

July 15, 2023

Search for rare decays and lepton-flavor-violating decays of the Higgs boson at the ATLAS experiment

PAWEŁ BRUCKMAN DE RENSTROM
ON BEHALF OF THE ATLAS COLLABORATION

Institute of Nuclear Physics PAN, Cracow, Poland

The Standard Model predicts several rare Higgs boson decay channels, among which are the decays to a Z boson and a photon, to a low-mass lepton pair and a photon, and to a meson and a photon. The observation of some of these decays could open the possibility of studying the CP and coupling properties of the Higgs boson in a complementary way to other analyses. In addition, lepton-flavor-violating decays of the observed Higgs boson are searched for, where an observation would be a clear sign of physics effects beyond the Standard Model. These proceedings present selected recent results for such decays based on proton–proton collision data at 13 TeV collected by the ATLAS experiment in Run 2 of the LHC.

PRESENTED AT

DIS2023: XXX International Workshop on Deep-Inelastic
Scattering and Related Subjects,
Michigan State University, USA, 27-31 March 2023



Copyright [2023] CERN for the benefit of the ATLAS Collaboration. CC-BY-4.0 license.



1 Introduction

Since the discovery of the Higgs boson by the CMS and ATLAS Collaborations in 2012, its properties have been measured to increasing precision. So far, an excellent agreement with the predictions for a Standard Model (SM) Higgs boson is observed. However, the SM, while highly successful, is not considered to be a complete theory as it is not capable of explaining some of the phenomena seen in nature. Studying Higgs decays which are highly suppressed or forbidden in the SM is particularly attractive to probe for the smoking gun of phenomena from beyond the SM. In the following, three categories of search analyses are reported. The first concerns with Higgs decays occurring via loop diagrams or suppressed by the small Yukawa coupling constant to the first or the second generation fermions. The second one are searches for lepton flavour violating (LFV) decays of the Higgs boson. The third category are Higgs decays to the first or the second generation leptons. The proceedings summarizes selected recent search results, obtained using proton–proton (pp) collision data at 13 TeV collected by the ATLAS experiment [1] in Run 2 of the LHC. All presented results concern rare processes and are statistically limited. Hence, no discussion of systematic uncertainties is included in the following.

2 Search for rare loop-induced or Yukawa-suppressed Higgs decays

Higgs decays to quarkonia or light mesons with an emission of a prompt photon occur via loop diagrams or direct diagrams suppressed by the small Yukawa coupling constant to the first or the second generation fermions. The branching fraction expected in the SM may be additionally suppressed due to strong destructive interference of the loop and the direct decay diagrams. Modifications to either Yukawa couplings or additional contributions to the loop diagrams could substantially enhance the branching.

$H \rightarrow Z\gamma$ with leptonic Z decays

The SM Higgs boson can decay into $Z\gamma$ through loop diagrams and the branching ratio is predicted to be $B(H \rightarrow Z\gamma) = (1.54 \pm 0.09) \times 10^{-3}$ at $m_H = 125.09$ GeV [2]. It can differ from the SM value for several scenarios beyond the SM, for example, if the Higgs boson was a neutral scalar of different origin, or a composite state. Different branching ratios are also expected for models with additional colourless charged scalars, leptons or vector bosons that couple to the Higgs boson, due to their contributions via loop corrections. A search for $Z\gamma$ decays of the SM Higgs boson in 139 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV is performed in the leptonic Z decay channel, where lepton accounts for either an electron or a muon [3]. The invariant mass $m_{Z\gamma}$ is reconstructed using kinematical fit with the Z mass constraint on the emerging lepton

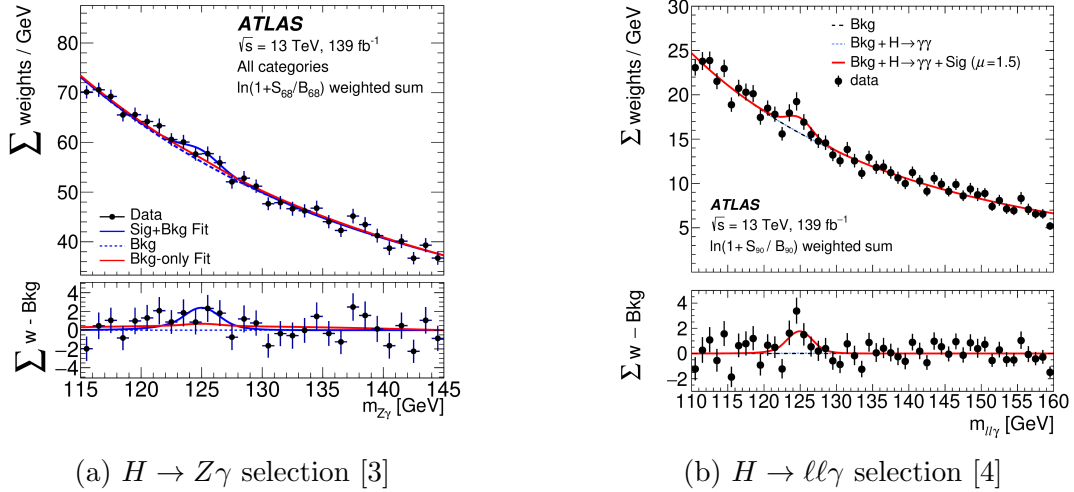


Figure 1: Invariant mass distribution of events satisfying signal selection criteria in data and fit results while fitting all signal categories simultaneously. Bottom panels show the residuals of the data with respect to the non-resonant background component of the signal plus background fit.

pair. The resulting mass spectrum is simultaneously fitted in six mutually exclusive signal regions. The weighted sum of all the region together with the fit results is shown in Fig. 1a. The observed data are consistent with the expected background with the p -value of 1.3%, while the expected p -value in the presence of the SM Higgs boson is 12.3%, corresponding to significances of 2.2 and 1.2 σ , respectively. The observed 95% confidence level (CL) upper limit on the $\sigma(pp \rightarrow H) \times B(H \rightarrow Z\gamma)$ is 3.6 times the SM prediction for the Higgs boson mass of 125.09 GeV. The expected limit on $\sigma(pp \rightarrow H) \times B(H \rightarrow Z\gamma)$ assuming either no Higgs boson decay into $Z\gamma$ or the presence of the SM Higgs boson decay is 1.7 and 2.6 times the SM prediction, respectively. The best-fit value for the signal yield normalised to the SM prediction is $2.0_{-0.9}^{+1.0}$ where the statistical component of the uncertainty is dominant.

$H \rightarrow \gamma^* \gamma$ with γ^* decaying into a low mass lepton pair

The analysis targets quasi the same final state as the one discussed above, but the requirement of low invariant mass of the lepton pair ($m_{\ell\ell} < 30$ GeV) makes this signal region completely dominated by the decay through a γ^* [4]. With the requirement of low $\ell\ell$ mass and high p_T electron clusters can overlap, hence the analysis introduces an additional signal category of merged electrons. Consequently, a dedicated reconstruction of merged electron pairs, based on machine learning methods is put in place. The weighted sum of the resulting 9 mutually exclusive signal regions together with the fit result is shown in Fig. 1b. For a Higgs boson with a mass of 125.09 GeV and $m_{\ell\ell} < 30$ GeV, evidence for the $H \rightarrow \ell\ell\gamma$ process is found with the significance of 3.2σ

over the background-only hypothesis, compared to an expected significance of 2.1σ . The best-fit value of the signal-strength parameter, defined as the ratio of the observed signal yield to the signal yield expected in the SM, is $\mu = 1.5 \pm 0.5$. The Higgs boson production cross-section times the $H \rightarrow \ell\ell\gamma$ branching ratio for $m_{\ell\ell} < 30$ GeV is determined to be $8.7^{+2.8}_{-2.7}$ fb. This result constitutes the first evidence for the decay of the Higgs boson into a pair of leptons and a photon, an important step towards probing Higgs boson couplings in this rare decay channel.

Higgs decays to exclusively reconstructed vector quarkonia or light mesons and a photon

Due to highly destructive interference between the indirect and direct Feynman diagrams, Higgs boson decays in the charmonium sector, $H \rightarrow J/\psi\gamma$ and $H \rightarrow \psi(2S)\gamma$, offer an opportunity to access both the magnitude and the sign of the charm-quark Yukawa coupling; the corresponding decays in the bottomonium sector, $H \rightarrow \Upsilon(1S, 2S, 3S)\gamma$, can provide information about the real and imaginary parts of the bottom-quark coupling to the Higgs boson. Exclusive decays to $\omega\gamma$ and $K^*\gamma$ can probe the flavour-conserving coupling of the Higgs boson to up and down quarks, and the flavour-violating coupling of the Higgs boson to down and strange quarks, respectively. The theoretical predictions for the corresponding branching fractions are tiny and range from $\mathcal{O}(10^{-6})$ for $J/\psi\gamma$ and $\omega\gamma$ final states through $\mathcal{O}(10^{-9} - 10^{-8})$ for $\Upsilon\gamma$ and a rough estimate of $\ll 10^{-11}$ for $K^*\gamma$. Searches for the above decays are performed using $\mu^+\mu^-$ decays of the vector quarkonia [5], while the decay $\omega \rightarrow \pi^+\pi^-\pi^0$ is used to reconstruct the ω meson, and the decay $K^* \rightarrow K^+\pi^-$ is used to reconstruct the K^* meson [6]. The non-trivial background shape is estimated using the correlated sampling method [7] and normalised from the fit to data, as can be seen in Fig. 2 for $J/\psi\gamma$ (a) and $\omega\gamma$ (b). The observed data are compatible with the expected backgrounds. The 95% CLs upper limits on the branching fractions of the Higgs boson decays into $J/\psi\gamma$, $\psi(2S)\gamma$, and $\Upsilon(1S, 2S, 3S)\gamma$ are found to be 2.1×10^{-4} , 10.9×10^{-4} , and $(2.6, 4.4, 3.5) \times 10^{-4}$, respectively, assuming SM production of the Higgs boson. The 95% CL upper limits on the branching fractions to light mesons and a photon are $\mathcal{B}(H \rightarrow \omega\gamma) < 1.5 \times 10^{-4}$ and $\mathcal{B}(H \rightarrow K^*\gamma) < 8.9 \times 10^{-5}$. An earlier analysis based on partial Run 2 ATLAS data extracted limits for the Higgs boson decays into $\rho\gamma$ and $\phi\gamma$ exclusive decays [8].

3 Searches for lepton flavour violation in the Higgs sector

Neutrino oscillations prove that lepton flavour is not an exact symmetry of nature. Higgs sector may be responsible. LFV naturally occurs in more than one Higgs doublet models, composite Higgs or Randall-Sundrum warped extra dimensions. The searches

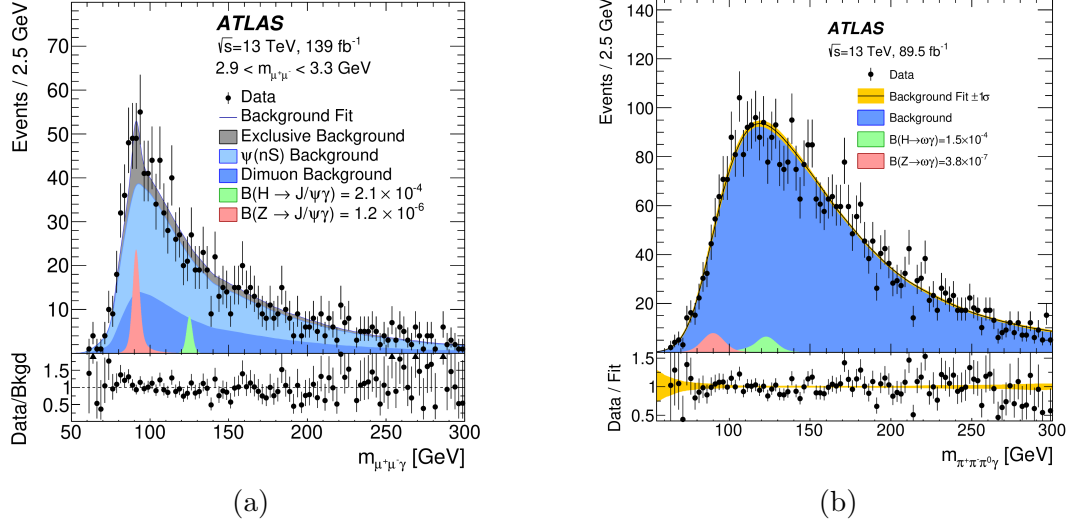


Figure 2: (a) Reconstructed invariant mass $m_{\mu^+\mu^-\gamma}$ for the $J\psi\gamma$ [5] and (b) reconstructed invariant mass $m_{\pi^+\pi^-\pi^0\gamma}$ for the $\omega\gamma$ search [6]. The branching fraction of each of the signals is set to the observed 95% CL upper limit.

reported below allow to put direct limits on the off-diagonal elements ($Y_{\tau\mu}$, $Y_{\tau e}$, $Y_{e\mu}$) of the Yukawa coupling matrix without making any assumptions about diagonal couplings.

Search for the Higgs boson decay to either a $e\tau$ or a $\mu\tau$ pair

The direct search for lepton flavour violation in Higgs boson decays, $H \rightarrow e\tau$ and $H \rightarrow \mu\tau$ is performed using both the leptonic and hadronic τ decay channels [9]. For leptonic tau decays only combinations with the different flavour lepton are considered. Two background estimation techniques are employed: the MC-template method, based on data-corrected simulation samples, and the Symmetry method, based on exploiting the symmetry between electrons and muons in the SM backgrounds. No significant excess of events is observed and the results are interpreted as upper limits on lepton-flavour-violating branching ratios of the Higgs boson. The observed (expected) upper limits set on the branching ratios at 95% CL, $\mathcal{B}(H \rightarrow e\tau) < 0.20\%$ (0.12%) and $\mathcal{B}(H \rightarrow \mu\tau) < 0.18\%$ (0.09%), are obtained with the MC-template method from a simultaneous measurement of potential $H \rightarrow e\tau$ and $H \rightarrow \mu\tau$ signals. The corresponding likelihood contour is shown in Fig. 3a, displaying a mild 2.1σ tension with the SM expectation. The best-fit branching ratio difference, $\mathcal{B}(H \rightarrow \mu\tau) - \mathcal{B}(H \rightarrow e\tau)$, measured with the Symmetry method in the channel where the τ -lepton decays to leptons, is $(0.25 \pm 0.10)\%$, compatible with a value of zero within 2.5σ .

Search for the Higgs boson decay to a $e\mu$ pair

The measurement relies on simultaneous fit of the narrow resonance on top of the continuum background in the invariant mass distributions reconstructed in multiple

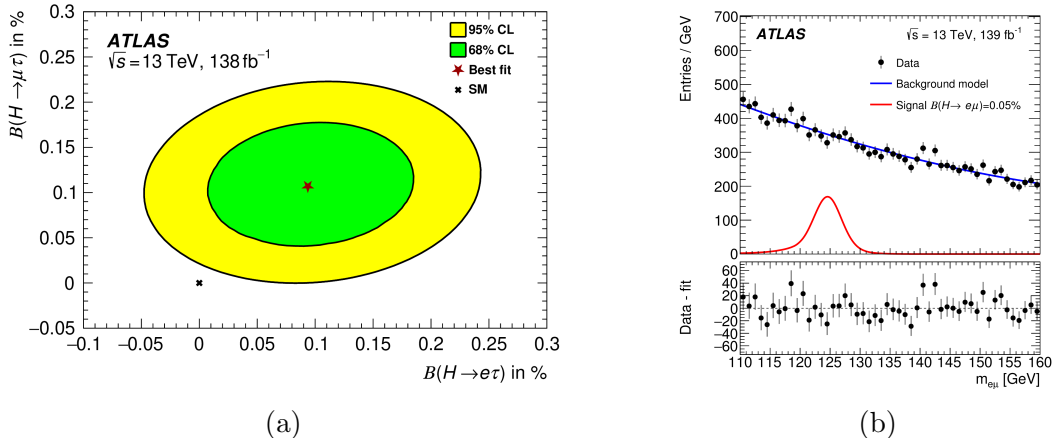


Figure 3: (a) Best-fit value (red star) of the branching ratios $\mathcal{B}(H \rightarrow e\tau)$ and $\mathcal{B}(H \rightarrow \mu\tau)$, given in % , and likelihood contours at 68% and 95% CL obtained from the simultaneous fit of $H \rightarrow e\tau$ and $H \rightarrow \mu\tau$ signals based on the MC-template method, compared with the SM expectation (black cross) [9]. (b) Simultaneous background-only fit to $e\mu$ data in all signal region categories. The signal parameterisation with branching fraction set to $\mathcal{B}(H \rightarrow e\mu) = 0.05\%$ is also shown (red line) [10].

categories of signal regions [10]. The categorisation is based on production mechanism, centrality and the transverse momentum of the lepton pair. Main backgrounds include Drell-Yan $\tau\tau$ pair production, $t\bar{t}$, di-boson and misidentified lepton events. The combined result of the background-only fit to all signal categories is shown in Fig. 3b. No evidence of the decay $H \rightarrow e\mu$ is observed, with the best-fit value of the branching fraction of $(0.4 \pm 2.9(\text{stat.}) \pm 0.3(\text{syst.})) \times 10^{-5}$. The observed (expected) upper limit at the 95% CL is found to be 6.2×10^{-5} (5.9×10^{-5}).

4 Higgs boson decays to 1st and 2nd generation leptons

SM predicts $\mathcal{B}(H \rightarrow ee)_{\text{SM}} \sim 5 \times 10^{-9}$ and $\mathcal{B}(H \rightarrow \mu\mu)_{\text{SM}} \sim 2 \times 10^{-4}$. Experimental verification of these predictions is important but challenging. At the same time, any significant enhancement of the branching fraction would point to phenomena from beyond the SM.

Search for the Higgs boson decay to a ee pair

The same analysis [10] described above is also utilised to look for Higgs decays to oppositely signed electron pairs. Here, background is substantially larger and dominated by the Drell-Yan ee production. No evidence of the decay $H \rightarrow ee$ is observed. The best-fit value of the branching fraction is $(0.0 \pm 1.7(\text{stat.}) \pm 0.6(\text{syst.})) \times 10^{-4}$.

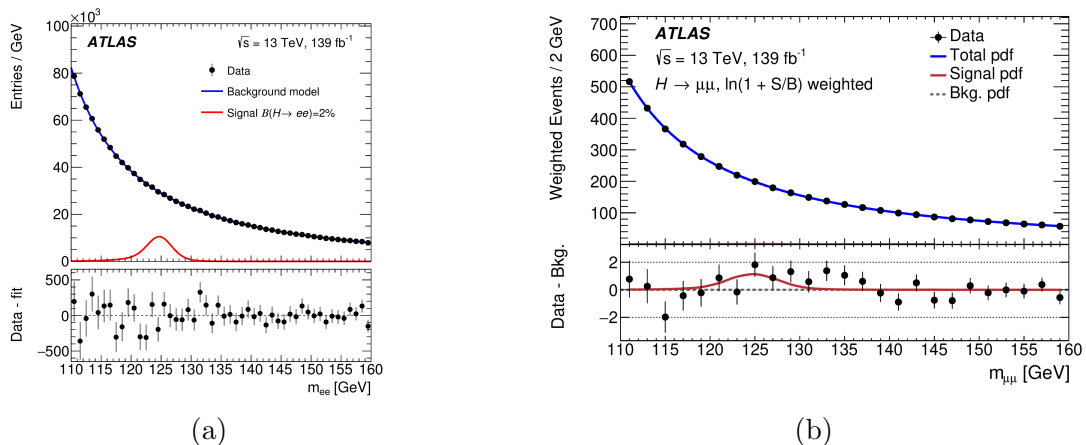


Figure 4: (a) Simultaneous background-only fit to ee data in all signal region categories. The signal parameterisation with branching fraction set to $\mathcal{B}(H \rightarrow ee) = 2\%$ is also shown (red line) [10]. (b) Simultaneous background-only fit to $\mu\mu$ data in all signal region categories weighted by $\ln(1 + S/B)$. 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 [11].

The observed (expected) upper limit on the branching fraction at the 95% CL, is found to be 3.6×10^{-4} (3.5×10^{-4}).

Search for the Higgs boson decay to a $\mu\mu$ pair

A similar analysis is performed in search for muonic Higgs decays [11]. It defines 20 mutually exclusive signal regions based on the production mechanism and S/B ratio. The classification is done by boosted decision tree classifiers constructed for each of the four production mechanisms (ggF, VBF, VH and ttH). A fit to the reconstructed invariant mass of the muon pair is performed in all signal categories simultaneously. The invariant mass distribution weighted sum in all signal regions together with the fitted signal is shown on Fig. 4b. The observed (expected) significance over the background-only hypothesis for a Higgs boson with a mass of 125.09 GeV is 2.0σ (1.7σ). The observed upper limit on the cross section times branching ratio for $pp \rightarrow H \rightarrow \mu\mu$ is 2.2 times the SM prediction at 95% CL, while the expected limit on the $H \rightarrow \mu\mu$ signal assuming the absence (presence) of a SM signal is 1.1 (2.0). The best-fit value of the signal strength parameter, defined as the ratio of the observed signal yield to the one expected in the SM, is $\mu = 1.2 \pm 0.6$.

5 Concluding remarks

Searches for strongly suppressed or forbidden decays of the Higgs boson offer an attractive probe of phenomena from beyond the SM. A wide range of such searches have been performed by the ATLAS Collaboration. The full review is beyond the scope of this contribution. Instead, the reader is encouraged to consult the ATLAS public results webpage [12]. So far, no significant deviation from the SM predictions have been observed. The sensitivity of the Higgs decay to a pair of muons is currently at the verge of an evidence. Observation of the muonic Higgs decays as well as confirmation or disproving of the currently seen departures from SM expectations (e.g. the LFV Higgs decay in the $\ell\tau$ channel) will require considerably more data to come with the ongoing LHC Run 3 and subsequently with the high luminosity phase of the LHC.

Acknowledgements This work is supported in part by the Polish Ministry of Education and Science project no. 2022/WK/08.

References

- [1] ATLAS Collaboration, JINST 3 (2008) S08003.
- [2] D. de Florian et al., arXiv:1610.07922 [hep-ph].
- [3] ATLAS Collaboration, Phys. Lett. B 809 (2020) 135754.
- [4] ATLAS Collaboration, Phys. Lett. B 819 (2021) 136412.
- [5] ATLAS Collaboration, arXiv:2208.03122 [hep-ex], submitted to EPJC.
- [6] ATLAS Collaboration, arXiv:2301.09938 [hep-ex], submitted to Phys. Lett. B.
- [7] A. Chisholm, T. Neep, K. Nikolopoulos, R. Owen, E. Reynolds and J. Silva, arXiv:2112.00650 [hep-ex].
- [8] ATLAS Collaboration, J. High Energ. Phys. 07 (2018) 127.
- [9] ATLAS Collaboration, arXiv:2302.05225 [hep-ex], submitted to JHEP.
- [10] ATLAS Collaboration, Phys. Lett. B 801 (2020) 135148.
- [11] ATLAS Collaboration, Phys. Lett. B 812 (2021) 135980.
- [12] <https://twiki.cern.ch/twiki/bin/view/AtlasPublic>