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Published in:
Physics Letters B

DOI:
10.1016/j.physletb.2012.10.069

Citation for published version (APA):

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Search for diphoton events with large missing transverse momentum in 7 TeV proton–proton collision data with the ATLAS detector

ATLAS Collaboration

A search for diphoton events with large missing transverse momentum has been performed using proton–proton collision data at \( \sqrt{s} = 7 \text{ TeV} \) recorded with the ATLAS detector, corresponding to an integrated luminosity of 4.8 fb\(^{-1}\). No excess of events was observed above the Standard Model prediction and model-dependent 95% confidence level exclusion limits are set. In the context of a generalised model of gauge-mediated supersymmetry breaking with a bino-like lightest neutralino of mass above 50 GeV, gluinos (squarks) below 107 TeV (0.87 TeV) are excluded, while a breaking scale \( \Lambda \) below 196 TeV is excluded for a minimal model of gauge-mediated supersymmetry breaking. For a specific model with one universal extra dimension, compactification scales \( 1/R < 1.40 \text{ TeV} \) are excluded. These limits provide the most stringent tests of these models to date.

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1. Introduction

This Letter reports on a search for diphoton (γγ) events with large missing transverse momentum (\( E_T^{\text{miss}} \)) in 4.8 fb\(^{-1}\) of proton–proton (pp) collision data at \( \sqrt{s} = 7 \text{ TeV} \) recorded with the ATLAS detector at the Large Hadron Collider (LHC) in 2011, extending and superseding a prior study performed with 1 fb\(^{-1}\) detector at the LHC in 2011, extending and superseding a prior study performed with 1 fb\(^{-1}\) detector.

The results are interpreted in the context of three models of new physics: a general model of gauge-mediated supersymmetry breaking (GGM) [2–4], a minimal model of gauge-mediated supersymmetry breaking (SPS8) [5], and a model with one universal extra dimension (UED) [6–8].

2. Supersymmetry

Supersymmetry (SUSY) [9–17] introduces a symmetry between fermions and bosons, resulting in a SUSY partner (sparticle) with identical quantum numbers except a difference by half a unit of spin for each Standard Model (SM) particle. As none of these sparticles have been observed, SUSY must be broken symmetry if realised in nature. Assuming R-parity conservation [18–22], sparticles are produced in pairs. These would then decay through cascades involving other sparticles until the lightest SUSY particle (LSP), which is stable, is produced.

In gauge-mediated SUSY breaking (GMSB) models [23–28] the LSP is the gravitino \( \tilde{G} \). GMSB experimental signatures are largely determined by the nature of the next-to-lightest SUSY particle (NLSP). In this study the NLSP is assumed to be the lightest neutralino \( \tilde{\chi}^0_1 \). Should the lightest neutralino be a bino (the SUSY partner of the SM U(1) gauge boson), the final decay in the cascade would predominantly be \( \tilde{\chi}^0_1 \rightarrow \gamma G \), with two cascades per event, leading to final states with \( \gamma\gamma + E_T^{\text{miss}} \), where \( E_T^{\text{miss}} \) results from the undetected gravitinos.

Two different classes of gauge-mediated models, described in more detail below, are considered as benchmarks to evaluate the reach of this analysis: the minimal GMSB model (SPS8) as an example of a complete SUSY model with a full particle spectrum and two different variants of the GGM model as examples of phenomenological models with reduced particle content.

In the SPS8 model, the only free parameter is the SUSY-breaking mass scale \( \Lambda \) that establishes the nature of the observable phenomena exhibited by the low-energy sector. The other model parameters are fixed to the following values: the messenger mass \( M_{\text{mess}} = 2 \Lambda \), the number of SU(5) messengers \( N_5 = 1 \), the ratio of the vacuum expectation values of the two Higgs doublets \( \tan \beta = 15 \), and the Higgs sector mixing parameter \( \mu > 0 \). The bino NLSP is assumed to decay promptly (\( \tau_{\text{NLSP}} < 0.1 \text{ nm} \)). For \( \Lambda \approx 200 \text{ TeV} \), the direct production of gaugino pairs such as \( \tilde{\chi}^0_2 \tilde{\chi}^\pm_1 \) or \( \tilde{\chi}^\pm_1 \tilde{\chi}^0_1 \) is expected to dominate at a LHC centre-of-mass energy \( \sqrt{s} = 7 \text{ TeV} \). The contribution from gluino and/or squark pairs is below 10% of the production cross section due to their high masses. The sparticle pair produced in the collision decays via cascades into two photons and two gravitinos. Further SM particles such as gluons, quarks, leptons and gauge bosons may be produced in the cascade decays. The current best limit on \( \Lambda \) in this model is 145 TeV [1].

Two different configurations of the GGM SUSY model are considered in this study, for which the neutralino NLSP, chosen to be the bino, and either the gluino or the squark masses are treated as
free parameters. For the squark–bino GGM model all squark masses are treated as degenerate except the right-handed up-type squarks whose mass is decoupled (set to inaccessibly large values). For the gluino–bino model all squark masses are decoupled. For both configurations all other sparticle masses are also decoupled, leading to a dominant production mode at $\sqrt{s} = 7$ TeV of a pair of squarks in one case and a pair of gluinos in the other case. These would decay via short cascades into the bino-like neutralino NLSP. Jets may be produced in the cascades from the gluino and squark decays. Further model parameters are fixed to $c_{\text{NLSP}} < 0.1$ mm and $\tan \beta = 2$; for this GGM scenario, restricted to the region of parameter space for which the NLSP is the bino-like neutralino, the final-state phenomenology relevant to this search is only weakly dependent on the value of $\tan \beta$ [4]. The decay into the wino-like neutralino NLSP is possible and was studied by the CMS Collaboration [29].

3. Extra dimensions

UED models postulate the existence of additional spatial dimensions in which all SM particles can propagate, leading to the existence of a series of excitations for each SM particle, known as a Kaluza–Klein (KK) tower. This analysis considers the case of a single UED, with compactification radius (size of the extra dimension) $R \approx 1$ TeV$^{-1}$. At the LHC, the main UED process would be the production via the strong interaction of a pair of first-excitation-level KK quarks and/or gluons [30]. These would decay via cascades involving other KK particles until reaching the lightest KK particle (LKP), i.e. the first-excitation-level KK photon $\gamma^*$. SM particles such as quarks, gluons, leptons and gauge bosons may be produced in the cascades. If the UED model is embedded in a larger space with $N$ additional ev$^{-1}$-sized dimensions accessible only to gravity [31], with a $(4 + N)$-dimensional Planck scale ($M_D$) of a few TeV, the LKP would decay gravitationally via $\gamma^* \rightarrow \gamma + G$. $G$ represents a tower of ev$^{-1}$-spaced graviton states, leading to a graviton mass between 0 and $1/R$. With two decay chains per event, the final state would contain $\gamma\gamma + E_{\text{miss}}$, where $E_{\text{miss}}$ results from the escaping gravitons. Up to $1/R \approx 1$ TeV, the branching ratio to the diphoton and $E_{\text{miss}}$ final state is close to 100%. As $1/R$ increases, the gravitational decay widths become more important for all KK particles and the branching ratio into photons decreases, e.g. to 50% for $1/R = 1.5$ TeV [7].

The UED model considered here is defined by specifying $R$ and $N$, the ultraviolet cut-off used in the calculation of radiative corrections to the KK masses. This analysis sets $N = 1$ [32] and $\mathcal{A} = 20$ [32]. The $\gamma^*$ mass is insensitive to $\mathcal{A}$, while other KK masses typically change by a few per cent when varying $\mathcal{A}$ in the range 10–30. For $1/R = 1.4$ TeV, the masses of the first-excitation-level KK photon, quark and gluon are 1.40 TeV, 1.62 TeV and 1.71 TeV, respectively [33].

4. Simulated samples

For the GGM model, the SUSY mass spectra were calculated using SUSPECT 2.4.1 [34] and SDECAY 1.3 [35]; for the SPS8 model, the SUSY mass spectra were calculated using ISAJET 7.80 [36]. The Monte Carlo (MC) SUSY signal samples were produced using Herwig++ 2.5.1 [37] with MRST2007 LO$^+$ [38] parton distribution functions (PDFs). Signal cross sections were calculated to next-to-leading order (NLO) in the strong coupling constant, including the resummation of soft gluon emission at next-to-leading-logarithmic accuracy [39–43]. The nominal cross sections and the uncertainties were taken from an envelope of cross-section predictions using different PDF sets and factorisation and renormalisation scales, as described in Ref. [44]. In the case of the UED model, cross sections were estimated and MC signal samples generated using the UED model as implemented at leading order (LO) in PYTHIA 6.423 [45,33] with MSTW2007 LO$^+$ PDFs.

The “irreducible” background from $W(\rightarrow \ell\nu) + \gamma\gamma$ and $Z(\rightarrow \nu\nu) + \gamma\gamma$ production was simulated at LO using Madgraph 4 [46] with the CTEQ6L1 [47] PDFs. Parton showering and fragmentation were simulated with PYTHIA. NLO cross sections and scale uncertainties were implemented via multiplicative constants ($K$-factors) that relate the NLO and LO cross sections. These have been calculated for several restricted regions of the overall phase space of the $Z(\rightarrow \nu\nu) + \gamma\gamma$ and $W(\rightarrow \ell\nu) + \gamma\gamma$ processes [48,49], and are estimated to be $2.0 \pm 0.3$ and $3 \pm 3$ for the $Z(\rightarrow \nu\nu) + \gamma\gamma$ and $W(\rightarrow \ell\nu) + \gamma\gamma$ contributions to the signal regions of this analysis, respectively. As described below, all other background sources are estimated through the use of control samples derived from data.

All samples were processed through the GEANT4-based simulation of the ATLAS detector [50,51]. The variation of the number of pp interactions per bunch crossing (pile-up) as a function of the instantaneous luminosity is taken into account by overlaying simulated minimum bias events according to the observed distribution of the number of pile-up interactions in data, with an average of $\sim 10$ interactions.

5. ATLAS detector

The ATLAS detector [52] is a multi-purpose apparatus with a forward-backward symmetric cylindrical geometry and nearly $4\pi$ solid angle coverage. Closest to the beamline are tracking devices comprising layers of silicon-based pixel and strip detectors covering $|\eta| < 2.5$ and straw-tube detectors covering $|\eta| < 2.0$, located inside a thin superconducting solenoid that provides a 2 T magnetic field. Outside the solenoid, fine-granularity lead/liquid-argon electromagnetic (EM) calorimeters provide coverage for $|\eta| < 3.2$ to measure the energy and position of electrons and photons. A presampler, covering $|\eta| < 1.8$, is used to correct for energy lost upstream of the EM calorimeter. An iron/scintillating-tile hadronic calorimeter covers the region $|\eta| < 1.7$, while a copper/liquid-argon medium is used for hadronic calorimeters in the end-cap region $1.5 < |\eta| < 3.2$. In the forward region $3.2 < |\eta| < 4.9$ liquid-argon calorimeters with copper and tungsten absorbers measure the electromagnetic and hadronic energy. A muon spectrometer consisting of three superconducting toroidal magnet systems each comprising eight toroidal coils, tracking chambers, and detectors for triggering surrounds the calorimeter system.

6. Reconstruction of candidates and observables

The reconstruction of converted and unconverted photons and of electrons is described in Refs. [53] and [54], respectively. Photon candidates were required to be within $|\eta| < 1.8$, and to be outside the transition region $1.37 < |\eta| < 1.52$ between the barrel and end-cap calorimeters. Identified on the basis of the characteristics of the longitudinal and transverse shower development in the EM calorimeter, the analysis made use of both “loose” and “tight” photons [53]. In the case that an EM calorimeter deposition was identified as both a photon and an electron, the photon candidate was discarded and the electron candidate retained. In addition,
converted photons were re-classified as electrons if one or more candidate conversion tracks included at least one hit from the pixel layers. Giving preference to the electron selection in this way reduced the electron-to-photon fake rate by 50–60% (depending on the value of $\eta$) relative to that of the prior $1 \text{ fb}^{-1}$ analysis [1], while preserving over 70% of the signal efficiency. Finally, an “isolation” requirement was imposed. After correcting for contributions from pile-up and the deposition ascribed to the photon itself, photon candidates were removed if more than 5 GeV of transverse energy was observed in a cone of $(\Delta \eta)^2 + (\Delta \phi)^2 < 0.2$ surrounding the energy deposition in the calorimeter associated with the photon.

The measurement of the two-dimensional transverse momentum vector $p_T^{miss}$ (and its magnitude $E_T^{miss}$) was based on energy deposits in calorimeter cells inside three-dimensional clusters with $|\eta| < 4.9$ and was corrected for contributions from muons, if any [55]. The cluster energy was calibrated to correct for the different response to electromagnetically- and hadronically-induced showers, energy loss in dead material, and out-of-cluster energy. The contribution from identified muons was accounted for by adding in the energy derived from the properties of reconstructed muon tracks.

Jets were reconstructed using the anti-$k_t$ jet algorithm [56] with radius parameter $R = 0.4$. They were required to have $p_T > 20$ GeV and $|\eta| < 2.8$ [57].

Two additional observables of use in discriminating SM backgrounds from potential GMSB and UED signals were defined. The total visible transverse energy $H_T$ was calculated as the sum of the magnitude of the transverse momenta of the two selected photons and any additional leptons and jets in the event. The photon–$E_T^{miss}$ separation $\Delta \phi(\gamma, E_T^{miss})$ was defined as the azimuthal angle between the missing transverse momentum vector and either of the two selected photons, with $\Delta \phi_{\text{min}}(\gamma, E_T^{miss})$ the minimum value of $\Delta \phi(\gamma, E_T^{miss})$ of the two selected photons.

7. Data analysis

The data sample, corresponding to an integrated luminosity of $(4.8 \pm 0.2) \text{ fb}^{-1}$ [58,59], was selected by a trigger requiring two loose photon candidates with $E_T > 20$ GeV. To ensure the event resulted from a beam collision, events required to have at least one vertex with five or more associated tracks. Events were then required to contain at least two tight photon candidates with $E_T > 50$ GeV, which MC studies suggested would provide the greatest separation between signal and SM background for a broad range of the parameter space of the new physics scenarios under consideration in this study. A total of 10 455 isolated $\gamma\gamma$ candidate events passing these selection requirements were observed in the data sample. The $E_T$ distributions$^2$ of the leading and sub-leading photon for events in this sample are shown in Figs. 1 and 2. Also shown are the $E_T$ spectra obtained from GGM MC samples for $m_{\tilde{g}} = 1000$ GeV and $m_{\tilde{\chi}_1^0} = 450$ GeV, from SPS8 MC samples with $\Lambda = 190$ TeV, and from UED MC samples for $1/R = 1.3$ TeV, representing model parameters near the expected exclusion limit. Figs. 3 and 4 show the $H_T$ and $\Delta \phi_{\text{min}}(\gamma, E_T^{miss})$ distributions of selected diphoton events, with those of the same signal models overlaid.

To maximise the sensitivity of this analysis over a wide range of model parameters that may lead to different kinematic properties, three different signal regions (SRs) were defined based on the observed values of $E_T^{miss}$, $H_T$ and $\Delta \phi_{\text{min}}(\gamma, E_T^{miss})$. SR A, optimised for gluino/squark production with a subsequent decay to a high-mass bino, requires large $E_T^{miss}$ and moderate $H_T$. SR B, optimised for gluino/squark production with a subsequent decay to a low-mass bino, requires moderate $E_T^{miss}$ and large $H_T$. SR C, optimised for the electroweak production of intermediate-mass gaugino pairs that dominates the SPS8 cross section in this regime, requires moderate $E_T^{miss}$ but makes no requirement on $H_T$. In addition, a requirement of $\Delta \phi_{\text{min}}(\gamma, E_T^{miss}) > 0.5$ was imposed on events in SR A and C; for the low-mass bino targeted by SR B, the separation between the photon and gravitino daughters of the bino is too slight to allow for the efficient separation of signal from background through the use of this observable. The selection requirements of the three SRs are summarised in Table 1. Of the three SRs, SR A provides the greatest sensitivity to the UED model, and is thus the SR used to test this model.

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$^2$ An excess of events relative to a smoothly-falling distribution of the leading-photon spectrum was observed for $E_T > 285$ GeV. Searching over the range 100 GeV < $E_T < 500$ GeV, a significance of 1.8$\sigma$ was found using BumpHunter [60], while the local significance was found to be 3.1$\sigma$. No correlation between the excess and the LHC running period or luminosity was observed. A comparison of other observables (e.g. diphoton mass, $E_T^{miss}$, leading-photon $\eta$, $\Delta \phi(\gamma, \gamma')$) between the excess and sideband regions exhibited no appreciable differences. It was concluded that the observed excess of events is compatible with a statistical fluctuation.
tributions from the SPS8 MC sample with \( \Lambda \) estimated background contributions from various sources (described were observed to pass all but the \( E_T \) stages of the selection. A total of 117, 9 and 7293 candidate events after the diphoton requirement. The signal samples are scaled by a factor of 100 for clarity.

Fig. 3. The \( H_T \) spectrum of \( \gamma \gamma \) candidate events in the data (points, statistical uncertainty only) together with the spectra from simulated GGM \( (m_\chi = 1000 \, \text{GeV}, m_\chi = 450 \, \text{GeV}) \), SPS8 \( (\Lambda = 190 \, \text{TeV}) \), and UED \( (1/R = 1.3 \, \text{TeV}) \) samples after the diphoton requirement. The signal samples are scaled by a factor of 100 for clarity.

Fig. 4. The minimum \( \Delta \phi (y, E_T^{\text{miss}}) \) spectrum of \( \gamma \gamma \) candidate events in the data (points, statistical uncertainty only) together with the spectra from simulated GGM \( (m_\gamma = 1000 \, \text{GeV}, m_\gamma = 450 \, \text{GeV}) \), SPS8 \( (\Lambda = 190 \, \text{TeV}) \), and UED \( (1/R = 1.3 \, \text{TeV}) \) samples after the diphoton requirement. The signal samples are scaled by a factor of 100 for clarity.

Table 1

| Definition of the three SRs (A, B and C) based on the quantities \( E_T^{\text{miss}} \), \( H_T \) and \( \Delta \phi_{\text{min}} (y, E_T^{\text{miss}}) \). |
|-----------------|-----------------|-----------------|
| SR A            | SR B            | SR C            |
| \( E_T^{\text{miss}} > \) | 200 GeV         | 100 GeV         | 125 GeV         |
| \( H_T > \)     | 600 GeV         | 1100 GeV        | –               |
| \( \Delta \phi_{\text{min}} (y, E_T^{\text{miss}}) > \) | 0.5             | –               | 0.5             |

Table 2 shows the numbers of events remaining after several stages of the selection. A total of 117, 9 and 7293 candidate events were observed to pass all but the \( E_T^{\text{miss}} \) requirement of SR A, B and C, respectively. After imposing the final \( E_T^{\text{miss}} \) requirement, no events remained for SR A and B, while two events remained for SR C.

Fig. 5 shows the \( E_T^{\text{miss}} \) distribution for SR C, the expected contributions from the SPS8 MC sample with \( \Lambda = 190 \, \text{TeV} \), and estimated background contributions from various sources (described below).

8. Background estimation

Following the procedure described in Ref. [61], the contribution to the large \( E_T^{\text{miss}} \) diphoton sample from SM sources can be grouped into three primary components. The first of these, referred to as “QCD background”, arises from a mixture of processes that include \( \gamma \gamma \) production as well as \( \gamma + \text{jet} \) and multijet events with at least one jet mis-reconstructed as a photon. The second background component, referred to as “EW background”, is due to \( W + X \) and \( t \bar{t} \) events (here “X” can be any number of photons or jets) for which mis-reconstructed photons arise from electrons and jets, and for which final-state neutrinos produce significant \( E_T^{\text{miss}} \). The QCD and EW backgrounds were estimated via dedicated control samples of data events. The third background component, referred to as “irreducible”, consists of \( W \) and \( Z \) bosons produced in association with two real photons, with a subsequent decay into one or more neutrinos.

To estimate the QCD background from \( \gamma \gamma, \gamma + \text{jet} \), and multijet events, a “QCD control sample” was selected from the diphoton trigger sample by selecting events for which at least one of the photon candidates passes the loose but not the tight photon identification. Events with electrons were vetoed to remove contamination from \( W \rightarrow ev \) decays. The \( H_T \) and \( \Delta \phi_{\text{min}} (y, E_T^{\text{miss}}) \) requirements associated with each of the three SRs were then applied, yielding three separate QCD samples, or “templates”. An estimate of the QCD background contribution in each SR was obtained from imposing the \( E_T^{\text{miss}} \) requirement associated with the given SR upon the corresponding QCD template, after normalising each template to the diphoton data with \( E_T^{\text{miss}} < 20 \, \text{GeV} \) from the given SR. This yielded a QCD background expectation of 0.85 ± 0.20(stat) events for SR C. No events above the corresponding \( E_T^{\text{miss}} \) requirement were observed for the A and B control samples, yielding an
estimate of 0 events with a 90% confidence-level (CL) upper limit of less than 1.01 and 1.15 background events for SR A and SR B, respectively.

To improve the constraint on the estimated background for SRs A and B, a complementary method making use of the Hτ requirement applied to the control samples, and systematic, the details of which are given in the text. For the irreducible background, the statistical uncertainty is due to limited numbers of events in the corresponding MC samples.

### Table 3

<table>
<thead>
<tr>
<th></th>
<th>SR A</th>
<th>SR B</th>
<th>SR C</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD</td>
<td>0.07 ± 0.00 ± 0.07</td>
<td>0.27 ± 0.00 ± 0.27</td>
<td>0.85 ± 0.30 ± 0.71</td>
</tr>
<tr>
<td>Electroweak</td>
<td>0.03 ± 0.03 ± 0.01</td>
<td>0.09 ± 0.05 ± 0.02</td>
<td>0.80 ± 0.16 ± 0.22</td>
</tr>
<tr>
<td>W(→ℓνγ)+γγ</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>0.18 ± 0.13 ± 0.18</td>
</tr>
<tr>
<td>Z(→νν)+γγ</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>0.27 ± 0.09 ± 0.04</td>
</tr>
<tr>
<td>Total</td>
<td>0.10 ± 0.03 ± 0.07</td>
<td>0.36 ± 0.05 ± 0.27</td>
<td>2.11 ± 0.37 ± 0.77</td>
</tr>
<tr>
<td>Observed events</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

After applying corresponding selection requirements on Hτ, Δφ_{miss}(γ, E_{T,miss}) and E_{T,miss}, a total of 1, 3 and 26 electron–photon events were observed for SRs A, B and C, respectively. After multiplying by the η-dependent electron-to-photon mis-reconstruction probability, the resulting EW background contamination was estimated to be 0.03 ± 0.03, 0.09 ± 0.05 and 0.80 ± 0.16 events for SRs A, B and C, respectively, where the uncertainties are statistical only.

The systematic uncertainty on the determination of the electron-to-photon mis-reconstruction probability is assessed by performing an independent tag-and-probe analysis with looser electron E_{T} and identification requirements. Differences with the nominal tag-and-probe analysis are taken as systematic uncertainty on the EW background estimate, resulting in relative systematic uncertainties of ±6.9%, ±7.1% and ±10.0% for SRs A, B and C, respectively. MC studies suggest that approximately 25% of the EW background involves no electron-to-photon mis-reconstruction, and thus are not accounted for with the electron–photon control sample. These events, however, typically involve a jet-to-photon mis-reconstruction (for example, an event with one radiated photon and a hadronic τ decay with an energetic leading π^0 mis-reconstructed as a photon), and are thus potentially accounted for in the QCD background estimate. A relative systematic uncertainty of ±25% is conservatively assigned to the EW background estimates for all three SRs to account for this ambiguity. The resulting EW background estimates for the three SRs, along with their uncertainties, are compiled in Table 3.

The contribution of the irreducible background from the Z(→ννγ)+γγ and W(→ℓνγ)+γγ processes was estimated using MC samples. It was found to be negligible for SRs A and B, and estimated to be 0.46 ± 0.16 ± 0.19 events for SR C, where the first uncertainty is due to the limited number of events in the MC sample and the second to the uncertainty on the applied K-factor. These estimates, along with the resulting estimates for the total background from all sources, are reported in Table 3.

The contamination from cosmic-ray muons, estimated using events triggered in empty LHC bunches, was found to be negligible.

### 9. Signal efficiencies and systematic uncertainties

Signal efficiencies were estimated using MC simulation. GGM signal efficiencies were estimated over an area of the GGM parameter space that ranges from 800 GeV to 1300 GeV for the gluino or squark mass, and from 50 GeV to within 10 GeV of the gluino or squark mass for the neutralino mass. For SR A the efficiency increases smoothly from 1.2% to 25% for (m_2, m_{1/2}) = (800, 50) GeV to (1300, 1280) GeV, but then drops to 20% for the case for which the gluino and neutralino masses are only separated by 10 GeV. For SR B the efficiency increases smoothly from 2.8% to 26% for (m_2, m_{3/2}) = (800, 790) GeV to (1300, 50) GeV. The SPS8 signal efficiency in SR C increases smoothly from 5.0% (A = 100 TeV) to
chosen reference points: UED) samples. A conservative systematic uncertainty of also evaluated on MC events using mis-reconstructed photons from selection. To estimate the systematic uncertainty due to the uncertainties due to the mating and modelling the effects of pile-up), leads to a systematic uncertainty of 0.9 (chosen to reflect the range of uncertainty inherent in estimating the number of pile-up events in the MC simulation by a factor of 4). The influence of pile-up on the signal efficiency, evaluated by scaling and efficiencies are taken into account as Gaussian-distributed nuisance parameters in the maximum likelihood fit, resulting in observed upper limits of 3.9% [58,59]. The efficiency of the required diphoton trigger was estimated using a single photon trigger according to [62], yielding 99.8±0.2% for events passing the diphoton selection. To estimate the systematic uncertainty due to the unknown composition of the data sample, the trigger efficiency was also evaluated on MC events using mis-reconstructed photons from filtered multijet samples and photons from signal (GGM, SPSS and UED) samples. A conservative systematic uncertainty of ±0.5% was derived from the difference between the obtained efficiencies. Uncertainties on the photon selection, the photon energy scale, and the detailed material composition of the detector, as described in Ref. [61], result in an uncertainty of ±4.4% for the GGM, SPSS and UED signals. The uncertainty due to the photon isolation requirement was estimated by varying the energy leakage and the pile-up corrections independently, resulting in an uncertainty of ±0.9%, ±0.2% and ±0.4% for the GGM, SPSS and UED signals, respectively. The influence of pile-up on the signal efficiency, evaluated by scaling the number of pile-up events in the MC simulation by a factor of 0.9 (chosen to reflect the range of uncertainty inherent in estimating and modelling the effects of pile-up), leads to a systematic uncertainty of ±0.8% (GGM), ±0.5% (SPSS) and ±0.5% (UED). Systematic uncertainties due to the isolation reconstruction, estimated by varying the cluster energies and the isolation resolution between the measured performance and MC expectations [55], contribute an uncertainty of ±0.1/0.5% to ±5.3/16.1% (GGM, SR A/B), ±1.6% to ±9.7% (SPSS) and ±0.9% to ±2% (UED). Systematic uncertainties due to the reconstruction, estimated by varying the energy scale and resolution of the individual objects entering the reconstruction, are below ±0.3% (GGM, SR A), ±0.1% to ±7.3% (GGM, SR B) and ±0.1% to ±1.1% (UED). The systematic uncertainties from the isolation and H$_T$ uncertainties are taken to be fully correlated. Added in quadrature, the total systematic uncertainty on the signal yield varies between ±6% and ±20% (GGM), ±6% and ±15% (SPSS), and ±6% and ±7% (UED).

The PDF and factorisation and renormalisation scale uncertainties on the GGM (SPSS) cross sections were evaluated as described in Section 4, leading to a combined systematic uncertainty between ±23–39%, ±29–49% and ±4.7–6.4% for the GGM (gluino), GGM (squark) and SPSS models, respectively. The different impact of the PDF and scale uncertainties on the GGM and SPSS yields is related to the different production mechanisms in the two models (see Section 2). In the case of UED, the PDF uncertainties were evaluated by using the MSTW2008 LO [63] PDF error sets in the LO cross-section calculation and are about ±4%. The scale of $\alpha_s$ in the LO cross-section calculation was increased and decreased by a factor of two, leading to a systematic uncertainty of ±4.5% and ±9%, respectively. NLO calculations are not yet available, so the LO cross-sections were used for the limit calculation without any theoretical uncertainty, and the effect of PDF and scale uncertainties on the final limit is discussed separately.

10. Results

No evidence for physics beyond the SM was observed in any of the SRs. Based on the numbers of observed events in SR A, B and C and the background expectation shown in Table 3, 95% CL upper limits are set on the numbers of events in the different SRs from any scenario of physics beyond the SM using the profile likelihood and CL$_S$ prescriptions [64]. Uncertainties on the background expectation are treated as Gaussian-distributed nuisance parameters in the maximum likelihood fit, resulting in observed upper limits of 3.1, 3.1 and 4.9 events for SRs A, B and C, respectively. In the context of the GGM model, these limits translate into 95% CL upper limits on the visible cross section for new physics, defined by the product of cross section, branching ratio, acceptance and efficiency for the different SR definitions, of 0.6, 0.6 and 1.0 fb, respectively. As for background uncertainties, uncertainties on the luminosity, acceptance and efficiency are taken into account as Gaussian-distributed nuisance parameters in the maximum likelihood fit. Because the observed numbers of events are close to the expected numbers of background events for all three SRs, expected limits on the numbers of events from and visible cross section for new physics are, to the quoted accuracy, identical to the observed limits.

Limits are also set on the GGM squark and gluino masses as a function of the bino-like neutralino mass, making use of the SR (A or B) that provides the most stringent expected limit for the given neutralino mass. Figs. 6 and 7 show the expected and observed lower limits on the GGM gluino and squark masses, respectively, as a function of the neutralino mass. Three observed-limit contours are shown, corresponding to the nominal assumption for the SUSY production cross section as well as those derived by

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Uncertainty</th>
<th>GGM</th>
<th>SPSS</th>
<th>UED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity</td>
<td>3.9%</td>
<td>3.9%</td>
<td>3.9%</td>
<td></td>
</tr>
<tr>
<td>Trigger</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0.5%</td>
<td></td>
</tr>
<tr>
<td>Photon identification</td>
<td>4.4%</td>
<td>4.4%</td>
<td>4.4%</td>
<td></td>
</tr>
<tr>
<td>Photon isolation</td>
<td>0.9%</td>
<td>0.2%</td>
<td>0.4%</td>
<td></td>
</tr>
<tr>
<td>Pile-up</td>
<td>0.8%</td>
<td>0.5%</td>
<td>0.5%</td>
<td></td>
</tr>
<tr>
<td>$E_T^{miss}$ reco.</td>
<td>3.9/1.1%</td>
<td>2.8%</td>
<td>1.5%</td>
<td></td>
</tr>
<tr>
<td>$H_T$</td>
<td>0.0/2.1%</td>
<td>-</td>
<td>0.4%</td>
<td></td>
</tr>
<tr>
<td>Signal MC statistics</td>
<td>3.0%</td>
<td></td>
<td>2.1%</td>
<td>1.4%</td>
</tr>
<tr>
<td>Total signal uncertainty</td>
<td>7.6/7.1%</td>
<td>6.8%</td>
<td>6.3%</td>
<td></td>
</tr>
<tr>
<td>PDF and scale</td>
<td>31%</td>
<td>5.5%</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>32%</td>
<td>8.7%</td>
<td>6.3%</td>
<td></td>
</tr>
</tbody>
</table>

21% ($\Lambda = 250$ TeV). For SR A the UED signal efficiency increases smoothly from 28% ($1/R = 1.0$ TeV) to 37% ($1/R = 1.5$ TeV).

The various relative systematic uncertainties on the GGM, SPSS and UED signal cross sections are summarised in Table 4 for the chosen reference points: $(m_{\tilde{g}}, m_{\tilde{\chi}_0^0}) = (1000, 450)$ GeV for GGM, $\Lambda = 190$ TeV for SPSS, and $1/R = 1.3$ TeV for UED. The uncertainty on the luminosity is ±3.9% [58,59]. The efficiency of the required diphoton trigger was estimated using a single photon trigger according to [62], yielding 99.8±0.2% for events passing the diphoton selection. To estimate the systematic uncertainty due to the unknown composition of the data sample, the trigger efficiency was also evaluated on MC events using mis-reconstructed photons from filtered multijet samples and photons from signal (GGM, SPSS and UED) samples. A conservative systematic uncertainty of ±0.5% was derived from the difference between the obtained efficiencies. Uncertainties on the photon selection, the photon energy scale, and the detailed material composition of the detector, as described in Ref. [61], result in an uncertainty of ±4.4% for the GGM, SPSS and UED signals. The uncertainty due to the photon isolation requirement was estimated by varying the energy leakage and the pile-up corrections independently, resulting in an uncertainty of ±0.9%, ±0.2% and ±0.4% for the GGM, SPSS and UED signals, respectively. The influence of pile-up on the signal efficiency, evaluated by scaling the number of pile-up events in the MC simulation by a factor of 0.9 (chosen to reflect the range of uncertainty inherent in estimating and modelling the effects of pile-up), leads to a systematic uncertainty of ±0.8% (GGM), ±0.5% (SPSS) and ±0.5% (UED). Systematic uncertainties due to the isolation reconstruction, estimated by varying the cluster energies and the isolation resolution between the measured performance and MC expectations [55], contribute an uncertainty of ±0.1/0.5% to ±5.3/16.1% (GGM, SR A/B), ±1.6% to ±9.7% (SPSS) and ±0.9% to ±2% (UED). Systematic uncertainties due to the isolation reconstruction, estimated by varying the energy scale and resolution of the individual objects entering the isolation, are below ±0.3% (GGM, SR A), ±0.1% to ±7.3% (GGM, SR B) and ±0.1% to ±1.1% (UED). The systematic uncertainties from the isolation and $H_T$ uncertainties are taken to be fully correlated. Added in quadrature, the total systematic uncertainty on the signal yield varies between ±6% and ±20% (GGM), ±6% and ±15% (SPSS), and ±6% and ±7% (UED).
and chargino masses is also shown. Fig. 7. Expected and observed 95% CL lower limits on the squark mass as a function of the neutralino mass in the GGM model with a bino-like lightest neutralino NLSP (the grey area indicates the region for which the squark mass is less than the bino mass, which is not considered here). The other sparticle masses are assumed to be decoupled. Further model parameters are $\tan \beta = 2$ and $c_{\tau_{NLSP}} < 0.1$ mm.

Fig. 8. Expected and observed 95% CL upper limits on the sparticle production cross section in the SPS8 model, and the NLO cross-section prediction, as a function of $\Lambda$ and the lightest neutralino and chargino masses. Further SPS8 model parameters are $M_{\text{miss}} = 2\Lambda$, $N_L = 1$, $\tan \beta = 15$ and $c_{\tau_{NLSP}} < 0.1$ mm. Limits are set based on SR C.

Expected and observed 95% CL upper limits on the KK particle production cross section times branching ratio to two photons in the UED model, and the LO cross-section prediction times branching ratio, as a function of $1/R$ and the KK quark ($Q^*$) and KK gluon ($g^*$) masses. The ±1σ expected-limit error band overlaps the observed limit contour and is too narrow to be distinguished. No error is shown for the UED cross section since the cross-section calculation is available only to LO (see text for further discussion). The UED model parameters are $N = 6$, $M_D = 5$ TeV and $AR = 20$. Limits are set based on SR A.

Fig. 9. Expected and observed 95% CL upper limits on the KK particle production cross section times branching ratio to two photons in the UED model, and the LO cross-section prediction times branching ratio, as a function of $1/R$ and the KK quark ($Q^*$) and KK gluon ($g^*$) masses. The ±1σ expected-limit error band overlaps the observed limit contour and is too narrow to be distinguished. No error is shown for the UED cross section since the cross-section calculation is available only to LO (see text for further discussion). The UED model parameters are $N = 6$, $M_D = 5$ TeV and $AR = 20$. Limits are set based on SR A.

11. Conclusions

A search for events with two photons and substantial $E_{T,\text{miss}}$, performed using 4.8 fb$^{-1}$ of 7 TeV pp collision data recorded with the ATLAS detector at the LHC, is presented. The sensitivity to different new physics models producing this final state was optimised by defining three different signal regions. No significant excess above the expected background is found in any signal region. The results are used to set model-independent 95% CL upper limits on possible contributions from new physics. In addition, under the GGM hypothesis, considering cross sections one standard deviation of theoretical uncertainty below the nominal value, a lower limit on the gluino/squark mass of 1.07 TeV/0.87 TeV is determined for bino masses above 50 GeV. Under similar assumptions, a lower limit of 196 TeV is set on the SUSY-breaking scale $\Lambda$ of the SPS8 model. Considering nominal values of the leading-order UED cross section, a lower limit of 1.40 TeV is set on the UED compactification scale $1/R$. These results provide the most stringent tests of these models to date.

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; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSTM CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; EPLANET and ERC, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINEVRA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNISW, Poland; GRICES and FCT, Portugal; MERSYS (MECTS), Romania; MES of Russia 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-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

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References


ATLAS Collaboration
