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Search for extra dimensions using diphoton events in 7 TeV proton–proton collisions with the ATLAS detector ☆

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ABSTRACT

Using data recorded in 2011 with the ATLAS detector at the Large Hadron Collider, a search for evidence of extra spatial dimensions has been performed through an analysis of the diphoton final state. The analysis uses data corresponding to an integrated luminosity of 2.12 fb^{-1} of $\sqrt{s}=7$ TeV proton–proton collisions. The diphoton invariant mass ($m_{\gamma\gamma}$) spectrum is observed to be in good agreement with the expected Standard Model background. In the large extra dimension scenario of Arkani-Hamed, Dimopoulos and Dvali, the results provide 95% CL lower limits on the fundamental Planck scale between 2.27 and 3.53 TeV, depending on the number of extra dimensions and the theoretical formalism used. The results also set 95% CL lower limits on the lightest Randall–Sundrum graviton mass of between 0.79 and 1.85 TeV, for values of the dimensionless coupling $k/\overline{M}_{Pl}$ varying from 0.01 to 0.1. Combining with previously published ATLAS results from the dielectron and dimuon final states, the 95% CL lower limit on the Randall–Sundrum graviton mass for $k/\overline{M}_{Pl}=0.01$ (0.1) is 0.80 (1.95) TeV.

1. Introduction

The enormous difference between the Planck scale and the electroweak scale is known as the hierarchy problem. A prominent class of new physics models addresses the hierarchy problem through the existence of extra spatial dimensions. In this Letter, we search for evidence of extra dimensions within the context of the models of Arkani-Hamed, Dimopoulos, and Dvali (ADD) [1] and of Randall and Sundrum (RS) [2]. In these models, gravity can propagate in the higher-dimensional bulk, giving rise to a so-called Kaluza–Klein (KK) tower of massive spin-2 graviton excitations (KK gravitons, G). Due to their couplings to Standard Model (SM) particle–antiparticle pairs, KK gravitons can be investigated in proton–proton (pp) collisions at the Large Hadron Collider (LHC) via a variety of processes, including virtual graviton exchange as well as direct graviton production through gluon–gluon fusion or quark–antiquark annihilation.

The ADD model [1] postulates the existence of n flat additional spatial dimensions compactified with radius R, in which only gravity propagates. The fundamental Planck scale in the $(4+n)$-dimensional spacetime, M_D, is related to the apparent scale M_{Pl} by Gauss' law: $\overline{M}_{Pl}^2 = M_D^{n+2}R^n$, where $\overline{M}_{Pl} = M_{Pl}/\sqrt{8\pi}$ is the reduced Planck scale. The mass splitting between subsequent KK states is of order $1/R$. In the ADD model, resolving the hierarchy problem requires typically small values of $1/R$, giving rise to an almost continuous spectrum of KK graviton states.

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 effects of the extra dimensions are typically parametrized by $\eta_G = \mathcal{F}/M_S^4$, where η_G describes the strength of gravity in the presence of the extra dimensions and $\mathcal{F}$ 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 $\mathcal{F}$ and, consequently, of M_S:

$$\mathcal{F} = 1 \quad \text{(GRW) [3];} \tag{1}$$

$$\mathcal{F} = \begin{cases} \log\left(\frac{M_S^2}{\hat{s}}\right) & n=2, \\ \frac{2}{n-2} & n>2 \end{cases} \quad \text{(HLZ) [4];} \tag{2}$$

$$\mathcal{F} = \pm\frac{2}{\pi} \quad \text{(Hewett) [5];} \tag{3}$$

where $\sqrt{\hat{s}}$ is the center-of-mass energy of the parton–parton collision. Effects due to ADD graviton exchange would be evidenced by a non-resonant deviation from the SM background expectation. Collider searches for ADD virtual graviton effects have been performed at HERA [6], LEP [7], the Tevatron [8], and the LHC [9,10]. Recent diphoton results from CMS are the most restrictive so far, setting limits on M_S in the range of 2.3–3.8 TeV [10].

The RS model [2] posits the existence of a fifth dimension with "warped" geometry, bounded by two $(3+1)$-dimensional branes, with the SM fields localized on the so-called TeV brane and gravity originating on the other, dubbed the Planck brane, but capable

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of propagating in the bulk. Mass scales on the TeV brane, such as the Planck mass describing the observed strength of gravity, correspond to mass scales on the Planck brane as given by $M_D = M_{Pl}e^{-k\pi r_c}$, where k and r_c are the curvature scale and compactification radius of the extra dimension, respectively. The observed hierarchy of scales can therefore be naturally reproduced in this model, if $kr_c \approx 12$ [11]. KK gravitons in this model would have a mass splitting of order 1 TeV and would appear as new resonances. 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, $k/\overline{M}_{Pl}$. It is theoretically preferred [11] for $k/\overline{M}_{Pl}$ to have a value in the range from 0.01 to 0.1. The most stringent experimental limits on RS gravitons are from the LHC. For $k/\overline{M}_{Pl} = 0.1$, ~ 1 fb^{-1} ATLAS results from $G \to ee/\mu\mu$ exclude gravitons below 1.63 TeV [12], assuming leading order (LO) cross section predictions, and a recent 2.2 fb^{-1} $G \to \gamma\gamma$ result from CMS excludes gravitons below 1.84 TeV [10], using next-to-leading order (NLO) cross section values. These results have surpassed the limits from searches at the Tevatron [13] and earlier searches at the LHC [14].

The diphoton final state provides a sensitive channel for this search due to the clean experimental signature, excellent diphoton mass resolution, and modest backgrounds, as well as a branching ratio for graviton decay to diphotons that is twice the value of that for graviton decay to any individual charged-lepton pair. In this Letter, we report on a search in the diphoton final state for evidence of extra dimensions, using a data sample corresponding to an integrated luminosity of 2.12 fb^{-1} of $\sqrt{s} = 7$ TeV pp collisions, recorded during 2011 with the ATLAS detector at the LHC. The measurement of the diphoton invariant mass spectrum is interpreted in both the ADD and RS scenarios.

2. The ATLAS detector

The ATLAS detector [15] is a multipurpose particle physics instrument with a forward–backward symmetric cylindrical geometry and near 4π solid angle coverage.[1] Closest to the beamline are tracking detectors to measure the trajectories of charged particles, including layers of silicon-based detectors as well as a transition radiation tracker using straw-tube technology. The tracker is surrounded by a thin solenoid that provides a 2 T magnetic field for momentum measurements. The solenoid is surrounded by a hermetic calorimeter system, which is particularly important for this analysis. A system of liquid-argon (LAr) sampling calorimeters is divided into a central barrel calorimeter and two endcap calorimeters, each housed in a separate cryostat. Fine-grained LAr electromagnetic (EM) calorimeters, segmented in three longitudinal layers, are used to precisely measure the energies of electrons, positrons and photons for $|\eta| < 3.2$. Most of the EM shower energy is collected in the second layer, which has a granularity of $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$. The first layer is segmented into eight strips per middle-layer cell in the η direction, extending over four middle-layer cells in ϕ, designed to separate photons from π^0 mesons. A presampler, covering $|\eta| < 1.81$, is used to correct for energy lost upstream of the calorimeter. The regions spanning $1.5 < |\eta| < 4.9$ are instrumented with LAr calorimetry also for hadronic measurements, while an iron-scintillator tile calorimeter provides hadronic coverage in the range $|\eta| < 1.7$. A muon spectrometer consisting of three superconducting toroidal magnet systems, tracking chambers, and detectors for triggering lies outside the calorimeter system.

3. Trigger and data selection

The analysis uses data collected between March and September 2011 during stable beam periods of 7 TeV pp collisions. Selected events had to satisfy a trigger requiring at least two photon candidates with transverse energy $E_T^{\gamma} > 20$ GeV and satisfying a set of requirements, referred to as the "loose" photon definition [16], which includes requirements on the leakage of energy into the hadronic calorimeter as well as on variables that require the transverse width of the shower, measured in the second EM calorimeter layer, be consistent with the narrow width expected for an EM shower. The loose definition is designed to have high photon efficiency, albeit with reduced background rejection. The trigger was essentially fully efficient for high mass diphoton events passing the final selection requirements.

Events were required to have at least one primary collision vertex, with at least three reconstructed tracks. Selected events had to have at least two photon candidates, each with $E_T^{\gamma} > 25$ GeV and pseudorapidity $|\eta^{\gamma}| < 2.37$, with the exclusion of $1.37 < |\eta^{\gamma}| < 1.52$, the transition region between the barrel and endcap calorimeters. As described in more detail in Ref. [16], photon candidates included those classified as unconverted photons, with no associated track, or photons which converted to electron–positron pairs, with one or two associated tracks. The two photons were required to satisfy several quality criteria and to lie outside detector regions where their energy was not measured in an optimal way. The two photon candidates each had to satisfy a set of stricter requirements, referred to as the "tight" photon definition [16], which included a more stringent selection on the shower width in the second EM layer and additional requirements on the energy distribution in the first EM calorimeter layer. The tight photon definition was designed to increase the purity of the photon selection sample by rejecting most of the remaining jet background, including jets with a leading neutral hadron (mostly π^0 mesons) that decay to a pair of collimated photons.

The isolation transverse energy E_T^{iso} for each photon was calculated [16] by summing over the cells of both the EM and hadronic calorimeters that surround the photon candidate within an angular cone of radius $\Delta R = \sqrt{(\eta - \eta^{\gamma})^2 + (\phi - \phi^{\gamma})^2} < 0.4$, after removing a central core that contains most of the energy of the photon. To reduce the jet background further, an isolation requirement was applied, requiring that each of the two leading photons satisfied $E_T^{iso} < 5$ GeV. An out-of-core energy correction was applied, to make E_T^{iso} essentially independent of E_T^{γ}. An ambient energy correction, based on the measurement of low transverse momentum jets [17], was 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.

For events with more than two photon candidates passing all the selection requirements, the two photons with the highest E_T^{γ} values were considered. The diphoton invariant mass had to exceed 140 GeV. A total of 6846 events were selected.

4. Monte Carlo simulation studies

Monte Carlo (MC) simulations were performed to study the detector response for various possible signal models, as well as to perform some SM background studies. All MC events were simulated [18] with the ATLAS detector simulation based on GEANT4 [19] and using ATLAS parameter tunes [20], and were processed through the same reconstruction software chain as used

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

for the data. The MC events were reweighted to mimic the pileup conditions observed in the data.

SM diphoton production was simulated with PYTHIA [21] version 6.424 and MRST2007LOMOD [22] parton distribution functions (PDFs). The PYTHIA events were reweighted as a function of diphoton invariant mass to the differential cross section predicted by the NLO calculation of DIPHOX [23] version 1.3.2. The reweighting factor varied from ≈ 1.6 for a diphoton mass of 140 GeV, decreasing smoothly to unity for large masses. For the DIPHOX calculation, the renormalization scale and the initial and final factorization scales of the model were all set to the diphoton mass. The various scales were varied by a factor of two both up and down, compared to this central value, to evaluate systematic uncertainties. The PDFs were chosen following the recommendations of the PDF4LHC working group [24], with MSTW2008 NLO PDFs [25] used for the NLO predictions, and CTEQ6.6 [26] and MRST2007LOMOD [22] used for systematic comparisons.

SHERPA [27] version 1.2.3 was used with CTEQ6L [26] PDFs to simulate the various ADD scenarios for a variety of M_S values. Due to the interference between the SM and gravity-mediated contributions, it is necessary to simulate events according to the full differential cross section as a function of the diphoton mass. A generator-level cut was applied to restrict the signal simulation to diphoton masses above 200 GeV. The ADD MC samples were used to determine the signal acceptance (A) and selection efficiency (ϵ). The acceptance, defined as the percentage of diphoton signal events with the two highest E_T photons passing the applied E_T^γ and η^γ cuts, varied somewhat for the various ADD implementations and fell from typical values of $\approx 20\%$ for $M_S = 1.5$ TeV down to $\approx 15\%$ for $M_S = 3$ TeV, due mostly to the variations in the η^γ distributions. The selection efficiency, for events within the detector acceptance, was found to be $\approx 70\%$.

RS model MC signal samples were produced using the implementation of the RS model in PYTHIA [21] version 6.424, which is fully specified by providing the values of m_G and $k/\overline{M}_{Pl}$. MC signal samples were produced for a range of m_G and $k/\overline{M}_{Pl}$ values, using the MRST2007LOMOD [22] PDFs. The products of $A \times \epsilon$ for the RS signal models were in the range $\approx (53\text{–}60)\%$, slowly rising with increasing graviton mass. The reconstructed shape of the graviton resonance was modeled by convolving the graviton Breit–Wigner lineshape with a double-sided Crystal Ball (CB) function to describe the detector response. The natural width of the Breit–Wigner was fixed according to the expected theoretical value, which varies as the square of $k/\overline{M}_{Pl}$. The values of the width increase, for $k/\overline{M}_{Pl} = 0.1$, from ≈ 8 GeV up to ≈ 30 GeV for m_G values from 800 GeV to 2200 GeV, respectively. The parameters of the CB function, which includes a Gaussian core to model the detector resolution matched to exponential functions on both sides to model the modest non-Gaussian tails, were determined by fitting to the reconstructed MC signals. The fitted values of σ of the Gaussian core approached a value of $\approx 1\%$ for high m_G values, as expected given the current value of the constant term in the EM calorimeter energy resolution, and were found to be independent of $k/\overline{M}_{Pl}$. The EM energy resolution has been verified in data using $Z \to ee$ decays [28], and MC used to describe the modest differences between the response to photons versus electrons. The fitted values of the CB parameters varied smoothly with m_G. Fitting this mass dependence provided a signal parametrization that was used to describe signals with any values of m_G and $k/\overline{M}_{Pl}$.

5. Background evaluation

The largest background for this analysis is the irreducible background due to SM $\gamma\gamma$ production. The shape of the diphoton invariant mass spectrum from this background was estimated using MC, reweighting the PYTHIA samples to the differential cross section predictions of DIPHOX.

Another significant background component is the reducible background that includes events in which one or both of the reconstructed photon candidates result from a different physics object being misidentified as a photon. This background is dominated by γ + jet (j) and jj events, with one or two jets faking photons, respectively. 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, were verified using MC to be small after the event selection and were neglected. Several background-enriched control samples were defined in order to determine the shape of the reducible background using data-driven techniques. In all control samples, the two photon candidates were required to pass the same isolation cut as for the signal selection, since removing the isolation requirement was seen to modify the diphoton mass spectrum. The first control sample contained those events where one of the photon candidates passed the tight requirement applied for the signal selection. However, the other photon candidate was required to fail the tight photon identification definition, but to pass the loose requirement; the latter restriction was applied to avoid any trigger bias, as the trigger required two loose photons. This sample is enriched in $\gamma + j$ events, where the photon passed the tight requirement and a jet passed the loose one, and also in jj events where both photon candidates were due to jets. A second control sample, dominated by jj events, was similarly defined, but both photon candidates were required to fail the tight photon identification while passing the loose definition.

The diphoton invariant mass distributions were compared for these control samples. To check for any kinematic bias, the control sample with one tight and one loose photon candidate was further divided, with the γj ($j\gamma$) subsample being defined as the case with the tight photon being the photon candidate with the highest (second highest) transverse energy. The diphoton invariant mass distributions of all three control subsamples were found to be consistent with each other, within statistical uncertainties. The sum of the control samples was used to provide the best estimate of the reducible background shape. Variations among the subsamples were taken into account as a source of systematic uncertainty in the reducible background prediction.

The data control samples have relatively few events in the high diphoton mass signal region. It was therefore necessary to extrapolate the reducible background shape to higher masses, which was done by fitting with a smooth function of the form $f(x) = p_1 \times x^{p_2 + p_3 \log x}$, where $x = m_{\gamma\gamma}$ and p_i are the fit parameters. This functional form has been used in previous ATLAS resonance searches [12,29], and describes well the shape of the control data samples.

The total background, calculated as the sum of the irreducible and reducible components, was normalized to the number of data events in a low mass control region with diphoton masses between 140 and 400 GeV, in which possible ADD and RS signals have been excluded by previous searches. The fraction of the total background in this region that is due to the irreducible background is defined as the purity of the sample. The purity (p) was determined by three complementary methods. The most precise measurement resulted from a method previously used in Refs. [30,31] that examines the E_T^{iso} values of the two photon candidates. Templates for the E_T^{iso} distributions of true photons and of fake photons from jets were both determined from the data. The shape for fake photons was found using a sample of photon candidates that failed at least one of a subset of several of the selection requirements used for the tight photon definition. The shape for photons was found from the tight photon sample, after subtracting the fake photon shape normalized to match the number of candidates with large values (greater than 10 GeV) of E_T^{iso}. In addition, for jj events, due to the observed significant ($\approx 20\%$) correlation between the E_T^{iso} values of the two photon candidates, a two-dimensional template was formed using events in which both photon candidates failed the tight identification. An extended maximum likelihood fit to the two-dimensional distribution formed from the E_T^{iso} values of the two photon candidates was performed in order to extract the contributions from $\gamma\gamma$, γj, $j\gamma$, and jj events. The fit was performed using the photon and fake photon E_T^{iso} templates, as well as the two-dimensional jj template. The resultant value of the purity in the low mass control region was $p = 71^{+5}_{-9}\%$. The uncertainty was determined by varying the subset of tight selection criteria failed by fake photon candidates, and then repeating the purity determination. Cross checks using either the DIPHOX prediction for the absolute normalization of the irreducible component, or fitting the shapes of the irreducible and reducible backgrounds to the data in the low mass control region, yielded consistent, but less precise results. The result from the isolation method was therefore used as the best estimate of the purity, and the total SM background prediction was set equal to the sum of the irreducible and reducible components, weighted appropriately by this purity value and normalized to data in the low mass control region.

6. Systematic uncertainties

Systematic uncertainties in the DIPHOX prediction for the shape of the irreducible background were obtained by varying the scales of the model and the PDFs, while keeping the overall normalization fixed in the low mass control region in which the total background prediction was normalized to the data. The resultant systematic uncertainties range from a few percent at low masses, up to $\approx 15\%$ for diphoton masses of ≈ 2 TeV. Systematic uncertainties in the reducible background shape were obtained by comparing the results of the extrapolation fit for the various control data subsamples, in each case maintaining the overall normalization to the data in the low mass control region. The resultant uncertainties increase from $\approx 5\%$ for low masses to $\approx 100\%$ at a mass of ≈ 2 TeV.

The systematic uncertainty on the shape of the total background was obtained by adding in quadrature the uncertainties on the shapes of the irreducible and reducible background components, weighted appropriately to account for the purity. In addition, there is a contribution, which is roughly constant with a value of $\approx 10\%$ for diphoton masses above 800 GeV, introduced by varying the purity value within its uncertainty. An additional overall uncertainty of $\approx 2\%$ was included due to the finite statistics of the data sample in the low mass control region.

The total background systematic uncertainty starts at $\approx 2\%$ for $m_{\gamma\gamma} = 140$ GeV, rises to $\approx 15\%$ by 700 GeV and then increases slowly up to almost 20% for the highest $m_{\gamma\gamma}$ values, above 2 TeV.

Systematic uncertainties on the signal yields were evaluated separately for the ADD and RS models. Since the differences were small, for simplicity the higher value was taken and applied to both models. The systematic uncertainties considered for the signal yield include the 3.7% uncertainty on the integrated luminosity [32], and a 1% uncertainty to account for the limited signal MC statistics. A value of 1% for the uncertainty on the bunch crossing identification (BCID) efficiency accounts for the ability of the Level 1 trigger hardware to pick the correct BCID when signal pulse saturation occurs in the trigger digitization. In addition, a value of 2% was applied for the uncertainty on the efficiency of the diphoton trigger. An uncertainty of 2.5% was applied due to the influence of pileup on the signal efficiency. Finally, a value of 4.3% was taken to account for the uncertainty in the selection and identification of the pair of photons, including uncertainties due to the photon isolation cut, the description of the detector material, the tight photon identification requirements, and extrapolation to the high photon E_T values typical of the signal models. Uncertainties due to the current knowledge of the EM energy scale and resolution were verified to have a negligible impact. Adding all effects in quadrature, the total systematic uncertainty on the signal yields was 6.7%.

Uncertainties in the theoretical signal cross sections due to PDFs and due to the NLO approximation were considered. The uncertainties due to PDFs range from ≈ 10–15% for ADD models and from ≈ 5–10% for RS models. The authors of Refs. [33,34] have privately updated their calculations of the NLO signal cross sections for 14 TeV, and provided k-factors to the LHC experiments to scale from LO to NLO cross section values for the case of 7 TeV pp collisions. The NLO k-factor values, evaluated in our case for $|\eta^\gamma| < 2.5$, have some modest dependence on the diphoton mass as well as on M_S for the ADD model, and on the $k/\overline{M}_{Pl}$ value for the RS model. However, the variations are within the theoretical uncertainty. For simplicity, therefore, constant values of 1.70 and 1.75 were assumed for the ADD and RS models, respectively, and an uncertainty in the k-factor value of ± 0.1 was assigned to account for the variations.

7. Results and interpretation

Fig. 1 shows the observed invariant mass distribution of diphoton events, with the predicted SM background superimposed as well as ADD and RS signals for certain choices of the model parameters. The reducible background component is shown separately, in addition to the total background expectation, which sums the reducible and irreducible contributions. The shaded bands around each contribution indicate the corresponding uncertainty. The bottom plot of Fig. 1 shows the statistical significance, measured in standard deviations and based on Poisson distributions, of the difference between the data and the expected background in each bin. The significance was calculated and displayed as detailed in Ref. [35], and plotted as positive (negative) where there was an excess (deficit) in the data in a given bin. Table 1 lists, in bins of diphoton mass, the expected numbers of events for the irreducible and reducible background components, as well as for the total background, and also the numbers of observed data events. Both Fig. 1 and Table 1 demonstrate that there is agreement between the observed mass distribution and the expectation from the SM backgrounds over the entire diphoton mass range; no evidence is seen for either resonant or non-resonant deviations which would indicate the presence of a signal due to new physics. An analysis using the BUMPHUNTER [36] tool found that the probability, given the background-only hypothesis, of observing discrepancies at least as large as observed in the data was 0.28, indicating quantitatively the good agreement between the data and the expected SM background.

Given the absence of evidence for a signal, 95% CL upper limits were determined on the ADD and RS signal cross sections, using a Bayesian approach [37] with a flat prior on the signal cross section. The systematic uncertainties were incorporated as Gaussian-distributed nuisance parameters and integrated over.

To set limits on the ADD model, the number of observed events with diphoton invariant mass in a high mass signal region was compared with the expected total SM background. To optimise the expected limit, the ADD signal search region was chosen as $m_{\gamma\gamma} > 1.1$ TeV. There are 2 observed events in this signal region, with a background expectation of 1.33 ± 0.26 events,

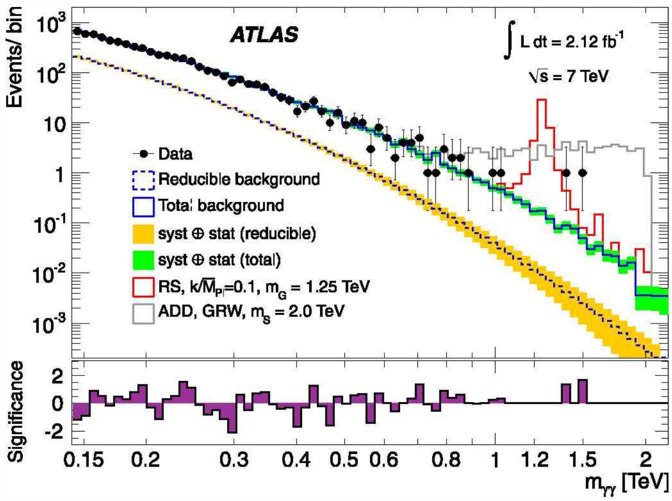

Fig. 1. The observed invariant mass distribution of diphoton events, superimposed with the predicted SM background and expected signals for ADD and RS models with certain choices of parameters. The bin width is constant in $\log(m_{\gamma\gamma})$. The bin-by-bin significance of the difference between data and background is shown in the lower panel.

Table 1
The expected numbers of events for the irreducible and reducible background components and for the total background, as well as the numbers of observed data events, in different diphoton mass bins. The first row, with masses from 140 to 400 GeV, corresponds to the control region in which the total background was normalized to the corresponding number of observed events. The errors include both statistical and systematic uncertainties. The errors on the irreducible and reducible background components do not include the contribution, which is anti-correlated between the two background components, from the uncertainty on the purity. However, this contribution is included in the errors listed for the total background.

Mass range (GeV)	Background expectation			Observed events
	Irreducible	Reducible	Total	
[140, 400]	4738 ± 180	1935 ± 97	6674	6674
[400, 500]	90.0 ± 8.5	19.9 ± 1.8	109.9 ± 9.2	102
[500, 600]	31.1 ± 4.0	5.8 ± 0.8	37.0 ± 4.2	36
[600, 700]	13.7 ± 2.3	2.0 ± 0.4	15.7 ± 2.4	16
[700, 800]	6.2 ± 1.2	0.8 ± 0.2	6.9 ± 1.3	9
[800, 900]	3.1 ± 0.4	0.3 ± 0.1	3.4 ± 0.5	5
[900, 1000]	1.6 ± 0.2	0.14 ± 0.05	1.8 ± 0.3	1
[1000, 1100]	1.0 ± 0.2	0.07 ± 0.03	1.0 ± 0.2	1
[1100, 1200]	0.50 ± 0.09	0.03 ± 0.02	0.54 ± 0.11	0
[1200, 1300]	0.29 ± 0.07	0.02 ± 0.01	0.31 ± 0.07	0
[1300, 1400]	0.14 ± 0.04	0.010 ± 0.005	0.15 ± 0.04	1
[1400, 1500]	0.13 ± 0.04	0.005 ± 0.003	0.14 ± 0.04	1
> 1500	0.18 ± 0.09	0.009 ± 0.006	0.19 ± 0.09	0

where the uncertainty includes both statistical and systematic errors. The observed (expected) 95% CL upper limit is 2.49 (1.94) fb for the product of the cross section due to new physics multiplied by the acceptance and efficiency. The cross section result can be translated into limits on η_G and, subsequently, on the parameter M_S of the ADD model. As summarized in Table 2, assuming a k-factor of 1.70, the 95% CL lower limits on M_S range between 2.27 and 3.53 TeV, depending on the number of extra dimensions assumed and the ADD model implementation. LO results are also included in Table 2, for reference.

To determine the limits on the RS model, the observed invariant mass distribution was compared to templates of the expected backgrounds and varying amounts of signal for various graviton masses and $k/\overline{M}_{Pl}$ values. A likelihood function was defined as the product of the Poisson probabilities over all mass bins in the search region, defined as $m_{\gamma\gamma} > 500$ GeV, where the Poisson probability in each bin was evaluated for the observed number of data events given the expectation from the template. The total signal acceptance as a function of mass was propagated into the expectation. The theory uncertainties were not included in the limit calculation, but are indicated by showing the theory prediction as a band with a width equal to the combined theory uncertainty when plotting the results. The resultant limits are summarized in Table 3. Using a constant k-factor value of 1.75, the 95% CL lower limits from the diphoton channel are $m_G > 0.79$ (1.85) TeV for $k/\overline{M}_{Pl} = 0.01$ (0.1).

The RS model results can be combined with the previously published ATLAS results [12] from the dilepton final state, where, assuming LO cross sections and $k/\overline{M}_{Pl} = 0.1$, RS gravitons with masses below 1.51 (1.45) TeV were excluded at 95% CL using data samples of 1.08 (1.21) fb^{-1} to search for $G \to ee$ ($G \to \mu\mu$). To ensure their statistical independence, the selection cuts of the diphoton analysis included a veto of any events which were also selected by the 1.08 fb^{-1} $G \to ee$ analysis. In performing the combination, correlations were considered between the systematic uncertainties in the $\gamma\gamma$ and ee channels. In the ee analysis [12], the background prediction was normalized such that the expected and observed numbers of events in the region of the Z peak agreed, eliminating the dependence of the ee result on the measured integrated luminosity. Therefore, the $\gamma\gamma$ and ee signal predictions were treated as uncorrelated, since there should be no correlation in the luminosity and efficiency uncertainties. The systematic uncertainty on the QCD dijet background was treated as being correlated; however, this background was quite small so the effect was minor. The PDF and scale uncertainties were 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 left plot of Fig. 2 shows the combined 95% CL upper limit on the product of the graviton production cross section times the branching ratio for $G \to \gamma\gamma/ee/\mu\mu$, obtained using the same k-factor value of 1.75 for all three channels. As summarized in Table 3, the combined 95% CL lower limit is $m_G > 0.80$ (1.95) TeV for $k/\overline{M}_{Pl} = 0.01$ (0.1). As shown in the right plot of Fig. 2, the results can be translated into a 95% CL exclusion in the plane of $k/\overline{M}_{Pl}$ versus graviton mass.

Table 2
95% CL limits on the value of M_S (in TeV) for various implementations of the ADD model, using both LO (k-factor = 1) and NLO (k-factor = 1.70) theory cross section calculations.

k-Factor value	GRW	Hewett		HLZ				
		Pos	Neg	$n = 3$	$n = 4$	$n = 5$	$n = 6$	$n = 7$
1	2.73	2.44	2.16	3.25	2.73	2.47	2.30	2.17
1.70	2.97	2.66	2.27	3.53	2.97	2.69	2.50	2.36

Table 3
95% CL lower limits on the mass (GeV) of the lightest RS graviton, for various values of $k/\overline{M}_{Pl}$. The results are shown for the diphoton channel alone and for the combination of the diphoton channel with the dilepton results of Ref. [12], using both LO (k-factor = 1) and NLO (k-factor = 1.75) theory cross section calculations.

k-Factor value	Channel(s) used	95% CL limit [TeV]			
		$k/\overline{M}_{Pl}$ value			
		0.01	0.03	0.05	0.1
1	$G \to \gamma\gamma$	0.74	1.26	1.41	1.79
	$G \to \gamma\gamma/ee/\mu\mu$	0.76	1.32	1.47	1.90
1.75	$G \to \gamma\gamma$	0.79	1.30	1.45	1.85
	$G \to \gamma\gamma/ee/\mu\mu$	0.80	1.37	1.55	1.95

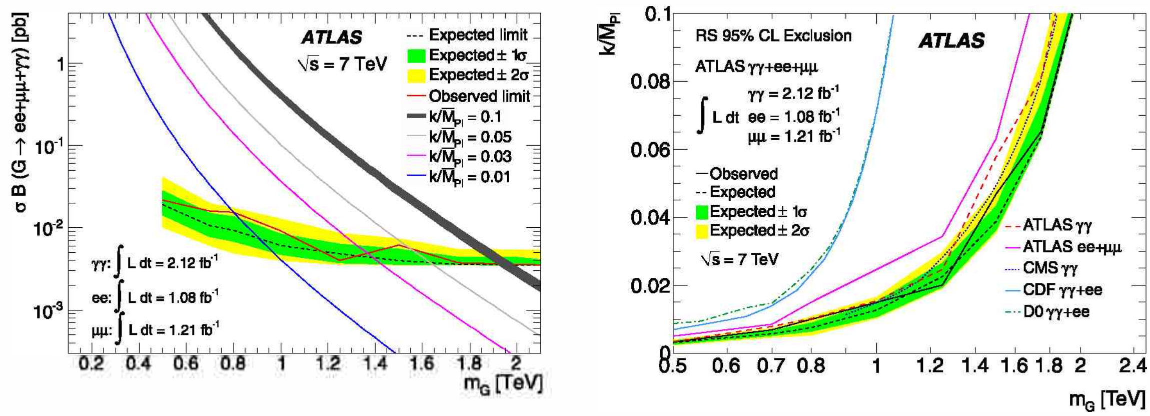

Fig. 2. (Left) Expected and observed 95% CL limits from the combination of $G \to \gamma\gamma/ee/\mu\mu$ channels on σB, the product of the RS graviton production cross section and the branching ratio for graviton decay via $G \to \gamma\gamma/ee/\mu\mu$, as a function of the graviton mass. The theory curves are drawn assuming a k-factor of 1.75. The thickness of the theory curve for $k/\overline{M}_{Pl} = 0.1$ illustrates the theoretical uncertainties. (Right) The RS results interpreted in the plane of $k/\overline{M}_{Pl}$ versus graviton mass, and including recent results from other experiments [13,10]. The region above the curve is excluded at 95% CL. In both figures, linear interpolations are performed between the discrete set of mass points for which the dilepton limits were calculated in Ref. [12].

8. Summary

Using a dataset corresponding to 2.12 fb^{-1}, an analysis of the diphoton final state was used to set 95% CL lower limits of between 2.27 and 3.53 TeV on the parameter M_S of the ADD large extra dimension scenario, depending on the number of extra dimensions and the theoretical formalism used. The diphoton results also exclude at 95% CL RS graviton masses below 0.79 (1.85) TeV for the dimensionless RS coupling $k/\overline{M}_{Pl} = 0.01$ (0.1). Combining with the previous ATLAS dilepton analyses further tightens these limits to exclude at 95% CL RS graviton masses below 0.80 (1.95) TeV for $k/\overline{M}_{Pl} = 0.01$ (0.1).

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