PROCEEDINGS OF SCIENCE

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

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The Standard Model predicts several rare Higgs boson processes, such as decays into a pair of muons or into a Z boson and a photon. Observing these rare decays would offer new and complementary insights into the Higgs boson's coupling structure beyond the more commonly studied channels. In addition, searches for lepton-flavor-violating decays of the Higgs boson are performed, where any observation would provide unambiguous evidence of physics beyond the Standard Model. Several recent results are presented from the ATLAS experiment based on proton-proton collision data collected in Run 2 at $\sqrt{s}$ = 13 TeV, with the inclusion of available Run 3 results at $\sqrt{s}$ = 13.6 TeV where relevant.

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1. Introduction

The discovery of the Higgs boson in 2012 by the ATLAS [1] and CMS [2] collaborations at the Large Hadron Collider (LHC) marked the beginning of a new era for testing the Standard Model (SM) and exploring its possible extensions. Precision studies of rare decay modes, such as $H \to \mu^+\mu^-$ and $H \to Z\gamma$, provide sensitive probes of the Higgs boson couplings and potential contributions from physics beyond the SM. In parallel, searches for lepton-flavor-violating (LFV) Higgs decays, which are forbidden in the SM, offer a direct way to test non-diagonal Yukawa interactions and possible new sources of flavor violation at the electroweak scale. The following sections present recent results on the above-mentioned Higgs boson decays, based on the full Run 2 and, where available, partial Run 3 datasets collected in pp collisions by the ATLAS detector at the LHC [3].

2. Search for $H \to \mu^+\mu^-$

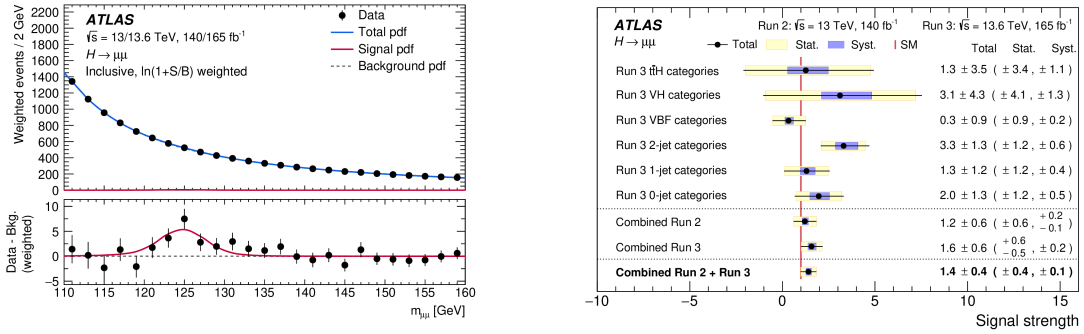
A direct probe of the Higgs coupling to second-generation fermions is provided by the rare decay $H \to \mu^+\mu^-$, with a Standard Model (SM) branching ratio of $\mathrm{BR}(H \to \mu^+\mu^-) \approx 2.18 \times 10^{-4}$. Among second-generation fermions, the muon channel offers the cleanest experimental signature, as the corresponding quark decays, such as $H \to c\bar{c}$ and $H \to s\bar{s}$, are difficult to isolate due to large QCD backgrounds and limited mass resolution in hadronic final states. This makes the muonic decay the most experimentally accessible probe of second-generation Yukawa couplings at the LHC.

The analysis faces the experimental challenge of a very small signal-to-background ratio of about 0.2% in the inclusive selection within the mass range $120 < m_{\mu\mu} < 130$ GeV, dominated by the Drell–Yan continuum production of dimuon pairs. Earlier analyses based on the Run 2 dataset have already provided initial evidence of the $H \to \mu^+\mu^-$ process, with the ATLAS Collaboration reporting an observed (expected) significance of 2.0σ (1.7σ) [4] and the CMS Collaboration achieving 3.0σ (2.5σ) [5].

The most recent ATLAS analysis [6] combines the full Run 2 and partial Run 3 datasets, corresponding to an integrated luminosity of 165 fb^{-1}, and implements several improvements in both event reconstruction and statistical modelling. The muon momentum resolution is refined through an improved reconstruction of the dimuon primary vertex, leading to a 1.8% enhancement in the invariant-mass resolution. The accessible phase space is expanded by introducing additional categories targeting $VH(2\ell)$ and fully hadronic $t\bar{t}H$ production modes, thereby increasing the overall signal acceptance. A more accurate background description is achieved through high-statistics next-to-leading-order (NLO) Drell–Yan simulations, while the inclusion of final-state radiation from muons provides a more precise modelling of the mass shape. Together, these developments enhance the sensitivity of the search to the $H \to \mu^+\mu^-$ signal.

Events are split into 23 exclusive categories optimised for different Higgs boson production modes (ggF, VBF, VH, and $t\bar{t}H$). Machine-learning classifiers, such as gradient-boosted decision trees (XGBoost) and neural networks (Keras/TensorFlow), are used to exploit final-state kinematics and event topology. The boundaries of these categories are optimised to maximise the expected signal sensitivity.

The signal extraction is performed via a simultaneous fit to the dimuon invariant-mass spectrum across all categories. The signal is modelled with a double-sided Crystal Ball function, while the background is described by an analytic function combining a core term and an empirical component smeared with the detector resolution. The signal extraction is performed through a profile likelihood fit, where the signal strength parameter μ quantifies the ratio of the observed Higgs boson production rate times branching ratio to the corresponding Standard Model expectation, see Figure 1.



(a) (b)

Figure 1: (a) Dimuon invariant mass spectrum observed in data in the Run 2 and Run 3 datasets combined. (b) Observed best-fit values of the signal-strengths for the analysis of the Run 3 data and the full Run 2 dataset [6].

The combined Run 2+Run 3 analysis yields an observed (expected) significance of 3.4σ (2.5σ), corresponding to a signal strength of

$$\mu = 1.4 \pm 0.4\,(\text{stat}) \pm 0.1\,(\text{syst}).$$

This result constitutes the first evidence of the $H \to \mu^+\mu^-$ decay by ATLAS, confirming the Higgs boson coupling to second-generation fermions in agreement with the Standard Model prediction. The corresponding Run 3–only dataset yields an observed (expected) significance of 2.8σ (1.8σ), demonstrating good compatibility (68%) between the Run 2 and Run 3 measurements. The sensitivity improvement of about 50% with respect to the previous Run 2 analysis is mainly driven by the increased statistics.

3. Search for $H \to Z\gamma$

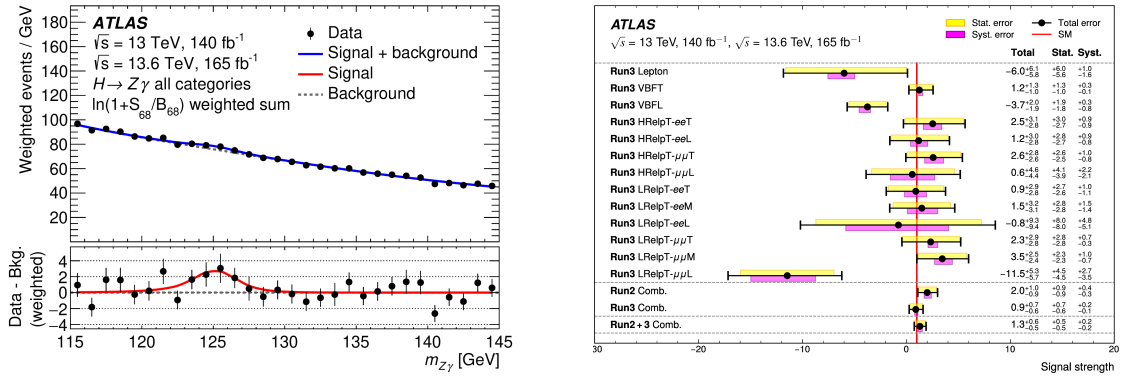
The $H \to Z\gamma$ decay proceeds via loop diagrams involving heavy charged particles and provides a complementary test of the Higgs boson's couplings to electroweak gauge bosons. In the Standard Model (SM), its branching ratio is predicted to be $\text{BR}(H \to Z\gamma) = (1.54 \pm 0.09) \times 10^{-3}$, which is comparable in size to $\text{BR}(H \to \gamma\gamma) = (2.27 \pm 0.07) \times 10^{-3}$. Precise measurements of this rare loop-induced process probe the structure of the Higgs–vector–boson coupling and possible contributions from new heavy particles running in the loop. Beyond the SM, deviations in either the absolute branching ratio or in the ratio $\text{BR}(H \to Z\gamma)/\text{BR}(H \to \gamma\gamma)$ could indicate non-standard Higgs dynamics such as composite Higgs scenarios or extended electroweak sectors.

The most sensitive experimental signature corresponds to leptonic Z-boson decays, $Z \to \ell^+\ell^-$ ($\ell = e, \mu$), which offer excellent mass resolution and background rejection, albeit at a small branching fraction of 6.7%. The dominant background arises from continuum $Z + \gamma$ production, with additional contributions from Z+jets events where a jet is misidentified as a photon.

The combination of Run 2 ATLAS and CMS results [7] established the first evidence for this decay, with an observed (expected) significance of 3.4σ (1.6σ) and a combined signal strength of

$$\mu = 2.2 \pm 0.6\ (\text{stat})^{+0.3}_{-0.2}\ (\text{syst}).$$

Individually, the ATLAS and CMS analyses achieved observed (expected) significances of 2.2σ (1.2σ) and 2.6σ (1.1σ), respectively [8, 9].



(a) (b)

Figure 2: (a) Observed invariant mass distribution of the $\ell^+\ell^-\gamma$ system across all categories for combined Run 2 and Run 3 dataset. (b) Observed best-fit signal strengths and corresponding uncertainties in each category of the Run 3 analysis, their combined values, the results of the previous Run 2 analysis, and the overall combination [10].

The latest ATLAS results [10] incorporate the full Run 2 dataset together with partial Run 3 data collected between 2022 and 2024, corresponding to an integrated luminosity of 165 fb^{-1}. Compared to the previous Run 2 search, the analysis introduces several methodological improvements aimed at increasing both the signal efficiency and the robustness of the background modelling. The object selection thresholds are optimized to maximize the signal acceptance, while the event categorization is refined to target all major Higgs boson production modes, including ggF, VBF, VH, and $t\bar{t}H$. A dedicated lepton-based category is introduced, and both the VBF and multivariate (MVA) discriminants are re-optimized to enhance signal–background separation. In addition, the choice of background function and fit range is carefully tuned to minimize potential spurious signal contributions, leading to a more stable and reliable extraction of the signal strength.

The $m_{\ell\ell\gamma}$ spectrum is simultaneously fitted in all categories using a double-sided Crystal Ball function for the signal and an empirical analytic function for the background. The fit is performed via a profile likelihood approach, with the signal strength μ defined as the ratio of the measured to predicted Higgs production rate times branching ratio, see Figure 2.

The Run 2 + Run 3 combination yields an observed (expected) significance of 2.5σ (1.9σ) and a signal strength

$$\mu = 1.3 \pm 0.5\ (\text{stat}) \pm 0.2\ (\text{syst}).$$

The Run 3-only dataset shows an observed (expected) significance of 1.4σ (1.5σ) with $\mu = 0.9^{+0.7}_{-0.6}$. The Run 3 measurements are compatible with Run 2 and Run 3 combined measurements at the 33% level, and the analysis achieves a 60% improvement in sensitivity compared to Run 2, mainly due to refined event selection, optimized categorization, and larger statistics. This represents the most stringent expected sensitivity to date in this decay channel, and all measurements remain consistent with the SM expectation.

4. Search for lepton-flavour-violating Higgs decays

In the Standard Model (SM), the Higgs boson couples to fermions proportionally to their masses, resulting in strictly flavour-diagonal Yukawa interactions. However, the observation of neutrino oscillations demonstrates that lepton flavour is not conserved in nature, motivating searches for Higgs-mediated flavour violation in the charged-lepton sector. Such lepton-flavour-violating (LFV) Higgs decays directly probe off-diagonal Yukawa couplings and are predicted in several SM extensions, including supersymmetric (SUSY) models, two-Higgs-doublet models (2HDM), composite Higgs frameworks, Randall–Sundrum scenarios, etc.

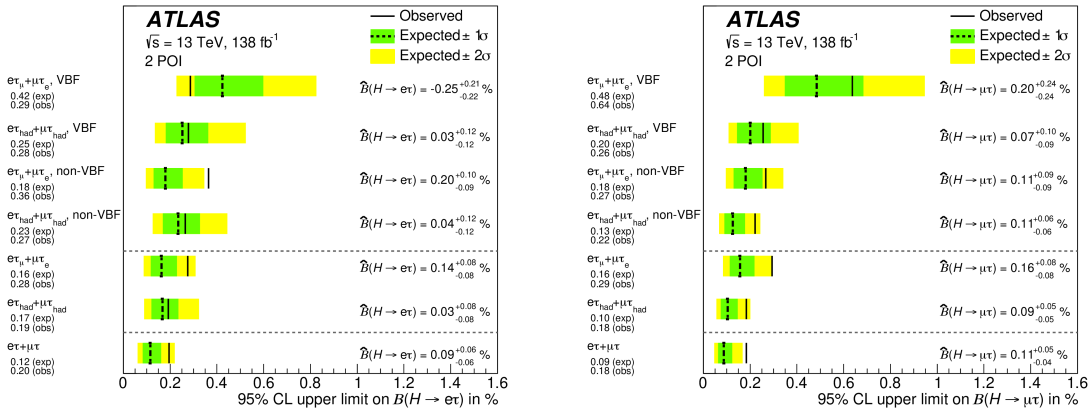
The ATLAS Run 2 analysis [11] investigates the most accessible channels, $H \to \tau\mu$ and $H \to \tau e$, using the full pp collision dataset at $\sqrt{s} = 13$ TeV. Events are categorized according to production topology, targeting both gluon–gluon fusion (ggF) and vector-boson fusion (VBF) processes. The background contributions are estimated using a combination of Monte Carlo simulation and data-driven techniques. Multivariate discriminants are employed to enhance the separation between signal and background, and profile-likelihood fits are performed to extract potential LFV signals.

No significant deviations from the SM are observed, see Figure 3. The measured limits are consistent with background expectations, with small upward fluctuations corresponding to significances of 2.2σ in the $H \to e\tau$ channel and 1.9σ in $H \to \mu\tau$. The corresponding 95% confidence level upper limits are $\mathcal{B}(H \to \mu\tau) < 0.15\%$ and $\mathcal{B}(H \to e\tau) < 0.18\%$. These results are globally compatible with the SM at the 2.1σ level and represent the most stringent constraints on LFV Higgs decays to date.

5. Summary and outlook

Rare and forbidden decays of the Higgs boson provide powerful tests of its coupling structure and sensitivity to physics beyond the Standard Model (SM). Recent ATLAS results, including partial Run 3 data, have significantly advanced the precision of these searches.

The decay $H \to \mu^+\mu^-$ offers a direct measurement of the second-generation Yukawa coupling. The combination of Run 2 and Run 3 datasets yields the first ATLAS evidence for this process, with an observed (expected) significance of 3.4σ (2.5σ) and a signal strength of $\mu = 1.4 \pm 0.4$ (stat) $\pm$ 0.1 (syst) [6], consistent with SM predictions.



(a) (b)

Figure 3: Observed 95% CL upper limits on the branching ratios for (a) $H \to e\tau$ and (b) $H \to \mu\tau$ decays from the ATLAS Run 2 analysis [11].

The loop-induced $H \to Z\gamma$ decay probes the electroweak structure of the Higgs sector. The updated ATLAS analysis, combining Run 2 and Run 3 data, reaches an observed (expected) significance of 2.5σ (1.9σ) and $\mu = 1.3 \pm 0.5$ (stat) ± 0.2 (syst) [10], the most stringent sensitivity achieved so far.

Searches for lepton-flavour-violating decays, $H \to \tau\mu$ and $H \to \tau e$, using the full Run 2 dataset, yield mild upward fluctuations with local significances of 2.2σ and 1.9σ, respectively, and 95% CL upper limits of $\mathcal{B}(H \to \mu\tau) < 0.15\%$ and $\mathcal{B}(H \to e\tau) < 0.18\%$ [11].

With the growing Run 3 dataset and the forthcoming High-Luminosity LHC, further exploration of rare Higgs decays will offer new precision tests of the SM and potential windows into new physics.

References

[1] ATLAS Collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, Phys. Lett. B **716** (2012) 1-29, doi:10.1016/j.physletb.2012.08.020.

[2] CMS Collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, Phys. Lett. B **716** (2012) 30, doi:10.1016/j.physletb.2012.08.021.

[3] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST **3** (2008) S08003, doi:10.1088/1748-0221/3/08/S08003

[4] ATLAS Collaboration, *A search for the dimuon decay of the Standard Model Higgs boson with the ATLAS detector*, Phys. Lett. B **812** (2021) 135980, doi:10.1016/j.physletb.2020.135980

[5] CMS Collaboration, *Evidence for Higgs boson decay to a pair of muons*, JHEP **01** (2021) 148, doi:10.1007/JHEP01(2021)148

[6] ATLAS Collaboration, *Evidence for the dimuon decay of the Higgs boson in pp collisions with the ATLAS detector*, CERN-EP-2025-149, doi:10.48550/arXiv.2507.03595

[7] ATLAS and CMS Collaboration, *Evidence for the Higgs boson decay to a Z boson and a photon at the LHC*, Phys. Rev. Lett. **132** (2024) 021803, doi:10.1103/PhysRevLett.132.021803

[8] ATLAS Collaboration, *A search for the $Z\gamma$ decay mode of the Higgs boson in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, Phys. Lett. B **809** (2020) 135754, doi:10.1016/j.physletb.2020.135754

[9] CMS Collaboration, *Search for Higgs boson decays to a Z boson and a photon in proton-proton collisions at $\sqrt{s}$ = 13 TeV*, JHEP **05** (2023) 233, doi:10.1007/JHEP05(2023)233

[10] ATLAS Collaboration, *Search for the Higgs boson decay to a Z boson and a photon in pp collisions at $\sqrt{s}$ = 13 TeV and* 13.6 *TeV with the ATLAS detector*, CERN-EP-2025-155, doi:10.48550/arXiv.2507.12598

[11] ATLAS Collaboration, *Searches for lepton-flavour-violating decays of the Higgs boson into $e\tau$ and $\mu\tau$ in $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector*, JHEP **07** (2023) 166, doi:10.1007/JHEP07(2023)166