LONG-LIVED STAUS AT THE LHC

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Supersymmetric scenarios with a very weakly interacting lightest superparticle (LSP)—like the gravitino or axino—naturally give rise to a long-lived next-to-LSP (NLSP). In the case of a stau NLSP, the scenario shows up in a very prominent way at colliders. We present the LHC sensitivity for these classes of scenarios in the framework of simplified models. This allows for deriving robust limits on the masses of the lightest stau, the gluino and squarks.

1 Introduction

In an R-parity conserving supersymmetric theory, the lightest supersymmetric particle (LSP) is stable and thus provides us with a candidate for dark matter (DM). Searching for supersymmetry at colliders always means searching for a certain LSP scenario. The neutralino LSP scenario is clearly the most widely studied scenario for the LHC and it is often referred to as *the* SUSY search. However, if one extends the MSSM, other cosmologically viable DM candidates show up. If, for instance, we impose the idea of SUSY on the fundamental theory of nature we have to supersymmetrize gravity predicting the gravitino, the superpartner of the graviton. The gravitino is indeed a very well motivated LSP[1] and may even be considered as favored since it alleviates the gravitino problem[2] allowing for larger reheating temperatures. Another perfectly viable DM candidate is the axino,[3] a supersymmetric partner of the QCD axion which is introduced in the Peccei-Quinn mechanism. Both candidates are very weakly interacting particles—the couplings are suppressed by the Planck- or the Peccei-Quinn scale, respectively. This naturally renders the next-to-LSP (NLSP) long-lived. If the decay length of the NLSP is large compared to the size of a detector of a collider experiment, the LSP is typically not involved in the interactions inside the detector at all and the NLSP determines the signature. For an electrically charged NLSP, like the stau, this leads to a very distinct SUSY signature—no missing energy but highly ionizing tracks leaving the detector.[4] Several studies for long-lived staus have been performed, assuming a certain underlying high scale model—such as minimal gauge mediated supersymmetry breaking or the constrained MSSM (CMSSM).[a] However, long-lived staus can basically occur in all common breaking models.

In this work we address the question whether it is possible to derive robust bounds on the mass parameters from the LHC experiment that cover all possible spectra accommodating a long-lived stau NLSP. We will therefore adopt the approach of simplified models.[7,8] As an important outcome, we will see that in the case of long-lived staus the simplified models provide a very powerful description covering a large set of possible realistic spectra. We will restrict ourselves to the production via squarks and gluinos as well as to direct pair production of staus.

[a] Currently, searches for heavy stable charged particles are performed by ATLAS[5] and CMS[6].

2 Simplified models for long-lived staus

Simplified models have successfully been used in the neutralino LSP scenario and have lead to bounds on the gluino and squark mass beyond those derived within the CMSSM. However, one immediately notices some important differences between that scenario and the one considered here. In the neutralino LSP scenario, the only signal from the LSPs is missing energy. The SUSY search is almost independent of the neutralino kinematics, rather it depends strongly on the type and hardness of the SM particle radiation. In the considered long-lived stau scenario it is—roughly speaking—the other way around. The kinematics of the staus, in particular their velocities are crucial quantities. For velocities well below one the signature is basically background free, whereas, if the velocity approaches one a comparatively huge amount of muon background is present. Consequently, the significance of the signal will drop drastically.

When the stau is produced in a cascade decay following the production of colored sparticles a very large number of parameters enter the computation through the mixing angles and masses of the intermediate sparticles that can participate in the cascade decay. But not all parameters are equally important. Obviously, the masses of the squarks and gluinos play an important role in determining the production cross section. Additionally, the mass of the stau determines the total phase space available in the cascade decay of the lightest colored sparticle (LCP) down to the stau and thus dominantly determines the stau velocity. The impact of the intermediate sparticles can successfully be described by introducing a few distinct simplified models which represent limiting cases of realistic spectra and allow for the free parameters $m_{\widetilde{g}}$, $m_{\widetilde{q}}$ and $m_{\widetilde{\tau}_1}$.

Considering a fixed mass gap $m_{\rm LCP} - m_{\widetilde{\tau}_1}$, in the limit of massless SM radiation a non-trivial extremum of the stau velocity is given by the mass pattern

$$m_i = (m_{\rm LCP})^{\frac{n-i}{n}} (m_{\widetilde{\tau}_1})^{\frac{i}{n}} \tag{1}$$

of $n-1$ intermediate sparticles i. This extremum is usually a minimum. The only other extremum is represented by the mass degenerate configurations

$$m_i = m_{\rm LCP}\,, \quad m_j = m_{\widetilde{\tau}_1} \quad \forall\, i < k,\ j \geq k\,, \quad k = 1, \ldots, n\,. \tag{2}$$

which is kinematically equivalent to a direct decay of the LCP into the stau. These observed extrema motivate the following simplified models. Model $\mathcal{A}$: The direct decay over a nearly degenerate neutralino ($m_{\widetilde{\chi}^0} \simeq m_{\widetilde{\tau}_1}$). Model $\mathcal{B}$: The mass pattern (1) for $n = 2$, LCP$\to \widetilde{\chi}^0_1 \to \widetilde{\tau}_1$, i.e. $m_{\widetilde{\chi}^0} = \sqrt{m_{\rm LCP} m_{\widetilde{\tau}_1}}$. Model $\mathcal{C}$: The mass pattern (1) for $n = 4$, LCP$\to \widetilde{\chi}^0_2 \to \widetilde{\ell} \to \widetilde{\chi}^0_1 \to \widetilde{\tau}_1$. In fact, these models represent limiting cases even for decay chains that radiate massive SM particles, like LCP$\to \widetilde{\chi}^0_2 \to \widetilde{\chi}^0_1 \to \widetilde{\tau}_1$. Decay chains longer than $n = 4$ are rather unlikely and will not make up the dominant decay mode within the MSSM.[9]

Another important difference between the neutralino LSP and the considered scenario is that the latter provides a perfectly well observable direct production mechanism. The production via the Drell-Yan (DY) process depends only on $m_{\widetilde{\tau}_1}$ and (less strongly) on the stau mixing angle $\theta_{\widetilde{\tau}}$. The stau mixing angle that provides the lowest cross section, $\theta_{\widetilde{\tau}}^{\rm min}$, is practically independent of the mass and kinematics of the stau (at least for stau masses above roughly 150 GeV). Thus the DY production provides an important lower limit on the stau mass, which is completely model-independent.[10]

3 LHC reach

To estimate the projected LHC reach of the scenario we performed a full-fledged Monte Carlo study. We imposed a set of selection criteria which was optimized in order to provide high efficiencies throughout the considered parameter space. This was achieved by only taking into

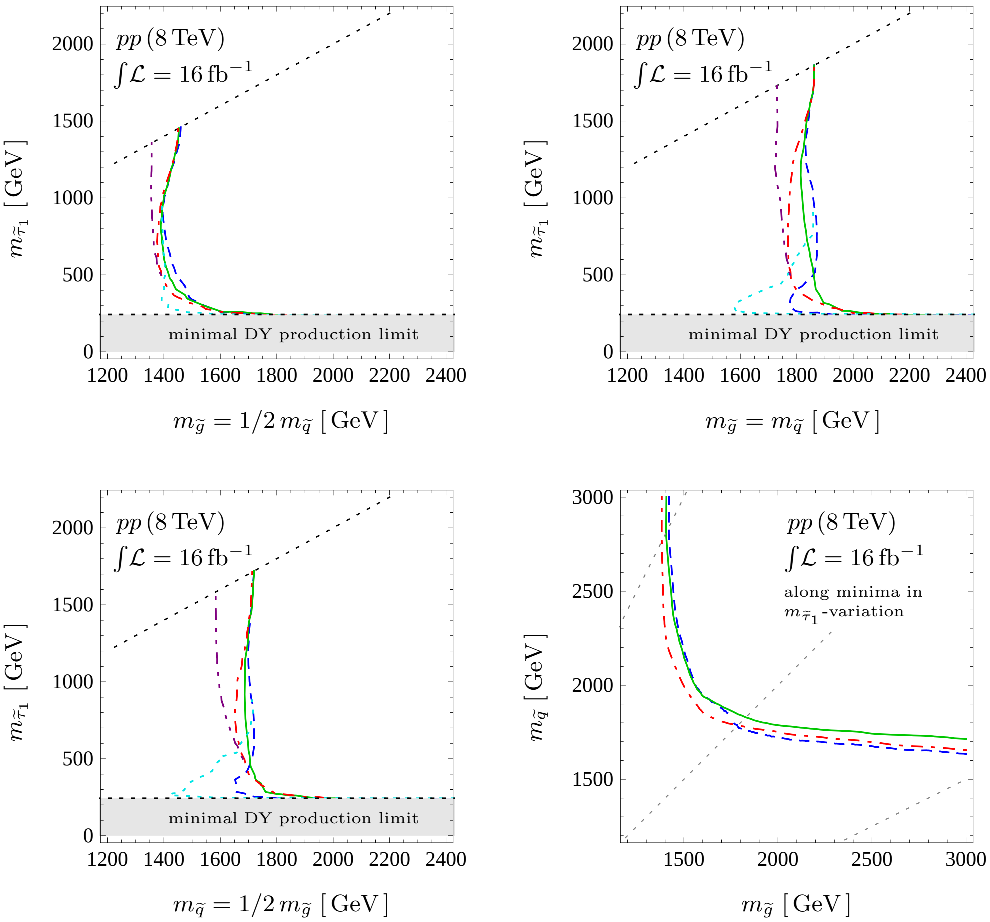

Figure 1: Projected LHC sensitivity (95% $\mathrm{CL_S}$ exclusion, see footnote b) for the models $\mathcal{A}$ (blue dashed), $\mathcal{B}$ (green solid) and $\mathcal{C}$ (red dot-dashed) as well as $\mathcal{A}$ (cyan dotted) and $\mathcal{C}$ (purple dot-dot-dashed) for a reduced set of selection criteria (see text for details). In the lower right panel the curves represent the minima in the sensitivity with respect to the variation of $m_{\tilde{\tau}_1}$. We assume a common squark mass for all flavors. Taken from reference 9.

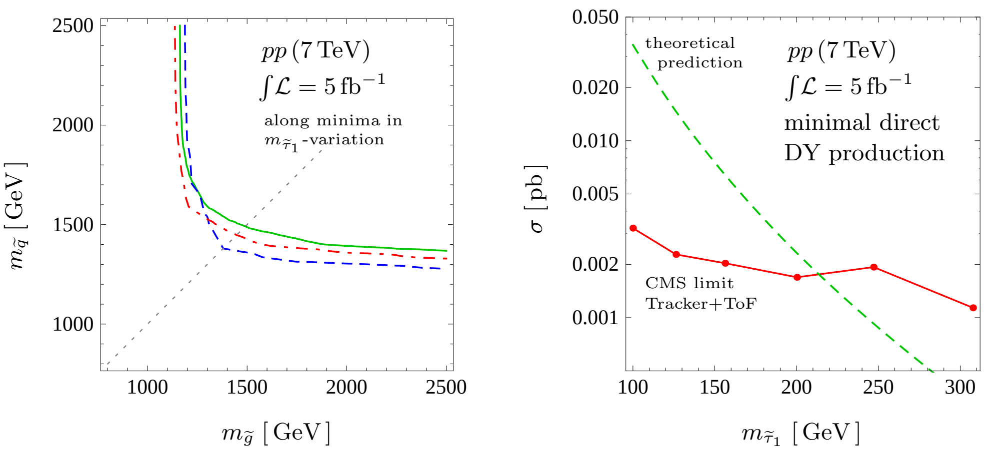

Figure 2: Left panel: Projected LHC sensitivity (95% $\mathrm{CL_S}$ exclusion, see footnote b) for the models $\mathcal{A}$ (blue dashed), $\mathcal{B}$ (green solid) and $\mathcal{C}$ (red dot-dashed). The curves represent the minima in the sensitivity w.r.t. the variation of $m_{\tilde{\tau}_1}$. We assume a common squark mass for all flavors. Right panel: The cross section limit on stau pair production from the 7 TeV CMS data and the NLO cross section prediction for the DY production with $\theta_{\tilde{\tau}}^{\min}$.

account the staus and up to two jets. The most important background is the DY production of muons, even when two hard jets ($p_T > 200\,\mathrm{GeV}$) are required.

Figure 1 shows the projected 95% $\mathrm{CL_S}$ exclusion limits[b] at the 8 TeV LHC for the three simplified models defined in section 2. In model $\mathcal{A}$ (blue dashed lines) the decay LCP$\rightarrow \widetilde{\chi}_1^0$ is the dominant decay leading to hard jets and potentially highly boosted staus. In an intermediate region of $m_{\mathrm{LCP}} - m_{\widetilde{\tau}_1}$ this leads to an enhancement of the significance whereas for large mass gaps $m_{\mathrm{LCP}} - m_{\widetilde{\tau}_1}$ the significance drops sharply, despite the fact that the jets become harder. (The cyan dotted curve shows the sensitivity without taking a jet-optimized selection criterium into account.) The scenario would hide very effectively from observation if it were not for the direct production which increases the sensitivity for lower $m_{\widetilde{\tau}_1}$. This results in a minimum in the sensitivity just above the limit provided by the minimal DY production. For small mass gaps $m_{\mathrm{LCP}} - m_{\widetilde{\tau}_1}$ the lower limit on the velocity becomes more important. Such a lower limit might be imposed by trigger restrictions. The purple dot-dot-dashed curves show the sensitivity for $\mathcal{C}$ after dropping a selection criterium that allows staus to fire the muon trigger in delay, i.e. requiring a buffering of the tracker data up to three bunch crossings in delay.

In the lower right panel of figure 1 and the left panel of figure 2 the LHC sensitivity in the $m_{\widetilde{g}}$-$m_{\widetilde{q}}$-plane is shown. The curves show the 95% $\mathrm{CL_S}$ taking the respective $m_{\widetilde{\tau}_1}$ that yields the lowest cross section at each point. The simplified models $\mathcal{A}$, $\mathcal{B}$ and $\mathcal{C}$ span a relatively narrow band in the $m_{\widetilde{g}}$-$m_{\widetilde{q}}$-plane. From the non-observation of heavy stable charged particles this allows for an estimation of model-independent limits on $m_{\widetilde{g}}$ and $m_{\widetilde{q}}$. In the right panel of figure 2 the cross section for direct DY production of staus is displayed as a function of the stau mass. We chose here the stau mixing angle which yields the smallest cross section. Additionally, we display the cross section limit curve from CMS[6] obtained for another choice of $\theta_{\widetilde{\tau}}$. Since the kinematics do not depend on $\theta_{\widetilde{\tau}}$, we do not expect any changes in the cut efficiencies.

4 Conclusion

The long-lived stau scenario can be very well described by simplified models. The direct detectable stau does not give rise to regions in parameter space where the scenario hides very effectively from observation, as it is e.g. the case in the neutralino LSP scenario where compressed or widely spread spectra are difficult to explore. From the minimal direct production, long-lived staus with a mass below $m_{\widetilde{\tau}_1} = 216\,\mathrm{GeV}$ can be excluded. This limit is completely model-independent. In the described framework, conservative limits on the gluino mass and a common squark mass of about $m_{\widetilde{g}} > 1100\,\mathrm{GeV}$ and $m_{\widetilde{q}} > 1250\,\mathrm{GeV}$ can be estimated.

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[b] Due to the special situation of a very clean signal region and thus only few required events these curves also represent an (even conservative) estimation on the 5σ discovery potential.