Search for Resonant Production of High-Mass Photon Pairs in Proton-Proton Collisions at $\sqrt{s} = 8$ and 13 TeV

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A search for the resonant production of high-mass photon pairs is presented. The analysis is based on samples of proton-proton collision data collected by the CMS experiment at center-of-mass energies of 8 and 13 TeV, corresponding to integrated luminosities of 19.7 and 3.3 fb^{-1}, respectively. The interpretation of the search results focuses on spin-0 and spin-2 resonances with masses between 0.5 and 4 TeV and with widths, relative to the mass, between 1.4×10^{-4} and 5.6×10^{-2}. Limits are set on scalar resonances produced through gluon-gluon fusion, and on Randall-Sundrum gravitons. A modest excess of events compatible with a narrow resonance with a mass of about 750 GeV is observed. The local significance of the excess is approximately 3.4 standard deviations. The significance is reduced to 1.6 standard deviations once the effect of searching under multiple signal hypotheses is considered. More data are required to determine the origin of this excess.

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The resonant production of high-mass photon pairs is a prediction that arises in several extensions of the standard model (SM) of particle physics. The spin of a resonance decaying to two photons must be either 0 or an integer greater than or equal to 2 [1,2]. Spin-0 resonances decaying to two photons are predicted by models with nonminimal Higgs sectors [3,4], while spin-2 resonances decaying to two photons can arise in models with additional spacelike dimensions [5].

In this Letter, we report on a search for high-mass resonances that decay to photon pairs. The search is based on proton-proton (pp) collision data collected in 2012 and 2015 by the CMS experiment at the CERN LHC at $\sqrt{s} = 8$ and 13 TeV, respectively, corresponding to integrated luminosities of 19.7 and 3.3 fb^{-1}. Events with at least two reconstructed photon candidates are selected and a search is performed in the diphoton mass spectrum for a localized excess of events consistent with the resonant production of a photon pair. The results are obtained through a combined analysis of the 8 and 13 TeV data. The data are interpreted in terms of spin-0 resonances produced through gluon-gluon fusion and in terms of spin-2 graviton resonances in Randall-Sundrum (RS) models [6]. In these models, the spin-2 resonances are produced through both gluon-gluon fusion and quark annihilation, with the first mechanism accounting for roughly 90% of the production cross section. A portion of the 13 TeV data (0.6 fb^{-1}) was collected when the CMS magnet was off (0 T), because of an intermittent problem, subsequently rectified, with the cryogenic system. The remainder of the 13 TeV data, and all of the 8 TeV data, were recorded with the magnet at its operational field strength (3.8 T).

Previous LHC searches for spin-0 resonances decaying to two photons were performed at $\sqrt{s} = 8$ TeV [7,8], and for spin-2 resonances decaying to a pair of photons, leptons, jets, or vector bosons at $\sqrt{s} = 7$, 8, and 13 TeV [8–24]. The results presented in this Letter exceed the sensitivity of these previous studies, for spin-0 and spin-2 resonance masses above 500 GeV.

A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found elsewhere [25]. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The ECAL consists of about 76 000 $PbWO_4$ crystals that have transverse sizes approximately matching the Molière radius of the material. The ECAL barrel (EB), covering the pseudorapidity (η) region $|\eta| < 1.45$, has a granularity $\Delta\eta \times \Delta\phi = 0.0174 \times 0.0174$, with ϕ the azimuthal angle. The ECAL endcaps (EE), which extend the coverage to $|\eta| < 3.0$, have a granularity that increases progressively up to $\Delta\eta \times \Delta\phi = 0.05 \times 0.05$. The particle-flow algorithm [26,27] reconstructs and identifies each individual particle with an optimized combination of information from the various elements of the CMS detector. Particle candidates are classified as either muons,

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electrons, photons, τ leptons, charged hadrons, or neutral hadrons.

Simulated signal samples of spin-0 and spin-2 resonances decaying to two photons are generated at leading order (LO) with the PYTHIA8.2 [28] event generator, using the NNPDF2.3 [29] parton distribution functions (PDFs), with values of the resonance mass m_X in the range $0.5 < m_X < 4$ TeV and for three values of the relative width Γ_X/m_X: 1.4×10^{-4}, 1.4×10^{-2}, and 5.6×10^{-2}. For the RS graviton model, where $\Gamma_X/m_X = 1.4\tilde{k}^2$ [6], this corresponds to dimensionless coupling values $\tilde{k} = 0.01$, 0.1, and 0.2. The chosen relative widths correspond, respectively, to resonances much narrower than, comparable to, and significantly wider than the detector resolution. The principal SM background processes, namely the direct production of two photons ($\gamma\gamma$), the production of $\gamma +$ jets events in which jet fragments are misidentified as photons, and the production of multijet events with misidentified jet fragments, are simulated with the SHERPA2.1 [30], MADGRAPH5_AMC@NLO2.2 [31] (interfaced with PYTHIA8.2 for parton showering and hadronization), and PYTHIA8.2 generators, respectively. For all simulated samples, the detector response is modeled with the GEANT4 package [32]. The kinematic requirements and the identification criteria described below are determined using the simulated signal and background samples and are finalized prior to inspecting the diphoton mass data distribution in the search region.

For the 8 TeV data, the results of Ref. [8] are used in the present study to place limits on resonances with $m_X \leq 850$ GeV. In this Letter, we extend these 8 TeV limits to masses $m_X > 850$ GeV using an analysis similar to the 13 TeV one. In the following, we first describe the 13 TeV analysis, then the manner in which the 8 TeV analysis differs.

For the $B = 3.8(0)$ T data at 13 TeV, the trigger selection requires at least two photon candidates, each with transverse momentum p_T above 60 (40) GeV. For each photon candidate, the ratio of the energy deposited in the hadron calorimeter to the photon energy (H/E ratio) is required to be less than 0.15. For resonances with $m_X > 0.5$ TeV, the trigger selection is fully efficient.

In the subsequent analysis, photons are reconstructed by clustering spatially correlated energy deposits in the ECAL. To obtain the best energy resolution, the ECAL signals are calibrated and corrected for the variation of the crystal transparency during the data collection period [33]. The energies of the photon candidates are estimated with a multivariate regression technique [33]. For the 3.8 T data, the interaction vertex, i.e., the pp collision point from which the photons are assumed to originate, is selected using the algorithm described in Ref. [34]. For resonances with $m_X > 500$ GeV, the fraction of events in which the interaction vertex is correctly assigned is estimated from simulation to be approximately 90%. For the 0 T data, the interaction vertex is identified as the reconstructed vertex with the largest number of charged tracks, yielding an estimated probability for the correct assignment of about 60%. The direction of a photon candidate's momentum is computed taking as the origin the position of the chosen interaction vertex. Corrections to account for residual differences in the photon energy scale and resolution between the data and simulation are determined using $Z \to e^+e^-$ events, through the procedure described in Ref. [33]. For the 3.8 (0) T data, energy scale and resolution corrections are derived in eight (four) bins defined in terms of the R_9 variable, which is the ratio of the energy deposited in the central 3×3 crystal matrix to the full cluster energy, and of the $|\eta_C|$ variable, which is the absolute value of the pseudorapidity of the cluster with respect to the center of the detector. The energy scale correction factors measured for the 3.8 T data are found to be about 1% higher than the 0 T factors, while similar values are measured for the resolution corrections. The variation of the corrections in the EB (EE) region is assessed as a function of p_T up to $p_T \approx 150$ (100) GeV using $Z \to e^+e^-$ data, and is found to be 0.5 (0.7)% or less for both the 3.8 and 0 T data.

Photon candidates are subject to additional identification requirements. The H/E ratio of the candidates must lie below 0.05. For the 3.8 (0) T data, the size of the electromagnetic clusters in η (η and ϕ) [33] is required to be compatible with that expected for a prompt photon, i.e., a photon produced directly in a hard-scattering process. For candidates in the 3.8 T sample, the scalar p_T sum of additional photons in a cone of radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the photon direction, corrected to account for the contributions from extraneous pp collisions in the same or nearby proton bunch crossing, must be less than 2.5 GeV. For the 0 T sample, the analogous sum must be less than 3.6 (3.0) GeV for the EB (EE) candidates. For the 3.8 T data, we additionally require the scalar p_T sum of the charged hadrons within a cone of radius $R = 0.3$ around the photon direction to be less than 5 GeV and for the 0 T data the number of charged hadrons within this cone, excluding an inner cone of radius $R = 0.05$, to be 3 or less. The photon isolation requirement for the 0 T data is less stringent than that for the 3.8 T data to compensate for the additional selection criterion for the 0 T data based on the size of the shower profile in the azimuthal direction. Photon candidates associated with an electron track that itself is not consistent with a photon conversion are rejected.

For the 3.8 T data, the efficiency of the identification criteria for prompt isolated photon candidates in the barrel (endcaps) is above 90 (85)% for the kinematic range considered in the analysis. For the 0 T data, the corresponding efficiency exceeds 85 (70)%. The identification and trigger efficiencies are measured, as a function of p_T, using data events containing a Z boson decaying to a pair of electrons, or to a pair of electrons or muons in association with a photon [33]. The efficiencies from data are found to be consistent with those from simulation.

In each event, photon candidates with $p_T > 75$ GeV are grouped in all possible pairs. We require $|\eta_C| < 2.5$ for each candidate in the pair and $|\eta_C| < 1.44$ for at least one of them. Candidates in the region $1.44 < |\eta_C| < 1.57$ are rejected because of difficulties in modeling the photon reconstruction efficiency in the transition region between the barrel and endcap detectors. The invariant mass $m_{\gamma\gamma}$ of the pair is required to exceed 230 GeV. For events in which one photon candidate is reconstructed in an endcap, $m_{\gamma\gamma}$ must exceed 330 GeV. The fraction of events in which more than one photon pair satisfies all the selection criteria is roughly 1%. In these cases, only the pair with the largest photon scalar p_T sum is retained.

Photon pairs are divided into two categories, denoted by "EBEB" when both photons are reconstructed in the ECAL barrel and by "EBEE" when one of the two photons is reconstructed in an ECAL endcap. Each category is further divided into events recorded at 3.8 and 0 T.

For the 3.8 (0) T analysis, the overall signal selection efficiency varies between 0.5–0.7 (0.4–0.5), depending on the signal hypothesis. Because of the different angular distribution of the decay products, the kinematic acceptance for the RS graviton resonances is lower than for scalar resonances; for $m_X < 1$ TeV the reduction is approximately 20%. The two acceptances become similar for $m_X > 3$ TeV. About 90 (80)% of the background events in the EBEB (EBEE) sample arises from the $\gamma\gamma$ process. These results, estimated from simulation, are validated for the 3.8 T analysis using the method described in Ref. [35].

The principal difference between the 8 TeV analysis described in Ref. [8] (used here in the search for resonances with $m_X \leq 850$ GeV) and the 13 TeV analysis described above is that, in the former, the events are further categorized according to the R_9 value of the photon candidates. Specifically, events are categorized as having either $\min(R_9) > 0.94$ or $\min(R_9) \leq 0.94$, where $\min(R_9)$ is the smaller of the two R_9 values in the photon pair. To search for resonances with $m_X > 850$ GeV in the 8 TeV data, we select photons with $p_T > 80$ GeV that satisfy the "loose" identification criteria of Ref. [33] and require that there be an EBEB photon pair with $m_{\gamma\gamma} > 300$ GeV. We do not include EBEE photon pairs in this case for reasons of simplicity, because such events would have improved the analysis sensitivity by at most a few percent.

The $m_{\gamma\gamma}$ distributions of the events selected in the 13 TeV analysis are shown in Fig. 1. The corresponding 8 TeV results used for the $m_X \leq 850$ GeV search are shown in Fig. 2 [8]. The $m_{\gamma\gamma}$ distributions of 8 TeV events used for the $m_X \leq 850$ GeV search are available in the Supplemental Material [36].

The results of the search are interpreted in the framework of a composite statistical hypothesis test. For each signal hypothesis, a simultaneous unbinned extended maximum likelihood fit to the $m_{\gamma\gamma}$ spectra observed in all categories is performed and the likelihood function used to construct the test statistic. The modified frequentist method [37,38] is utilized to set upper limits on the production of diphoton resonances, following the prescription described in Ref. [39]. The compatibility of the observation with the background-only hypothesis is evaluated by computing the background-only p value [39], denoted p_0 in the following. Asymptotic formulas [40] are used in the calculations. The accuracy of the formulas in the estimation of limits and significance is studied for a subset of the hypothesis tests and is found to be about 10%. Thus the upper limits on the production cross section times branching fraction for the resonant production of two photons could be up to 10% higher, and the significance of an excess over the SM up to 10% lower, than the results presented below.

The shape of the $m_{\gamma\gamma}$ signal distribution in the likelihood function is given by the convolution of the intrinsic shape, taken from the PYTHIA generator, with a function characterizing the CMS detector response. The normalization is a free parameter of the fit. The intrinsic shape is generated for various m_X values. The detector response is derived from a PYTHIA sample including GEANT4 modeling using a coarser spacing in m_X, assuming a small intrinsic width, and incorporating corrections derived from $Z \to e^+e^-$ data. The intrinsic width and detector response are interpolated to intermediate points using the "moment morphing" technique of Ref. [41]. At 13 TeV, the signal mass resolution, defined as the ratio of the full width at half maximum (FWHM) of the distribution, divided by 2.35, to the peak position, is roughly 1.0 (1.5)% for the EBEB (EBEE) categories.

The background $m_{\gamma\gamma}$ spectra are described by parametric functions of $m_{\gamma\gamma}$. The coefficients are obtained from a fit to the data events, and considered as unconstrained nuisance parameters in the fit. In this manner, the description of the background is derived from data. For the 13 TeV data and for the 8 TeV data in the $m_X > 850$ GeV search, a parametrization of the form $f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b\log(m_{\gamma\gamma})}$ is chosen, where a and b are parameters determined independently for each of the five event categories: the four shown in Fig. 1 plus that of the 8 TeV $m_X > 850$ GeV search. The validity of the procedure is tested, using simulated background samples, by examining the difference between the true and predicted numbers of background events in 14 contiguous intervals in $m_{\gamma\gamma}$ within the search region. For each interval, a sampling distribution of the pull variable is constructed using pseudoexperiments with the same sample size as the data. Background-only fits are performed on the pseudoexperiments using the same $m_{\gamma\gamma}$ ranges employed in data. In each region, the pull is defined as the difference between the true and estimated numbers of events divided by the estimated statistical uncertainty. If the absolute

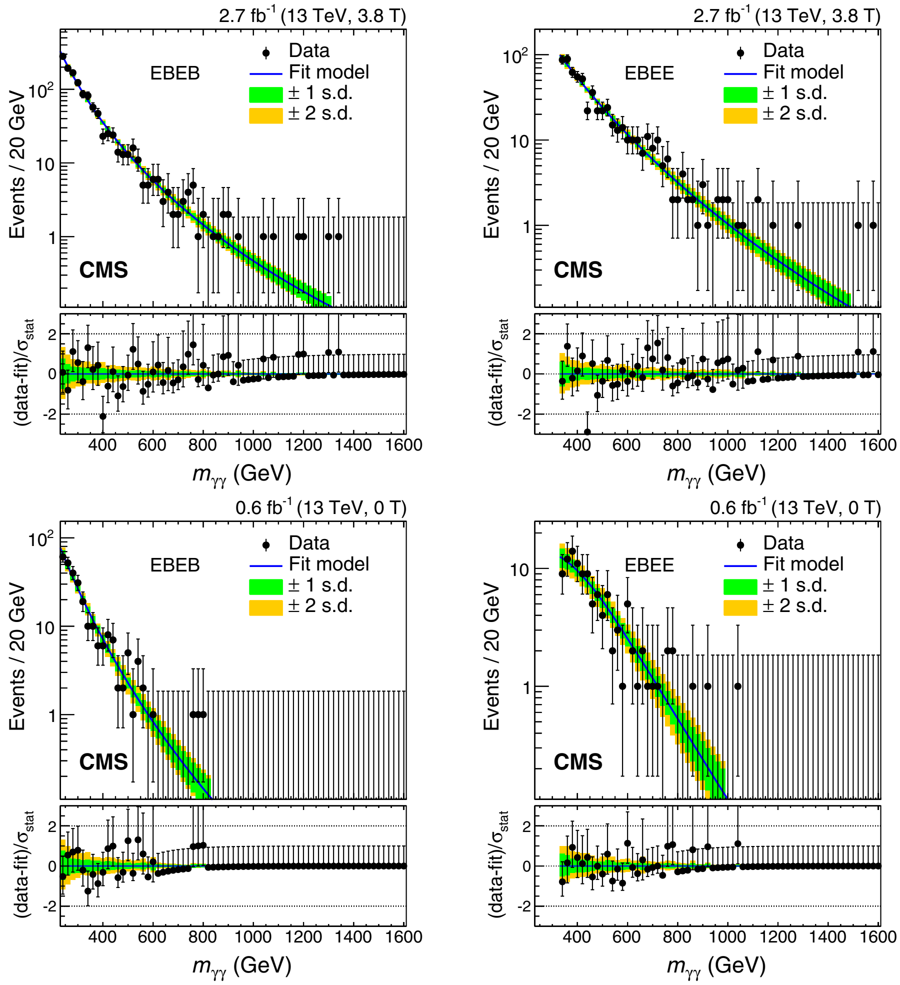

FIG. 1. Observed diphoton invariant mass $m_{\gamma\gamma}$ spectra for the event categories used in the analysis of the 13 TeV data: (upper row) magnetic field strength $B = 3.8$ T; (lower row) $B = 0$ T; (left column) both photons in the ECAL barrel detector, (right column) one photon in the ECAL barrel detector and the other in an ECAL endcap detector. No event with $m_{\gamma\gamma} > 1600$ GeV is selected in the analysis. The results of a likelihood fit to the background-only hypothesis are also shown. The shaded regions show the 1 and 2 standard deviation uncertainty bands associated with the fit, and reflect the statistical uncertainty of the data. The lower panels show the difference between the data and fit, divided by the statistical uncertainty in the data points.

value $|m|$ of the median of the sampling distribution exceeds 0.5 in any interval, the statistical uncertainty in the predicted number of background events is increased by an additional term, denoted the "bias term," which is parametrized as a continuous function of $m_{\gamma\gamma}$. The bias term is tuned in such a manner that the sampling distribution of a pull variable that includes the bias term yields $|m| < 0.5$ for all intervals. The additional uncertainty is then included in the likelihood function by adding to the background model a component having the same shape as the signal, with a normalization coefficient distributed as a Gaussian of mean zero and width equal to the integral of the bias term over the FWHM of the tested signal shape. The inclusion of the additional component, whose magnitude is comparable to the 1 standard deviation band shown in Fig. 1, has the effect of avoiding falsely positive or negative tests that could be induced by a mismodeling of the background shape, and it degrades the analysis sensitivity by 5% or less.

For the 8 TeV data in the $m_X \leq 850$ GeV search, the background shape is parametrized as $g(m_{\gamma\gamma}) = m_{\gamma\gamma}^{-c} e^{-dm_{\gamma\gamma}}$, where c and d are parameters fit independently for each event category of Fig. 2, and different $m_{\gamma\gamma}$ intervals are used for each m_X. The intervals are chosen by comparing the results of the nominal parametrization with those obtained using alternative parametrizations of the background, with the intervals determined to minimize differences in the predicted background yields [8]. The method used for 13 TeV and the one of Ref. [8] yield similar levels of uncertainty in the background estimation. The latter approach, however, is not easily applicable when only a small number of events populate the $m_{\gamma\gamma} > m_X$ region, which is why this approach is not adopted for the 13 TeV analysis or for the 8 TeV search with $m_X > 850$ GeV.

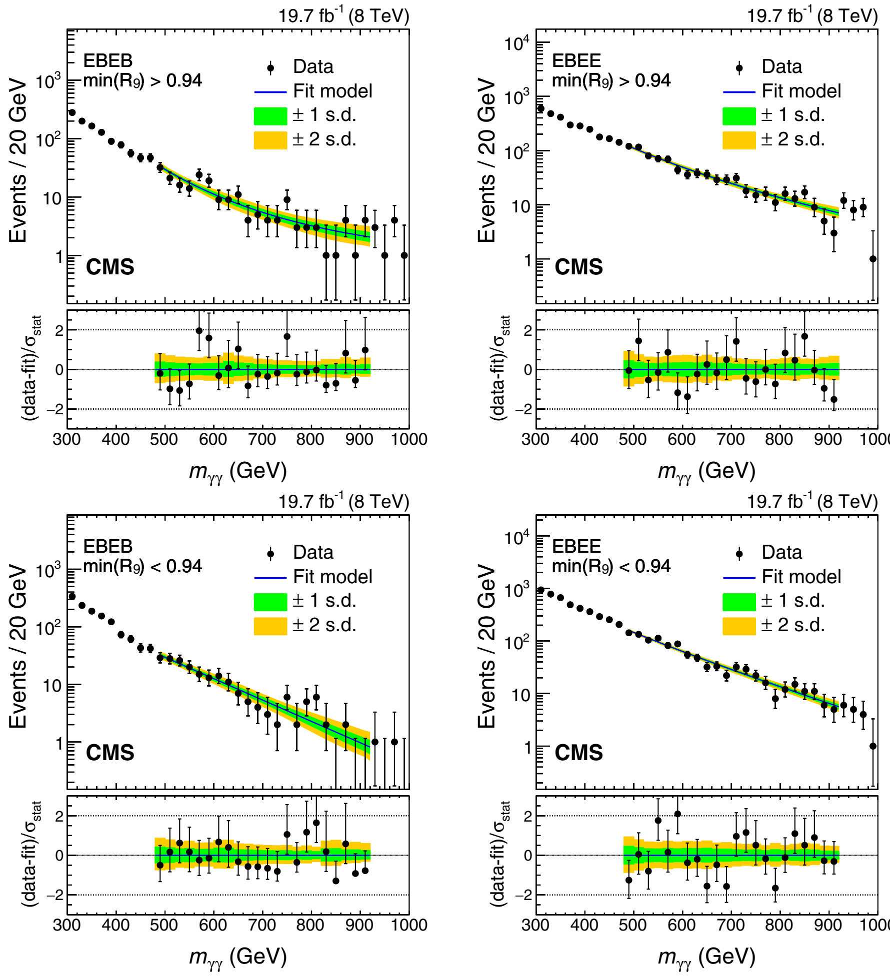

FIG. 2. Observed diphoton invariant mass $m_{\gamma\gamma}$ spectra for the event categories used in the analysis of the 8 TeV data for resonance mass $m_X \leq 850$ GeV: (upper row) $\min(R_9) > 0.94$, (lower row) $\min(R_9) \leq 0.94$; (left column) both photons in the ECAL barrel detector; (right column) one photon in the ECAL barrel detector and the other in the ECAL endcap detector. The results of background-only parametric fits to the data corresponding to the fit range used for the $m_X = 750$ GeV hypothesis test are also shown [8]. The shaded regions show the 1 and 2 standard deviation uncertainty bands associated with the fit, and reflect the statistical uncertainty of the data. The lower panels show the difference between the data and fit, divided by the statistical uncertainty in the data points.

We evaluate systematic uncertainties in the signal model predictions. For the 8 TeV data, these are discussed in Ref. [8]. For the 13 TeV analysis they are as follows. For 3.8 (0) T, a 2.7 (12)% uncertainty is due to the limited knowledge of the total integrated luminosity [42]. An 8 (16)% uncertainty is attributed to the selection efficiency and a 6 (6)% uncertainty to the PDFs. An uncertainty of 1% is assigned to the absolute photon energy scale, with an additional 1% to account for possible differences between the energy scales of the 3.8 and 0 T samples. An uncertainty in the signal mass resolution is assessed by varying the photon energy resolution corrections derived from $Z \to e^+e^-$ events by $\pm 0.5\%$. Energy resolution uncertainties are taken to be uncorrelated between the 8 and 13 TeV data, while a linear correlation of 0.5 is assumed for the energy scale. Taking the value of the linear correlation to be 0 or 1 leads to negligible changes in the results. Other systematic uncertainties are taken to be uncorrelated between the two data sets, except for the one associated with the PDFs, which is taken to be fully correlated.

The ratio of the 8 TeV to the 13 TeV production rates is determined from simulation and is held constant in the fit. For the scalar (RS graviton) resonance, this ratio decreases from 0.27 (0.29) at $m_X = 500$ GeV to 0.03 (0.04) at $m_X = 4$ TeV and equals 0.22 (0.24) for $m_X = 750$ GeV. The uncertainty in this ratio, determined by varying the PDFs, is found to have a negligible impact on the results and is therefore ignored.

The median expected and observed 95% confidence level (C.L.) exclusion limits on the product of the 13 TeV signal production cross section and decay branching fraction, $\sigma_X^{13\ \mathrm{TeV}}\mathcal{B}_{\gamma\gamma}$, are presented in Fig. 3 for the combined analysis. The upper (lower) plot shows the results for a narrow (broad) resonance width,

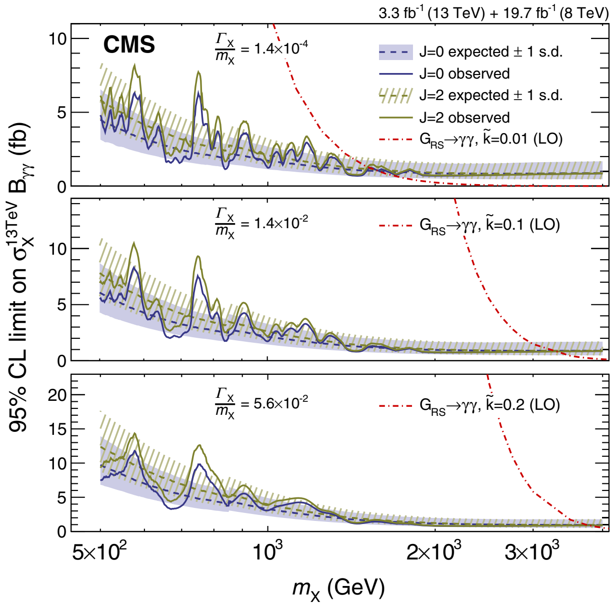

FIG. 3. The 95% C.L. upper limits on the production of diphoton resonances as a function of the resonance mass m_X, from the combined analysis of the 8 and 13 TeV data. The 8 TeV results are scaled by the ratio of the 8 to 13 TeV cross sections. The blue-grey (darker) curves and the green (lighter) ones correspond to the scalar and RS graviton signals, respectively. Solid (dashed) curves represent the observed (median expected) exclusion limit. The expected results are shown with their 1 standard deviation dispersion bands. The leading-order RS graviton production cross section is shown by the red dot-dashed curves. The results are shown for (upper) a narrow, (middle) an intermediate width, and (lower) a broad resonance, with the value of the width Γ_X/m_X, relative to the mass, indicated in the legend of each plot.

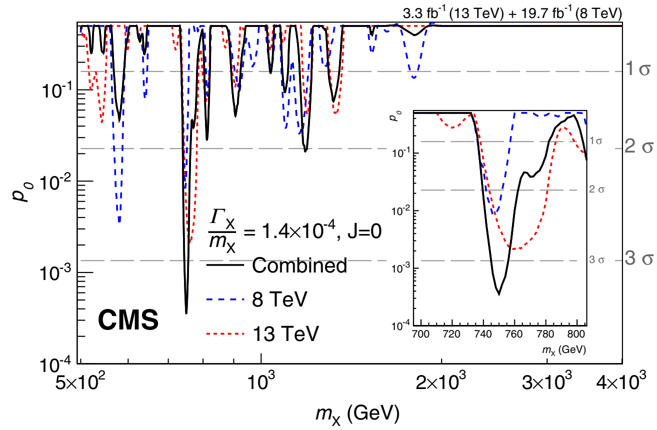

FIG. 4. Observed background-only p values for narrow-width scalar resonances as a function of the resonance mass m_X, from the combined analysis of the 8 and 13 TeV data. The results for the separate 8 and 13 TeV data sets are also shown. The inset shows an expanded region around $m_X = 750$ GeV.

$\Gamma_X/m_X = 1.4 \times 10^{-4}$ (5.6×10^{-2}). The results for $\Gamma_X/m_X = 1.4 \times 10^{-2}$ are shown in the middle plot. The blue-grey (darker) and green (lighter) solid curves indicate the observed limits for a scalar resonance and an RS graviton. The corresponding dashed curves show the expected limits, with their one standard deviation intervals. Using the LO cross sections from PYTHIA8.2, RS gravitons with masses below 1.6, 3.3, and 3.8 TeV are excluded for $\tilde{k} = 0.01$, 0.1, and 0.2, respectively, corresponding to $\Gamma_X/m_X = 1.4 \times 10^{-4}$, 1.4×10^{-2}, and 5.6×10^{-2}.

The observed value of p_0 as a function of m_X is shown in Fig. 4 for the scalar narrow-width hypothesis ($\Gamma_X/m_X = 1.4 \times 10^{-4}$). The largest excess, observed for $m_X \approx 750$ GeV, has a local significance of approximately 3.4 standard deviations. Similar values are obtained for the two spin hypotheses, while lower values of the local significance are obtained for wider signal hypotheses. For $\Gamma_X/m_X = 5.6 \times 10^{-2}$ a local significance of 2.3 standard deviations is estimated.

Trial factors associated with the test of several mass hypotheses are estimated for fixed width and spin assumptions by counting the number of times the value of p_0 observed in data crosses the level corresponding to 0.5 standard deviations and applying the asymptotic formulas of Ref. [43], where a trial factor refers to the ratio of the probability to observe an excess at a given m_X value to the probability to observe it anywhere in the examined m_X range. To account for the different width and spin hypotheses tested, a correction factor is estimated using the 13 TeV event categories, as follows. A sampling distribution of the minimum value of p_0 is generated from an ensemble of background-only pseudoexperiments, testing for all examined spin, width, and mass hypotheses. The correction factor is given by the ratio of the trial factors obtained varying only the signal mass to those obtained also varying the width and spin. A global significance for the 750 GeV excess, taking into account the effect of testing all the signal hypotheses considered, is thereby estimated to be approximately 1.6 standard deviations. The estimated global significance increases by about 5% if the spin hypothesis is not varied and by an additional 5% if only narrow-width signal hypotheses are considered. A statistical uncertainty of roughly 10% in the estimated global significance is associated with the counting of p_0 crossings in data.

The excess is primarily due to events in which both photons are in the ECAL barrel. The shape of the associated ECAL clusters is in agreement with the expectation for high-p_T prompt photons. In particular, the R_9 value exceeds 0.94 for more than 80% of the photon pair candidates in the 13 TeV data in the region corresponding to the excess, i.e., the showers are compact, with lateral shapes like those of unconverted photons at lower energy, in agreement with the expectation for a sample of prompt high energy photon pairs. Within the limited statistical precision currently available, the kinematic distributions of the diphoton candidates in the $m_{\gamma\gamma}$ region corresponding to the largest excess, as well as the multiplicity and kinematic distributions of the hadronic jets reconstructed in the same events, do not exhibit significant deviations from the distributions expected for SM processes.

In summary, a search for the resonant production of high-mass photon pairs is presented. The analysis is based on 19.7 and 3.3 fb^{-1} of proton-proton collisions collected at $\sqrt{s} = 8$ and 13 TeV, respectively, by the CMS experiment. Limits on the production cross section of scalar resonances and Randall-Sundrum gravitons for resonance masses $0.5 < m_X < 4$ TeV and relative widths $1.4 \times 10^{-4} < \Gamma_X/m_X < 5.6 \times 10^{-2}$ are determined. Using leading-order cross sections for RS graviton production, RS gravitons with masses below about 1.6, 3.3, and 3.8 TeV are excluded at 95% confidence level for $\tilde{k} = 0.01$, 0.1, and 0.2, respectively, corresponding to $\Gamma_X/m_X = 1.4 \times 10^{-4}$, 1.4×10^{-2}, and 5.6×10^{-2}. A modest excess of events over the background-only hypothesis is observed for $m_X \approx 750$ GeV. The local p value under the narrow-width hypothesis of $\Gamma_X/m_X = 1.4 \times 10^{-4}$ is 3.4 standard deviations. At $m_X = 750$ GeV, the 8 and 13 TeV data contribute with similar weights to the combined result. The significance of the excess is reduced to about 1.6 standard deviations once the effect of searching under multiple signal hypotheses is taken into account. More data are required to determine the origin of this excess. A similar analysis is presented by the ATLAS Collaboration [44].

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

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