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

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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 $k/\overline{M}_{\mathrm{Pl}} = 0.1$ (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 ($M_{\mathrm{Pl}} \approx 10^{16}$ 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 $m = e^{-k\pi r_{\mathrm{c}}} m_0$, 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_{Pl} if $k r_{\mathrm{c}} \approx 12$ [3]. The compactification of the extra dimension gives rise to a Kaluza-Klein (KK) [4] tower of graviton excitations G^* – 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^*}) and the dimensionless coupling to the SM fields, $k/\overline{M}_{\mathrm{Pl}}$, where $\overline{M}_{\mathrm{Pl}} = M_{\mathrm{Pl}}/\sqrt{8\pi}$ is the reduced Planck scale. The masses and couplings of the individual graviton states are determined by the scale $\Lambda_{\pi} = e^{-k\pi r_{\mathrm{c}}} \overline{M}_{\mathrm{Pl}} \approx \mathcal{O}(\mathrm{TeV})$ [3]. Values of $k/\overline{M}_{\mathrm{Pl}}$ 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 $k/\overline{M}_{\mathrm{Pl}} < 0.3$ [3]. Its natural width varies like the square of $k/\overline{M}_{\mathrm{Pl}}$. For $k/\overline{M}_{\mathrm{Pl}} = 0.1$, the natural width increases from ∼8 GeV at $m_{G^*} = 800$ GeV to ∼30 GeV at $m_{G^*} = 2200$ 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[1] of the mass peak.

Searches for high-mass diphoton resonances at the LHC have been reported by both the ATLAS and CMS

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[1]The experimental mass resolution at $m_{G^*} = 2200$ GeV is only marginally (6%) better than at $m_{G^*} = 800$ GeV.

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.

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

collaborations, and the latest results are summarized in Table I. The most stringent experimental limits on RS gravitons to date have been obtained at the LHC, using a combination of the dielectron and dimuon channels. Limits from searches for narrow resonances in other channels are available in, for example, the dijet and *WW* channels, but these channels are not competitive for the specific case of RS gravitons. The limits obtained using these channels are included in Table I, along with those from earlier searches at the Tevatron.

II. THE ATLAS DETECTOR

The ATLAS detector is described in detail in Ref. [1]. 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. In the pseudorapidity[2] region $|\eta| < 2.5$, the ID provides measurements of the tracks originating from the primary pp 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 η direction for efficient candidate-by-candidate discrimination between single photon showers and two overlapping showers originating from π^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 $E_{\mathrm{T}}^{\gamma} > 35$ GeV and at least one other photon with $E_{\mathrm{T}}^{\gamma} > 25$ 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 $E_{\mathrm{T}}^{\gamma} > 50$ GeV as well as the *loose* identification requirements from Ref. [13] updated for 2012 run conditions. The two highest-E_{T}^{γ} 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

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[2]ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the center of the detector and the z axis along the beam pipe. The x axis points from the interaction point to the center of the LHC ring, and the y axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

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 $pp \rightarrow \gamma\gamma + X$ 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 E_T^{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 5×7 grid of EM cells in the center of the cone.

The measurement of E_T^{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^{γ}. The expected soft contributions are subtracted from E_T^{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 E_T^{iso} from leakage are subtracted based on simulations. The fluctuations (from one photon shower to another) around the average expected leakage contribution to E_T^{iso} become more important as E_T^{γ} increases. In particular, the tail at large E_T^{iso} becomes more pronounced and would cause significant inefficiencies at large E_T^{γ} if a fixed upper limit on E_T^{iso} were imposed in the event selection. To avoid inefficiencies, a negative E_T^{γ}-dependent offset is added to E_T^{iso}, and the requirement $E_T^{iso} < 8$ GeV is imposed on both photon

candidates after the addition of the offset. In the following, the symbol E_T^{iso} refers to the isolation energy with the offset applied. The E_T^{γ}-dependence of the offset is chosen such that the efficiency of the E_T^{iso} requirement is independent of E_T^{γ} in simulated samples, and the size of the offset varies from zero at low E_T^{γ} to -5 GeV at $E_T^{\gamma} = 1$ 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 $E_T^{iso} < 14$ GeV is used. Examples of the E_T^{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 $t\bar{t}$ 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 CTEQ6L1 [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 $gg \rightarrow \gamma\gamma$ 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. $\mathcal{O}(\alpha_{EM}^2 \alpha_s^2)$, 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 $q\bar{q} \rightarrow \gamma\gamma$ process, which corresponds to a LO, i.e. $\mathcal{O}(\alpha_{EM}^2)$, 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 $m_{\gamma\gamma} < 600$ 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 $179 < m_{\gamma\gamma} < 409$ 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^{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^{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 $E_T^{iso} < 14$ 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^{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^{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 $E_T^{iso} > 10$ 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
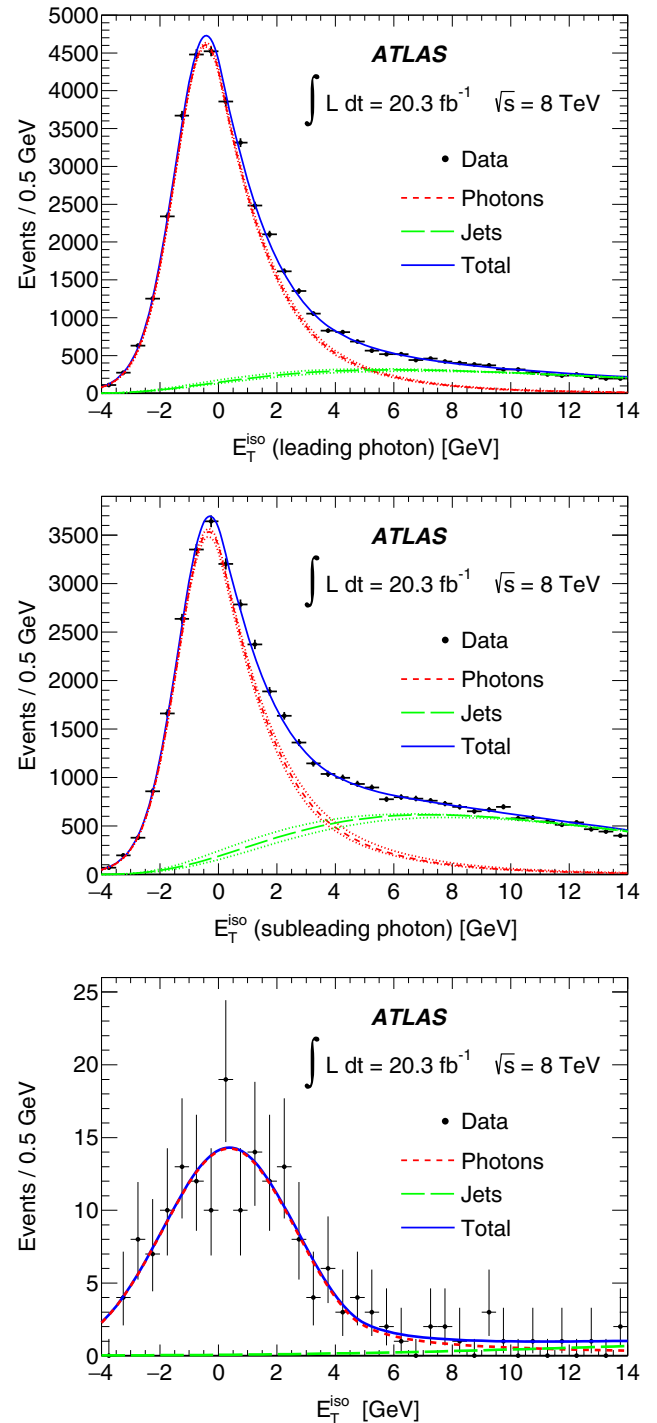

FIG. 1 (color online). Top: distribution of the isolation energy E_T^{iso} for the leading photon candidate in events in the low-mass control region. Middle: corresponding distribution for the subleading photon. The black points represent the data. The blue line shows the result of the template fit to the data. The red and green lines show the templates for photon and jet background respectively, normalized according to the fit result. The red and green bands represent the uncertainties in the photon and jet contributions due to the uncertainties in the template shapes. Bottom: distribution of E_T^{iso} for photon candidates with $E_T^\gamma > 400$ GeV at any diphoton mass. The E_T^{iso} values always include the E_T^γ-dependent offset discussed in the text.

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^{γ} described above, Fig. 1 also includes the E_T^{iso} distribution for photons with $E_T^{\gamma} > 400$ GeV.

The backgrounds in the search region, i.e. at masses higher than the low-mass control region, are predicted using estimates of the $m_{\gamma\gamma}$ 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 $m_{\gamma\gamma}$, 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 shapes of the reducible backgrounds to high $m_{\gamma\gamma}$. 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^{γ}) are compared to the shapes predicted using simulation. The impact of the small observed differences in the isolation distributions on the predicted $m_{\gamma\gamma}$ 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 $m_{\gamma\gamma}$. The uncertainties in the shape of the $m_{\gamma\gamma}$ 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
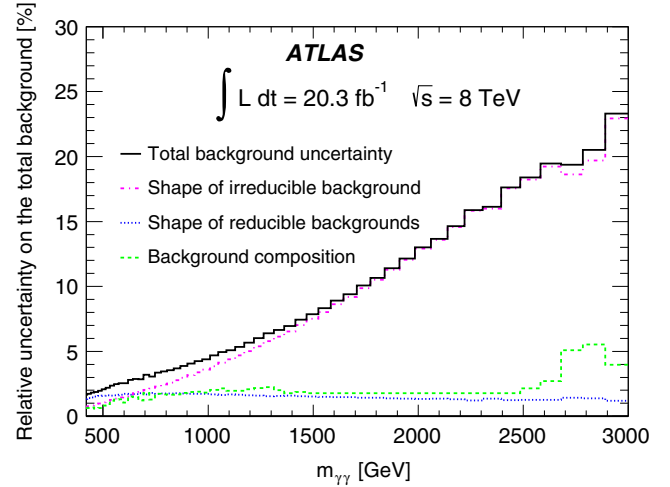

FIG. 2 (color online). Uncertainty on the total background estimate as a function of $m_{\gamma\gamma}$. The individual contributions due to the uncertainties in the irreducible and reducible components, as well as the contribution from the uncertainties in the normalization of the different background components (labeled "background composition"), are also shown.

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.

Source	Uncertainty in signal yield [%]
Integrated luminosity	2.8
MC statistics	1.0
Trigger efficiency	1.0
Photon ID efficiency	3.0
Photon isolation efficiency	0.3–2.1 (for $m_{G^*} = 500$–3000 GeV)
Total	≈ 5

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 events in which both photons satisfy the requirements on $|\eta|$ and E_{T}^{γ} described above) for the RS scenario with $m_{G^*} = 2.0$ TeV and $k/\overline{M}_{\mathrm{Pl}} = 0.1$ is 89.3% and the selection efficiency for events within acceptance is $(55.9 \pm 2.6)\%$. 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
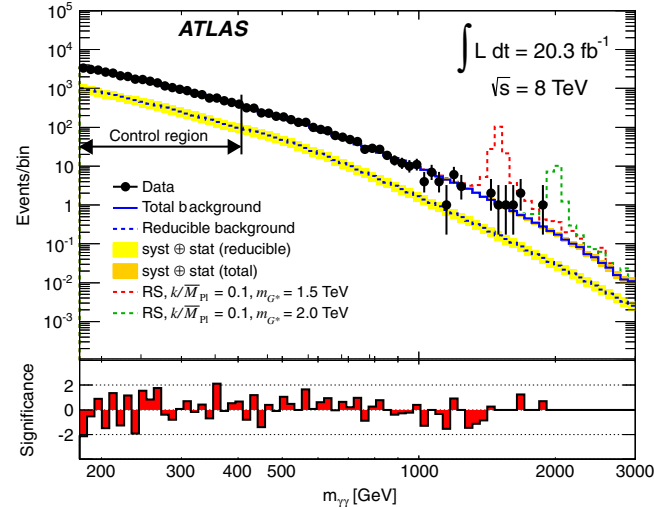

FIG. 3 (color online).   Observed invariant mass distribution of the selected diphoton events (black dots; the vertical and horizontal axes on logarithmic scales). To compensate for the rapid decrease of the spectrum, the bins are chosen to have constant logarithmic width. Specifically, the ratio of the upper to lower bin boundary is equal to 1.038 for all bins, and the first bin starts at 179 GeV. Superimposed are the SM background prediction including irreducible and reducible components and two examples of signal predictions. The low-mass control region is indicated by an arrow. Bottom: bin-by-bin significance of the difference between data and background expectation.

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, $\sigma \times BR(G^* \to \gamma\gamma)$, 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 $\sigma \times BR(G^* \to \gamma\gamma)$. Using Bayes's theorem, the likelihood is converted into a posterior probability. A uniform positive prior in $\sigma \times BR(G^* \to \gamma\gamma)$ 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, $\sigma \times BR(G^* \to \gamma\gamma)$, and the 95% CL limit on $\sigma \times BR(G^* \to \gamma\gamma)$ is obtained via integration of the posterior probability.

The resulting limits on $\sigma \times BR(G^* \to \gamma\gamma)$, 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 $k/\overline{M}_{\mathrm{Pl}}$, i.e. $\sigma \times BR(G^* \to \gamma\gamma)$ 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 $k/\overline{M}_{\mathrm{Pl}}$ in Fig. 4. They are

TABLE III. Number of events expected from the reducible and irreducible background components as well as the total background and observed number of events in different mass bins. Each bin boundary in the table corresponds to a bin boundary in Fig. 3, but the binning of the table is more coarse than in the figure. Since the combined statistical and systematic uncertainties are strongly anticorrelated between the two components, the uncertainty in the total background prediction is smaller than the sum in quadrature of the uncertainties of the individual components.

Mass window [GeV]	Background expectation (number of events)			Observed events
	Irreducible	Reducible	Total	
[179, 409] Control region	23800 ± 2400	9100 ∓ 2400	32866	32866
[409, 513]	1070 ± 110	400 ± 100	1463 ± 27	1465
[513, 596]	369 ± 37	129 ± 34	498 ± 12	524
[596, 719]	240 ± 24	74 ± 20	314.4 ± 8.8	335
[719, 805]	75.8 ± 7.7	20.6 ± 5.5	96.4 ± 3.2	99
[805, 901]	46.6 ± 4.8	11.5 ± 3.2	58.1 ± 2.1	60
[901, 1009]	28.2 ± 3.0	6.3 ± 1.8	34.5 ± 1.5	33
[1009, 1129]	16.8 ± 1.9	3.4 ± 1.0	20.2 ± 1.0	15
[1129, 1217]	6.92 ± 0.89	1.35 ± 0.46	8.27 ± 0.45	7
[1217, 1312]	4.85 ± 0.73	0.88 ± 0.39	5.74 ± 0.36	3
[1312, 1415]	3.11 ± 0.54	0.58 ± 0.28	3.69 ± 0.25	0
[1415, 1644]	3.39 ± 0.59	0.61 ± 0.29	4.00 ± 0.32	5
[1644, 3000]	2.12 ± 0.61	0.41 ± 0.22	2.52 ± 0.30	3

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 $k/\overline{M}_{Pl}$. These results for the K-factor were

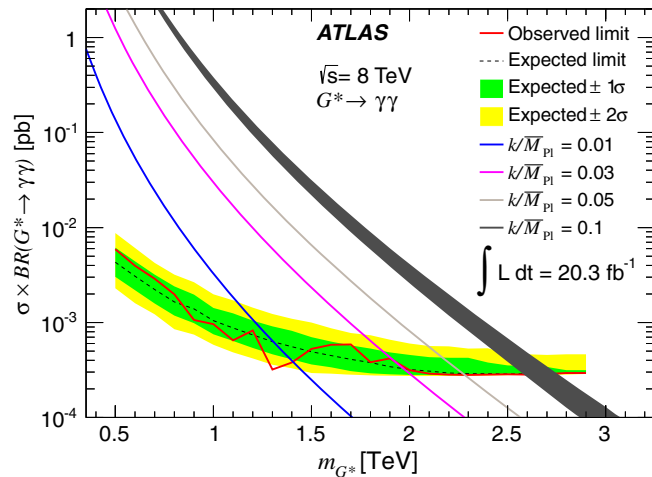FIG. 4 (color online). Expected and observed upper limits on $\sigma \times BR(G^* \to \gamma\gamma)$ expressed at 95% CL, as a function of the graviton mass. At large m_{G^*}, the -1σ and -2σ variations of the expected limit tend to be particularly close to the expected limit. This is expected, since 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 $k/\overline{M}_{Pl}$ 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 $k/\overline{M}_{Pl} = 0.1$ illustrates the PDF uncertainties expressed at 90% CL.

provided by the authors of Refs. [38,39], using updated calculations at $\sqrt{s} = 8$ TeV. Given these theory predictions for $\sigma \times BR(G^* \to \gamma\gamma)$, the upper limits on $\sigma \times BR(G^* \to \gamma\gamma)$ from Fig. 4 can be translated into upper limits on $k/\overline{M}_{Pl}$. The results are shown, as a function of m_{G^*}, in Fig. 5. Alternatively, the upper limits on $\sigma \times BR(G^* \to \gamma\gamma)$ can be translated into lower limits on the graviton mass. The results are shown in Table IV, for different values of $k/\overline{M}_{Pl}$. The limits presented in Fig. 5 and in Table IV do not take into account any theory uncertainties in the prediction of $\sigma \times BR(G^* \to \gamma\gamma)$ 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.
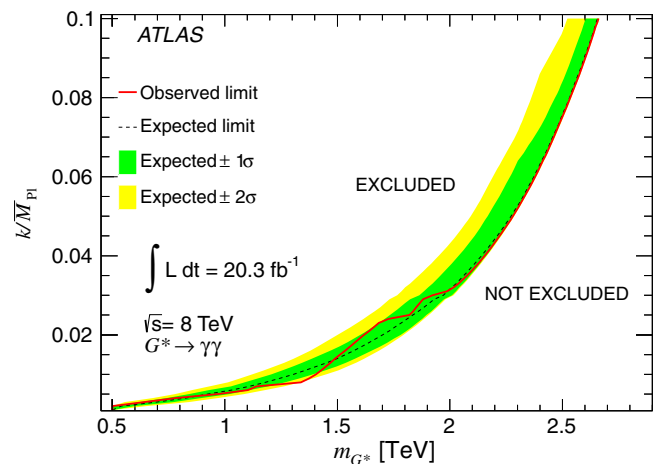

FIG. 5 (color online). Expected and observed upper limits on $k/\overline{M}_{Pl}$ expressed at 95% CL, as a function of the graviton mass.

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TABLE IV. Expected and observed lower limits at 95% CL on m_{G^*} for different values of $k/\overline{M}_{\mathrm{Pl}}$.

	Expected limit [TeV]					Observed limit [TeV]
$k/\overline{M}_{\mathrm{Pl}}$	-2σ	-1σ	central	$+1\sigma$	$+2\sigma$	
0.010	1.45	1.38	1.30	1.20	1.11	1.41
0.020	1.80	1.78	1.70	1.60	1.49	1.62
0.030	2.02	2.01	1.96	1.86	1.77	1.92
0.040	2.17	2.16	2.14	2.04	1.94	2.15
0.050	2.29	2.28	2.27	2.17	2.08	2.28
0.060	2.38	2.38	2.37	2.27	2.19	2.38
0.070	2.47	2.46	2.45	2.37	2.27	2.46
0.080	2.54	2.54	2.53	2.46	2.38	2.54
0.090	2.61	2.60	2.60	2.53	2.45	2.60
0.100	2.67	2.66	2.66	2.60	2.51	2.66

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 ($k/\overline{M}_{\mathrm{Pl}}$), i.e. $\sigma \times BR(G^* \to \gamma\gamma)$ can be calculated once the values of these two parameters are specified. The limits can therefore be expressed in terms of m_{G^*} for a given value of $k/\overline{M}_{\mathrm{Pl}}$. A lower limit of 2.66 (1.41) TeV at 95% confidence level is obtained on the mass of the lightest graviton for a coupling $k/\overline{M}_{\mathrm{Pl}} = 0.1$ (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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