Search for supersymmetry in events with photons, bottom quarks, and missing transverse momentum in proton–proton collisions at a centre-of-mass energy of 7

The MIT Faculty has made this article openly available. Please share how this access benefits you. Your story matters.

| As Published | http://dx.doi.org/10.1016/j.physletb.2013.01.041 |
| Publisher | Elsevier |
| Version | Final published version |
| Accessed | Wed Mar 13 02:28:47 EDT 2019 |
| Citable Link | http://hdl.handle.net/1721.1/91892 |
| Terms of Use | Article is made available in accordance with the publisher’s policy and may be subject to US copyright law. Please refer to the publisher’s site for terms of use. |
| Detailed Terms | |
Search for supersymmetry in events with photons, bottom quarks, and missing transverse momentum in proton–proton collisions at a centre-of-mass energy of 7 TeV with the ATLAS detector

ATLAS Collaboration

A search has been performed for the experimental signature of an isolated photon with high transverse momentum, at least one jet identified as originating from a bottom quark, and high missing transverse momentum. Such a final state may originate from supersymmetric models with gauge-mediated supersymmetry breaking in events in which one of a pair of higgsino-like neutralinos decays into a photon and a gravitino while the other decays into a Higgs boson and a gravitino. The search is performed using the full dataset of 7 TeV proton–proton collisions recorded with the ATLAS detector at the LHC in 2011, corresponding to an integrated luminosity of 4.7 fb$^{-1}$. A total of 7 candidate events are observed while 7.5 ± 2.2 events are expected from the Standard Model background. The results of the search are interpreted in the context of general gauge mediation to exclude certain regions of a benchmark plane for higgsino-like neutralino production.

© 2013 CERN. Published by Elsevier B.V. All rights reserved.

1. Introduction

Theories of gauge-mediated supersymmetry breaking (GMSB) presume a hidden sector in which supersymmetry is broken and the symmetry breaking is communicated to the visible sectors through Standard Model gauge boson interactions [1–6]. Such theories are attractive because the hypothesis of an intermediate hidden sector suppresses the magnitude of flavour-changing neutral currents. The lightest supersymmetric particle (LSP) in GMSB is the ultra-light gravitino ($\tilde{G}$), which under certain circumstances is a viable dark matter candidate [7]. The next-to-lightest supersymmetric particle (NLSP) may be the lightest neutralino $\tilde{\chi}_1^0$, often assumed to be a bino-like particle. The bino is the supersymmetric partner of the U(1) gauge field, coupling to the photon and Z boson with strengths that are determined by the weak mixing angle. This results in the $\tilde{\chi}_1^0$ decaying predominantly to a photon and the LSP. The classical signature of GMSB is, therefore, events with two isolated energetic photons and large missing transverse momentum ($E_T^{\text{miss}}$). Searches for such a signature at the LHC and the Tevatron established strong experimental constraints on GMSB models [8,5]. Recent extensions of the original GMSB idea, known as general gauge mediation (GGM) [10], evade these limits by allowing decoupled mass scales for strongly-interacting supersymmetric partners of the Standard Model particles.

In the GGM models considered in this Letter, the neutralino has higgsino or neutral wino (supersymmetric partners of the Higgs and neutral W bosons) components instead of being predominantly bino-like, and therefore, in addition to its conventional decay to a gravitino and a photon, it may decay to a gravitino and a Higgs boson or to a gravitino and a Z boson. This GGM signature could be identified as an excess of events with pairs of neutralinos decaying to these bosons, in all combinations, associated with high $E_T^{\text{miss}}$ [11]. In particular, for a light Higgs boson ($m_h < 130$ GeV), which decays predominantly to $bb$, one final-state signature is the combination of an isolated high transverse momentum ($p_T$) photon, jets originating from bottom quarks, and high $E_T^{\text{miss}}$. Such a signature arises when one neutralino decays to a gravitino and a photon and the other to a gravitino and a Higgs boson. This decay mode is therefore significant when both branching fractions are large, namely when the bino mass term $M_1$ approximately equals the higgsino mass parameter $-\mu$ [1].

This Letter describes the search for events with a "$\gamma + b + E_T^{\text{miss}}$ topology", consisting of an isolated high-$p_T$ photon, large $E_T^{\text{miss}}$, and at least one jet that contains a $b$-hadron ("$b$-tagged jet"), in the full dataset of $\sqrt{s} = 7$ TeV pp collisions recorded in 2011 with the ATLAS detector at the LHC, corresponding to a total integrated luminosity of 4.7 fb$^{-1}$. This signature is complementary to searches for diphoton production accompanied by $E_T^{\text{miss}}$ [12,13], searches for $b$-jet production plus $E_T^{\text{miss}}$ [14,15], searches for lepton production plus $E_T^{\text{miss}}$ [16], and searches for Z bosons accompanied by photons and $E_T^{\text{miss}}$ [17]. The $\gamma + b + E_T^{\text{miss}}$ topology has not been
studied in any previous search and therefore the present analysis can also be considered as a model-independent search for new phenomena in this final state.

2. ATLAS detector

The ATLAS experiment [18] is a multi-purpose particle physics detector with a forward–backward symmetric cylindrical geometry and nearly 4π coverage in solid angle. The collision point is surrounded by inner tracking devices followed by a superconducting solenoid providing a 2 T magnetic field, a calorimeter system, and a muon spectrometer. The inner tracker provides precision tracking of charged particles for pseudorapidities \( |\eta| < 2.5 \). It consists of pixel and silicon microstrip detectors inside the transition radiation tracker. The calorimeter system has liquid argon (LAr) or scintillator tiles as the active media. In the pseudorapidity region \( |\eta| < 3.2 \), high-granularity LAr electromagnetic (EM) sampling crystals are used. An iron/scintillator tile calorimeter provides hadronic coverage for \( |\eta| < 1.7 \). The end-cap and forward regions, spanning 1.5 < \( |\eta| < 4.9 \), are instrumented with LAr calorimeters for both EM and hadronic measurements. The muon spectrometer consists of three large superconducting toroids with 24 coils, a system of trigger chambers, and precision tracking chambers, which provide triggering and tracking capabilities in the ranges \( |\eta| < 2.4 \) and \( |\eta| < 2.7 \), respectively.

3. Simulated samples

Standard Model processes that constitute the background to this search are simulated using several different generator programs. Events with single- or pair-production of top quarks are simulated using the MC@NLO [19] generator with the CT10 [20] parton distribution functions (PDFs), where the generator is interfaced to the HERWIG [21] and JIMMY [22] programs to include effects of fragmentation and hadronization and the underlying event. The POWHEG generator [23–25] is also used for studies of systematics in these events. The \( t\bar{t}\gamma \) background is simulated with the WHIZARD [26] generator, which incorporates a full calculation of the seven-particle final states \( \ell vq\ell'q'\ell''b\ell''b' \) and \( \ell v\ell'v'b\ell'b' \) (with \( \ell/\ell' = e, \mu, \tau \)) at leading order (LO). These events are generated with the CTEQ6L1 [27] PDFs and hadronized with HERWIG; additional photon(s) that may be radiated in the fragmentation process are generated by PHOTOS [28]. Multijet background ("QCD multijet") events are simulated using the PYTHIA [29] generator. Diboson background events (\( W^+W^-, W^+Z, \) and \( ZZ \)) are simulated using HERWIG. Events with vector bosons accompanied by \( b\bar{b} \) or light jets are simulated using ALPGEN [30] and HERWIG [21].

The production of signal events is simulated in two separate two-dimensional benchmark grids of points defined by specific GGM model parameters. The first grid has various gluino and neutralino masses (\( m_{\tilde{g}}, m_{\tilde{\chi}^o_1} \)), while the second grid has varying squark and neutralino masses (\( m_{\tilde{q}}, m_{\tilde{\chi}^o_1} \)). The fundamental parameters \( M_1 \) and \( \mu \) together determine the lightest neutralino mass and are adjusted in such a way that the following branching ratios of the \( \tilde{\chi}^0_1 \) are approximately constant: \( BR(\tilde{\chi}^0_1 \to h + \tilde{\chi}^0_1) \approx 56\% \), \( BR(\tilde{\chi}^0_1 \to \gamma + \tilde{\chi}^0_1) \approx 33\% \), and \( BR(\tilde{\chi}^0_1 \to Z + \tilde{\chi}^0_1) \approx 11\% \). These numbers vary by ±2% throughout the grids. The value of \( \mu \) is chosen to be negative in order to make the branching ratio of the \( \tilde{\chi}^0_1 \) to the lightest Higgs boson greater than that to the Z boson. Masses of the sleptons and coloured supersymmetric particles not to make the grid are set to 2.5 TeV, and the lightest Higgs boson is in the decoupled regime with \( m_h = 2 \) TeV and \( m_0 = 115 \) GeV, which results in a branching ratio \( BR(h \to bb) = 74\% \). Other parameters are the wino mass \( M_2 = 2.5 \) TeV, the ratio of Higgs doublet vacuum expectation values \( \tan\beta = 1.5 \), and the neutralino decay length \( \tau r < 0.25 \) mm. The small effect of a different choice of Higgs boson mass, \( m_H = 125 \) GeV, is discussed in Section 9. More generally, different choices of these parameters can modify slightly the relevant branching ratios but do not affect significantly the overall sensitivity reach for models of gauge mediation. The full mass spectrum and decay widths are calculated using SUJet, SDECAY, and HDECAY with the SUSY-HIT interface [31]. Events are generated with Herwig++ [32].

The signal production rate is dominated at high neutralino masses by strong production of gluinos and squarks, but at low neutralino masses the direct production of charginos and neutralinos is greatly enhanced. Signal cross sections are calculated to next-to-leading order in the strong coupling constant (NLO) using PROSPINO2 [33]. The nominal cross section and its uncertainty are taken from an envelope of cross-section predictions using different PDF sets and factorization and renormalization scales, as described in Ref. [38]. The PDF sets used for those calculations are CTEQ6.6M [39] and MSTW2008NLO [40].

Monte Carlo simulated event samples are generated with multiple pp interactions (pile-up) and are re-weighted by matching the distribution of the number of interactions per bunch crossing to that observed in the data. The samples are passed through the GEANT4 [41,42] simulation of the ATLAS detector and the same reconstruction software used for the data.

4. Event reconstruction

Jets are reconstructed from calibrated clustered energy deposits in the calorimeter using the anti-\( k_T \) jet clustering algorithm [43] with radius parameter \( R = 0.4 \). Clusters of calorimeter cells are seeded by cells with energy significantly above the measured noise. Jet energies are corrected for the effects of calorimeter non-compensation and inhomogeneities using \( p_T \)- and \( \eta \)-dependent calibration factors based on Monte Carlo simulations validated with extensive test-beam and collision-data studies [44]. Reconstructed jets with \( p_T > 20 \) GeV and \( |\eta| < 2.8 \) are used in this analysis.

A multivariate \( b \)-tagging algorithm that exploits both impact parameter and secondary vertex information is used to identify jets with \( |\eta| < 2.5 \) containing a b-hadron [45]. The working point used in this analysis has a 60% efficiency on a sample of b-jets from simulated \( t\bar{t} \) events, with typical misidentification rates of 12% for c-jets and less than 0.2% for light-quark/gluon jets with \( p_T > 20 \) GeV and \( |\eta| < 2.5 \).

A photon candidate must have transverse momentum \( p_T > 20 \) GeV and must fulfill a set of "tight" identification requirements [46]. Moreover, the cluster associated with the photon should have \( |\eta| < 2.37 \) and should not be in the transition region between the barrel and end-cap calorimeters (1.37 < \( |\eta| \) < 1.52). An isolation criterion is applied in order to suppress the background from photons originating inside jets: the total calorimeter energy deposit, not including the photon candidate, inside a cone of \( \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.2 \) around the photon direction is required to be less than 5 GeV. Photon candidates identified from

---

1 ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (\( r, \phi \)) are used in the transverse plane, \( \phi \) being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle \( \theta \) as \( \eta = -\ln \tan(\theta/2) \).

2 The addition of the resummation of soft gluon emission at next-to-leading-logarithmic accuracy (NLL) [33–37] is performed in the case of strong SUSY pair-production.
conversions are included, but, in order to suppress the background from primary electrons misidentified as photons, the tracks of converted photon candidates are required to have no hits in the pixel detector.

Electron candidates are clustered energy deposits in the electromagnetic calorimeter matched to a track in the inner detector. They are required to have $p_T > 10$ GeV and $|\eta| < 2.47$, and must satisfy the “medium” electron shower shape and track selection criteria described in Ref. [47]. As for photons, electron candidates in the calorimeter transition region are vetoed.

Muon candidates with $|\eta| < 2.4$, reconstructed by combining tracks in the inner detector and tracks in the muon spectrometer, are required to have $p_T > 10$ GeV and also to pass muon quality requirements [48].

The measurement of the missing transverse momentum, including its magnitude $E^{\text{miss}}_T$, is based on the vector sum of the reconstructed transverse momenta in the event. Objects included in the sum are muons and electrons with $p_T > 10$ GeV, photons with $p_T > 20$ GeV, jets with $p_T > 20$ GeV, and calibrated calorimeter clusters that are not associated with any object with $|\eta| < 4.9$, as described in Ref. [49].

Any jet candidate lying within a distance $\Delta R < 0.2$ from an electron or photon is discarded. Also, in order to ensure that selected leptons and photons are not purely the result of hadronic activity, electrons and photons with distances $0.2 < \Delta R < 0.4$ from a jet are rejected, as are muons within $\Delta R < 0.4$ of a jet. The difference in requirements reflects the fact that only photons and electrons can potentially be reconstructed as jets. Since one of the main backgrounds in this analysis is due to electrons misidentified as photons, a preliminary suppression of the background is achieved by labelling an object an electron whenever an electron/photon ambiguity exists and by discarding the photon candidate if it lies within $\Delta R < 0.2$ of any electron.

5. Event selection

The data sample is collected with a trigger requiring at least one photon passing “loose” identification requirements [46] with $p_T > 80$ GeV; this trigger is fully efficient for the selection described below. The following selection criteria were optimized to maximize the sensitivity to the GGM scenarios considered, especially gluino/squark production: a candidate event should contain a photon with $p_T > 125$ GeV, at least two jets with $p_T > 20$ GeV, at least one of which is $b$-tagged, and $E^{\text{miss}}_T > 150$ GeV. The transverse mass of the photon and the missing transverse momentum $m_T(\gamma, E^{\text{miss}}_T) = \sqrt{2E^{\text{miss}}_T p_T^\gamma (1 - \cos \phi)}$, where $\phi$ is the azimuthal angle between the missing transverse momentum and the photon, is required to be greater than 100 GeV. This criterion removes events in which electrons or decay products of $\tau$ leptons, originating from $W$ decay, are misidentified as photons. The minimum azimuthal angle between the $E^{\text{miss}}_T$ direction and each of the two leading jets must be greater than 0.4. This condition suppresses multijet events in which the measured $E^{\text{miss}}_T$ is due mostly to jet mismeasurement effects. Events with an identified electron or muon satisfying the criteria given in Section 4 are vetoed. This veto suppresses dileptonic and semileptonic $t\bar{t}$ events with a prompt photon or with a jet misidentified as a photon, and dileptonic events with an electron or a $\tau$ lepton misidentified as a photon. Finally, events with a second photon with $p_T > 50$ GeV are rejected. The main selection requirements are summarized in Table 1.

6. Background estimation

Events from $t\bar{t}$ production with a $W$ boson decaying into leptons in the final state (leptonic $t\bar{t}$ background) contain a pair of $b$-jets and genuine $E^{\text{miss}}_T$. These events may survive the signal selection procedure if an isolated high-$p_T$ photon candidate is also present. Such a photon may be the result of the misidentification of an electron produced in the leptonic $W$ decay, a genuine prompt photon, or a $\tau$ decay product or jet misidentified as a photon. All processes that give rise to final states $W(\rightarrow \ell\nu) + X$, including leptonic $t\bar{t}$, diboson, and single top backgrounds, are estimated using data-driven methods. Another large background estimated with data-driven methods is from multijet events. Finally, the small contribution from $Z(\rightarrow \ell\ell) +$ jets background is estimated using Monte Carlo simulation.

A control sample (CS) is defined by selecting events according to the criteria described in Section 5 but replacing the photon selection by requiring the presence of an electron. Once the probability of an electron being misidentified as a photon (the “$e \rightarrow \gamma$ misidentification rate”) is known, the number of events in the signal region with misidentified electrons can be deduced from this CS. The $e \rightarrow \gamma$ misidentification rate for different $\eta$ regions is measured by selecting events with a photon and an electron in which the $e\gamma$ invariant mass is less than 20 GeV from the nominal $Z$ boson mass of 91.2 GeV. The electron is required to pass the “tight” identification criteria [46], and the photon is required to pass the quality requirements of the signal region. The number of $e\gamma$ events is then divided by the number of $e^+e^-$ pairs with one tight and one medium electron, and the ratio is taken to be the misidentification rate. The average misidentification rate for photons with $p_T > 100$ GeV is 1.8%. When this technique is applied to the data, $1.1 \pm 0.1$ (stat.) background events with electrons misidentified as photons are predicted in the signal region.

The prompt photon background cannot be separated from the backgrounds in which a jet or $\tau$ lepton is misidentified as a photon. Therefore, a single CS is used to estimate these backgrounds. The “lepton control region” is defined by requiring the presence of a lepton, in addition to the photon, and relaxing the $E^{\text{miss}}_T$ cut to $80 < E^{\text{miss}}_T < 150$ GeV while keeping all the other selection criteria of Section 5. The lepton requirement strongly suppresses the multijet contamination, making it possible to use a lower $E^{\text{miss}}_T$ threshold in order to increase the number of selected events and hence reduce the uncertainty on the background estimate. The lower $E^{\text{miss}}_T$ threshold is chosen to be 80 GeV to ensure that the $t\bar{t}$ background remains the dominant contribution in the lepton control region. The results of the method for the signal region and the lepton control region are shown in Table 2. In order to prevent double counting, the background with electrons misidentified as photons is subtracted, leaving 10.1 events in the CS. Multiplying the 10.1 events observed in the CS by the simulation-based scale factor of

<table>
<thead>
<tr>
<th>Sample</th>
<th>Signal region</th>
<th>Lepton control region</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$ MC@NLO</td>
<td>$0.3 \pm 0.2$</td>
<td>$0.5 \pm 0.3$</td>
</tr>
<tr>
<td>$t\bar{t}$ WHIZARD</td>
<td>$2.5 \pm 0.2$</td>
<td>$7.9 \pm 0.4$</td>
</tr>
<tr>
<td>Total</td>
<td>$2.8 \pm 0.3$</td>
<td>$8.4 \pm 0.5$</td>
</tr>
<tr>
<td>Data</td>
<td>$10.1 \pm 3.5$</td>
<td></td>
</tr>
</tbody>
</table>

Table 1

Summary of event selection requirements.

1 photon ($p_T > 125$ GeV)  $\gamma$ ($p_T > 20$ GeV)  $\geq 1$ jet ($p_T > 20$ GeV)  $\geq 1$ $b$-tagged jet  $E^{\text{miss}}_T > 150$ GeV

Table 2

Number of events in the signal region and in the lepton control region, as predicted by the $t\bar{t}$ MC@NLO and $t\bar{t}$ WHIZARD calculations, after subtracting the overlapping contribution from electrons misidentified as photons. Only statistical uncertainties are quoted.
The uncertainty is dominated by the limited number of events in the CS data. An important issue in evaluating the scale factor with simulated events is that the MC@NLO generator does not produce the CS data.

To verify that the event characteristics used in this method are representative of the true background, the distribution of jets and mismeasured jets or by heavy-flavour quark jets decaying semileptonically. To estimate the multijet contribution in the signal region (SR), control regions (CRs) are defined with events that fail the b-tag requirement or the \( E_T^{miss} \) requirement (see Table 3).

The CR3 data sample is contaminated by \( t\bar{t} \), single top, and \( W/Z + \) jets events that have genuine \( E_T^{miss} \), and this contamination must be removed. This contamination \( N_{\text{MC,multijet}}^{\text{CR3}} \) is estimated from the Monte Carlo simulation and accounts for approximately 45\% of the events in the CR3. A scale factor between the tagged and untagged samples is calculated in the low \( E_T^{miss} < 100 \) GeV control regions \( (N_{\text{CR1}}^{\text{MC}}/N_{\text{CR1}}^{\text{Data}}) \), and this scale factor is subsequently applied to the high-\( E_T^{miss} \) region of the untagged CS to obtain the prediction for the signal region:

\[
N_{SR}^{\text{Pred}} = \left( N_{\text{Data}}^{\text{SR}} / N_{\text{MC,multijet}}^{\text{SR}} \right) \times \left( N_{\text{Data}}^{\text{CR3}} / N_{\text{CR3}}^{\text{Data}} \right).
\]

To check the accuracy of this method, the background estimate is calculated after all selection requirements and then repeated without the \( m_\ell(\ell\nu) \) requirement, to contribute 0.3\% events in the CR3.

Finally, the \( Z(\rightarrow \nu\bar{\nu}) + \) jets process is estimated, from studies of simulated events, to contribute 0.3\% events in the signal region. The background from other sources is estimated to be negligible.

### 7. Systematic uncertainties on the background

The main source of systematic uncertainties on the background is the scale factor derived from simulation for prompt photon and misidentified jet/ background events in the signal region. The uncertainty on this factor is estimated by comparing two POWHEG samples, one from Monte Carlo simulation and accounts for approximately 45\% of the events in the CR3. A scale factor between the tagged and untagged samples is calculated in the low \( E_T^{miss} < 100 \) GeV control regions \( (N_{\text{CR1}}^{\text{MC}}/N_{\text{CR1}}^{\text{Data}}) \), and this scale factor is subsequently applied to the high-\( E_T^{miss} \) region of the untagged CS to obtain the prediction for the signal region:

\[
N_{SR}^{\text{Pred}} = \left( N_{\text{Data}}^{\text{SR}} / N_{\text{MC,multijet}}^{\text{SR}} \right) \times \left( N_{\text{Data}}^{\text{CR3}} / N_{\text{CR3}}^{\text{Data}} \right).
\]

To check the accuracy of this method, the background estimate is calculated after all selection requirements and then repeated without the \( m_\ell(\ell\nu) \) requirement, to contribute 0.3\% events in the CR3.

Finally, the \( Z(\rightarrow \nu\bar{\nu}) + \) jets process is estimated, from studies of simulated events, to contribute 0.3\% events in the signal region. The background from other sources is estimated to be negligible.
in the event selection, is estimated to be 6%. The impact of the luminosity uncertainty is less than 1% because only the small contribution from $Z(\to \ell\ell) + \text{jets}$ background is normalized using the integrated luminosity.

8. Signal efficiencies and systematic uncertainties

The combined product of acceptance and efficiency of the event selection is calculated with simulated events for each point in the GGM benchmark grids. Low $m_{\tilde{g}}$ values typically result in gravitinos with relatively low $p_T$, which translates to lower efficiency for the $E_T^{\text{miss}}$ requirement relative to high-$m_{\tilde{g}}$ points. A typical efficiency for high-mass gluino points ($m_{\tilde{g}} = 900$ GeV, $m_{\tilde{g}} = 450$ GeV) is 10%, including the branching ratio for all Higgs boson decays and the contribution from neutralino decays to $Z$ bosons that subsequently decay to $b\bar{b}$. Uncertainties on the signal cross section originate from the PDFs, renormalization and factorization scales, and the strong coupling constant $\alpha_s$ are calculated separately for each production process as described in Ref. [38] and combined into an overall uncertainty that varies significantly for different signal points. Most of the signal points have a combined cross-section uncertainty of 2−5% but the total uncertainty can reach 50% for the points with very large gluino masses. The uncertainties on the signal acceptance include an uncertainty ranging from 3% to 16% due to the limited number of simulated events at each benchmark grid point. The uncertainty on the jet energy scale and jet energy resolution, $b$-tagging efficiency, photon and lepton identification, luminosity, and pile-up are evaluated as in Section 7. The uncertainties on the jet energy scale and jet energy resolution vary from 1% to 10% across the different signal points. The relative uncertainty on the signal selection efficiency due to the uncertainty in the $b$-tagging efficiency varies between 1% and 16% throughout the signal grid. The systematic uncertainty on the photon identification is less than 6%. The systematic uncertainty on lepton identification is 3%. Scaling the number of pile-up events in simulation gives rise to variations of up to 6% throughout the grid. The systematic uncertainty on luminosity is evaluated to be 4% [52,53]. All the sources of described background and signal systematic uncertainties are summarized in Table 4.

9. Results

Table 5 summarizes the expected number of Standard Model events in the signal region and the number of events observed in the data. The systematic and statistical uncertainties, both included, are of the same order.

![Figure 2](image_url)

The $E_T^{\text{miss}}$ distribution after all selection criteria except the $E_T^{\text{miss}}$ cut (top) and the $p_T^\gamma$ distribution after all selection criteria except those on $m_T(y, E_T^{\text{miss}})$ and $\Delta\phi(E_T^{\text{miss}}, \text{jet})$ (bottom), along with the distribution of $p_T^\gamma$ after all requirements except those on $m_T(y, E_T^{\text{miss}})$ and $\Delta\phi(E_T^{\text{miss}}, \text{jet})$. The distribution of $m_T(y, E_T^{\text{miss}})$ after all requirements except that on $\Delta\phi(E_T^{\text{miss}}, \text{jet})$ and the distribution of $\Delta\phi(E_T^{\text{miss}}, \text{jet})$ after all requirements except that on $m_T(y, E_T^{\text{miss}})$ are shown in Fig. 3. The observed data agree with the background-only predictions. Since no excess is observed above the background-only prediction, the main result of the search is to constrain contributions from physics beyond the Standard Model. The profile likelihood is used with an asymptotic approximation and the CL_s method to calculate confidence limits [54,55]. From the number of observed and expected events, a 95% confidence level upper limit on the visible

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Background</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton identification</td>
<td>6%</td>
<td>3%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>4%</td>
<td>1%</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>2%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Photon identification</td>
<td>1%</td>
<td>6%</td>
</tr>
<tr>
<td>$b$-Tagging</td>
<td>1%</td>
<td>4%</td>
</tr>
<tr>
<td>Pile-up</td>
<td>4%</td>
<td>1%</td>
</tr>
<tr>
<td>Theoretical uncertainties</td>
<td>17%</td>
<td>9%</td>
</tr>
<tr>
<td>Monte Carlo statistics</td>
<td>-</td>
<td>3%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>&lt;1%</td>
<td>4%</td>
</tr>
</tbody>
</table>

Table 4 Summary of relative systematic uncertainties on the numbers of background and signal events for the representative signal point $m_{\tilde{g}} = 900$ GeV, $m_{\tilde{g}} = 450$ GeV. Theoretical uncertainties on the background originate from the Monte Carlo modelling and different initial- and final-state radiation models. Theoretical uncertainties on the signal cross section originate from the PDFs, renormalization and factorization scales, and $\alpha_s$. 

Table 5 Summary of the expected number of Standard Model events in the signal region and the number of events observed in the data. 

<table>
<thead>
<tr>
<th>Background source</th>
<th>Expected events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron misidentified as photon</td>
<td>$1.1 \pm 0.1$</td>
</tr>
<tr>
<td>Prompt photon and misidentified jet/$\tau$</td>
<td>$3.4 \pm 1.8$</td>
</tr>
<tr>
<td>QCD multijet</td>
<td>$2.7 \pm 1.1$</td>
</tr>
<tr>
<td>$Z(\to \ell\ell) + \text{jets}$</td>
<td>$0.3 \pm 0.3$</td>
</tr>
<tr>
<td>Total number of expected events</td>
<td>$7.5 \pm 2.2$</td>
</tr>
<tr>
<td>Observed events in the data</td>
<td>7</td>
</tr>
</tbody>
</table>

Fig. 2. The $E_T^{\text{miss}}$ distribution after all selection criteria except the $E_T^{\text{miss}}$ cut (top) and the $p_T^\gamma$ distribution after all selection criteria except those on $m_T(y, E_T^{\text{miss}})$ and $\Delta\phi(E_T^{\text{miss}}, \text{jet})$ (bottom).
cross section, defined by the product of production cross section times efficiency times acceptance, is derived. The expected 95% confidence limit is 8.1 events, corresponding to an upper limit on the visible cross section of 1.7 fb. The observed limit is 7.4 events, corresponding to a visible cross section of 1.6 fb.

The calculated acceptances for the simulated signal events and their cross sections are used in the framework of the specific GGM models described in Section 1 to map the excluded signal region. For each point in the benchmark plane observed upper limits on the signal strength are calculated, including both strong production of squarks and gluinos and weak production of neutralinos and charginos. Observed and expected limits for the combined production processes are shown in Fig. 4. The grey lower-right regions, corresponding to models with gluino or squark NLSP, are not considered.

If a Higgs boson mass $m_h = 125$ GeV is used instead of 115 GeV, the branching ratio to $b\bar{b}$ is reduced, and the exclusion is weakened. The important differences in excluded cross section for supersymmetric particle production, at high gluino mass and moderately high neutralino mass, are about 10%. In this relevant region, a 10% change in cross section corresponds to a 10 GeV reduction in the 900 GeV gluino mass exclusion.

10. Conclusions

A search for supersymmetry with a signature consisting of an isolated high transverse momentum photon, a $b$-tagged jet, and high missing transverse momentum is performed using 4.7 fb$^{-1}$ of $\sqrt{s} = 7$ TeV $pp$ collision data recorded with the ATLAS detector at the LHC. Seven events are observed, consistent with the expected Standard Model background of 7.5 ± 2.2 events. A model-independent 95% confidence level upper limit of 1.6 fb is set on the visible cross section of events passing the selection. The cross-section limits are used to constrain higgsino-like neutralino production for a typical GGM model in two benchmark planes. These
are the first direct experimental constraints on this signature. For neutralino masses greater than 220 GeV, this search excludes gluino masses less than 900 GeV and squark masses less than 1020 GeV in the gluino–neutralino and squark–neutralino benchmark planes, respectively.

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 and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CONICYT, Chile; CAS, MOST and NSFC, China; COCENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNDRC, DNRSC and Lundbeck Foundation, Denmark; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; MES and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-PPD (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

P. Grenier 143, J. Griffiths 8, N. Grigalashvili 54, A.A. Grillo 137, K. Grimm 71, S. Grinstein 12, Ph. Gris 34
K. Grybel 141, D. Guest 176, C. Guicheney 34, E. Guido 50a,50b, S. Guindon 54, U. Gul 53, J. Gunther 125
F. Hahn 30, Z. Hajduk 39, H. Hakobyan 177, D. Hall 118, K. Hamacher 175, P. Hamal 113, K. Hamano 86
C. Handel 81, P. Hanke 58a, J.R. Hansen 36, J.B. Hansen 36, J.D. Hansen 36, P.H. Hansen 36, P. Hansson 143
M. Hauschild 30, R. Hauser 88, M. Hravanek 21, C.M. Hawkes 18, R.J. Hawkins 79
V. Hedberg 79, L. Heelan 8, S. Heim 120, B. Heinemann 15, S. Heisterkamp 36, L. Helary 22, C. Heller 98,
M. Hektor 37, P.O. Holland 46a,46b, D. Hellman 146a,146b, D. Hellmich 21, C. Helsens 12, R.C.W. Henderson 71, M. Henke 58a
E. Hines 120, M. Hirose 116, F. Hirsch 43, D. Hirschbuehl 175, J. Hobbs 148, N. Hodgkin 139, M.C. Hodgkinson 139,
P. Hodgson 139, A. Hoecker 30, M.R. Hoeferkamp 103, J. Hoffman 40, D. Hoffmann 83, M. Hohlfeld 81,
M. Horder 141, S.O. Holmgren 146a,146b, T. Holy 120, J.L. Holzbauer 88, T.M. Hong 120
J. Howard 82, I. Hristova 16, J. Hrivnac 115, T. Hryn’ova 5, P.J. Hsu 81, S.-C. Hsu 138, D. Hu 35, Z. Hubacek 126
F. Hubat 83, F. Huegging 21, A. Huettmann 42, T.B. Huffman 118, E.W. Hughes 35, G. Hughes 71
M. Huhtinen 30, M. Hurwitz 15, N. Huseynov 64a, J. Huston 88, J. Huth 57, G. Iacobucci 49, G. Iakovidis 10
M. Ibbotson 82, I. Ibragimov 141, L. Icomomidou-Fayard 115, J. Idarraga 115, P. Iengo 102a, O. Igonkina 105,
Y. Ikegami 65, M. Ikeno 65, D. Iliadis 154, N. Ilic 158, T. Ince 118, P. Ioannou 9, M. Iodice 134a, K. Iordanidou 9,
V. Ippolito 132a,132b, A. Irles Quiles 167, C. Isaksson 166, M. Ishino 67, M. Ishitsuka 157
V. Izzo 102a, B. Jackson 120, J.N. Jackson 73, P. Jackson 1, M.R. Jaekel 30, V. Jain 2, K. Jakobs 48, S. Jakobsen 36,
Y. Jiang 33b, M. Jimenez Belenguer 42, C. Jin 33a, O. Jinnow 157, M.D. Joergensen 36, D. Joffe 40
M. Johansson 146a,146b, K.E. Johansson 146a, P. Johansson 139, S. Johnert 42, K.A. Johns 7, K. Jon-And 146a,146b,
G. Jones 170, R.W.L. Jones 71, T.J. Jones 73, C. Jordan 30, P.M. Jorg 124a, K.D. Joshi 82, J. Jovicevic 147
M. Kaci 167, A. Kaczmarska 39, P. Kadlecek 38, M. Kado 115, H. Kagan 109, M. Kagan 57, E. Kajomovitz 152,
S. Kalinin 175, L.V. Kalinovskaya 54, S. Kama 40, N. Kanaya 155, M. Kaneda 30, S. Kaneti 28, T. Kanno 157
M. Karsch 146a,146b, A. Khanov 112, D. Kharchenko 64, A. Khodinov 96, A. Khomich 58a, T.J. Khoo 28,
G. Khoriauli 21, A. Khoroshilov 75, V. Khovanskiy 85, E. Khramov 64, J. Khubua 51b, H. Kim 146a,146b,
T. Kishimoto 66, D. Kisielewska 38, T. Kitamura 66, T. Kittelmann 123, K. Kiuchi 160, E. Kladivko 144b,
M. Klein 73, U. Klein 73, K. Kleinknecht 81, M. Klemetti 85, A. Klier 172, P. Klimek 146a,146b, A. Klimontov 25,
R. Klingenberg 43, J.A. Klinger 82, E.B. Klinkby 36, T. Klioutchnikova 30, P.F. Klok 104, S. Klos 105,

277

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, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantepe University, Gaziantepe;
19 (d) Department of Physics, Istanbul Technical University, Istanbul, Turkey
20 (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica, Università di Bologna, Bologna, Italy
21 Physicalisches Institut, Universität Bonn, Bonn, Germany
22 Department of Physics, Boston University, Boston, MA, United States
23 Department of Physics, Brandeis University, Waltham, MA, United States
24 (a) Universidade Federal do Rio De Janeiro COPEE/EE/IF, Rio de Janeiro; (b) Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, (d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
25 Physics Department, Brookhaven National Laboratory, Upton, NY, United States
26 (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) University Politehnica Bucharest, Bucharest; (c) West University in Timisoara, Timisoara, Romania
27 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
28 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
29 Department of Physics, Carleton University, Ottawa, ON, Canada
30 CERN, Geneva, Switzerland
31 Enrico Fermi Institute, University of Chicago, Chicago, IL, United States
32 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
33 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong; (e) Physics Department, Shanghai Jiao Tong University, Shanghai, China
34 Laboratoire de Physique Corpusculaire, Clermont Université and CNRS/IN2P3, Clermont-Ferrand, France
35 Nevis Laboratory, Columbia University, Irvington, NY, United States
36 Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
37 (a) INFN Gruppo Collegato di Cosenza; (b) Dipartimento di Fisica, Università della Calabria, Arcavatâ di Rende, Italy
38 Aachen University of Science and Technology, Faculty of Physics and Applied Computer Science, Aachen, Germany
39 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
40 Physics Department, Southern Methodist University, Dallas, TX, United States
41 Physics Department, University of Texas at Dallas, Richardson, TX, United States
42 DESY, Hamburg and Zeuthen, Germany
43 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
44 Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
45 Department of Physics, Duke University, Durham, NC, United States
46 SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, 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 (a) E. Andronikashvili Institute of Physics, Tbilisi; (b) Department of Physics, Tbilisi; (c) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
52 Il Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
53 SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
54 Il 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 Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
60 Department of Physics, Indiana University, Bloomington, IN, United States
61 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
62 University of Iowa, Iowa City, IA, United States
63 Department of Physics and Astronomy, Iowa State University, Ames, IA, United States
64 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
65 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
66 Graduate School of Science, Kobe University, Kobe, Japan
67 Faculty of Science, Kyoto University, Kyoto, Japan
68 Kyoto University of Education, Kyoto, Japan
69 Department of Physics, Kyushu University, Fukuoka, Japan
70 Instituto de Fisica 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 Matematica e Fisica, Università del Salento, Lecce, Italy
73 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
74 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
75 School of Physics and Astronomy, 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 Nucléaire et de Hautes Energies, UPMC Paris-Diderot and CNRS/IN2P3, Paris, France
79 Fysiska institutionen, Lunds universitet, Lund, Sweden
80 Departamento de Física Teórica 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
Also at Department of Physics, King's College London, London, United Kingdom.
Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas – LIP, Lisboa, Portugal.
Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
Also at Institute of Physics, Jagiellonian University, Krakow, Poland.
Also at Institute of Physics, Jagiellonian University, Krakow, Poland.
Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.
Also at Department of Physics, Oxford University, Oxford, United Kingdom.
Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.
Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.
Deceased.