PROCEEDINGS OF SCIENCE

Search for low and high mass resonances with $\gamma\gamma/Z\gamma$ final states with the ATLAS detector

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Searches for new resonances decaying to two photons and a Z boson and a photon in the ATLAS experiment at the LHC are presented. The analyses are based on pp collision data corresponding to an integrated luminosity of 139 fb^{-1} at $\sqrt{s}$ = 13 TeV recorded between 2015 and 2018. Three independent searches are performed: a boosted resonance search in the diphoton final state probing masses between 10 and 70 GeV, a diphoton resonance search from 70 to 110 GeV, and a resonance search in the $Z\gamma$ final state covering masses between 220 GeV up to 3.4 TeV. No significant deviations with respect to the Standard Model are observed and upper limits on their production cross-section times branching ratio are provided.

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1. Introduction

Many extensions of the Standard Model (BSM) predict the existence of new states that can appear at very different energies accessible at the CERN Large Hadron Collider. While the theoretical motivations vary with the mass of the hypothetical new field, resonances are a generic signature that can be searched for experimentally. In particular, resonance searches involving clean signatures, such as those with photons and/or Z bosons, combined with excellent detector performances provide high sensitivity to a wide range of energy and models.

The results reported here are resonance searches with a pair of photons [1, 2] or a Z boson and a photon in the final state [3]. The three analyses utilize a common strategy in which the background is estimated by fitting the data to an analytical function and searching for a narrow excess modeled by the expected signature of the signal. All of them use data collected by the ATLAS detector [4] between 2015 and 2018 using pp collisions at a center-of-mass energy of $\sqrt{s}$ = 13 TeV and an average of pp interactions of 34. After data-quality requirements, the data sample used in the three analyses corresponds to an integrated luminosity of 139.5 ± 1.2 fb^{-1}.

2. $Z\gamma$ resonance search

A complete description of this search can be found in Ref. [3]. Events from pp collisions were recorded with a combination of single photon and lepton triggers and dilepton triggers[1]. The threshold for the single muon and electron triggers is 26 GeV, while for the dielectron trigger is 17 GeV. An asymmetric threshold is used for the dimuon trigger, where the lead muon is required to have more than 22 GeV and the subleading more than 8 GeV. The lowest threshold for the single photon trigger is 140 GeV.

Simulated Monte Carlo (MC) samples are used to optimize the search strategy, evaluate signal selection efficiencies and for background estimation purposes. MC signal samples were produced for two different spin hypotheses (0 and 2), produced via gluon-gluon fusion (ggF) and quark-antiquark processes and for various masses between 200 and 3500 GeV with an intrinsic resonance width of 4 MeV. Interference effects between signal and background processes are neglected. The generated events are interfaced with Pythia 8.186 for the underlying event, parton showering and hadronisation. Simulated background samples from SM processes consist mainly from $Z + \gamma$ and Z+jets events.

Candidate events are required to have two same-flavour opposite-charge leptons to form a Z boson candidate and at least one photon candidate. Muon candidates are reconstructed using tracks from the inner tracking detector and the muon spectrometer. They are required to have more than 10 GeV of transverse momentum p_T, to be within the acceptance of the detector with $|\eta| < 2.7$ and to pass medium identification quality criteria. Electron and photon candidates are reconstructed from tracks reconstructed in the tracking detectors and electromagnetic (EM) energy deposits in the EM calorimeter. Only electrons and photons with $|\eta| < 2.37$ are considered, excluding the transition region $1.37 < |\eta| < 1.52$ between the barrel and end-cap calorimeters. The identification criteria are based on the shower shapes in the EM calorimeter, optimized differently for electrons and photons. Photon candidates are required to have more than 15 GeV and to pass tight identification quality criteria. To further reject background candidates from jets misidentified as photons, they are required to be isolated from nearby energy flow using both calorimeter and tracking information.

[1] In the following, lepton refers only to electron or muon

Electron candidates are required to satisfy $p_T > 10$ GeV and to fulfill specific identification criteria developed to select collimated electrons due to the boosted topology that arises from the recoil of the Z boson with respect to a high energy photon. A dedicated MVA using tracks and shower shape variables improves the electron loose identification in the mass range of the search from 6.2% to 12.7%. Z boson candidates are reconstructed from the two same-flavour opposite-sign lepton candidates with an invariant mass closest to the Z boson pole $m_Z = 91.2$ GeV. The dilepton invariant mass is required to be within a 15 GeV window around the Z boson mass. In order to further reduce background events, the transverse momentum of the photon is required to be larger than 20% of the invariant mass of the system $m_{ll\gamma}$. The total signal selection efficiency ranges from 15% to 40% over the mass range between 200 GeV and 3.5 TeV, varying between production mode (ggF or $q\overline{q}$) and spin (0 or 2).

The invariant mass distribution of the signal is expected to peak in the vicinity of the mass of the hypothetical resonance, with the width driven by the experimental resolution. The shape is modeled with a 5 per mille difference by a Double Sided Crystal Ball (DSCB), which consists of a Gaussian core with power-law tails on both sides. The parameters of the DSCB fit function are then parameterized as a function of the mass of the resonance in order to interpolate between the generated mass points. The background is composed by non-resonant production of a Z boson with a photon and Z+jets events, in which the jet is misidentified as a photon. The relative contribution of true Z+γ events is estimated to be 0.92 obtained from a simultaneous fit of the isolation energy to signal and control regions. A family of functions is chosen to describe the shape of the invariant mass distribution denominated "Dijet" functions[2]. The signal and background models are shown in Figure 1.

Such choice is validated using the methodology detailed in Ref. [5], in which the flexibility of the functional form is enough to accommodate different underlying distributions. The systematic uncertainty related to the choice of analytical function is estimated from the spurious signal fitted over background-only pseudo-data obtained from simulated samples and it is evaluated to be from 30 to 10% of the statistical uncertainty, varying with the mass of the resonance. The fit bias is the dominant systematic uncertainty on this statistically limited analysis.

The numbers of signal and background events are obtained from a maximum likelihood fit of the $Z\gamma$ distribution of the selected events for the different spin and production mechanism. No significant excess is observed and an upper limit is placed on the production cross-section of such a resonance as a function of the the $Z\gamma$ invariant mass using a modified frequentist (CL_S) approach. The observed upper limits at 95% confidence level under the spin-0 hypothesis range between 65.5 and 0.6 fb at 220 GeV and 3.4 TeV respectively. For the spin-2 hypothesis the observed upper limits on the production cross-section times branching ratio are similar for both production mechanisms and range between 76 and 0.5 fb.

3. Diphoton resonance searches

The diphoton resonance searches documented here are further documented in Ref. [1] and [2]. Both analysis use events recorded with the lowest unprescaled triggers available, with thresholds varying from 20 to 22 GeV on the transverse momentum of each of the photons. Additional online identification and isolation requirements are used to select quality photons and reduce the rate.

[2]Defined as $f_{bkg}(x; b, a_0) = N(1-x)^b x^{a_0}$ where N is the normalization factor, $x = m_{Z\gamma}/\sqrt{s}$ and b and a_0 are free parameters of the fit.

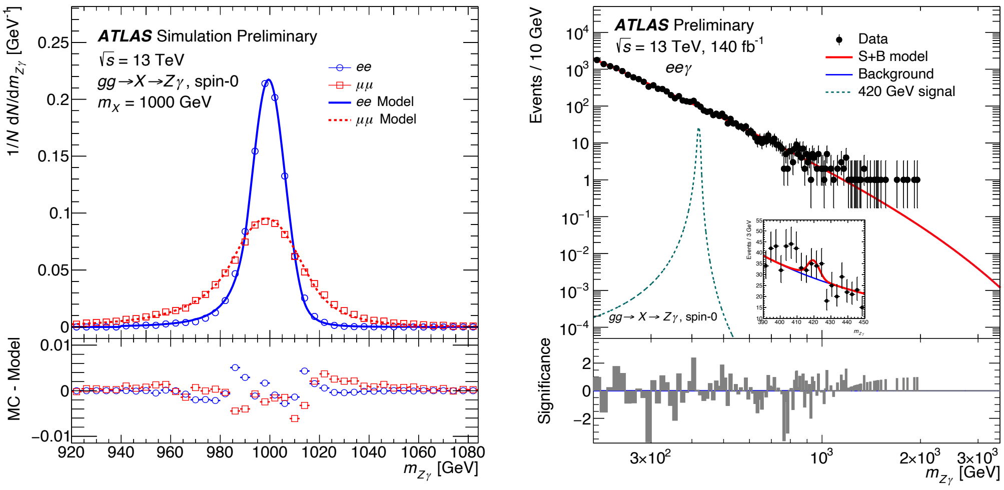

Figure 1: (Left) Differential distributions of the $Z\gamma$ invariant mass of the spin-0 resonance with m_X = 1000 GeV via ggF. The markers show the distributions of the simulated events and the solid and dashed lines show the fitted models in the $ee\gamma$ and $\mu\mu\gamma$ channels. (Right) Invariant $Z\gamma$ invariant mass distribution of events for the $ee\gamma$ channel. The solid blue line represents the background component of the full signal+background model shown in red. The cyan dashed line shows the spin-0 signal component obtained from the best fit to data of a model with a resonance mass of 420 GeV. The bottom panel shows the per-bin significance, defined as the ratio between the residuals and the statistical uncertainty of the data. [3]

MC signal samples are generated for various signal hypothesis on their respective mass ranges, from 10 to 70 GeV for the boosted diphoton resonance search and from 60 to 110 GeV for the higher mass search. Only production via ggF is assumed for the first one while also vector-boson fusion and associated production with a W boson, Z boson or a top-quark pair is assumed for the latter. Background simulated samples consist essentially of QCD diphoton events.

Similarly to the previous analysis, photon candidates are required to be within the acceptance of the calorimeters, excluding the transition region, to have more than 22 GeV of transverse momentum and to pass tight identification and loose isolation criteria.

The boosted diphoton resonance search also requires photon pairs to be highly collimated in the detector by requiring the transverse momentum of the diphoton system to be larger than 50 GeV. This eases the modeling of the shape of the background invariant mass distribution, sculpted by the trigger energy thresholds.

On the other hand, the analysis searching for resonances in the 70 to 110 GeV mass range categorizes the selected events into 3 categories depending on the number of photons converted to electron-positron pairs in the final state[3]. A gradient Boosted Decision Tree (BDT) is used to reduce the amount of events from electrons faking photons arising from Z boson decays, improving the sensitivity of the categories involving converted photons. An additional categorization is also done in order to produce a model-dependent result in which the resonance behaves as a Higgs-like particle (e.g. assuming SM Higgs cross-sections). Three categories are obtained from a subsequent BDT trained on the generated signal samples against the SM diphoton background depending on the BDT score. In total, two different results are obtained for this search: an independent result obtained from the 3 conversion-dependent categories and a model-dependent one performed on the

[3]In the following denoted simply as converted photons

9 categories arising from the second BDT and the conversion-dependent ones.

The same signal modelling strategy is followed in both diphoton searches, in which the invariant mass diphoton shape of the signal is modeled with a DSCB. The background is mainly composed by events with true diphoton candidates and events in which one or both photon candidates are jets misidentified as photons. The relative contribution between them is obtained from a two-dimensional ABCD method using relaxed identification criteria and isolation variables. The purity of diphoton events in the boosted resonance search is 62 ± 3% for the mass range between 10 and 70 GeV while for the high mass analysis ranges from 60 to 70% with an uncertainty of 1-5% depending on the category. As previously mentioned, an additional background is present in the high mass resonance search from electrons faking photons, whose shape is obtained from simulated samples and its normalization from data.

The invariant mass distribution of the background in the boosted resonance search analysis is described by an analytical function built as the sum of a turn-on function to the describe the low mass edge around ~15 GeV and a power-law to describe the smoothly falling component observed for masses above ~20 GeV. A Fermi-Dirac function is used as an activation function to improve the flexibility for masses above ~45 GeV. An analytical function is also fit to the data the high mass resonance search, using in this case a third or fourth order exponential (category dependent). Figure 2 shows the analytical models fit to the collected data for both search ranges.

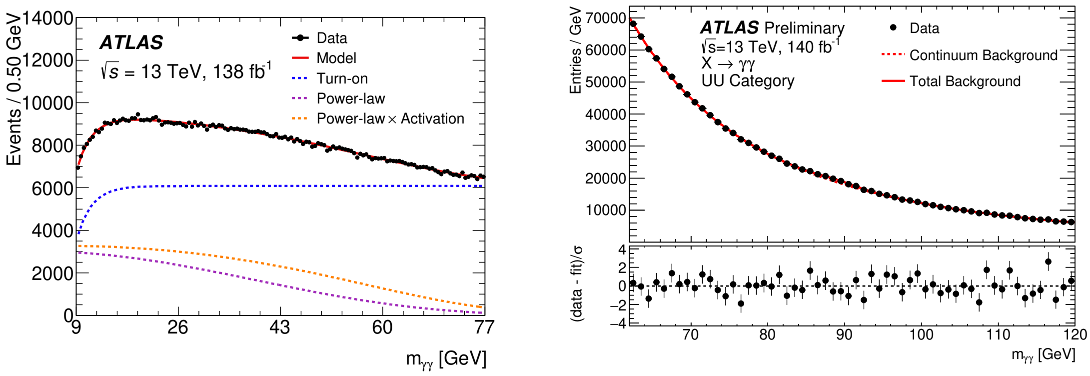

Figure 2: Invariant diphoton mass distributions for both diphoton resonance searches, being the boosted resonance search on the left and the higher mass resonance search on the right. (Left) The functional form used in the boosted resonance search is decomposed into the different pieces described in the text. (Right) The bottom panel shows the residuals of the fit to the data devided by the statistical uncertainty of the latter. [1, 2]

The systematic uncertainty induced by the fit bias in these two analyses benefits from the usage of Gaussian Processes to smooth the statistically limited background-only templates, which would otherwise artificially lead to a larger spurious signal. Its impact on the spurious signal estimation is therefore mitigated and the fit bias uncertainty is reduced by up to 50% both analyses.

The numbers of signal and background events are obtained from a binned maximum likelihood fit of the diphoton invariant mass distribution of the selected events. No significant excess is observed and an upper limit is placed on the production cross-section times branching ratio to photon pairs. Figure 3 shows the upper limits for both searches, on the left for the boosted resonance search under a model independent approach and on the right for the higher mass resonance search under the resonance couples with SM fields as the SM Higgs boson.

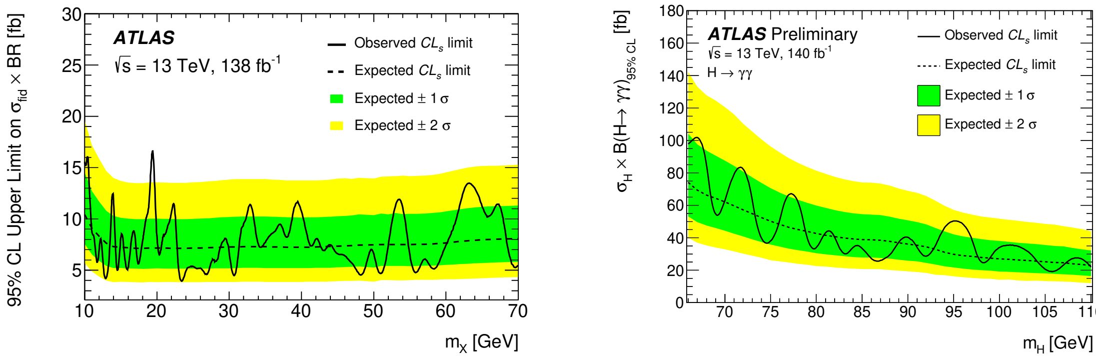

Figure 3: Observed (solid) and expected (dashed) upper limits on the product of the production cross-section times the branching ratio of a narrow width resonance X(H) for the mass range between 10 and 70 GeV (left) and between 65 and 110 GeV (right). The upper limit on the right plot assumes that the resonance H couples with SM similarly as the SM Higgs boson. The green and yellow bands correspond to the $\pm 1\sigma$ and $\pm 2\sigma$ intervals for the expected upper limit respectively [1, 2].

4. Summary

Searches for new resonances decaying to two photons and a Z boson and a photon in the ATLAS experiment at the LHC are presented, using 139 fb^{-1} pp collision data collected recorded from 2015 to 2018. The observed data are in agreement with the background-only hypotheses used in each of the analyses presented.

References

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