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

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ABSTRACT

A search for diphoton events with large missing transverse momentum has been performed using proton–proton collision data at $\sqrt{s} = 7$ 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 1.07 TeV (0.87 TeV) are excluded, while a breaking scale Λ 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 $1/R < 1.40$ TeV are excluded. These limits provide the most stringent tests of these models to date.

1. Introduction

This Letter reports on a search for diphoton ($\gamma\gamma$) events with large missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$) in 4.8 fb^{-1} of proton–proton (pp) collision data at $\sqrt{s} = 7$ 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} [1]. 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 a 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 $\tilde{\chi}_1^0$. 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 $\tilde{\chi}_1^0 \to \gamma\tilde{G}$, with two cascades per event, leading to final states with $\gamma\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$, where $E_{\mathrm{T}}^{\mathrm{miss}}$ 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 Λ 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 $M_{\mathrm{mess}} = 2\Lambda$, 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 ($c\tau_{\mathrm{NLSP}} < 0.1$ mm). For $\Lambda \simeq 200$ TeV, the direct production of gaugino pairs such as $\tilde{\chi}_2^0\tilde{\chi}_1^{\pm}$ or $\tilde{\chi}_1^+\tilde{\chi}_1^-$ pairs is expected to dominate at a LHC centre-of-mass energy of $\sqrt{s} = 7$ 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 Λ 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

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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 $c\tau_{\text{NLSP}} < 0.1$ 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 γ^*. 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 $\gamma^* \to \gamma + G$. G represents a tower of eV-spaced graviton states, leading to a graviton mass between 0 and $1/R$. With two decay chains per event, the final state would contain $\gamma\gamma + E_{\text{T}}^{\text{miss}}$, where $E_{\text{T}}^{\text{miss}}$ results from the escaping gravitons. Up to $1/R \sim 1$ TeV, the branching ratio to the diphoton and $E_{\text{T}}^{\text{miss}}$ 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 Λ, the ultraviolet cut-off used in the calculation of radiative corrections to the KK masses. This analysis sets Λ such that $\Lambda R = 20$ [32]. The γ^* mass is insensitive to Λ, while other KK masses typically change by a few per cent when varying ΛR 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 2.41 [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 MRST2007 LO* PDFs.

The "irreducible" background from $W(\to \ell\nu) + \gamma\gamma$ and $Z(\to \nu\bar{\nu}) + \gamma\gamma$ 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 $Z(\to \nu\bar{\nu}) + \gamma\gamma$ and $W(\to \ell\nu) + \gamma\gamma$ processes [48,49], and are estimated to be 2.0 ± 0.3 and 3 ± 3 for the $Z(\to \nu\bar{\nu}) + \gamma\gamma$ and $W(\to \ell\nu) + \gamma\gamma$ 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 ~ 10 interactions.

5. ATLAS detector

The ATLAS detector [52] is a multi-purpose apparatus with a forward-backward symmetric cylindrical geometry and nearly 4π solid angle coverage. Closest to the beamline are tracking devices comprising layers of silicon-based pixel and strip detectors covering $|\eta| < 2.5$[1] 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 $|\eta| < 1.81$, 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,

[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, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

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 η) relative to that of the prior 1 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 $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.2$ surrounding the energy deposition in the calorimeter associated with the photon.

The measurement of the two-dimensional transverse momentum vector $\mathbf{p}_T^{miss}$ (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 $\Delta\phi_{min}(\gamma, E_T^{miss})$ 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 ± 0.2) 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 were 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 search. 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 $\Delta\phi_{min}(\gamma, E_T^{miss})$ distributions of selected diphoton events, with those of the same signal models overlaid.

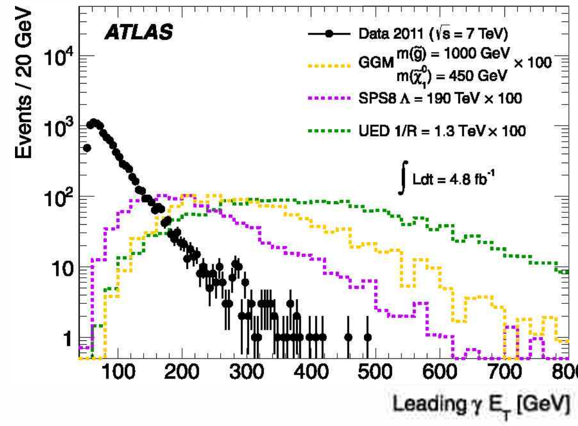

Fig. 1. The E_T spectrum of the leading photon in the $\gamma\gamma$ candidate events in the data (points, statistical uncertainty only) together with the spectra from simulated GGM ($m_{\tilde{g}} = 1000$ GeV, $m_{\tilde{\chi}_1^0} = 450$ GeV), SPS8 ($\Lambda = 190$ TeV), and UED ($1/R = 1.3$ TeV) samples after the diphoton requirement. The signal samples are scaled by a factor of 100 for clarity.

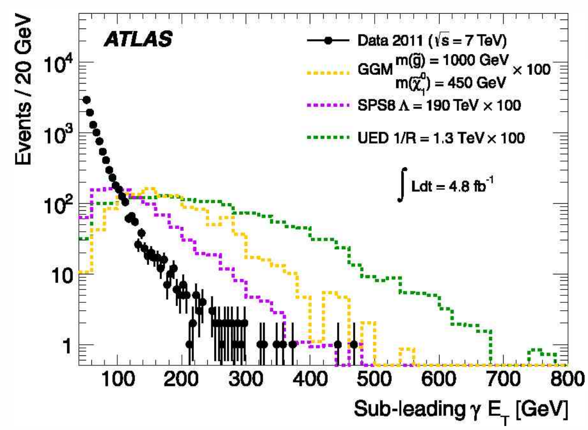

Fig. 2. The E_T spectrum of the sub-leading photon in the $\gamma\gamma$ candidate events in the data (points, statistical uncertainty only) together with the spectra from simulated GGM ($m_{\tilde{g}} = 1000$ GeV, $m_{\tilde{\chi}_1^0} = 450$ GeV), SPS8 ($\Lambda = 190$ TeV), and UED ($1/R = 1.3$ TeV) samples after the diphoton requirement. The signal samples are scaled by a factor of 100 for clarity.

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 $\Delta\phi_{min}(\gamma, E_T^{miss})$. 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 $\Delta\phi_{min}(\gamma, E_T^{miss}) > 0.5$ 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.

[2] An excess of events relative to a smoothly-falling distribution of the leading-photon spectrum was observed for $E_T \sim 285$ GeV. Searching over the range 100 GeV $< E_T <$ 500 GeV, a significance of 1.9σ was found using BumpHunter [60], while the local significance was found to be 3.1σ. 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 η, $\Delta\phi(\gamma_1, \gamma_2)$) 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.

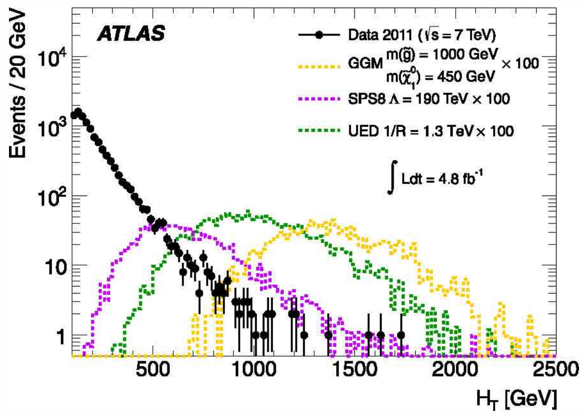

Fig. 3. The H_T spectrum of $\gamma\gamma$ candidate events in the data (points, statistical uncertainty only) together with the spectra from simulated GGM ($m_{\tilde{g}} = 1000$ GeV, $m_{\tilde{\chi}_1^0} = 450$ GeV), SPS8 ($\Lambda = 190$ TeV), and UED ($1/R = 1.3$ TeV) samples after the diphoton requirement. The signal samples are scaled by a factor of 100 for clarity.

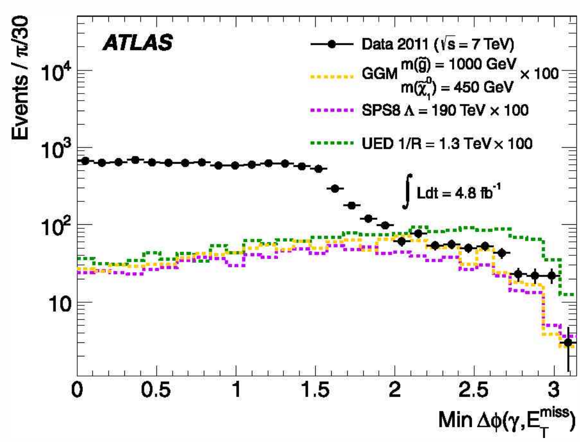

Fig. 4. The minimum $\Delta\phi(\gamma, E_T^{miss})$ spectrum of $\gamma\gamma$ candidate events in the data (points, statistical uncertainty only) together with the spectra from simulated GGM ($m_{\tilde{g}} = 1000$ GeV, $m_{\tilde{\chi}_1^0} = 450$ GeV), SPS8 ($\Lambda = 190$ TeV), and UED ($1/R = 1.3$ 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^{miss}, H_T and $\Delta\phi_{min}(\gamma, E_T^{miss})$.

	SR A	SR B	SR C
$E_T^{miss} >$	200 GeV	100 GeV	125 GeV
$H_T >$	600 GeV	1100 GeV	–
$\Delta\phi_{min}(\gamma, E_T^{miss}) >$	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^{miss} requirement of SR A, B and C, respectively. After imposing the final E_T^{miss} requirement, no events remained for SR A and B, while two events remained for SR C.

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

Table 2
Samples of selected events at progressive stages of the selection. Where no number is shown the cut was not applied.

	A	B	C
Triggered events	1 166 060		
Diphoton selection	10 455		
$\Delta\phi_{min}(\gamma, E_T^{miss})$ requirement	7293	–	7293
H_T requirement	117	9	–
E_T^{miss} requirement	0	0	2

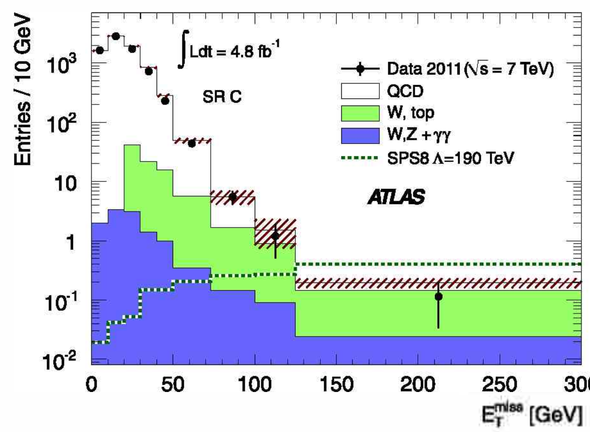

Fig. 5. E_T^{miss} spectra in SR C for the $\gamma\gamma$ candidate events in data (points, statistical uncertainty only) and the estimated QCD background (normalised to the number of $\gamma\gamma$ candidates with $E_T^{miss} < 20$ GeV), the $W(\to e\nu) + \text{jets}/\gamma$ and $t\bar{t}(\to e\nu) + \text{jets}$ backgrounds as estimated from the electron–photon control sample, and the irreducible background of $Z(\to \nu\bar{\nu}) + \gamma\gamma$ and $W(\to \ell\nu) + \gamma\gamma$. The hatched region represents the extent of the uncertainty on the total background prediction. Also shown is the expected signal from the SPS8 ($\Lambda = 190$ TeV) sample.

8. Background estimation

Following the procedure described in Ref. [61], the contribution to the large E_T^{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 γ + 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^{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 $\gamma\gamma$, γ + 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 $W \to e\nu$ decays. The H_T and $\Delta\phi_{min}(\gamma, E_T^{miss})$ requirements associated with each of the three SRs were then applied, yielding three separate QCD samples, or "templates". An estimate of the QCD background contamination in each SR was obtained from imposing the E_T^{miss} requirement associated with the given SR upon the corresponding QCD template, after normalising each template to the diphoton data with $E_T^{miss} < 20$ GeV from the given SR. This yielded a QCD background expectation of 0.85 ± 0.30(stat) events for SR C. No events above the corresponding E_T^{miss} requirement were observed for the A and B control samples, yielding an

Table 3
The expected number of $\gamma\gamma$ events for each of the three signal regions. The uncertainties are statistical, arising from the limited numbers of events in 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.

	SR A	SR B	SR C
QCD	$0.07 \pm 0.00 \pm 0.07$	$0.27 \pm 0.00 \pm 0.27$	$0.85 \pm 0.30 \pm 0.71$
Electroweak	$0.03 \pm 0.03 \pm 0.01$	$0.09 \pm 0.05 \pm 0.02$	$0.80 \pm 0.16 \pm 0.22$
$W(\rightarrow \ell\nu) + \gamma\gamma$	< 0.01	< 0.01	$0.18 \pm 0.13 \pm 0.18$
$Z(\rightarrow \nu\bar{\nu}) + \gamma\gamma$	< 0.01	< 0.01	$0.27 \pm 0.09 \pm 0.04$
Total	$0.10 \pm 0.03 \pm 0.07$	$0.36 \pm 0.05 \pm 0.27$	$2.11 \pm 0.37 \pm 0.77$
Observed events	0	0	2

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 H_T sidebands of the QCD control sample was employed. The H_T requirement applied to the QCD templates of SR A and B was relaxed in three steps: to 400 GeV, 200 GeV and 0 GeV for the SR A control sample, and to 800 GeV, 400 GeV and 200 GeV for the SR B control sample. For each SR, the E_T^{miss} distribution of each of these relaxed control samples was scaled to the diphoton E_T^{miss} distribution for $E_T^{miss} < 20$ GeV of the given SR, yielding a series of three expected values for the QCD background as a function of the applied H_T requirement. The complementary estimate for the background contribution to the signal region employed a parabolic extrapolation to the actual H_T requirement used for the analysis (600 GeV and 1100 GeV for SRs A and B, respectively); a linear fit yielded a significantly lower background estimate for both SRs. The parabolic extrapolation yielded conservative upper estimates of 0.14 and 0.54 events for SRs A and B, respectively. The overall QCD background estimates for SRs A and B were taken to be 0.07 ± 0.07(syst) and 0.27 ± 0.27(syst) events, respectively, half of the value of this upper estimate, with systematic uncertainty assigned to cover the entire range between 0 and the upper estimate. The choice of a parabolic function constrained by three H_T points does not permit an estimation of statistical uncertainty on the extrapolation.

Other sources of systematic uncertainty in the estimated QCD background were considered. Using the E_T^{miss} distribution from a sample of $Z \rightarrow e^+e^-$ events instead of that of the QCD sample yielded estimates of 0, 0 and 0.15 events for SRs A, B and C, respectively. The difference between this estimate and that of the QCD sample was incorporated as a systematic uncertainty of ± 0.71 on the SR C QCD background estimate. Making use of the alternative ranges 5 GeV $< E_T^{miss} <$ 25 GeV and 10 GeV $< E_T^{miss} <$ 30 GeV over which the QCD sample was normalised to the $\gamma\gamma$ sample resulted in a further systematic uncertainty of ± 0.03 events on the QCD background estimate for SR C. The resulting QCD background estimates for the three SRs, along with their uncertainties, are compiled in Table 3.

The EW background, from $W + X$ and $t\bar{t}$ events, was estimated via an "electron–photon" control sample composed of events with at least one tight photon and one electron, each with $E_T > 50$ GeV, and scaled by the probability for an electron to be mis-reconstructed as a tight photon, as estimated from a "tag-and-probe" study of the Z boson in the ee and $e\gamma$ sample. The scaling factor varies between 2.5% ($0 < |\eta| < 0.6$) and 7.0% ($1.52 < |\eta| < 1.81$), since it depends on the amount of material in front of the calorimeter. Events with two or more tight photons were vetoed from the control sample to preserve its orthogonality to the signal sample. In case of more than one electron, the one with the highest p_T was used.

After applying corresponding selection requirements on H_T, $\Delta\phi_{min}(\gamma, E_T^{miss})$ 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 $\pm 6.9\%$, $\pm 7.1\%$ and $\pm 10.0\%$ 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 $\pm 25\%$ 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 $Z(\rightarrow \nu\bar{\nu}) + \gamma\gamma$ and $W(\rightarrow \ell\nu) + \gamma\gamma$ processes was estimated using MC samples. It was found to be negligible for SRs A and B, and estimated to be $0.46 \pm 0.16 \pm 0.19$ 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 $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0}) = (800, 50)$ 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 $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0}) = (800, 790)$ GeV to (1300, 50) GeV. The SPS8 signal efficiency in SR C increases smoothly from 5.9% ($\Lambda = 100$ TeV) to

Table 4
Relative systematic uncertainties on the expected signal yield for the GGM model with $m_{\tilde{g}} = 1000$ GeV and $m_{\tilde{\chi}_1^0} = 450$ GeV, the SPS8 model with $\Lambda = 190$ TeV, and the UED model with $1/R = 1.3$ TeV. For the GGM model, when the uncertainty differs for SRs A and B, it is presented as SRA/SRB. No PDF and scale uncertainties are given for the UED case as the cross section is evaluated only to LO.

Source of uncertainty	Uncertainty		
	GGM	SPS8	UED
Integrated luminosity	3.9%	3.9%	3.9%
Trigger	0.5%	0.5%	0.5%
Photon identification	4.4%	4.4%	4.4%
Photon isolation	0.9%	0.2%	0.4%
Pile-up	0.8%	0.5%	0.5%
E_T^{miss} reconstruction	3.9/1.1%	2.8%	1.5%
H_T	0.0/2.1%	–	0.4%
Signal MC statistics	3.0%	2.1%	1.4%
Total signal uncertainty	7.6/7.1%	6.8%	6.3%
PDF and scale	31%	5.5%	–
Total	32%	8.7%	6.3%

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, SPS8 and UED signal cross sections are summarised in Table 4 for the chosen reference points: $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0}) = (1000, 450)$ GeV for GGM, $\Lambda = 190$ TeV for SPS8, 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 $99.8^{+0.2}_{-0.8}$% 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, SPS8 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, SPS8 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, SPS8 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% (SPS8) and ±0.5% (UED). Systematic uncertainties due to the E_T^{miss} reconstruction, estimated by varying the cluster energies and the E_T^{miss} 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% (SPS8) and ±0.9% to ±2% (UED). Systematic uncertainties due to the H_T reconstruction, estimated by varying the energy scale and resolution of the individual objects entering H_T, 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 E_T^{miss} and H_T 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% (SPS8), and ±6% and ±7% (UED).

The PDF and factorisation and renormalisation scale uncertainties on the GGM (SPS8) 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 SPS8 models, respectively. The different impact

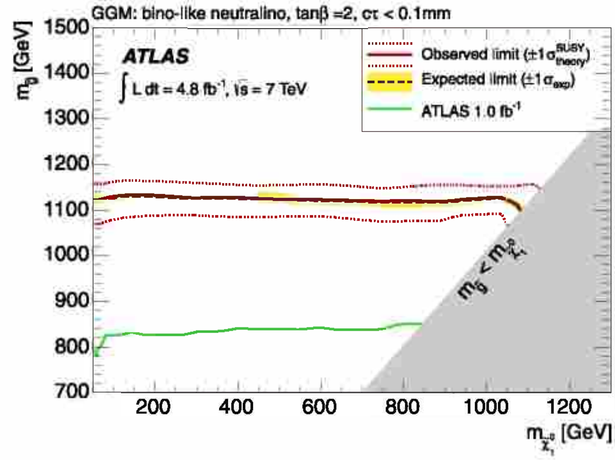

Fig. 6. Expected and observed 95% CL lower limits on the gluino mass as a function of the neutralino mass in the GGM model with a bino-like lightest neutralino NLSP (the grey area indicates the region for which the gluino mass is less than the bino mass, which is not considered here). The other sparticle masses are assumed to be decoupled. Further model parameters are $\tan\beta = 2$ and $c\tau_{NLSP} < 0.1$ mm. The previous ATLAS limit [1] is also shown.

of the PDF and scale uncertainties on the GGM and SPS8 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 α_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% 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

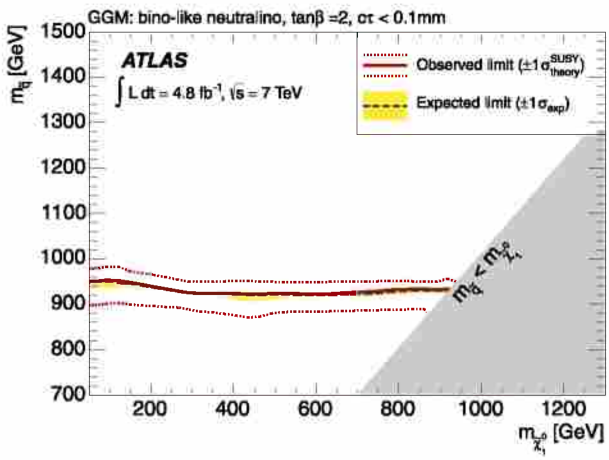

Fig. 7. Expected and observed 95% CL lower limits on the squark mass as a function of the neutralino mass in the GGM model with a bino-like lightest neutralino NLSP (the grey area indicates the region for which the squark mass is less than the bino mass, which is not considered here). The other sparticle masses are assumed to be decoupled. Further model parameters are $\tan\beta = 2$ and $c\tau_{\mathrm{NLSP}} < 0.1$ mm.

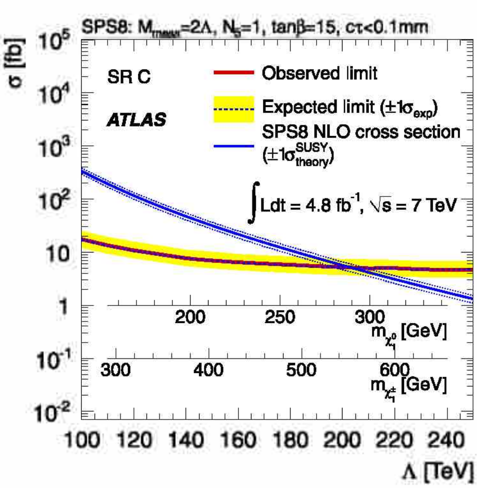

Fig. 8. Expected and observed 95% CL upper limits on the sparticle production cross section in the SPS8 model, and the NLO cross-section prediction, as a function of Λ and the lightest neutralino and chargino masses. Further SPS8 model parameters are $M_{\mathrm{mess}} = 2\Lambda$, $N_5 = 1$, $\tan\beta = 15$ and $c\tau_{\mathrm{NLSP}} < 0.1$ mm. Limits are set based on SR C.

reducing and increasing the cross section by one standard deviation of theoretical uncertainty (the combined uncertainty due to the PDFs and renormalisation and factorisation scales). For comparison the lower limits on the GGM gluino mass from ATLAS [1] based on 1 fb^{-1} from 2011 are also shown.

Including all sources of uncertainty other than the theoretical uncertainty, 95% CL upper limits on the cross section of the SPS8 model are derived from the SR C result and displayed in Fig. 8 for the range $\Lambda = 100$–250 TeV along with the overall production cross section and its theoretical uncertainty. For illustration the cross-section dependence as a function of the lightest neutralino and chargino masses is also shown.

Fig. 9 shows the limit on the cross section times branching ratio for the UED model as a function of the compactification scale $1/R$, derived from the result of SR A. A 95% CL lower limit of $1/R > 1.40$ TeV is set. For illustration the cross-section dependence as a function of the KK quark and KK gluon masses is also shown. Again, neither PDF nor scale uncertainties are included when calculating the limits; including PDF and scale uncertainties, com-

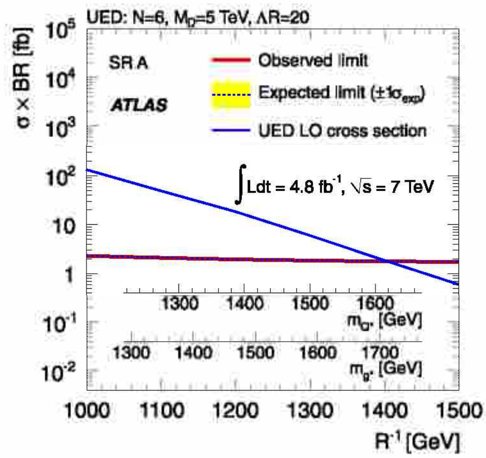

Fig. 9. Expected and observed 95% CL upper limits on the KK particle production cross section times branching ratio to two photons in the UED model, and the LO cross-section prediction times branching ratio, as a function of $1/R$ and the KK quark (Q^*) and KK gluon (g^*) masses. The $\pm 1\sigma$ expected-limit 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 $\Lambda R = 20$. Limits are set based on SR A.

puted at LO, in the limit calculation degrades the limit on $1/R$ by a few GeV.

11. Conclusions

A search for events with two photons and substantial $E_{\mathrm{T}}^{\mathrm{miss}}$, 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 Λ 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.

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