Long-lived next-to-lightest supersymmetric particles

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Abstract

We consider the parameter space of the Constrained Minimal Supersymmetric Standard Model. It is shown that for the particular choice of parameters there are certain regions where long-living charged superparticles exist. The interesting regions are the co-annihilation region with light staus, the region with large negative trilinear scalar coupling A distinguished by light stops, and the focus-point region where relatively light charginos may be long-lived. The phenomenology of the long-lived superparticles is briefly discussed.

1 Introduction

Search for supersymmetric particles at colliders usually proceeds from the assumption that all of them are relatively heavy (few hundreds of GeV), with masses determined by the values of soft supersymmetry breaking mass parameters m_0, $m_{1/2}$, A, and short-lived. Being heavier than the Standard Model particles they usually decay faster and result in usual particles with additional missing energy taken away by the neutral stable lightest supersymmetric particle (LSP) – neutralino. This situation takes place almost everywhere in the parameter space of the Minimal supersymmetric Standard Model (MSSM) and for various mechanisms of supersymmetry breaking [1, 2, 3].

There are, however, regions in the MSSM parameter space where the LSP is not the usual neutralino, but a slepton (mainly stau), or the relatively light superpartner of the t-quark (stop), or the lightest chargino. These regions are obviously considered as forbidden ones. However, at the border of these regions staus, stops, and charginos become next-to-lightest superparticles, heavier than the neutralino and thus unstable.

One of the important constraints on the parameter space of the MSSM is the relic density one. Given the amount of the dark matter from the WMAP experiment [4, 5] one is left with a narrow band of allowed region which goes along the stau border line (the co-annihilation region), then along the Higgs limit line and then along the radiative electroweak symmetry breaking line (the focus-point region). All three regions are consistent with WMAP data.

We found out that in this narrow band at the border the forbidden regions staus, stops, and charginos might be rather stable with the lifetime long enough to go through the detector, or produce secondary decay vertices inside the detector. Due to relatively small masses (approximately within the range 150 − 850 GeV) the production cross-section of long-lived next-to-lightest superparticles at LHC may reach a few per cent of pb for staus and charginos, and stop production cross-sections can be as large as tens or even hundreds pb.

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2 Long-lived tau-sleptons in the coannihilation region

The co-annihilation region is shown qualitatively in the $m_0 - m_{1/2}$ plane, Fig. 1. The dark triangle shows the region where stau is the LSP. To the right of it the neutralino is the LSP. The WMAP constraint goes along the LSP triangle border and is shown as a straight line.

Though the boundary of the LSP region with the WMAP allowed band is very narrow, its position depends on the value of $\tan\beta$. In Fig. 1 we also show how the LSP triangle increases with $\tan\beta$. Hence, even if it is very difficult to get precisely into this narrow band, changing $\tan\beta$ one actually sweeps up a wide area.

The boundary region happens to be a transition region from the stau-LSP to the neutralino-LSP. In this very narrow zone the lifetime of stau rapidly changes from infinity to almost zero passing the tiny interval (smeared by the change of $\tan\beta$) where stau is a long-lived particle.

When the stau mass becomes larger than that of the neutralino, stau decays $\tilde\tau \to \tilde\chi_1^0\tau$. The life time crucially depends on the mass difference between $\tilde\tau$ and $\tilde\chi_1^0$ and quickly decreases while departing from the boundary line. If we neglect mixing in the stau sector, then the NLSP is the $\tilde\tau_R$ and the decay width is given by [6]

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

where N_{11} and N_{12} are the elements of the matrix diagonalizing the neutralino mass matrix. In Fig. 2 we show the lifetime of stau as a function of m_0 for different values of $m_{1/2}$ and $\tan\beta = 50$.

Consider now how these long-lived staus can be produced at LHC. The main process is given by a quark-antiquark annihilation channel. To calculate the mass of stau and the production cross-section, we choose a set of points along the LSP borderline for various values of $\tan\beta = 10 \div 50$. One can see that for a small stau mass, the cross sections are relatively large for staus to be produced at LHC with the luminosity around 100 pb^{-1}. They may well be long-lived and go through the detector or decay in the secondary vertices, though the precise lifetime is very sensitive to the parameter space point and, hence, can not be predicted with high accuracy. Still this leaves a very interesting possibility of production of a heavy charged long-lived spinless particle [7, 8].

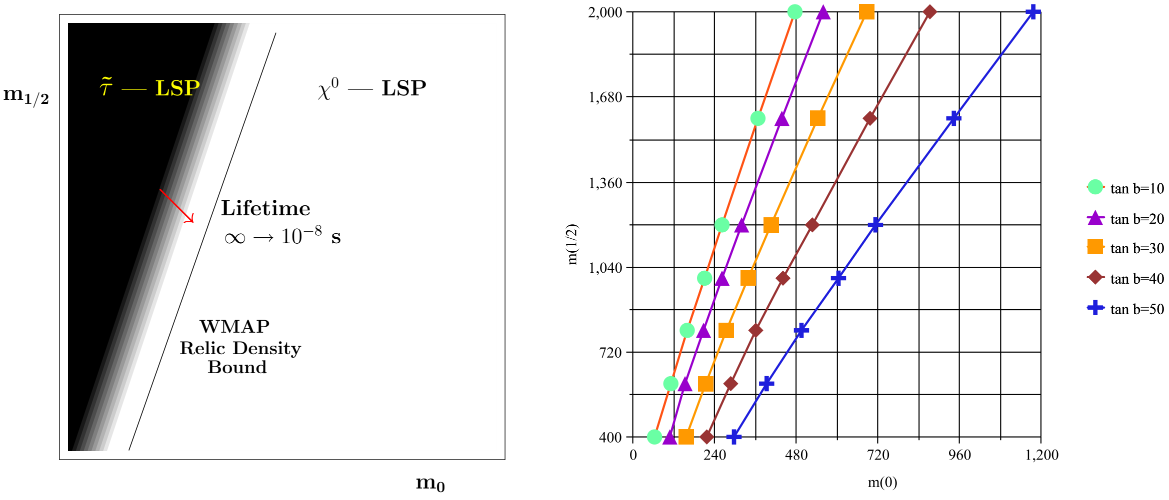

Figure 1: On the left the LSP constraint in the $m_0 - m_{1/2}$ plane is shown. On the right the $\tan\beta$ dependence of the LSP allowed region is depicted. $\tan\beta$ increases from left to right.

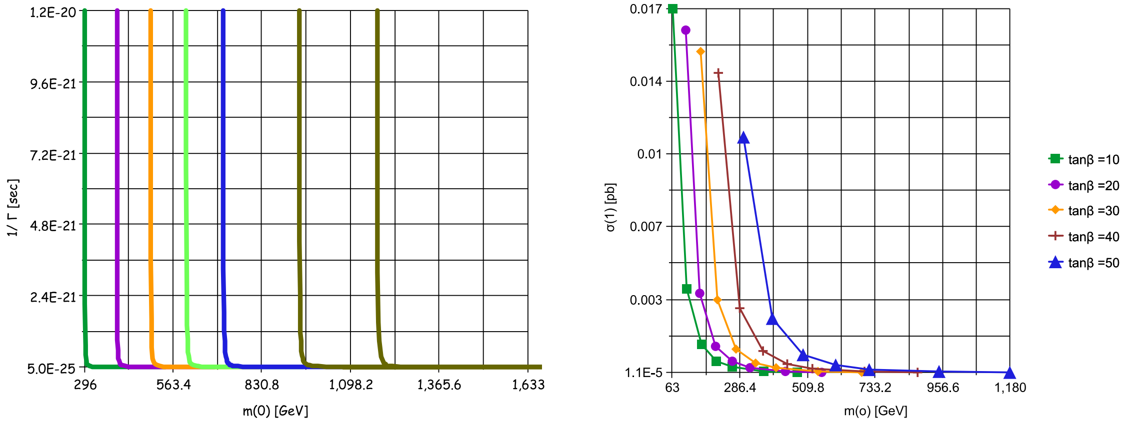

Figure 2: On the left the lifetime of stau as a function of m_0 near the border line for $\tan\beta = 50$ is shown. $m_{1/2}$ increases from left to right. On the right the cross-sections for pair slepton production at LHC in pb as functions of m_0 for various values of $\tan\beta$ in co-annihilation regionis presented.

3 Lond-lived top-squarks

Another interesting region of parameter space is the one distinguished by the light stops. It appears only for large negative trilinear soft supersymmetry breaking parameter A_0. On the border of this region, in full analogy with the stau co-annihilation region, the top squark becomes the LSP and near this border one might get the long-living stops.

Projected to the $m_0 - m_{1/2}$ plane the position of this region depends on the values of $\tan\beta$ and A. In case when $|A|$ is large enough the squarks of the third generation, and first of all the lightest stop $\tilde{t}_1$, become relatively light. This happens via the see-saw mechanism while diagonalizing the stop mass matrix

$$\left(\begin{array}{cc} \tilde{m}^2_{t_L} & m_t(A_t - \mu\cot\beta) \\ m_t(A_t - \mu\cot\beta) & \tilde{m}^2_{t_R} \end{array}\right),$$

where

$$\begin{aligned} \tilde{m}^2_{t_L} &= \tilde{m}^2_Q + m_t^2 + \frac{1}{6}(4M_W^2 - M_Z^2)\cos 2\beta, \\ \tilde{m}^2_{tR} &= \tilde{m}^2_U + m_t^2 - \frac{2}{3}(M_W^2 - M_Z^2)\cos 2\beta. \end{aligned}$$

The off-diagonal terms increase with A, become large for large m_q (that is why the third generation) and give negative contribution to the lightest top squark mass defined by minus sign in

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

Hence, increasing $|A|$ one can make the lightest stop as light as one likes it to be, and even make it the LSP. The situation is similar to that with stau for small m_0 and large $m_{1/2}$ when stau becomes the LSP. For stop it takes place at small m_0 and small $m_{1/2}$. One actually gets the border line where stop becomes the LSP. The region below this line is forbidden. It exists only for large negative A, for small A it is completely ruled out by the LEP Higgs limit [8, 9].

It should be noted that 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

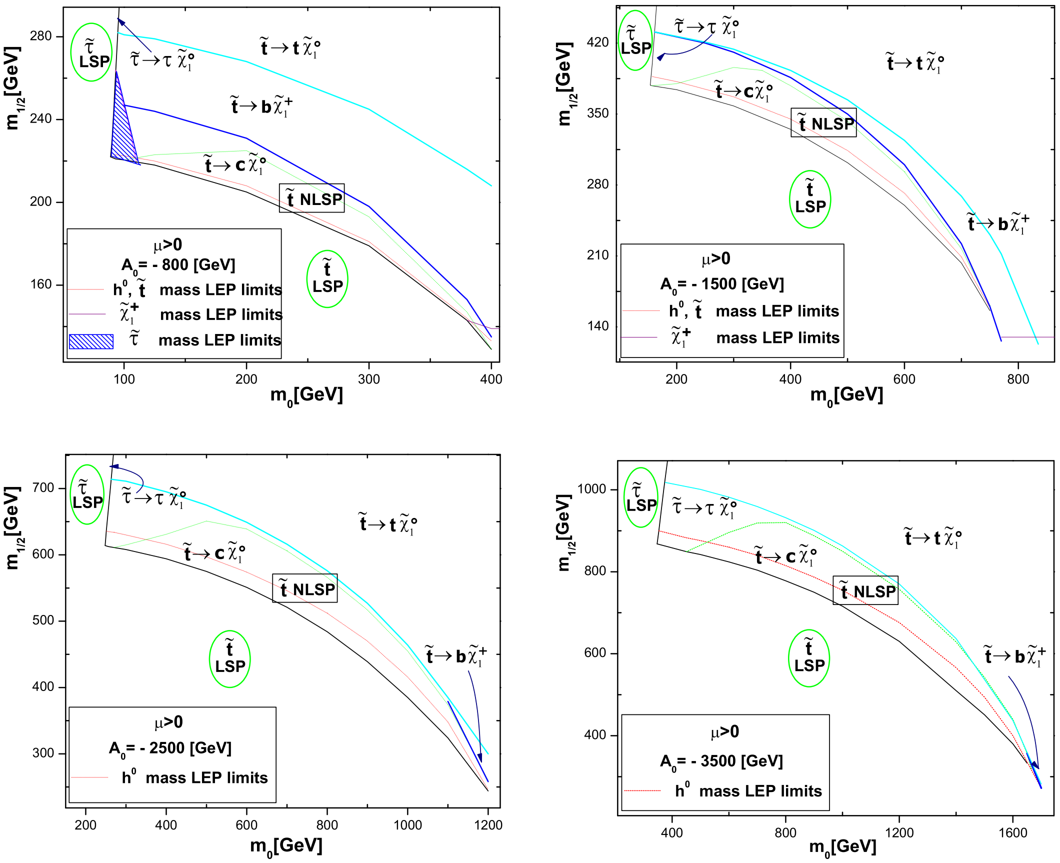

Figure 3: Allowed region of the mSUGRA parameter space for $A_0 = -800, -1500, -2500, -3500$ GeV and $\tan\beta = 10$. At the left from the border stau is an LSP, below the border stop is the LSP. The dotted line is the LEP Higgs mass limit. Also shown are the contours where various stop decay modes emerge.

values of $\tan\beta$. We show the projection of SUSY parameter space to the $m_0 - m_{1/2}$ plane in Fig. 3 for different values of A and fixed $\tan\beta$.

One can see that when $|A|$ decreases the border line moves down and finally disappears. On the contrary, 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 the stau border line which moves to the right with increase of $\tan\beta$.

It should be mentioned that the region near the border line is very sensitive to the Standard Model parameters, a minor shift in α_s or m_t and m_b leads to noticeable change of spectrum.

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 $m_{\tilde{t}} < 150$ GeV. The cross sections and their dependence on the stop mass for different values of $|A|$ are shown in Fig. 4. As one expects they quickly fall down when the mass of stop is increased. The range of each curve corresponds to the region in the $(m_0 - m_{1/2})$ plane where the light stop is the next-to-lightest SUSY particle, and the Higgs and chargino mass limits are satisfied as well. One may notice, that even for very large values of $|A|$ when stops become heavier than several hundreds GeV, the cross sections are of order of few per cent of pb, which is still enough for detection with the high LHC luminosity.

Being created the stop decay. There are several different decay modes depending on the stop mass. If stop is heavy enough it decays to the bottom quark and the lightest chargino $(\tilde{t} \to b\tilde{\chi}_1^{\pm})$. However, for large values of $|A_0|$, namely $A_0 < -1500$ GeV the region where this decay takes place is getting smaller and even disappear due to mass inequality $m_{\tilde{t}} < m_b + m_{\tilde{\chi}_1^{\pm}}$.

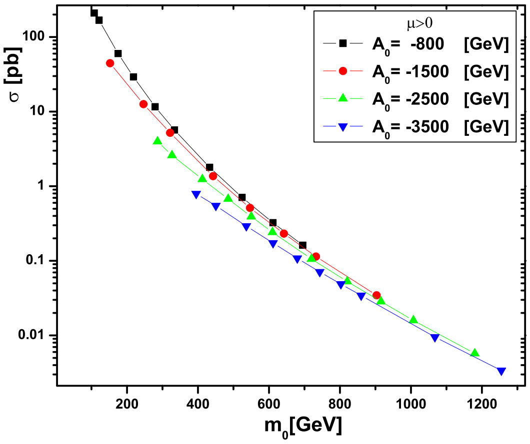

Figure 4: Cross sections of the pair stop production as a function of the stop mass. Different curves correspond to different values of A_0 parameter ($A_0 = -800, -1500, -2500, -3500$ GeV).

In this case the dominant decay mode is the decay to the top quark and the lightest neutralino ($\tilde{t} \to t\tilde{\chi}_1^0$). Light stop decays to the charm quark and the lightest neutralino ($\tilde{t} \to c\tilde{\chi}_1^0$). The latter decay, though it is loop-suppressed, has the branching ratio 100 %.

4 Focus-point region and long-lived charginos

In this section we explore yet another region of parameter space which is a narrow band along the line where the radiative electroweak symmetry breaking fails (the focus-point region). On the border of this region the Higgs mixing parameter μ tends to zero. In this case the lightest chargino ($\chi_1^\pm$) and two lightest neutralinos ($\chi_{1,2}^0$) are almost degenerate and have a mass of the order of μ. The mass terms are nondiagonal and look like

$$\mathcal{L}_{Gaugino-Higgsino} = -\frac{1}{2}M_3\bar{\lambda}_a\lambda_a - \frac{1}{2}\bar{\chi}M^{(0)}\chi - (\bar{\psi}M^{(c)}\psi + h.c.). \tag{1}$$

At the tree level the neutralino mass matrix is

$$M^{(0)} = \begin{pmatrix} M_1 & 0 & -M_Z\cos\beta\sin_W & M_Z\sin\beta\sin_W \\ 0 & M_2 & M_Z\cos\beta\cos_W & -M_Z\sin\beta\cos_W \\ -M_Z\cos\beta\sin_W & M_Z\cos\beta\cos_W & 0 & -\mu \\ M_Z\sin\beta\sin_W & -M_Z\sin\beta\cos_W & -\mu & 0 \end{pmatrix}, \tag{2}$$

For charginos one has

$$M^{(c)} = \begin{pmatrix} M_2 & \sqrt{2}M_W\sin\beta \\ \sqrt{2}M_W\cos\beta & \mu \end{pmatrix}. \tag{3}$$

The physical neutralino and chargino masses are obtained as eigenvalues of these matrices after diagonalization. The mass matrices obtain radiative corrections which are known in the leading order. Typically they are of the order of a few per cent.

When μ is small, which takes place in the focus point region near the border line of radiative electroweak symmetry breaking, the lightest chargino ($\chi_1^\pm$) and two lightest neutralinos ($\chi_{1,2}^0$) are almost degenerate and have a mass of the order of μ. All of them in this case are predominantly higgsinos. In Fig.5 it is shown how the mass of the lightest neutralino and the mass of the lightest chargino depend on μ.

The degeneracy of masses $m_{\chi_1^0}, m_{\chi_2^0}, m_{\chi_1^\pm}$ takes place for any choice of the other parameters. However, since the value of μ is not arbitrary in this approach but taken from the requirement

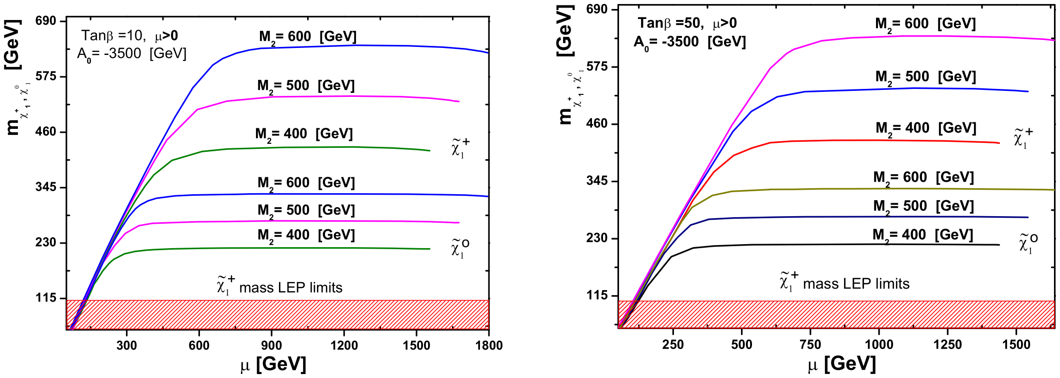

Figure 5: The masses of the lightest chargino and neutralino as functions of μ for the rest of parameters fixed. The value of M_2 is taken to be 600, 500 and 400 GeV, and $\tan\beta$=10,50, respectively. Dark (red) lower band shows the experimental limit on chargino mass.

of electroweak symmetry breaking, one has to find the region of parameter space where it is small. In Fig.5 this region is just above the chargino LEP limit in the right bottom corner of the plots. One can see that masses are degenerate, and the value of μ there is of the order of 150–200 GeV depending on the value of $\tan\beta$. There is also a slight dependence on M_2 (that is on $m_{1/2}$), however, this dependence only show how far we may go along the lines having masses degenerate. It is clearly seen that the bigger M_2 the larger values of μ are allowed. The mass of χ_2^0 is not shown, it almost coincides with the $\chi_1^\pm$ mass.

In Fig.6 we show the projection of SUSY parameter space to the $m_0, m_{1/2}$ plane for different values of A and $\tan\beta$.

One can see that for small values of A_0 the Dark matter line does not go along the electroweak symmetry breaking border but deviates from it, thus not allowing the small values of μ. For large negative A_0, on the contrary, these two lines almost coincide, the bigger the value of $\tan\beta$ the better.

Note 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 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 which is the lighest chargino.

Whence the parameters are chosen in such a way that one has mass degeneracy between the lightest chargino and the lightest neutralino and thus one again has a long-lived NLSP. Its mass is typically in the 100 GeV range and the cross-section of production at the LHC is considerably high. Since three states are almost degenerate, one has also co-production which has to be taken into account. This refers also to the annihilation process that defines the amount of the Dark matter.

On average the cross-sections reach a few tenth of pb and slightly vary with the change of $\tan\beta$. The cross-sections mainly depend on μ: the bigger the value of μ the smaller the cross-section [10].

In Fig. 7 we show the lifetime of the lightest chargino as a function of the mass difference between the lightest chargino (NLSP) and the lightest neutralino (LSP). It appears that in order to get reasonable "large" lifetimes one has to go very far along the focus point region. Then keeping μ small one can get lifetimes of the order of 10^{-10} s for practically degenerate LSP and NLSP. When the mass difference increases the lifetime falls down. However, if the degeneracy is within a few GeV, charginos are long-lived.

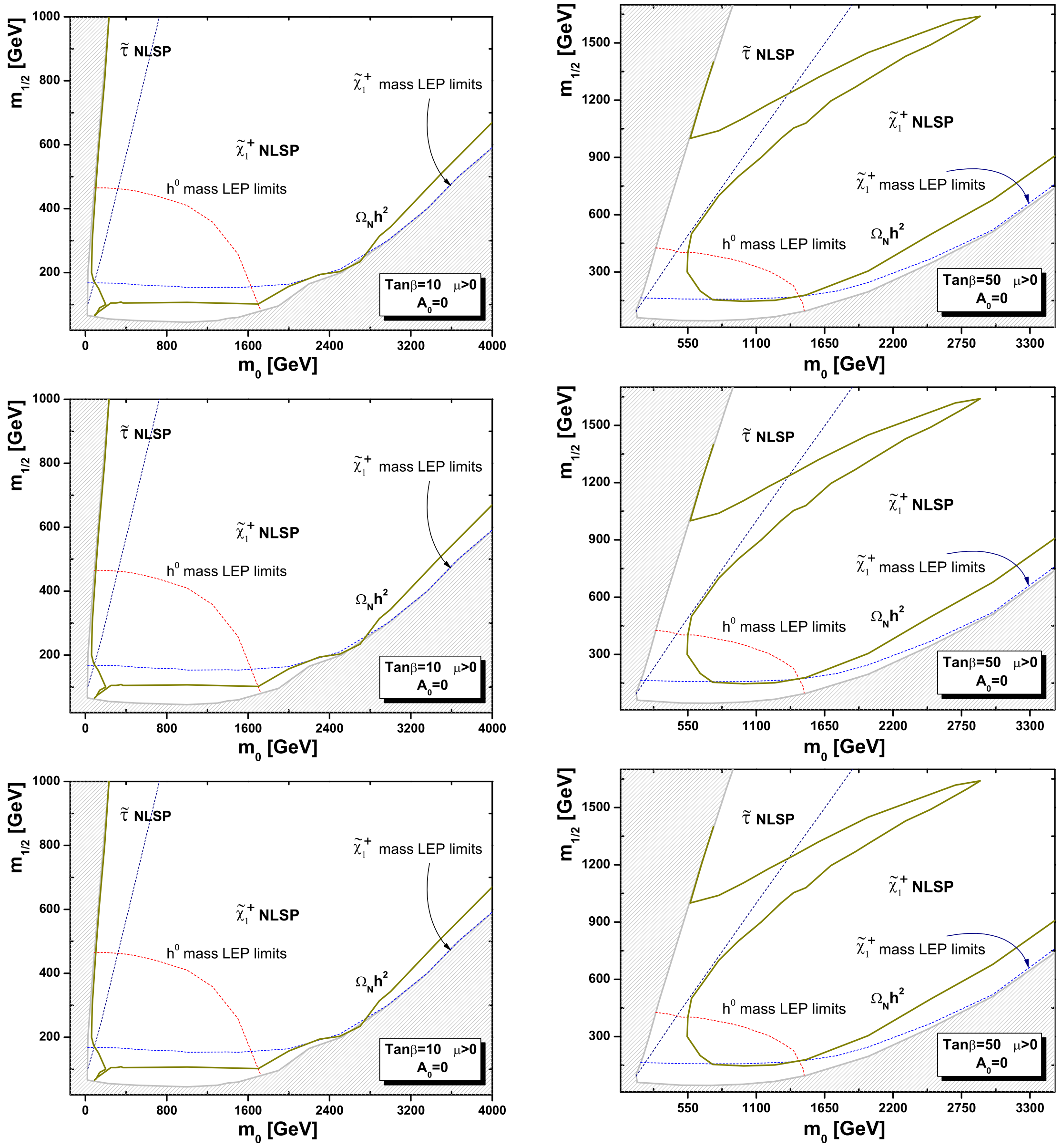

Figure 6: Allowed region of the mSUGRA parameter space for $A_0 = 0, -800, -3500$ GeV and $\tan\beta = 10, 50$, respectively. Dark (blue) areas show theoretically forbidden regions. Along the narrow green curve the amount of the Dark matter corresponds to WMAP data $\Omega h^2 = 0.09 \pm 0.04$. Also shown are experimental limits on the Higgs and chargino masses.

5 Conclusions

We have shown that within the framework of the Minimal Supersymmetric Standard Model with soft supersymmetry breaking mechanism it is possible to get long-lived superpartners of tau-lepton, top-quark and charged Higgs (or W-boson) which might be produced at the Large Hadronic Collider. The production cross-sections crucially depend 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 supersymmetry breaking parameter A_0. The events would have an unusual signature and produce a noticable signal rather than pure missing energy taken away by the lightest neutralino. The options are:

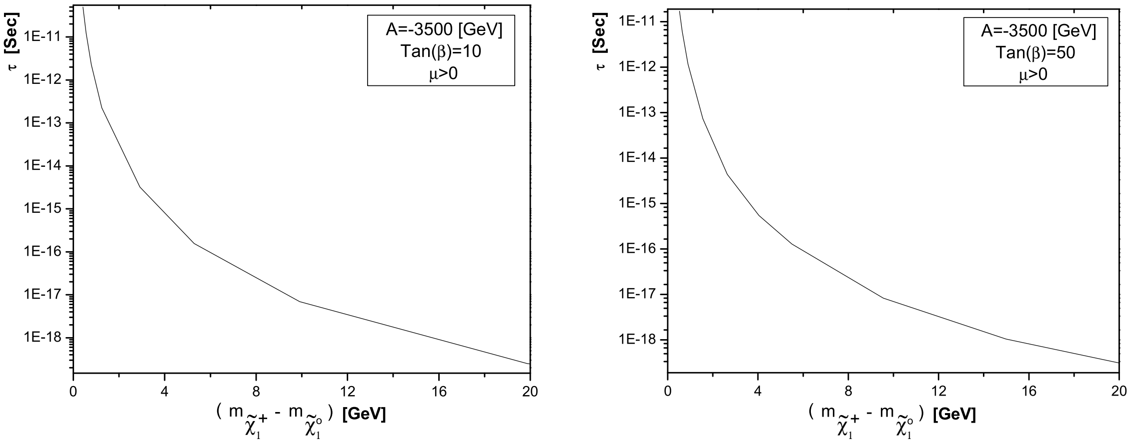

Figure 7: The lightest chargino lifetimes as a function of the mass difference between the lightest chargino (NLSP) and the lightest neutralino (LSP).

- 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.

Experimental Higgs and chargino mass limits as well as WMAP relic density limit can be easily satisfied in our scenario. However, the strong fine-tuning is required. Moreover, it is worth mentioning that light stops are favoured by the baryon asymmetry of the Universe.

Our stau/stop/charginoNLSP scenarios differ from the gauge mediated supersymmetry breaking scenario where next-to-lightest supersymmetric particles typically live longer.

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