Search for Extra Dimensions in diphoton events from proton-proton collisions at $\sqrt{s} = 7$ TeV in the ATLAS detector at the LHC

The ATLAS Collaboration

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The large difference between the Planck scale and the electroweak scale, known as the hierarchy problem, is addressed in certain models through the postulate of extra spatial dimensions. A search for evidence of extra spatial dimensions in the diphoton channel has been performed using the full set of proton-proton collisions at $\sqrt{s} = 7$ TeV recorded in 2011 with the ATLAS detector at the CERN Large Hadron Collider. This dataset corresponds to an integrated luminosity of 4.9 fb$^{-1}$. The diphoton invariant mass spectrum is observed to be in good agreement with the Standard Model expectation. In the context of the model proposed by Arkani-Hamed, Dimopoulos and Dvali, 95% confidence level lower limits of between 2.52 TeV and 3.92 TeV are set on the ultraviolet cutoff scale $M_S$ depending on the number of extra dimensions and the theoretical formalism used. In the context of the Randall–Sundrum model, a lower limit of 2.06 (1.00) TeV at 95% confidence level is set on the mass of the lightest graviton for couplings of $k/M_{Pl} = 0.1$ (0.01). Combining with the ATLAS dilepton searches based on the 2011 data, the 95% confidence level lower limit on the Randall–Sundrum graviton mass is further tightened to 2.23 (1.03) TeV for $k/M_{Pl} = 0.1$ (0.01).
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1. Introduction

One of the major goals of particle physicists in the past decades has been to solve the hierarchy problem: the fact that the electroweak scale is 16 orders of magnitude smaller than the Planck scale. One possible solution to the hierarchy problem is the existence of extra spatial dimensions. In this paradigm, gravity appears much weaker than the other interactions because it is diluted by the presence of extra spatial dimensions.

In the Randall-Sundrum (RS) model [1], a five-dimensional geometry is assumed, in which the fifth dimension is compactified with length $r_c$. There are two four-dimensional branes sitting in a five-dimensional bulk with a “warped” geometry. The Standard Model (SM) fields are located on the so-called TeV brane, while gravity originates from the other brane, called the Planck brane. Gravitons are capable of propagating in the bulk. Mass scales on the TeV brane correspond to mass scales on the Planck brane ($M_{Pl}$) as given by $M_D = M_{Pl} e^{-k\pi r_c}$, where $k$ is the curvature scale of the extra dimension. The observed hierarchy of scales can be naturally reproduced in this model if $kr_c \approx 12$ [2]. The compactification of the extra dimension gives rise to a Kaluza–Klein (KK) tower of graviton excitations $G$, a set of four-dimensional particles with increasing masses. The phenomenology can be described in terms of the mass of the lightest KK graviton excitation ($m_G$) and the dimensionless coupling $k/M_{Pl}$, where $M_{Pl} = M_{Pl}/\sqrt{8\pi}$ is the reduced Planck scale. From theoretical arguments [2], $k/M_{Pl}$ values in the range [0.01, 0.1] are preferred. The lightest RS graviton is expected to be a fairly narrow resonance for $k/M_{Pl} < 0.3$. The most stringent experimental limits on RS gravitons have been obtained at the LHC: the current best 95% confidence level (CL) lower limits on the graviton mass for $k/M_{Pl} = 0.1$ are 2.16 TeV [3] and 2.14 TeV [4]. The former limit has been obtained from an analysis of the $G \rightarrow ee/\mu\mu$ channels in data corresponding to an integrated luminosity of $5\text{ fb}^{-1}$ collected by the ATLAS experiment. The latter limit has been obtained from an analysis of the same channels in data corresponding to an integrated luminosity of $\approx 5\text{ fb}^{-1}$ collected by the CMS experiment. The limits from earlier searches at the Tevatron can be found in Refs. [5,6].

Arkani-Hamed, Dimopoulos, and Dvali (ADD) [7] proposed a different scenario for extra dimensions. Motivated by the weakness of gravity, they postulated the existence of $n$ flat additional spatial dimensions compactified with radius $R$, and proposed a model in which only gravity propagates in the extra dimensions. The fundamental Planck scale in the $(4 + n)$-dimensional spacetime, $M_D$, is related to the apparent scale $\overline{M}_{Pl}$ by Gauss’s law: $\overline{M}_{Pl}^2 = M_D^{n+2} R^n$. The mass splitting of the graviton KK modes is $1/R$ for each of the $n$ extra dimensions. In the ADD model, resolving the hierarchy problem usually requires small values of $1/R$, giving rise to an almost continuous spectrum of KK graviton states. The symbol $G$ is used to denote KK graviton states in both the RS and ADD models. The existence of ADD extra dimensions can manifest itself in proton-proton ($pp$) collisions through a variety of processes, including virtual graviton exchange as well as direct graviton production. While processes involving direct graviton
emission depend on $M_D$, effects involving virtual gravitons depend on the ultraviolet cutoff of the KK spectrum, denoted $M_S$. The strength of gravity in the presence of extra dimensions is typically parameterised by $\eta_G = F/M_S^4$, where $F$ is a dimensionless parameter of order unity reflecting the dependence of virtual KK graviton exchange on the number of extra dimensions. Several theoretical formalisms exist in the literature, using different definitions of $F$ and, consequently, of $M_S$:

\[ F = 1, \quad (\text{GRW}) \quad [8]; \quad (1) \]

\[ F = \begin{cases} 
\log (M_S^2/\hat{s}) & n = 2 \\
2/(n-2) & n > 2 \end{cases}, \quad (\text{HLZ}) \quad [9]; \quad (2) \]

\[ F = \pm 2/\pi, \quad (\text{Hewett}) \quad [10]; \quad (3) \]

where $\sqrt{\hat{s}}$ is the centre-of-mass energy of the parton-parton collision. The effect of ADD graviton exchange manifests itself as a non-resonant deviation from the SM background expectation. The effective diphoton cross section is the result of the SM and ADD amplitudes, as well as their interference. The interference term in the effective cross section is linear in $\eta_G$ and the pure graviton exchange term is quadratic in $\eta_G$. In previous analyses by the ATLAS and CMS collaborations, 95% CL lower limits on $M_S$ of 2.26–3.52 TeV [11] and 2.4–3.8 TeV [12] respectively were set, depending on the theoretical formalism used. Searches for ADD virtual graviton effects have also been performed at other colliders, e.g. at HERA [13, 14], LEP [15, 16, 17] and the Tevatron [18, 19].

This Letter reports the results of a search for extra dimensions in the diphoton channel using the full data sample recorded by the ATLAS detector in 2011, corresponding to a total integrated luminosity of 4.9 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 7$ TeV. The results are interpreted in the context of both the ADD and RS scenarios. The dilepton and diphoton channels are particularly sensitive for this search due to the clean experimental signature, excellent mass resolution and modest backgrounds. The branching ratio for graviton decay to two photons is twice the value of that for graviton decay to any individual charged-lepton pair. This search, based on the full $\sqrt{s} = 7$ TeV 4.9 fb$^{-1}$ dataset, is an extension of an earlier study [11] performed using 1.0 to 2.1 fb$^{-1}$ of data. The earlier data are included in the present study but they benefit from improvements in the reconstruction and calibration procedures. Moreover, the techniques used for the background estimation and their associated uncertainties have been also significantly improved. This results to an overall improvement of a factor 2 to 3 in the excluded production cross section of diphoton events predicted by the Randall-Sundrum model, corresponding to a graviton mass limit which is 10% to 15% larger.
2. The ATLAS detector

The ATLAS detector is a multipurpose particle physics instrument with a forward-backward symmetric cylindrical geometry and near $4\pi$ solid angle coverage. A detailed description of the ATLAS detector can be found in Ref. [20]. The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker. The ID is surrounded by a superconducting solenoid that provides a 2 T axial magnetic field. The ID allows an accurate reconstruction of tracks from the primary $pp$ collision and also identifies tracks from secondary vertices, permitting the efficient identification of photon conversions.

The electromagnetic calorimeter (ECAL) is a lead/liquid-argon (LAr) sampling calorimeter with an accordion geometry. It is divided into a barrel section, covering the pseudorapidity region $|\eta| < 1.475$, and two endcap sections, covering the pseudorapidity regions $1.375 < |\eta| < 3.2$. It consists of three longitudinal layers for $|\eta| < 2.5$ and two for $2.5 < |\eta| < 3.2$. Up to $|\eta| < 2.4$, the first one uses highly granular “strips” segmented in the $\eta$ direction for efficient event-by-event discrimination between single photon showers and two overlapping showers originating from $\pi^0$ decay. The second layer collects most of the energy deposited in the electromagnetic calorimeter by photon showers. Significant energy deposits in the third layer are an indication for leakage beyond the ECAL from a high energy shower. The measurements from the third layer are used to correct for this effect. A thin presampler layer in front of the accordion calorimeter, covering the pseudorapidity interval $|\eta| < 1.8$, is used to correct for energy loss upstream of the calorimeter.

The hadronic calorimeter (HCAL), surrounding the ECAL, includes a central ($|\eta| < 1.7$) iron/scintillator tile calorimeter, two endcap ($1.5 < |\eta| < 3.2$) copper/LAr calorimeters and two forward calorimeters that extend the coverage to $|\eta| < 4.9$, using copper and tungsten as absorber. The muon spectrometer, located beyond the calorimeters, consists of three large air-core superconducting toroid systems, instrumented with precision tracking chambers as well as fast detectors for triggering.

3. Trigger and event selection

The analysis uses data recorded by ATLAS between March and October 2011 during stable-beam periods of $pp$ collisions at $\sqrt{s} = 7$ TeV. A three-level trigger system is used to select events containing two photon candidates. The first level trigger is hardware-based and relies on a readout with coarse granularity. The second- and third-level triggers, collectively referred to as the high-level trigger (HLT), are implemented in software and exploit the full granularity and energy calibration of the calorimeter.

‡ 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 $\eta = -\ln\tan(\theta/2)$. 
Selected events have to satisfy a diphoton trigger where each photon is required to satisfy, at the HLT level, a transverse energy requirement $E_T^\gamma > 20$ GeV and a set of requirements on the shape of the energy deposit. This set includes criteria for the energy leakage into the hadronic calorimeter and for the width of the shower in the second layer of the ECAL. This trigger is nearly 100% efficient for diphoton events passing the final selection requirements.

Only events satisfying the standard ATLAS data quality requirements and having at least one primary collision vertex with at least three tracks are kept. Photon candidates reconstructed in the precision regions of the barrel ($|\eta| < 1.37$) or the endcaps ($1.52 < |\eta| < 2.37$), with $E_T^\gamma > 25$ GeV and satisfying the same requirements on the shower shape as the trigger are preselected. These requirements on the photon candidates are referred to as the loose selection. The two highest-$E_T^\gamma$ photon candidates each have to satisfy a set of stricter requirements, referred to as the tight photon definition, which includes a more stringent selection on the shower width in the second layer of the ECAL and additional requirements on the energy distribution in the first layer of the ECAL. In addition, the two photon candidates of interest have to satisfy a calorimetric isolation requirement, $E_{\text{iso}}^T < 5$ GeV. This isolation is computed by summing the transverse energy over the cells of the calorimeters in a cone of radius $\Delta R = \sqrt{(\eta - \eta^\gamma)^2 + (\phi - \phi^\gamma)^2} < 0.4$ surrounding the photon candidate. Here $(\eta, \phi)$ denotes the cell position and $(\eta^\gamma, \phi^\gamma)$ denotes the position of the photon cluster. The transverse energy contribution in the centre of the cone, which contains the photon cluster, is subtracted. Corrections, based on simulations, are applied to account for the expected energy leakage from the photon into the isolation region. An ambient-energy correction, based on the measurement of low-transverse-momentum jets is also applied, on an event-by-event basis, to remove the contributions from the underlying event and from pileup which results from the presence of multiple $pp$ collisions within the same or nearby bunch crossings.

4. Event simulation

Monte Carlo (MC) simulations are used to study the response of the detector to various RS and ADD scenarios as well as SM diphoton processes. The MC generators used in this analysis are listed below. For samples generated using PYTHIA, the ATLAS parameter tunes are used in the event generation. For samples generated using PYTHIA or SHERPA, the generated events are processed through the GEANT4 detector simulation. Then the simulated events are reconstructed with the same procedure as is used for the data. To reproduce the pileup conditions of the data, the simulated events are reweighted to match the observed distribution of the average number of interactions per bunch crossing. The determination of the number of interactions per bunch crossing is discussed in Ref. 30.

PYTHIA 6.424 with MRST2007LOMOD parton distribution functions (PDFs) is used to simulate the SM diphoton production at leading order (LO). In addition, the
next-to-leading (NLO) correction and the contribution of the fragmentation processes are evaluated using DIPHOX \(^{32}\) 1.3.2 with MSTW2008NLO \(^{33}\) PDFs and lead to an invariant-mass-dependent correction of the PYTHIA prediction. The so-called box contribution \(gg \rightarrow \gamma \gamma\) through a quark loop is included in both the PYTHIA and the DIPHOX predictions. From the point of view of power counting, this diagram is a next-to-next-to-leading (NNLO) contribution, but the gluon luminosity at the LHC is so large compared to the quark-antiquark one that this process represents a contribution that is comparable to the \(qq \rightarrow \gamma \gamma\) process. Samples of RS events are produced using the same generator and PDFs as for the SM diphoton samples. They are used to study the selection efficiency and the shape of the reconstructed invariant mass spectrum for various values of the graviton mass \(m_G\) between 400 GeV and 3000 GeV and values of \(k/M_P l\) in the range [0.01,0.1]. ADD models are simulated for various \(M_S\) values using SHERPA 1.3.1 with CTEQ6L \(^{34}\) PDFs. The ADD MC samples are used to evaluate the number of signal events passing the selection as a function of \(M_S\). An NLO K-factor of 1.75±0.10 is considered for the RS scenario and 1.70±0.10 is considered for the ADD scenario. These K-factors have been provided by the authors of Refs. \(^{35}\) \(^{36}\).

5. Background estimate

The dominant background in this analysis is the irreducible background due to SM \(\gamma \gamma\) production. Another significant background component is the reducible background which arises from events in which one or both of the photon candidates result from a different object being misidentified as a photon. This background is dominated by \(\gamma +\) jet (\(j\)) and \(j + j\) events, with one or both photon candidates arising from jets. Backgrounds with electrons faking photons, such as the Drell–Yan production of electron-positron pairs as well as \(W/Z +\gamma\) and \(t\bar{t}\) processes, have been verified to be negligible after the event selection.

We first describe the tools and samples that are used to predict the contributions from the SM \(\gamma \gamma\) background to the high-mass signal region, as well as their main limitation. We then describe in detail the two-step procedure that is used to overcome this limitation and to obtain our background estimate.

The estimate of the irreducible background makes use of the NLO calculations \(^{32}\) that are available for the SM \(\gamma \gamma\) production processes. The uncertainty in the absolute normalisation of the \(\gamma \gamma\) cross section is, however, quite substantial: \(\simeq 20\%\) (\(\simeq 25\%\)) uncertainty on the cross section for \(\gamma \gamma\) events with an invariant mass \(m_{\gamma \gamma} > 200\) GeV \((m_{\gamma \gamma} > 1200\) GeV\) with both photons in the detector acceptance. The background estimates, which are discussed in detail below, are therefore normalised to the data in the low-mass control region \(\parallel\) ([142, 409] GeV) where the presence of any signal beyond the SM has been excluded by previous searches. Compared to the use of NLO calculations to

\(\parallel\) The exact values of the upper and lower bound of the low-mass control region have been chosen to coincide with the boundaries of the first bin in Table[1]. The results of this search are not altered by small variations of the control region edges nor a change of the binning.
predict the absolute rate of SM $\gamma\gamma$ production in the high-mass signal region, the use of NLO calculations for the extrapolation of the SM $\gamma\gamma$ production rates from the low-mass control region to the high-mass signal region results in significantly smaller uncertainties. The extrapolation method is described in detail below, along with quantitative estimates of the final uncertainties.

Following these considerations, the estimate the $m_{\gamma\gamma}$ spectrum of the background events is done in two steps. First the shape of the $m_{\gamma\gamma}$ spectrum is determined, separately for each background component. Then the normalisation for each component is determined using the low-mass control region.

The shape of the $m_{\gamma\gamma}$ spectrum from SM $\gamma\gamma$ production is estimated using simulated events, reweighting the PYTHIA samples to the differential (in $m_{\gamma\gamma}$) cross section predicted using DIPHOX.

The shape of the reducible background is estimated using data-driven techniques. It is split into three components: $\gamma + j$ events (the leading-$E_T$ photon candidate is due to a real photon), $j + \gamma$ (fake leading photon candidate) and $j + j$. The shapes of the $j + \gamma$ and $\gamma + j$ differ significantly because of the strong $p_T$-dependence of the probability to mis-identify a jet as a photon. Separately for each component, several data control samples that are enriched in the given component are defined. The shape of the $\gamma + j$ background is estimated from a data control sample that is selected in the same way as the signal sample, except that the subleading $\gamma$ candidate is required to pass loose identification criteria and to fail tight identification criteria. The control samples used to extract the shapes of the $m_{\gamma\gamma}$ spectra of $j + \gamma$ and $j + j$ backgrounds are defined following the same approach, i.e. by requiring the leading photon candidate ($j + \gamma$ background) or both candidates ($j + j$ background) to pass loose and to fail tight identification criteria. Since the data control samples contain relatively few events at high $m_{\gamma\gamma}$, a fit to a smooth function of the form $f(m_{\gamma\gamma}) = p_1 \times (m_{\gamma\gamma})^{p_2 + p_3 \log m_{\gamma\gamma}}$, where the $p_i$ are free parameters, is used to extrapolate the reducible background shapes to higher masses. This functional form has been used in the CDF dijet search [37] and in previous ATLAS searches in the dilepton [38], dijet [39], photon–jet [40] and diphoton [11] channels, and it describes the shapes of the data control samples well. In contrast to the earlier version of this analysis [11], the shapes of the three components of the reducible background are modelled separately.

To determine the contributions of each of the four sources (the irreducible $\gamma\gamma$ component plus the three reducible components, $\gamma + j$, $j + \gamma$ and $j + j$) to the low-mass control region, a two-dimensional template fit to the distributions of the calorimetric isolation ($E^{\text{iso}}_T$) of the two photon candidates is used. For the purpose of this fit, the isolation requirement in the event selection is relaxed to $E^{\text{iso}}_T < 25$ GeV. This method has been used previously in Refs. [11] [42] and in an earlier version of this analysis [11]. Templates for the $E^{\text{iso}}_T$ distribution of true photons and of fake photons from jets are both determined from data. The shape for fake photons is determined using a sample of photon candidates that fail the tight requirement but pass a set of requirements referred as the non-tight selection. This non-tight selection
Table 1. Expected numbers of events from the irreducible and reducible background components, as well as the total background prediction and observed numbers of events in $m_{\gamma\gamma}$ bins. The table quotes the sum of the statistical and systematic uncertainties in the background expectations. The boundaries of all bins in this table have been chosen to coincide with bin boundaries in Fig. 1. As discussed in the text, the background estimate is normalised to the data in the low-mass control region $[142, 409]$ GeV. Since the uncertainties in the normalisation are strongly anticorrelated between the reducible and irreducible components, their impact on the estimate of the total background is smaller than their impact on the individual components. By construction, the uncertainties in the control region are 100% anticorrelated and the total background expectation is identical to the number of observed events.

<table>
<thead>
<tr>
<th>Mass Window (GeV)</th>
<th>Background Expectation</th>
<th>Observed Events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Irreducible</td>
<td>Reducible</td>
</tr>
<tr>
<td>[142, 409]</td>
<td>10195 ± 1092</td>
<td>4586 ± 1092</td>
</tr>
<tr>
<td>Control region</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[409, 512]</td>
<td>192 ± 26</td>
<td>43 ± 10</td>
</tr>
<tr>
<td>[512, 596]</td>
<td>57 ± 8</td>
<td>10.7 ± 2.7</td>
</tr>
<tr>
<td>[596, 719]</td>
<td>35 ± 5</td>
<td>5.4 ± 1.5</td>
</tr>
<tr>
<td>[719, 805]</td>
<td>12.0 ± 1.8</td>
<td>1.4 ± 0.4</td>
</tr>
<tr>
<td>[805, 901]</td>
<td>7.8 ± 1.2</td>
<td>0.70 ± 0.23</td>
</tr>
<tr>
<td>[901, 1008]</td>
<td>4.6 ± 0.7</td>
<td>0.35 ± 0.13</td>
</tr>
<tr>
<td>[1008, 1129]</td>
<td>2.7 ± 0.4</td>
<td>0.18 ± 0.07</td>
</tr>
<tr>
<td>[1129, 1217]</td>
<td>1.14 ± 0.18</td>
<td>0.064 ± 0.028</td>
</tr>
<tr>
<td>[1217, 1312]</td>
<td>0.72 ± 0.12</td>
<td>0.040 ± 0.018</td>
</tr>
<tr>
<td>[1312, 1414]</td>
<td>0.50 ± 0.08</td>
<td>0.024 ± 0.012</td>
</tr>
<tr>
<td>[1414, 1644]</td>
<td>0.61 ± 0.10</td>
<td>0.024 ± 0.013</td>
</tr>
<tr>
<td>[1644, 2889]</td>
<td>0.39 ± 0.08</td>
<td>0.013 ± 0.009</td>
</tr>
</tbody>
</table>

includes the same requirements as the loose selection plus additional requirements that reduce the correlation between the identification and the isolation. The shape for true photons is found from the sample of tight photon candidates, after subtracting the fake photon shape normalised to match the number of candidates with large values of $E_{T}^{\text{iso}}$ ($E_{T}^{\text{iso}} > 10$ GeV; this control region is dominated by fake photons). Both the signal templates and fake templates are constructed separately for leading and subleading photon candidates. The significant correlation ($\sim 20\%$) between the $E_{T}^{\text{iso}}$ values of the two fake photons in the $j + j$ background is included in the two-dimensional template for this background component. The background expectation as a function of $m_{\gamma\gamma}$ is summarised in Fig. 1 and Table 1. Fig. 2 details the different contributions to the uncertainty in the background expectation.

The uncertainties in the shape of the irreducible background are dominated by the uncertainties in the PDFs that are used with DIPHOX. Those uncertainties are evaluated using the MSTW2008 NLO eigenvector PDF sets and using CTEQ6.6
Figure 1. Observed invariant mass distribution of diphoton events. Superimposed are the SM background expectation and the expected signals for an example each for RS and ADD models. In addition to the total background, the contribution from the reducible component is shown. The black arrow indicates the control region. To compensate the rapid decrease of the spectrum, the bins have been chosen to have constant logarithmic width. Specifically, the ratio of the upper to lower bin boundary is equal to 1.038 for all bins, and the first bin starts at 142 GeV. The bin-by-bin significance of the difference between data and predicted background is shown below the main plot. Following the convention of Ref. [43], the significance is set to zero for bins with insignificant deviations with respect to a small expected background. This concerns mainly the bins at large $m_{\gamma\gamma}$ where a fraction of an event is expected (on average) and where zero events are observed.

and MRST2007LOMOD PDF sets for comparisons. The spread of the variations includes the difference between the central values obtained with the different PDF sets. Smaller contributions arise from residual imperfections in the simulation of the isolation variable $E_T^{iso}$ and from higher-order contributions that are not included in the DIPHOX model. The latter contribution is evaluated by varying in a coherent and an incoherent way the renormalisation, the initial factorisation and the final factorisation scales by a factor two around their nominal value, which is the invariant mass of the diphoton system. The shape predictions from DIPHOX are found to be in good
Figure 2. Uncertainty in the total background expectation as a function of $m_{\gamma\gamma}$. Also shown are the individual contributions from the uncertainties in the shapes of the irreducible and the reducible components, as well as the contribution from the uncertainties in the yields (normalisations) of the different background components extracted from the low-mass control region. Since the number of events in the low-mass control region is dominated by the lowest masses, the background uncertainties are particularly small at the low end of the control region.
templates. They are then propagated to the normalisations by repeating the template fits with the varied templates.

6. Systematic uncertainties in the signal models

Experimental systematic uncertainties on the signal yields are evaluated for both the RS and the ADD signals. The main systematic uncertainties arise from the non-perfect simulation of the quantities used for the identification of photons and in the isolation requirements. For the former, the data-driven estimates from Ref. [22] are used, together with an extrapolation to larger values of $p_T$, which are relevant in the present search. In the RS scenario, these uncertainties on the photon identification translate into a relative uncertainty of 4.7% to 3.3% on the signal yield for $m_G$ values of 0.5 TeV to 2.5 TeV. In the ADD scenario, the relative uncertainty on the signal yield is 4.5% with a weak dependence on $M_S$. For the latter, a study comparing the data sample and simulation has shown that a 1 GeV shift of the isolation distribution in the simulation covers possible discrepancies between data and simulation in the signal region. In the RS scenario, these uncertainties translate into a relative uncertainty of 4% to 7% on the signal yield for $m_G$ values of 0.5 TeV to 2.5 TeV. In the ADD scenario the relative uncertainty on the signal yield is of $\sim$ 6% with a weak dependence on $M_S$. The uncertainty on the integrated luminosity for the complete 2011 dataset is 3.9%, based on the calibration described in Refs. [30, 45] plus an additional uncertainty for the extrapolation to the later data-taking period with higher instantaneous luminosity. An uncertainty of 2% on the trigger efficiency arises from differences between the measured trigger efficiency in data and simulated samples. Given that the sum in quadrature of all experimental systematic uncertainties depends only weakly on the signal scenario, a common relative uncertainty value of 9% on signal yield is used for all scenarios.

Uncertainties from limited Monte Carlo sample sizes, as well as uncertainties in the RS resonant shape due to the current knowledge of the electromagnetic energy scale of the calorimeter, the resolution of the detector and the pileup conditions were verified to have a negligible impact on the result. Theoretical uncertainties due to the PDFs and due to uncomputed higher perturbative orders were considered. The uncertainty in the PDFs translates into an uncertainty of $\pm 10\%$ in the signal yields predicted by the ADD models. In the RS scenario the PDF uncertainty in the signal yield is between 6% and 25% for $m_G$ values between 0.5 TeV and 2.5 TeV. As detailed in Ref. [11], an uncertainty of $\pm 0.1$ is considered on the NLO K-factor value. The theory uncertainties are not included in the limit calculation, but their size is indicated in Figs. 3 and 5, where graphical representations of the limits discussed in Section 7 are shown.

7. Results and interpretation

A comparison of the observed invariant mass spectrum of diphoton events and the background expectation is shown in Fig. 1, along with the statistical significance of the
bin-by-bin difference\[43\] between data and the expected background. This significance is plotted as positive (negative) for bins with an excess (deficit) of data. Also shown are the expected signals for two examples of RS and ADD models. The geometrical acceptance for the RS scenario with \(m_G = 1.5\) TeV and \(k/\sqrt{M_{pl}} = 0.1\) shown in Fig.\[4\] is 88% and the selection efficiency for events within the acceptance is \((54\pm5\%)\). Both Fig.\[4\] and Table\[1\] show that, over the entire \(m_{\gamma\gamma}\) range, the data are in good agreement with the expectations from SM backgrounds. The BumpHunter algorithm\[46\] is used to further quantify the level of agreement between data and the SM background expectation. The BumpHunter performs a scan of the mass spectrum in windows of progressively increasing width. It identifies the window with the most significant excess of data events over the background expectation anywhere in a predefined search region. In this analysis, the binned mass spectrum of Fig.\[4\] is used, the search region is defined as \(142 < m_{\gamma\gamma} < 3000\) GeV and the window size is allowed to vary from one bin to half the number of bins in the search region.\[4\] The most significant excess is found in the region \(1312 < m_{\gamma\gamma} < 1644\) GeV. The probability of observing, due to fluctuations in the background only, an excess that is at least as significant as the one in data is \(0.86\). This confirms the absence of a significant excess in the mass spectrum.

Given the absence of evidence for a signal, 95% CL upper limits were determined on the RS signal cross section. The limits are computed using a Bayesian approach\[47\] assuming a flat prior for the RS cross section. The likelihood function is defined as the product of the Poisson probabilities over all mass bins in the search region defined as \(m_{\gamma\gamma} > 409\) GeV. In each bin the Poisson probability is evaluated for the observed number of data events given the model prediction. The model prediction is the sum of the expected background and the expected signal yield. The expected signal yield is a function of the graviton mass \(m_G\) and the signal cross section times branching ratio \(\sigma \times B(G \rightarrow \gamma\gamma)\). Systematic uncertainties are incorporated as nuisance parameters with Gaussian priors; the computation of the likelihood function includes integration over the variation in each of these. The RS model results can be combined with the results from the dilepton channel\[3\] to obtain limits on \(\sigma \times B(G \rightarrow \gamma\gamma/ee/\mu\mu)\). Relative branching ratios of \(B(G \rightarrow ee)/B(G \rightarrow \mu\mu) = 1\) and \(B(G \rightarrow \gamma\gamma)/B(G \rightarrow ee) = 2\)[48] are assumed for the purpose of this combination. Correlations between the systematic uncertainties for different channels are taken into account in the combination, as discussed in Ref.\[11\]. Specifically, the systematic uncertainty in the QCD dijet background is treated as fully correlated across the \(ee\) and \(\gamma\gamma\) channels. The PDF and scale uncertainties are treated as correlated across all three channels, and affect the irreducible background in the \(\gamma\gamma\) channel as well as the Drell–Yan background in the \(ee/\mu\mu\) channels. The resulting limits are shown in Fig.\[5\]. The limit can be interpreted in the plane \((m_G, k/\sqrt{M_{pl}})\) using the theoretical dependence of the cross section on these parameters (Fig.\[4\]). Alternatively, for a given value of \(k/\sqrt{M_{pl}}\), the limit can be translated into a limit on \(m_G\). The limits

\[\footnote{While the background is normalised to the data in the low-mass control region, the presence of a bump inside this region would still be visible. This motivates the choice of the lower limit of the search region.}\]
on $m_G$ are summarised in Table 2. Using a constant K-factor of 1.75, the 95% CL lower limit from the diphoton channel is 1.00 (2.06) TeV for $k/\sqrt{p_T} = 0.01$ (0.1), and the combined 95% CL lower limit is 1.03 (2.23) TeV for $k/\sqrt{p_T} = 0.01$ (0.1).

Figure 3. Expected and observed 95% CL limits from the combination of $G \rightarrow \gamma\gamma/\mu\mu/ee$ channels on $\sigma \times B$, the product of the RS graviton production cross section and the branching ratio for graviton decay via $G \rightarrow \gamma\gamma/\mu\mu/ee$, as a function of the graviton mass. The $-1\sigma$ and $-2\sigma$ variations of the expected limit exhibit a tendency to be particularly close to the expected limit at large $m_G$. This behaviour is expected as signals with large $m_G$ would manifest themselves in regions of $m_{\gamma\gamma}$ where the SM background is small and the poissonian fluctuations around the mean expected background are highly asymmetric. The theory curves are obtained using the PYTHIA generator, which implements the calculations from Ref. [48]. A K-factor of 1.75 is applied on top of these predictions to account for NLO corrections. The thickness of the theory curve for $k/\sqrt{p_T} = 0.1$ illustrates the theoretical uncertainties due to the PDFs expressed at 90% CL.

A counting experiment is performed to set limits on the ADD model. Specifically, the number of diphoton events is counted in a search region above a given threshold in $m_{\gamma\gamma}$. The mass threshold is chosen to optimise the expected limit on the difference in the diphoton cross section for $m_{\gamma\gamma} > 500$ GeV between the ADD model and the SM-only hypothesis. For the purpose of this optimisation, a specific implementation of the ADD model and specific values of the parameters have to be chosen. For $M_S = 2500$ GeV
in the GRW convention, an optimal search region is obtained at $m_{\gamma\gamma} > 1217$ GeV. In the data, 4 events are observed in this search region, with a background expectation of $2.32 \pm 0.37$ events. The expected and observed 95\% CL upper limits on the number of signal events above the SM background in the search region are given in Table 3.

![Graph](image-url)  

**Table 2.** 95\% CL lower limits on the mass [TeV] of the lightest RS graviton, for various values of $k/M_{Pl}$. The results are shown for the diphoton channel alone and for the combination of the diphoton and dilepton channels, and also for both LO and NLO (K-factor = 1.75) theory cross-section calculations.

<table>
<thead>
<tr>
<th>K-factor value</th>
<th>Channel(s) Used</th>
<th>$95%$ CL Observed (Expected) Limit [TeV]</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td>$k/M_{Pl}$ value</td>
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<tr>
<td>1</td>
<td>$G \to \gamma\gamma$</td>
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<tr>
<td></td>
<td>$G \to \gamma\gamma/ee/\mu\mu$</td>
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</tr>
<tr>
<td>1.75</td>
<td>$G \to \gamma\gamma$</td>
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</tr>
<tr>
<td></td>
<td>$G \to \gamma\gamma/ee/\mu\mu$</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 4.** The RS results interpreted in the plane of $k/M_{Pl}$ versus graviton mass. The region above the curve is excluded at 95\% CL.
Table 3. Expected and observed limits at 95% CL on the number of signal events in the search region at \( m_{\gamma\gamma} \) > 1217 GeV.

<table>
<thead>
<tr>
<th>Expected limit</th>
<th>Observed limit</th>
</tr>
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<tbody>
<tr>
<td>(-2\sigma)</td>
<td>3.08</td>
</tr>
<tr>
<td>(-1\sigma)</td>
<td>3.08</td>
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<tr>
<td>mean</td>
<td>5.18</td>
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<tr>
<td>(+1\sigma)</td>
<td>5.96</td>
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<tr>
<td>(+2\sigma)</td>
<td>8.53</td>
</tr>
<tr>
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<td>7.21</td>
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</table>

These limits on the event yield can be translated into limits on the parameter \( \eta_G \) of the ADD model using a prediction of the expected excess of events over the SM-only background as a function of \( \eta_G \). This translation is shown, for one specific implementation of the ADD model, in Fig. 5.

Figure 5. Number of signal events as a function of \( \eta_G \). The solid horizontal line corresponds to the observed limit, the dashed line corresponds to the expected limit and the bands to the \( \pm 1\sigma \) and \( \pm 2\sigma \) uncertainty on the expected limit. The black curve corresponds to MC predictions from various samples without applying the K-factor of 1.70. The band around it illustrates the theoretical uncertainties due to the PDFs expressed at 90% CL. The samples at positive (negative) \( \eta_G \) have been simulated using the GRW (Hewett) formalism. When the prediction is greater than the observed limit, the corresponding value for \( \eta_G \) is excluded.
The limits for different ADD scenarios are summarised in Table 4. Using a constant K-factor of 1.70, the 95% CL upper (lower) limit on $\eta_G$ is 0.0085 ($-0.0159$) TeV$^{-4}$ for constructive (destructive) interference.

<table>
<thead>
<tr>
<th>K-factor Value</th>
<th>ADD Parameter</th>
<th>GRW Neg.</th>
<th>Hewett Pos.</th>
<th>n=2</th>
<th>n=3</th>
<th>n=4</th>
<th>n=5</th>
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<th>n=7</th>
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<tbody>
<tr>
<td>1</td>
<td>$\eta_G$</td>
<td>0.0115</td>
<td>0.0115</td>
<td>3.11</td>
<td>3.63</td>
<td>3.05</td>
<td>2.76</td>
<td>2.57</td>
<td>2.43</td>
</tr>
<tr>
<td></td>
<td>$M_S$</td>
<td>3.05</td>
<td>2.40 2.73</td>
<td>3.11</td>
<td>3.63</td>
<td>3.05</td>
<td>2.76</td>
<td>2.57</td>
<td>2.43</td>
</tr>
<tr>
<td>1.70</td>
<td>$\eta_G$</td>
<td>0.0085</td>
<td>-0.0159 0.0085</td>
<td>3.55</td>
<td>3.92</td>
<td>3.29</td>
<td>2.98</td>
<td>2.77</td>
<td>2.62</td>
</tr>
<tr>
<td></td>
<td>$M_S$</td>
<td>3.29</td>
<td>2.52 2.94</td>
<td>3.55</td>
<td>3.92</td>
<td>3.29</td>
<td>2.98</td>
<td>2.77</td>
<td>2.62</td>
</tr>
</tbody>
</table>

8. Summary

A search for evidence of extra dimensions has been performed in the diphoton channel, based on the full 2011 dataset collected by the ATLAS detector at the LHC (4.9 fb$^{-1}$ of proton–proton collisions at $\sqrt{s} = 7$ TeV). In the ADD scenario, lower limits of between 2.52 and 3.92 TeV at 95% CL are set on the $M_S$ scale, depending on the number of extra dimensions and the theoretical formalism used. The combination with the dilepton channel presented in Ref. [49] further tightened these limits to 2.6–4.2 TeV.

In the RS scenario, a lower limit of 1.00 (2.06) TeV at 95% CL is set on the mass of the lightest RS graviton, for RS couplings of $k/M_{P_l} = 0.01 (0.1)$. These new limits are a significant improvement over the previous best limit in the diphoton channel of 0.80 (1.85) TeV for $k/M_{P_l} = 0.01 (0.1)$ [11]. The combination with the latest ATLAS dilepton searches [3] yields an improvement by a factor of 2–3 in the cross-section limits compared to Ref. [11] and further tightens the RS graviton mass limits to 1.03 (2.23) TeV for $k/M_{P_l} = 0.01 (0.1)$.

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The ATLAS Collaboration

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H.H. Williams, W. Willis, S. Willocq, J.A. Wilson, M.G. Wilson,
A. Wilson, I. Wingenter-Seez, S. Winkelmann, F. Winklmeier, M. Wittgen,
S.J. Wollstadt, M.W. Wolter, H. Wolters, W.C. Wong, G. Wooden,
B.K. Wosiek, J. Wotschack, M.J. Woodstra, K.W. Wozniak, K. Wraight,
M. Wright, B. Wrona, S.L. Wu, X. Wu, Y. Wu, E. Wulf, B.M. Wynne,
S. Xella, M. Xiao, S. Xie, C. Xu, D. Xu, D. Yu, C. Zeitnitz, H. Zhang,
Z. Zhan, D. Zhang, X. Zhang, H. Zhang, J. Zhang, Z. Zhang,
A. Zayed, A.M. Zaitsev, V. Zhuravlov, B.K. Wosiek, G. Zobernig,
M. Yamada, H. Yamaguchi, A. Yamamoto, K. Yamamoto, S. Yamamoto,
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C. Xu, S. Xie, C. Xu, D. Xu, D. Yu, C. Zeitnitz, H. Zhang, J. Zhang,
Search for Extra Dimensions in diphoton events with the ATLAS detector

14 Department for Physics and Technology, University of Bergen, Bergen, Norway
15 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
16 Department of Physics, Humboldt University, Berlin, Germany
17 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19 (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
20 (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica, Università di Bologna, Bologna, Italy
21 Physikalisches Institut, University of Bonn, Bonn, Germany
22 Department of Physics, Boston University, Boston MA, United States of America
23 Department of Physics, Brandeis University, Waltham MA, United States of America
24 (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
25 Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
26 (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) University Politehnica Bucharest, Bucharest; (c) West University in Timisoara, Timisoara, Romania
27 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
28 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
29 Department of Physics, Carleton University, Ottawa ON, Canada
30 CERN, Geneva, Switzerland
31 Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
32 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
33 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong; (e) Physics Department, Shanghai Jiao Tong University, Shanghai, China
34 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
35 Nevis Laboratory, Columbia University, Irvington NY, United States of America
Search for Extra Dimensions in diphoton events with the ATLAS detector

36 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
37 (a) INFN Gruppo Collegato di Cosenza; (b) Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
38 AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
39 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
40 Physics Department, Southern Methodist University, Dallas TX, United States of America
41 Physics Department, University of Texas at Dallas, Richardson TX, United States of America
42 DESY, Hamburg and Zeuthen, Germany
43 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
44 Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
45 Department of Physics, Duke University, Durham NC, United States of America
46 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
49 Section de Physique, Université de Genève, Geneva, Switzerland
50 (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
51 (a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) 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 of America
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
58 (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
59 Faculty of Applied Information Science, Hiroshima Institute of Technology,
Search for Extra Dimensions in diphoton events with the ATLAS detector

of America

Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America

(a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy

B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus

National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus

Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America

Group of Particle Physics, University of Montreal, Montreal QC, Canada

P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia

Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia

Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany

Nagasaki Institute of Applied Science, Nagasaki, Japan

Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan

(a) INFN Sezione di Napoli; (b) Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy

Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America

Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands

Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands

Department of Physics, Northern Illinois University, DeKalb IL, United States of America

Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia

Department of Physics, New York University, New York NY, United States of America

Ohio State University, Columbus OH, United States of America

Faculty of Science, Okayama University, Okayama, Japan

Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America

Department of Physics, Oklahoma State University, Stillwater OK, United States of America

Palacký University, RCPTM, Olomouc, Czech Republic
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Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
Graduate School of Science, Osaka University, Osaka, Japan
Department of Physics, University of Oslo, Oslo, Norway
Department of Physics, Oxford University, Oxford, United Kingdom
(a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
Petersburg Nuclear Physics Institute, Gatchina, Russia
(a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
(a) Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal; (b) Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
Czech Technical University in Prague, Praha, Czech Republic
State Research Center Institute for High Energy Physics, Protvino, Russia
Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
Physics Department, University of Regina, Regina SK, Canada
Ritsumeikan University, Kusatsu, Shiga, Japan
(a) INFN Sezione di Roma I; (b) Dipartimento di Fisica, Università La Sapienza, Roma, Italy
(a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
(a) INFN Sezione di Roma Tre; (b) Dipartimento di Fisica, Università Roma Tre, Roma, Italy
(a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (b) Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France
Search for Extra Dimensions in diphoton events with the ATLAS detector

Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America

Department of Physics, University of Washington, Seattle WA, United States of America

Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom

Department of Physics, Shinshu University, Nagano, Japan

Fachbereich Physik, Universität Siegen, Siegen, Germany

Department of Physics, Simon Fraser University, Burnaby BC, Canada

SLAC National Accelerator Laboratory, Stanford CA, United States of America

(a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic

(a) Department of Physics, University of Johannesburg, Johannesburg; (b) School of Physics, University of the Witwatersrand, Johannesburg, South Africa

(a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden

Physics Department, Royal Institute of Technology, Stockholm, Sweden

Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America

Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom

School of Physics, University of Sydney, Sydney, Australia

Institute of Physics, Academia Sinica, Taipei, Taiwan

Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel

Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan

Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan

Department of Physics, Tokyo Institute of Technology, Tokyo, Japan

Department of Physics, University of Toronto, Toronto ON, Canada

(a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada

Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan

Department of Physics and Astronomy, Tufts University, Medford MA, United States of America

Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
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(a) INFN Gruppo Collegato di Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
Department of Physics, University of Illinois, Urbana IL, United States of America
Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
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
Department of Physics, University of British Columbia, Vancouver BC, Canada
Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
Department of Physics, University of Warwick, Coventry, United Kingdom
Waseda University, Tokyo, Japan
Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
Department of Physics, University of Wisconsin, Madison WI, United States of America
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
Department of Physics, Yale University, New Haven CT, United States of America
Yerevan Physics Institute, Yerevan, Armenia
Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
a Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal
b Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal
c Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
d Also at Department of Physics, University of Johannesburg, Johannesburg, South Africa
e Also at TRIUMF, Vancouver BC, Canada
f Also at Department of Physics, California State University, Fresno CA, United States of America
g Also at Novosibirsk State University, Novosibirsk, Russia
h Also at Department of Physics, University of Coimbra, Coimbra, Portugal
i Also at Department of Physics, UASLP, San Luis Potosi, Mexico
j Also at Università di Napoli Parthenope, Napoli, Italy
k Also at Institute of Particle Physics (IPP), Canada
l Also at Department of Physics, Middle East Technical University, Ankara, Turkey
m Also at Louisiana Tech University, Ruston LA, United States of America
n Also at Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
o Also at Department of Physics and Astronomy, University College London, London,
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United Kingdom

Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada

Also at Department of Physics, University of Cape Town, Cape Town, South Africa

Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany

Also at Manhattan College, New York NY, United States of America

Also at School of Physics, Shandong University, Shandong, China

Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China

Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan

Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy

Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France

Also at Section de Physique, Université de Genève, Geneva, Switzerland

Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal

Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America

Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary

Also at California Institute of Technology, Pasadena CA, United States of America

Also at Institute of Physics, Jagiellonian University, Krakow, Poland

Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France

Also at Nevis Laboratory, Columbia University, Irvington NY, United States of America

Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom

Also at Department of Physics, Oxford University, Oxford, United Kingdom

Also at Institute of Physics, Academia Sinica, Taipei, Taiwan

Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa

* Deceased