

Searches for direct pair production of third generation squarks with the ATLAS detector

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Abstract. The most recent results of the searches for direct production of third generation squarks with the ATLAS detector are presented. All the selected analyses use 21 fb^{-1} of pp collisions at $\sqrt{s} = 8 \text{ TeV}$ and follow the assumptions of a Minimal Supersymmetric extension of the Standard Model of Particle Physics where the R-parity is conserved and the lightest supersymmetric particle (LSP) is the lightest neutralino. Naturalness considerations require that the partners of the top and bottom quarks are light ($O(1 \text{ TeV})$) and hence have a relatively high production cross-section at the LHC. Since no deviations from the Standard Model predictions are observed, limits are set for different mass hierarchies and mass relations between the bottom and top squarks and the lightest chargino and neutralino.

1 Introduction

The results of the searches for direct stop and direct sbottom production with the ATLAS detector [1], all updated to the full 2012 $\sqrt{s} = 8 \text{ TeV}$ dataset of $\sim 20 \text{ fb}^{-1}$, are presented.

The searches are based on a Minimal Supersymmetric (SUSY) extension of the Standard Model (SM) of particle physics, where the R-parity is conserved. SUSY particles are therefore pair-produced and the lightest supersymmetric particle (LSP) is a stable, neutral and only weakly interacting particle and hence a good Dark Matter candidate.

Naturalness requires low fine tuning in the theory and implies a light higgsino sector, gluinos with a mass below 2 TeV and light partners of the 3rd generation SM quarks, making their production cross-section accessible for searches at the LHC.

Since no significant excess over the SM expectations was observed in any of the analyses, they were interpreted in different scenarios and exclusion limits were set. For direct sbottom (\tilde{b}_1) production (Sect. 2), the decays considered are $\tilde{b}_1 \rightarrow b + \tilde{\chi}_1^0$ [2], where $\tilde{\chi}_1^0$ is the lightest neutralino, and $\tilde{b}_1 \rightarrow t + \tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm \rightarrow W^{(*)} + \tilde{\chi}_1^0$ [3], where $\tilde{\chi}_1^\pm$ is the lightest chargino.

The direct stop (\tilde{t}_1) searches (Sect. 3) target mainly two scenarios: $\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$ [4, 5] and $\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm \rightarrow W^{(*)} + \tilde{\chi}_1^0$ [2, 5, 6]. Different \tilde{t}_1 - $\tilde{\chi}_1^\pm$ - $\tilde{\chi}_1^0$ mass relations are considered. When the mass difference between the stop and the neutralino is smaller than the mass of the top quark, the decay $\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$ through an on-shell top is suppressed, whilst the three body decay (through an off-shell top) $\tilde{t}_1 \rightarrow b + W + \tilde{\chi}_1^0$ opens up. Results for the interpretation in a three-body decay scenario have been presented

for the first time at LHCP 2013 [6]. The chosen results include also interpretations in more complex direct stop production scenarios for which Z-bosons are present in the decay chain [7], e.g. $\tilde{t}_2 \rightarrow \tilde{t}_1 Z$, $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$, powerful in covering the region $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = m(t)$, and Natural GMSB scenarios $\tilde{t}_1 \rightarrow XZ\tilde{G}$, where \tilde{G} is the gravitino.

2 Searches for direct sbottom production

The direct sbottom production and decay scenarios have been covered by two analyses, one focusing on final states with two leptons with the same charge and jets (Sect. 2.1) and one that requires two b-tagged jets and high E_T^{miss} (Sect. 2.2).

2.1 Searches in final states with 2 same-sign leptons and jets

The search for Supersymmetry in final states with two Same Sign (SS) leptons [3] has interpretations in many SUSY production and decay scenarios. Here only the interpretation for direct sbottom production with $\tilde{b}_1 \rightarrow t + \tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm \rightarrow W^{(*)} + \tilde{\chi}_1^0$, with branching ratio BR=1, is considered.

This analysis exploits the low SM background to get a good sensitivity to SUSY processes. The only sources of SS leptons in the Standard Model are the associated production of $t\bar{t}$ +vector-boson and the diboson production, that have to be added to the contributions containing mis-identified leptons. These consist of processes where the SS pair arises either from charge-misidentification (radiation of a hard photon bremsstrahlung followed by an asymmetric conversion) or from a non-prompt lepton mainly produced in a b -hadron decay.

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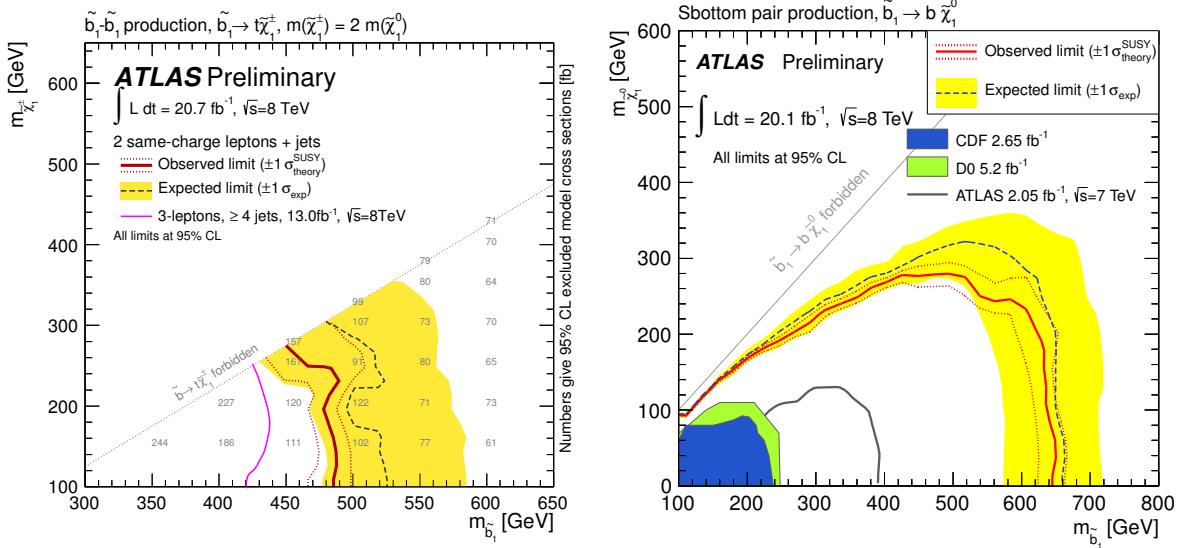


Figure 1. Expected (dashed lines) and observed (solid lines) limits at 95% CL for direct sbottom pair production. On the left the $\tilde{b}_1 \rightarrow t\tilde{\chi}_1^\pm$ model with $m(\tilde{\chi}_1^\pm) = 2 \cdot m(\tilde{\chi}_1^0)$ is shown [3]; the numbers give the limits on the excluded model cross sections in fb. The right plot shows the limit obtained in the $\tilde{b}_1\tilde{\chi}_1^0$ plane assuming $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$ with 100% BR [2].

The signal selection requires, on top of the SS lepton pair, the presence of at least three jets with $p_T > 40$ GeV, of which one identified as b-jet with $p_T > 20$ GeV, $E_T^{\text{miss}} > 150$ GeV,

$$m_T(\ell_1, E_T^{\text{miss}}) = \sqrt{2p_T^\ell E_T^{\text{miss}} - 2\mathbf{p}_T^\ell \cdot \mathbf{p}_T^{\text{miss}}} > 100 \text{ GeV} \text{ and high effective mass, } m_{eff} = \sum_{i=1}^2 p_T^{\ell_i} + \sum_{k=1}^{n-\text{jets}} p_T^{jet_k} + E_T^{\text{miss}}, \text{ in the event.}$$

To maximise the exclusion reach, a shape fit in m_{eff} is performed. The limits are computed as 95% Confidence Levels (CL), using the CL_s method, with a fit based on the profile likelihood ratio [13]. Exclusion limits are extracted for two different signal assumptions in the $m(\tilde{b}_1) - m(\tilde{\chi}_1^\pm)$ plane. For a fixed neutralino mass $m(\tilde{\chi}_1^0) = 60$ GeV sbottom masses up to 470 GeV are excluded at 95% CL for all the allowed chargino masses. Figure 1 left shows the excluded area for the model $m(\tilde{\chi}_1^\pm) = 2 \cdot m(\tilde{\chi}_1^0)$: sbottom masses up to 450 GeV are excluded at 95% CL for the allowed $\tilde{\chi}_1^\pm$ masses.

2.2 Searches in final states with 2 b-jets and E_T^{miss}

The search focusing on final states with 2 b-tagged jets, E_T^{miss} and very low additional hadronic activity [2] is developed to investigate direct sbottom and direct stop production, for which the results are reported in section 3.1. The scenario considered for direct sbottom production and decay is $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$, BR=1, and limits are extracted in the $m(\tilde{b}_1) - m(\tilde{\chi}_1^0)$ plane.

The main backgrounds to this analysis come from the semi-leptonic decay of $t\bar{t}$ pairs, where the lepton is either an hadronic decaying τ or is lost or misidentified, and $Z \rightarrow \nu\nu$ and W production in association with b-jets.

Two different signal selections (SR) are defined, one sensitive to large mass splitting between the relevant SUSY particles, in this case \tilde{b}_1 and $\tilde{\chi}_1^0$, and one that exploits

an initial state radiation (ISR) signature, that is, a hard jet emitted back to back to the $\tilde{b}_1\tilde{b}_1^*$ system giving higher E_T^{miss} in the event, and is sensitive to compressed scenarios. For both SRs the selected events must pass the requirements for a E_T^{miss} trigger, not contain any lepton, have two b-tagged jets, and have almost no additional hadronic activity on top of the requested jets. The selection for large mass splittings scenarios uses the con-transverse mass [14] of the two b-jets, $m_{CT}^2(v_1, v_2) = [E_T(v_1) + E_T(v_2)]^2 - [\mathbf{p}_T(v_1) - \mathbf{p}_T(v_2)]^2$, as main discriminating variable against $t\bar{t}$, and the invariant mass of the bb system, $m_{bb} > 200$ GeV, against the Z background. Five signal enhanced selections are defined in step of 50 GeV for increasing values of m_{CT} starting from $m_{CT} > 150$ GeV. For the ISR selection, the leading jet is required to be a high p_T non b-tagged jet with a big angular separation with the E_T^{miss} , and the b-tagged jets are selected as the second and third leading jets. A tight requirement is then applied on $E_T^{\text{miss}} > 250$ GeV and on the scalar sum of the momenta carried by the additional jets in the event, $H_{T,3} = \sum_{i=4}^{n-\text{jets}} (p_T^{\text{jet}})_i < 50$ GeV.

No significant excess over the SM model was observed and 95% CL limits were set using the CL_s prescription. The obtained exclusion curve is shown in figure 1 on the right. Sbottom masses up to 620 GeV are excluded for neutralino masses up to 220 GeV.

3 Searches for direct stop production

Searches for direct stop production are performed for final states with 0,1,2 and 3 leptons. The area of the parameter space excluded by the stop searches at 95% CL is summarised in figure 2 for the $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ and $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$ models and in figure 3 for the searches in final states with a Z-boson.

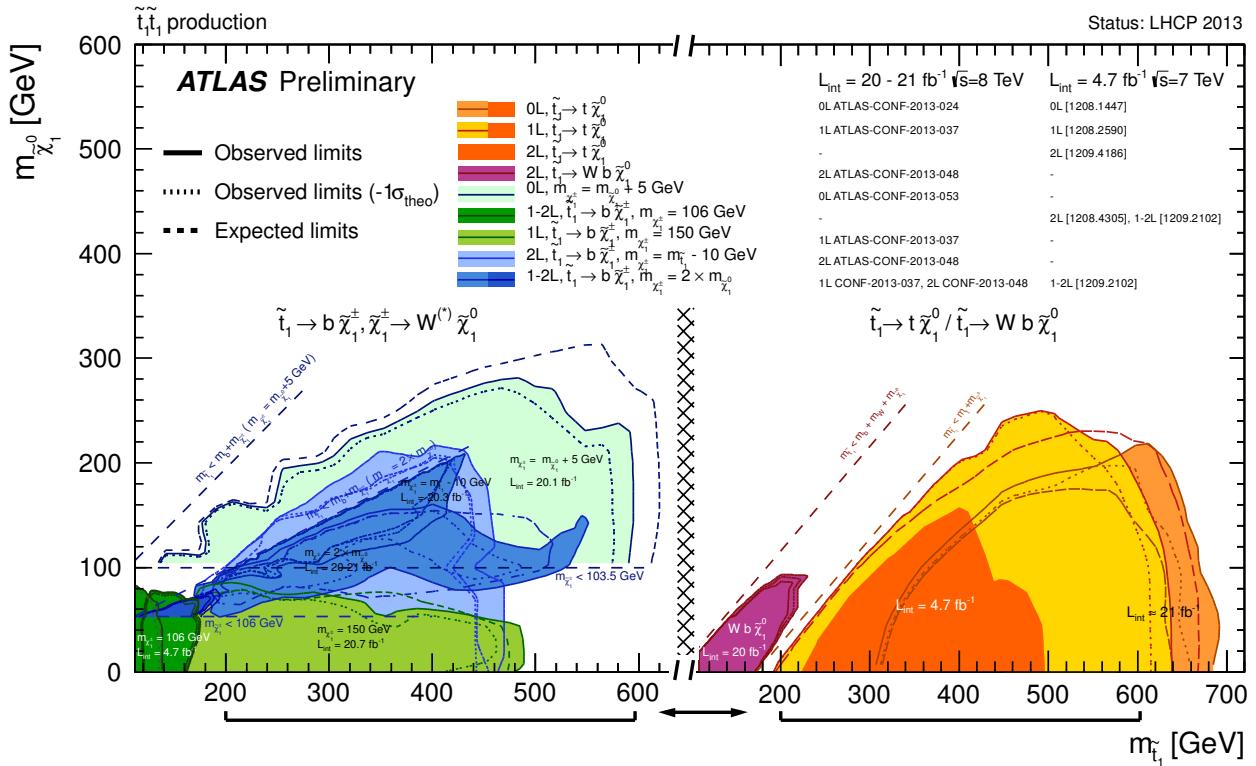


Figure 2. Summary of the dedicated ATLAS searches for top squark (stop) pair production based on up to $13\text{-}21\text{ fb}^{-1}$ of pp collision data taken at $\sqrt{s} = 8\text{ TeV}$ and 4.7 fb^{-1} of pp collision data taken at $\sqrt{s} = 7\text{ TeV}$. Exclusion limits at 95% CL are shown in the $\tilde{t}_1\tilde{\chi}_1^0$ mass plane. The dashed and solid lines show the expected and observed limits, respectively, including all uncertainties except the theoretical signal cross section uncertainty (PDF and scale). The dotted lines represent the results obtained when reducing the nominal signal cross section by 1σ of its theoretical uncertainty. Three decay modes are considered separately with 100% BR: $\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$ (7 TeV : [8–10], 8 TeV [4, 5], where the \tilde{t}_1 is mostly \tilde{t}_R), $\tilde{t}_1 \rightarrow W + b + \tilde{\chi}_1^0$ (3-body decay for $m(\tilde{t}_1) < m(t) + m(\tilde{\chi}_1^0)$, 8 TeV [6]), and $\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow W^{(*)} + \tilde{\chi}_1^0$. In the latter case, several hypotheses on the $\tilde{t}_1\tilde{\chi}_1^\pm, \tilde{\chi}_1^0$ mass hierarchy are assumed: fixed $\tilde{\chi}_1^\pm$ mass (106 GeV [11, 12], 150 GeV [5]), $m(\tilde{\chi}_1^\pm) \sim 2 \times m(\tilde{\chi}_1^0)$ [5, 6, 12], fixed $m(\tilde{t}_1) - m(\tilde{\chi}_1^\pm) = 10\text{ GeV}$ [6], and fixed $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 5\text{ GeV}$ [2].

3.1 Searches in final states with 2 b-jets and E_T^{miss}

The structure of the 2 b-jets and E_T^{miss} analysis has already been described in detail in section 2.2 in relationship to the interpretation in a direct sbottom production model. This final state is powerful also to detect direct stop production in the scenarios $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow W^{(*)}\tilde{\chi}_1^0$, with $\text{BR}=1$, where the mass difference between the chargino and the neutralino becomes small and therefore the decay products of the W get lost [2].

The exclusion contour at 95% CL in the $\tilde{t}_1\tilde{\chi}_1^0$ mass plane for a fixed $m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = 5\text{ GeV}$ covers stop masses up to 580 GeV and neutralino masses up to 250 GeV for a mass of the stop of 500 GeV , see figure 2 teal-coloured contour. When considering a $m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = 20\text{ GeV}$ the excluded area shrinks and stop masses up to 420 GeV are excluded at 95% CL for neutralino masses below 200 GeV . The simulated signal grids respect the LEP limit on the mass of the $\tilde{\chi}_1^\pm$ just above 100 GeV .

3.2 Searches in final states with jets and E_T^{miss}

The search for direct stop production in all hadronic final states with high missing transverse momentum [4] has an interpretation for $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ with $\text{BR}=1$, orange curve in

figure 2.

The main background sources to the analysis come from the $t\bar{t}$ semi-leptonic decay, the associated production of $Z \rightarrow \nu\nu$ with b-jets, the associated production of $t\bar{t}$ +vector-boson, which is the only irreducible background, and fake sources such as multi-jet production and all-hadronic $t\bar{t}$. The signal signature is obtained requiring high E_T^{miss} and six jets of which at least two b-tagged, the two leading ones with a 80 GeV transverse momentum threshold, the others with $p_T > 35\text{ GeV}$. The rejection of the semi-leptonic decaying top and the electroweak background is achieved by vetoing the events with a τ lepton, by requiring that the transverse mass between the nearest b-jet to the E_T^{miss} and the E_T^{miss} itself is above the top mass ($m_T(b_{\text{near}}, E_T^{\text{miss}}) > 175\text{ GeV}$) and by reconstructing the two hadronic decaying tops. The final discriminating variable is E_T^{miss} and inclusive signal regions are defined for increasing values of the missing transverse momentum, $E_T^{\text{miss}} > 200, 300, 350\text{ GeV}$.

Exclusion limits at 95% CL were placed on the $m(\tilde{t}_1) - m(\tilde{\chi}_1^0)$ plane for stop masses below 670 GeV for $m(\tilde{\chi}_1^0) = 1\text{ GeV}$ and for neutralino masses up to 200 GeV for a mass of the stop of 600 GeV , see orange contour of figure 2. The generated signal grid has a stop decaying mostly in a top

with right polarisation. It has been verified that the analysis results are independent on the top polarisation choice. A study has then been done to determine the maximum branching ratio excluded at 95% CL assuming that the analysis is completely insensitive to the decay products not coming from the $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ decay. For a BR of 75% stop masses between 340 GeV and 600 GeV are excluded for an almost massless neutralino.

3.3 Searches in final states with 1 lepton, jets and E_T^{miss}

The search for direct stop production in final states with one lepton, jets and E_T^{miss} [5] is the analysis able to cover better the bulk of the $\tilde{t}_1, \tilde{\chi}_1^\pm, \tilde{\chi}_1^0$ parameter space. It has interpretations for $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ and for $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$ scenarios. The baseline signal selection requires exactly one well identified and isolated lepton, e or μ , with $p_T > 25$ GeV, 4 jets or more, the four leading with $p_T > 80, 60, 40, 25$ GeV; among them at least one or two, depending on the signal model under consideration, has to be identified as b-jet. The main background processes to the analysis arise, therefore, from $t\bar{t}$ and $W + \text{jets}$ production.

To suppress the SM contributions, a series of selections are further applied. The most powerful variables used to reject the $t\bar{t}$ and W backgrounds are the E_T^{miss} and the transverse mass between the lepton and the E_T^{miss} . The analysis makes also use of a τ veto and of two asymmetric version of the m_{T2} variable [15, 16]. The m_{T2} variable is powerful to discriminate against the semi-leptonic $t\bar{t}$ background since the variable presents a sharp endpoint for the top and not for the signal. The endpoint depends on the mass of the invisible particles in the $t\bar{t}$ decay, while for the signal the dependency comes from the $\tilde{t}_1\tilde{\chi}_1^0$ or $\tilde{\chi}_1^\pm\tilde{\chi}_1^0$ mass difference. It is defined as

$$m_{T2} \equiv \min_{\vec{p}_{T,a}^C + \vec{p}_{T,b}^C = \vec{p}_T^{\text{miss}}} \{\max(m_{T,a}, m_{T,b})\}$$

and the two variations considered are am_{T2} and m_{T2}^τ . The former is an asymmetric definition where the missing particles in the dileptonic top decay are defined as the W and the neutrinos and has the end point at $m(t)$; the latter is defined for dileptonic top decays where one of the leptons is an hadronic decaying τ and in this case the end point of the top distribution is at $m(W)$.

Different thresholds and combinations of the discriminating variables are chosen depending on the targeted scenario $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ or $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$ and three signal enhanced regions are defined for each of the two signal models. For $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ a SR is defined in bins of m_T and E_T^{miss} and a combined shape fit is performed to extend the analysis sensitivity as much as possible towards the region $m(\tilde{t}_1) \sim m(t) + m(\tilde{\chi}_1^0)$.

In the $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ scenario, for an almost massless neutralino, stop masses are excluded at 95% CL between 200 and 620 GeV and for a stop mass of 500 GeV a neutralino is excluded up to 250 GeV, as shown in figure 2 with a dark yellow contour. As for the stop search in all hadronic final states, described in section 3.2, the signal grid has

been simulated with a stop decaying mainly in t_R . This analysis is found to be sensitive to the top polarisation; when considering a stop decaying only in left polarised top, a loss in acceptance is observed that translates in a weaker upper limit on the stop mass of about 50 GeV. The exclusion contour at 95% CL for the $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow W^{(*)}\tilde{\chi}_1^0$ model considering $m(\tilde{\chi}_1^\pm) = 2 \cdot m(\tilde{\chi}_1^0)$, figure 2 blue contour, greatly extends the area excluded with the 7 TeV ATLAS dataset, dark blue contour. Now stop masses between 200 and almost 500 GeV are excluded at 95% CL for neutralino masses ranging between 70 and 140 GeV. The light green contour of figure 2 shows the excluded area at 95% CL for a fixed $m(\tilde{\chi}_1^\pm) = 150$ GeV, here the analysis is able to exclude stop decaying in $b\tilde{\chi}_1^\pm$ up to a mass of 450 GeV for a 40 GeV neutralino.

3.4 Searches in final states with 2 opposite charged leptons and E_T^{miss}

Final states with two opposite charged (OS) leptons allow to select a clean signature without the requirement of high jet multiplicity and E_T^{miss} in the event. The stop search that exploits the two lepton selection [6] is therefore sensitive to all the scenarios were jets are soft or are out of the detector acceptance and hence not correctly reconstructed. In particular, a good sensitivity is reached for the $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow W^{(*)}\tilde{\chi}_1^0$ model when assuming a small $\Delta m(\tilde{t}_1, \tilde{\chi}_1^\pm)$ and for the region $m(\tilde{t}_1) \sim m(b) + m(\tilde{\chi}_1^\pm)$ with $m(\tilde{\chi}_1^\pm) = 2 \cdot m(\tilde{\chi}_1^0)$. For the first time a limit under the assumption of a three-body decay of the stop in $\tilde{t}_1 \rightarrow b + W + \tilde{\chi}_1^0$ is extracted. The three-body decay channel opens when the mass difference between the stop and the neutralino becomes smaller than the mass of the top and the $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ decay with an off-shell top is disfavoured with respect to the stop three-body decay in $b + W + \tilde{\chi}_1^0$. The main SM backgrounds in this channel are the dileptonic top and the diboson production. The signal selection is based on the requirement of the lepton pair and uses as discriminating variable

$$m_{T2}(\mathbf{p}_T^{\ell_1}, \mathbf{p}_T^{\ell_2}, \mathbf{p}_T^{\text{miss}}) = \min_{\mathbf{q}_T + \mathbf{r}_T = \mathbf{p}_T^{\text{miss}}} \{\max[m_T(\mathbf{p}_T^{\ell_1}, \mathbf{q}_T), m_T(\mathbf{p}_T^{\ell_2}, \mathbf{r}_T)]\}$$

that has an endpoint at the W mass for the $t\bar{t}$ background. Four signal enhanced region are defined by increasing the lower threshold of the m_{T2} variable; the most inclusive SR is defined for $m_{T2} > 90$ GeV and has no requirements on jets, the tighter SRs require $m_{T2} > 100, 110, 120$ GeV and the presence of two jets in the event.

In the $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$ model for $m(\tilde{\chi}_1^\pm) = 2 \cdot m(\tilde{\chi}_1^0)$, the analysis excludes at 95% CL on the diagonal $m(\tilde{t}_1) = m_b + m(\tilde{\chi}_1^\pm)$ stop masses between 200 and 420 GeV, as shown in figure 2 blue contour; the light blue area of figure 2 represent, instead, the excluded region at 95% CL under the constraint $m(\tilde{t}_1) - m(\tilde{\chi}_1^\pm) = 10$ GeV for which stop masses up to 440 GeV are discarded for an almost massless neutralino.

The purple contour of figure 2 is the 95% CL limit obtained for the three-body decay scenario where stop masses up to 200 GeV are excluded for almost all allowed neutralino masses.

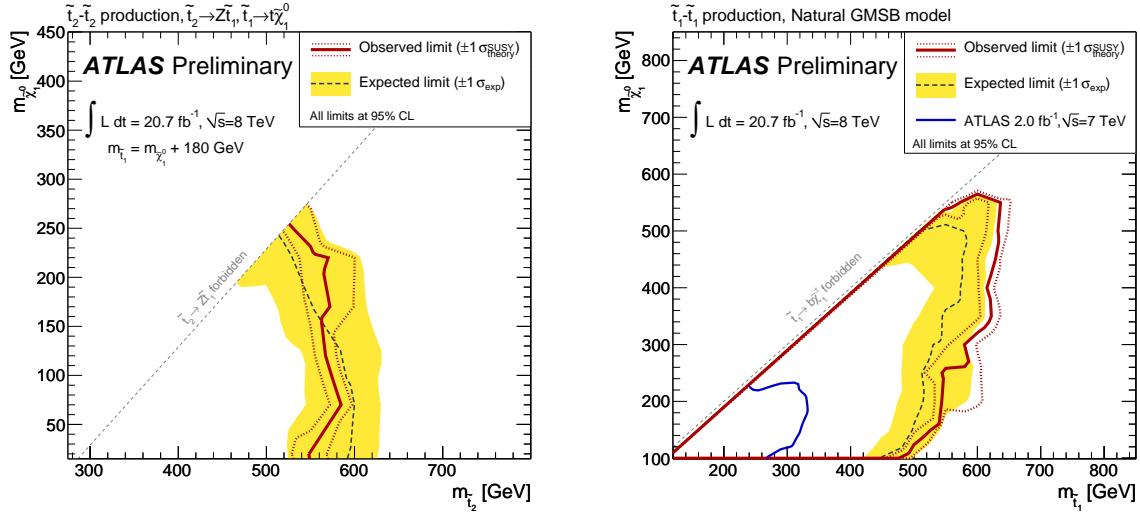


Figure 3. Expected (dashed lines) and observed (solid lines) limits at 95% CL for the $m(\tilde{t}_2) - m(\tilde{\chi}_1^0)$ plane for the \tilde{t}_2 analysis, on the left, and for the stop natural GMSB model, on the right [7].

3.5 Searches in decay chains with Z

The search for direct stop production in decay chains with a Z-boson exploits final states where at least two leptons are present [7]. Two different models are considered, the direct pair production and decay of $\tilde{t}_2 \rightarrow Z\tilde{t}_1$, $\tilde{t}_1 \rightarrow t\chi_1^0$, particularly interesting for covering the region $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = m(t)$, and a natural GMSB (Gauge-Mediated Supersymmetry Breaking) scenario where a pair of \tilde{t}_1 is produced and decays in final states with a Z and a gravitino, in this case the LSP.

The signal selection requires two oppositely charged leptons, whose invariant mass is compatible with the Z-boson mass, jets, of which at least one identified as b-jet, and high $E_{\text{miss}}^{\text{miss}}$; for the \tilde{t}_2 model an additional lepton is also required. The main SM backgrounds come from $t\bar{t}$, also in association with vector boson, and diboson production. The obtained exclusion limits at 95% CL are shown in figure 3; on the left, for $\tilde{t}_2 \rightarrow Z\tilde{t}_1$, with $m(\tilde{t}_1) = m(\tilde{\chi}_1^0) + 180$ GeV, \tilde{t}_2 masses are excluded up to 530 GeV for all the allowed neutralino masses; in the natural GMSB scenario the extracted exclusion is for \tilde{t}_1 masses up to 450 GeV for all the allowed neutralino masses, as shown in the right plot.

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