

# Searches for third generation SUSY in ATLAS

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Recent results on searches for third generation supersymmetry carried out by the ATLAS collaboration with  $2.05 \text{ fb}^{-1}$  of  $\sqrt{s} = 7 \text{ TeV}$  pp collisions recorded with the LHC in 2011 are reported. These analyses focus on search for gluino- and squark-mediated stau production, direct scalar bottom pair production and gluino-mediated sbottom and stop pair production.

## 1 Introduction

Supersymmetry (SUSY) <sup>1</sup> provides an extension of the Standard Model (SM) by introducing supersymmetric partners of the known bosons and fermions. In the framework of an  $R$ -parity conserving minimal supersymmetric extension of the SM (MSSM), SUSY particles are produced in pairs and the lightest supersymmetric particle (LSP) is stable, providing a possible candidate for dark matter. An important motivation for SUSY third generation searches is the fact that SUSY can naturally resolve the hierarchy problem, by preventing “unnatural” fine-tuning in the Higgs sector, provided that superpartners of the top quark ( $\tilde{t}$ , stop) have relatively low masses. This condition requires that the superpartner of the gluon ( $\tilde{g}$ , gluino) is not heavier than about 1.5 TeV due to its contribution to the radiative correction of the stop mass. Furthermore, in the MSSM the scalar partners of right-handed and left-handed fermions,  $\tilde{f}_R$  and  $\tilde{f}_L$ , can mix to form two mass eigenstates. This mixing is proportional to the corresponding SM fermion masses and is therefore more important for the third generation. Large mixing can yield stau ( $\tilde{\tau}_1$ ), sbottom ( $\tilde{b}_1$ ) and stop ( $\tilde{t}_1$ ) mass eigenstates which are significantly lighter than other sparticles. Consequently, they could be produced with large cross sections at the LHC. Depending on the SUSY particle mass spectrum, the cascade decays of gluino-mediated and pair-produced sbottoms or stops result in complex final states consisting of missing transverse momentum ( $\cancel{E}_T$ ), several jets, among which  $b$ -quark jets are expected, and possibly leptons.

In this document, several ATLAS searches for third generation supersymmetry carried out using  $2.05 \text{ fb}^{-1}$  of LHC pp data at  $\sqrt{s} = 7 \text{ TeV}$  are reported. No significant excess above the SM expectation has been observed and exclusion limits at 95% confidence level (C.L.) on SUSY parameters or masses of SUSY particles are derived.

## 2 Search for gluino- and squark-mediated stau production

Two searches for events with large  $\cancel{E}_T$ , at least two jets and at least one <sup>2</sup> or two <sup>3</sup> hadronically decaying tau leptons ( $\tau$ ) have been carried out. The results have been interpreted in the framework of minimal gauge mediated supersymmetry breaking (GMSB) which can be described by six parameters : the SUSY breaking mass scale felt by the low-energy sector ( $\Lambda$ ), the messenger mass ( $M_{\text{mess}}$ ), the number of SU(5) messengers ( $N_5$ ), the ratio of the vacuum expectation values

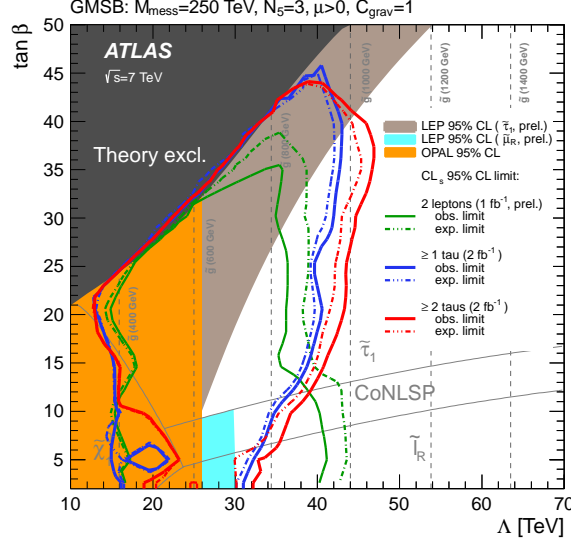


Figure 1: Expected and observed exclusion limits at 95% C.L. on the minimal GMSB model parameters  $\Lambda$  and  $\tan\beta$  assuming  $M_{\text{mess}} = 250$  TeV,  $N_5 = 3$ ,  $\mu > 0$  and  $C_{\text{grav}} = 1$ . The dark grey area indicates the region which is theoretically excluded due to unphysical sparticle mass values. The different NLSP regions are indicated. In the CoNLSP region the  $\tilde{\tau}_1$  and the  $\tilde{\ell}_R$  are the NLSP.

of the two Higgs doublets ( $\tan\beta$ ), the Higgs sector mixing parameter ( $\mu$ ) and the scale factor for the gravitino mass ( $C_{\text{grav}}$ ). Assuming  $M_{\text{mess}} = 250$  TeV,  $N_5 = 3$ ,  $\mu > 0$  and  $C_{\text{grav}} = 1$ , squarks and/or gluino pairs are expected to be copiously produced at the LHC. These sparticles then decay directly or through cascades into the next-to-lightest supersymmetric particle (NLSP), which subsequently decays into its SM partner and the LSP (light gravitino  $\tilde{G}$ ). The experimental signature of the final state is thus driven by the nature of the LSP, which is the stau ( $\tilde{\tau}_1$ ) for a large part of the parameter space at large  $\tan\beta$ .

The dominant backgrounds in the 1- $\tau$  analysis arise from top-pair plus single top production, vector boson production ( $W/Z + \text{jets}$ ) and multi-jets production, either with real  $\tau$  leptons or mis-reconstructed  $\tau$  from hadronic activity in the final state. These backgrounds are estimated in a semi-data-driven way, by normalizing the Monte Carlo (MC) event yield to the observed event yield in dedicated control regions, and then using the simulation to extrapolate into the signal region. In the 2- $\tau$  analysis, the main backgrounds are from top-pair, single top and  $W$  events with one real  $\tau$  lepton correctly reconstructed and one mis-reconstructed  $\tau$ . Their contributions are also estimated using a control region enriched in top and  $W$  events. The subdominant contribution due to the background from  $Z \rightarrow \tau\tau$  events is extracted from simulations.

Figure 1 shows the expected and observed exclusion limits at 95% C.L. on  $\Lambda$  and on  $\tan\beta$  as derived with the one and two  $\tau$  leptons analyses. These results significantly improve the exclusion limits obtained with the previous ATLAS search in two opposite-sign leptons and the LEP results.

### 3 Search for direct sbottom pair production

As search<sup>4</sup> for direct sbottom pair production has been performed assuming sbottom decay into a bottom quark plus a neutralino (LSP) with a branching ratio 100%. Selected events are required to have exactly two  $b$ -tagged jets with  $p_T > 130$ , 50 GeV and  $\cancel{E}_T > 130$  GeV. Electrons (muons) with  $p_T > 20$  GeV (10 GeV) are vetoed, and events are rejected if a third jet with  $p_T > 50$  GeV is found. The cuts on the leading jet and the  $\cancel{E}_T$  are driven by the trigger thresholds. The kinematic variable used to further discriminate the signal from the background is the boosted-

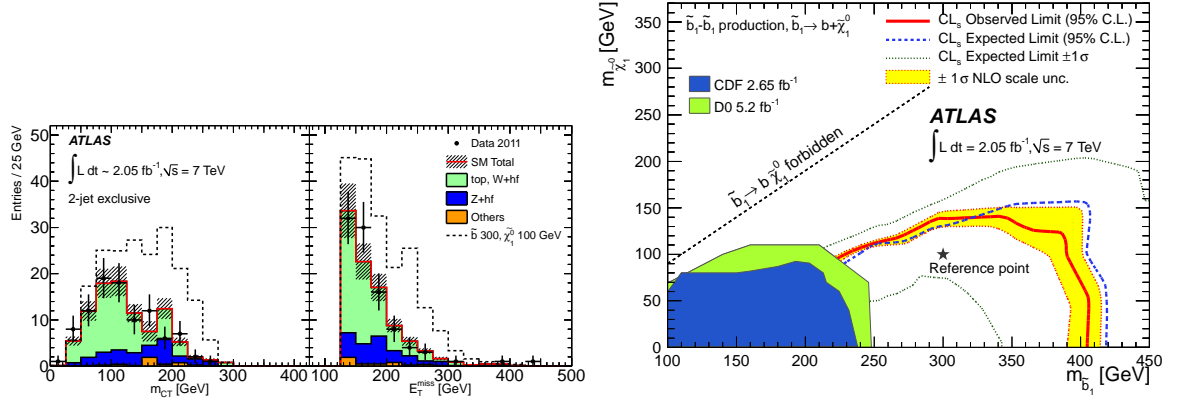


Figure 2: *Left* :  $m_{CT}$  and  $E_T$  distributions before the final  $m_{CT}$  cuts. *Right* : Expected and observed 95% C.L. exclusion limits in the  $(m_{\tilde{b}_1}, m_{\tilde{\chi}_1^0})$  plane resulting from the analysis searching for sbottom quark pair production, assuming sbottom to bottom plus neutralino decay.

corrected contranverse mass  $m_{CT}$  <sup>5,6</sup>. The contranverse mass for two pair produced heavy particles with semi-invisible decay is defined as  $([E_T(v_1) + E_T(v_2)]^2 - [\mathbf{p}_T(v_1) - \mathbf{p}_T(v_2)]^2)^{1/2}$ , where  $v_1$  and  $v_2$  are the visible products of each decay chain. In the case of the considered signal, the  $m_{CT}$  distribution has an end-point at  $[m(\tilde{b}_1)^2 - m(\tilde{\chi}_1^0)^2]/m(\tilde{b}_1)$ . The boosted-corrected contranverse mass is corrected for recoils in the transverse plane against initial state radiation to preserve the expected end-point in the distribution. Three signal regions are defined with  $m_{CT} > 100, 150$  and  $200$  GeV to maximize the sensitivity for different mass splitting between the sbottom and the neutralino.

The dominant SM background processes are top-pair plus single top production and associated production of  $W/Z$  bosons with heavy flavour jets. The  $t\bar{t}$  background is dominant in the signal region with  $m_{CT} > 100$  GeV due to the end-point at 135 GeV in the  $m_{CT}$  distribution for  $t\bar{t}$  events. The two tighter signal regions are dominated by  $Z \rightarrow \nu\nu$  + heavy flavour events, followed by  $W \rightarrow \tau\nu$  + heavy flavour events. The sum of the top and  $W$  plus heavy flavour contributions is estimated in a 1-lepton control region, while the contribution from  $Z$  plus heavy flavour production is estimated in a 2-leptons control region. The background yield in each signal region is then obtained by multiplying the number of events observed in the corresponding control region by the transfer factors defined as the ratio of the MC predicted yield in the signal region to that in the control regions. Subdominant backgrounds from diboson,  $t\bar{t} + b\bar{b}$  and  $t\bar{t} + W/Z$  are estimated from MC simulations. The contribution from multi-jet events with possibly large  $E_T$  is obtained by smearing jet energies in low  $E_T$  “seed” events according to jet response functions extracted from MC simulation and tuned to data. This prediction is then normalised to the observed event yield in a multi-jets dominated control region.

Figure 2 (*left*) shows the  $m_{CT}$  and  $E_T$  distributions before the final  $m_{CT}$  cuts for data and SM background as predicted by the semi-data-driven method. Figure 2 (*right*) shows the expected and observed exclusion limits at 95% C.L. in the  $(m_{\tilde{b}_1}, m_{\tilde{\chi}_1^0})$  plane. For each signal point, the signal region leading to the best expected limit is chosen to extract the exclusion limits. In the most conservative hypothesis, sbottom masses up to 390 GeV are excluded for neutralino masses below 60 GeV, which significantly extends the previous results from the CDF and D0 experiments.

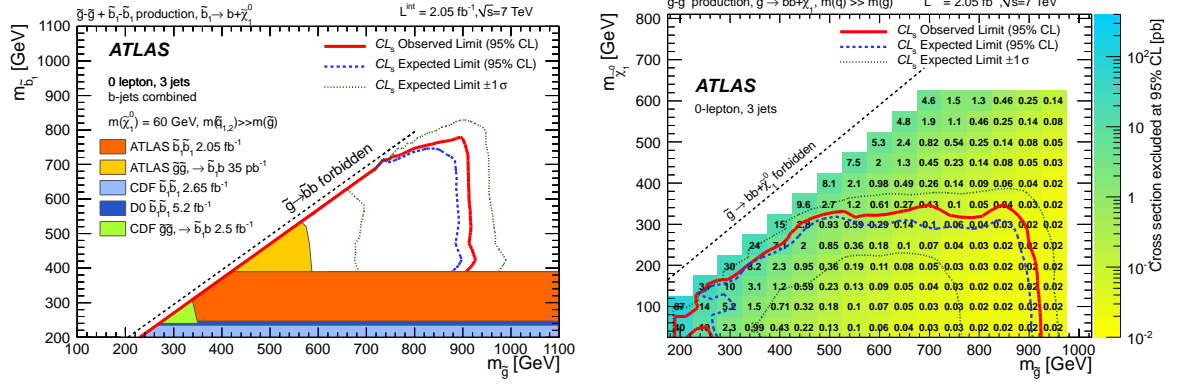


Figure 3: *Left* : Expected and observed 95% C.L. exclusion limits in the context of a MSSM model in the  $(m_{\tilde{g}}, m_{\tilde{b}_1})$  plane. *Right* : Expected and observed 95% C.L. exclusion limits in the context of a simplified model in the  $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0})$  plane.

#### 4 Search for gluino-mediated sbottom pair production

ATLAS also searched<sup>7</sup> for gluino-mediated sbottom pair production assuming on-shell or off-shell sbottom decay into a bottom quark plus a neutralino (LSP) with a branching ratio of 100%, leading to a final state of four  $b$ -jets plus  $\cancel{E}_T$ . In this analysis, events are selected by requiring at least three jets with  $p_T > 130, 50, 50$  GeV,  $\cancel{E}_T > 130$  GeV and no lepton, the thresholds on the leading jet and  $\cancel{E}_T$  being driven by the trigger requirement. Six signal regions are then characterized by the number of  $b$ -tagged jets ( $\geq 1, 2$ ) and the cut on the effective mass  $m_{eff}$  ( $> 500, 700, 900$  GeV) defined as the scalar  $p_T$  sum of all selected objects in the event.

The strategy employed to estimate the SM backgrounds is similar to the semi-data-driven method used in the direct sbottom search. The dominant top background is estimated using two control regions which differ only in the number of  $b$ -jets required. These control regions are defined by applying the same selection cuts as for the signal regions, but requiring exactly 1 isolated lepton ( $e, \mu$ ). The multi-jets background is estimated with the jet smearing method described above and the remaining contribution from  $W$  and  $Z$  production in association with heavy flavour jets is estimated using MC simulations.

Results are first interpreted in the context of a MSSM scenario where the  $\tilde{b}_1$  is the lightest squark and all other squarks are heavier than the gluino (with  $m_{\tilde{g}} > m_{\tilde{b}_1} + m_b$ ) such that the branching ratio for  $\tilde{g} \rightarrow \tilde{b}_1 b$  is 100%. In this case, the sbottom is produced in gluino decays of via direct pair production and is assumed to decay exclusively via  $\tilde{b}_1 \rightarrow b + \tilde{\chi}_1^0$ , where the neutralino mass is set at 60 GeV. The expected and observed 95% C.L. exclusion limits in the  $(m_{\tilde{g}}, m_{\tilde{b}_1})$  plane are shown on Figure 3 (*left*). Gluino masses below 920 GeV are excluded for sbottom masses up to about 800 GeV.

Results are then interpreted in the context of a simplified model where the  $\tilde{b}_1$  is the lightest squark but with a mass above the TeV scale such that pair production of gluinos is the only process taken into account. A three-body final decay  $\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$  is assumed for the gluino with a branching ratio of 100% via an off-shell sbottom decay  $\tilde{b}_1^* \rightarrow b + \tilde{\chi}_1^0$ . Such a scenario, defined in a  $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0})$  plane at fixed (large) sbottom mass, can be considered complementary to the previous one, defined in the  $(m_{\tilde{g}}, m_{\tilde{b}_1})$  plane at fixed  $\tilde{\chi}_1^0$  mass. The expected and observed 95% C.L. exclusion limits and the maximum 95% C.L. upper cross section limits in the  $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0})$  plane are shown on Figure 3 (*right*). Gluino masses below 900 GeV are excluded for neutralino masses below 300 GeV.

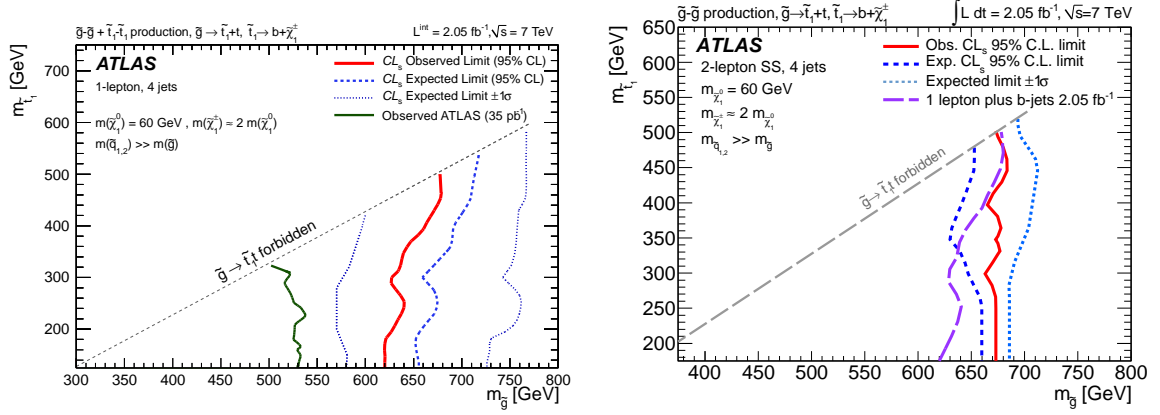


Figure 4: Expected and observed 95% C.L. exclusion limits in the context of a constrained MSSM model in the  $(m_{\tilde{g}}, m_{\tilde{t}_1})$  plane as obtained with the 1-lepton (*left*) and 2-leptons (*Right*) analyses.

## 5 Search for gluino-mediated stop pair production

Finally, two analyses targeting gluino-mediated stop pair production have been performed selecting events with one<sup>7</sup> or two<sup>8</sup> isolated leptons ( $e, \mu$ ). Assuming the stop decays  $\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$  and  $\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^\pm$ , the final state consists in many jets, including  $b$ -jets, leptons and large  $\cancel{E}_T$ . In the one lepton analysis, events are selected if they contain exactly one isolated lepton and at least four jets with  $p_T > 60, 50, 50, 50$  GeV, amongst them a least one  $b$ -tagged jet. The transverse mass  $m_T$  between the lepton and the  $\cancel{E}_T$  must be larger than 100 GeV and the effective mass greater than 700 GeV. Two signal regions are then defined applying a cut on the  $\cancel{E}_T$  at 80 GeV or 200 GeV. In the two leptons analysis, the selection requires at least two leptons with the same charge, at least four jets with  $p_T > 50$  GeV and  $\cancel{E}_T$  greater than 150 GeV. Two signal regions are then defined by applying or not a cut at 100 GeV on the transverse mass  $m_T$  between the highest  $p_T$  lepton and the  $\cancel{E}_T$ .

The SM background in the 1-lepton analysis is dominated by  $t\bar{t}$  events, followed by  $W$  events produced in association with heavy flavour jets. In the 2-lepton analysis, the dominant SM background processes are  $t\bar{t}W$ ,  $t\bar{t}Z$  and  $t\bar{t}WW$  (referred as  $t\bar{t}+X$ ), followed by multi-jets production with a non-prompt lepton arising from  $b/c$  decay,  $\gamma$  conversion or jet misidentification. The number of multi-jets events is estimated in both analyses using a matrix method based on the event count in two data samples which differ only by the lepton selection criteria. The contribution from other SM background sources in the 1-lepton analysis is normalized using the same semi-data-driven method as in the previous analyses. The control region is defined by reverting the  $m_T$  cut and by relaxing the cuts on the  $m_{eff}$  and the  $\cancel{E}_T$  to 500 GeV and 80 GeV, respectively, to increase the statistics and minimize the contamination from hypothetical signal events. The contribution of background events with charge misidentification in the 2-leptons analysis is estimated using a partially data-driven technique. This background is dominated by electron producing hard bremsstrahlung with subsequent photon conversion, the contribution from muon with incorrect charge assignment being negligible. The method consists in applying the probability of charge misidentification, measured in MC and tuned to data, to simulated  $t\bar{t}$  events with  $e^\pm \ell^\mp$  in the final state. The other SM background processes, namely  $t\bar{t}+X$  and diboson, are extracted from simulations.

Results are first interpreted in the context of a MSSM scenario where the  $\tilde{t}_1$  is the lightest squark and all other squarks are heavier than the gluino (with  $m_{\tilde{g}} > m_{\tilde{t}_1} + m_t$ ) such that the branching ratio for  $\tilde{g} \rightarrow \tilde{t}_1 t$  is 100%. In this case, the stop is produced in gluino decays of via direct pair production and is assumed to decay exclusively via  $\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^\pm$ , with the neutralino

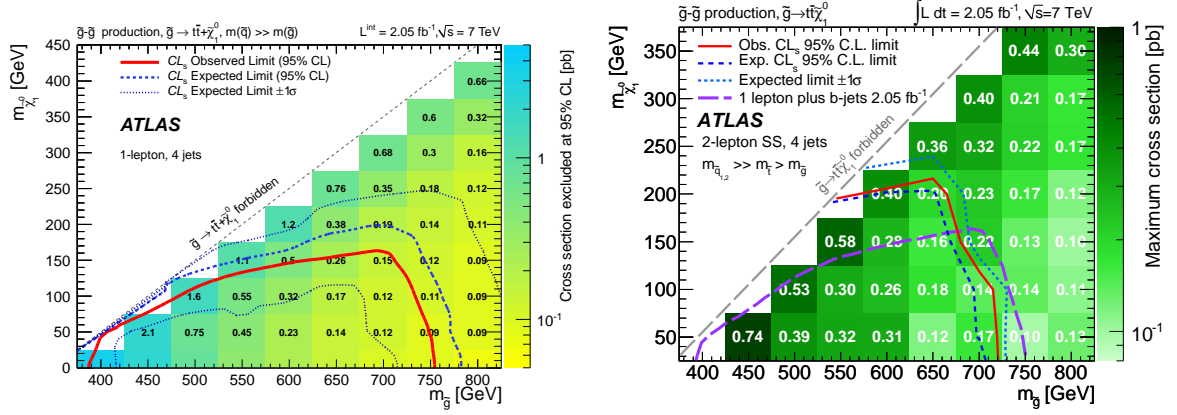


Figure 5: Expected and observed 95% CL exclusion limits in the context of a simplified model in the  $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0})$  plane as obtained with the 1-lepton (*left*) and 2-leptons (*right*) analyses.

mass fixed at 60 GeV. Figure 4 shows the expected and observed 95% C.L. exclusion limits in the  $(m_{\tilde{g}}, m_{\tilde{t}_1})$  plane for both 1-lepton (*left*) and 2-lepton analyses (*right*). Gluino masses below 660 GeV are excluded for sbottom masses up to about 460 GeV.

Results are then interpreted in the context of a simplified model where the  $\tilde{t}_1$  is the lightest squark but with a mass above the TeV scale such that pair production of gluinos is the only process taken into account. A three-body final decay  $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$  is assumed for the gluino with a branching ratio of 100% via an off-shell stop decay  $\tilde{t}_1^* \rightarrow t + \tilde{\chi}_1^0$ . Such a scenario, defined in a  $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0})$  plane at fixed (large) stop mass, can be considered complementary to the previous one, defined in the  $m_{\tilde{g}}, m_{\tilde{t}_1}$  mass plane at fixed  $\tilde{\chi}_1^0$  mass. Resulting limits in the  $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0})$  plane are shown on Figure 5 for the 1-lepton (*left*) and 2-leptons analyses (*right*). Gluino masses below 750 GeV are excluded for neutralino masses up to about 50 GeV. The 2-leptons analysis has the best sensitivity at low  $\tilde{t}_1 - \tilde{\chi}_1^0$  mass splitting due to softer kinematic cuts.

## 6 Conclusion and prospects

ATLAS has carried out several searches for superpartners of third generation fermions with an integrated luminosity of  $2.05 \text{ fb}^{-1}$ . No excess in data with respect to the SM expectation has been observed so far. However, large regions of the parameter space for “natural” SUSY are still not excluded. In particular, no direct limits on the stop mass have been derived yet. Searches for direct stop pair production are currently in progress. These searches are challenging due to similarity with the  $t\bar{t}$  final state for low stop masses, and due to the low cross sections for higher stop mass values. In this respect, new results obtained with the full 2011 data set, corresponding to  $4.7 \text{ fb}^{-1}$ , and the 2012 data at  $\sqrt{s} = 8 \text{ TeV}$  will be very important.

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