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

Y Kano, on behalf of the ATLAS Collaboration

Nagoya University, Japan

E-mail: yuya.kano@cern.ch

Abstract. Searches for rare decays of the Standard Model Higgs boson and additional Higgs bosons are performed by the ATLAS experiment at the LHC. They use the unprecedented amount of collision data collected during the LHC pp collision run at $\sqrt{s} = 13$ TeV in 2015–2018, corresponding to an integrated luminosity of 139 fb^{-1} after the data quality requirements. For the search for the dimuon decay of the Standard Model Higgs boson, the observed (expected) significance is 2.0σ (1.7σ), and the best-fit value of the signal strength parameter is $\mu = 1.2 \pm 0.6$. For the search for the $Z\gamma$ decay of the Standard Model Higgs boson, the observed (expected) significance is 2.2σ (1.2σ), and the best-fit value of the signal strength parameter is $\mu = 2.0^{+1.0}_{-0.9}$. For the search for new resonances decaying into photon pairs, no significant excess is observed. The experimental sensitivity of these analyses to the signal processes is increased, due not only to the increase in the dataset but also to the improvement in the analysis techniques.

1. Introduction

The Standard Model (SM) of elementary particle physics is established with the discovery of the Higgs boson in 2012 by the ATLAS and CMS experiments [1, 2] at the LHC. However, there are reasons to believe in the existence of new physics beyond the Standard Model (BSM), for instance the hierarchy problem.

Searches for unobserved processes in the Higgs sector provide important probes for new physics phenomena. In this paper, results for the search of rare decays of the SM Higgs boson ($H \rightarrow \mu\mu$, $H \rightarrow Z\gamma$) and of additional resonances decaying into photon pairs are presented. These results are based on the entire Run 2 dataset of the ATLAS experiment [3] collected in the years 2015–2018, that correspond to the integrated luminosity of 139 fb^{-1} after the data quality requirements.

2. Search for the dimuon decay of the Standard Model Higgs boson

The Yukawa coupling of the Higgs boson to the third-generation charged fermions (t, b, τ) and weak bosons (W, Z) are already measured, but the decays into the second-generation charged fermions are unobserved. The search for the $H \rightarrow \mu\mu$ process provides a unique opportunity to observe the coupling to a second-generation charged fermion at the LHC. Additionally, measuring

the branching ratio $B(H \rightarrow \mu\mu)$ serves as a probe to new physics, because the existence of new physics may alter the branching ratio [4, 5]. The decay $H \rightarrow \mu\mu$ is a rare process with a SM prediction for the branching ratio of $B(H \rightarrow \mu\mu) = (2.17 \pm 0.04) \times 10^{-4}$.

The signal-to-background ratio is as low as $S/B \sim 0.2\%$ in the analysis signal region near the dimuon mass peak $120 \text{ GeV} < m_{\mu\mu} < 130 \text{ GeV}$, with the Drell-Yan process being the dominant background component. This makes the observation of such process challenging.

The analysis [6] first selects events with two high-energetic reconstructed muons that are isolated and have opposite electrical charge. Adding up to one final-state-radiation photon to the calculation of $m_{\mu\mu}$ improves the mass resolution by 3%. The events in the analysis signal region are categorized into 20 mutually exclusive categories. They are defined to target different production modes of the Higgs boson, namely the top-quark-pair associated production ($t\bar{t}H$), vector-boson associated production (VH), the vector-boson fusion (VBF), and the gluon-gluon fusion (ggF) processes. They are based on the number of reconstructed high-energetic jets, the number of reconstructed high-energetic leptons (e or μ), and discriminants of boosted decision trees (BDTs). The BDTs target the kinematic differences between the background processes and the different Higgs boson production modes.

The signal extraction is performed by simultaneous fit to the $m_{\mu\mu}$ distributions of all event categories. The signal component is modelled by a double-sided Crystal Ball function, which has a Gaussian central part and power-law tails. The background component is modelled by a product of the *core* function and the *empirical* function. The *core* function is a leading-order (LO) Drell-Yan line-shape that is convolved with detector effects (assuming a Gaussian function). The *empirical* function is an analytic function with free parameters, that is used to describe the distortions in the shape of the $m_{\mu\mu}$ spectrum due to e.g. the kinematic selections, event categorizations, and contributions from minor background components. The validation of this background-modelling approach is performed using templates of $m_{\mu\mu}$ distribution that are obtained using simulated samples of the Drell-Yan process, produced using the fast-simulation procedure to obtain a high statistical precision. This is illustrated in Figure 1.

The $m_{\mu\mu}$ distribution in the analysis signal region and the fit to the spectrum is illustrated in Figure 2. The observed (expected) significance with respect to a null hypothesis is 2.0σ (1.7σ). The best-fit value of the signal strength parameter μ obtained from the statistical analysis is 1.2 ± 0.6 , where μ is defined as the ratio of the observed signal event yield and the SM expected one. The uncertainty of the signal strength parameter is dominated by the statistical error, which correspond to ± 0.58 . The obtained limit on the signal strength parameter is $\mu < 2.2$ at the 95% confidence level.

Overall, the expected sensitivity improves by a factor 2.5 compared to the previous ATLAS publication using a dataset corresponding to 36 fb^{-1} [7]. Of this improvement, a factor of about two is due to the larger size of the dataset, and a factor of about 25% is due to the improvement in the analysis techniques.

3. Search for the $Z\gamma$ decay of the Standard Model Higgs boson

The decay $H \rightarrow Z\gamma$ is a rare process with a predicted SM branching ratio of $B(H \rightarrow Z\gamma) = (1.54 \pm 0.09) \times 10^{-3}$. It proceeds through loop diagrams. The measurement of the branching ratio is sensitive to new physics, for instance the contribution of new charged particles to the loop [8, 9, 10].

The search [11] is performed in the $ee\gamma$ and $\mu\mu\gamma$ final states. This targets the decay of the Z boson to electrons to muons, corresponding to approximately 7% of its branching ratio. These final states provide good mass resolution and a better signal purity than other decays of the Z boson.

The analysis selects pairs of opposite-sign isolated electrons or muons produced in association with an isolated photon. The events are categorized into six mutually exclusive event categories.

Figure 1: An illustration of the background-modelling procedure in one of the event categories targeting the ggF production of the Higgs boson. The markers in the top panel represents the template of the $m_{\mu\mu}$ distribution that are obtained using simulated samples of the Drell-Yan process. The middle panel shows the background template divided by the core component of the background pdf, and it is superimposed with the empirical component of the background pdf. The red line represents the signal pdf normalised to the predicted cross-section, and it is divided by the background pdf in the bottom panel. [6]

Figure 2: The reconstructed mass $m_{\mu\mu}$ in the analysis signal region of the collision data, combined for all of the event categories. The result of the fit is superimposed. For (b), the events are weighted by a factor $\ln(1 + S/B)$, where S is the observed signal yields and B is the observed background yields in each of the event categories in the region $120 \text{ GeV} < m_{\mu\mu} < 130 \text{ GeV}$. [6]

Figure 3: The reconstructed mass $m_{Z\gamma}$ in the analysis signal region, combined for all of the event categories. The result of the fit is superimposed. The events are weighted by a factor $\ln(1 + S_{68}/B_{68})$. Here, S_{68} is the observed signal yields and B_{68} is the observed background yields in each of the event categories, calculated in the $m_{Z\gamma}$ window containing 68% of the expected signal events. The blue solid line represents the result of the signal plus background fit to the $m_{Z\gamma}$ spectrum, with the blue dashed line representing the background component. The red solid line represents the result of the background-only fit. [11]

The categories are defined by using a BDT targeting the VBF production mode of the Higgs boson, and also selections on kinematic variables and lepton flavours (ee or $\mu\mu$). The kinematic variables used are the transverse momentum of the Higgs boson candidate, and the ratio of the transverse momentum of the photon p_T^γ and the invariant mass of the reconstructed $Z\gamma$ system $m_{Z\gamma}$.

The signal extraction is performed by simultaneous fit to the $m_{Z\gamma}$ distributions of all event categories. The signal component is modelled by a double-sided Crystal Ball function. The background component is modelled by analytic functions with free parameters. The validation of this background-modelling approach is performed using templates of $m_{Z\gamma}$ distribution. The template for the $Z\gamma$ background component is obtained from the simulated samples of the process. The template for the Z +jets component is derived from a control sample, obtained by inverting the photon identification criteria with respect to the signal region.

The $m_{Z\gamma}$ distribution in the analysis signal region and the fit to the spectrum is shown in Figure 3. The observed (expected) significance with respect to a null hypothesis is 2.2σ (1.2σ). The best-fit value of the signal strength parameter $\mu_{Z\gamma}$ obtained from the statistical analysis is $2.0^{+1.0}_{-0.9}$. The uncertainty of $\mu_{Z\gamma}$ is dominated by the statistical error, which correspond to ± 0.9 . The obtained limit is $\mu_{Z\gamma} < 3.6$ at the 95% confidence level.

Overall, the expected sensitivity improves by a factor 2.4 compared to the previous ATLAS publication using a dataset corresponding to 36 fb^{-1} [12]. Of this improvement, a factor of about two is due to the larger size of the dataset, and a factor of about 20% is due to the improvement in the analysis techniques.

Figure 4: The reconstructed mass $m_{\gamma\gamma}$ in the analysis signal region. The result of the background-only fit is superimposed. The lower panel shows the normalized residuals between the event yield and the fit, with σ denoting only the statistical error. [18]

4. Search for resonances decaying into photon pairs

This analysis [18] searches for new resonances decaying into two photons in the diphoton mass region $m_{\gamma\gamma} > 160$ GeV. It assumes two benchmark BSM scenarios: a spin-0 resonant state, that arises from e.g. extensions to the Higgs sector [13, 14], and a spin-2 graviton, that arises from e.g. Kaluza-Klein [15] excitations in Randall-Sundrum models [16, 17]. For the spin-0 scenario, a ratio of the width of the resonance Γ_X to its mass m_X up to $\Gamma_X/m_X = 10\%$ is assumed. The upper limits are evaluated for the fiducial cross sections, as a model-independent approach.

The analysis first selects events with at least two isolated photons. The signal extraction is performed by a fit to the $m_{\gamma\gamma}$ distribution in the analysis signal region. The signal component is modelled by a double-sided Crystal Ball function for the spin-0 state, and it is convolved with a relativistic Breit-Wigner form for signal scenarios with large width. The background component is modelled by an analytic function with free parameters. The validation of this background-modelling approach is performed using templates of the $m_{\gamma\gamma}$ distribution. The template for the $\gamma\gamma$ background component is obtained from the simulated samples of the process. To suppress the impact of the statistical fluctuations of the simulated samples on the validation procedure, a smoothing is applied to the template using the functional decomposition method. The template for the $\gamma + \text{jets}$ component is derived from the control sample of the collision data, obtained in a region with the inverted photon identification criteria with respect to the analysis signal region.

The fitted $m_{\gamma\gamma}$ distribution in the signal region is shown in Figure 4. No significant excess is observed. The most significant excess corresponds to a local significance of 3.29σ , for a resonance with a mass of 684 GeV and a narrow width ($\Gamma_X/m_X \sim 0$ for the spin-0 scenario and the graviton coupling $k/\bar{M}_{\text{Pl}} = 0.01$ for the spin-2 scenario). This corresponds to a global significance of 1.30σ and 1.36σ for the two scenarios, respectively. The upper limits on the signal cross sections times branching ratios are shown in Figure 5.

5. Summary

Searches for unobserved processes in the Higgs sector provide probes for physics beyond the Standard Model. The results are presented for the searches for rare decays of the SM Higgs boson, and the search for a new diphoton resonance, performed by the ATLAS experiment at the LHC.

The $H \rightarrow \mu\mu$ and $H \rightarrow Z\gamma$ processes are rare decays of the SM Higgs boson with branching

Figure 5: (a) Upper limits on the fiducial cross section times branching ratio of the spin-0 scenario at the 95% confidence level. A narrow width is assumed for the spin-0 resonance, and here it is taken to be 4 MeV that is smaller than the detector resolution. (b) Upper limits on the production cross section times branching ratio of the spin-2 scenario at the 95% confidence level. The lightest Kaluza-Klein graviton with $k/\bar{M}_{\text{Pl}} = 0.1$ is assumed. [18]

ratios of $O(10^{-4})$. The searches for these rare processes have resulted in the observed significance at the level of 2σ . For the search for a new diphoton resonance, no significant excess is observed. The upper limits on the fiducial cross sections are evaluated as low as 0.03 fb for a resonance mass of 3 TeV. These results gain from improvements in the analysis sensitivity due to the increase in the size of the data set, and advancements in the analysis techniques.

References

- [1] ATLAS Collaboration 2012 *Phys. Lett. B* **716** 1 *Preprint* hep-ex/1207.7214
- [2] CMS Collaboration 2012 *Phys. Lett. B* **716** 30 *Preprint* hep-ex/1207.7235
- [3] ATLAS Collaboration 2008 *JINST* **3** S08003
- [4] Vignaroli N 2009 *Phys. Rev. D* **80** 095023
- [5] Dery A, Efrati A, Hochberg Y, et al. 2019 *JHEP* **05** 039
- [6] ATLAS Collaboration 2020 *Preprint* hep-ex/2007.07830
- [7] ATLAS Collaboration 2017 *Phys. Rev. Lett.* **119** no.5 051802
- [8] Carena M, Low I and Wagner C E M 2012 *JHEP* **08** 060
- [9] Chiang C W and Yagyu K 2012 *Phys. Rev. D* **87** no.3 033003
- [10] Chen C S, Geng C Q, Huang D, et al. 2013 *Phys. Rev. D* **87** 075019
- [11] ATLAS Collaboration 2020 *Phys. Lett. B* **809** 135754 (*Preprint* hep-ex/2005.05382)
- [12] ATLAS Collaboration 2017 *JHEP* **10** 112
- [13] Schabinger RM and Wells JD 2005 *Phys. Rev. D* **72** 093007
- [14] Pruna G M and Robens T 2013 *Phys. Rev. D* **88** no.11 115012
- [15] Appelquist T, Chodos A and Freund P G O 1987 *Modern Kaluza-Klein theories* (Reading: Addison-Wesley)
- [16] Randall L and Sundrum R 1999 *Phys. Rev. Lett.* **83** 3370-3373
- [17] Randall L and Sundrum R 1999 *Phys. Rev. Lett.* **83** 4690-4693
- [18] ATLAS Collaboration 2020 *ATLAS-CONF-2020-037* <http://cdsweb.cern.ch/record/2727744>