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SUSY search with two same-sign leptons and jets with the ATLAS detector using 21 fb^{-1} of pp collisions at 8 TeV

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Abstract. A search for the production of supersymmetric particles decaying into final states with jets, b-jets, missing transverse momentum and two isolated leptons, e or μ, with the same electric charge (same-sign leptons) is presented. The analysis uses a data sample collected during 2012, which corresponds to a total integrated luminosity of 20.7 fb^{-1} of $\sqrt{s}$ = 8 TeV proton–proton collisions recorded with the ATLAS detector at the Large Hadron Collider. No significant deviation from the Standard Model expectation is observed in any of these signal regions. Exclusion limits are derived for a mSUGRA/CMSSM model, and for a wide variety of simplified models of supersymmetry. The ATLAS result on which this note is based significantly extends previous exclusion limits..

1 Introduction

The standard Model (SM) is giving an excellent description of currently known phenomena. However this theory has some known problems, such as explaining the hierarchy problem. An extension that solves in a natural way several problems of the SM is Supersymmetry (SUSY) [1], a theory which predicts a new partner for each SM particle (sparticle) differing by half a unit of spin.

In the Minimal Supersymmetric Standard Model (MSSM), with R-parity, the scalar partners of right-handed and left-handed quarks, $\tilde{q}_R$ and $\tilde{q}_L$, can mix to form two mass eigenstates, $\tilde{q}_1$ and $\tilde{q}_2$, where $\tilde{q}_1$ denotes the lighter particle. Large mixing can yield a bottom squark, $\tilde{b}_1$, and a top squark, $\tilde{t}_1$, mass eigenstates which are significantly lighter than other squarks. Consequently, $\tilde{b}_1$ and $\tilde{t}_1$ could be produced with large cross sections at the LHC, either directly in pairs, or through $\tilde{g}\tilde{g}$ production with subsequent $\tilde{g} \to b\tilde{b}_1$ or $\tilde{g} \to t\tilde{t}_1$ decays (gluino-mediated production). Several possible decay chains can lead to same-sign (SS) leptons. For instance, the gluino mediated top squark production, followed by the decay $\tilde{t}_1 \to t\tilde{\chi}^0_1$, leads to four top quarks in the final state. Alternatively, the decay via a chargino ($\tilde{\chi}^\pm_1$), $\tilde{t}_1 \to b\tilde{\chi}^\pm_1 \to bW^\pm\tilde{\chi}^0_1$ can also lead to SS lepton pairs. Direct pair-production of bottom squarks, $\tilde{b}_1\tilde{b}^*_1$, with $\tilde{b}_1 \to \tilde{t}\tilde{\chi}^+_1$, can give final states with 4 W bosons, 2 bottom quarks and 2 neutralinos. Several scenarios are also considered for $\tilde{g}\tilde{g}$ decays to gauginos through squarks from the two first generations, via $\tilde{g} \to qq\tilde{\chi}^\pm_1 \to qqW^\pm\tilde{\chi}^0_1$ or sleptons $\tilde{g} \to qq\tilde{\chi}^\pm_1 \to qq\tilde{l}\nu/l\tilde{\nu}$ (or $\tilde{g} \to qq\tilde{\chi}^0_2 \to qq\tilde{l}l/\tilde{\nu}\nu$) with $\tilde{l} \to l\tilde{\chi}^0_1$ and $\tilde{\nu} \to \nu\tilde{\chi}^0_1$. In these cases, advantage is taken of the Majorana nature of the gluino and q and $\bar{q}$ (or l and $\bar{l}$) can be obtained in the final state. Therefore this enhances

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Table 1. Three signal regions are defined depending on number of b-jets identified in the final state:

SR	N_{b-jets}	Other variables, exclusion case	Additional cuts for discovery case
SR0b	==0	$N_{jets} \geq 3$, $\not{E}_T > 150$ GeV, $\mathrm{m_T} > 100$ GeV	$\mathrm{m_{eff}}$ >400 GeV
SR1b	≥1	$N_{jets} \geq 3$, $\not{E}_T > 150$ GeV, $\mathrm{m_T}$ >100 GeV	$\mathrm{m_{eff}}$ >700 GeV
SR3b	≥3	$N_{jets} \geq 5$, ($\not{E}_T < 150$ GeV or $\mathrm{m_T} < 100$ GeV)	$N_{jets} \geq 4$

the probability to obtain same-sign lepton pairs when only one lepton is produced in each gluino decay.

This proceeding describes a search [2] that utilizes final states with SS lepton pairs, multiple jets, and missing transverse momentum ($\not{E}_T$) observed by the ATLAS detector [3] at the LHC. The search is conducted using 20.7 fb^{-1} of proton-proton collisions at $\sqrt{s} = 8$ TeV recorded in 2012. Production of SS pairs in association with jets is rare for SM processes but can have high cross-section for the considered SUSY models.

2 Event selection and signal regions definition

Event selection requirements rely on electrons, muons, jets (including b-tagged jets) and $\not{E}_T$. To cover the full phase space for control samples and signal region a combination of $\not{E}_T$, single and di-lepton triggers is used.

All jets are required to have $p_T > 25$ GeV (> 40 GeV in the signal regions) and $|\eta| < 2.8$. If b-tagging is required, the threshold is lowered to 20 GeV. Leptons are required to have $p_T > 20$ GeV and $|\eta| < 2.47$ (2.4 for muons).

Signal region definitions are presented in Table 1. Selection criteria for the regions used for model-independent limits on cross-sections (discovery case) include additional requirements for effective mass ($\mathrm{m_{eff}}$) or number of jets (N_{jets}). We performed a fit of distributions in $\mathrm{m_{eff}}$ to set model-specific limits using the signal regions for the exclusion case. All signal regions are made exclusive to each other to allow statistical combination of the limits on cross-sections.

SR1b is designed to be sensitive to a wide range of supersymmetry model signatures. The signal region with a veto on the presence of b-jets (SR0b) is complementary to SR1b and is designed to cover the models which have no top in the final state. SR3b is considered to increase the sensitivity for models with compressed mass spectra involving third generation squarks with low $\not{E}_T$, or models with R-parity violation that do not feature intrinsically high $\not{E}_T$.

3 Background estimation and validation

Searches in events with two same-sign leptons are characterized by very low backgrounds. Three main classes of backgrounds can be distinguished: prompt same-sign lepton pairs, charge mis-measurement and fake leptons. Background evaluation is performed using a combination of Monte Carlo (MC) simulations and data-driven techniques.

Sources of real SS leptons arise mainly from the production of a W or Z boson, decaying leptonically, in association with $t\bar{t}$, and from dibosons (WZ, ZZ) produced in association with jets. These backgrounds are estimated with MC simulation.

Reducible background from charge mis-measurement consists mostly of events with two opposite-sign (OS) leptons for which the charge of an electron is mis-identified. The dominant mechanism is due to the radiation of a hard photon bremsstrahlung followed by an asymmetric conversion for which the electron with the opposite charge dominates ($e^{\pm} \rightarrow e^{\pm}\gamma \rightarrow e^{\pm}e^{\pm}e^{\mp}$). This type of background generally appears in dilepton $t\bar{t}$ events and the estimation is done using a fully data-driven method. The charge flip rate is measured inside the Z boson invariant mass peak using the ratio of SS to OS electron pairs. The probability that one electron has its charge mis-measured varies from 10^{-4} to 0.02 in the range $0 \leq |\eta| \leq 2.5$ and $20 < p_T < 200$ GeV.

Another reducible background, so called fake lepton background, is caused by leptons from decays of hadrons, especially b hadrons. Other candidates can result from mis-measurement of hadronic jets. The fake lepton estimation is performed in data using a matrix method after loosening the lepton identification and isolation criteria. This method requires the measurement of lepton identification efficiency and lepton fake rate as input. Lepton identification efficiency is measured in a data sample enriched with prompt OS leptons from $Z \rightarrow l^+l^-$ events. Lepton fake rate is measured in a sample enriched in one prompt muon and one fake lepton of identical charge. For the electron fake rate the measurement is done for two selections, with a b-jet veto and with at least one b-jet.

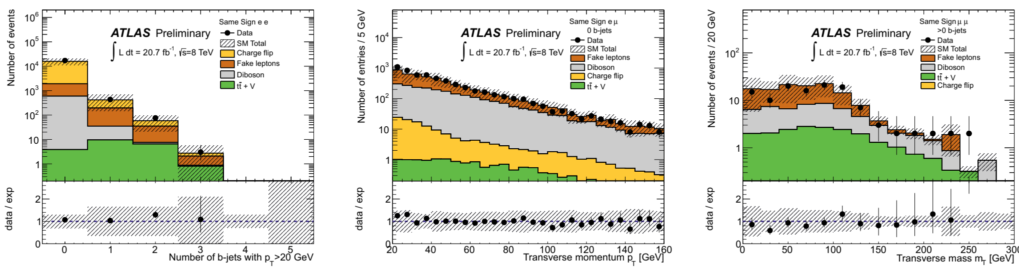

Figure 1. Left: ee channel, distribution of the b-jet multiplicity ($p_T > 20$ GeV). Middle: $e\mu$ channel, distribution of the p_T of the selected leptons with a b-jet veto. Right: $\mu\mu$ channel, transverse mass distribution after lepton selections with at least one b-jet [2].

Background systematic uncertainty

For the charge mis-measurement background the main uncertainty is coming mainly form the statistical uncertainty of the charge flip rate measurement and from a potential systematic bias of the data-driven method. The later one is estimated by taking the relative difference between the true rate (MC, truth-matching) and the one obtained with the data-driven method. For the fake lepton background the main uncertainty comes from the statistical uncertainty of the fake lepton rate and from a potential systematic bias estimated by changing the measurement region definition (eg: higher jet multiplicity, tighter cuts on $\not{E}_T$, $\mathrm{m_T}$). For prompt SS pair production the main uncertainties come from systematic variations of the jet energy scale, b-tagging efficiency and pile-up modeling in the MC simulations. Additional uncertainties are assigned corresponding to different acceptance predictions from alternative generators. In all SRs the dominant systematic uncertainty is coming from lepton fake rate, jet energy scale, $t\bar{t} + V$ and b-jets identification.

Background validation

The background estimates obtained using both data-driven and Monte Carlo techniques are checked by comparison with the data. Good agreement between the data and the background prediction is observed. Some example distributions for the ee, $e\mu$ and $\mu\mu$ channels can be found in Figure 1.

In addition, to validate the Monte Carlo description of events with high b-jet multiplicity containing both real and fake b-tags, a control region enriched in events containing OS dilepton pairs and $\geq$3 b-jets has been studied.The distributions in this region, including the p_T distributions of the b-jets which play an important role in the selection, are found to agree well with the data.

Three regions are defined to validate the dominant backgrounds with prompt same-sign leptons, which are estimated by Monte Carlo simulation, i.e. $t\bar{t}\,W$, $t\bar{t}\,Z$ and diboson. These validation regions

Table 2. Background fit results for the VR-diboson, VR-ttW and VR-ttZ regions, with the discovery fit configuration, for an integrated luminosity of 20.7 fb^{-1}. Nominal MC and data-driven expectations are given for comparison. The errors shown are the systematic uncertainties.

Event classes	**VR-diboson**	**VR-ttW**	**VR-ttZ**
Observed events	54	9	4
Expected background events	74 ± 13	4.2 ± 1.9	8.0 ± 2.0
Expected $t\bar{t}$+V events	1.6 ± 0.8	2.7 ± 1.5	3.2 ± 1.1
Expected diboson events	60 ± 7	0.4 ± 0.1	3.9 ± 1.3
Expected fake lepton events	12 ± 11	1.1 ± 1.1	0.9 ± 0.5
Expected charge mis-meas. events	0	0	0

are not used to constrain the backgrounds in the fits but to verify the validity of the MC predictions. There is no overlap with the signal regions.

The validation region for $t\bar{t}\,W$ (VR-ttW) uses exactly two same-sign muons (no electrons) to reduce the background of fake leptons and charge mis-measurement. The event selection requires one or more jets with $p_T > 30$ GeV, exactly two b-jets with $p_T > 20$ GeV, $20 < \not{E}_T < 120$ GeV and transverse mass (m_T) > 80 GeV.

The validation region for $t\bar{t}\,Z$ (VR-ttZ) requires three leptons (electrons or muons), where the two leading leptons must have $p_T > 20$ GeV and the third lepton $p_T > 10$ GeV. A pair of opposite-sign, same-flavour leptons is required with the invariant mass of $83 < m_{l^+l^-} < 96$ GeV. In addition, the event selection requires two or more jets with $p_T > 40$ GeV, one or two b-jets with $p_T > 20$ GeV, $20 < \not{E}_T < 120$ GeV and $m_{\rm eff} > 300$ GeV.

The diboson validation region (VR-diboson) requires two same-sign muons to reduce the fake and charge mis-measurement backgrounds. In addition, the event selection requires two or more jets with $p_T > 20$ GeV, no b-jet with $p_T > 20$ GeV, $20 < \not{E}_T < 120$ GeV and $m_T > 100$ GeV.

The number of observed events and expected background events in all three validation regions are shown in Table 2. The background checks in the validation regions provide confidence that the MC simulations predict the SM background rate of prompt like-sign lepton pairs in events with multiple jets and b-jets within a factor of approximately 2, where the accuracy is limited by the statistical uncertainty from the number of events in the validation region.

4 Results

A simultaneous fit of all signal regions using a profile-likelihood method is done to determine the best estimate of each component (signal / background) in the data. The simultaneous fit is notably used to test the statistical compatibility of the background-only hypothesis as well as the one of many signal models with our observed data.

Table 3 presents the number of observed data events and expected background for the discovery (upper table) and exclusion cases (lower table). The background for the SR0b region is dominated by events containing fake leptons and dibosons (both with large uncertainties). In signal regions SR1b and SR3b the largest background contribution and uncertainty is due to $t\bar{t}$ plus vector boson events. A comparison of tables *A* and *B* shows, that the event sample for the exclusion case has a larger background contribution from fake leptons in SR1b. This is due to the relaxed $m_{\rm eff}$ cut in the exclusion case sample. Figure 2 shows the $m_{\rm eff}$ distribution in SR0b and SR1b using the exclusion cuts.

A good agreement between the observed number of events in signal regions and SM expectation is obtained, without any significant excess.

Table 3. Number of observed data events and expected backgrounds for the three signal regions. The event counts correspond to the signal selection for the discovery limits (table A) and the exclusion limits (table B). The quoted background errors include statistical and systematic uncertainties

A) Discovery case	**SR0b**	**SR1b**	**SR3b**
Observed events	5	8	4
Expected background events	7.5 ± 3.3	3.7 ± 1.6	3.1 ± 1.6
Expected $t\bar{t} + V$ events	0.5 ± 0.4	2.2 ± 1.0	1.7 ± 0.8
Expected diboson events	3.4 ± 1.0	0.7 ± 0.4	0.1 ± 0.1
Expected fake lepton events	3.4 ± 3.1	$0.3^{+1.1}_{-0.3}$	$0.9^{+1.4}_{-0.9}$
Expected charge mis-measurement events	0.1 ± 0.1	0.5 ± 0.2	0.4 ± 0.1

B) Exclusion case	**SR0b**	**SR1b**	**SR3b**
Observed events	5	11	1
Expected background events	7.5 ± 3.2	10.1 ± 3.9	1.8 ± 1.3
Expected $t\bar{t} + V$ events	0.5 ± 0.4	3.4 ± 1.5	0.6 ± 0.4
Expected diboson events	3.4 ± 1.1	1.4 ± 0.7	< 0.1
Expected fake lepton events	3.4 ± 2.9	4.4 ± 3.1	1.0 ± 1.1
Expected charge mis-measurement events	0.2 ± 0.1	0.8 ± 0.3	0.1 ± 0.1

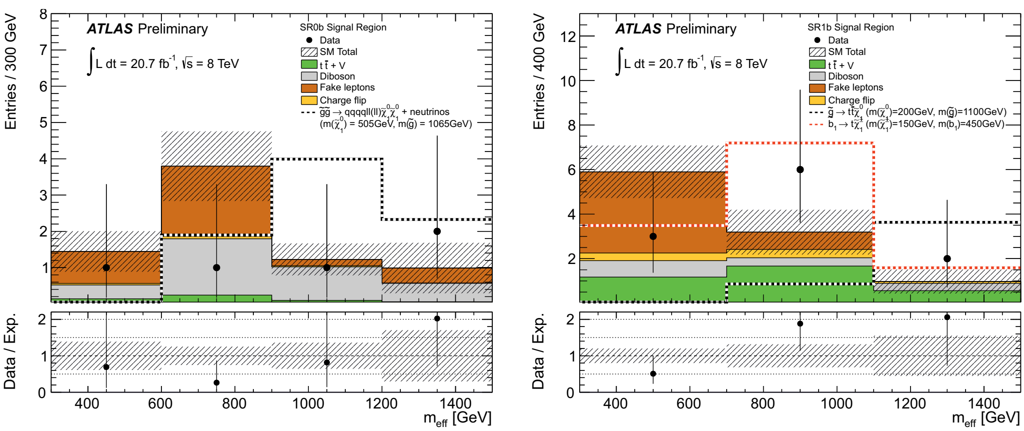

Figure 2. Effective mass distributions in the signal regions SR0b (left) and SR1b (right) using the exclusion case event sample. The last bin includes overflows [2].

5 Interpretation

Model dependent exclusion limits are provided in the parameter space of several SUSY models. Five typical SUSY models are presented: gluino mediated stop ($t\tilde{\chi}_1^0$) off-shell, gluino mediated stop ($\tilde{b}\tilde{\chi}_1^{\pm}$) on-shell, direct sbottom $\tilde{b}_1\tilde{b}_1$ ($t\tilde{\chi}_1^{\pm}$), direct-squark (via slepton) and mSUGRA/CMSSM.

Gluino mediated stop ($t\tilde{\chi}_1^0$) off-shell. In this model gluinos are produced in pairs and are assumed to be lighter than all squark flavors. Gluinos decay through mediation of a virtual (off-shell) top squark to a pair of top quarks and the lightest supersymmetric particle, LSP ($\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$). In the simulation the mass of the top squark is set to $m_{\tilde{t}_1} = 2.5$ TeV and the masses of all other squarks are much higher (decoupled). The final state is characterized by 4 top and two LSPs.

Results for this model are presented in $m_{\tilde{g}} - m_{\tilde{\chi}^0}$ plane. Figure 3 displays the observed and the expected limits for each individual SR and the combined limits.

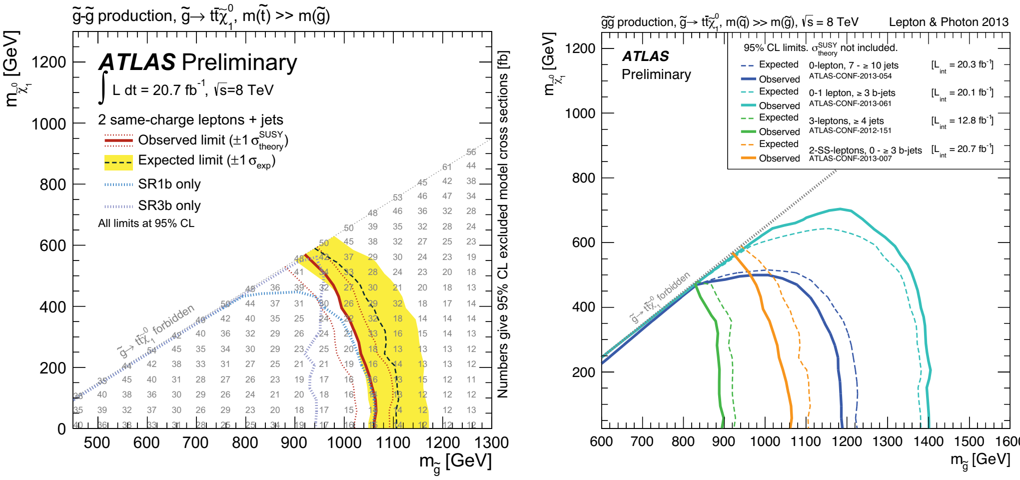

Figure 3. Expected and observed limits for gluino mediated stop model ($t\tilde{\chi}_1^0$) off-shell. The left figure shows the individual exclusion limits for each signal region. The grey numbers show the upper limits on the cross-section for this scenario. The right figure compares these results with the limits obtained by other ATLAS searches also using the 2012 data. Limits are computed at 95% CL [2].

The yellow band around the expected limit shows the $\pm 1\sigma$ uncertainty region including all statistical and systematic uncertainties except the theoretical uncertainties on the signal cross section. The $\pm 1\sigma^{SUSY}_{theory}$ lines around the observed limit are obtained by changing the signal cross section by $\pm 1\sigma$. The grey numbers show the upper limits on the production cross-section for this scenario.

For comparison, results for this model from other ATLAS searches using the same data are shown in Figure 3 right. The exclusion lines show the interplay between SR1b, which performs best at a large mass difference between the gluino and the LSP, and SR3b, which performs best at a small mass difference (compressed region) between the gluino and the LSP. At 95% CL gluinos are excluded up to masses of 900 - 1020 GeV for LSP masses below 550 GeV.

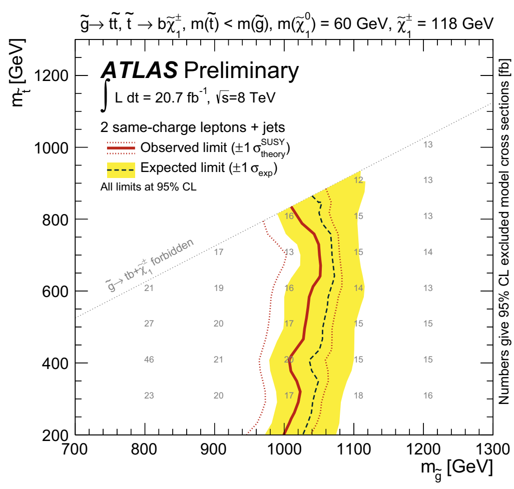

Figure 4. Expected and observed limits for the Gluino mediated stop ($b\tilde{\chi}_1^{\pm}$) on-shell model. The grey numbers show the upper limits on the cross-section for this scenario. All limits are computed at 95% CL[2].

Gluino mediated stop ($\tilde{b}\tilde{\chi}_1^{\pm}$) on-shell. In this model the lightest squark is $\tilde{t}$ and all other squarks are heavier than the gluino with the gluino mass higher than $m_{\tilde{t}_1} + m_t$. Therefore the decay $\tilde{g} \rightarrow \tilde{t}_1 t$ has 100% branching ratio (BR). The stop decay mode is assumed to be $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}$ with $m_{\chi_1^{\pm}} = 120$ GeV. Hence, chargino decay is via a virtual W boson $\tilde{\chi}_1^{\pm} \rightarrow W^*\tilde{\chi}_1^0$. The LSP mass is set to 60 GeV. The final state is characterized by a pair of top and bottom quarks, two LSP and the decay products of the virtual W boson.

Figure 4 presents the limits for this model in the $m_{\tilde{g}} - m_{\tilde{t}}$ plane. At 95% CL gluinos are excluded up to masses of about 940 - 1000 GeV for stop masses up to 750 GeV.

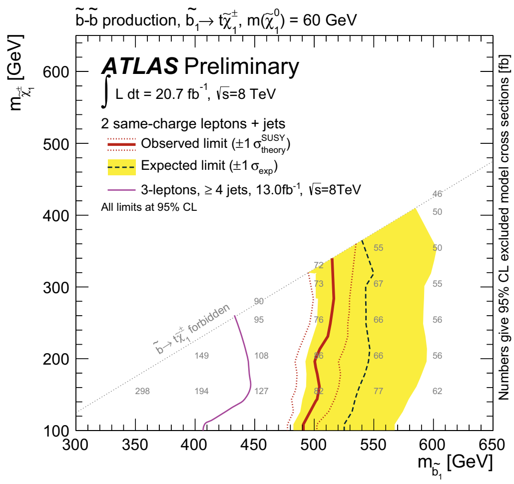

Figure 5. Expected and observed limits for direct sbottom model, ($t\tilde{\chi}_1^{\pm}$). Limits are computed at 95% CL [2].

Direct sbottom, $\tilde{b}_1\tilde{b}_1$ ($t\tilde{\chi}_1^{\pm}$). This model assumes that only direct pair production of bottom squarks is relevant. The decay mode is $\tilde{b} \rightarrow t\tilde{\chi}_1^{\pm}$ followed by $\tilde{\chi}_1^{\pm} \rightarrow W^{(*)\pm}\tilde{\chi}_1^0$. The final state is characterized by two top quarks, W bosons (on or off shell, depending on $m_{\tilde{\chi}_1^{\pm}} - m_{\tilde{\chi}_1^0}$) and $\not{E}_T$.

Figure 5 (left) shows the observed and the expected limits in the $m_{\tilde{b}} - m_{\tilde{\chi}^{\pm}}$ plane. In this model the LSP mass is set to 60 GeV. Bottom squarks with masses up to 470 - 480 GeV for chargino masses below 320 GeV are excluded. As shown on the plot, this search improves the existing ATLAS limits for this model.

Direct-squark (via slepton). The model consists of direct squark pair production (first and second generation) followed by decays which include sleptons. The decay chains are $\tilde{q} \rightarrow q\tilde{\chi}_1^{\pm}$ and $\tilde{q} \rightarrow q\tilde{\chi}_2^0$, with equal probability. Then the $\tilde{\chi}_1^{\pm}$ decays with equal probability into a slepton and a neutrino or into a lepton and a sneutrino. The $\tilde{\chi}_2^0$ decays with equal probability into a slepton and a lepton or a neutrino and a sneutrino. Finally the slepton decays into a lepton and LSP, or the sneutrino decays into a neutrino and a LSP. The masses of the $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ are assumed to be equal to the average of the squark and the LSP masses, and the slepton and sneutrino masses are assumed to be equal to the average of the $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^0$ and the LSP masses. All three flavours of sleptons are considered and are degenerate in mass. The final state is characterized by two light jets, up to four leptons and $\not{E}_T$.

In this model, squarks masses up to 600-660 GeV are excluded with 95% CL for neutralino masses below 380 GeV.

mSUGRA/CMSSM. In this constrained SUSY model three parameters are fixed to tan(β) = 30, A_0 = -2m_0 and $\mu > 0$, in order to accommodate a lightest Higgs boson mass around 126 GeV. Only strong production and associated electroweak (gluino-gaugino, squark-gaugino) processes are included.

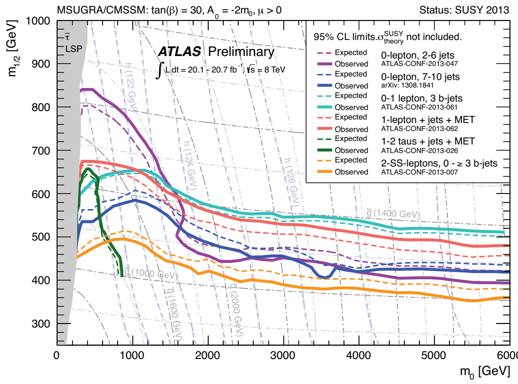

Figure 6. Expected and observed exclusion limits in the mSUGRA/CMSSM model with parameters tan(β) = 30, A_0 = -2m_0 and $\mu > 0$. Limits are computed at 95% CL [2].

Figure 6 presents the 95% CL exclusion limits for this model in the $(m_0, m_{1/2})$ parameter space. The measurement allows one to exclude a large region of the mSUGRA/CMSSM parameter space.

6 Conclusions

A search for the production of supersymmetric particles decaying into final states with jets, b-jets, $\not{E}_T$ and two isolated leptons, e or μ, of the same sign is presented. The analysis uses a data sample collected during 2012 corresponding to a total integrated luminosity of 20.7 fb^{-1} of $\sqrt{s}$ = 8 TeV proton-proton collisions recorded with the ATLAS detector at the Large Hadron Collider.

Three signal regions are defined with 0, ≥1 and ≥3 b-jets, respectively. No significant deviation from the Standard Model expectation is observed. Therefore the results are presented as model-independent limits and as exclusion limits in a mSUGRA/CMSSM model and in several simplified models of supersymmetry.

The diversity of the simplified models demonstrates the versatility of the analysis. This search improves sensitivity of the ATLAS experiment especially to SUSY processes where the mass difference between the decay products can be small, and, therefore, inaccessible via other decay modes. Hence this analysis covers several important aspects of the searches for supersymmetry at the LHC.

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