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Proposing a new LHC search for light compressed stop squarks

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The LHC searches for light compressed stop squarks have resulted in considerable bounds in the case where the stop decays to a neutralino and a charm quark. However, in the case where the stop decays to a neutralino, a bottom quark and two fermions via an off-shell W-boson, there is currently an unconstrained region in the stop-neutralino mass plane, still allowing for stop masses around 100 GeV. In this note we will propose a new monojet-like search for light stops, optimized for the four-body decay mode, in which at least one b-tagged jet is required. We show that, already by using the existing 8 TeV LHC data set, such a search would cover the entire unconstrained region. This note is based on ref. [1].

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1. Introduction

With the discovery of a Standard Model-like Higgs boson, the so called hierarchy problem is more sharply defined than ever. The top quark gives rise to the leading quantum correction to the Higgs mass parameter, introducing a quadratic sensitivity to the scale of new physics beyond the Standard Model. If the scale of new physics is significantly above the electroweak scale, unless the parameters of the new physics are so fine-tuned that the sum of all the quantum corrections almost exactly cancel, this correction destabilizes the electroweak scale. In supersymmetry, the Higgs mass parameter is quadratically sensitive to the mass of the top quark superpartner, the stop, corresponding to the scale of new physics. In order to evade the need for fine-tuning, the stop mass should be around or below the electroweak scale, and hence be observable at the LHC.

The LHC searches have placed stringent limits on the masses of several superpartners, including the stop. However, there exists a region in which light stops are still unconstrained. This is mainly due to the particularly challenging final states that are produced in this region, corresponding to compressed spectra that give rise to soft particles and a small amount of missing transverse energy ($\not{E}_T$). To cover this unconstrained region is clearly important from the point of view of the hierarchy problem. In this note, after a brief review of stop squark searches after the first LHC run, we propose a new monojet-like analysis, exploiting b-tagging, to test the compressed region in which the stop decays via a four body decay.

2. Current bounds on light compressed stops

The simplified model we consider involves only the lightest of the two stop squarks, $\tilde{t}_1$, which decays to the lightest supersymmetric particle, the neutralino $\tilde{\chi}_1^0$. We distinguish three main kinematical regions, characterized by the stop-neutralino mass difference $\Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$. The current bounds in the $m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0}$ plane are represented by the dashed curves in Figure 1.

In the case when the mass difference is larger than the top mass, $\Delta m > m_t$, the stop decays via the two-body decay to a top quark and the neutralino. This is the region where the strongest bounds on the stop mass are attained [2, 3] – for a neutralino lighter than 250 GeV, stop masses below 600–750 GeV are excluded. Up until recently, there was a unconstrained triangular region for an almost massless neutralino and 180 GeV $< m_{\tilde{t}_1} <$ 200 GeV, but this triangle has been essentially closed by the constraint on the stop production cross section coming from the spin correlation measurement of $t\bar{t}$ production [4].

In the intermediate region $m_W + m_b < \Delta m < m_t$, the two body decay is precluded and the stop decays via a three body process involving the W-boson and the b-quark from the off-shell top, and the neutralino [3, 5, 6]. The current data exclude stop masses up to roughly 300 GeV in the central region of this domain.

Lastly, for $m_b < \Delta m < m_W + m_b$, the above channels are closed and the stop decays to the neutralino and either one or three light Standard Model fermions. The first option corresponds to the one-loop decay process $\tilde{t}_1 \to c + \tilde{\chi}_1^0$, while the second option is the logical extension of the decays discussed above, where now even the W is forced to be off-shell, i.e. $\tilde{t}_1 \to b + f + f' + \tilde{\chi}_1^0$. This is perhaps the most difficult region to investigate since there are two competing decay channels with model dependent branching ratios. The model dependency is mainly due to the first process, which involves the masses of all the superpartners that enter the loop as well as the squark flavor structure.

The majority of searches in the most squeezed region have targeted the decay mode $\tilde{t}_1 \to c + \tilde{\chi}_1^0$, assuming this decay mode to have 100% branching ratio (BR) [7, 8]. Under this assumption, stop masses below 250 GeV have been excluded. The four body decay process $\tilde{t}_1 \to b + f + f' + \tilde{\chi}_1^0$ has been targeted by the ATLAS searches [3, 7, 9], in which 100% BR is assumed. However, under these assumptions, there is still a small unconstrained region at stop masses around 100 GeV.

The searches [3, 7, 9], introduced in the above discussion, cover complementary kinematical regions. The search [7] is basically a monojet search in which at least one hard jet is required in order to have a sufficient recoil that gives rise to a large amount of $\not{E}_T$. The very nature of the selection criteria is such that the search is most sensitive near the $\Delta m = m_b$ region where the stop decay products are soft. On the contrary, the searches [3, 9] are sensitive for larger values of Δm. This is so because these searches require the presence of one or two leptons, respectively, in the final state that need to be sufficiently hard to be reconstructed. Due to the difficulties in the reconstruction of soft leptons using fast detector simulation, it is in general difficult to recast this search. Similarly, the proposal of its improvement suffers from the difficulty of dealing with soft leptons. For this reason we do not attempt to recast and improve this latter search. Instead we have chosen to focus on improving the former search strategy [7].

We are now ready to discuss the targeted region of our proposal. Figure 1 (left) summarizes the status of searches for light stops in the squeezed region with the assumption of a 100% BR into a four-body final state. There is an unconstrained region for 80 GeV $\lesssim m_{\tilde{t}_1} \lesssim$ 110 GeV GeV, bounded by the exclusion curves from the ATLAS one and two lepton searches [3, 9], the ATLAS monojet search [7] and LEP [10].

3. Proposal for a monojet search with a b-tag

In ref. [7] ATLAS performed the search for pair produced compressed stop squarks that our proposal is trying to improve upon. They considered a total of five signal regions. Two of them (C1 and C2) target the decay mode $\tilde{t}_1 \to c + \tilde{\chi}_1^0$ and will not be considered further. The remaining three (M1, M2 and M3) are monojet-like searches that target both the charm decay mode and the four-body decay mode we are interested in.

After a preselection that includes a lepton veto, the three ATLAS monojet signal regions are first characterized by a common set of selections criteria, namely the presence of at most three jets with $p_T > 30$ GeV and $|\eta| < 2.8$ and an azimuthal angular separation between these jets and the $\not{E}_T$, $\Delta\phi > 0.4$. The difference between the three regions is then based on the p_T of the leading jet and the $\not{E}_T$ in the event. The values for these last two cuts are $(p_T^{j_1}, \not{E}_T) = (280, 220), (340, 340)$ and (450,450) GeV in the signal regions M1, M2 and M3 respectively.

The different signal regions are optimized for different regions of parameter space. Since we are interested in targeting the low-mass region we only consider the M1 selections in the following. Our proposal is quite straightforward and can be summarized by saying that the sensitivity to the low mass region can be improved by adding a b-tag requirement on one of the (at most) three jets.

More specifically, we require the presence of at least one b-tagged jet with 30 GeV $< p_T <$ 300 GeV, $|\eta| < 2.5$. In the above p_T and η range, the ATLAS calibration algorithm for b-tagging

Background	$t\bar{t}$	$Z(\to\nu\nu)$	$W(\to\ell\nu)$	Dibosons	Others	Total
M1 (ATLAS [7])	780 ± 73	17400 ± 720	14100 ± 337	650 ± 99	565 ± 301	33450 ± 960
M1+b-tag	307 ± 57	261 ± 22	144 ± 7	55 ± 17	-	767 ± 64

Table 1: Estimated numbers of background events with 20.3 fb^{-1} of 8 TeV LHC data. The background is given as $B\pm\delta B$, B being the central value and δB the 1σ error. The error in the M1 case is simply taken from ATLAS. For the error in the M1+b-tag region we quote twice the relative error, see [1] for a discussion.

is data-driven, thus reducing the systematic uncertainties coming from Monte Carlo simulations. In what follows we denote the new signal region by “M1+b-tag".

Looking at the background estimations by ATLAS for the M1 signal region it is easy to see why the addition of a b-tag is expected to improve the sensitivity to the signal. For 20.3fb^{-1} at 8 TeV, out of a total of expected 33450 $\pm$ 960 background events, 17400 $\pm$ 720 come from SM processes involving $Z\to\nu\nu$ and 14100 ± 337 come from the processes involving $W\to\ell\nu$. The key point is that both of these leading backgrounds are dramatically reduced by the extra b-tag requirement.

We simulated both signal and background by using MADGRAPH5 [11], PYTHIA6 [12], FASTJET3 [13, 14] and DELPHES3 [15]. In the fast detector simulation we used the standard ATLAS detector specification. The PDF set used is the CTEQ6L1, jets are reconstructed using the anti-k_t algorithm [16] with $\Delta R=0.4$ and MLM matching [17, 18] is used throughout the simulation. Table 1 summarizes the expected leading backgrounds with and without the b-tagging requirement.

In order to reproduce as faithfully as possible the ATLAS situation we used the following strategy. We generated, fully independently, a large sample of background events and passed them through the same cuts as those performed by ATLAS in M1. From this analysis, we found the central values for all the backgrounds to be within 20% of the ATLAS results. This gives us confidence that the remaining background sample is representative of the physical situation after the cuts. Since we are only interested in the further improvements in efficiency arising from the b-tagging, we normalize the expected number of events to the ATLAS numbers and only multiply by the b-tag efficiency we get when passing from M1 to M1+b-tag.

Table 1 conveys the idea of the discriminating power of the b-tag in rejecting invisible Z decays and leptonic W decays. The two leading backgrounds in [7] are now subleading with respect to the $t\bar{t}$ background which, since it contains b-jets, is only mildly affected by the extra cut. The signal, as will be discussed below, is found to behave in a similar way as the $t\bar{t}$ background and thus the overall sensitivity is significantly improved.

Turning now to the signal, we simulated a grid of points with $70\ \text{GeV}\leq m_{\tilde{t}_1}\leq 250\ \text{GeV}$ and $0\ \text{GeV}\leq m_{\tilde{\chi}_1^0}\leq 200\ \text{GeV}$ in steps of 10 GeV inside the region 10 GeV $\leq\Delta m\leq$ 80 GeV. As mentioned above, we only considered stop pair production as production mode. For stop masses above 100 GeV we used the NLO+NLL cross sections of ATLAS [19] while for the few points below 100 GeV, we used PROSPINO [20] to determine the main slope and fixed the absolute normalization with the ATLAS values above 100 GeV.

After imposing the M1 cuts we again found agreement within 20% with ATLAS. We used the same normalization procedure as for the background, normalizing the number of events before the

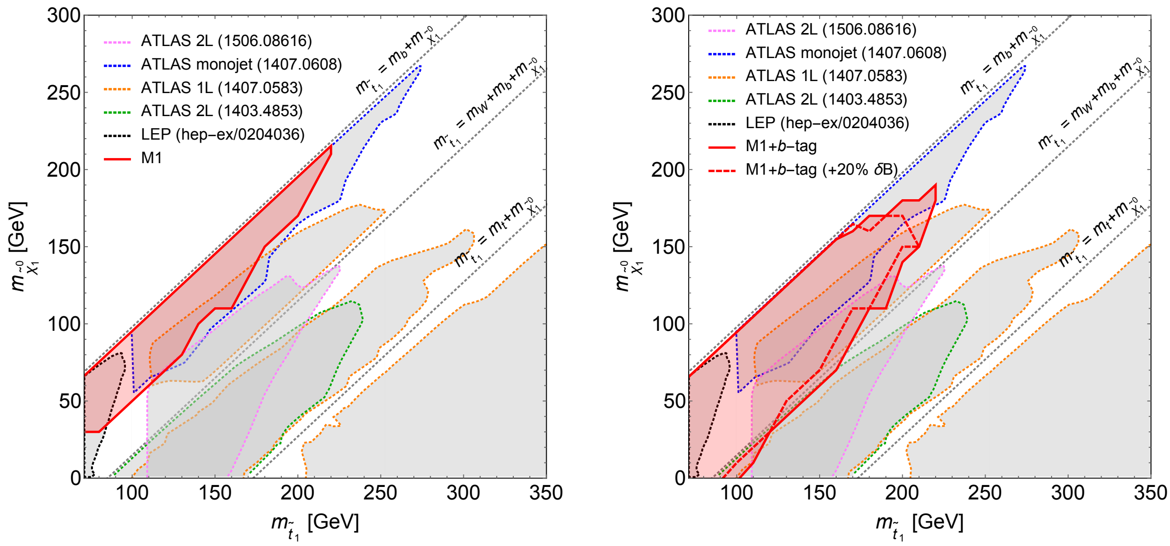

Figure 1: Left: Existing limits in the stop-neutralino mass plane, superimposed with the M1 exclusion curve as obtained in our analysis and extended to $m_{\tilde{t}_1} < 100$ GeV. Right: The main result from our proposed search "M1+b-tag", (red solid curve), with the change induced by increasing the background error by 20 % (red dashed curve). This figure is an updated version of the figure in ref. [1] (see also ref. [21]).

b-tag requirement to the ATLAS numbers and using only the b-tag efficiency to obtain the final results for the signal. The main difference with the previous background simulation is that, due to the large number of points on the grid and the small efficiencies, we are unable to generate a statistically significant fully matched sample of events. We thus resort to the following strategy. For each point we generate two exclusive samples, one containing zero jets at the parton level and one containing exactly one such jet with $p_T > 200$ GeV. The ratio of the LO cross sections obtained is used to estimate the efficiency of the p_T cut: $\varepsilon_{p_T > 200\ \mathrm{GeV}} = \sigma(pp \to \tilde{t}_1\tilde{t}_1 j(p_T > 200\ \mathrm{GeV}))/\sigma(pp \to \tilde{t}_1\tilde{t}_1)$. The one-jet unmatched sample is then used throughout the analysis. We have checked this procedure on a number of points and we have found good agreement with the results from the fully matched sample.

We set limits by excluding points for which the number of events $N > 1.96\,\delta B$. Notice that the analysis is essentially all driven by systematics and not by statistics. In the left panel of Figure 1 we present, for comparison, the exclusion limits we obtain repeating the M1 analysis of ATLAS (red exclusion curve). We are able to reproduce their exclusion boundaries fairly accurately, which validates the analysis on the right. Note that the limits in [7] are broader since they take into account the signal regions M2 and M3 that become more relevant for large masses. We have tested imposing the b-tag requirement on those regions as well but the low signal efficiency makes them not viable, at least for the 20.3fb^{-1} 8 TeV data. In fact, we tested changing the p_T and $\not{E}_T$ cuts within the intervals defined by M1 and M2 and we found that M1 essentially gives the best S/B ratio within statistical fluctuations. The red curve in the right panel of Figure 1 is our main result. It fully covers the so far unconstrained region exposed in the left panel of Figure 1.

With an eye to the Run-2 of LHC it is worth studying if a search of this type can be further optimized to cover an even larger region. Here we conclude by pointing out that it may be possible also to move in the opposite direction and relax some of the constraints imposed by the current search. The M1 ATLAS cut flow was heavily relying on the isolation requirement between the jets and the $\not{E}_T$, $\Delta\phi > 0.4$. This is necessary to reduce the QCD jet contamination and $\not{E}_T$ from jet mismeasurements. The requirement of a b-jet however already dramatically cuts the QCD background and could be considered an alternative to the former requirement. However, due to the uncertainties involved in calculating the QCD background with our simulation tools, we refrain from making any estimates of the potential gain in sensitivity. Nevertheless, we would like to encourage the experimental collaborations to also consider this possibility.

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