International Workshop on Discovery Physics at the LHC (Kruger2012) IOP Publishing
Journal of Physics: Conference Series **455** (2013) 012017 doi:10.1088/1742-6596/455/1/012017

Searches for Natural Supersymmetry with the ATLAS Detector

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Abstract. The ATLAS collaboration has performed searches for signals of natural Suypersymmetry. These signals include the production of charginos and neutralinos, third generation squarks and sleptons and cover an extensive list of scenarios. The direct production of Supersymmetric particles and the indirect production via a gluino decay has been investigated. No excess has been observed in any scenario and limits are placed on the masses of squarks and gluinos in a number of Supersymmetry based models using both 8 TeV and 7 TeV proton-proton collision data recorded with the ATLAS detector at the LHC.

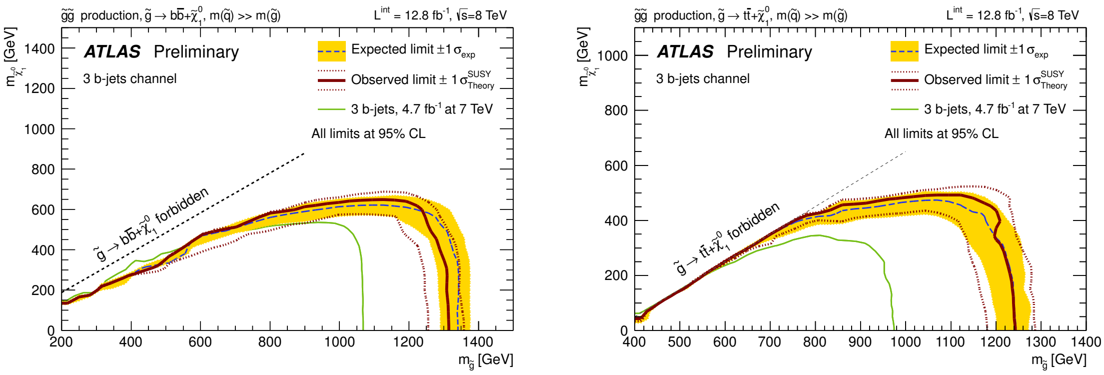
1. Introduction

A typical natural Supersymmetry (SUSY) spectrum contains light third generation squarks (stops and sbottoms), charginos and neutralinos. It is motivated by the fact that the dominant radiative corrections to the Higgs boson mass arise from the top quark in the Standard Model (SM). Thus a relatively light stop can cancel out these corrections. Furthermore the SM Z boson mass, the neutralino and chargino masses are related to the μ parameter in SUSY. Therefore one can argue it is possible the gaugino masses will be as low as the electroweak scale. The ATLAS collaboration has performed searches for stops, sbottoms, charginos, neutralinos and sleptons using 7 TeV and 8 TeV proton-proton collision data recorded at the LHC in the ATLAS detector [1]. Stops and sbottoms are searched for with analyses sensitive to both direct production and indirect production via a gluino decay. Charginos, neutralinos and sleptons are searched for with analyses sensitive to direct production of these sparticles.

2. Search for gluino mediated stop or sbottom production with 3 b-tagged jets and Missing Transverse Energy in 8 TeV data

This analysis [2] is sensitive to pair production of gluinos where each gluino can decay via $\tilde{g} \rightarrow \tilde{t}_1 t \rightarrow t\bar{t}\tilde{\chi}_0^1$ or $\tilde{g} \rightarrow \tilde{b}_1 b \rightarrow b\bar{b}\tilde{\chi}_0^1$. Therefore the final state contains at least 4 bottom quark jets and Missing Transverse Energy ($E_{\mathrm{T}}^{\mathrm{miss}}$) from the neutralinos. Both a 4 jet and a 6 jet signal region are defined, each requiring 3 b-tagged jets with transverse momentum (p_{T}) > 50 GeV and $E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV. $E_{\mathrm{T}}^{\mathrm{miss}}$ is calculated, in a object based way, using all calorimeter clusters in the objects (electrons, muons, jets, etc.) in the analysis and in addition clusters not contained in such objects. To suppress the multi jet background none of the signal jets are allowed to be within 0.4 in the azimuthal (ϕ) direction of the $E_{\mathrm{T}}^{\mathrm{miss}}$ vector ($\Delta\phi < 0.4$). Furthermore the ratio of $E_{\mathrm{T}}^{\mathrm{miss}}$ to m_{eff} (the Effective Mass defined as the scalar sum of the signal jet p_{T} and $E_{\mathrm{T}}^{\mathrm{miss}}$) must be larger than 0.2 to enhance the signal. The main background comes from top pair production after this data selection. A control region in data is defined which requires exactly 2 b-tagged jets and relaxes both the $E_{\mathrm{T}}^{\mathrm{miss}}$ and $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$ cuts to increase statistics. This control region, which is dominated by top pair production, is used to normalise the top pair Monte Carlo (MC). Good agreement between data and MC is observed.

No excess is observed in either signal region. Limits are set on the gluino mass in two simplified models where the gluino is lighter than the squarks and either decays exclusively into a bottom-antibottom or top-antitop pair, in both cases with an accompanying neutralino. Figure 1 shows that gluino masses below 1320 GeV in the bottom-antibottom scenario are excluded, and below 1240 GeV in the top-antitop scenario when the neutralino is massless.



(a) (b)

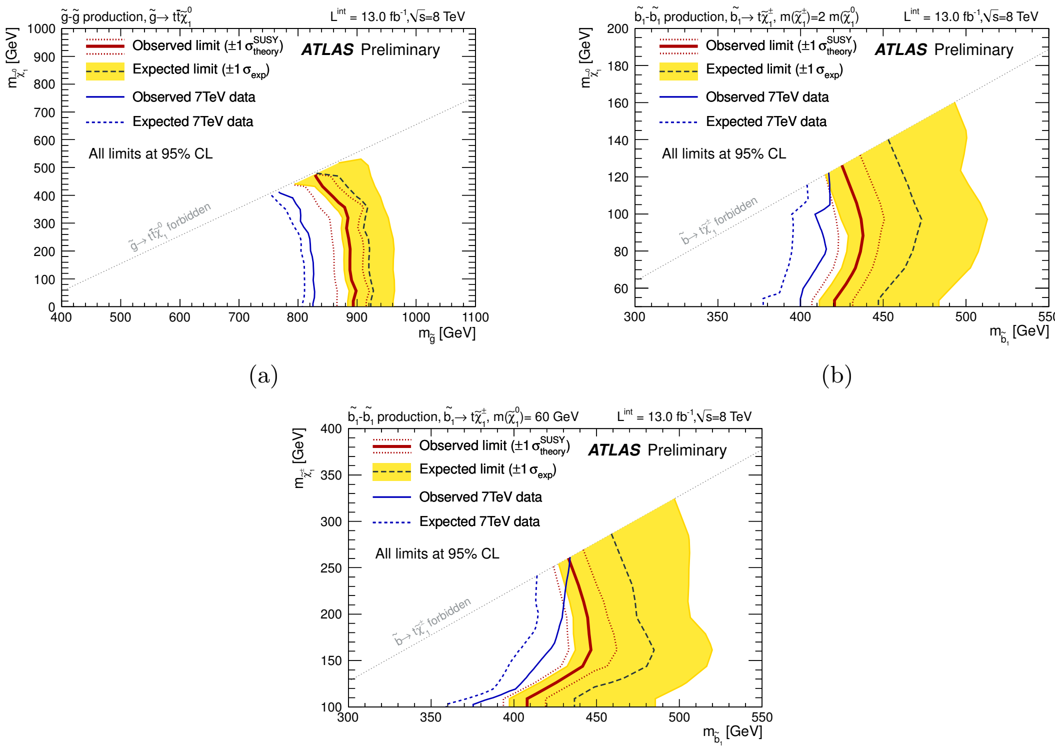
Figure 1. Limits on the gluino mass, where the final state contains a bottom-antibottom pair (a) and a top-antitop pair (b) [2].

3. Search for gluino mediated stop production, and direct sbottom production with leptons and jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ in 8 TeV data

Gluino mediated stop production can also result in a final state with leptons from the top decays. The final state in this analysis is also sensitive to direct sbottom production because of leptons from both W boson and top quark decays: $\tilde{b}_1 \to \tilde{\chi}_1^- t \to \tilde{\chi}_1^0 W^- t \to \tilde{\chi}_1^0 l^- \bar{\nu}_l t$

The analysis [3] defines 6 signal regions based on the possible electron and muon combinations. All of these require at least 4 jets, $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV and a same-flavor-opposite-sign (SFOS) lepton pair with an invariant mass outside the range 81 to 101 GeV. Three control regions are used to estimate the main backgrounds in the signal region. A Z boson control region with the SFOS invariant mass in the range 81 to 101 GeV, a top control region with less than 4 jets and a $E_{\mathrm{T}}^{\mathrm{miss}}$ control region with $E_{\mathrm{T}}^{\mathrm{miss}} < 50$ GeV are used. These control regions are further subdivided into regions sensitive to different fake rates (light or heavy flavour jets faking electrons or muons). A likelihood fit is performed in these regions to correct the MC fake rates. Good agreement between data and MC is seen in all three control regions, and no excess in data is found in any of the signal regions.

The results are interpreted in terms of two simplified models. In the first model the gluino always decays into a top-antitop pair and a neutralino. The second model requires the directly produced sbottoms to decay to a final state with a W boson, neutralino and top quark. In the first model gluinos with masses below 860 GeV are excluded at 95% Confidence Limit (CL) and in the second model sbottoms are excluded up to 430 GeV at 95% CL. The limits are illustrated in the respective mass planes in Figure 2.



(a) (b) (c)

Figure 2. Limit in neutralino-gluino plane for gluino mediated stop production (a), limit in neutralino-sbottom plane for direct sbottom production, where $m(\tilde{\chi}_1^{\pm}) = 2m(\tilde{\chi}_1^0)$ (b) and limit in neutralino-sbottom plane for direct sbottom production, where $m(\tilde{\chi}_1^{\pm}) = 60$ GeV (c) [3].

4. Search for direct sbottom production with 2 b-jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ in 7 TeV data

The sbottom can decay into a final state with a bottom quark and a neutralino: $\tilde{b} \to b\tilde{\chi}_1^0$. The mass difference between the sbottom and neutralino affects the kinematics of the decay. For large mass differences we expect two hard b-tagged jets, and make use of the contransverse mass (m_{CT}) [4] variable shown in equation 1, defined for two particles ν_1 and ν_2 in the final state, to separate signal and background.

$$m_{\mathrm{CT}}^2(\nu_1, \nu_2) = [E_{\mathrm{T}}(\nu_1) + E_{\mathrm{T}}(\nu_2)]^2 - [p_{\mathrm{T}}(\nu_1) + p_{\mathrm{T}}(\nu_2)]^2 \quad (1)$$

When the mass difference is small we make use of a third jet from initial state radiation (ISR) being present in each event, which recoils against the two b-tagged jets thus boosting them above the minimal jet p_{T} thresholds used in ATLAS. A 1-lepton control region is used for top pair production and W boson production in association with heavy flavour jets. The 1-lepton selection ensures no signal events of interest are in this control region. A 2-lepton control region is used for Z bosons decaying to neutrinos in association with heavy flavour jets and top pair production. The 2 leptons can be added vectorially to the $E_{\mathrm{T}}^{\mathrm{miss}}$ to mimic neutrinos, and ensure no signal of interest is present in the control region. The control regions are used to normalise the MC and no excess in data was found in the signal regions. Limits are set in a SUSY model where the sbottom decays exclusively to a bottom quark and neutralino. The sbottom mass below 490 GeV is excluded for massless neutralinos, as shown in Figure 3 [5].

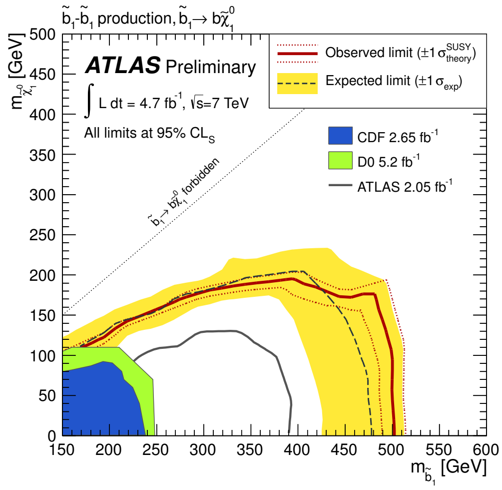


Figure 3. Limit in neutralino-sbottom plane for direct sbottom production [5].

5. Search for direct stop production in 7 TeV data

If the stop is heavier than the top quark, then the stop can decay to a top and a neutralino. We search for this process using final states with 0,1 or 2 leptons in association with jets and $E_{\mathrm{T}}^{\mathrm{miss}}$. When the stop is similar in mass to the top quark it is more likely to decay into a bottom quark and chargino: $\tilde{t}_1 \to \tilde{\chi}_1^- b \to W^- \tilde{\chi}_1^0 b$. We search for this process using a final state with 1 or 2 leptons in association with b-tagged jets and $E_{\mathrm{T}}^{\mathrm{miss}}$. If the stop is extremely light then the leptons will be very soft and a dedicated analysis is performed looking for 1 or 2 soft leptons in association with jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ [6–10].

In the heavy stop scenario in the 0-lepton search we require at least 5 jets and no leptons or tau-like jets. Furthermore the invariant mass of the hadronic top candidate should be between 80 and 270 GeV and the transverse mass constructed from the b-tagged jet and $E_{\mathrm{T}}^{\mathrm{miss}}$ larger than 175 GeV. Two signal regions are then defined with $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ or 260 GeV along with a control region for top pair production with a tau faking a jet - here we require an isolated non-tau lepton with transverse mass between 40 and 120 GeV. In the 1-lepton analysis we construct 5 signal regions based on $E_{\mathrm{T}}^{\mathrm{miss}}$ and $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ where H_{T} is the scalar sum of jet p_{T} and the transverse mass. Furthermore three control regions are defined for the top and W boson backgrounds. In the 2-lepton analysis we use m_{T2} [11], defined in equation 2 where $p_{\mathrm{T}}^{\mathrm{miss}}$ is decomposed into two hypotheses for the 2-vectors of invisible particles q_{T} and r_{T}, to separate the signal and background. A same-flavour and different-flavour signal region can then be defined alongside a control region for top and Z boson production.

$$m_{\mathrm{T2}}(p_{\mathrm{T}}^{\mathrm{l1}}, p_{\mathrm{T}}^{\mathrm{l2}}, p_{\mathrm{T}}^{\mathrm{Miss}}) = min[max[m_{\mathrm{T}}(p_{\mathrm{T}}^{\mathrm{l1}}, q_{\mathrm{T}}), m_{\mathrm{T}}(p_{\mathrm{T}}^{\mathrm{l2}}, r_{\mathrm{T}})]] \quad (2)$$

When the stop is lighter, around the top mass, we require 1 or 2 leptons along with b-tagged jets and $E_{\mathrm{T}}^{\mathrm{miss}}$. Then $\sqrt{S_{\mathrm{min}}^{\mathrm{sub}}}$ [12], which can be calculated for a subsystem of final state particles defined in equation 3, is used to separate signal and background. Three control regions are used for the top and W/Z boson backgrounds.

$$\sqrt{S^{\rm sub}_{\rm min}} = \sqrt{(\sqrt{m^2_{\rm sub} + \bar{p}^2_{\rm T,sub}} + \sqrt{m^2_{\rm miss} + E_{\rm T}^{\rm miss}})^2 - (\bar{p}^{\rm sub}_{\rm T} + \bar{p}^{\rm Miss}_{\rm T})^2} \quad (3)$$

No excess in data is seen in any of the signal regions defined in the five direct stop analyses. Hence limits can be set in the neutralino-stop mass plane. Depending on the assumptions made we exclude a stop mass up to 500 GeV, though as can be seen from Figure 4 we cannot exclude a stop mass from just above 150 GeV to just below 225 GeV using 7 TeV data.

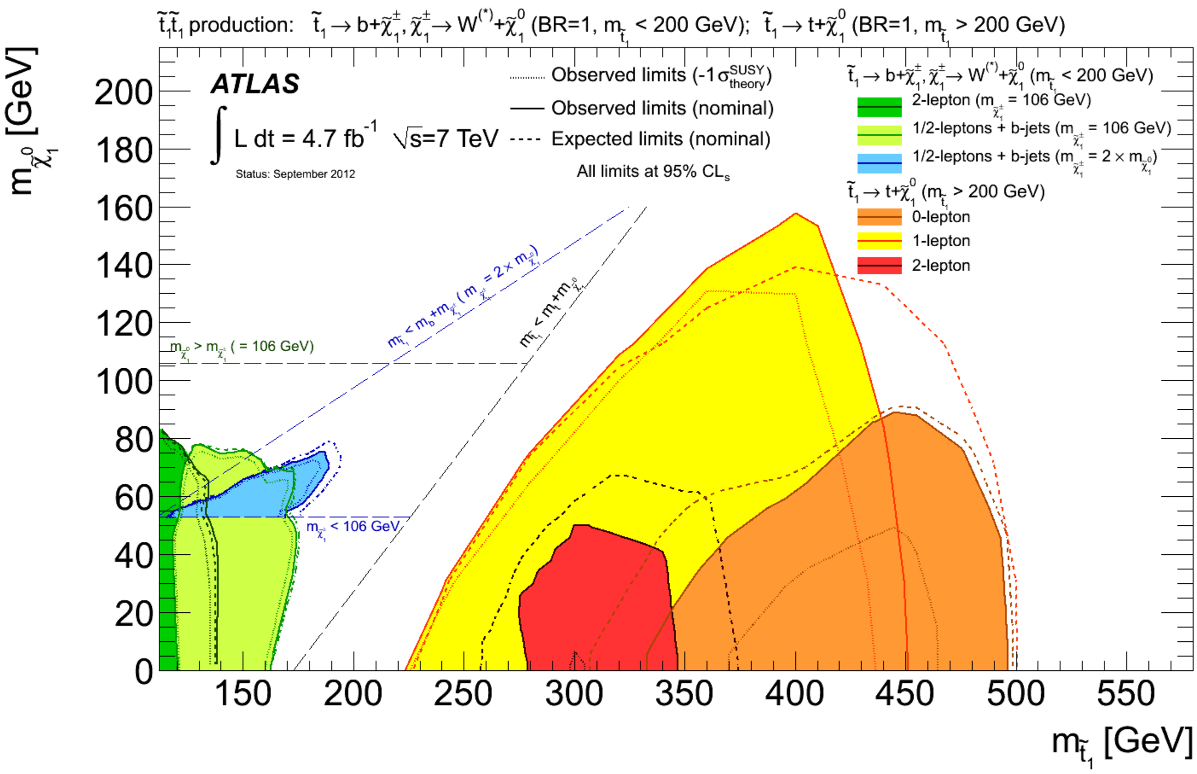
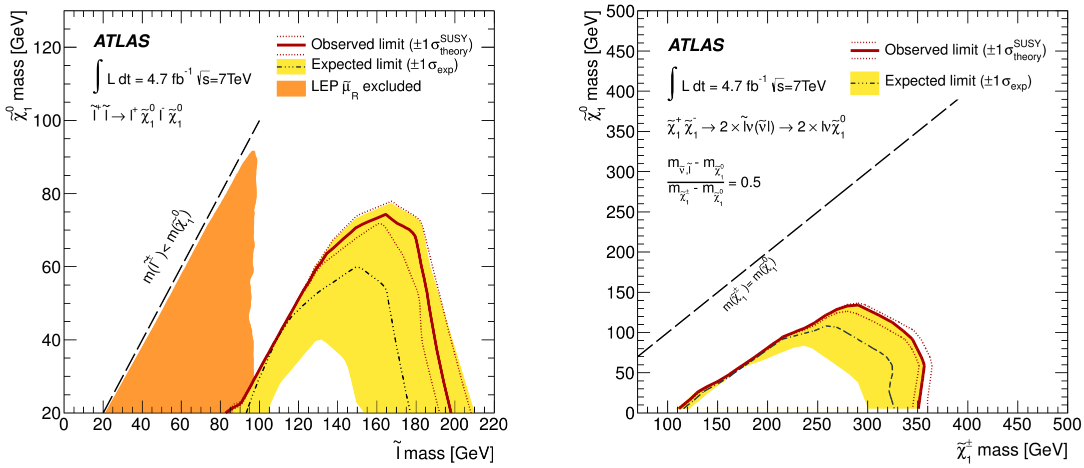


Figure 4. Limits on direct stop production with 7 TeV data [13].

6. Search for direct slepton and gaugino pair production in 7 TeV data with 2 leptons and $E_{\rm T}^{\rm miss}$

Direct production of sleptons is possible if the sleptons are light enough, and for masses in the range 70 to 190 GeV cross-sections of 0.05 to 3.9 pb occur in the models considered. The cross-sections are independent of the neutralino mass. This leads to a final state containing 2 leptons and 2 neutralinos via the decay: $\tilde{l}^- \to l\chi^0_1$. Light sleptons can also be produced via chargino pair production, where each chargino decays via $\tilde{\chi}^{\mp}_1 \to \bar{l}\nu \to \nu l\tilde{\chi}^0_1$ or $\tilde{\chi}^{\mp}_1 \to \bar{\nu}l \to l\nu\tilde{\chi}^1_0$. This analysis [14] is also sensitive to 3 lepton final states where one of the leptons is not reconstructed or impinges on non-instrumented regions of the detector. In this scenario both a chargino and neutralino are produced, with the latter decaying via $\tilde{\chi}^0_2 \to \tilde{l}l \to ll\tilde{\chi}^0_1$. If the sleptons are heavy then the decays of the chargino and neutralino instead proceed via W and Z bosons. In this 2 lepton analysis the first signal region requires that the opposite sign (OS) di-lepton invariant mass is inconsistent with the Z boson mass, no signal like jets (defined to have $p_{\mathrm{T}} > 30$ GeV and $|\eta| < 2.5$ with a jet vertex fraction larger than 0.75) , $E_{\mathrm{T}}^{\mathrm{miss}}$ larger than 40 GeV and m_{T2} larger than 90 GeV. The second signal region removes the m_{T2} cut and tightens the $E_{\mathrm{T}}^{\mathrm{miss}}$ cut to 100 GeV. A third signal region with same sign (SS) lepton pairs requires no signal like jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ larger than 100 GeV. Finally a fourth signal region with SFOS lepton pairs with an invariant mass inconsistent with the Z boson mass, at least 2 jets, no b-tagged jets, $E_{\mathrm{T}}^{\mathrm{miss}}$ greater than 50 GeV and a m_{CT} veto is defined. Control regions are defined for top, di-boson and Z boson + jets production. No excess of data is seen in the signal regions. Limits are placed in the chargino-neutralino plane and neutralino-slepton plane. For 10 GeV neutralinos we exclude a chargino with mass between 110 and 340 GeV, and for a 20 GeV neutralino we exclude sleptons between 85 and 195 GeV.



(a) (b)

Figure 5. Limits in the neutralino-slepton plane (a) and the chargino-neutralino plane (b) [14]
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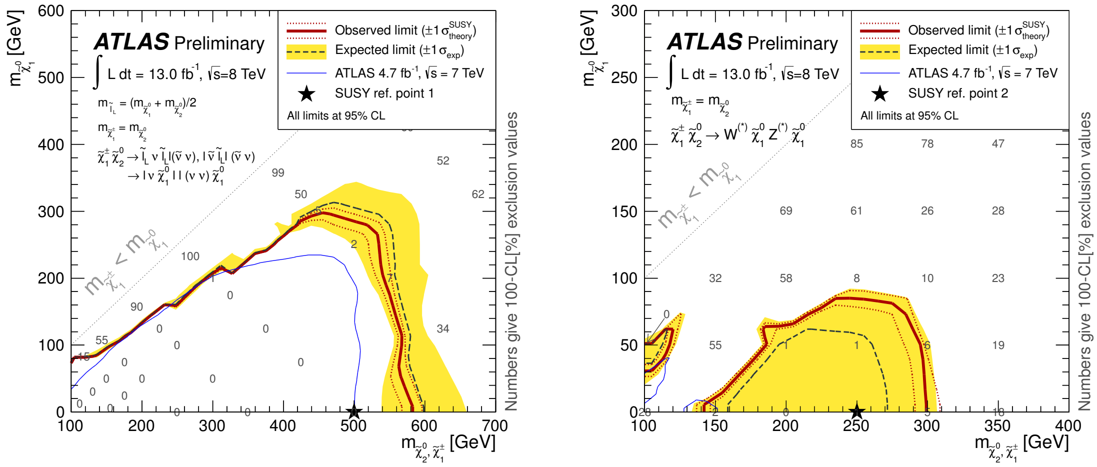
7. Search for gaugino pair production in 8 TeV data with 3 leptons and $E_{\mathrm{T}}^{\mathrm{miss}}$

This analysis [15], sensitive to the production of a chargino and neutralino as discussed in the previous section, requires 3 isolated leptons in each signal region. The first signal region, targeting the neutralino decay via a slepton, requires the SFOS lepton pair mass to be more than 10 GeV from the Z boson mass, no b-tagged jets, $E_{\mathrm{T}}^{\mathrm{miss}} > 75$ GeV and the lepton p_{T} to be above 10 GeV. The second signal region targeting the neutralino decay via an off-shell Z boson in addition asks for the transverse mass of the lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$ to be larger than 100 GeV and the lepton p_{T} to be greater than 30 GeV. The final signal region, targeting neutralino decay via an on-shell Z boson, requires the SFOS lepton pair invariant mass to be within 10 GeV of the Z boson mass, $E_{\mathrm{T}}^{\mathrm{miss}}$ larger than 120 GeV, the transverse mass of the lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$ to be larger than 100 GeV and the lepton p_{T} to be greater than 10 GeV. A control region with $E_{\mathrm{T}}^{\mathrm{miss}}$ between 50 and 75 GeV and transverse mass between 50 and 100 GeV is defined for WZ boson production. No excess is observed in data in any of the signal regions. We exclude charginos up to 580 GeV in simplified models in the presence of light sleptons, and 150 to 300 GeV if the sleptons are heavy and neutralinos light. This is shown in Figure 6. We also interpret these results in the framework of the phenomenological Minimal Supersymetric Model (pMSSM), which is shown in Figure 7, in terms of the gaugino mass parameters M_1 and M_2, as well as the Higgs mass parameter μ. For all values of M_1, regions low M_2 and μ are excluded.



(a) (b)

Figure 6. Limits in the chargino-neutralino1 plane and neutralino2-neutralino1 plane, for decays via a slepton (a). Limits in the chargino-neutralino1 plane and neutralino2-neutralino1 plane, for decays via a *W* boson (b) [15].

8. Conclusion

ATLAS has performed careful searches for production of third generation squarks and gauginos. An extensive range of scenarios have been covered using leptons, jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ - no analysis observed any excess of data. Natural SUSY Searches in ATLAS exclude a gluino mass below 1320 GeV and stop masses are excluded up to masses of 500 GeV. 8 TeV searches have already extended the 7 TeV limits on SUSY models, whilst other searches are in the process of being updated with 8 TeV data. After the Long Shutdown 1 (LS1) the LHC will resume data taking at a far higher centre of mass energy, and therefore future searches for natural SUSY in ATLAS are expected to be even more sensitive.

[1] The ATLAS Collaboration 2008 *JINST 3* **S08003**
[2] The ATLAS Collaboration 2012 *ATLAS-CONF-2012-145, http://cds.cern.ch/record/1493484*
[3] The ATLAS Collaboration 2012 *ATLAS-CONF-2012-151, http://cds.cern.ch/record/1493490*
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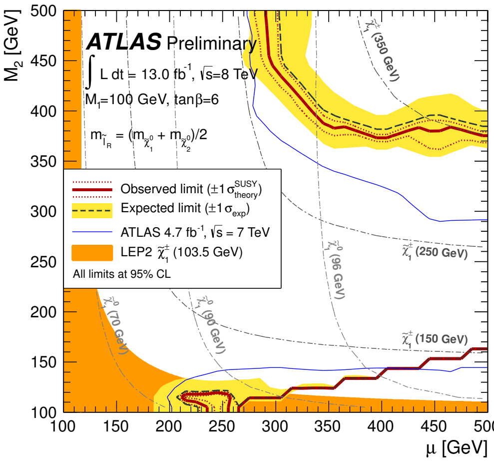
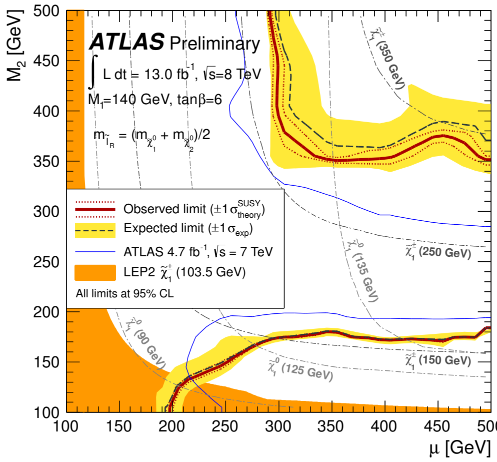


(a)



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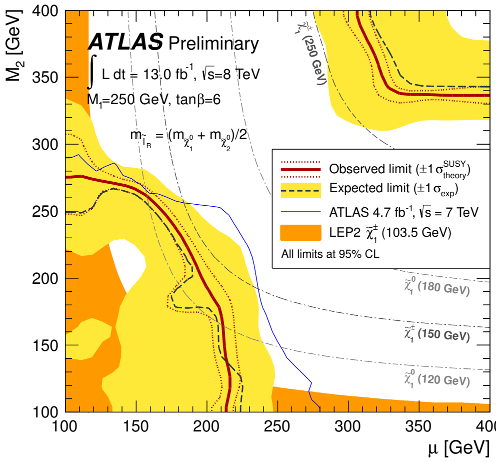

(c)

Figure 7. Limits in the M_2-μ plane, for M_1 = 100 GeV (a), M_1 = 140 GeV (b) and M_1 = 250 GeV (c) [15].

[14] The ATLAS Collaboration 2013 *PLB* **718** 879
[15] The ATLAS Collaboration 2012 *ATLAS-CONF-2012-154, http://cds.cern.ch/record/1493493*