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Search for rare and lepton-flavor violating decays of the Higgs boson with the ATLAS detector

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Abstract. The Standard Model predicts several rare Higgs boson decays, which have not yet been observed, but that could be enhanced in theories beyond the Standard Model. Among these are decays to light leptons, e.g. $H \rightarrow \mu\mu$. In addition, theories beyond the Standard Model may predict lepton-flavor violating decays of the Higgs boson. Results for these searches based on LHC pp collision data recorded at 13 TeV by the ATLAS experiment will be presented.

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1. Introduction

In July 2012, the ATLAS and CMS Collaborations [1, 2], announced the discovery of a new particle with a mass of approximately 125 GeV [3, 4] at the CERN Large Hadron Collider (LHC). Subsequent measurements of its properties have indicated that this particle is consistent with the Standard Model (SM) Higgs boson [5, 6, 7, 8].

This discovery completed the SM of particle physics; however, several experimental observations (such as dark matter), as well as theory arguments (e.g., the hierarchy problem), may imply that the SM represents just the low-energy limit of a more fundamental theory. A potential observation of deviations from the SM predictions might lead to the discovery of new physics.

While the interaction between the Higgs boson and the charged fermions of the third generation has already been observed by the ATLAS and CMS Collaborations, only upper limits exist on the interactions with fermions of the first two generations and lepton-flavor violating (LFV) decays. Therefore, precise measurements of these couplings might show significant deviations from the SM predictions.

In this document, we present recent searches for rare and LFV decays of the Higgs boson using up to 139 fb^{-1} of $\sqrt{s} = 13 \text{ TeV}$ proton–proton (pp) collision data collected by the ATLAS detector during the LHC Run-2.

2. Searches for $H \rightarrow \mu\mu$ decays

The Higgs boson decays into two muons offer the best opportunity to measure the Higgs boson coupling to the second generation fermions. The SM branching ratio (BR) for these decays is 2.7×10^{-4} for $m_H = 125.09 \text{ GeV}$; however, physics beyond the SM could modify this BR.

In this section, we present a search for $H \rightarrow \mu\mu$ decays using the full Run-2 dataset recorded by the ATLAS detector, corresponding to an integrated luminosity of 139 fb^{-1} [9].

Events are selected if they contain two opposite-charge muon candidates, while the leading muon is required to have a transverse momentum $p_T > 27 \text{ GeV}$. The top-quark production is the second largest background and is suppressed by vetoing events with b -tagged jets. This selection provides a total acceptance times efficiency of about 59% for the gluon-gluon fusion (ggF) and vector boson fusion (VBF) signal events. The main event selection criteria are summarized in Table 1, which also defines three ranges of the dimuon invariant mass $m_{\mu\mu}$ considered in the analysis for different purposes.

Selected events are further classified into twelve mutually exclusive categories with different signal to background ratios (S/B). The categorization is based on the number of reconstructed jets§ (0-jet, 1-jet and ≥ 2 -jet) and boosted decision tree (BDT)

§ In the ≥ 2 -jet category, a boosted decision tree (BDT) is trained to disentangle VBF signal events from background events. The remaining events are split by jet multiplicity and considered for further

Selection	
Primary vertex	
Two opposite-charge muons	
Common	Muons: $ \eta < 2.7$, $p_T^{\text{lead}} > 27$ GeV, $p_T^{\text{sublead}} > 15$ GeV
No b -tagged jets	
Z region	$76 < m_{\mu\mu} < 106$ GeV
Sideband region	$110 < m_{\mu\mu} < 120$ GeV or $130 < m_{\mu\mu} < 180$ GeV
Fit region	$110 < m_{\mu\mu} < 160$ GeV
Jets	$p_T > 25$ GeV and $ \eta < 2.5$ or with $p_T > 30$ GeV and $2.5 < \eta < 4.5$

Table 1. Summary of the main event selection criteria common to all events (top) as well as the criteria applied to the selection of hadronic jets (bottom). The middle section defines three ranges in the dimuon invariant mass $m_{\mu\mu}$ used in the analysis [9].

discriminants. These discriminants are defined to exploit the kinematic differences between the ggF and VBF production modes, and the background processes dominated by the Drell-Yan (DY) process $Z/\gamma^* \rightarrow \mu\mu$, which accounts for more than 90% of the total background. Signal events are characterized by a more central dimuon system with harder p_T spectrum, and the jet multiplicity is expected to be higher in ggF and VBF production with respect to the DY background. In addition, the VBF process has a unique signature with two high p_T jets with a large rapidity gap and little hadronic activity between them.

Previous released $H \rightarrow \mu\mu$ search results [10] used 79.8 fb^{-1} of the Run-2 dataset. In the search presented in this section, several improvements with respect to [10] are incorporated: the classification of the events in different jet multiplicities with dedicated multivariate discriminants, a better modeling of the background based on a much larger DY simulation dataset, the use of reconstructed photons to improve the signal mass resolution for events with final state radiation and increased rejection of jets from pile-up in the forward region.

The functional form used for the Higgs boson signal model is a double-sided Crystal Ball $||$. The $m_{\mu\mu}$ background spectrum is parameterized by analytical functions, which can describe this distribution at the per mill level to avoid a significant bias on the extracted signal yields.

The signal yield is obtained by a simultaneous binned maximum-likelihood fit to the twelve $m_{\mu\mu}$ distributions of the individual categories in the range 110–160 GeV, together with the background normalization and shape parameters, exploiting the resonant behavior of the Higgs boson signal. The inclusive spectrum of the dimuon invariant mass after the signal plus background fit is shown in Figure 1.

classification using three BDTs.

$||$ This function is a modification of the Crystal-Ball function, consisting of a Gaussian central part and power-law tails on both sides.

Figure 1. Dimuon invariant mass $m_{\mu\mu}$ spectrum in all the analysis categories, as observed in data. The figure shows the unweighted sum of all events and signal plus background probability density functions (PDF) [9].

The best fit value of the signal strength parameter from the fit is $\mu = 0.5 \pm 0.7$, corresponding to an observed significance of 0.8σ with respect to the hypothesis of no $H \rightarrow \mu\mu$ signal. The signal strength uncertainty is dominated by the statistical error on the data of about 0.7. The impact of the systematic uncertainties on the signal strength is found to be $^{+0.2}_{-0.1}$, dominated by theoretical and instrumental uncertainties. No significant excess is observed in data, and an upper limit on the signal strength at 1.7 is set at 95% confidence level (CL), while 1.3 was expected under the hypothesis of no $H \rightarrow \mu\mu$ signal. The inclusion of pp data collected in 2018, together with the refinement of the techniques employed by the analysis, has led to a 50% improvement of the sensitivity, with respect to the previous search [10].

3. Searches for $H \rightarrow ee$ and $H \rightarrow e\mu$ decays

Searches for the $H \rightarrow ee$ and LFV decays $H \rightarrow e\mu$ probe the structure of the Yukawa sector of the SM as well. The SM predicts the $\text{BR}(H \rightarrow ee)$ far below the sensitivity of the LHC experiments and LFV Higgs boson decays in the SM can only proceed through neutrino mixing and are thus expected to have vanishingly small BR¶. The LHC collision data offer the best tool to constrain the electron Yukawa coupling Y_{ee} as well as to set strong indirect constraints on the off-diagonal $Y_{e\mu}$ coupling.

In this section, we present the first ATLAS searches for $H \rightarrow ee$ and the LFV decay $H \rightarrow e\mu$ using the full Run-2 dataset with an integrated luminosity of 139 fb^{-1} [11].

Both analyses closely follow the search for the SM $H \rightarrow \mu\mu$ decays described in [9]. The signal is separated from the background processes primarily by identifying a narrow

¶ Theories with extended Higgs sectors, including non-diagonal Yukawa couplings, such as $Y_{e\mu}$, can enhance these BRs.

peak in the invariant mass distribution of the two leptons $m_{\ell\ell}^+$ corresponding to the Higgs boson mass of 125 GeV.

The background for the ee search is dominated by the DY processes, with smaller contributions from top-quark pair ($t\bar{t}$) and diboson (ZZ , WZ and WW) production. In the $e\mu$ search, a much smaller yield of SM background events is expected. The DY background only contributes through decays of $Z/\gamma^* \rightarrow \tau\tau \rightarrow e\nu_\tau\nu_e\mu\nu_\tau\nu_\mu$. As a consequence, the production of top-quark pairs, dibosons, W +jets and multijets, with jets misidentified as leptons, are more important than in the ee search.

Each search is performed in the range of dilepton invariant masses between 110 and 160 GeV, which allows to determine the background with analytical functions constrained by the sidebands on either side of the potential signal. The event sample passing the basic lepton selection is divided into 7 (8) categories for the ee ($e\mu$) channels. The categories are based on those used in the $H \rightarrow \mu\mu$ search [9], and are found to provide good sensitivity for the present analyses.

The observed dilepton-mass spectra in each category are fitted simultaneously in the ee ($e\mu$) channel. The inclusive data and SM expectation for all categories are shown in Figure 2.

No evidence for either decay is found and observed (expected) upper limits at the 95% CL of 3.6×10^{-4} (3.5×10^{-4}) for $BR(H \rightarrow ee)$ and 6.1×10^{-4} (5.8×10^{-4}) for $BR(H \rightarrow e\mu)$ are obtained.

Figure 2. Dilepton invariant mass summed over all categories for the ee channel (left) and the $e\mu$ channel (right) compared with the background only model. The signal parametrization with branching fractions (BF) set to 2% for $H \rightarrow ee$ and 0.05% for $H \rightarrow e\mu$ are also shown (red line). The bottom panels show the difference between data and the background-only fit [11].

⁺ Unless explicitly mentioned otherwise, leptons (denoted by ℓ or ℓ') refer to electrons or muons.

4. Searches for lepton-flavor violating $H \rightarrow \ell\tau$ decays

Searches for LFV decays of the Higgs boson, $H \rightarrow e\tau$ and $H \rightarrow \mu\tau$, have been performed using 36 fb^{-1} of 13 TeV pp collision data collected by the ATLAS detector [12].

Opposite-sign $\ell\tau$ pairs are selected, considering both leptonic ($\tau \rightarrow \ell'\nu\bar{\nu}$) and hadronic ($\tau \rightarrow \text{hadrons} + \nu$) τ -lepton decays, denoted as $\tau_{\ell'}$ and τ_{had} , respectively. The dilepton final state $\ell\tau_{\ell'}$ only considers pairs of leptons with different flavors. Same-flavor lepton pairs are rejected due to the large lepton pair-production arising from DY processes. Two channels are considered for each of the searches: $e\tau_{\mu}$ and $e\tau_{\text{had}}$ for the $H \rightarrow e\tau$ search, $\mu\tau_e$ and $\mu\tau_{\text{had}}$ for the $H \rightarrow \mu\tau$ search.

Events selected in the $\ell\tau_{\ell'}$ channel contain exactly one electron and one muon of opposite sign charges. Similarly, in the $\ell\tau_{\text{had}}$ channel, a lepton and a $\tau_{\text{had-vis}}^*$ of opposite sign charges are required and events with more than one lepton are rejected. Events are further divided into two categories, in particular VBF and non-VBF. The VBF selection is based on the kinematics of the two jets with the highest p_T . The non-VBF category contains events failing the VBF selection. Table 2 summarizes the criteria for the baseline selection, analysis categorization as well as control regions (CRs).

The analysis exploits BDT algorithms to enhance the signal separation from the background in the individual searches, channels and categories. The components of the four-momenta of the analysis objects, as well as derived event variables (e.g., invariant masses and angular separations), are the input variables of the BDT discriminants. The invariant mass is reconstructed with the Missing Mass Calculator (MMC) algorithm [13] (m_{MMC}) for the $\ell\tau_{\ell'}$ channel, while for the $\ell\tau_{\text{had}}$ channel, the collinear approximation (m_{coll}) is utilized. The analysis CRs are used to validate the level of agreement between data and simulated distributions of the BDT score and input variables, as well as their correlations.

The most significant background in these searches arises from events with $Z \rightarrow \tau\tau$ decays or with top-quarks, as well as from events with misidentified objects. The latter are estimated using data-driven techniques.

Searches for $H \rightarrow e\tau$ and $H \rightarrow \mu\tau$ are treated independently. For each search, the analysis exploits the four signal regions (SRs) and the two CRs specified in Table 2. The BDT score distributions of all SRs are analyzed to test the presence of a signal, simultaneously with the event yields in CRs, which are included to constrain the normalizations of the major backgrounds estimated from the simulation.

No significant excess with respect to the predicted background is observed in any category, as shown in Figure 3 for the $\mu\tau_e$ channel in the VBF category (left) and the $\mu\tau_{\text{had}}$ channel in the non-VBF category (right). The best-fit value of the BR is consistent with 0 within 1σ in both final states. The observed (median expected) 95% CL upper limits on the BRs are 0.47% ($0.34_{-0.10}^{+0.13}\%$) and 0.28% ($0.37_{-0.10}^{+0.14}\%$) for $H \rightarrow e\tau$ and $H \rightarrow \mu\tau$, respectively.

* The visible products of the τ_{had} decays are labeled as $\tau_{\text{had-vis}}$.

Selection	$\ell\tau_{\ell'}$	$\ell\tau_{\text{had}}$
Baseline	exactly 1e and 1 μ , OS	exactly 1 ℓ and 1 $\tau_{\text{had-vis}}$, OS
	$p_{\text{T}}^{\ell_1} > 45 \text{ GeV}$	$p_{\text{T}}^{\ell} > 27.3 \text{ GeV}$
	$p_{\text{T}}^{\ell_2} > 15 \text{ GeV}$	$p_{\text{T}}^{\tau_{\text{had-vis}}} > 25 \text{ GeV}, \eta^{\tau_{\text{had-vis}}} < 2.4$
	$30 \text{ GeV} < m_{\text{vis}} < 150 \text{ GeV}$	$\sum_{i=\ell, \tau_{\text{had-vis}}} \cos \Delta\phi(i, E_{\text{T}}^{\text{miss}}) > -0.35$
	$p_{\text{T}}^e(\text{track})/p_{\text{T}}^e(\text{cluster}) < 1.2$ ($\mu\tau_e$ only)	$ \Delta\eta(\ell, \tau_{\text{had-vis}}) < 2$
	b -veto (for jets with $p_{\text{T}} > 25 \text{ GeV}$ and $ \eta < 2.4$)	
VBF	Baseline	
	≥ 2 jets, $p_{\text{T}}^{\text{j}_1} > 40 \text{ GeV}, p_{\text{T}}^{\text{j}_2} > 30 \text{ GeV}$	
	$ \Delta\eta(\text{j}_1, \text{j}_2) > 3, m(\text{j}_1, \text{j}_2) > 400 \text{ GeV}$	
	$p_{\text{T}}^{\tau_{\text{had-vis}}} > 45 \text{ GeV}$	
Non-VBF	Baseline plus fail VBF categorization	
	$m_{\text{T}}(\ell_1, E_{\text{T}}^{\text{miss}}) > 50 \text{ GeV}$	—
	$m_{\text{T}}(\ell_2, E_{\text{T}}^{\text{miss}}) < 40 \text{ GeV}$	—
	$ \Delta\phi(\ell_2, E_{\text{T}}^{\text{miss}}) < 1.0$	—
	$p_{\text{T}}^{\tau}/p_{\text{T}}^{\ell_1} > 0.5$	—
Top-quark CR	inverted b -veto:	
VBF and non-VBF	≥ 1 b -tagged jet ($p_{\text{T}} > 25 \text{ GeV}$ and $ \eta < 2.4$)	
Z $\rightarrow \tau\tau$ CR	inverted $p_{\text{T}}^{\ell_1}$ requirement:	
VBF and non-VBF	$35 \text{ GeV} < p_{\text{T}}^{\ell_1} < 45 \text{ GeV}$	

Table 2. Baseline event selection and further categorization for the $\ell\tau_{\ell'}$ and $\ell\tau_{\text{had}}$ channels. The same criteria are also used for the control region (CR) definitions in the $\ell\tau_{\ell'}$ channel, but one requirement of the baseline selection is inverted to achieve orthogonal event selection. There is no CR in the $\ell\tau_{\text{had}}$ channel [12].

Figure 3. Distributions of the BDT score after the background plus signal fit in each signal region of the $\mu\tau_e$ search in the VBF category (left) and the $\mu\tau_{\text{had}}$ search in the non-VBF category (right), with both lepton-flavor violating (LFV) signals overlaid, normalized with $\text{BR}(H \rightarrow \mu\tau) = 1\%$ and enhanced by a factor 10 for visibility. The size of the combined statistical, experimental and theoretical uncertainties of the background is indicated by the hatched bands [12].

5. Conclusion

The results of the searches for several rare or lepton-flavor violating Higgs boson decays have been presented: $H \rightarrow \mu\mu$, $H \rightarrow ee$, $H \rightarrow e\mu$, $H \rightarrow \ell\tau$, which are potentially sensitive to the beyond SM physics. The searches have been performed with 13 TeV pp collision data recorded by the ATLAS detector at the LHC corresponding to an integrated luminosity of up to 139 fb^{-1} ; however, no significant signal was observed.

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