Searches for High Mass BSM Scalars in $Z\gamma$ and $\gamma\gamma$ Final States

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Searches for heavy scalar resonances decaying to $Z\gamma$ and $\gamma\gamma$ are presented. These searches are based on the data collected with the CMS detector at 13 TeV. The search strategy is to look for an excess above the non-resonant Standard Model background in the $Z\gamma$ and $\gamma\gamma$ invariant mass spectra. The background is extracted directly from data and compared with the signal expected to be produced by hypothetical scalar resonances.

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1. Introduction

The discovery of a Higgs boson at 125 GeV [1, 2], while generally seen as the completion of the Standard Model (SM) of particle physics, can also be a first hint for a more fundamental theory of nature to which the SM might be only a low-energy approximation. A variety of models beyond the SM predict the existence of new scalar bosons and this paper describes the results of searches for such heavy resonances decaying to $Z\gamma$, with further decay of $Z \rightarrow \ell^+\ell^-$ [3] and $Z \rightarrow q\bar{q}$ [4], and $\gamma\gamma$ [5]. The searches are based on 13 TeV proton-proton collision data collected by the CMS experiment [6] in 2016, corresponding to the integrated luminosity of 12.9 fb^{-1}. The search strategy measures the non-resonant SM background directly on data, and looks for localized excesses, similarly to what is done in Ref. [7] and [8].

2. Event Selection

2.1 $Z(\ell^+\ell^-)\gamma$

Events are selected with exactly two opposite-sign electrons or muons with a photon. Then events are required to pass either a double-electron tigger, a double-muon trigger, or single-muon trigger paths. All lepton and photon candidates must pass the CMS standard electron [9], muon [10] [11], and photon [12] identifications respectively. The leading lepton is required to have transverse momentum $p_T > 25$ GeV, while the subleading lepton must have $p_T > 20$ GeV, and both are required to have pseudorapidity $|\eta| < 2.4$. The chosen p_T thresholds ensure that trigger turn-on effects may be neglected. The photon is required to have $p_T > 40$ GeV and $|\eta| < 2.5$. In addition, the angular separation between each of the selected leptons and the photon must satisfy $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} > 0.4$ in order to minimize the effect of lepton final state radiation. Photons and electrons in the electromagnetic calorimeter gap region $1.44 < |\eta| < 1.57$ are excluded. The system of the selected dilepton is required to have an invariant mass between 50 and 130 GeV. Finally, the photon p_T has to be greater than $(40/150) \times m_{Z\gamma}$, where $m_{Z\gamma}$ is the invariant mass of the $Z\gamma$ candidate. This condition suppresses backgrounds from photon misidentification, without losing signal sensitivity nor introducing a bias in the $m_{Z\gamma}$ spectrum. $m_{Z\gamma}$ spectra of data and Monte Carlo (MC) simulations after event selection are compared in Figure 1.

2.2 $Z(q\bar{q})\gamma$

Events are required to pass either single photon triggers or single jet triggers. A photon in each event is identified by the CMS standard photon identification criteria and required to have $p_T > 200$ GeV and $|\eta| < 1.44$. Two jets decayed from from Z are boosted by the back-to-back photon in the same event and reconstructed as a single jet of large radius. Therefore, a jet clustered with anti-kT algorithm with a cone size of $\Delta R < 0.8$ is selected at first. The jet is required to pass the CMS standard jet identification criteria and also have $p_T > 200$ GeV and $|\eta| < 2.0$ to ensure that the core of the jet is within the tracker volume of the CMS detector ($|\eta| < 2.4$). In addition, ΔR between the photon and the jet must be larger than 1.1. After the selection, the jet is pruned with the Cambridge-Achen algorithm and the invariant mass of pruned jets must be between 75 GeV and 105 GeV to ensure the jet is the decay product of a Z boson. Finally, the pruned jets are split

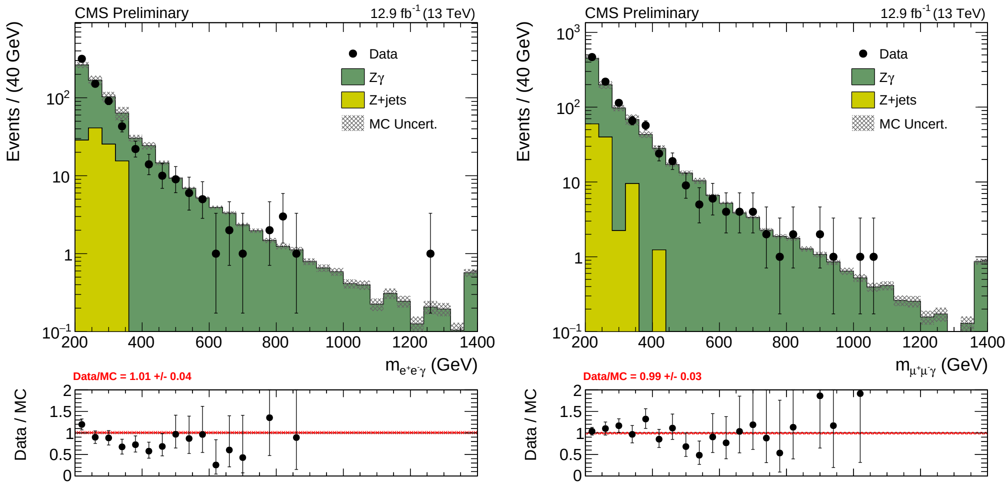

Figure 1: $m_{Z\gamma}$ distributions of data and the MC simulation in $e^+e^-\gamma$ (left) and $\mu^+\mu^-\gamma$ (right) channels after event selection [3]. They are in good agreement in both search channels.

into two subjets by reversing the final iteration in the clustering and the selected events are divided into two orthogonal categories based on subjet b-tagging for better sensitivity. Events that both subjets are identified as jets from b quarks are defined as "b-tagged" category and the others are named as "anti-b-tagged" category.

2.3 $\gamma\gamma$

Events are required to pass a double photon trigger. Two photon candidates have to pass the standard identification criteria and $p_T > 75$ GeV and $|\eta| < 2.5$ excluding the gap region 1.44 < $|\eta|$ < 1.57. Among the two photons, at least one must have $|\eta| < 1.44$. Events with both photons in the detector endcap are not included due to a large jet background contribution. Selected events are divided into two categories. Events with both photons in the barrel belong to "EBEB" category and the others belong to "EBEE" category.

3. Background and Signal Modeling

The non-resonant SM background in the $m_{Z(\ell^+\ell^-)\gamma}$, $m_{Z(q\bar{q})\gamma}$ and $m_{\gamma\gamma}$ spectra can be extracted by an unbinned likelihood fit with a parametric function of m: $f(m) = m^{a+b\log m}$. The parametric coefficients are obtained from a fit to the data events, and considered as unconstrained nuisance parameters in the hypothesis test, providing a data-driven estimation for the shape of the background in each invariant mass spectrum. The background bias is studied using MC simulations. Signal modeling is based on the MC simulation based on various benchmark scenarios written in Table 1. The signal MC is used in the analysis for two parts: first, it provides the shape of the signal invariant mass spectrum, which is parametrized by a function with a Gaussian core and two power-law tails, an extended form of the Crystal Ball function [13] for $Z(\ell^+\ell^-)\gamma$ and $\gamma\gamma$ channels and a sum of the Crystal Ball function and the Gaussian function for $Z(q\bar{q})\gamma$ channel; second, acceptance and selection efficiency are measured using the signal MC. The best-fit values of the six parameters of the signal shape and efficiency are measured on MC samples at the benchmark resonance masses, separately for each channel, and then interpolated through polynomial fits to generic resonance mass values.

Table 1: Signal benchmark scenarios with respect to spin and width.

	$Z(l^+l^-)\gamma$	$Z(q\bar{q})\gamma$	$\gamma\gamma$
Spin	0	0	0, 2
Width (Γ/m)	0.014%	0.014%, 5.6%	0.014%, 1.4%, 5.6%

4. Results

No significant excess above expected backgrounds is observed in $m_{Z(\ell^+\ell^-)\gamma}$, $m_{Z(q\bar{q})\gamma}$, and $m_{\gamma\gamma}$ spectra. Therefore, we set upper limits on the production cross section of scalar resonances, using the modified frequentist method, commonly known as CLs [14], with the asymptotic formulae [15]. Figure 2 – 4 show 95% confidence level upper limits on the signal production cross section times branching fraction. Figure 2 and Figure 3 show the results of $Z(\ell^+\ell^-)\gamma$ and $Z(q\bar{q})\gamma$ channels. The expected limit for the background-only hypothesis is represented by a dashed black line, and its 1σ and 2σ standard deviations are shown with green and yellow bands, respectively. The observed limit is represented by a solid black line. Only small statistical fluctuations of significance less than 2σ are observed in both channels. In the case of the search in $\gamma\gamma$ channel, the result is also combined with the previous results based on 13 TeV proton-proton collision data in 2015 and 8 TeV proton-proton collision data in 2012 as shown in Figure 4. The lower limits on Randall-Sundrum graviton mass are set to 1.95, 3.85, and 4.45 TeV for values of the dimensionless coupling parameter $\tilde{k}$ = 0.01, 0.1 and 0.2 respectively.

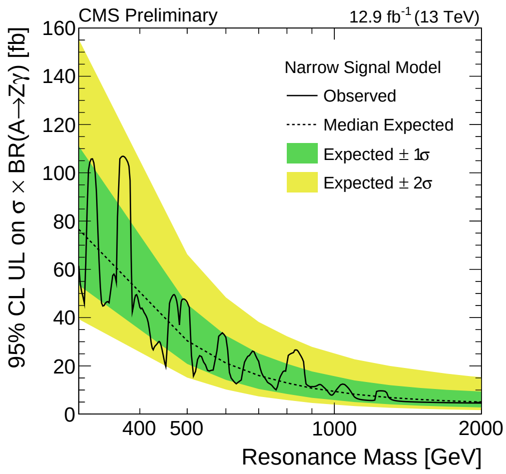

Figure 2: 95% confidence level upper limits on $\sigma \times BR(Z\gamma)$ obtained by combining $e^+e^-\gamma$ and $\mu^+\mu^-\gamma$ channels [3].

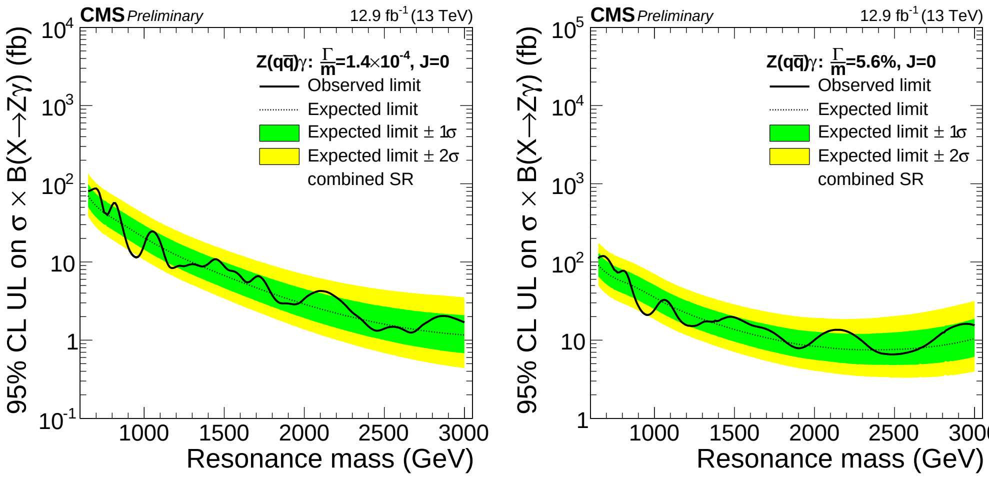

Figure 3: 95% confidence level upper limits on $\sigma \times BR(Z\gamma)$ obtained by combining the anti-b-tagged and b-tagged categories with the narrow (left) and wide (right) width scenarios [4].

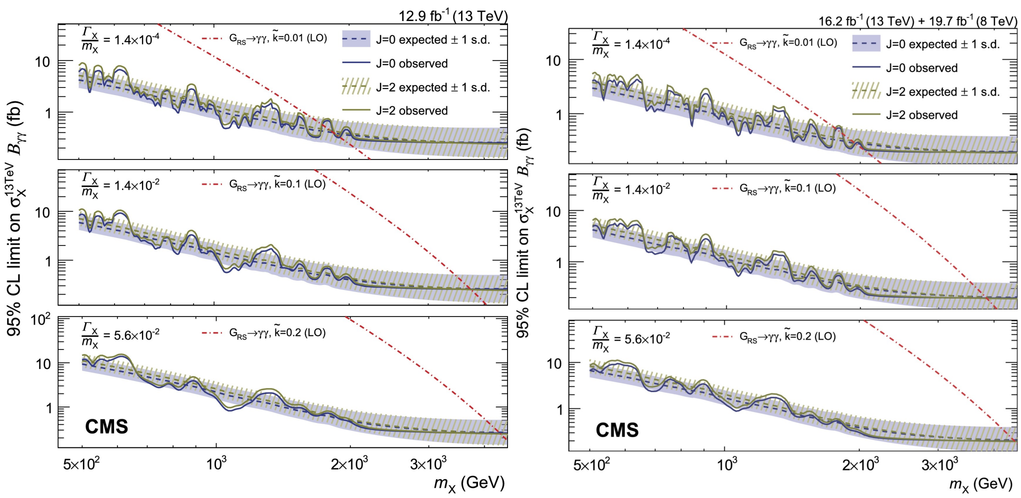

Figure 4: 95% confidence level upper limits on $\sigma \times BR(\gamma\gamma)$ obtained by combining the EBEB and EBEE categories. The left is the result using 2016 data and the right is the combination of 2016 result and the previous results [5].

5. Conclusion

Searches for high-mass scalar resonances in the $X \to Z\gamma \to e^+e^-\gamma/\mu^+\mu^-\gamma$, $X \to Z\gamma \to q\bar{q}\gamma$ and $X \to \gamma\gamma$ channels have been performed, using 12.9 fb^{-1} 13 TeV pp collision data collected with the CMS detector. No significant excess is observed above the background-only hypothesis and therefore upper limits are placed in the $300 < m_{Z(\ell^+\ell^-)\gamma} < 2000$ GeV, $650 < m_{Z(q\bar{q})\gamma} < 3000$ GeV, and $500 < m_{\gamma\gamma} < 4500$ GeV ranges respectively.

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