Searches for BSM physics in diphoton final state at CMS

Milena Eleonore Quittnat for the CMS Collaboration

Abstract

Many physics scenarios beyond the standard model predict the existence of heavy resonances decaying to diphotons. This note presents searches for BSM physics in the diphoton final state at CMS, focusing on the recent results obtained using data collected at the LHC in 2015.

Presented at DIS 2016 XXIV International Workshop on Deep-Inelastic Scattering and Related Subjects
Many physics scenarios beyond the standard model predict the existence of heavy resonances decaying to diphotons. This note presents searches for BSM physics in the diphoton final state at CMS, focusing on the recent results obtained using data collected at the LHC in 2015.
Introduction
The resonant production of high mass diphoton 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 SM extensions with non-minimal Higgs sectors \[3\], while spin-2 resonances decaying to two photons arise in models with additional space-like dimensions, namely the Randall-Sundrum (RS) graviton model \[4\]. Recently, the ATLAS \[5\] and CMS \[6\] collaborations reported results on searches for diphoton resonances at \(\sqrt{s} = 13\)TeV, in the mass ranges \(200\)GeV - \(2\)TeV and \(500\)GeV - \(4.5\)TeV, respectively. The results reported in this note are based on \(3.3\) fb\(^{-1}\) of proton-proton collisions collected by the CMS experiment in 2015 at \(\sqrt{s} = 13\)TeV. The results obtained on the \(\sqrt{s} = 13\)TeV dataset are combined statistically with those obtained by the CMS collaboration in similar searches carried out at \(\sqrt{s} = 8\)TeV and are published in \[7\], \[8\].

Event selection and reconstruction
A detailed description of the CMS detector, together with the relevant kinematic variables, can be found in Ref. \[9\] and a description of the used simulation in Ref. \[8\]. In the 13TeV dataset and with \(B = 3.8\)T (\(B = 0\)T), the trigger selection requires at least two photon candidates of transverse momentum above \(60\) (\(40\))GeV and is fully efficient for the search range of \(m_X > 0.5\)TeV. Photons are reconstructed by clustering spatially correlated energy deposits in the ECAL, the calibrations, corrections and techniques used are described in Ref. \[11\]. In the search region for the 3.8 T dataset the interaction vertex is correctly assigned for about 90\% of the signal events \[8\]. Due to a different vertex algorithm, the probability for the correct assignment is about 60\% for \(B = 0\)T data. Corrections to account for residual differences in the photon energy scale and resolution between the data and simulation are determined using \(Z \rightarrow e^+e^-\) events through the procedure described in Ref. \[11\]. 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 the transverse momentum \(p_T\) up to \(150\) (\(100\))GeV using \(Z \rightarrow e^+e^-\) data, and is found to be \(0.5(0.7)\%\) or less for both the 3.8 and 0 T data. The identification and trigger efficiencies were checked and found in agreement with simulation. In each event, photon candidates are required to have \(p_T > 75\)GeV and a pseudorapidity of \(|\eta_{SC}| < 2.5\) as well as \(|\eta_{SC}| < 1.44\) for at least one of them. The invariant mass \(m_{\gamma\gamma}\) of the pair is required to exceed \(230\)GeV for events in which both photon are centrally detected (“EBEB”) and \(320\)GeV when one photon is found in the endcaps (“EBEE”). Photon candidates are further required to satisfy different sets of identification criteria, depending on whether the data was recorded at \(B = 3.8\)T or at \(B = 0\)T, which are detailed in \[8\]. In the \(B = 3.8\)T dataset the efficiency of the identification criteria for prompt isolated photon candidate is above 90(85)% in the barrel (endcaps). In the \(B = 0\)T dataset, the identification efficiency is above 85 (70)% for prompt isolated photon candidates in the barrel (endcaps). 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, for \(m_X < 1\)TeV, the kinematic acceptance for the RS graviton resonances is approximately 20% lower than for scalar resonances. The two acceptances become similar for \(m_X > 3\)TeV. About 90 (80)% of the back-
ground 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. [7].

**Figure 1:**Observed invariant mass spectra for the EBEB (left) and EBEE (right). Top (bottom) row shows the $B = 3.8T(B = 0T)$ dataset. The results of parametric fits to the data are also shown.

### Diphoton mass spectrum and statistical analysis

The $m_{\gamma\gamma}$ distributions of the events selected in the 13 TeV analysis are shown in Fig. 1. The results of the search are interpreted in the frame of a composite statistical hypothesis test. A simultaneous fit to the invariant mass spectra of the EBEB, EBEE and $B = 3.8T, B = 0T$ event categories is used to study the compatibility of the data with the background-only and the signal+background hypotheses, described in Ref. [8]. The signal distribution in $m_{\gamma\gamma}$ is determined from the convolution of the intrinsic shape of the resonance and the ECAL detector response. In order to determine the signal normalisation, the efficiency of the final event selection is combined with the kinematic acceptance. The background $m_{\gamma\gamma}$ spectrum is described by a parametric function of $m_{\gamma\gamma}$. The parametric coefficients are obtained from a fit to the data events, and considered as unconstrained nuisance parameters in the hypothesis test, allowing the building of a data-driven description of the shape. The uncertainty on the accuracy of the background determination is assessed by a bias.
term [8] and accounted for in the hypothesis test. All uncertainties are evaluated independently for each of the four analysis categories and are assumed to be uncorrelated. In this analysis the impact of the systematic uncertainties is smaller than that of the statistical uncertainties.

Results of the search at 13 TeV and combined analysis of $\sqrt{s} = 8$ TeV and 13 TeV datasets
The search range of a resonance mass $m_X$ in the range $500 \text{GeV} < m_X < 4.5 \text{TeV}$ is interpreted for three values of relative width: $\Gamma/m = 1.4 \times 10^{-4}, 0.14 \times 10^{-2}$ and $5.6 \times 10^{-2}$. For the RS graviton model, where $\Gamma/m = 1.4 \kappa^2$ [10], this corresponds to dimensionless coupling values $\kappa = 0.01, 0.1$ and 0.2. To set upper limits on the resonant diphoton production rate, the modified frequentist method, commonly known as CL$_s$, and asymptotic formulas are used [8]. Expected and observed upper limits on the production of scalar and RS graviton resonances are shown in Fig. 2 for values $\Gamma/m$ of $1.4 \times 10^{-4}$ and $5.6 \times 10^{-2}$. The results for all signal hypotheses can be found in Ref. [7].

The compatibility of the observation with the background-only hypothesis is evaluated computing the background-only $p$-value. This “local $p$-value” $p_0$, does not take into account the fact that many signal hypotheses are tested. The largest excess observed in data has a $p_0$ value corresponding to 2.9 standard deviations when testing for the production of an RS graviton with $m_G = 760 \text{GeV}$ and $\Gamma/m = 1.4 \times 10^{-2}$, depicted in Figure 3. The probability of observing an excess more significant than this for at least one of the signal spin and width hypotheses in the mass range between 500 GeV and 4.5 TeV is estimated constructing the sampling distribution of max($p_0$) on an ensemble of background-only pseudo-experiments and found to be less than one standard deviation. The results obtained on the 13 TeV dataset are combined statistically with those obtained on the data recorded by the CMS experiment at $\sqrt{s} = 8$ TeV with an integrated luminosity of 19.7 fb$^{-1}$. Two analyses were performed using the 8 TeV dataset: the analysis described in Ref. [12] searched for diphoton resonances in the mass range between 150 and 850 GeV under the spin-0 and spin-2 hypotheses, the analysis described in Ref. [13] focused on the mass range above 500 GeV and only on the spin-2 hypothesis. Since the event samples partially overlap, at each $m_X$, the analysis leading to the most stringent median expected exclusion limit on resonant diphoton production is taken. Following this criterion, we use the results of Ref. [12] for $m_X < 850 \text{GeV}$ and those of Ref. [13] for $m_X > 850 \text{GeV}$. The ratio of the signal production cross sections at $\sqrt{s} = 8$ TeV and 13 TeV has

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2}
\caption{Expected and observed 95% C.L. exclusion limits in the range $500 \text{GeV} < m_X < 4.5 \text{TeV}$ for $\Gamma/m = 1.4 \times 10^{-4}$ (left) and $5.6 \times 10^{-2}$ (right) for scalar signals.}
\end{figure}
been calculated [8]. It is roughly 0.29 (0.27) for $m_G (m_S) = 500\text{GeV}$ and decreases to 0.04 (0.03) when $m_G (m_S) = 3\text{TeV}$. For $m_G (m_S) = 750\text{GeV}$ we find a cross section ratio of 0.24 (0.22). Further details of the statistical combination can be found in Ref. [8]. In the combined analysis, a simultaneous fit to the $m_{\gamma\gamma}$ spectra in all the event categories is performed, assuming a common signal strength modifier for all categories. Upper limits are set using the CL$_S$ method and background-only $p$-values are computed as described for the 13 TeV only dataset. The expected and observed median 95% C.L. exclusion limits on the equivalent 13 TeV production cross section, $\sigma_{G.S}^{13\text{TeV}} \cdot \mathcal{B}_{\gamma\gamma}$, for the combined analysis are shown on the left side of Figure 4. For the signal hypotheses below roughly 1.5 TeV, the exclusion limits obtained with the combined analysis are more stringent than those obtained individually on the 8 or 13 TeV datasets by 20-40%. In the region above 1.5 TeV the exclusion limit is determined mostly by the 13 TeV analysis. The background only $p$-value, $p_0$, for the combined analysis is shown on the right side of Figure 4, for the narrow and largest width scalar signal hypotheses. Further results can be found in Ref. [7]. The largest excess is observed for the narrow width hypothesis at $m_S = 750\text{GeV}$ and has a local significance of approximately 3.4 standard deviations. The significance of the excess, taking into account the effect of testing all the signal hypotheses considered, is estimated to be approximately 1.6 standard deviations [8].

**In summary**, a search for new physics using the diphoton mass spectrum is presented. The analysis is based on 3.3 fb$^{-1}$ and 19.7 fb$^{-1}$ of pp collisions collected at $\sqrt{s} = 13\text{ TeV}$ and at $\sqrt{s} = 8\text{ TeV}$, respectively, by the CMS experiment. Limits on the production of scalar resonances and RS gravitons for resonance masses $500\text{GeV} < m_X < 4.5\text{TeV}$ and $1.4 \times 10^{-4} < \Gamma/m < 5.6 \times 10^{-2}$ 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 a 95% confidence level for $\kappa = 0.01, 0.1,$ and 0.2, respectively, corresponding to $\Gamma/m = 1.4 \times 10^{-4}, 1.4 \times 10^{-2}$ and $5.6 \times 10^{-2}$. A modest excess of events over the background-only hypothesis is observed for $m_X = 750\text{ GeV}$. The local $p$-value under the narrow-width hypothesis of $\Gamma/m = 1.4 \times 10^{-4}$ 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.

References