LIGHT STOPS IN THE MSSM PARAMETER SPACE

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Received (Day Month Year)
Revised (Day Month Year)

We consider the regions of the MSSM parameter space where the top squarks become light and even may be the LSP. This happens when the triple scalar coupling $A$ becomes very big compared to $m_0$. We show that in this case the requirement that the LSP is neutral imposes noticeable constraint on the parameter space excluding low $m_0$ and $m_{1/2}$ similar to constraint from the Higgs mass limit. In some cases these constraints overlap. This picture takes place in a wide region of $\tan\beta$. In a narrow band close to the border line the stops are long-lived particles and decay into quarks and neutralino (chargino). The cross-section of their production at LHC via gluon fusion mechanism in this region may reach a few pb.

Keywords: Supersymmetry; long-lived particles.

PACS Nos.: 12.60.Jv, 14.80.Ly

1. Introduction

Preparing for SUSY discovery at LHC one faces the problem of well defined predictions since the variety of models and scenarios open up a wide range of possibilities. Due to the absence of a SUSY golden mode, one has to explore the parameter space looking for high cross-sections, low background processes, typical missing energy events, etc. All these possibilities are realized within some mechanism of SUSY breaking (mSUGRA and gauge mediation are the most popular) and depend on particular choice of a region in SUSY parameter space.

Besides commonly accepted benchmark points which are widely discussed in the literature there still exist some exotic regions in parameter space where unusual relations hold and one can expect interesting phenomena. In particular, in Ref. we considered the so-called coannihilation region in mSUGRA parameter space where one can have long-lived staus which can decay at some distance from the collision point or even fly through detector. This region of $m_0 - m_{1/2}$ plane
exists for all values of $\tan \beta$ and moves towards higher values of $m_0$ and $m_{1/2}$ with increase of the latter. However, the area where one can have long-lived particles is very narrow (for each $\tan \beta$) and needs severe fine-tuning.

Here we explore another region of parameter space which appears only for large negative scalar triple coupling $A_0$ and is distinguished by the light stops. On the border of this region, in full analogy with the stau coannihilation region, the top squark becomes the LSP and near this border one might get the long-lived stops. Below we discuss this possibility in detail and consider also its phenomenological consequences for the LHC.

2. Constraints on the MSSM Parameter Space for Large Negative Values of $A$

In what follows we consider the MSSM with gravity mediated supersymmetry breaking and the universal soft terms. We thus have the parameter space defined by $m_0, m_{1/2}, A, \tan \beta$ and we take the sign of $\mu$ to be positive motivated by contribution to the anomalous magnetic moment of muon [20,21,22,23,24,25]. Imposing the constraints like: i) the gauge couplings unification [26,27], ii) neutrality of the LSP [31,32], iii) the Higgs boson and SUSY mass experimental limits [33,34,35,36], iv) radiative electroweak symmetry breaking, we get the allowed region of parameter space. Projected to the $m_0 - m_{1/2}$ plane 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 stop, become relatively light. This happens via the see-saw mechanism while diagonalizing the stop mass matrix

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

where

$$
\tilde{m}_{tL}^2 = \tilde{m}_Q^2 + m_t^2 + \frac{1}{6}(4M_W^2 - M_Z^2)\cos 2\beta,
$$

$$
\tilde{m}_{tR}^2 = \tilde{m}_U^2 + m_t^2 - \frac{2}{3}(M_W^2 - M_Z^2)\cos 2\beta.
$$

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 squark mass defined by minus sign in eq. (1).

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

Hence, increasing $|A|$ one can make the lightest stop as light as one likes it to be and even make it the LSP. 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 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.
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 values of $\tan \beta$. We show the projection of SUSY parameter space to the $m_0 - m_{1/2}$ plane in Figs. 1 and 2 for different values

Fig. 1. Allowed region of the mSUGRA parameter space for $A_0 = -800, -1500$ 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.
Fig. 2. Allowed region of the mSUGRA parameter space for $-2500$, $-3500$ 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.

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 stau border line. It moves to the right with increase of $\tan \beta$ as shown in Fig.3 so that the whole forbidden area increases and covers the left bottom corner of the $m_0 - m_{1/2}$ plane.

It should be mentioned that the region near the border line is very sensitive to the SM parameters, a minor shift in $\alpha_s$ or $m_t$ and $m_b$ leads to noticeable change of spectrum as can be seen from comparison of different codes at 37,38,39.

The other constraint that is of interest in this region is the relic density one. Given the amount of the Dark matter from WMAP experiment 40,41 one is left with a narrow band of allowed region which goes along the stau border line, then along the Higgs limit line and then along the radiative symmetry breaking line. In the case of light stop when it is almost degenerate with the lightest chargino and neutralino, when calculating the relic density one has to take into account not only the annihilation of two stops, but also the coannihilation diagrams. There are two side processes: stop chargino annihilation and stop neutralino annihilation. Calculating the relic density with the help of MicrOmegas package 42,43 one finds that again it is very sensitive to the input parameters, however, since the stop border line is very close to the Higgs one, the relic density constraint may be met here fitting $A_0$ and/or $\tan \beta$.

Fig. 3. Stau and stop constraints in the $m_0 - m_{1/2}$ plane for $A_0 = -3500$ GeV and different values of $\tan \beta$. 
3. Phenomenological Consequences of the Light Stop Scenario

The phenomenology of the discussed scenario is of great interest at the moment since the first physics results of the coming LHC are expected in the nearest future. Light stops could be produced already during first months of its operation\textsuperscript{14,15}. The main diagrams of pair stop production (as well as other type of squarks) are presented in Fig. 4. A single stop production via weak interactions is also possible.

![Main stop production diagrams at LHC.](image)

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. 5. 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 ($\tilde{t} \rightarrow b \tilde{\chi}^\pm_1$). 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 $m_{\tilde{t}} < m_b + m_{\tilde{\chi}^\pm_1}$ (see right bottom corner in Fig. 2). In this case the dominant decay mode is the decay to the top quark and the lightest neutralino ($\tilde{t} \rightarrow t\tilde{\chi}^0_1$). Light stop decays to the charm quark and the lightest neutralino ($\tilde{t} \rightarrow c\tilde{\chi}^0_1$)\textsuperscript{46}. The latter decay, though it is loop-suppressed, has the branching ratio 100%.

In Fig. 6 we show different allowed decay modes for different values of $|A_0| = 800, 1500, 2500, 3500$ GeV as functions of the $m_{1/2}$ parameter. The values of $m_0$ were chosen in the middle of allowed regions in Figs 1 and 2, namely $m_0 = 250, 450, 650, 1000$ GeV. One can see that for small values of $m_{1/2}$ we are very close
to the neutralino–stop border line and the only allowed decay mode is $\tilde{t} \to c\tilde{\chi}_1^0$. With the increase of the $m_{1/2}$ the stop mass becomes larger which opens the possibility of new decay modes ($\tilde{t} \to b\tilde{\chi}_1^{\pm}$, and later $\tilde{t} \to t\tilde{\chi}_1^0$).

The bottom part of Fig. 6 shows the stop lifetimes for different values of $|A_0|$. The biggest lifetime corresponds to the $\tilde{t} \to c\tilde{\chi}_1^0$ decay. Breaks on the curves correspond to switching on the new decay mode. As one can see the lifetime can be quite large in a wide area of the $A_0 - m_{1/2}$ parameter space, even for heavy stops if $|A_0|$ is very big.

4. Conclusion

In this letter we have demonstrated that there is a possibility of stop next-to-lightest supersymmetric particle. For large negative values of the trilinear soft supersymmetry breaking parameter $A_0$ there exist a narrow band along the line $m_t = m_{\tilde{\chi}_1^0}$ in the $m_0 - m_{1/2}$ plane where the cross section of stop pair production is quite large at the LHC energy and stops have relatively large lifetime. This may give interesting signatures, like secondary vertices inside the detector, or even escaping the detector. Another interesting possibility is a formation of so-called $R$-hadrons (bound states of supersymmetric particles). This may happen if stops live longer than hadronisation 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.
Acknowledgements

Financial support from RFBR grant # 05-02-17603 and grant of the Ministry of Education and Science of the Russian Federation # 5362.2006.2 is kindly acknowledged.

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