Search for supersymmetry in pp collisions at $\sqrt{s} = 7$ TeV in final states with missing transverse momentum and b-jets


DOI
10.1016/j.physletb.2011.06.015

Publication date
2011

Document Version
Final published version

Published in
Physics Letters B

Citation for published version (APA):
https://doi.org/10.1016/j.physletb.2011.06.015
Search for supersymmetry in \( pp \) collisions at \( \sqrt{s} = 7 \) TeV in final states with missing transverse momentum and \( b \)-jets

\*ATLAS Collaboration

1. Introduction

Supersymmetry (SUSY) \([1]\) is one of the most compelling theories to describe physics beyond the Standard Model (SM). It naturally solves the hierarchy problem and provides a possible candidate for dark matter. SUSY is a symmetry that relates fermionic and bosonic degrees of freedom, and postulates the existence of superpartners for the SM particles. Experimental data imply that supersymmetry is broken and that the superpartners are expected to be heavier than the SM partners. In the framework of a generic \( R \)-parity conserving minimal supersymmetric extension of the SM, the MSSM \([2]\), SUSY particles are produced in pairs and the lightest supersymmetric particle (LSP) is stable. In a large variety of models, the LSP is the lightest neutralino, \( \tilde{\chi}_1^0 \), which is only weakly interacting.

If supersymmetric particles exist at the TeV energy scale, the coloured superpartners of quarks and gluons, the squarks (\( \tilde{q} \)) and gluinos (\( \tilde{g} \)), are expected to be copiously produced via the strong interaction at the Large Hadron Collider (LHC) \([3,4]\). Their decays via cascades ending with the LSP produce striking experimental signatures leading to final states containing multi-jets, missing transverse momentum (its magnitude is referred to as \( E_T^{\text{miss}} \) in the following) – resulting from the undetected neutralinos – and possibly leptons. First searches for the production of SUSY particles at the LHC have been published recently \([5–7]\).

In the MSSM, the scalar partners of right-handed and left-handed quarks, \( \tilde{q}_R \) and \( \tilde{q}_L \), can mix to form two mass eigenstates. These mixing effects are proportional to the corresponding fermion masses and therefore become important for the third generation. In particular, large mixing can yield sbottom (\( \tilde{b}_1 \)) and stop (\( \tilde{t}_1 \)) 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 via direct pair production or, if kinematically allowed, through \( \tilde{g} \tilde{g} \) production with subsequent \( \tilde{g} \to \tilde{b}_1 \tilde{b}_1 \) or \( \tilde{g} \to \tilde{t}_1 \tilde{t}_1 \) decays. 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 \( E_T^{\text{miss}} \), several jets, among which \( b \)-quark jets (\( b \)-jets) are expected, and possibly leptons.

In this Letter, a search for final states involving \( E_T^{\text{miss}} \) and \( b \)-quark jets is discussed. Results on searches for direct sbottom \([8,9]\) and gluino mediated production \([12]\) have been previously reported by the Tevatron experiments, placing exclusion limits on the mass of these particles in several MSSM scenarios.

The search described here is based on \( pp \) collision data at a centre-of-mass energy of 7 TeV recorded by the ATLAS experiment at the LHC in 2010. The total data set corresponds to an integrated luminosity of 35 \( \text{pb}^{-1} \) \([13]\). To enhance the sensitivity to different SUSY models, the search was performed using two mutually exclusive final states, characterised by the presence of leptons. They are referred to as zero-lepton and one-lepton analyses in the following.

In the zero-lepton analysis, events are required to contain energetic jets, of which one must be identified as a \( b \)-jet, large \( E_T^{\text{miss}} \) and no isolated leptons (\( e \) or \( \mu \)). The zero-lepton analysis
is employed to search for gluinos and sbottoms in MSSM scenarios where the $b_1$ is the lightest squark, all other squarks are heavier than the gluino, and $m_{b_1} > m_{b_1} > m_{b_1}$. Such that the branching ratio for $\tilde{g} \to b_1b_1$ decays is 100%. Stopbottoms are produced via gluino-mediated processes or via direct pair production. They are assumed to decay exclusively via $b_1 \to b_1 \tilde{\chi}_1^0$, where $m_{b_1}$ is assumed to be 60 GeV, above the present exclusion limit [14].

In the one-lepton analysis, events are required to contain energetic jets, of which one must be identified as a b-jet, large $E_T^{miss}$ and at least one high-$p_T$ electron or muon. This analysis is sensitive to SUSY scenarios in which the stop is the lightest squark and the gluino is assumed to decay exclusively via $b_1 \to b_1 \tilde{\chi}_1^0$, where $m_{b_1}$ is assumed to be greater than the gluino, and $m_{b_1} > m_{b_1} > m_{b_1}$. Such that the branching ratio for $\tilde{g} \to b_1b_1$ decays is 100%. Stopbottoms are produced via gluino-mediated processes or via direct pair production. They are assumed to decay exclusively via $b_1 \to b_1 \tilde{\chi}_1^0$, where $m_{b_1}$ is assumed to be 60 GeV, above the present exclusion limit [14].

In the one-lepton analysis, events are required to contain energetic jets, of which one must be identified as a b-jet, large $E_T^{miss}$ and at least one high-$p_T$ electron or muon. This analysis is sensitive to SUSY scenarios in which the stop is the lightest squark and the gluino is assumed to decay exclusively via $b_1 \to b_1 \tilde{\chi}_1^0$, where $m_{b_1}$ is assumed to be greater than the gluino, and $m_{b_1} > m_{b_1} > m_{b_1}$. Such that the branching ratio for $\tilde{g} \to b_1b_1$ decays is 100%. Stopbottoms are produced via gluino-mediated processes or via direct pair production. They are assumed to decay exclusively via $b_1 \to b_1 \tilde{\chi}_1^0$, where $m_{b_1}$ is assumed to be 60 GeV, above the present exclusion limit [14].

In the one-lepton analysis, events are required to contain energetic jets, of which one must be identified as a b-jet, large $E_T^{miss}$ and at least one high-$p_T$ electron or muon. This analysis is sensitive to SUSY scenarios in which the stop is the lightest squark and the gluino is assumed to decay exclusively via $b_1 \to b_1 \tilde{\chi}_1^0$, where $m_{b_1}$ is assumed to be 60 GeV, above the present exclusion limit [14].

In the one-lepton analysis, events are required to contain energetic jets, of which one must be identified as a b-jet, large $E_T^{miss}$ and at least one high-$p_T$ electron or muon. This analysis is sensitive to SUSY scenarios in which the stop is the lightest squark and the gluino is assumed to decay exclusively via $b_1 \to b_1 \tilde{\chi}_1^0$, where $m_{b_1}$ is assumed to be 60 GeV, above the present exclusion limit [14].

In the one-lepton analysis, events are required to contain energetic jets, of which one must be identified as a b-jet, large $E_T^{miss}$ and at least one high-$p_T$ electron or muon. This analysis is sensitive to SUSY scenarios in which the stop is the lightest squark and the gluino is assumed to decay exclusively via $b_1 \to b_1 \tilde{\chi}_1^0$, where $m_{b_1}$ is assumed to be 60 GeV, above the present exclusion limit [14].
Table 1  

<table>
<thead>
<tr>
<th>Physics process</th>
<th>$\sigma$ (BR [nb])</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \to \ell^+\ell^-$ (jets)</td>
<td>$31.4 \pm 1.6$ [24–26]</td>
</tr>
<tr>
<td>$Z/\gamma^* \to \ell^+\ell^-$ (jets)</td>
<td>$3.2 o \pm 0.16$ [24–26]</td>
</tr>
<tr>
<td>$Z \to \ell^+\ell^-$ (jets)</td>
<td>$5.8 \pm 0.29$ [24–26]</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$0.165 \pm 0.016$ [27–29]</td>
</tr>
<tr>
<td>Single top</td>
<td>$0.037 \pm 0.002$ [27–29]</td>
</tr>
<tr>
<td>Dijet ($p_T &gt; 8$ GeV)</td>
<td>$10.47 \times 10^5$ [30]</td>
</tr>
</tbody>
</table>

For the comparison to data, all background cross sections, except the QCD background cross section, were normalised to the results of higher order QCD calculations. A summary of the relevant cross sections is given in Table 1. For the next-to-next-to-leading order (NNLO) W and Z production cross sections, an uncertainty of $\pm 5\%$ is assumed [40].

In the one-lepton analysis, events were required to have at least one jet with $p_T > 120$ GeV and $E_T^{\text{miss}} > 25$ GeV applied [41]. For the one-lepton analysis, the trigger selection was based on single lepton triggers, which retain events if an electron with $p_T > 15$ GeV or a muon with $p_T > 13$ GeV is present within the trigger acceptance.

In the selected data sample, jets were reconstructed by using the anti-$k_t$ jet clustering algorithm [42,43] with a distance parameter of $R = 0.4$. The inputs to this algorithm are three-dimensional topological calorimeter energy clusters. The jet energies were corrected for inhomogeneities and for the non-compensating nature of the calorimeter by using $p_T$- and $\eta$-dependent calibration factors. They were determined from Monte Carlo simulation and validated using extensive test-beam measurements and studies of $pp$ collision data (Ref. [44] and references therein). Only jets with $p_T > 20$ GeV and within $|\eta| < 2.5$ were retained. Candidates for $b$-jets were identified among jets with $p_T > 30$ GeV using an algorithm that reconstructs a vertex from all tracks which are displaced from the primary vertex and associated with the jet. The parameters of the algorithm were chosen such that a tagging efficiency of $50\%$ ($1\%$) was achieved for $b$-jets (light flavour or gluon jets) in $t\bar{t}$ events in Monte Carlo simulation [45].

Electron candidates were required to satisfy the ‘medium’ (zero-lepton analysis) or ‘tight’ (one-lepton analysis) selection criteria. Muon candidates were identified either as a match between an extrapolated inner detector track and one or more segments in the muon spectrometer, or by associating an inner detector track to a muon spectrometer track. The combined track parameters were derived from a statistical combination of the two sets of track parameters. Electrons and muons were required to have $p_T > 20$ GeV and $|\eta| < 2.47$ or $|\eta| < 2.4$, respectively. Further details on lepton identification can be found in Ref. [40].

The calculation of $E_T^{\text{miss}}$ is based on the modulus of the vectorial sum of the $p_T$ of the reconstructed jets (with $p_T > 20$ GeV and over the full calorimeter coverage $|\eta| < 4.9$), leptons (including non-isolated muons) and the calorimeter clusters not belonging to reconstructed objects.

After object identification, overlaps were resolved. Any jet within a distance $\Delta R = 0.2$ of a ‘medium’ electron candidate was discarded. The event was rejected if one or more ‘medium’ jets were identified in the transition region $1.37 < |\eta| < 1.52$ between the barrel and endcap calorimeters. Any remaining lepton within $\Delta R = 0.4$ of a jet was discarded.

Events were selected if a reconstructed primary vertex was found associated with five or more tracks, and if they passed basic quality criteria against detector noise and non-collision backgrounds.

In the one-lepton analysis, events were required to have at least one muon or a ‘tight’ electron, two jets with $p_T > 60$ GeV and $p_T > 30$ GeV respectively, $E_T^{\text{miss}} > 80$ GeV and $m_T > 100$ GeV, where $m_T$ is the transverse mass constructed using the highest $p_T$ lepton and $E_T^{\text{miss}}$. At least one jet is required to be $b$-tagged. The $m_T$ cut rejects events with a $W$ boson in the final state. In both analyses, further cuts on $m_{\text{eff}}$ were applied to maximise the sensitivity to gluino-mediated production of sbottoms or stops. A threshold on $m_{\text{eff}}$ at 600 GeV (500 GeV) was chosen for the zero-lepton (one-lepton) analysis. It should be noted that for the one-lepton analysis the transverse momenta of reconstructed leptons are included in the definition of the $m_{\text{eff}}$.

The event selection efficiency for each SUSY signal hypothesis was calculated as the sum of the efficiencies for the $g\tilde{g}$ and $b\tilde{t}_1$ ($\tilde{t}_1\tilde{t}_1$) processes, weighted by their respective NLO cross sections. For the zero-lepton selection, the efficiency varies between 7% and 50% across the $(m_{\tilde{g}}, m_{\tilde{b}_1})$ plane. The lowest values are found at large $\Delta m = m_{\tilde{g}} - m_{\tilde{b}_1}$, where the production of $b\tilde{t}_1\tilde{b}_1$ pairs dominates. As $\Delta m$ decreases, high efficiency values are found down to $\Delta m \approx 20$ GeV. For the one-lepton channel, the efficiency for the $(\tilde{g}, \tilde{t}_1)$-type SUSY signals varies between 0.4% and 3% across the $(m_{\tilde{g}}, m_{\tilde{t}_1})$ plane and depends on $\Delta m = m_{\tilde{g}} - m_{\tilde{t}_1}$ in a similar way to the gluino–bottom case.

No additional dedicated optimisations were performed for the MSSUGRA/CMSSM and SO(10) scenarios. The efficiencies for the zero-lepton (one-lepton) selection for MSSUGRA/CMSSM range between 8% (1%) for $m_{\tilde{g}_1} \approx 130$ GeV and 23% (12%) for $m_{\tilde{g}_1} \approx 340$ GeV, with a smaller dependence on $m_{\tilde{g}}$. For SO(10) models, the highest sensitivity is reached in the zero-lepton analysis, with dominant contributions via $g\tilde{g}$ production. In this case, the efficiencies vary between 7% and 20% as the gluino mass increases and are generally found to be larger for the DR3 scenario than for the HS scenario.
5. Standard model background estimation

Standard Model processes contribute to the events that survive the selection described in the previous section. The dominant source is $t\bar{t}$ production due to the presence of jets, $E_T^{miss}$ and $b$-quarks in the final state.

The QCD background to the zero-lepton final state was estimated by normalising the PYTHIA Monte Carlo prediction to data in a QCD-enriched control region defined by $\Delta p_{T\text{min}} < 0.4$. The Monte Carlo was then used to evaluate the ratio between the number of events in this control region and the signal region ($\Delta p_{T\text{min}} > 0.4$). In the one-lepton final state the number of QCD multi-jet events was estimated using a matrix method similar to the one described in Ref. [40]. Cuts on the electron and muon identification were relaxed to obtain “loose” control samples that are dominated by QCD jets.

The non-QCD background in the zero-lepton final state was estimated using Monte Carlo simulation, while in the case of the one-lepton final state a data-driven technique is employed. This method exploits the low correlation between $m_{\text{eff}}$ and $m_T$. Four regions were defined: (A) $40 < m_T < 100$ GeV and $m_{\text{eff}} < 500$ GeV, (B) $m_T > 100$ GeV and $m_{\text{eff}} < 500$ GeV, (C) $40 < m_T < 100$ GeV and $m_{\text{eff}} > 500$ GeV, and (D) $m_T > 100$ GeV and $m_{\text{eff}} > 500$ GeV. Regions A–C are dominated by background from $t\bar{t}$ and $W +$ jet production. Assuming that the variables are uncorrelated, the number of background events in the signal region is given by $N_D = N_C \times \Delta \phi / \Delta m$, where $N_A, N_B, N_C$ are the numbers of events in the regions A, B and C, respectively. A Monte Carlo simulation was used to validate the method and to establish possible sources of systematic uncertainties. The small number of events in the control regions is the main limitation of the method. It was also checked that a SUSY signal contamination does not bias the estimated background and that any bias is smaller than the systematic uncertainties assigned to the method and on the expected SUSY prediction.

6. Systematic uncertainties

Various systematic uncertainties affecting signal and background rates were considered.

For the zero-lepton analysis, the backgrounds from $t\bar{t}$ and $W/Z +$ jet production are taken from Monte Carlo simulation. The total uncertainty on this prediction was estimated to be $\pm 35\%$ after the final selection. It is dominated by the uncertainty on the jet energy scale (JES) [44], the uncertainty on the theoretical prediction of the background processes and the uncertainty on the determination of the $b$-tagging efficiency [45]. The uncertainty on the jet energy scale varies as a function of jet $p_T$, and decreases from 6% at 20 GeV to 4% at 100 GeV, with additional contributions taking into account the dependence of the jet response on the jet isolation and flavour. This translates into a $\pm 25\%$ uncertainty on the absolute prediction of the background from SM processes.

Uncertainties on the theoretical cross sections of the background processes (see Section 3), on the modelling of initial and final-state soft gluon radiation and the limited knowledge of the PDFs of the proton lead to uncertainties of $\pm 20\%$ and $\pm 25\%$ on the absolute predictions of the $t\bar{t}$ and the $W/Z +$ jet backgrounds, respectively. The uncertainty on the determination of the tagging efficiency for $b$-jets, $c$-jets and light-jets introduces further uncertainties on the predicted background contributions at the level of $\pm 12\%$ for $t\bar{t}$ and $\pm 25\%$ for $W/Z +$ jets. Other uncertainties result from the modelling of additional pile-up interactions ($\pm 5\%$) and of the trigger efficiency ($\pm 3\%$) in the Monte Carlo simulation. For the QCD background estimation, the uncertainty is dominated by the limited number of Monte Carlo events available for the zero-lepton analysis.

For the one-lepton analysis, where a data-driven technique was employed, the small event number in the control regions was the dominant uncertainty ($\pm 25\%$). Residual uncertainties associated to the method due to the JES, $b$-tagging, lepton identification and theoretical predictions of the relative contributions of $W$ and $t\bar{t}$ backgrounds were studied using Monte Carlo simulation and estimated to be at the level of $\pm 8\%$.

For the SUSY signal processes, various sources of uncertainties affect the theoretical NLO cross sections. Variations of the renormalisation and factorisation scales by a factor of two result in uncertainties of $\pm 16\%$ for $q\bar{q}$ production and $\pm 30\%$ ($\pm 27\%$) for $b_1\bar{b}_1$ ($t_1\bar{t}_1$) pair production, almost independently of the sparticle mass and the SUSY model. Uncertainties for $q\bar{q}$ and $g\bar{g}$ production, relevant in MSSM/CMSSM scenarios, were estimated to be at the level of $\pm 10\%$ and $\pm 15\%$, respectively.

The number of predicted signal events is also affected by the PDF uncertainties, estimated using the CTEQ 6.6M PDF error eigenvector sets at the 90% C.L. limit, and rescaled by 1/1.645. The relative uncertainties on the $g\bar{g}$ ($b_1\bar{b}_1$, $t_1\bar{t}_1$) cross sections were estimated to be in the range from $\pm 11\%$ to $\pm 25\%$ ($\pm 7\%$ to $\pm 16\%$) for the $g\bar{g}$ ($b_1\bar{b}_1$, $t_1\bar{t}_1$) processes, depending on the gluino (stop, stop-) masses. For first and second generation squark-pair and associated gluino-squark production, the uncertainty on the PDFs varies between $\pm 5\%$ and $\pm 15\%$ as the squark masses increase. The impact of detector related uncertainties, such as the JES and $b$-tagging, on the signal event yields depends on the masses of the most copiously produced sparticles. The total uncertainty varies between $\pm 25\%$ and $\pm 10\%$ as the gluino/squark masses increase from 300 GeV to 1 TeV, across the different scenarios, and it is dominated by the JES and the $b$-tagging uncertainty for low and high mass sparticles, respectively.

Finally, an additional $\pm 11\%$ uncertainty on the quoted total integrated luminosity was taken into account.

7. Results

In Fig. 1 the distributions of $m_{4\ell}$ and of $E_T^{miss}$ are shown for the two analyses. For the $E_T^{miss}$ distributions all cuts described in Section 4 are applied. The $m_{4\ell}$ distributions are shown after the application of all cuts, except for the $m_{\text{eff}}$ cut.

The expectations from Standard Model background processes are superimposed. For illustration, the figures also include the distributions expected for SUSY signals. For the zero-lepton channel, a scenario with $m_{\tilde{g}} = 500$ GeV and $m_{\tilde{q}} = 380$ GeV is chosen, while for the one-lepton channel the relevant masses are $m_{\tilde{g}} = 400$ GeV and $m_{\tilde{t}} = 210$ GeV. In Table 2, the observed number of events and the predictions for contributions from Standard Model processes are presented. For both analyses, the data are in agreement with the Standard Model predictions, within uncertainties.

The results are translated into 95% C.L. upper limits on contributions from new physics. Limits were derived using a profile likelihood ratio [46,47]. $A(s)$, where the likelihood function of the fit was written as $L(n_\text{s}, b, \theta) = P_s \times C_{\text{Syst}} + n$ represents the number of observed events in data, $s$ is the SUSY signal under consideration, $b$ is the background, and $\theta$ represents the systematic uncertainties. The $P_s$ function is a Poisson-probability distribution for event counts in the defined signal region and $C_{\text{Syst}}$ represents the constraints on systematic uncertainties, which are treated as nuisance parameters with a Gaussian probability density function and correlated when appropriate. The exclusion $p$-values are obtained from the test statistic $A(s)$ using pseudo-experiments. One-sided upper limits are set with the power-constrained limits procedure [48].

Upper limits at 95% C.L. on the number of signal events in the signal regions are obtained independently of new physics models for the zero- and one-lepton final states. These numbers are
Fig. 1. Distributions of the effective mass, $m_{\text{eff}}$ (left) and the $E_{\text{T}}^{\text{miss}}$ (right) for data and for the expectations from Standard Model processes after the baseline selections in the zero-lepton (top) and one-lepton channel (bottom). The data correspond to an integrated luminosity of 35 pb$^{-1}$. Black vertical bars show the statistical uncertainty of the data. The yellow band shows the full systematic uncertainty on the SM expectation. The $E_{\text{T}}^{\text{miss}}$ distributions are shown after a cut on $m_{\text{eff}}$ at 600 GeV (zero-lepton) and 500 GeV (one-lepton). For illustration, the distributions for one reference SUSY signal, relevant for each channel, are superimposed.

Table 2
Summary of the expected and observed event yields. The QCD prediction for the zero-lepton channel is based on the semi-data-driven method described in the text. For the one-lepton channel, the results for both the Monte Carlo and the data-driven approach are given. Since the data-driven technique does not distinguish between top and $W/Z$ backgrounds the total background estimate is shown in the top row. The errors are systematic for the expected Monte Carlo prediction and statistical for the data-driven technique.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Monte Carlo</th>
<th>Data-driven</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-lepton</td>
<td>12.2 ± 5.0</td>
<td>12.3 ± 4.0</td>
</tr>
<tr>
<td>1-lepton</td>
<td>6.0 ± 2.6</td>
<td>0.8 ± 0.4</td>
</tr>
<tr>
<td>QCD</td>
<td>1.4 ± 1.0</td>
<td>0.4 ± 0.4</td>
</tr>
<tr>
<td>Total SM</td>
<td>19.6 ± 6.9</td>
<td>13.5 ± 4.1</td>
</tr>
<tr>
<td>Data</td>
<td>15</td>
<td>9</td>
</tr>
</tbody>
</table>

111 and 5.2, respectively, and correspond to 95% C.L. upper limits on effective cross sections for new processes of 0.32 pb and 0.15 pb for the zero- and one-lepton channel, respectively. These upper limits include the ±11% uncertainty on the quoted total integrated luminosity.

These results can be interpreted in terms of 95% C.L. exclusion limits in several SUSY scenarios. In Fig. 2 the observed and expected exclusion regions are shown in the ($m_{\tilde{g}}$, $m_{\tilde{b}_1}$) plane, for the hypothesis that the lightest squark $\tilde{b}_1$ is produced via gluino-mediated or direct pair production and decays exclusively via $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$. The zero-lepton channel was considered for this model and the largest acceptance was found for $\tilde{g}\tilde{g}$ production. The limits do not strongly depend on the neutralino mass assumption as long as $m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$ is larger than 250–300 GeV, due to the harsh kinematic cuts. Gluino masses below 590 GeV are excluded for sbottom masses up to 500 GeV. These limits depend weakly – via the dependence of the production cross section for $\tilde{g}\tilde{g}$ production – on the masses of the first and second generation squarks, $\tilde{q}_{1,2}$. Variations of these masses in the range between $\sim 3$ TeV and $2 \cdot m_{\tilde{g}}$ reduce the excluded mass region by less than 20 GeV.

The zero-lepton analysis was also employed to extract limits on the gluino mass in the two SO(10) scenarios, DR3 and HS. Gluino masses below 500 GeV are excluded for the DR3 models considered, where $\tilde{g} \rightarrow bb\tilde{\chi}_1^0$ decays dominate. A lower sensitivity ($m_{\tilde{g}} < 420$ GeV) was found for the HS model, where larger branching ratios of $\tilde{g} \rightarrow bb\tilde{\chi}_2^0$ are expected and the efficiency of the selection is reduced with respect to the DR3 case.

The results of the one-lepton analysis were interpreted as exclusion limits on the ($m_{\tilde{g}}$, $m_{\tilde{t}_1}$) plane in the hypothesis that the lightest $\tilde{t}_1$ is produced via gluino-mediated or direct pair production. Stop masses above 130 GeV are considered, and $\tilde{t}_1$ is assumed to decay exclusively via $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$. In Fig. 3 the observed and expected exclusion limits are shown as a function of $m_{\tilde{g}}$ for...
two representative values of the stop mass. Gluino masses below 520 GeV are excluded for stop masses in the range between 130 and 300 GeV.

Finally, the results of both analyses were used to calculate 95% C.L. exclusion limits in the MSUGRA/CMSSM framework with large tan $\beta$. Fig. 4 shows the observed and expected limits in the ($m_0$, $m_{1/2}$) plane, assuming $\tan \beta = 40$, and fixing $\mu > 0$ and $A_0 = 0$. The largest sensitivity is found for the zero-lepton analysis, on the gluino-mediated and direct production of sleptons and stops, the supersymmetric partners of the third generation quarks, which, due to mixing effects, might be the lightest squarks.

Since no excess above the expectations from Standard Model processes was found, the results are used to exclude parameter regions in various $R$-parity conserving SUSY models. Under the assumption that the lightest squark $b_1$ is produced via gluino-mediated processes or direct pair production and decays exclusively via $b_1 \rightarrow b \tilde{\chi}_1^0$, gluino masses below 590 GeV are excluded with 95% C.L. up to sbottom masses of 500 GeV. Alternatively, assuming that $\tilde{t}_1$ is the lightest squark and the gluino decays exclusively via $\tilde{g} \rightarrow \tilde{t}_1 t$, $\tilde{t}_1 \rightarrow b \tilde{\chi}_1^+$, gluino masses below 520 GeV are excluded for stop masses in the range between 130 and 300 GeV.

In specific models based on the gauge group SO(10), gluinos with masses below 500 GeV and 420 GeV are excluded for the DR3 and HS models, respectively.

In an MSUGRA/CMSSM framework with large $\tan \beta$, a significant region in the ($m_0$, $m_{1/2}$) plane can be excluded. For the parameters $\tan \beta = 40$, $A_0 = 0$ and $\mu > 0$, sbottom masses below 550 GeV and stop masses below 470 GeV are excluded with 95% C.L.
masses below 500 GeV are excluded for the $m_Q$ range between 100 GeV and 1 TeV, independently on the squark masses.

These analyses improve significantly on the regions of SUSY parameter space excluded by previous experiments that searched for similar scenarios.

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CF, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSM CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; ARTEMIS, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Georgia; BMBF, DFG, MPG and AvH Foundation, Germany; GSRT, Greece; INFN, Italy; FOM and NWO, Netherlands; INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

Open access

This article is published Open Access at sciencedirect.com. It is distributed under the terms of the Creative Commons Attribution License 3.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original authors and source are credited.

References


ATLAS Collaboration

1 University at Albany, Albany, NY, United States
2 Department of Physics, University of Alberta, Edmonton, AB, Canada
3 [a] Department of Physics, Ankara University, Ankara; [b] Department of Physics, Dumlupinar University, Kütahya; [c] Department of Physics, Gaziantep University, Ankara; [d] Division of Physics, TOBB University of Economics and Technology, Ankara; [e] Turkish Atomic Energy Authority, Ankara, Turkey
4 LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
5 High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States
6 Department of Physics, University of Arizona, Tucson, AZ, United States
7 Department of Physics, The University of Texas at Arlington, Arlington, TX, United States
8 Physics Department, University of Athens, Athens, Greece
9 Physics Department, National Technical University of Athens, Zografou, Greece
10 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
11 Instituto de Física de Altes Energies and Universitat Autònoma de Barcelona and ICEFA, Barcelona, Spain
12 [a] Institute of Physics, University of Belgrade, Belgrade; [b] Vinca Institute of Nuclear Sciences, Belgrade, Serbia
13 Department for Physics and Technology, University of Bergen, Bergen, Norway
14 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States
15 Department of Physics, Humboldt University, Berlin, Germany
16 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
17 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
18 [a] Department of Physics, Bogazici University, Istanbul; [b] Division of Physics, Bogazici University, Istanbul; [c] Department of Physics Engineering, Gaziantep University, Gaziantep; [d] Department of Physics, Istanbul Technical University, Istanbul, Turkey
19 [a] INFN Sezione di Bologna; [b] Dipartimento di Fisica, Università di Bologna, Bologna, Italy
20 Physikalisches Institut, University of Bonn, Bonn, Germany
21 Department of Physics, Boston University, Boston, MA, United States
22 Department of Physics, Brandeis University, Waltham, MA, United States
23 [a] Universidade Federal do Rio de Janeiro COPPE/EE/FEEC; [b] Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
24 Physics Department, Brookhaven National Laboratory, Upton, NY, United States
25 [a] National Institute of Physics and Nuclear Engineering, Bucharest; [b] University Politehnica Bucharest, Bucharest; [c] West University in Timisoara, Timisoara, Romania
26 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
27 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
28 Department of Physics, Carleton University, Ottawa, ON, Canada
29 CERN, Geneva, Switzerland
30 Enrico Fermi Institute, University of Chicago, Chicago, IL, United States
31 [a] Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; [b] Departamento de Fisica, Universidad Técnica Federico Santa María, Valparaiso, Chile
32 [a] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; [b] Department of Modern Physics, University of Science and Technology of China, Anhui, China; [c] Department of Physics, Nanjing University, Jiangsu; [d] High Energy Physics Group, Shanghai Jiao Tong University, Shanghai, China
33 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France
34 Nevis Laboratory, Columbia University, Irvington, NY, United States
35 Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
36 [a] INFN Sezione di Cosenza; [b] Dipartimento di Fisica, Università della Calabria, Arcavacata di Rende, Italy
37 Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland
38 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
39 Physics Department, Southern Methodist University, Dallas, TX, United States
40 Physics Department, University of Texas at Dallas, Richardson, TX, United States
41 DESY, Hamburg and Zeuthen, Germany
42 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
43 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
44 Department of Physics, Duke University, Durham, NC, United States
45 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
46 Fachhochschule Wiener Neustadt, Wiener Neustadt, Austria
47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
49 Section de Physique, Université de Genève, Geneva, Switzerland
50 [a] INFN Sezione di Genova; [b] Dipartimento di Fisica, Università di Genova, Genova, Italy
51 Institute of Physics and HEP Institute, Georgian Academy of Sciences and Tbilisi State University, Tbilisi, Georgia
52 II Physikalisches Institut, Justus-Liebig-Universität Gießen, Gießen, Germany
53 SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
54 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
55 Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
56 Department of Physics, Hampton University, Hampton, VA, United States
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States
58 [a] Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [b] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [c] ZITI Institut für Technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
59 Faculty of Science, Hiroshima University, Hiroshima, Japan
60 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
61 Department of Physics, Indiana University, Bloomington, IN, United States
62 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
63 University of Iowa, Iowa City, IA, United States
64 Department of Physics and Astronomy, Iowa State University, Ames, IA, United States
65 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
66 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
67 Graduate School of Science, Kobe University, Kobe, Japan
68 Faculty of Science, Kyoto University, Kyoto, Japan
69 Kyoto University of Education, Kyoto, Japan
70 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
71 Physics Department, Lancaster University, Lancaster, United Kingdom
72 [a] INFN Sezione di Lecce; [b] Dipartimento di Fisica, Università del Salento, Lecce, Italy
73 Qifer Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
Also at Laboratoire de Instrumentacao e Fisica Experimental de Particulas – LIP, Lisboa, Portugal.

Also at Faculdade de Ciencias and CFNUI, Universidade de Lisboa, Lisboa, Portugal.

Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

Also at TRIUMF, Vancouver, BC, Canada.

Departament de Fisica, Universitat de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain

Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

Department of Physics, University of British Columbia, Vancouver, BC, Canada

Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada

Waseda University, Tokyo, Japan

Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

Department of Physics, University of Wisconsin, Madison, WI, United States

Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany

Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany

Department of Physics, Yale University, New Haven, CT, United States

Yerevan Physics Institute, Yerevan, Armenia

Department of Physics, University of Illinois, Urbana, IL, United States

Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain

Department of Physics, University of British Columbia, Vancouver, BC, Canada

Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada

Waseda University, Tokyo, Japan

Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

Department of Physics, University of Wisconsin, Madison, WI, United States

Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany

Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany

Department of Physics, Yale University, New Haven, CT, United States

Yerevan Physics Institute, Yerevan, Armenia

Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

Also at Laboratory of Instrumentation and Physics – LIP, Lisbon, Portugal.

Also at Faculdade de Ciencias and CFNUI, Universidade de Lisboa, Lisboa, Portugal.

Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

Also at TRIUMF, Vancouver, BC, Canada.

Also at Department of Physics, California State University, Fresno, CA, United States.

Also at Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland.

Also at Department of Physics, University of Coimbra, Coimbra, Portugal.

Also at Università di Napoli Parthenope, Napoli, Italy.

Also at Institute of Particle Physics (IPP), Canada.

Also at Louisiana Tech University, Ruston, LA, United States.

Also at Group of Particle Physics, University of Montreal, Montreal, QC, Canada.

Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

Also at Manhattan College, New York NY, United States.

Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.

Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

Also at High Energy Physics Group, Shandong University, Shandong, China.

Also at California Institute of Technology, Pasadena, CA, United States.

Also at Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.

Also at Section de Physique, Université de Genève, Geneva, Switzerland.

Also at Departamento de Física, Universidade de Minho, Braga, Portugal.

Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.

Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.

Also at Institute of Physics, Jagiellonian University, Krakow, Poland.

Also at Department of Physics, Oxford University, Oxford, United Kingdom.

Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique), Gif-sur-Yvette, France.

Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.

Also at Department of Physics, Nanjing University, Jiangsu, China.

* Deceased.