Title
Search for supersymmetry in pp collisions at √s=7 TeV in final states with missing transverse momentum and b-jets

Permalink
https://escholarship.org/uc/item/9208z1fr

Journal
Physics Letters, Section B: Nuclear, Elementary Particle and High-Energy Physics, 701(4)

ISSN
0370-2693

Authors
Aad, G
Abbott, B
Abdallah, J
et al.

Publication Date
2011-07-18

DOI
10.1016/j.physletb.2011.06.015

License
CC BY 4.0

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

ATLAS Collaboration

ARTICLE INFO

Article history:
Received 23 March 2011
Received in revised form 25 May 2011
Accepted 7 June 2011
Available online 16 June 2011
Editor: H. Weerts

Keywords:
Supersymmetry
ATLAS
LHC
Stop
Gluino

ABSTRACT

Results are presented of a search for supersymmetric particles in events with large missing transverse momentum and at least one heavy flavour jet candidate in $\sqrt{s} = 7$ TeV proton–proton collisions. In a data sample corresponding to an integrated luminosity of 35 pb$^{-1}$ recorded by the ATLAS experiment at the Large Hadron Collider, no significant excess is observed with respect to the prediction for Standard Model processes. For $R$-parity conserving models in which sbottoms (stops) are the only squarks to appear in the gluino decay cascade, gluino masses below 590 GeV (520 GeV) are excluded at the 95% C.L. The results are also interpreted in an MSUGRA/CMSSM supersymmetry breaking scenario with $\tan\beta = 40$ and in an SO(10) model framework.

© 2011 CERN. Published by Elsevier B.V. Open access under CC BY-NC-ND license.

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 $\tilde{g} \rightarrow \tilde{b}_1 b$ or $\tilde{g} \rightarrow \tilde{t}_1 t$ 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 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], stop [10,11] 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 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 stop is the lightest squark, and all other squarks are heavier than the gluino, and \( m_{\tilde{g}} > m_{\tilde{b}} > m_{\tilde{\ell}^0} \), such that the branching ratio for \( \tilde{g} \to \tilde{b} \tilde{\ell} \) decays is 100\%. Sbottoms are produced via gluino-mediated processes or via direct pair production. They are assumed to decay exclusively via \( \tilde{b} \to b \tilde{\chi}_1^0 \), where \( m_{\tilde{b}} \) 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 \( E_{\text{T}}^{\text{miss}} \) 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 \( m_{\tilde{g}} > m_{\tilde{b}} \). If the stop decay channel \( \tilde{t}_1 \to b \tilde{\chi}_1^\pm \) dominates, possible subsequent \( \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \tilde{\ell}^\mp \) decays result in experimental signatures with energetic charged leptons in addition to b-jets and \( E_{\text{T}}^{\text{miss}} \). In the present analysis, only \( g\tilde{g} \) and \( t_1\tilde{t}_1 \) pair production are considered, with 100\% branching ratios for the \( \tilde{g} \to t_1\tilde{t}_1 \) and \( t_1 \to b \tilde{\chi}_1^\pm \) decays. The chargino is assumed to have a mass \( m_{\tilde{\chi}_1^\pm} \approx 2 \cdot m_{\tilde{\ell}^0} \), with \( m_{\tilde{\ell}^0} = 60 \text{ GeV} \), and to decay through a virtual W boson (BR(\( \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \tilde{\ell}^\pm \)) = 11\%).

In addition to the aforementioned phenomenological MSSM models, the results are interpreted in the framework of minimal supergravity (MSUGRA/CMSSM [15]) and in specific Grand Unification Theories (GUTs) based on the gauge group SO(10) [16]. For MSUGRA/CMSSM, limits on the universal scalar and gaugino mass parameters \((m_0, m_{1/2})\) are presented for fixed values of the ratio of the Higgs vacuum expectation value, \( \tan \beta = 40 \), the common trilinear coupling at the GUT scale \( \Lambda_0 = 0 \text{ GeV} \), and the sign of the Higgsino mixing parameter \( \mu > 0 \). Taking large values of \( \tan \beta \) or negative values of \( \Lambda_0 \), with other model parameters held fixed leads to lower third generation sparticle masses compared to those of the other sparticles. Depending on \( m_0 \) and \( m_{1/2} \), any of the final states such as \( q\tilde{q}, g\tilde{g} \) and \( g\tilde{g} \) might be dominant. In the SO(10) scenario, the SUSY particle mass spectrum is characterised by the low masses of the gluinos (300–600 GeV), charginos (100–180 GeV) and neutralinos (50–90 GeV), whereas all scalar particles have masses beyond the TeV scale. Depending on the sparticle masses, chargino–neutralino and gluino-pair production dominate.

2. The ATLAS detector

The ATLAS detector [18] comprises an inner detector surrounded by a thin superconducting solenoid, and a calorimeter system. Outside the calorimeters is an extensive muon spectrometer in a toroidal magnetic field.

The inner detector system is immersed in a 2 T axial magnetic field and provides tracking information for charged particles in a pseudorapidity range \(|\eta| < 2.5\)\(^3\). The highest granularity is achieved around the vertex region using silicon pixel and microstrip detectors. These detectors allow for an efficient tagging of jets originating from b-quark decays using impact parameter measurements and the reconstruction of secondary decay vertices. The transition radiation tracker, which surrounds the silicon detectors, contributes to track reconstruction up to \(|\eta| = 2.0\) and improves the electron identification by the detection of transition radiation.

The calorimeter system covers the pseudorapidity range \(|\eta| < 4.9\). The highly segmented electromagnetic calorimeter consists of lead absorbers with liquid argon as the active material and covers the pseudorapidity range \(|\eta| < 3.2\). In the region \(|\eta| < 1.8\), a presampler detector consisting of a thin layer of liquid argon is used to correct for the energy lost by electrons, positrons, and photons upstream of the calorimeter. The hadronic tile calorimeter is a steel/scintillating-tile detector and is placed directly outside the envelope of the electromagnetic calorimeter. In the forward regions, it is complemented by two end-cap calorimeters using liquid argon as active material and copper or tungsten as absorber material.

Muon detection is based on the magnetic deflection of muon tracks in the large superconducting air-core toroid magnets, instrumented with separate trigger and high-precision tracking chambers. A system of three toroids, a barrel and two end-caps, generates the magnetic field for the muon spectrometer in the pseudorapidity range \(|\eta| < 2.7\).

3. Simulated event samples

Simulated event samples were used to determine the detector acceptance, the reconstruction efficiencies and the expected event yields for signal and background processes.

SUSY signal processes were generated for various models using the HERWIG++ [19] v2.4.2.2 Monte Carlo program. The particle mass spectra and decay modes were determined using the ISASUSY from ISAJET [20] v7.80 and SUSYHIT [21] v1.3 programs. The latter was used for the assumed MSSM scenarios, which are parametrised in the \((m_3, m_{\tilde{g}}, m_{\tilde{\chi}_1^0})\) planes, with gluino masses above 300 GeV. The SUSY sample yields were normalised to the results of next-to-leading order (NLO) calculations, as obtained using the PROSPECT [22] v2.1 program. For these calculations the CTEQ6.6M [23] parametrisation of the parton density functions (PDFs) was used and the renormalisation and factorisation scales were set to the average mass of the sparticles produced in the hard interaction.

For the backgrounds the following Standard Model processes were considered:

- \( t\bar{t} \) and single top production: events were generated using the generator MC@NLO [31,32] v3.41. For the evaluation of systematic uncertainties, additional \( t\bar{t} \) samples were generated using the POWHEG [33] and ACERMC [34] programs.
- \( W(\to \ell\nu) + \text{jet}, Z(\to \ell\ell') + \text{jet} \) (where \( \ell, \ell' = e, \mu, \tau \) and \( Z(\to \ell\ell') + \text{jet} \) production: events with light and heavy (b) flavour jets were generated using the ALPGEN [35] v2.13 program. A generator level cut \( m_{\ell\ell} > 40 \text{ GeV} \) was applied to the \( Z/\gamma^* \to \ell\ell' \) process.
- Jet production via QCD processes (referred to as “QCD background” in the following): events were generated using the PYTHIA [30] v6.4.21 generator. For the evaluation of systematic uncertainties, samples produced with ALPGEN were used.
- Di-boson \((WW, WZ \text{ and } ZZ) \) production: events were generated using ALPGEN, however, compared to the other backgrounds their contribution was found to be negligible, after the application of the selection criteria.

All signal and background samples were generated at \( \sqrt{s} = 7 \text{ TeV} \) using the ATLAS MC09 parameter tune [36], processed with the GEANT4 [37] simulation of the ATLAS detector [38], and then reconstructed and passed through the same analysis chain as the data. For all generators, except for PYTHIA, the HERWIG + JIMMY [19,39] modelling of the parton shower and underlying event was used (v6.510 and v4.31, respectively).
The most important background processes and their production cross sections, multiplied by the relevant branching ratios (BR). Contributions from higher order QCD corrections are included for $W$ and $Z$ boson production (NNLO corrections) and for $t\bar{t}$ production (NNLO + NNLL corrections). The inclusive QCD jet cross section is given at leading order (LO). The QCD sample was generated with a cut on the transverse momentum of the partons involved in the hard-scattering process, $p_T$.

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 $Z/\gamma^*\gamma^*$ production cross sections, an uncertainty of ±5% is assumed [40]. For the $t\bar{t}$ production cross section, the corresponding uncertainty on the NLO + NNLL (next-to-next-to-leading logarithms) cross section was estimated to be ±6.2%. For the QCD background, no reliable prediction can be obtained from a leading order Monte Carlo simulation and data-driven methods were used to determine the residual contributions of this background to the selected event samples, as discussed in Section 5.

4. Data and event selection

After the application of beam, detector and data-quality requirements, the data set used for this analysis resulted in a total integrated luminosity of 35 pb$^{-1}$.

For the zero-lepton analysis, events were selected at the trigger level by requiring jets with high transverse momentum. The selection is fully efficient for events containing at least one jet with $p_T > 120$ GeV. A further trigger level requirement of $E_T^{miss} > 25$ GeV was 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 data sample selected, jet candidates 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.

4. Data and event selection

For the zero-lepton analysis, events were selected at the trigger level by requiring jets with high transverse momentum. The selection is fully efficient for events containing at least one jet with $p_T > 120$ GeV. A further trigger level requirement of $E_T^{miss} > 25$ GeV was 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 data sample selected, jet candidates 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.
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 \(\Delta \phi > 0.4\). The Monte Carlo was then used to evaluate the ratio between the number of events in this control region and the signal region \(\Delta \phi < 0.4\). 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 \(m_{\rm{eff}}\) and \(m_T\). Four regions were defined: (A) \(40 < m_T < 100\) GeV and \(m_{\rm{eff}} < 500\) GeV, (B) \(m_T > 100\) GeV and \(m_{\rm{eff}} < 500\) GeV, (C) \(40 < m_T < 100\) GeV and \(m_{\rm{eff}} > 500\) GeV and (D) \(m_T > 100\) GeV and \(m_{\rm{eff}} > 500\) GeV. Regions A–C are dominated by background from \(t\bar{t}\) and \(W + \text{jet}\) production. Assuming that the variables are uncorrelated, the number of background events in the signal region is given by

\[
N_{\text{b}} = N_{\text{C}} \times \frac{\theta_{\text{b}}}{\theta_{\text{A}}},
\]

where \(N_{\text{A}}, N_{\text{B}}, N_{\text{C}}\) 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 \(W/Z + \text{jet}\) 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 \(W/Z + \text{jet}\) 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 \(W/Z + \text{jet}\) backgrounds. 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 \(\pm 8\%\).

The number of predicted signal events is also affected by other 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 \(gg \rightarrow (b\bar{b}, \tau\tau)\) cross sections were estimated to be in the range from \(\pm 15\%\) to \(\pm 25\%\) (\(\pm 7\%\) to \(\pm 16\%\)) for the \(gg \rightarrow (b\bar{b}, \tau\tau)\) processes, depending on the gluino (stotom, stop) mass. 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 particles. 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 squarks, 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 \(m_{\text{eff}}\) 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 \(m_{\text{eff}}\) 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 \(m_3^g = 500\) GeV and \(m_3 = 380\) GeV is chosen, while for the one-lepton channel the relevant masses are \(m_3^g = 400\) GeV and \(m_3 = 210\) 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 \(L(n|s, b, \theta) = P_s \times C_{\text{Syst}}\) for \(s\) the number of observed events in data, \(b\) is the SUSY signal under consideration, \(\theta\) 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 \(\Lambda\)-values are obtained from the test statistic \(A(\theta)\) 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.

|         | 0-lepton Monte Carlo | 1-lepton Monte Carlo | 1-lepton data-driven |
|---------|----------------------|----------------------|----------------------|
| $t\bar{t}$ and single top | 12.2 ± 5.0 | 12.3 ± 4.0 | 14.7 ± 3.7 |
| $W$ and $Z$ | 6.0 ± 2.6 | 0.8 ± 0.4 | - |
| QCD | 1.4 ± 1.0 | 0.4 ± 0.4 | 0.6 ± 0.6 |
| Total SM | 19.6 ± 6.9 | 13.5 ± 4.1 | 14.7 ± 3.7 |
| Data | 15 | 9 | 9 |

11.1 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 $\tilde{b}_1 \rightarrow b \tilde{\chi}^0_1$. 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 $m_{\tilde{g}} - m_{\tilde{\chi}^0_1}$ 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 $\tilde{g} \rightarrow b\bar{b}\tilde{\chi}^0_1$ decays dominate. A lower sensitivity ($m_{\tilde{g}} < 420$ GeV) was found for the HS model, where larger branching ratios of $\tilde{g} \rightarrow b\bar{b}\tilde{\chi}^+_1$ 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 $\tilde{t}_1 \rightarrow b \tilde{\chi}^\pm_1$. In Fig. 3 the observed and expected exclusion limits are shown as a function of $m_{\tilde{g}}$ for 402
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 β. For the zero-lepton analysis, 95% C.L. exclusion limits on the SUSY parameter space, mostly sensitive to sbottom masses, extend the zero-lepton reach by about 20 GeV in the (m_{\tilde{b}_1}, m_{\tilde{g}}) plane. The neutralino mass is assumed to be 60 GeV and the NLO cross sections are calculated using PROSPINO in the hypothesis of m_{\tilde{b}_1} ≫ m_{\tilde{g}}. Theoretical uncertainties on the NLO cross sections are included in the limit calculation.

Changing the assumption that the lightest squark \( t_1 \) is produced via gluino-mediated processes ex-clusively via \( g \rightarrow t_1 \tilde{g} \), gluino masses below 500 GeV lead to significant variations in third generation squark mixing. Across the (m_{\tilde{b}_1}, m_{1/2}) parameter space, sbottom and stop masses decrease by about 10% and 30%, respectively, if A_0 is changed from 0 to −500 GeV. The exclusion region of the one-lepton analysis, mostly sensitive to stop final states, extends the zero-lepton reach by about 20 GeV in m_{1/2} for m_{0} < 600 GeV.

8. Conclusions

The ATLAS Collaboration has presented a first search for supersymmetry in final states with missing transverse momentum and at least one b-jet candidate in proton–proton collisions at 7 TeV. The results are based on data corresponding to an integrated luminosity of 35 pb^{-1} collected during 2010. These searches are sensitive to the gluino-mediated and direct production of sbottoms 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 \( b_1 \rightarrow b \tilde{q}_1 \), gluino masses below 590 GeV are excluded with 95% C.L. up to sbottom masses of 500 GeV. Alternatively, assuming \( t_1 \) is the lightest squark and the gluino decays exclusively via \( g \rightarrow t_1 \tilde{g} \) and \( t_1 \rightarrow b \tilde{q}_1 \), 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 β, a significant region in the (m_{\tilde{b}_1}, m_{1/2}) plane can be excluded. For the parameters tan β = 40, A_0 = 0 and \( \mu > 0 \), sbottom masses below 550 GeV and stop masses below 470 GeV are excluded with 95% C.L. Gluino to first and second generation squarks. From the present analysis, masses of these squarks below 600 GeV are excluded for m_{\tilde{g}} ∼ m_{\tilde{b}}. Gluino masses below 500 GeV are excluded for the m_{0} range between 100 GeV and 1 TeV, independently on the squark masses. Changing the A_0 value from 0 to −500 GeV lead to significant variations in third generation squark mixing. Across the (m_{\tilde{b}_1}, m_{1/2}) parameter space, sbottom and stop masses decrease by about 10% and 30%, respectively, if A_0 is changed from 0 to −500 GeV. The exclusion region of the one-lepton analysis, mostly sensitive to stop final states, extends the zero-lepton reach by about 20 GeV in m_{1/2} for m_{0} < 600 GeV.
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 CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT 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, HGF, MPG and AvH Foundation, Germany; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; MST and RFBR, Russia; MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT, METI, and JSPS, Japan; DOE and NSF, United States of America.

Open access

This article is published Open Access at scientificdirect.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

[1] Yu.A. Goland, E.P. Likhtman, JETP Lett. 713 (1971) 323; A. Neveu, J.H. Schwartz, Nucl. Phys. B 31 (1971) 86; A. Neveu, J.H. Schwartz, Phys. Rev. D 4 (1971) 1109; P. Ramond, Phys. Rev. D 3 (1971) 2415; D.V. Volkov, V.P. Akulov, Phys. Lett. B 46 (1973) 109; J. Wess, B. Zumino, Phys. Lett. B 49 (1974) 52; J. Wess, B. Zumino, Nucl. Phys. B 70 (1974) 39; P. Fayet, Phys. Lett. B 69 (1977) 489; C.R. Farrar, P. Fayet, Phys. Lett. B 76 (1978) 575.

[2] S.P. Martin, arXiv:hep-ph/9700356, 1997.

[3] ATLAS Collaboration, arXiv:0901.0512 [hep-ex], 2009.

[4] CMS Collaboration, J. Phys. G 34 (2007) 995.

[5] ATLAS Collaboration, Phys. Rev. Lett. 106 (2011) 131802.

[6] CMS Collaboration, Phys. Lett. B 698 (2011) 196.

[7] ATLAS Collaboration, arXiv:1102.5290v1 [hep-ex], 2011, Phys. Lett. B, doi:10.1016/j.physletb.2011.05.061, in press.

[8] CDF Collaboration, Phys. Rev. Lett. 105 (2010) 081802.

[9] D0 Collaboration, Phys. Lett. B 693 (2010) 95.

[10] CDF Collaboration, Phys. Rev. D 82 (2010) 092001.

[11] D0 Collaboration, Phys. Lett. B 674 (2009) 4.

[12] CDF Collaboration, Phys. Rev. Lett. 102 (2009) 221801.

[13] ATLAS Collaboration, Eur. Phys. J. C 71 (2011) 1630.

[14] LEP SUSY Working Group (ALEPH, DELPHI, L3, OPAL), Notes LEPSUSYWG/01-03 and 04-011, http://lepsusy.web.cern.ch/lepsusy/Welcome.html.

[15] A.H. Chamseddine, R.L. Arnowitt, P. Nath, Phys. Rev. Lett. 49 (1982) 970; R. Barbieri, S. Ferrara, C.A. Savoy, Phys. Lett. B 119 (1982) 343; L. Ibanez, Phys. Lett. B 118 (1982) 73; L.J. Hall, J.D. Lykken, S. Weinberg, Phys. Rev. D 27 (1983) 2359; N. Obata, Prog. Theor. Phys. 70 (1983) 542 (1982).

[16] M. Gell-Mann, P. Ramond, R. Slansky, Rev. Mod. Phys. 50 (1978) 721.

[17] H. Baer, S. Kraml, A. Lessa, S. Sekmen, JHEP 1002 (2010) 055.

[18] ATLAS Collaboration, JINST 3 (2008) S08003.

[19] G. Corcella, et al., JHEP 0101 (2001) 010.

[20] F.E. Paige, S.D. Protopopescu, H. Baer, X. Tata, arXiv:hep-ph/0312045, 2003.

[21] A. Djouadi, M.M. Muhlleitner, M. Spira, Acta Phys. Polon. B 38 (2007) 635.

[22] W. Beenakker, R. Hopker, M. Spira, arXiv:hep-ph/9611232, 1996.

[23] D. Stump, et al., JHEP 0310 (2003) 046.

[24] R. Hamberg, W.L. van Neerven, T. Matsuura, Nucl. Phys. B 539 (1999) 343; R. Hamberg, W.L. van Neerven, T. Matsuura, Nucl. Phys. B 644 (2002) 403, Erratum.

[25] K. Melnikov, F. Petriello, Phys. Rev. D 74 (2006) 114017.

[26] K. Melnikov, F. Petriello, Phys. Rev. Lett. 96 (2006) 231803.

[27] R. Bonciani, S. Catani, M.L. Mangano, P. Nason, Nucl. Phys. B 529 (1998) 424.

[28] S. Moch, P. Uwer, Phys. Rev. D 78 (2008) 034003.

[29] M. Beneke, M. Czakon, P. Fallsari, A. Mitov, C. Schwinn, Phys. Lett. B 690 (2010) 483.

[30] T. Sjostrand, S. Mrenna, P.Z. Skands, JHEP 0605 (2006) 026.

[31] S. Frixione, B. Webber, arXiv:hep-ph/0601192, 2006.

[32] S. Frixione, P. Nason, B.R. Webber, JHEP 0308 (2003) 007.

[33] S. Frixione, et al., JHEP 0711 (2007) 070.

[34] B.P. Kersevan, E. Richter-Was, arXiv:hep-ph/0405247, 2004.

[35] M. Mangano, et al., JHEP 0307 (2003) 001.

[36] ATLAS Collaboration, ATL-PHYS-PUB-2010-002 (2010).

[37] GEANT4 Collaboration, S. Agostinelli, et al., Nucl. Instrum. Meth. A 506 (2003) 250.

[38] ATLAS Collaboration, Eur. Phys. J. C 70 (2010) 823.

[39] J. Butterworth, J.R. Forshaw, M. Seymour, Z. Phys. C 72 (1996) 637.

[40] ATLAS Collaboration, JHEP 1012 (2010) 060.

[41] D. Casadei, et al. ATLAS-DAQ-PUB-2011-001 (2011).

[42] M. Cacciari, G. Salam, G. Soyez, JHEP 0804 (2008) 063.

[43] M. Cacciari, G.P. Salam, Phys. Lett. B 641 (2006) 57.

[44] ATLAS Collaboration, ATL-CONF-2011-007 (2011).

[45] ATLAS Collaboration, Eur. Phys. J. C 71 (2011) 1577.

[46] ATLAS Collaboration, arXiv:0901.0512 [hep-ex], 2009, p. 1480.

[47] C. Cowan, et al., Eur. Phys. J. C 71 (2011).

[48] ATLAS Collaboration / Physics Letters B 701 (2011) 398–416
74 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
75 Department of Physics, Queen Mary University of London, London, United Kingdom
76 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
77 Department of Physics and Astronomy, University College London, London, United Kingdom
78 Laboratoire de Physique Nucleaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
79 Fysiska institutionen, Lund university, Lund, Sweden
80 Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
81 Institut für Physik, Universität Mainz, Mainz, Germany
82 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
83 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
84 Department of Physics, University of Massachusetts, Amherst, MA, United States
85 Department of Physics, McGill University, Montreal, QC, Canada
86 School of Physics, University of Melbourne, Victoria, Australia
87 Department of Physics, The University of Michigan, Ann Arbor, MI, United States
88 Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States
89 (a) INFN Sezione di Milano, (b) Dipartimento di Fisica, Università di Milano, Milano, Italy
90 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
91 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus
92 Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, United States
93 Group of Particle Physics, University of Montreal, Montreal, QC, Canada
94 P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
95 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
96 Moscow Engineering and Physics Institute (MIPT), Moscow, Russia
97 Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
98 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
99 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
100 Nagasaki Institute of Applied Science, Nagasaki, Japan
101 Graduate School of Science, Nagoya University, Nagoya, Japan
102 (a) INFN Sezione di Napoli, (b) Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
103 Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States
104 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
105 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
106 Department of Physics, Northern Illinois University, Dekalb, IL, United States
107 Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia
108 Department of Physics, New York University, New York, NY, United States
109 Ohio State University, Columbus, OH, United States
110 Faculty of Science, Okayama University, Okayama, Japan
111 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States
112 Department of Physics, Oklahoma State University, Stillwater, OK, United States
113 Palacký University, KCPM, Olomouc, Czech Republic
114 Center for High Energy Physics, University of Oregon, Eugene, OR, United States
115 LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France
116 Graduate School of Science, Osaka University, Osaka, Japan
117 Department of Physics, University of Oslo, Oslo, Norway
118 Department of Physics, Oxford University, Oxford, United Kingdom
119 (a) INFN Sezione di Pavia; (b) Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy
120 Department of Physics, Pennsylvania State University, University Park, PA, United States
121 Petersburg Nuclear Physics Institute, Gatchina, Russia
122 (a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
123 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States
124 (a) Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa, Portugal; (b) Departamento de Fisica Teorica y del Cosmos y CAIFPE, Universidad de Granada, Spain
125 Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
126 Faculty of Mathematics and Physics, Charles University in Prague, Prague, Czech Republic
127 Czech Technical University in Prague, Prague, Czech Republic
128 State Research Center Institute for High Energy Physics, Protvino, Russia
129 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
130 Physics Department, University of Regina, Regina, SK, Canada
131 Ritsumeikan University, Kusatsu, Shiga, Japan
132 (a) INFN Sezione di Roma I; (b) Dipartimento di Fisica, Università La Sapienza, Roma, Italy
133 (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
134 (a) INFN Sezione di Roma Tre; (b) Dipartimento di Fisica, Università Roma Tre, Roma, Italy
135 (a) Faculté des Sciences Am Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (b) Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat; (c) Université Cadi Ayyad, Faculté des sciences Semlalia Département de Physique, B.P. 2390 Marrakech 40000; (d) Faculté des Sciences, Université Mohamed Premier and LIPTPM, Oujda; (e) Faculté des Sciences, Université Mohamed V, Rabat, Morocco
136 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France
137 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States
138 Department of Physics, University of Washington, Seattle, WA, United States
139 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
140 Department of Physics, Shinshu University, Nagano, Japan
141 Fachbereich Physik, Universität Siegen, Siegen, Germany
142 Department of Physics, Simon Fraser University, Burnaby, BC, Canada
143 CLAC National Accelerator Laboratory, Stanford, CA, United States
144 (a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Košice, Slovak Republic
145 (a) Department of Physics, University of Johannesburg, Johannesburg; (b) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
146 (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
147 Physics Department, Royal Institute of Technology, Stockholm, Sweden
148 Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY, United States
