



# Search for diphoton events with large missing transverse momentum in $1 \text{ fb}^{-1}$ of 7 TeV proton–proton collision data with the ATLAS detector<sup>☆</sup>

ATLAS Collaboration<sup>\*</sup>

## ARTICLE INFO

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## ABSTRACT

A search for diphoton events with large missing transverse momentum has been performed using  $1.07 \text{ fb}^{-1}$  of proton–proton collision data at  $\sqrt{s} = 7 \text{ TeV}$  recorded with the ATLAS detector. No excess of events was observed above the Standard Model prediction and 95% Confidence Level (CL) upper limits are set on the production cross section for new physics. The limits depend on each model parameter space and vary as follows:  $\sigma < (22\text{--}129) \text{ fb}$  in the context of a generalised model of gauge-mediated supersymmetry breaking (GGM) with a bino-like lightest neutralino,  $\sigma < (27\text{--}91) \text{ fb}$  in the context of a minimal model of gauge-mediated supersymmetry breaking (SPS8), and  $\sigma < (15\text{--}27) \text{ fb}$  in the context of a specific model with one universal extra dimension (UED). A 95% CL lower limit of 805 GeV, for bino masses above 50 GeV, is set on the GGM gluino mass. Lower limits of 145 TeV and 1.23 TeV are set on the SPS8 breaking scale  $\Lambda$  and on the UED compactification scale  $1/R$ , respectively. These limits provide the most stringent tests of these models to date.

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## 1. Introduction

This Letter reports on the search for diphoton ( $\gamma\gamma$ ) events with large missing transverse momentum ( $E_T^{\text{miss}}$ ) in  $1.07 \text{ fb}^{-1}$  of proton–proton ( $pp$ ) collision data at  $\sqrt{s} = 7 \text{ TeV}$  recorded with the ATLAS detector in the first half of 2011, extending a prior study performed with  $36 \text{ pb}^{-1}$  [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 positing one universal extra dimension (UED) [6–8].

## 2. Supersymmetry

Supersymmetry (SUSY) [9–14] 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 realized in nature. Assuming  $R$ -parity conservation [15,16], sparticles have to be produced in pairs. These would then decay through cascades involving other sparticles until the lightest SUSY particle (LSP) is produced, which is stable.

In gauge-mediated SUSY breaking (GMSB) models [17–21] the LSP is the gravitino  $\tilde{G}$ . GMSB experimental signatures are largely

determined by the nature of the next-to-lightest SUSY particle (NLSP), which for a large part of the GMSB parameter space is the lightest neutralino  $\tilde{\chi}_1^0$ . Should the lightest neutralino have similar couplings as the SM  $U(1)$  gauge boson, also referred to as “bino” in this case, the final decay in the cascade would predominantly be  $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ , 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.

Searches for GMSB performed at the Tevatron [22,23] were optimized to be sensitive to a minimal GMSB model (SPS8) [5]. To reduce the number of free parameters in this model, several assumptions are made. These assumptions lead to a mass hierarchy in which squarks and gluinos are much heavier than the lightest neutralino and chargino  $\tilde{\chi}_1^\pm$ . The SUSY breaking mass scale felt by the low-energy sector,  $\Lambda$ , is the only free parameter of the SPS8 model. The other model parameters are fixed to the following values: the messenger mass  $M_{\text{mess}} = 2\Lambda$ , the number of copies of  $5 + \bar{5}$   $SU(5)$  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 NLSP is assumed to decay promptly ( $c\tau_{\text{NLSP}} < 0.1 \text{ mm}$ ). At the present LHC energy the main contribution to the production cross section in the SPS8 model is via gaugino pair production, i.e. production of  $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$  or  $\tilde{\chi}_2^0\tilde{\chi}_2^0$  pairs. The contribution from gluino and/or squark pairs is below 10% of the production cross section due to their high masses. Besides the two photons and the two gravitinos, jets, leptons, and gauge bosons may be produced in the cascades. This Letter presents the first limits on the SPS8 model at the LHC. Furthermore, a GGM SUSY model is considered in which the

<sup>☆</sup> © CERN for the benefit of the ATLAS Collaboration.

<sup>\*</sup> E-mail address: [atlas.publications@cern.ch](mailto:atlas.publications@cern.ch).

gluino and neutralino masses are treated as free parameters. The other sparticle masses are fixed at  $\sim 1.5$  TeV, leading to a dominant production mode at  $\sqrt{s} = 7$  TeV of a pair of gluinos via the strong interaction that would decay via cascades into the bino-like neutralino NLSP. Jets may be produced in the cascades from the gluino decays if kinematically allowed. Further model parameters are fixed to  $\tan\beta = 2$  and  $c\tau_{\text{NLSP}} < 0.1$  mm. The decay into the wino-like neutralino NLSP is possible and was studied by the CMS Collaboration [24].

### 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-level KK quarks and/or gluons [25]. These would decay via cascades involving other KK particles until reaching the lightest KK particle (LKP), i.e. the first 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 [26], 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-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  $\Lambda$ , the ultraviolet cut-off used in the calculation of radiative corrections to the KK masses. This analysis sets  $\Lambda$  such that  $\Lambda R = 20$ . The  $\gamma^*$  mass is insensitive to  $\Lambda$ , while other KK masses typically change by a few per cent when varying  $\Lambda R$  in the range 10–30. For  $1/R = 1200$  GeV, the masses of the first-level KK photon, quark, and gluon are 1200, 1387 and 1468 GeV, respectively [27]. Further details of the model are given in Ref. [1].

### 4. Simulated samples

For the GGM model, the SUSY mass spectra were calculated using SUSPECT 2.41 [28] and SDECAY 1.3 [29]. The Monte Carlo (MC) signal samples were produced using PYTHIA 6.423 [30] with MRST2007 LO\* [31] parton distribution functions (PDF). Cross sections were calculated at next-to-leading order (NLO) using PROSPINO 2.1 [32,33]. For the SPS8 model, the SUSY mass spectra were calculated using ISAJET 7.80 [34]. The MC signal samples were produced using HERWIG++ 2.4.2 [35] with MRST2007 LO\* PDF. NLO cross sections were calculated using PROSPINO. In the case of the UED model, MC signal samples were generated using the UED model as implemented at leading order (LO) in PYTHIA [27].

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 [36] with CTEQ6L1 [37] PDF. Parton showering and fragmentation were simulated with PYTHIA. NLO cross sections and scale uncertainties from Refs. [38,39] were used. In all cases the underlying event was simulated within the respective generator.

All samples were processed through the GEANT4-based simulation [40] of the ATLAS detector [41]. In addition, the signal samples were overlaid with simulated minimum bias events to model the average number of six  $pp$  interactions per bunch crossing (pile-up) experienced during the considered data-taking period. More details may be found in Ref. [1].

### 5. ATLAS detector

The ATLAS detector [42] 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 comprised of 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. The straw-tube detectors also provide discrimination between electrons and charged hadrons based on transition radiation. Outside the solenoid, fine-granularity lead/liquid-argon (LAR) electromagnetic (EM) calorimeters provide coverage for  $|\eta| < 3.2$  to measure the energy and position of electrons and photons. In the region  $|\eta| < 2.5$ , the EM calorimeters are segmented into three layers in depth. The second layer, in which most of the EM shower energy is deposited, is divided into cells of granularity of  $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ . The first layer is segmented with finer granularity to provide discrimination between single photons and overlapping photons coming from the decays of neutral mesons. 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 copper and liquid-argon technology is used for hadronic calorimeters in the end-cap region  $1.5 < |\eta| < 3.2$ . In the forward region  $3.2 < |\eta| < 4.5$  liquid-argon calorimeters with copper and tungsten absorbers measure the electromagnetic and hadronic energy. A muon spectrometer consisting of three superconducting toroidal magnet systems, tracking chambers, and detectors for triggering surrounds the calorimeter system.

### 6. Object reconstruction

The reconstruction of converted and unconverted photons and of electrons is described in Refs. [43] and [44], respectively.

Converted photons have EM calorimeter clusters matched to tracks coming from a conversion vertex. A conversion vertex is either a vertex that has two tracks with large transition radiation in the straw-tube detector and an invariant mass of the two tracks consistent with a massless particle, i.e. a photon, or one track with large transition radiation that has no associated hits in the pixel layer closest to the beam line. Electrons have a track matched to the EM calorimeter cluster, and the track must have hits in the silicon detectors, momentum not smaller than one tenth the cluster energy, and transverse momentum of at least 2 GeV. Clusters matched to neither a track or tracks coming from a conversion vertex nor an electron track as described above are classified as unconverted photons. A heuristic using the pixel hits closest to the beam line and the track momenta is applied to choose between the photon and electron interpretation in cases where the object can be both.

<sup>1</sup> 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  $\eta = -\ln \tan(\theta/2)$ .

Photon candidates were required to be within  $|\eta| < 1.81$ , the value being chosen by an optimization of the signal acceptance versus background rejection, and to be outside the transition region  $1.37 < |\eta| < 1.52$  between the barrel and the end-cap calorimeters. The analysis used “loose” and “tight” photon selections [43]. The loose photon selection includes a limit on the fraction of the energy deposit in the hadronic calorimeter as well as a requirement that the transverse width of the shower, measured in the middle layer of the EM calorimeter, be consistent with the narrow shape expected for an EM shower. The tight photon selection additionally uses shape information from the first layer to distinguish between isolated photons and photons from the decay of neutral mesons.

The reconstruction of  $E_T^{\text{miss}}$  is based on energy deposits in calorimeter cells inside three-dimensional clusters with  $|\eta| < 4.5$  and is corrected for contributions from muons, if any [45]. The cluster energy is calibrated to correct for the non-compensating calorimeter response, energy loss in dead material, and out-of-cluster energy.

Jets were reconstructed using the anti- $k_t$  jet algorithm [46] with four-momentum recombination and radius parameter  $R = 0.4$  in  $\eta$ - $\phi$  space. They were required to have  $p_T > 25$  GeV and  $|\eta| < 2.8$ .

## 7. Data analysis

The data sample, corresponding to an integrated luminosity of  $(1.07 \pm 0.04) \text{ fb}^{-1}$ , was selected by a trigger requiring two loose photon candidates with a transverse energy ( $E_T$ ) above 20 GeV. In the offline analysis events were retained if they contained at least two tight photon candidates with  $E_T > 25$  GeV. In addition, a photon isolation cut was applied, whereby the  $E_T$  deposit in a cone of radius 0.2 in the  $\eta$ - $\phi$  space around the centre of the cluster, excluding the cells belonging to the cluster, had to be less than 5 GeV. The  $E_T$  was corrected for leakage from the photon energy outside the cluster and for soft energy deposits from pile-up interactions. A cut of  $E_T^{\text{miss}} > 125$  GeV [1] defined the signal region. Preference was given to a common signal region for the three models considered.

A total of 27293  $\gamma\gamma$  candidate events were observed passing all selections except the  $E_T^{\text{miss}}$  cut. The  $E_T$  distribution of the leading photon for events in this sample is shown in Fig. 1. Also shown are the  $E_T$  spectra obtained from GGM MC samples for  $m_{\tilde{g}} = 800$  GeV and  $m_{\tilde{\chi}_1^0} = 400$  GeV, from SPS8 MC samples with  $\Lambda = 140$  TeV, and from UED MC samples for  $1/R = 1200$  GeV, representing model parameters near the expected exclusion limit. After the  $E_T^{\text{miss}} > 125$  GeV cut, 5 candidate events survived.

## 8. Background estimation

Following the procedure described in Ref. [1], the contribution to large  $E_T^{\text{miss}}$  diphoton events from SM sources can be grouped into two primary components and estimated with dedicated control samples using data. The first of these components, referred to as “QCD background” for brevity, arises from a mixture of processes that include  $\gamma\gamma$  production as well as  $\gamma$  + jet and multijet events with at least one jet mis-reconstructed as a photon. The second background component is due to  $W + X$  and  $t\bar{t}$  events, where mis-reconstructed photons can arise from electrons and jets, for which final-state neutrinos produce significant  $E_T^{\text{miss}}$ .

In order to estimate the QCD background from  $\gamma\gamma$ ,  $\gamma$  + jet, and multijet events, a “QCD control sample” was extracted from the diphoton trigger sample by selecting events for which at least one of the photon candidates does not pass the tight photon identification. Electrons were vetoed to remove contamination from  $W \rightarrow e\nu$  decays. The QCD background contamination in the signal

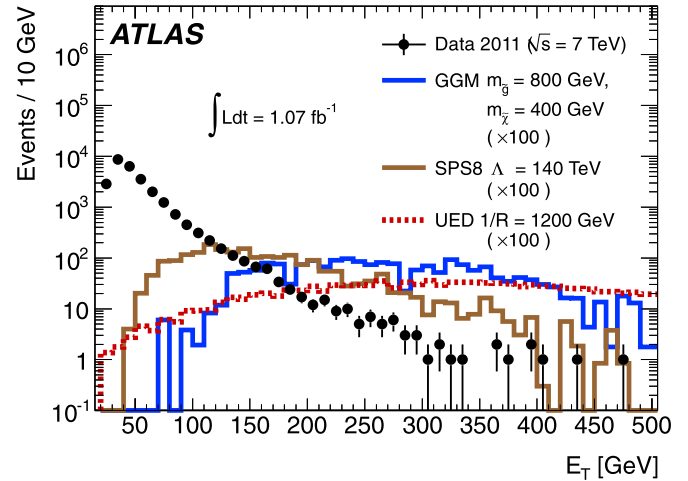


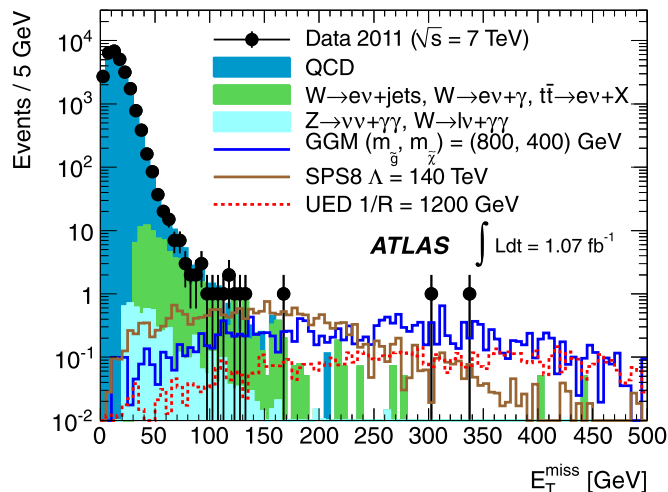
Fig. 1. The  $E_T$  spectrum of the leading photon in the  $\gamma\gamma$  candidate events in the data (points, statistical uncertainty only) together with the spectra from simulated GGM ( $m_{\tilde{g}}, m_{\tilde{\chi}_1^0} = (800, 400)$  GeV), SPS8 ( $\Lambda = 140$  TeV), and UED ( $1/R = 1200$  GeV) samples, prior to the application of the  $E_T^{\text{miss}} > 125$  GeV cut. The signal samples are scaled by a factor of 100 for clarity.

region  $E_T^{\text{miss}} > 125$  GeV was obtained from this QCD template after normalizing it to data in the region  $E_T^{\text{miss}} < 20$  GeV. This gives a QCD background expectation in the signal region of  $0.8 \pm 0.3$  (stat) events. An alternate model for the QCD background was obtained using a sample of dielectron events, with no jets, selected by requiring two electrons with  $E_T > 25$  GeV and  $|\eta| < 1.81$  and an invariant mass consistent with the  $Z$  boson mass. As confirmed by MC simulation, the  $E_T^{\text{miss}}$  spectrum of this  $Z \rightarrow ee$  sample with no additional jets, which is dominated by the calorimeter response to two genuine EM objects, accurately represents the  $E_T^{\text{miss}}$  spectrum of SM  $\gamma\gamma$  events. This spectrum was normalized in the same way as the QCD control sample. An uncertainty of 0.6 events was assigned as the systematic uncertainty on the background prediction from the relative fractions of  $\gamma\gamma$ ,  $\gamma$  + jet, and multijet events using the difference between the background estimates obtained using the QCD and the  $Z \rightarrow ee$  templates, yielding the result of  $0.8 \pm 0.3$  (stat)  $\pm 0.6$  (syst) events. The  $E_T^{\text{miss}}$  spectra of the QCD background and the  $\gamma\gamma$  sample are shown in Fig. 2.

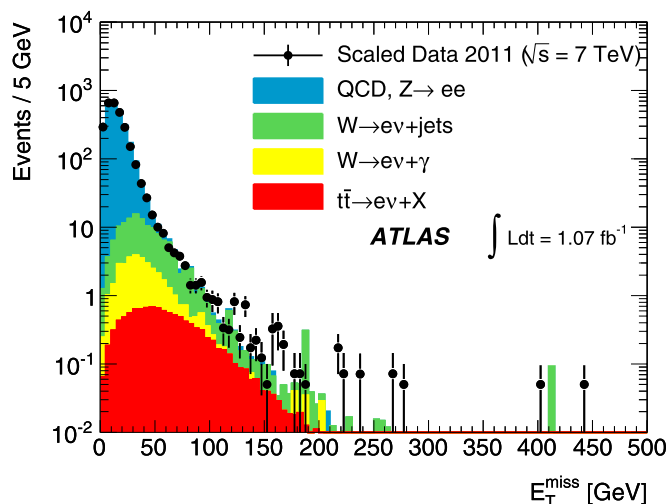
The second significant background contribution, from  $W + X$  and  $t\bar{t}$  events, was estimated via an “electron-photon” control sample composed of events with at least one photon and one electron, each with  $E_T > 25$  GeV, and scaled by the probability for an electron to be mis-reconstructed as a tight photon, as estimated from a study of the  $Z$  boson in the  $ee$  and  $e\gamma$  sample. The scaling factor varies between 5% and 17% as a function of  $\eta$ , since it depends on the amount of material in front of the calorimeter. Events with two or more photons were vetoed from the control sample to keep it orthogonal to the signal sample. In case of more than one electron, the one with the highest  $p_T$  was used. The  $E_T^{\text{miss}}$  spectrum for the scaled electron-photon control sample is shown in Fig. 3, where it is compared to the expected contributions from various background sources as computed from MC simulation. The electron-photon control sample has a significant contamination from  $Z \rightarrow ee$  events, in which one electron is mis-reconstructed as a photon, and from QCD processes mentioned above. Both of these contaminations must be subtracted in order to extract the contribution to the  $E_T^{\text{miss}}$  distribution from events with genuine  $E_T^{\text{miss}}$ , such as  $W + X$  and  $t\bar{t}$ . The contribution from QCD and  $Z \rightarrow ee$  events was estimated by normalizing the QCD control sample to the scaled electron-photon  $E_T^{\text{miss}}$  distribution in the re-

**Table 1**  
Number of observed  $\gamma\gamma$  candidates in various  $E_T^{\text{miss}}$  ranges in the data, as well as the expected numbers of SM background events estimated from the QCD and electron-photon control samples and, for the irreducible  $Z(\rightarrow \nu\bar{\nu}) + \gamma\gamma$  and  $W(\rightarrow \ell\nu) + \gamma\gamma$  processes, from MC simulation. Also shown are the expected numbers of signal events from GGM with  $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0}) = (800, 400)$  GeV, SPS8 with  $\Lambda = 140$  TeV, and UED with  $1/R = 1200$  GeV. The uncertainties are statistical only. The  $E_T^{\text{miss}} < 20$  GeV region (first row) is used to normalize the QCD background to the number of observed  $\gamma\gamma$  candidates.

$E_T^{\text{miss}}$ range [GeV]	Data events	Predicted background events				Expected signal events		
		Total	QCD	$W/\bar{t}\bar{t}(\rightarrow e\nu) + X$	Irreducible	GGM	SPS8	UED
0–20	20881	–	–	–	–	$0.20 \pm 0.05$	$0.22 \pm 0.04$	$0.02 \pm 0.01$
20–50	6304	$5968 \pm 29$	$5951 \pm 28$	$13.3 \pm 8.1$	$3.55 \pm 0.35$	$0.45 \pm 0.08$	$1.53 \pm 0.10$	$0.11 \pm 0.01$
50–75	86	$87.1 \pm 3.3$	$60.9 \pm 2.8$	$25.2 \pm 1.7$	$1.01 \pm 0.16$	$0.48 \pm 0.08$	$2.19 \pm 0.12$	$0.14 \pm 0.01$
75–100	11	$14.7 \pm 1.2$	$6.7 \pm 0.9$	$7.4 \pm 0.8$	$0.52 \pm 0.10$	$0.75 \pm 0.10$	$2.09 \pm 0.11$	$0.15 \pm 0.01$
100–125	6	$4.9 \pm 0.7$	$1.6 \pm 0.4$	$3.0 \pm 0.5$	$0.32 \pm 0.08$	$1.20 \pm 0.12$	$2.53 \pm 0.13$	$0.29 \pm 0.02$
>125	5	$4.1 \pm 0.6$	$0.8 \pm 0.3$	$3.1 \pm 0.5$	$0.23 \pm 0.05$	$17.2 \pm 0.5$	$12.98 \pm 0.28$	$9.67 \pm 0.11$



**Fig. 2.**  $E_T^{\text{miss}}$  spectra for the  $\gamma\gamma$  candidate events in data (points, statistical uncertainty only) and the estimated QCD background (normalized to the number of  $\gamma\gamma$  candidates with  $E_T^{\text{miss}} < 20$  GeV), the  $W(\rightarrow e\nu) + \text{jets}/\gamma$  and  $t\bar{t}(\rightarrow e\nu) + \text{jets}$  backgrounds as estimated from the electron-photon control sample, and the irreducible background of  $Z(\rightarrow \nu\bar{\nu}) + \gamma\gamma$  and  $W(\rightarrow \ell\nu) + \gamma\gamma$ . Also shown are the expected signals from GGM  $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0}) = (800, 400)$  GeV, SPS8 ( $\Lambda = 140$  TeV), and UED ( $1/R = 1200$  GeV) samples.



**Fig. 3.**  $E_T^{\text{miss}}$  spectrum for the electron-photon control sample in data (points, statistical uncertainty only), normalized according to the probability for an electron to be mis-reconstructed as a tight photon, compared to the expected backgrounds displayed by components (stacked histograms). For the purpose of this comparison, the expected contributions from  $W(\rightarrow e\nu) + \text{jets}/\gamma$  and  $t\bar{t}(\rightarrow e\nu) + \text{jets}$  events are taken from MC simulation.

gion  $E_T^{\text{miss}} < 20$  GeV where they dominate, as shown in Fig. 3. This distribution was then subtracted from the scaled electron-photon control sample, yielding a prediction for the contribution to the high- $E_T^{\text{miss}}$  diphoton sample from  $W + X$  and  $t\bar{t}$  events. This procedure led to an estimate of the background from  $W + X$  and  $t\bar{t}$  production of  $3.1 \pm 0.5(\text{stat})$  events in the signal region. A systematic uncertainty of 0.06 events was assigned by using the  $Z \rightarrow ee$  template in place of the QCD template when subtracting the contamination due to  $Z \rightarrow ee$  and QCD processes. The contribution from  $WW$  events to the electron-photon control sample was estimated using MC simulation and found to be negligible.

A parallel study using MC samples of  $W(\rightarrow e\nu) + \text{jets}/\gamma$  and  $t\bar{t}(\rightarrow e\nu) + \text{jets}$ , rather than the electron-photon control sample, gave an estimate of  $1.8 \pm 1.2(\text{stat})$  background events. The difference was taken as an estimate of the systematic uncertainty, yielding the result of  $3.1 \pm 0.5(\text{stat}) \pm 1.4(\text{syst})$  events. Also included in the quoted systematic uncertainty is the relative uncertainty ( $\pm 10\%$ ) on the probability for an electron to be mis-reconstructed as a photon.

A small irreducible background of  $0.23 \pm 0.05(\text{stat}) \pm 0.04(\text{syst})$  events from  $Z(\rightarrow \nu\bar{\nu}) + \gamma\gamma$  and  $W(\rightarrow \ell\nu) + \gamma\gamma$  events was estimated from MC simulation. The systematic uncertainty accounts for variations in the factorization and renormalization scales in the NLO calculations. The contamination from cosmic-ray muons was found to be negligible.

Fig. 2 shows the  $E_T^{\text{miss}}$  spectrum of the selected  $\gamma\gamma$  candidates, superimposed on the estimated backgrounds. Table 1 summarizes the number of observed  $\gamma\gamma$  candidates, the expected backgrounds, and three representative GGM, SPS8, and UED signal expectations, in several  $E_T^{\text{miss}}$  ranges. No indication of an excess at high  $E_T^{\text{miss}}$  values, where the signal is expected to dominate, is observed.

## 9. Signal efficiencies and systematic uncertainties

The GGM signal efficiency was determined using MC simulation over an area of the GGM parameter space that ranges from 400 GeV to 1200 GeV for the gluino mass, and from 50 GeV to within 20 GeV of the gluino mass for the neutralino mass. The efficiency increases smoothly from 5.5% to 31% for  $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0}) = (400, 50)$  GeV to (1200, 1100) GeV. The SPS8 signal efficiency increases smoothly from 9.2% ( $\Lambda = 80$  TeV) to 29.4% ( $\Lambda = 220$  TeV). The UED signal efficiency, also determined using MC simulation, increases smoothly from 48.9% ( $1/R = 1000$  GeV) to 52.6% ( $1/R = 1500$  GeV).

The various relative systematic uncertainties on the GGM, SPS8, and UED signal cross sections are summarized in Table 2 for the chosen GGM, SPS8, and UED reference points. The uncertainty on the luminosity is 3.7% [47,48]. The trigger efficiency of the required diphoton trigger was estimated from the efficiency of the corresponding single photon trigger, which was estimated using a bootstrap method [49]. The result is  $99.92_{-0.18}^{+0.04}\%$  for events passing

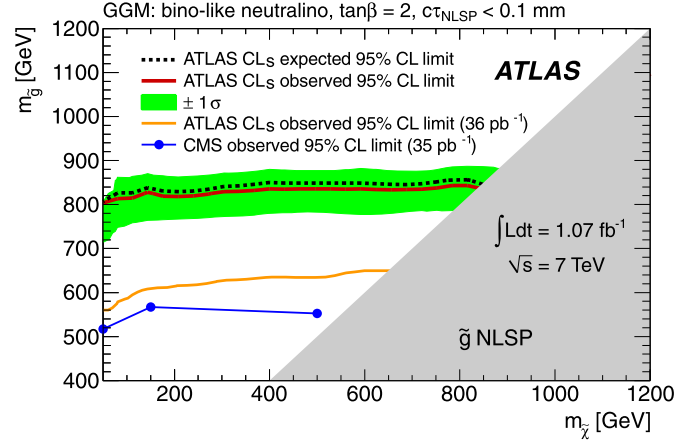
**Table 2**

Relative systematic uncertainties on the expected signal yield for GGM with  $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0}) = (800, 400)$  GeV, SPS8 with  $\Lambda = 140$  TeV, and UED with  $1/R = 1200$  GeV. 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	3.7%	3.7%	3.7%
Trigger	0.6%	0.6%	0.6%
Photon identification	3.9%	3.9%	3.7%
Photon isolation	0.6%	0.6%	0.5%
Pile-up	1.3%	1.3%	1.6%
$E_T^{\text{miss}}$ reconstruction and scale	1.7%	5.6%	0.7%
LAr readout	1.0%	0.7%	0.4%
Signal MC statistics	2.9%	2.3%	1.8%
Total signal uncertainty	6.6%	8.3%	6.0%
PDF and scale	31%	5.5%	–
Total	32%	10%	6.0%

all selections except the final  $E_T^{\text{miss}}$  cut. To estimate the systematic uncertainty due to the unknown composition of the data sample, the trigger efficiency was also evaluated on MC events using misreconstructed photons from filtered multijet samples and photons from signal (SUSY and UED) samples. A conservative systematic uncertainty of 0.6% 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. [1], result in an uncertainty of 3.9% for the GGM and SPS8 signals and 3.7% for the UED signal. The uncertainty from the photon isolation was estimated by varying the energy leakage and the pile-up corrections independently, resulting in an uncertainty of 0.6% for GGM and SPS8 and 0.5% for UED. The influence of pile-up on the signal efficiency, evaluated by comparing GGM/SPS8 (UED) MC samples with different pile-up configurations, leads to a systematic uncertainty of 1.3% (1.6%). Systematic uncertainties due to the  $E_T^{\text{miss}}$  reconstruction, estimated by varying the cluster energies within established ranges and the  $E_T^{\text{miss}}$  resolution between the measured performance and MC expectations, contribute an uncertainty of 0.1% to 12.4% (GGM), 1.7% to 13.8% (SPS8), and 0.5% to 1.5% (UED). A systematic uncertainty was also assigned to account for temporary failures of the LAr calorimeter readout during part of the data-taking period, which was not modeled in the MC samples. Electrons and photons were removed from the afflicted area, but jets, being larger objects, were not. Jet energy corrections were therefore applied. Varying these corrections over their range of uncertainty results in systematic uncertainties of 1.0%, 0.7%, and 0.4% for GGM, SPS8, and UED, respectively. Added in quadrature, the total systematic uncertainty on the signal yield varies between 6.3% and 15% (GGM), 6.2% and 15% (SPS8), and 5.8% and 6.0% (UED).

The PDF uncertainties on the GGM (SPS8) cross sections were evaluated by using the CTEQ6.6M PDF error sets [50] in the PROSPINO cross section calculation and range from 12% to 44% (4.7% to 6.6%). The factorization and renormalization scales in the NLO PROSPINO calculation were increased and decreased by a factor of two, leading to a systematic uncertainty between 16% and 23% (1.7% and 6.7%) on the expected cross sections. The different impact of the PDF and scale uncertainties of 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 [51] 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 avail-



**Fig. 4.** 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 where the NLSP is the gluino, which is not considered here). The other sparticle masses are fixed to  $\sim 1.5$  TeV. Further model parameters are  $\tan\beta = 2$  and  $c\tau_{\text{NLSP}} < 0.1$  mm. The previous ATLAS [1] and CMS [52] limits are also shown.

able, but are expected to be much larger than the PDF and scale uncertainties. Thus, 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 given separately.

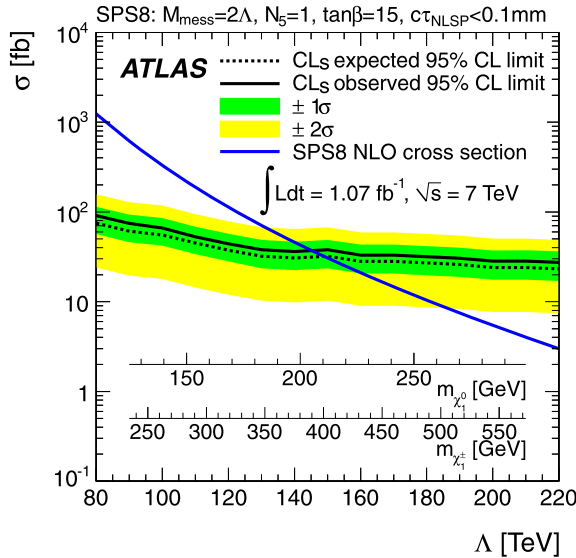
## 10. Results

Based on the observation of 5 events with  $E_T^{\text{miss}} > 125$  GeV and a background expectation of  $4.1 \pm 0.6(\text{stat}) \pm 1.6(\text{syst})$  events, a 95% CL upper limit is set on the number of events in the signal region from any scenario of physics beyond the SM using the profile likelihood and  $CL_s$  method [53]. The result is 7.1 events at 95% CL.

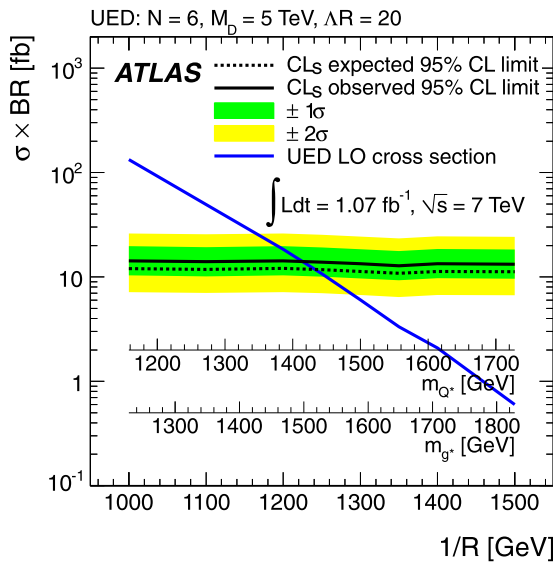
Further, 95% CL upper limits on the cross sections of the considered models are calculated, including all systematic uncertainties except for theory uncertainties, i.e. PDF and scale. In the GGM model the upper limit on the cross section is (22–129) fb, where the larger value corresponds to  $m_{\tilde{g}}, m_{\tilde{\chi}_1^0} = (400, 50)$  GeV. For  $m_{\tilde{\chi}_1^0} \geq 150$  GeV, the limit is below 30 fb, reaching 22 fb for heavy neutralino masses. Fig. 4 shows the expected and observed lower limits on the GGM gluino mass as a function of the neutralino mass. For comparison the lower limits from ATLAS [1] and CMS [52] based on the 2010 data are also shown. The total systematic uncertainty includes the theory uncertainties, which are dominant. Excluding the PDF and scale uncertainty in the limit calculation would improve the observed limit on the gluino mass by  $\sim 10$  GeV.

In the SPS8 model the cross section limit is  $\sigma < (27\text{--}91)$  fb as shown in Fig. 5, corresponding to  $\Lambda = 220\text{--}80$  TeV. For illustration the cross section dependence as a function of the lightest neutralino and chargino masses is also shown. A lower limit on the SPS8 breaking scale  $\Lambda > 145$  TeV at 95% CL is set including the theory uncertainties, i.e. PDF and scale uncertainties, in the total systematic uncertainty.

For the UED model the cross section limit is  $\sigma < (15\text{--}27)$  fb for  $1/R = 1000\text{--}1500$  GeV. Fig. 6 shows the limit on the cross section times branching ratio for the UED model, which is  $\sigma < (13\text{--}15)$  fb. For illustration the cross section dependence as a function of the KK quark and KK gluon masses is also shown. A lower limit on the UED compactification scale  $1/R > 1.23$  TeV at 95% CL is set. In this case PDF and scale uncertainties are not included when calculating



**Fig. 5.** 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  $M_{\text{mess}} = 2\Lambda$ ,  $N_5 = 1$ ,  $\tan\beta = 15$ , and  $c\tau_{\text{NLSP}} < 0.1$  mm.



**Fig. 6.** Expected and observed 95% CL upper limits on the KK particle production cross section times branching fraction to two photons in the UED model, and the LO cross section prediction times branching fraction, as a function of  $1/R$  and the KK quark ( $Q^*$ ) and KK gluon ( $g^*$ ) masses. The UED model parameters are  $N = 6$ ,  $M_D = 5$  TeV, and  $\Lambda R = 20$ .

the limits. Including PDF and scale uncertainties computed at LO degrade the limit on  $1/R$  by a few GeV.

## 11. Conclusions

A search for events with two photons and  $E_T^{\text{miss}} > 125$  GeV, performed using  $1.07 \text{ fb}^{-1}$  of 7 TeV  $pp$  collision data recorded with the ATLAS detector at the LHC, found 5 events with an expected background of  $4.1 \pm 0.6(\text{stat}) \pm 1.6(\text{syst})$ . The results are used to set a model-independent 95% CL upper limit of 7.1 events from new physics. Upper limits at 95% CL are also set on the production cross section for three particular models of new physics:  $\sigma < (22\text{--}129)$  fb for the GGM model,  $\sigma < (27\text{--}91)$  fb for the SPS8 model, and  $\sigma < (15\text{--}27)$  fb for the UED model. Under the GGM

hypothesis, a lower limit on the gluino mass of 805 GeV is determined for bino masses above 50 GeV. A lower limit of 145 TeV is set on the SPS8 breaking scale  $\Lambda$ , which is the first limit on the SPS8 model at the LHC. A lower limit of 1.23 TeV is set on the UED compactification scale  $1/R$ . These results provide the most stringent tests of these models to date, significantly improving upon previous best limits of 560 GeV [1] for the GGM gluino mass, 124 TeV [23] for  $\Lambda$  in SPS8, and 961 GeV [1] for  $1/R$  in UED, respectively.

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<sup>1</sup> University at Albany, Albany, NY, United States

<sup>2</sup> Department of Physics, University of Alberta, Edmonton, AB, Canada

<sup>3</sup> (a) Department of Physics, Ankara University, Ankara; (b) Department of Physics, Dumlupinar University, Kutahya; (c) Department of Physics, Gazi University, Ankara; (d) Division of Physics, TOBB University of Economics and Technology, Ankara; (e) Turkish Atomic Energy Authority, Ankara, Turkey

<sup>4</sup> LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France

<sup>5</sup> High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States

<sup>6</sup> Department of Physics, University of Arizona, Tucson, AZ, United States

<sup>7</sup> Department of Physics, The University of Texas at Arlington, Arlington, TX, United States

<sup>8</sup> Physics Department, University of Athens, Athens, Greece

<sup>9</sup> Physics Department, National Technical University of Athens, Zografou, Greece

<sup>10</sup> Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

<sup>11</sup> Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain

<sup>12</sup> (a) Institute of Physics, University of Belgrade, Belgrade; (b) Vinca Institute of Nuclear Sciences, Belgrade, Serbia

<sup>13</sup> Department for Physics and Technology, University of Bergen, Bergen, Norway

<sup>14</sup> Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States

<sup>15</sup> Department of Physics, Humboldt University, Berlin, Germany

<sup>16</sup> Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

<sup>17</sup> School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

<sup>18</sup> (a) Department of Physics, Bogazici University, Istanbul; (b) Division of Physics, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep;

(d) Department of Physics, Istanbul Technical University, Istanbul, Turkey

<sup>19</sup> (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica, Università di Bologna, Bologna, Italy

<sup>20</sup> Physikalisches Institut, University of Bonn, Bonn, Germany

<sup>21</sup> Department of Physics, Boston University, Boston, MA, United States

<sup>22</sup> Department of Physics, Brandeis University, Waltham, MA, United States

<sup>23</sup> (a) Universidade Federal do Rio De Janeiro COPPE/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 Física, Universidade de Sao Paulo, Sao Paulo, Brazil

<sup>24</sup> Physics Department, Brookhaven National Laboratory, Upton, NY, United States

<sup>25</sup> (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) University Politehnica Bucharest, Bucharest; (c) West University in Timisoara, Timisoara, Romania

<sup>26</sup> Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

<sup>27</sup> Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

<sup>28</sup> Department of Physics, Carleton University, Ottawa, ON, Canada

<sup>29</sup> CERN, Geneva, Switzerland

<sup>30</sup> Enrico Fermi Institute, University of Chicago, Chicago, IL, United States

<sup>31</sup> (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

<sup>32</sup> (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) High Energy Physics Group, Shandong University, Shandong, China

<sup>33</sup> Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France

<sup>34</sup> Nevis Laboratory, Columbia University, Irvington, NY, United States

<sup>35</sup> Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark

<sup>36</sup> (a) INFN Gruppo Collegato di Cosenza; (b) Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy

<sup>37</sup> Faculty of Physics and Applied Computer Science, AGH – University of Science and Technology, Krakow, Poland

<sup>38</sup> The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland

<sup>39</sup> Physics Department, Southern Methodist University, Dallas, TX, United States



- 40 Physics Department, University of Texas at Dallas, Richardson, TX, United States
- 41 DESY, Hamburg and Zeuthen, Germany
- 42 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- 43 Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
- 44 Department of Physics, Duke University, Durham, NC, United States
- 45 SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- 46 Fachhochschule Wiener Neustadt, Johannes Gutenbergstrasse 3, 2700 Wiener Neustadt, Austria
- 47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
- 48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
- 49 Section de Physique, Université de Genève, Geneva, Switzerland
- 50 <sup>(a)</sup> INFN Sezione di Genova; <sup>(b)</sup> Dipartimento di Fisica, Università di Genova, Genova, Italy
- 51 <sup>(a)</sup> E.Andronikashvili Institute of Physics, Georgian Academy of Sciences, Tbilisi; <sup>(b)</sup> High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- 52 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- 53 SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- 54 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- 55 Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
- 56 Department of Physics, Hampton University, Hampton, VA, United States
- 57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States
- 58 <sup>(a)</sup> Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; <sup>(b)</sup> Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; <sup>(c)</sup> ZITI Institut für Technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
- 59 Faculty of Science, Hiroshima University, Hiroshima, Japan
- 60 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- 61 Department of Physics, Indiana University, Bloomington, IN, United States
- 62 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- 63 University of Iowa, Iowa City, IA, United States
- 64 Department of Physics and Astronomy, Iowa State University, Ames, IA, United States
- 65 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- 66 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- 67 Graduate School of Science, Kobe University, Kobe, Japan
- 68 Faculty of Science, Kyoto University, Kyoto, Japan
- 69 Kyoto University of Education, Kyoto, Japan
- 70 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- 71 Physics Department, Lancaster University, Lancaster, United Kingdom
- 72 <sup>(a)</sup> INFN Sezione di Lecce; <sup>(b)</sup> Dipartimento di 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 Department of Physics, Queen Mary University of London, London, United Kingdom
- 76 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- 77 Department of Physics and Astronomy, University College London, London, United Kingdom
- 78 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- 79 Fysiska Institutionen, Lunds Universitet, Lund, Sweden
- 80 Departamento de Física Teórica, C-15, Universidad Autónoma 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 <sup>(a)</sup> INFN Sezione di Milano; <sup>(b)</sup> Dipartimento di Fisica, Università di Milano, Milano, Italy
- 90 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
- 91 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus
- 92 Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, United States
- 93 Group of Particle Physics, University of Montreal, Montreal, QC, Canada
- 94 P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
- 95 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- 96 Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
- 97 Skobel'syn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- 98 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- 99 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- 100 Nagasaki Institute of Applied Science, Nagasaki, Japan
- 101 Graduate School of Science, Nagoya University, Nagoya, Japan
- 102 <sup>(a)</sup> INFN Sezione di Napoli; <sup>(b)</sup> Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
- 103 Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States
- 104 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- 105 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- 106 Department of Physics, Northern Illinois University, DeKalb, IL, United States
- 107 Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia
- 108 Department of Physics, New York University, New York, NY, United States
- 109 Ohio State University, Columbus, OH, United States
- 110 Faculty of Science, Okayama University, Okayama, Japan
- 111 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States
- 112 Department of Physics, Oklahoma State University, Stillwater, OK, United States
- 113 Palacký University, RCPTM, Olomouc, Czech Republic
- 114 Center for High Energy Physics, University of Oregon, Eugene, OR, United States
- 115 LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France
- 116 Graduate School of Science, Osaka University, Osaka, Japan
- 117 Department of Physics, University of Oslo, Oslo, Norway

- 118 Department of Physics, Oxford University, Oxford, United Kingdom  
 119 <sup>(a)</sup> INFN Sezione di Pavia; <sup>(b)</sup> Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy  
 120 Department of Physics, University of Pennsylvania, Philadelphia, PA, United States  
 121 Petersburg Nuclear Physics Institute, Gatchina, Russia  
 122 <sup>(a)</sup> INFN Sezione di Pisa; <sup>(b)</sup> Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy  
 123 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States  
 124 <sup>(a)</sup> Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa, Portugal; <sup>(b)</sup> Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain  
 125 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic  
 126 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic  
 127 Czech Technical University in Prague, Praha, Czech Republic  
 128 State Research Center Institute for High Energy Physics, Protvino, Russia  
 129 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom  
 130 Physics Department, University of Regina, Regina, SK, Canada  
 131 Ritsumeikan University, Kusatsu, Shiga, Japan  
 132 <sup>(a)</sup> INFN Sezione di Roma I; <sup>(b)</sup> Dipartimento di Fisica, Università La Sapienza, Roma, Italy  
 133 <sup>(a)</sup> INFN Sezione di Roma Tor Vergata; <sup>(b)</sup> Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy  
 134 <sup>(a)</sup> INFN Sezione di Roma Tre; <sup>(b)</sup> Dipartimento di Fisica, Università Roma Tre, Roma, Italy  
 135 <sup>(a)</sup> Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies, Université Hassan II, Casablanca; <sup>(b)</sup> Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat; <sup>(c)</sup> Université Cadi Ayyad, Faculté des Sciences Semlalia, Département de Physique, B.P. 2390 Marrakech 40000; <sup>(d)</sup> Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; <sup>(e)</sup> Faculté des Sciences, Université Mohammed V, Rabat, Morocco  
 136 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique), Gif-sur-Yvette, France  
 137 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States  
 138 Department of Physics, University of Washington, Seattle, WA, United States  
 139 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom  
 140 Department of Physics, Shinshu University, Nagano, Japan  
 141 Fachbereich Physik, Universität Siegen, Siegen, Germany  
 142 Department of Physics, Simon Fraser University, Burnaby, BC, Canada  
 143 SLAC National Accelerator Laboratory, Stanford, CA, United States  
 144 <sup>(a)</sup> Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; <sup>(b)</sup> Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic  
 145 <sup>(a)</sup> Department of Physics, University of Johannesburg, Johannesburg; <sup>(b)</sup> School of Physics, University of the Witwatersrand, Johannesburg, South Africa  
 146 <sup>(a)</sup> Department of Physics, Stockholm University; <sup>(b)</sup> The Oskar Klein Centre, Stockholm, Sweden  
 147 Physics Department, Royal Institute of Technology, Stockholm, Sweden  
 148 Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY, United States  
 149 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom  
 150 School of Physics, University of Sydney, Sydney, Australia  
 151 Institute of Physics, Academia Sinica, Taipei, Taiwan  
 152 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel  
 153 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel  
 154 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece  
 155 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan  
 156 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan  
 157 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan  
 158 Department of Physics, University of Toronto, Toronto, ON, Canada  
 159 <sup>(a)</sup> TRIUMF, Vancouver BC; <sup>(b)</sup> Department of Physics and Astronomy, York University, Toronto, ON, Canada  
 160 Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki, Japan  
 161 Science and Technology Center, Tufts University, Medford, MA, United States  
 162 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia  
 163 Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States  
 164 <sup>(a)</sup> INFN Gruppo Collegato di Udine; <sup>(b)</sup> ICTP, Trieste; <sup>(c)</sup> Dipartimento di Fisica, Università di Udine, Udine, Italy  
 165 Department of Physics, University of Illinois, Urbana, IL, United States  
 166 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden  
 167 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain  
 168 Department of Physics, University of British Columbia, Vancouver, BC, Canada  
 169 Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada  
 170 Waseda University, Tokyo, Japan  
 171 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel  
 172 Department of Physics, University of Wisconsin, Madison, WI, United States  
 173 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany  
 174 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany  
 175 Department of Physics, Yale University, New Haven, CT, United States  
 176 Yerevan Physics Institute, Yerevan, Armenia  
 177 Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

<sup>a</sup> Also at Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa, Portugal.

<sup>b</sup> Also at Faculdade de Ciências and CFNUL, Universidade de Lisboa, Lisboa, Portugal.

<sup>c</sup> Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.

<sup>d</sup> Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

<sup>e</sup> Also at TRIUMF, Vancouver, BC, Canada.

<sup>f</sup> Also at Department of Physics, California State University, Fresno, CA, United States.

<sup>g</sup> Also at Fermilab, Batavia, IL, United States.

<sup>h</sup> Also at Department of Physics, University of Coimbra, Coimbra, Portugal.

<sup>i</sup> Also at Università di Napoli Parthenope, Napoli, Italy.

<sup>j</sup> Also at Institute of Particle Physics (IPP), Canada.

<sup>k</sup> Also at Department of Physics, Middle East Technical University, Ankara, Turkey.

- <sup>l</sup> Also at Louisiana Tech University, Ruston, LA, United States.
- <sup>m</sup> Also at Faculty of Physics and Applied Computer Science, AGH – University of Science and Technology, Krakow, Poland.
- <sup>n</sup> Also at Group of Particle Physics, University of Montreal, Montreal, QC, Canada.
- <sup>o</sup> Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
- <sup>p</sup> Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
- <sup>q</sup> Also at Manhattan College, New York, NY, United States.
- <sup>r</sup> Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.
- <sup>s</sup> Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
- <sup>t</sup> Also at High Energy Physics Group, Shandong University, Shandong, China.
- <sup>u</sup> Also at Section de Physique, Université de Genève, Geneva, Switzerland.
- <sup>v</sup> Also at Departamento de Física, Universidade de Minho, Braga, Portugal.
- <sup>w</sup> Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.
- <sup>x</sup> Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.
- <sup>y</sup> Also at California Institute of Technology, Pasadena, CA, United States.
- <sup>z</sup> Also at Institute of Physics, Jagiellonian University, Krakow, Poland.
- <sup>aa</sup> Also at Department of Physics, Oxford University, Oxford, United Kingdom.
- <sup>ab</sup> Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
- <sup>ac</sup> Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.
- <sup>ad</sup> Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique), Gif-sur-Yvette, France.
- <sup>ae</sup> Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.
- <sup>af</sup> Also at Department of Physics, Nanjing University, Jiangsu, China.
- \* Deceased.