Search for rare decays of the observed Higgs boson and additional Higgs bosons with the ATLAS detector

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Abstract. The rare decays of the Standard Model (SM) Higgs boson and additional Higgs boson are searched for with the data recorded by the ATLAS experiment during the LHC pp collision run at 13 TeV corresponding to an integrated luminosity of 139 fb^{-1} . For the search for the dimuon decay of the SM Higgs boson, the observed (expected) significance is 2.0σ (1.7σ), and the signal strength is 1.2 ± 0.6 . For the search for the $Z\gamma$ decay of SM Higgs boson, the observed (expected) significance is 2.2σ (1.2σ), and the signal strength is $2.0^{+1.0}_{-0.9}$. For the search for new heavy resonance decaying into photon pairs, the mass range of the search has reached 3 TeV and no significant deviation from the SM is observed. These searches provide us a deeper understanding of the Higgs sector.

1. Introduction

In July 2012, the Standard Model (SM) Higgs boson (H) was discovered by the ATLAS and CMS collaborations using proton–proton (pp) collisions at the Large Hadron Collider (LHC) [1, 2]. After that, several studies for measurements of the Higgs boson’s properties have been performed. As one of the results, the Higgs couplings of the electroweak bosons or the third-generation charged fermions were observed and they are in agreement with the SM [15–17]. The study of the Higgs couplings to the second-generation fermions is a next major step. In addition, the SM cannot address several issues, for example dark matter [18, 19] and fine-tuning problem [20, 21], and thus we search for the physics beyond the SM (BSM) through:

- the search in the rare ”loop-mediated” decays of the observed Higgs boson,
- searches for additional Higgs bosons predicted by several BSM scenarios.

The large pp collision data set collected with the ATLAS detector [7] at LHC in 2015–2018 corresponding to an integrated luminosity of 139 fb^{-1} , referred to as the full Run-2 data set, provides high sensitivities for the above studies.

In this document, we present search for $H \rightarrow \mu\mu$ rare decay [3], search for $H \rightarrow Z\gamma$ rare decay [4], and search for heavy $\gamma\gamma$ resonance [5] using the Run-2 data.

2. Search for $H \rightarrow \mu\mu$ rare decay

In this section, results of the search for $H \rightarrow \mu\mu$ rare decays using the full Run-2 dataset [3] is presented. The $H \rightarrow \mu\mu$ rare decay offers the best possibility to measure the Higgs coupling to a second-generation fermion. This decay mode has very clean final state, but the signal yield is small due to the small SM branching ratio (BR) of 2.17×10^{-4} for $m_H = 125.09$ GeV. There is a large irreducible background dominated by Drell-Yan processes. The typical signal-to-background ratio is 0.2%.

The events are required to have two opposite-charge, isolated muons and leading and subleading muon having $p_T > 27$ GeV and $p_T > 10$ GeV, respectively. To improve the sensitivity by isolating regions of higher signal-to-background ratio, the events are classified into 20 categories using a production-driven boosted decision tree (BDT) categorization. The targeted production modes are ttH, VH, VBF and ggF in order.

The ttH production mode's targets are the dileptonic or semileptonic decay of the $t\bar{t}$ system. In this mode, events are required to have at least one additional lepton (electron or muon) and at least one b -tagged jet. In order to separate signal from background, a BDT discriminant is used. The VH production mode's targets are $W(\rightarrow \ell\nu)H$ or $Z(\rightarrow \ell\ell)H$ processes. For the VH (WH or ZH) process, there are one or two leptons in addition to the muon pair in the final state. Due to the difference in the number of leptons in the final state between these processes, the events are separated into two channels by the number of leptons. For the event selection targeting the WH process, the events are required to have one additional lepton and are referred to as "VH3L". For the ZH process, the events are required to have two additional leptons and are referred to as "VH4L". Both events are required to have no b -jets and are classified into three categories using two BDTs separately trained in VH3L and VH4L. Two categories are defined for the VH3L and are named VH3LH and VH3LM, where the former has the higher signal-to-background ratio. For the VH4L, only one category is selected and is named VH4L. In the ttH and VH categories, two muons are selected by the minimum χ^2 for the $m_{\mu\mu}$ calculation. Figure 1 shows the $m_{\mu\mu}$ distributions for ttH and VH3LM categories after application of the event selection and the BDT selection.

For the ggF and VBF production mode, events are required exactly two opposite-charge muons and no b -jets. The events are divided into 0-jet, 1-jet and ≥ 2 -jet regions and then events are classified based on dedicated BDT output in each jet multiplicity to fully exploit the differences between signal and background. The VBF classifier is used for events in 2-jet region and is trained to disentangle VBF and background. Figure 2(a) shows the BDT output, O_{VBF} , distribution. The events in the 2-jet region are classified into four VBF categories and a region not part of the VBF categories ($O_{\text{VBF}} < 0.62$). The ggF classifier is used for events in each 2, 1 and 0-jet region and is trained to disentangle ggF+VBF and background. The events are classified into four categories in

each region. Figure 2(b) shows the BDT output, O_{ggF} , distribution in 0-jet region.

Figure 1. Dimuon invariant mass $m_{\mu\mu}$ spectrum for (a) ttH and (b) $VH3LM$ categories [3]. The data (points) and a set of simulated backgrounds (solid colour) are shown, while the $H \rightarrow \mu\mu$ signal is shown as open line scaled to 5 or 50 times the SM prediction. Statistical uncertainties on all distributions are shown.

Figure 2. The BDT output distribution for the VBF classifier (a) and the ggF classifier in 0-jet region (b) [3]. The normalised distributions are shown for signal from VBF (red line) and ggF production (orange line) as well as the simulated background used in the BDT training (blue) and the observed data (black). The grey vertical dashed lines show the boundaries of the four categories extracted from each classifier, and these four categories have high occupancy of target process in order from the right. For the VBF classifier, the region of $O_{VBF} < 0.62$, as indicated by the left-pointing arrow labelled with ggF , is not part of the “VBF categories”, but instead further classified with the ggF classifier in the 2-jet region. Statistical uncertainties on all distributions are shown, although they are often smaller than the width of the lines.

Figure 3 shows the categorization summary. The compositions of the signal

production modes are different among the categories. The signal-to-background ratio (S/B) is quite different between categories and it is wide range from 0.1% to 20%.

Figure 3. Summary of the signal and background composition in the twenty analysis categories in the mass region $120 \text{ GeV} < m_{\mu\mu} < 130 \text{ GeV}$ [3]. The top panel shows the number of background events (B , multiplied by a factor of 10^{-5}), the expected signal-to-background ratio for the SM $H \rightarrow \mu\mu$ signal (S/B), as well as the counting significance $S/\sqrt{B}$. The middle panel shows the expected contributions of different Higgs-boson production modes to the total signal in each category. The bottom panel shows the background composition from Drell-Yan, diboson and top-quark processes in simulation.

Finally, a simultaneous signal-plus-background fit is performed to $m_{\mu\mu}$ spectrum in each category to extract signal. We add the final state radiation photon to $m_{\mu\mu}$ calculation to improve $m_{\mu\mu}$ resolution only in ggF and VBF categories. By this correction, the mass resolution is improved by 3%. The fit functions are parametric, and several parameters for the background are free in fit to data. Double-sided Crystal Ball function with shape parameters fixed in each category from fit to MC is used for signal. For background, the product of core and empirical functions are used. Figure 4 shows the

background modelling procedure. For the core function, the LO Drell-Yan analytic line shape smeared with Gaussian distribution for mass resolution is used. For empirical functions, we use exponential with polynomial on index or power laws depending on categories. The empirical function was selected so that the systematic uncertainty due to the mismodeling is less than 20% of the data statistical uncertainty.

Figure 4. Illustration of the background modelling procedure in the VBF Very High category [3]. The top panel shows the dimuon invariant mass spectra overlaid with background-only fit (blue curve) and core function (green dashed line). The red line in the top and bottom panels represents the signal pdf normalised to the predicted cross section, for the bottom panel it is divided by the background pdf. The dashed horizontal lines in the bottom panel indicate one plus or minus the expected SM signal-to-background ratio integrated in the range of $120 \text{ GeV} < m_{\mu\mu} < 130 \text{ GeV}$. The middle panel shows the Drell-Yan template and the background pdf, both divided by the core component of the background pdf, thus showing the empirical part of the background pdf. In the bottom panel the ratio between the Drell-Yan template and the background function is shown. The statistical uncertainties in the Drell-Yan templates are shown on the points.

The dimuon invariant mass distribution after the signal plus background fit is shown in Figure 5. The observed (expected) significance is 2.0σ (1.7σ). The signal strengths for the five major groups of categories and the combined one is shown in Figure 6. The best-fit values of the combined signal strength is found to be 1.2 ± 0.6 . The total uncertainty is dominated by statistical uncertainty of data. The observed upper limit on the signal strength at 95% confidence level (CL) is 2.2 times the SM prediction, and the expected limit is 1.1 for no $H \rightarrow \mu\mu$ signal scenario. The observed upper limit on the BR at 95% CL is 4.7×10^{-4} , assuming the SM cross section. These results are

consistent with the SM, representing that the coupling strength of the Higgs boson and the muon is much smaller than that of the third-generation fermions.

Figure 5. Dimuon invariant mass $m_{\mu\mu}$ spectrum in all the analysis categories observed in data [3]. All events and signal plus background probability density functions (PDFs) are weighted by $\ln(1 + S/B)$, where S are the observed signal yields and B are the background yields derived from the fit to data in the $120 \text{ GeV} < m_{\mu\mu} < 130 \text{ GeV}$ window. The lower panel compares the fitted signal PDF, normalised to the signal best-fit value, to the difference between the data and the background model. The error bars represent the data statistical uncertainties.

Figure 6. The best-fit values of the signal strength parameters for the five major groups of categories (ttH+VH, ggF 0-jet, 1-jet, 2-jet, and VBF) together with the combined value [3].

3. Search for $H \rightarrow Z\gamma$ rare decay

In this section, the search for $H \rightarrow Z\gamma$ rare decays using the full Run-2 dataset [4] is presented. The $H \rightarrow Z\gamma$ rare decay search is important to understand the Higgs loop interaction. The SM BR is small as $(1.54 \pm 0.09) \times 10^{-3}$, and it can differ from the SM value in several BSM scenarios. Only the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ decays are considered in this analysis since the decays provide good invariant mass resolution and relatively small backgrounds.

The events with two same-flavour opposite-charge leptons and at least one photon are selected. To improve the $m_{Z\gamma}$ resolution, radiated photons are added to $m_{Z\gamma}$ calculation in the $\mu\mu$ channel, and Z mass constrained kinematic fit is performed in both channels. In order to improve the $H \rightarrow Z\gamma$ sensitivity, the selected events are classified into six categories. The classification is based on a BDT discriminant, lepton flavour, and event kinematics. Here, the BDT discriminant targets VBF-like events. For signal extraction, the simultaneous fit is performed to $m_{Z\gamma}$ spectrum in all the categories. The double-sided Crystal Ball function is used for the signal. For the background, an analytical function with floating parameters, shape and an uncertainty determined using background templates from $Z\gamma$ MC simulation sample and Z +jets data in the control region is used.

The $m_{Z\gamma}$ distribution observed in data is shown in Figure 7. The observed (expected) significance is 2.2σ (1.2σ). The signal strength is found to be $2.0^{+1.0}_{-0.9}$. The total uncertainty is dominated by statistical uncertainties associated with the data. The observed upper limit on the signal strength at 95% CL is 3.6 times the SM prediction, and the expected limit is 1.7 for no $H \rightarrow Z\gamma$ signal scenario. The observed upper limit on the cross section times BR at 95% CL is 305 fb. The observed upper limit on the BR at 95% CL is found to be 0.55% assuming the SM cross section. Since statistical uncertainties dominate the current measurement, higher-statistics data sets will be needed to probe BSM physics associated with the production of Higgs bosons via loops.

4. Search for heavy $\gamma\gamma$ resonance

In this section, the search for heavy $\gamma\gamma$ resonance using the full Run-2 dataset [5] is presented. The search is performed in the high mass spectrum of $m_{\gamma\gamma} > 160$ GeV. The spin-0 resonant state predicted by theories with extended Higgs sector and the spin-2 graviton are considered as benchmarks. This document focuses on the spin-0 benchmark [8–14]. The $\gamma\gamma$ final state provides the excellent invariant mass resolution and smoothly falling background.

For the spin-0 and 2 benchmarks, the following common event selection are used. The events are required to have at least two photon candidates that satisfy $E_T/m_{\mu\mu}$ and η requirements. In the signal modeling, the double-sided Crystal Ball function is used for narrow width assumption, and double-sided Crystal Ball function convoluted

Figure 7. Weighted invariant mass $m_{Z\gamma}$ distribution observed in data after the event selection [4]. The black points represent data. The error bars represent only the statistical uncertainty of the data. The events are weighted by $\ln(1+S_{68}/B_{68})$, where S_{68} and B_{68} are the expected signal and background events in a $m_{Z\gamma}$ window containing 68% of the expected signal. The solid blue curve shows the combined fitted signal-plus-background model when fitting all analysis categories simultaneously, the dashed line shows the model of the background component.

with relativistic Breit-Wigner function is used for large width assumption. For the background, a similar procedure is used as for the $H \rightarrow \mu\mu$ analysis. In the background modeling, an analytical function with floating parameters, shape and uncertainty determined using background templates from signal MC simulation and γ +jet data in the control region is used.

In the search, narrow or large width resonances with decay widths up to 10% of the mass are searched for. The fit is performed using analytical functions that model background and signal shape to the $m_{\gamma\gamma}$ distribution.

The $m_{\gamma\gamma}$ distribution observed in data is shown in Figure 8. The highest mass candidate selected in data has a mass of 2.36 TeV. No significant deviation from the SM is observed. The local significance for narrow width assumption is 3.29σ at mass of 684 GeV. The corresponding global significance is 1.30σ . The local significance is obtained for the decay width up to 10% of the mass and shown in Figure 9. The observed upper limit on the fiducial cross section times BR as a function of signal mass is shown in Figure 10. The mass range of the search has reached 3 TeV by this analysis

Figure 8. The background-only fit (red solid line) to the $m_{\gamma\gamma}$ distribution observed in data (black dots) with several generic narrow width signal shapes overlaid (red dotted lines) [5]. The generic signal shapes are scaled to 5 times the value of the corresponding expected upper limit at 95% CL on the fiducial cross section times branching ratio, with pole masses of 0.4, 1 and 2 TeV. The lower panel shows the normalized residuals between the data and the fit with σ denoting only the statistical error of the data. There is no data event with $m_{\gamma\gamma} > 2.36$ TeV.

Figure 9. The local significance in standard deviations σ with the background-only hypothesis as a function of the assumed signal mass and relative width for the spin-0 benchmark search [5].

Figure 10. The observed upper limit on the fiducial cross section times BR as a function of signal mass for narrow width assumption spin-0 benchmark [5].

5. Conclusion

Results of searches for rare decays of the observed Higgs boson and additional Higgs bosons are searched for with full Run-2 dataset. From the $H \rightarrow \mu\mu$ search, the signal strength is found to be 1.2 ± 0.6 and the observed significance is 2.0σ . From the $H \rightarrow Z\gamma$ search, the signal strength is $2.0^{+1.0}_{-0.9}$ and the observed significance is 2.2σ . In the heavy $\gamma\gamma$ resonance search, the mass range of the search has reached 3 TeV, and no significant deviation from the SM is observed. From these searches, we gained a deeper understanding of the Higgs sector. Especially, the uncertainty on the coupling strength of the muon became approximately 26% thanks to the $H \rightarrow \mu\mu$ search as shown in Figure 11, which shows the measured coupling strength as a function of the particle mass [6]. We expect higher sensitivities with Run-3 dataset and beyond.

Figure 11. Reduced coupling-strength modifiers $\kappa_F \frac{m_F}{v}$ for fermions ($F = t, b, \tau, \mu$) and $\kappa_V F \frac{m_V}{v}$ for weak gauge bosons ($V = W, Z$) as a function of their masses m_F and m_V , respectively [6]. The vacuum expectation value of the Higgs field $v = 246 \text{ GeV}$.

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