Search for high-mass diphoton resonances in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

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Search for high-mass diphoton resonances in \( pp \) collisions at \( \sqrt{s} = 8 \) TeV with the ATLAS detector

G. Aad et al.

(ATLAS Collaboration)

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This article describes a search for high-mass resonances decaying to a pair of photons using a sample of 20.3 fb\(^{-1}\) of \( pp \) collisions at \( \sqrt{s} = 8 \) TeV recorded with the ATLAS detector at the Large Hadron Collider. The data are found to be in agreement with the Standard Model prediction, and limits are reported in the framework of the Randall-Sundrum model. This theory leads to the prediction of graviton states, the lightest of which could be observed at the Large Hadron Collider. A lower limit of 2.66 (1.41) TeV at 95% confidence level is set on the mass of the lightest graviton for couplings of \( k/M_{\text{Pl}} = 0.1 \) (0.01).

I. INTRODUCTION

One of the primary goals of the experiments at the Large Hadron Collider (LHC) is the search for new phenomena which might manifest themselves in the high-energy regime made accessible for the first time by this machine. This article reports on a search for new high-mass resonances in the diphoton channel using the full data set of proton-proton (\( pp \)) collisions recorded with the ATLAS detector [1] at \( \sqrt{s} = 8 \) TeV in 2012.

The diphoton channel is important for searches for physics beyond the Standard Model (SM) since new high-mass states decaying to two photons are predicted in many extensions of the SM, and since searches in the diphoton channel benefit from a clean experimental signature: excellent mass resolution and modest backgrounds. One popular example of theories predicting a new high-mass diphoton resonance is the Randall-Sundrum (RS) model [2]. This model attempts to solve the so-called hierarchy problem of the SM, i.e. the fact that the electroweak scale is 16 orders of magnitude smaller than the Planck scale (\( M_{\text{Pl}} \approx 10^{16} \) TeV). The hierarchy problem poses the question of the naturalness of the SM, and despite significant efforts over the past few decades, this problem has not been solved so far. In the RS model, the observed hierarchy of scales is accommodated assuming an extra spatial dimension. In this paradigm, the fundamental strength of gravity is comparable to the strength of the electroweak interaction, but gravity appears much weaker than the other interactions because it is diluted by the presence of the extra spatial dimension.

The RS model postulates a “warped” five-dimensional spacetime configuration. In this configuration there are two 3-branes that are the boundaries of the five-dimensional spacetime. The 3-branes can support (3 + 1)-dimensional field theories. The SM fields are located on one of the two 3-branes, the so-called TeV brane, while gravity originates from the other brane, called the Planck brane. Gravitons propagate in the five-dimensional bulk. The fifth dimension is compactified with length \( r_c \). The solution to Einstein’s equations for this configuration is given by a spacetime metric that couples the standard four dimensions to the extra dimension with an exponential “warp factor.” In this configuration, a field with the fundamental mass parameter \( m_0 \) will appear to have the physical mass \( m = e^{-k r_c} m_0 \), where \( k \) is the curvature scale of the extra dimension. Scales of the order of 1 TeV are therefore generated from fundamental scales of the order of \( M_{\text{Pl}} \) if \( k r_c \approx 12 \) [3]. The compactification of the extra dimension gives rise to a Kaluza-Klein (KK) [4] tower of graviton excitations \( G^j \) – a set of particles on the TeV brane with increasing mass. The phenomenology can be described in terms of the mass of the lightest KK graviton excitation (\( m_{G^1} \)) and the dimensionless coupling to the SM fields, \( k/M_{\text{Pl}} \), where \( M_{\text{Pl}} = M_{\text{Pl}}/\sqrt{8 \pi} \) is the reduced Planck scale. The masses and couplings of the individual graviton states are determined by the scale \( \Lambda_x = e^{-k r_c} M_{\text{Pl}} \approx O(\text{TeV}) \) [3]. Values of \( k/M_{\text{Pl}} \) in the range [0.01, 0.1] are preferred from theoretical arguments [3]. The lightest graviton state is expected to be a fairly narrow resonance for \( k/M_{\text{Pl}} < 0.3 \) [3]. Its natural width varies like the square of \( k/M_{\text{Pl}} \). For \( k/M_{\text{Pl}} = 0.1 \), the natural width increases from \( \sim 8 \) GeV at \( m_{G^1} = 800 \) GeV to \( \sim 30 \) GeV at \( m_{G^1} = 2200 \) GeV. In the first example, the natural width and the experimental mass resolution are similar; in the second example the natural width dominates the total width of the mass peak.

Searches for high-mass diphoton resonances at the LHC have been reported by both the ATLAS and CMS collaborations.
TABLE I. Overview of previous limits on the mass of the lightest RS graviton state, expressed at 95% confidence level. The notation $\ell^+ \ell^-$ refers to a combination of the dielectron and dimuon channels. The CDF and D0 experiments operated at the Tevatron $p\bar{p}$ collider.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\sqrt{s}$ [TeV]</th>
<th>Luminosity [fb$^{-1}$]</th>
<th>Channel</th>
<th>Limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>7</td>
<td>4.9</td>
<td>$\gamma\gamma$</td>
<td>2.06 (1.00) TeV for $k/\sqrt{s}$ = 0.1 (0.01)</td>
<td>[5]</td>
</tr>
<tr>
<td>CMS</td>
<td>7</td>
<td>2.2</td>
<td>$\gamma\gamma$</td>
<td>1.84 (0.86) TeV for $k/\sqrt{s}$ = 0.1 (0.01)</td>
<td>[6]</td>
</tr>
<tr>
<td>ATLAS</td>
<td>8</td>
<td>20.5</td>
<td>$\ell^+ \ell^-$</td>
<td>2.68 (1.25) TeV for $k/\sqrt{s}$ = 0.1 (0.01)</td>
<td>[7]</td>
</tr>
<tr>
<td>CMS</td>
<td>7 and 8</td>
<td>5.3 and 4.1</td>
<td>$\ell^+ \ell^-$</td>
<td>2.39 TeV for $k/\sqrt{s}$ = 0.1</td>
<td>[8]</td>
</tr>
<tr>
<td>CMS</td>
<td>8</td>
<td>4.0</td>
<td>jet-jet</td>
<td>1.45 TeV for $k/\sqrt{s}$ = 0.1</td>
<td>[9]</td>
</tr>
<tr>
<td>ATLAS</td>
<td>7</td>
<td>4.7</td>
<td>$W^+ W^-$</td>
<td>1.23 TeV for $k/\sqrt{s}$ = 0.1</td>
<td>[10]</td>
</tr>
<tr>
<td>CDF</td>
<td>1.96</td>
<td>5.7 and 5.4</td>
<td>$e^+ e^-$ and $\gamma\gamma$</td>
<td>1.06 TeV for $k/\sqrt{s}$ = 0.1</td>
<td>[11]</td>
</tr>
<tr>
<td>D0</td>
<td>1.96</td>
<td>5.4</td>
<td>$e^+ e^-$ and $\gamma\gamma$</td>
<td>1.05 (0.56) TeV for $k/\sqrt{s}$ = 0.1 (0.01)</td>
<td>[12]</td>
</tr>
</tbody>
</table>

II. THE ATLAS DETECTOR

The ATLAS detector is described in detail in Ref. [11]. It consists of an inner detector (ID) surrounded by a solenoid that produces a 2 T magnetic field, electromagnetic (EM) and hadronic calorimeters, and a muon spectrometer which employs air-core toroidal magnets. The ATLAS detector is divided into a barrel section covering the region $|\eta| < 2.5$, the ID provides measurements of the tracks originating from the primary $p\bar{p}$ collision as well as tracks from secondary vertices, permitting the efficient identification of photon conversions. The EM calorimeter (ECAL) is a lead/liquid-argon (LAr) sampling calorimeter. It is divided into a barrel section covering the region $|\eta| < 1.475$ and two endcap sections covering 1.375 $< |\eta| < 3.2$. The ECAL is segmented longitudinally in shower depth into three layers for $|\eta| < 2.5$ and two for 2.5 $< |\eta| < 3.2$. Up to $|\eta| < 2.4$, the first layer consists of highly granular strips segmented in the $\eta$ direction for efficient candidate-by-candidate discrimination between single photon showers and two overlapping showers originating from $\pi^0$ decay. The second layer, with a typical granularity of $\Delta \eta \times \Delta \phi = 0.025 \times 0.025$, collects most of the energy from photon showers. Significant energy deposited in the third layer is an indication for leakage beyond the ECAL from a high-energy shower, and the measurements from the third layer are used to correct for this effect. A thin presampler layer, installed in front of the ECAL and covering the pseudorapidity interval $|\eta| < 1.8$, is used to correct for energy loss before the ECAL. In the region $|\eta| < 1.7$, the hadronic sampling calorimeter uses iron absorbers and plastic scintillator tiles as the active material. In the region 1.5 $< |\eta| < 4.9$, LAr is used as the active material, with copper or/and tungsten absorbers. The muon spectrometer features three stations of precision chambers that allow for accurate measurements of the muon track curvature in the region $|\eta| < 2.7$. Fast detectors enable muon triggering in the range $|\eta| < 2.4$. A three-level trigger system is used to select the events to be recorded for subsequent offline analysis.

III. EVENT RECONSTRUCTION AND SELECTION

The events used in this analysis were recorded using a diphoton trigger. At the highest, software-based level of the trigger system, this trigger requires at least one photon with transverse energy $E_T > 35$ GeV and at least one other photon with $E_T > 25$ GeV. Both photons need to satisfy requirements on the shape of the energy deposit in the calorimeter. This trigger is nearly fully efficient for diphoton pairs that pass the offline event selection.

In the offline analysis, only events that pass the standard ATLAS data quality requirements are considered. Photons are reconstructed from fixed-size clusters of cells in the EM calorimeter. To ensure good diphoton mass resolution, photons are required to be located inside the precision region of the EM calorimeter ($|\eta| < 1.37$ or 1.52 $< |\eta| < 2.37$). They are further required to satisfy $E_T > 50$ GeV as well as the "loose" identification requirements from Ref. [13] updated for 2012 run conditions. The two highest-$E_T$ photon candidates that pass these requirements are retained for further analysis. Events are retained for the main analysis if both candidates also satisfy the "tight" identification requirements [13] updated for the 2012 run.
conditions. These requirements include upper limits on the energy leakage into the hadronic calorimeter and on the width of the shower in the first and second layers of the EM calorimeter. Events where at least one candidate fails the tight photon identification are retained for the study of backgrounds with misidentified (fake) photons in data control samples.

The invariant mass of the diphoton system is evaluated using the photon energies measured in the calorimeter as well as the direction of the photon momenta determined from the positions of the photons in the calorimeter and the position of the primary vertex of the hard interaction. Primary vertices are reconstructed from the tracks in the ID and are required to be formed from at least three tracks. The primary vertex of the hard interaction is identified using information on the directions of flight of the photons as determined using the longitudinal segmentation of the ECAL (calorimeter pointing), the parameters of the beam spot and the properties of the tracks associated with each reconstructed vertex [14]. This procedure ensures good diphoton mass resolution despite the presence of pileup. Pileup refers to the additional \( pp \) interactions that occur in the same bunch crossing as the \( pp \to \gamma\gamma + X \) interaction or in the adjacent crossings.

A calorimetric isolation observable is defined for photon candidates. This observable provides further discrimination between genuine photons and fake candidates from jets (\( j \)). It is used for two purposes in this analysis: to quantify the composition of the data sample in terms of true and fake photon candidates, and to suppress the reducible background by requiring both photons to be isolated. The isolation energy \( \Delta E_{\text{iso}} \) is defined as the sum of the transverse energies of cells inside clusters of variable size (also called “topo-clusters” [15]) inside a cone of \( \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.4 \) around the photon candidate, excluding a \( 5 \times 7 \) grid of EM cells in the center of the cone.

The measurement of \( \Delta E_{\text{iso}} \) is corrected for the following two effects: (i) soft energy contributions from the underlying event and pileup that fall inside the isolation cone, and (ii) leakage of photon energy outside the central core, causing the isolation energy to grow as a function of photon \( E_T \). The expected soft contributions are subtracted from \( \Delta E_{\text{iso}} \) on an event-by-event basis; the correction is based on a measurement of the properties of low-\( p_T \) jets [16] in the event. The average expected contributions to \( \Delta E_{\text{iso}} \) from leakage are subtracted based on simulations. The fluctuations (from one photon shower to another) around the average expected leakage contribution to \( \Delta E_{\text{iso}} \) become more important as \( E_T \) increases. In particular, the tail at large \( \Delta E_{\text{iso}} \) becomes more pronounced and would cause significant inefficiencies at large \( E_T \) if a fixed upper limit on \( \Delta E_{\text{iso}} \) were imposed in the event selection. To avoid inefficiencies, a negative \( E_T \) -dependent offset is added to \( \Delta E_{\text{iso}} \), and the requirement \( \Delta E_{\text{iso}} < 8 \text{ GeV} \) is imposed on both photon candidates after the addition of the offset. In the following, the symbol \( \Delta E_{\text{iso}} \) refers to the isolation energy with the offset applied. The \( E_T \) -dependence of the offset is chosen such that the efficiency of the \( \Delta E_{\text{iso}} \) requirement is independent of \( E_T \) in simulated samples, and the size of the offset varies from zero at low \( E_T \) to \(-5 \text{ GeV} \) at \( E_T = 1 \text{ TeV} \). The corresponding efficiency of the isolation requirement is 96% per photon. For the purpose of the determination of the background composition, a less stringent requirement of \( \Delta E_{\text{iso}} < 14 \text{ GeV} \) is used. Examples of the \( \Delta E_{\text{iso}} \) distributions will be shown after the discussion of the backgrounds.

IV. BACKGROUND ESTIMATE

An important contribution to the background arises from prompt \( \gamma\gamma \) production via Standard Model processes. This contribution is irreducible and, as quantified below, represents the dominant source of background. Another significant contribution is due to events in which one or both of the photon candidates arise from other objects, such as misidentified jets or electrons. This background component is dominated by \( \gamma + j \) and \( j + j \) events with one or two jets reconstructed as photons. Backgrounds with electrons misidentified as photons – e.g. electron-positron events from Drell-Yan production, in \( W/Z + \gamma \) or in \( tt \) events – were verified to be negligible after the event selection.

The irreducible background is estimated using Monte Carlo (MC) simulations normalized to the data in a control region defined below, and the reducible background is estimated using control samples in data. A combination of the leading-order (LO) event generator \PYTHIA\ [17] and the next-to-leading-order (NLO) parton-level simulation \DIPHOX\ [18] is used to simulate the irreducible background. Monte Carlo samples are generated using \PYTHIA\ 8.163 with the CTEQ6.0L [19] parton distribution functions (PDFs) and the AU2 \PYTHIA\ parameter tune [20]. The detector response is simulated using \GEANT\ 4 [21,22], including pileup conditions similar to those observed in data. The simulated events are reweighted such that the number of \( pp \) interactions per bunch crossing has the same distribution as in data. The NLO correction and the contributions of the fragmentation process are evaluated using \DIPHOX 1.3.2\ with the CTEQ6.6M [23] PDF set and are used to scale the \PYTHIA\ prediction by a factor that depends on the generated mass of the diphoton system. The so-called box contribution \( gg \to \gamma\gamma \) through a quark loop is included in both the \PYTHIA\ and \DIPHOX\ predictions. From the point of view of power counting, this diagram is a next-to-next-to-leading-order (NNLO), i.e. \( \mathcal{O}(\alpha_s^3, \alpha_{\text{EM}}^2) \), contribution. But given the large gluon luminosity at the LHC compared to the quark-antiquark one, the contribution of the box diagram is comparable to that of the \( q\bar{q} \to \gamma\gamma \) process, which corresponds to a LO, i.e. \( \mathcal{O}(\alpha_s^2, \alpha_{\text{EM}}^2) \), diagram.
To reduce the impact of the theory uncertainties in the absolute normalization of the production cross section of the irreducible background, the background estimates are scaled to the data at low mass. In the mass region \( m_{\gamma\gamma} < 600 \text{ GeV} \), where \( m_{\gamma\gamma} \) denotes the measured invariant mass of the diphoton system, the most sensitive searches for narrow resonances in the diphoton channel rely on background estimates that make use of low-mass and high-mass sidebands [24]. The search described in the present article focuses on higher diphoton masses where the sidebands, especially at high mass, provide insufficient event yields. This search therefore uses a different approach to obtain the background prediction at high \( m_{\gamma\gamma} \). Specifically, the simulated irreducible background is normalized to the data in a low-mass control region after subtraction of the reducible backgrounds. This control region is defined to coincide with the first 22 bins in Fig. 3, i.e. as \( 179 < m_{\gamma\gamma} < 409 \text{ GeV} \). To determine the composition of the data sample in the low-mass control region in terms of irreducible and reducible backgrounds, a template fit to the \( E_T^{\text{iso}} \) distributions of the leading and subleading photon candidates is performed. A similar technique was used in earlier analyses of low-mass diphoton events [25,26]. The \( E_T^{\text{iso}} \) distributions, along with the result of the template fit, are shown in Fig. 1 (top and middle). The full event selection described in Sec. III, with the relaxed requirement \( E_T^{\text{iso}} < 14 \text{ GeV} \), has been applied. The fit is performed simultaneously to the two distributions, and the normalizations for four background components are allowed to float in the fit, namely the irreducible \( \gamma\gamma \) component plus three reducible components: \( \gamma + j \) (subleading photon candidate is fake), \( j + \gamma \) and \( j + j \). Templates for the \( E_T^{\text{iso}} \) distribution of true photons and of fake photons are determined from data. The template for fake photons is obtained using a sample of photon candidates that pass the non-tight selection: photon candidates must satisfy the loose identification criteria and fail to meet a subset of the criteria in the tight selection. This subset has been chosen to include criteria that have been found to be only weakly correlated with \( E_T^{\text{iso}} \). The template for true photons is obtained from the sample of tight photon candidates after subtraction of the fake-photon template normalized to the tight data sample at \( E_T^{\text{iso}} > 10 \text{ GeV} \) where fake photons dominate.

The fit is performed separately in five subsamples of the data, because the relative contributions of the four background components vary significantly from one subsample to another. The five subsamples correspond to different combinations of pseudorapidities of the leading and subleading photon candidates: both photons in the “central” region (|\( \eta \)| < 1.37), leading photon central and subleading photon in the “endcap” region (1.52 < |\( \eta \)| < 2.37), leading photon in endcap and subleading central, both photons in same endcap and both photons in endcaps of opposite-sign pseudorapidity. In Fig. 1, the data from the five subsamples, as well as the corresponding fit results are combined, and
only the sum of the photon and jet components over the four background components is shown. To illustrate the broadening of the $E_{T}^{iso}$ distribution at large $E_{T}$ described above, Fig. 1 also includes the $E_{T}^{iso}$ distribution for photons with $E_{T} > 400$ GeV.

The backgrounds in the search region, i.e. at masses higher than the low-mass control region, are predicted using estimates of the $m_{T}$ shape of each background component and the normalizations obtained in the low-mass control region described above. As discussed above, the shape of the irreducible component is obtained using simulation. The shapes of the reducible components are obtained from data control samples. The control sample used to extract the shape of the $\gamma + j$ background is selected in the same way as the signal sample, except that the subleading photon candidate has to satisfy the "loose" identification criteria and fail to meet the "tight" criteria. The control samples for the $j + \gamma$ and $j + j$ backgrounds are defined using the same approach. Since these data control samples contain relatively few events at high $m_{T}$, a fit to a smooth function of the form $f(m_{T}) = p_{1} + p_{2} \times \log(m_{T})$, where the $p_{i}$ are free parameters, is used to extrapolate the shapes of the reducible backgrounds to high $m_{T}$. This functional form describes well the shapes of the data in the control samples of this analysis. It was also successful in describing the shapes of the background control samples in earlier searches in the dijet [27,28], dilepton [29], photon-jet [30] and diphoton [5] channels.

The shapes of the distribution of the isolation energy for genuine photons extracted from data (in bins of $E_{T}^{iso}$) are compared to the shapes predicted using simulation. The impact of the small observed differences in the isolation distributions on the predicted $m_{T}$ shape of the irreducible background and on the signal efficiency is quantified and taken into account in the systematic uncertainties.

The uncertainties in the prediction of the total background are shown in Fig. 2 as a function of $m_{T}$. The uncertainties in the shape of the $m_{T}$ distribution of the irreducible background are dominated by the uncertainties in the PDF set used for the DIPHOX simulation. The set of PDF variations provided with the CTEQ6.6M PDF set are used to propagate the PDF uncertainty to the shape of the irreducible background. The comparatively small difference between the irreducible background shapes obtained with the CTEQ6.6M and the MSTW2008 [31] PDF sets is added in quadrature to the uncertainty. An additional uncertainty arises from higher-order contributions that are not included in the DIPHOX generator. This uncertainty is evaluated by varying in a correlated and anticorrelated way the renormalization scale and the factorization scales in the hard scattering process and in the photon fragmentation function [18] by a factor two around their nominal value, which is set to the mass of the diphoton system. A small uncertainty arises from residual imperfections in the simulation of the isolation energy $E_{T}^{iso}$. The uncertainties in the shape of the reducible background arise from the finite size of the corresponding control samples, and from the extrapolation of the background shapes from the control samples to the signal region. The latter are assessed by varying the definition of the "loose" selection requirement that is used to define the control samples. The uncertainties in the normalizations of the individual background components are dominated by the uncertainties in the template shapes that are used in the fit to the isolation energy. They are assessed by varying the definition of the "non-tight" selection requirements that are used to obtain the template shapes.

V. SIGNAL RESPONSE

Simulated event samples of RS graviton signals at different values of $m_{G}$ are used to study the response of the detector for signal events. The samples are generated using PYTHIA 8.163 with the CTEQ6L1 PDF set, the AU2 tune and the same detector and pileup simulation as for the SM $\gamma \gamma$ samples described above. The sources of uncertainty in the expected signal yield are summarized in Table II. The systematic uncertainty is dominated by the uncertainty in the efficiency due to residual imperfections in the simulation of the observables that are used in the "tight" photon identification criteria and in the simulation of the isolation energy. Smaller contributions arise due to the limited size of the simulated samples and the determination of the trigger efficiency. The uncertainty in the integrated luminosity is also propagated to the expected yield. Uncertainties in the RS resonance shape due to our current knowledge of the photon energy scale and resolution as well as imperfections in the simulation of the pileup conditions were verified to have a negligible effect on the result.
TABLE II. Summary of systematic uncertainties on the expected signal yield, excluding those on the production cross section and the acceptance. The total systematic uncertainty is obtained by summing the individual contributions in quadrature.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty in signal yield [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity</td>
<td>2.8</td>
</tr>
<tr>
<td>MC statistics</td>
<td>1.0</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>1.0</td>
</tr>
<tr>
<td>Photon ID efficiency</td>
<td>3.0</td>
</tr>
<tr>
<td>Photon isolation efficiency</td>
<td>0.3–2.1 (for ( m_{G'} = 500–3000 ) GeV)</td>
</tr>
<tr>
<td>Total</td>
<td>≈ 5</td>
</tr>
</tbody>
</table>

VI. RESULTS

The observed diphoton mass spectrum is shown in Fig. 3, together with the background expectation and the predicted signal for two examples of values of the RS model parameters. The acceptance (i.e. the fraction of simulated signal for two examples of values of the RS model and \( E_T^\gamma \) described above) for the RS scenario with \( m_{G'} = 2.0 \) TeV and \( k/\sqrt{M_{pp}} = 0.1 \) is 89.3% and the selection efficiency for events within acceptance is (55.9 ± 2.6)%). The bottom inset in Fig. 3 shows, bin by bin, the statistical significance of the difference between the data and the expected background. This significance is calculated using the prescription in Ref. [32] and is plotted as positive (negative) for bins with an excess (deficit) of data. The observed event yields and expected backgrounds are also summarized in Table III. No significant deviation of the data from the expected background is observed. To further quantify the level of agreement, the BUMPHUNTER [33] algorithm is used to search for any “bump” on top of the expected background, i.e. any excess of events localized in a relatively narrow mass region. Specifically, the BUMPHUNTER algorithm scans the mass distribution in windows of progressively increasing width in order to identify the window with the most significant excess of observed events over the background anywhere in a predefined search region. In this analysis, the binned \( m_{\gamma\gamma} \) spectrum from Fig. 3 is used, the search region is defined as \( 409 < m_{\gamma\gamma} < 3000 \) GeV, and the window size is allowed to vary from one bin to half the number of bins in the search region. The most significant excess is found in the region \( 494 < m_{\gamma\gamma} < 745 \) GeV. The probability to observe anywhere in the search region an excess that is at least as significant as the one observed in data and that arises from fluctuations in the background is 58%. This confirms the absence of any significant excess in the data.

As no evidence for a signal is found, upper limits at 95% confidence level (CL) are set on the production cross section times branching ratio, \( \sigma \times BR(G^+ \rightarrow \gamma\gamma) \), for the lightest RS graviton. A Bayesian approach is used to calculate the limits, and the corresponding computer program is implemented using the toolkit from Refs. [34,35]. A likelihood function is used to describe the probability to obtain the \( m_{\gamma\gamma} \) distribution observed in data, given the background and signal predictions. The likelihood is defined as the product of the per-bin probabilities over all bins in the search region (\( m_{\gamma\gamma} > 409 \) GeV) in Fig. 3. In each bin, the probability is computed from a Poisson distribution given the observed number of events and the model prediction, where the model prediction is the sum of the expected numbers of background and signal events. The expected signal yield depends on \( m_{G'} \) and \( \sigma \times BR(G^+ \rightarrow \gamma\gamma) \). Using Bayes’s theorem, the likelihood is converted into a posterior probability. A uniform positive prior in \( \sigma \times BR(G^+ \rightarrow \gamma\gamma) \) is assumed, and systematic uncertainties are incorporated using nuisance parameters with Gaussian priors. For a given value of \( m_{G'} \), the posterior probability is reduced to one parameter of interest, \( \sigma \times BR(G^+ \rightarrow \gamma\gamma) \), and the 95% CL limit on \( \sigma \times BR(G^+ \rightarrow \gamma\gamma) \) is obtained via integration of the posterior probability.

The resulting limits on \( \sigma \times BR(G^+ \rightarrow \gamma\gamma) \), as a function of the mass hypothesis (value of \( m_{G'} \)), are shown in Fig. 4. The phenomenology of the RS model can be described in terms of the parameters \( m_{G'} \) and \( k/\sqrt{M_{pp}} \), i.e. \( \sigma \times BR(G^+ \rightarrow \gamma\gamma) \) can be calculated [36,37] for a given pair of values for these parameters. The results of this calculation are represented by the lines for given values of \( k/\sqrt{M_{pp}} \) in Fig. 4. They are
obtained using the PYTHIA generator, which implements the calculations from Ref. [37]. A K-factor is applied to these predictions to account for QCD corrections at NLO. The value of the K-factor varies between 1.6 and 1.9, depending on $m_G$ and $k/M_{Pl}$. These results for the K-factor were provided by the authors of Refs. [38,39], using updated calculations at $\sqrt{s} = 8$ TeV. Given these theory predictions for $\sigma \times BR(G^* \rightarrow \gamma\gamma)$, the upper limits on $\sigma \times BR(G^* \rightarrow \gamma\gamma)$ from Fig. 4 can be translated into upper limits on $k/M_{Pl}$. The results are shown, as a function of $m_G$, in Fig. 5. Alternatively, the upper limits on $\sigma \times BR(G^* \rightarrow \gamma\gamma)$ can be translated into lower limits on the graviton mass. The results are shown in Table IV, for different values of $k/M_{Pl}$. The limits presented in Fig. 5 and in Table IV do not take into account any theory uncertainties in the prediction of $\sigma \times BR(G^* \rightarrow \gamma\gamma)$ for the RS signal. The size of one of the dominant theory uncertainties (the PDF uncertainty) is included in Fig. 4; uncertainties due to missing higher-order contributions in the calculation of the K-factor are estimated to be of comparable size.

FIG. 4 (color online). Expected and observed upper limits on $\sigma \times BR(G^* \rightarrow \gamma\gamma)$ expressed at 95% CL, as a function of the graviton mass. At large $m_G$, the $-\sigma$ and $-2\sigma$ variations of the expected limit tend to be particularly close to the expected limit. This is expected, since signals with high $m_G$, would appear in regions of $m_{\gamma\gamma}$ where the background expectation is small and the Poissonian fluctuations around the mean expected background are highly asymmetric. The curves show the RS model prediction for given values of $k/M_{Pl}$ as a function of $m_G$. They are obtained using the PYTHIA generator plus a K-factor to account for NLO corrections (see text). The thickness of the theory curve for $k/M_{Pl} = 0.1$ illustrates the PDF uncertainties expressed at 90% CL.

FIG. 5 (color online). Expected and observed upper limits on $k/M_{Pl}$ expressed at 95% CL, as a function of the graviton mass.
TABLE IV. Expected and observed lower limits at 95% CL on \(m_G\) for different values of \(k/\sqrt{\mathcal{M}_{\text{Pl}}}\).

<table>
<thead>
<tr>
<th>(k/\sqrt{\mathcal{M}_{\text{Pl}}})</th>
<th>-2(\sigma)</th>
<th>-1(\sigma)</th>
<th>central</th>
<th>+1(\sigma)</th>
<th>+2(\sigma)</th>
<th>observed limit [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.010</td>
<td>1.45</td>
<td>1.38</td>
<td>1.30</td>
<td>1.20</td>
<td>1.11</td>
<td>1.41</td>
</tr>
<tr>
<td>0.020</td>
<td>1.80</td>
<td>1.78</td>
<td>1.70</td>
<td>1.60</td>
<td>1.49</td>
<td>1.62</td>
</tr>
<tr>
<td>0.030</td>
<td>2.02</td>
<td>2.01</td>
<td>1.96</td>
<td>1.86</td>
<td>1.77</td>
<td>1.92</td>
</tr>
<tr>
<td>0.040</td>
<td>2.17</td>
<td>2.16</td>
<td>2.14</td>
<td>2.04</td>
<td>1.94</td>
<td>2.15</td>
</tr>
<tr>
<td>0.050</td>
<td>2.29</td>
<td>2.28</td>
<td>2.27</td>
<td>2.17</td>
<td>2.08</td>
<td>2.28</td>
</tr>
<tr>
<td>0.060</td>
<td>2.38</td>
<td>2.38</td>
<td>2.37</td>
<td>2.27</td>
<td>2.19</td>
<td>2.38</td>
</tr>
<tr>
<td>0.070</td>
<td>2.47</td>
<td>2.46</td>
<td>2.45</td>
<td>2.37</td>
<td>2.27</td>
<td>2.46</td>
</tr>
<tr>
<td>0.080</td>
<td>2.54</td>
<td>2.54</td>
<td>2.53</td>
<td>2.46</td>
<td>2.38</td>
<td>2.54</td>
</tr>
<tr>
<td>0.090</td>
<td>2.61</td>
<td>2.60</td>
<td>2.56</td>
<td>2.45</td>
<td>2.36</td>
<td>2.60</td>
</tr>
<tr>
<td>0.100</td>
<td>2.67</td>
<td>2.66</td>
<td>2.66</td>
<td>2.60</td>
<td>2.51</td>
<td>2.66</td>
</tr>
</tbody>
</table>

VII. CONCLUSIONS

In summary, a search for high-mass diphoton resonances has been performed using the full 2012 dataset collected by the ATLAS detector at the LHC (20.3 fb\(^{-1}\) of \(pp\) collisions at \(\sqrt{s} = 8\) TeV). No significant excess over the expected background is observed, and upper limits on the production cross section times branching fraction \(\sigma \times BR(G^* \to \gamma\gamma)\) for narrow resonances are reported as a function of the resonance mass. High-mass diphoton resonances are predicted e.g. in models that postulate the existence of extra spatial dimensions in order to address the hierarchy problem, and could be observed at the LHC. Limits on the mass of the lightest graviton state in the framework of the Randall-Sundrum model of extra dimensions are derived from the limits on \(\sigma \times BR(G^* \to \gamma\gamma)\). The only free parameters of this model are the mass of the lightest graviton \(m_G\) and the coupling to the SM fields \(k/\sqrt{\mathcal{M}_{\text{Pl}}}\). The lower limit of 2.66 TeV at 95% confidence level is obtained on the mass of the lightest graviton for a coupling \(k=0.01\). The results reported in this article constitute a significant improvement over the results in Ref. [5] obtained at \(\sqrt{s} = 7\) TeV. The upper limits on \(\sigma \times BR(G^* \to \gamma\gamma)\) are reduced by a factor of 2.1 (3.6) for a resonance with a mass of 0.5 TeV (2.75 TeV). Furthermore, the new limits are expressed in terms of the production cross section at \(\sqrt{s} = 8\) TeV, compared to \(\sqrt{s} = 7\) TeV for the old limits, and the production cross section for any new heavy particle is expected to be larger at \(\sqrt{s} = 8\) TeV. The lower limits on the mass of the lightest RS graviton are also significantly improved compared to the previous analysis.

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(ATLAS Collaboration)

1Department of Physics, University of Adelaide, Adelaide, Australia
2Physics Department, SUNY Albany, Albany New York, USA
3Department of Physics, University of Alberta, Edmonton AB, Canada
4Department of Physics, Ankara University, Ankara, Turkey
5Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
6IAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France
7High Energy Physics Division, Argonne National Laboratory, Argonne Illinois, USA
8Department of Physics, University of Arizona, Tucson Arizona, USA
9Department of Physics, The University of Texas at Arlington, Arlington Texas, USA
10Physics Department, National Technical University of Athens, Zografou, Greece
11Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
12Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
13Institute of Physics, University of Belgrade, Belgrade, Serbia
14Department for Physics and Technology, University of Bergen, Bergen, Norway
15Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley California, USA
16Department of Physics, Humboldt University, Berlin, Germany
17Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19Department of Physics, Bogazici University, Istanbul, Turkey
20Department of Physics, Dogus University, Istanbul, Turkey
21Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
22Department of Physics, Instituto Balseiro, San Carlos de Bariloche, Argentina
23Department of Physics, Universidad de Buenos Aires, Buenos Aires, Argentina
24Department of Physics, University of California, Berkeley, USA
25Department of Physics, Brookhaven National Laboratory, Upton New York, USA
26National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania
27University Politehnica Bucharest, Bucharest, Romania
28INFN Sezione di Bologna, Italy
29Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
30Physikalisches Institut, University of Bonn, Bonn, Germany
31Department of Physics, Boston University, Boston Massachusetts, USA
32Department of Physics, Brandeis University, Waltham Massachusetts, USA
33Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
34Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
35Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
36Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
37Physics Department, Brookhaven National Laboratory, Upton New York, USA
38National Institute of Physics and Nuclear Engineering, Bucharest, Romania
39National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania
40University Politehnica Bucharest, Bucharest, Romania
West University in Timisoara, Timisoara, Romania
Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
Department of Physics, Carleton University, Ottawa ON, Canada
CERN, Geneva, Switzerland
Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
Department of Modern Science and Technology, China, Anhui, China
Department of Physics, Nanjing University, Jiangsu, China
School of Physics, Shandong University, Shandong, China
Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai, China
Physics Department, Tsinghua University, Beijing 100084, China
Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
Nevis Laboratory, Columbia University, Irvington New York, USA
Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
Dipartimento di Fisica, Università della Calabria, Rende, Italy
AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
Physics Department, Southern Methodist University, Dallas Texas, USA
Physics Department, University of Texas at Dallas, Richardson Texas, USA
DESY, Hamburg and Zeuthen, Germany
Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
Department of Physics, Duke University, Durham North Carolina, USA
SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
INFN Laboratori Nazionali di Frascati, Frascati, Italy
Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
Section de Physique, Université de Genève, Geneva, Switzerland
INFN Sezione di Genova, Italy
E. Andronikashvili Institute of Physics, Tbilisi, Georgia
High Energy Physics Institute, Tbilisi, Georgia
II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
Department of Physics, Hampton University, Hampton Virginia, USA
Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
Department of Physics, The University of Hong Kong, Hong Kong, China
Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
Department of Physics, Indiana University, Bloomington Indiana, USA
Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
University of Iowa, Iowa City, Iowa, USA
Department of Physics and Astronomy, Iowa State University, Ames Indiana, USA
Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
bb Also at Section de Physique, Université de Genève, Geneva, Switzerland.
c Also at International School for Advanced Studies (SISSA), Trieste, Italy.
dd Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America.
ee Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
f Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.
gg Also at National Research Nuclear University MEPhI, Moscow, Russia.
h Also at Department of Physics, Stanford University, Stanford CA, United States of America.
i Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
j Also at Department of Physics, Oxford University, Oxford, United Kingdom.
k Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America.
l Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.
m Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.