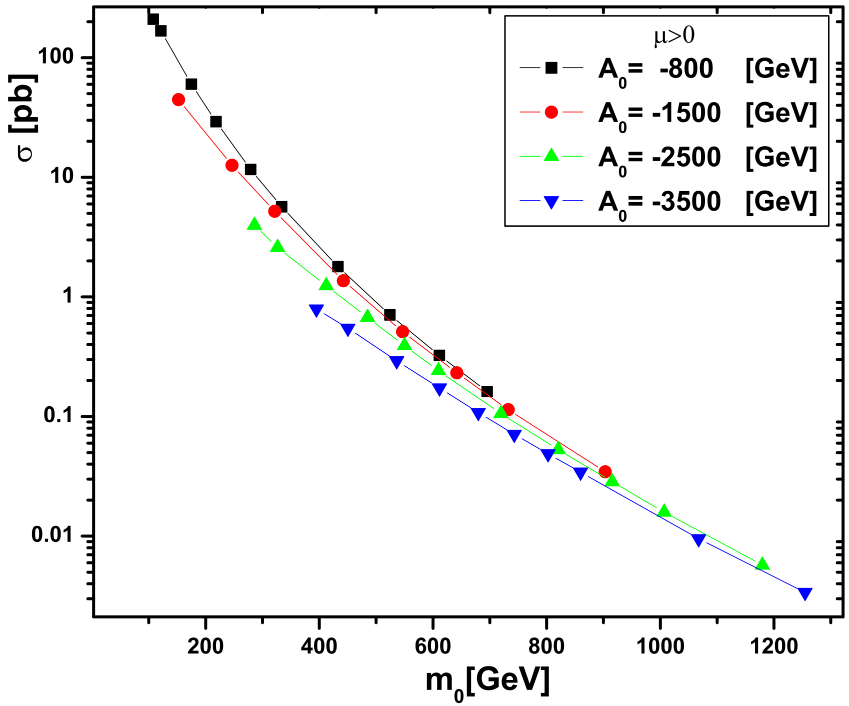


- Changing $\tan\beta$ one does not influence the stop border line, the only effect is the shift of stau border line. It moves to the right with increase of $\tan\beta$, so the whole area increases and covers the left bottom corner of the $m_0 - m_{1/2}$ plane.

Phenomenology of light stop scenario

- Light stops could be produced already in the beginning of LHC operation.



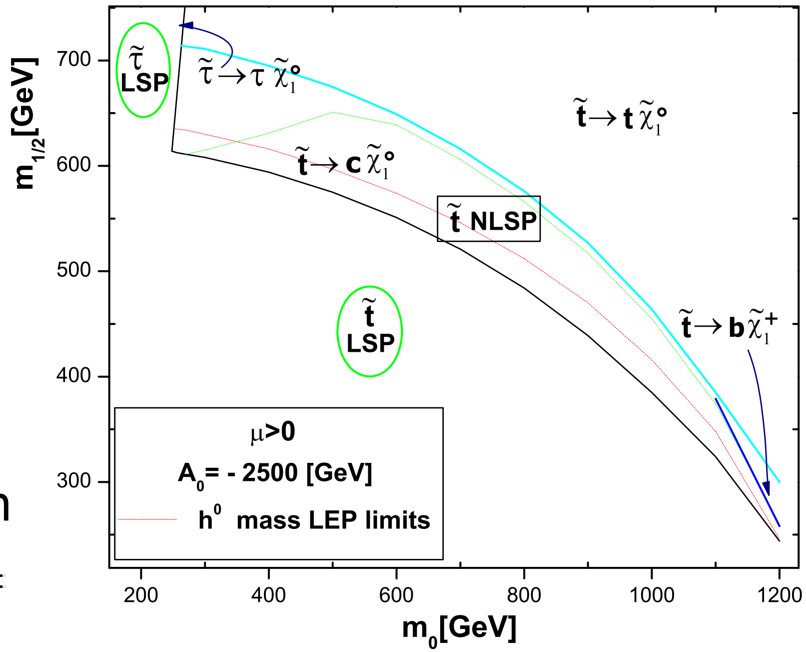


- Since stops are relatively light in our scenario, the production cross sections are quite large and may achieve tens or even hundreds of pb for the stop mass less than 150 GeV.

Phenomenology of light stop scenario

- Heavy stop decays to the b-quark and the lightest chargino $\tilde{t} \to b\tilde{\chi}_1^{\pm}$ or to the t-quark and the lightest neutralino $\tilde{t} \to t\tilde{\chi}_1^0$

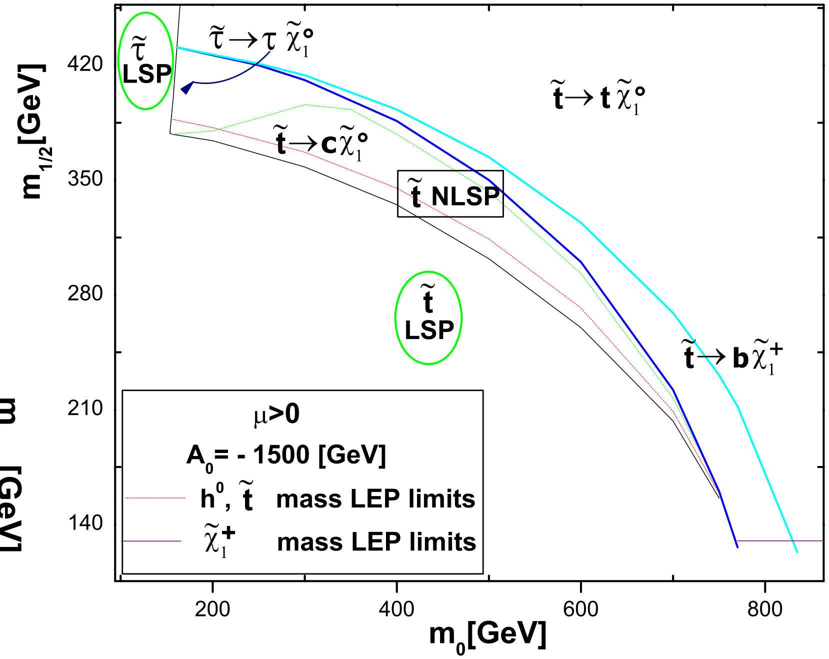
- For large $|A| > 1500$ GeV the region $\tilde{t} \to b\tilde{\chi}_1^{\pm}$ is getting smaller and even disappear due to $m_{\tilde{t}} < m_b + m_{\tilde{\chi}_1^{\pm}}$

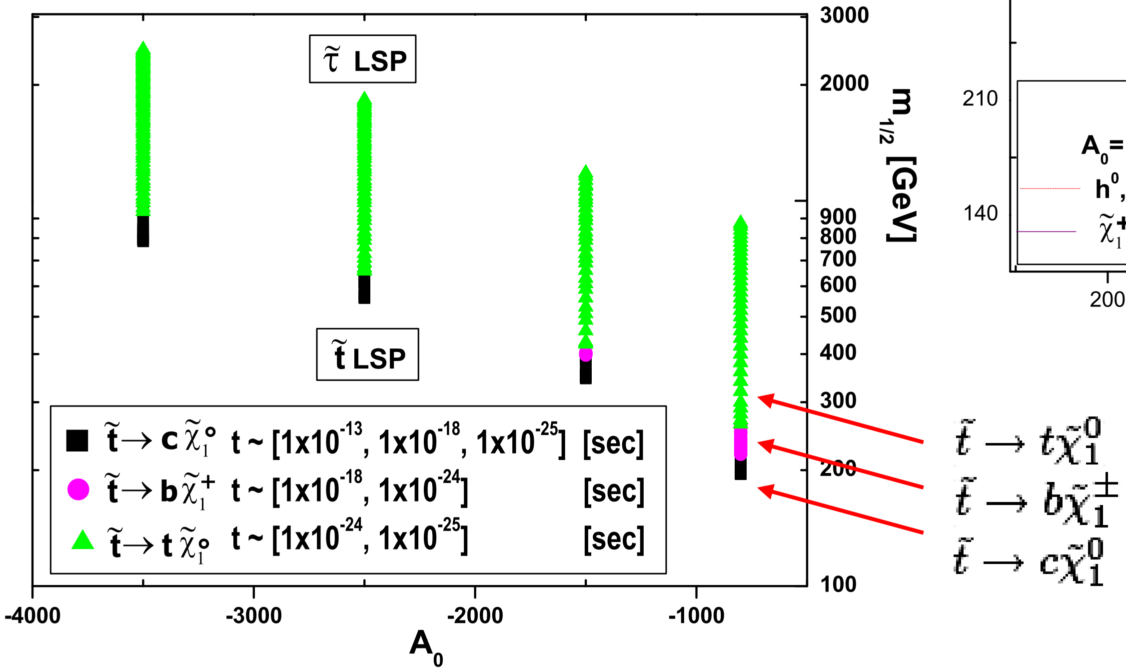


- Light stop decays to the charm quark and the lightest neutralino $\tilde{t} \to c\tilde{\chi}_1^0$. The decay, though it is loop-suppressed, has the BR 100 %.

Phenomenology of light stop scenario

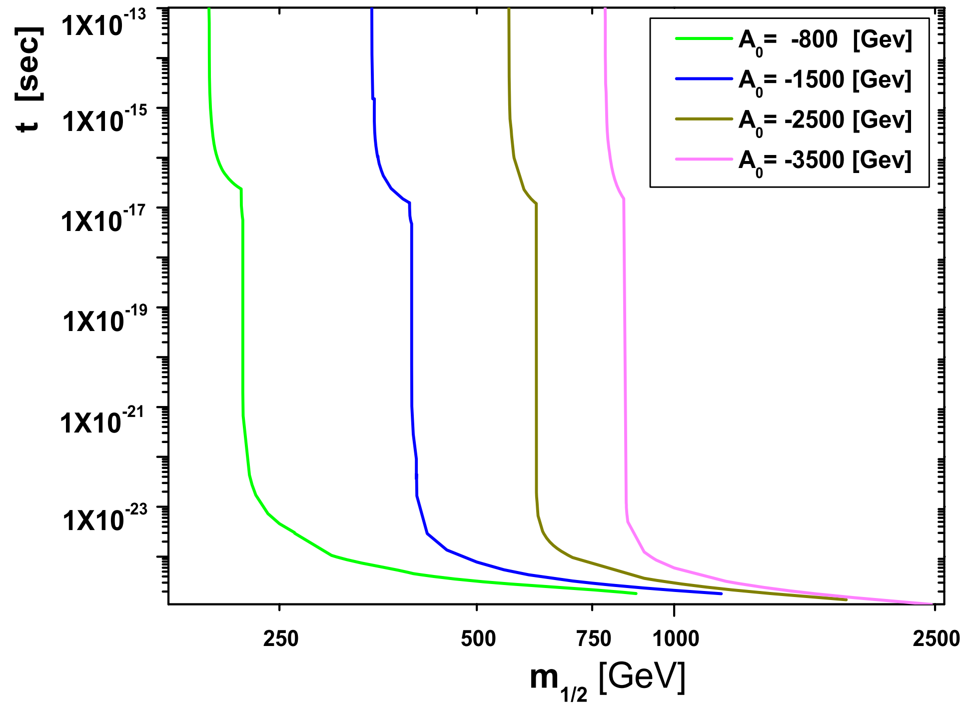
- Different stop decay modes for
  $|A|$ = 800; 1500; 2500; 3500 GeV
  (m_0 = 250; 450; 650; 1000 GeV)





Phenomenology of light stop scenario

- Stop lifetimes for different values of $|A|$. The biggest lifetime corresponds to the mode $\tilde{t} \to c\tilde{\chi}_1^0$



- Breaks on the curves correspond to switching on the new decay mode.

- The lifetime could be quite large in a wide area of the $A - m_{1/2}$ parameter space, even for heavy stops if A is very large and negative

Long-lived charginos

- The mass matrix for charginos has the form

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

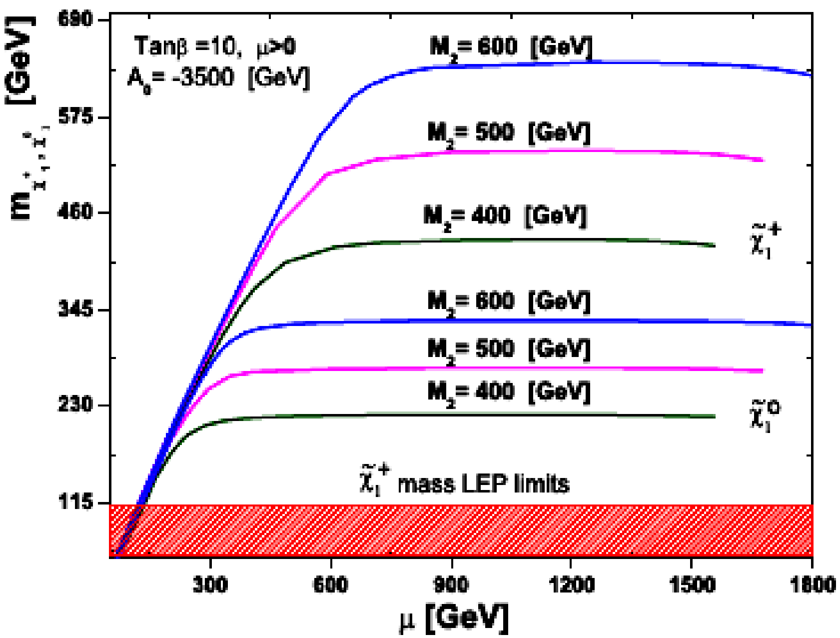
after diagonalization one gets masses of the two physical states

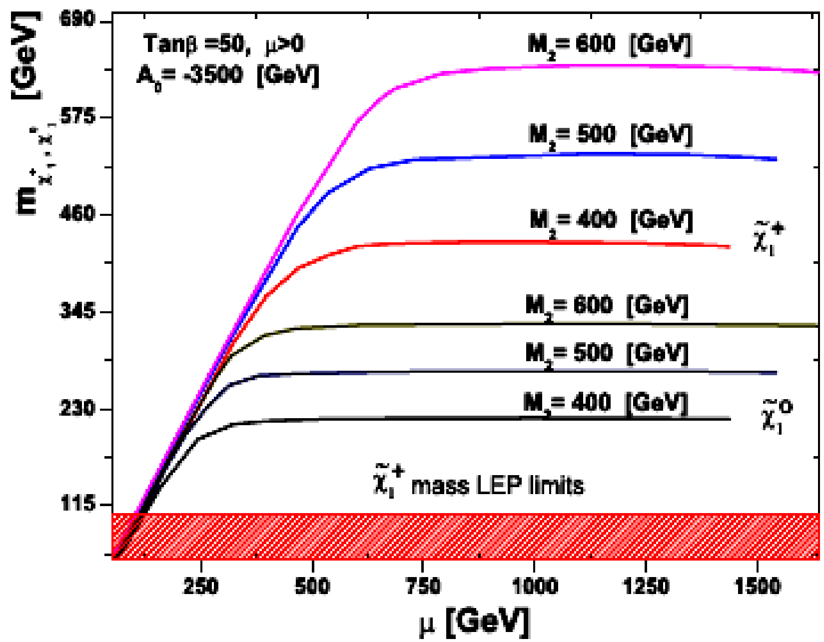
$$\begin{aligned} M_{1,2}^2 &= \frac{1}{2}\Big[M_2^2 + \mu^2 + 2M_W^2 \\ &\mp \sqrt{(M_2^2-\mu^2)^2 + 4M_W^4\cos^2 2\beta + 4M_W^2(M_2^2+\mu^2+2M_2\mu\sin 2\beta)}\Big] \end{aligned}$$

Radiative corrections are known in the leading order, and typically they are of the order of a few percent

Long-lived charginos

- In case when μ is small (less than M_Z), which takes place near the border line of radiative EWSB, the lightest chargino χ_1 and two lightest neutralinos are almost degenerate and have a mass of the order of μ

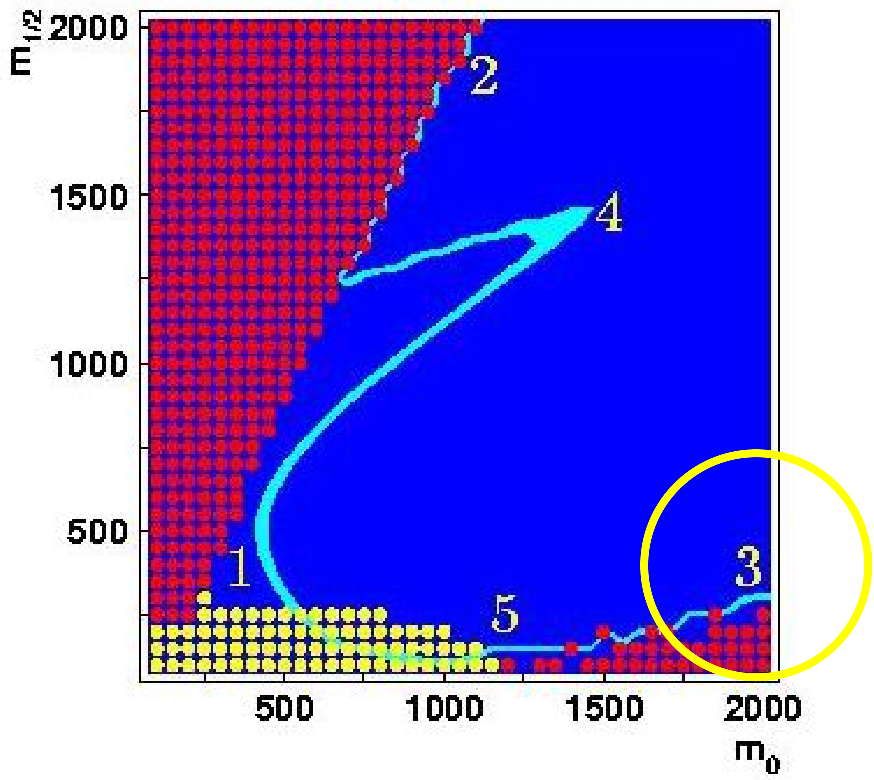




Long-lived charginos

- The degeneracy takes place for any choice of the other parameters since tree level formulae weakly depend on them and corrections are small.

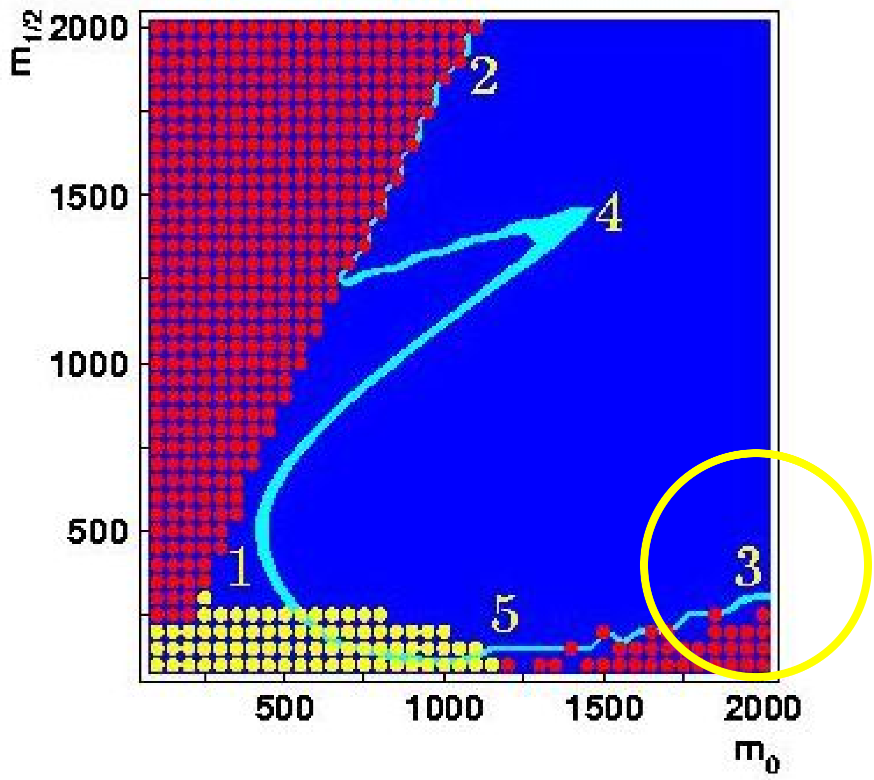
- However, since the value of μ is not arbitrary but taken from the EWSB requirement, one has to find the region where it is small. The region is known as a focus-point region

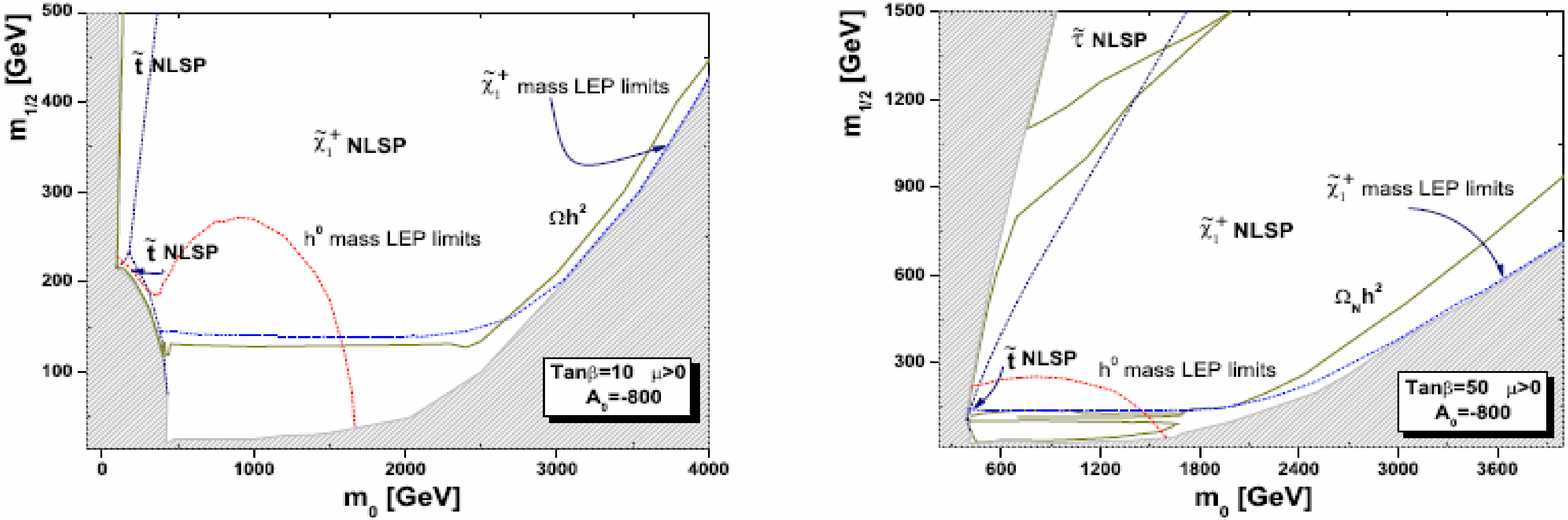


Long-lived charginos

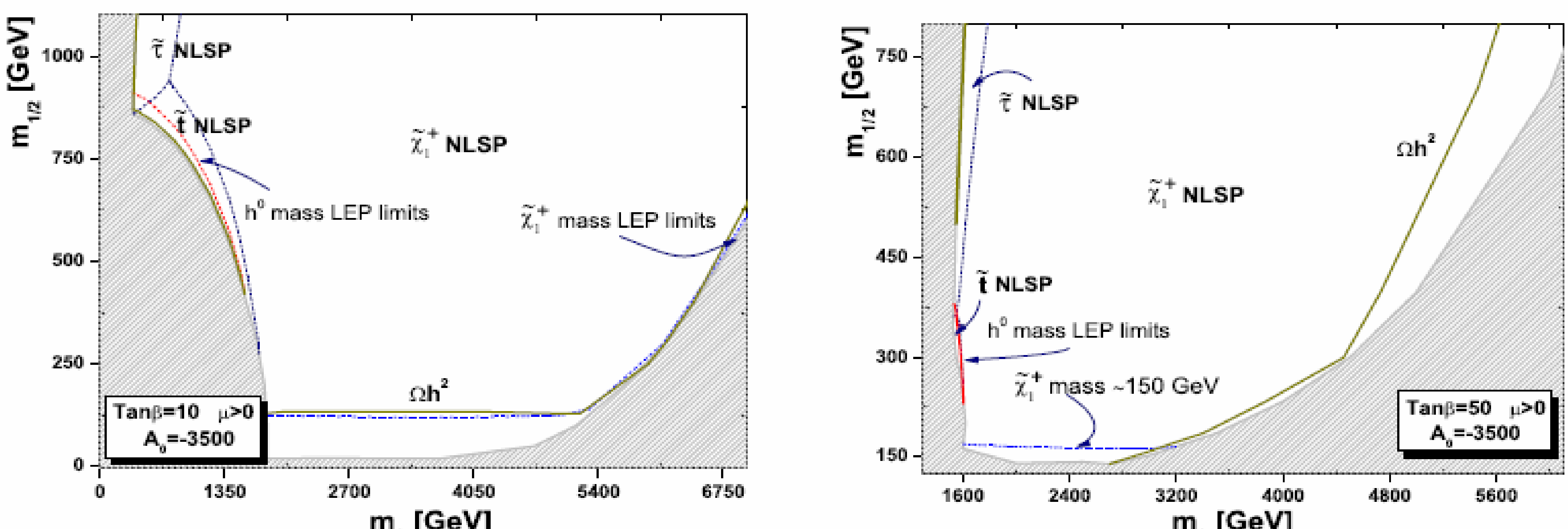
- One has to check that other requirements are satisfied in this region

- In the case of almost degenerate NLSPs and LSP, when calculating the relic density one has to take into account coannihilation of charginos $\chi^{\pm}$ and neutralinos χ^{0}



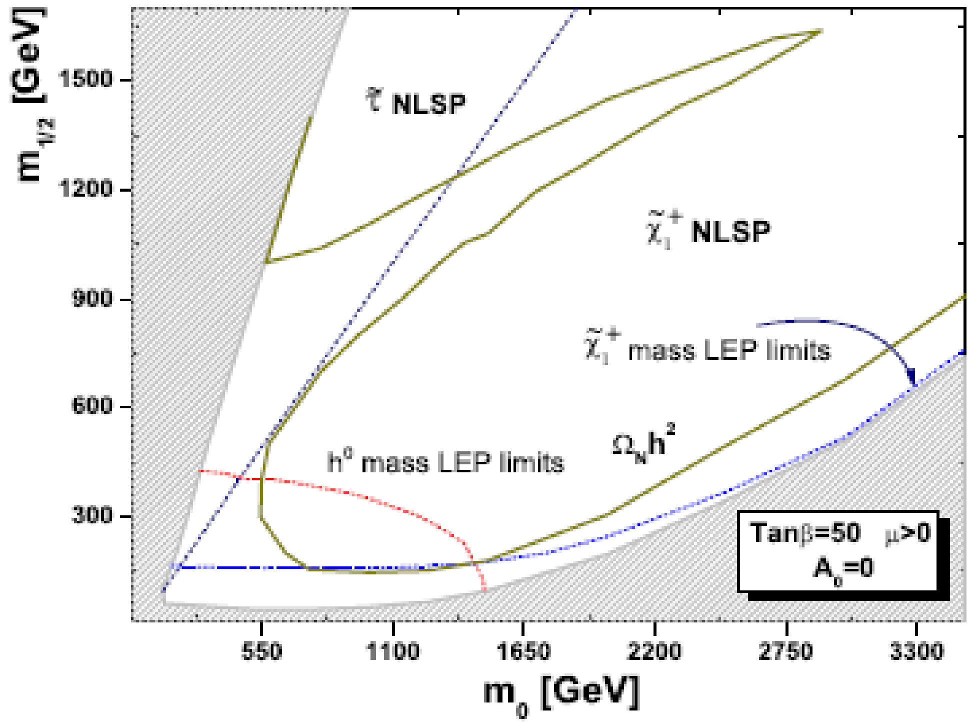


- Regions of the parameter space for different A_0 and tan β (very big m_0 !)



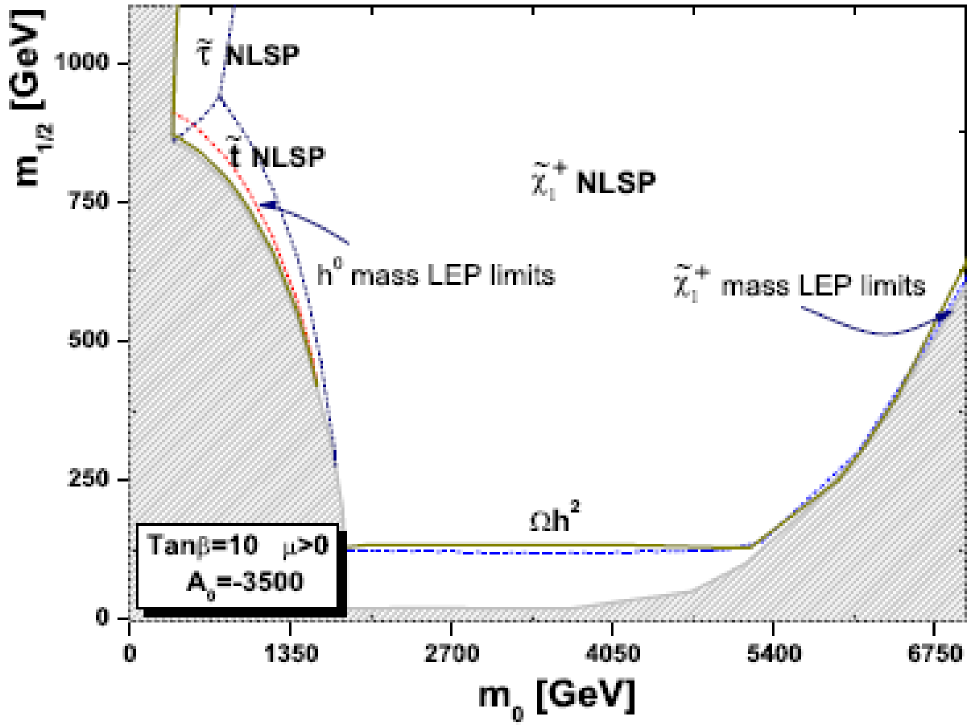
Long-lived charginos

- For small values of A_0 the DM line does not go along the EWSB border but deviates from it, thus not allowing the small values of μ.



Long-lived charginos

- For large negative A_0, these lines almost coincide. Changing tan β one can reach smaller values of m_0 and $m_{1/2}$, thus allowing the other particles to be lighter without changing the chargino mass.



Long-lived charginos

- It should be mentioned that the region near the EWSB border line is very sensitive to the SM parameters; a minor shift in α_s or m_t and m_b leads to noticeable change of spectrum

- Notice that though the region of small μ looks very fine-tuned and indeed is very sensitive to all input parameters, still in the whole four dimensional parameter space (assuming universality) it swaps up a wide area and can be easily reached

- The accuracy of fine-tuning defines the accuracy of degeneracy of the masses and, hence, the life time of the NLSP

Conclusions

- Within the framework of the MSSM with mSUGRA SUSY breaking it is possible to get long-lived superpartners of tau-lepton, top-quark and Higgs which might be produced at LHC

- The cross-section crucially depends on a single parameter – the mass of the superparticle and for light staus can reach a few % pb. The stop production cross-section can achieve even hundreds pb

- The light stop and light chargino NLSP scenarios require large negative values of the soft trilinear SUSY breaking parameter *A*

Conclusions

- The events would have an unusual signature and produce noticable signal rather than missing energy taken away by the lightest neutralino
  - staus / stops / charginos go through the detector
  - staus / stops / charginos produce a secondary vertex when they decay inside the detector
  - stops can form of so-called *R*-hadrons (bound states of SUSY particles) if their lifetime is bigger than hadronization time.
- Stau/stop/chargino–NLSP scenarios differ from the GMSB scenario where NLSP typically lives longer