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Exotic decays of the Higgs and Z bosons

Florencia L. Castillo* on behalf of the ATLAS collaboration

**Kirchhoff-Institute for Physics, University of Heidelberg, Germany*

E-mail: fcastill@cern.ch

Precision studies of the properties of the Higgs and gauge bosons may provide a unique window for the discovery of new physics at the LHC. New phenomena can in particular be revealed in the search for lepton-flavor-violating or exotic decays of the Higgs and Z bosons, as well as in their possible couplings to hidden-sector states that do not interact under Standard Model gauge transformations. This document presents recent searches by the ATLAS experiment for decays of the Higgs and Z bosons to new particles, using collision data at $\sqrt{s}$ = 13 TeV collected during the LHC Run 2.

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1. Introduction

Ten years ago, the 4th of July 2012, the discovery of the Higgs boson was announced to the world. The experimental program around this particle has begun. Several measurements of the Higgs properties were performed over the years. So far, these experimental results have agreed with the Standard Model (SM) predictions. But, there are still mysteries behind the nature of the Higgs boson. Its existence does not explain the hierarchy problem, neither can it resolve the dark matter phenomenon, as well the observed matter–antimatter asymmetry. There are several models which can give an answer to these questions, and predict nonstandard "exotic" decays of the observed 125 GeV Higgs boson [1]. Recent constraints from fits to SM Higgs couplings define the upper limit of the branching ratio: $\mathcal{B}[H \to \text{undetected}] < 19\%$ and $\mathcal{B}[H \to \text{invisible}] < 9\%$ [2] and open the possibility of the SM 125 GeV Higgs being the bridge between the SM and beyond the Standard Model (BSM) theories.

The physics interest of exotic Higgs decays is very well substantiated, as well the search for a new Z' vector gauge boson, which can address the observed anomalies of the muon $g-2$ and rare B decay measurements. Below, several exotic and lepton-flavor-violation (LFV) of Z and Higgs decays are summarised. All searches are performed using 139 fb^{-1} of LHC proton–proton (pp) collisions at $\sqrt{s} = 13$ TeV collected with the ATLAS experiment [3].

2. Z' searches using the 4 μ final state

The new gauge boson Z', which only interacts with leptons of the second and third generations, is predicted by $\mathcal{L}_\mu - \mathcal{L}_\tau$ models which extend the SM. These models also aim to explain outstanding questions related to dark matter and neutrino masses. In pp collisions at the LHC, the Z' could be produced from final state radiation of μ or τ pairs of the Drell-Yan (DY) process.

A search for a Z' boson production with a mass between 5 and 75 GeV is explored. Two deep neural networks (DNNs) are applied, one for low mass ($m_{Z'} < 42$ GeV) and another for the high mass ($m_{Z'} > 42$ GeV) region to further separate signal from background. The main background for this signature is the SM 4μ production from a final state boson pair. In this search the statistical uncertainty is dominant. No significant excess of events over the expected SM background is observed. Therefore, upper limits are set on the Z' production cross-section times the decay branching fraction. These values vary from 0.425 to 2.04 fb at 95% CL [4]. This analysis shows significant sensitivity improvements over previous results presented by CMS at 77 fb^{-1} [5].

3. Higgs boson decays to dark bosons

This analysis looks for a SM Higgs boson H decaying via new bosons into a final state of four charged leptons ($\ell \equiv e, \mu$). The new boson (X) could be either a dark-sector vector boson or a scalar boson. The analysis separates 3 channels:

- High mass (HM) : $H \to XX \to 4\ell$, 15 GeV $< m_X <$ 60 GeV
- Low mass (LM): $H \to XX \to 4\mu$, 1 GeV $< m_X <$ 15 GeV
- Single Z-boson (ZX): $H \to ZX \to 4\ell$, 15 GeV $< m_X <$ 55 GeV

where the Z corresponds to the SM boson. For the high mass selection it is required that the invariant mass of the four-lepton system is consistent with the SM Higgs boson: 115 GeV < $m_{4\ell}$ < 130 GeV. The invariant masses of the two lepton pairs must not be consistent with the decays of Z bosons (Z-veto): 10 GeV < $m_{12,34}$ < 64 GeV. The LM analysis uses only the 4μ final state since they can be reconstructed at low-energy threshold. The $m_{4\mu}$ requirement is narrowed to 120 GeV < $m_{4\mu}$< 130 GeV, because muons have smaller radiative losses than electrons, and both lepton pairs must satisfy 1.2 GeV < $m_{12,34}$ < 20 GeV. The final requirement for this signal region is simplified to m_{12}/m_{34} > 0.85. The last channel, ZX, one pair has to be consistent with m_Z and the total invariant mass is required to be consistent with the decay of a Higgs boson, in the same manner as in the HM analysis: 115 GeV < $m_{4\ell}$ < 130 GeV.

There is no event observed in the LM signal region. A small excess is seen around 28 GeV (local significance 2.5 σ) in the HM channel. No significant excess is found in all channels. Limits are set on fiducial cross sections and on the branching ratio of the Higgs boson to decay into XX/ZX [6]. Figure 1 shows the upper limit of the fiducial cross section of the ZX channel. The results are improved compared to a previous publication by a factor between two and four due to larger data sample, improved lepton reconstruction and identification, and an optimised event selection [7].

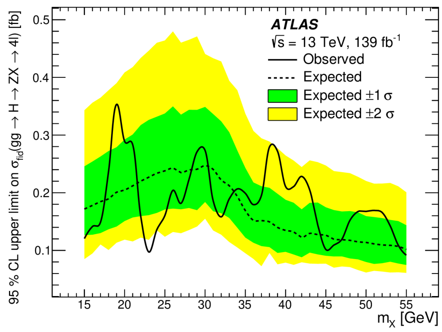

Figure 1: From [7] it is shown the upper limit at 95% CL on the fiducial cross section for the $H \to ZX \to 4\ell$ process, for all channels combined.

4. Higgs boson decays to scalars

Models of a Higgs boson with a mass of 125 GeV decaying into a pair of new pseudoscalar particles ($H \to aa$) are inspired by the 2HDM+S. The channels to search for and the dominant decay modes change as a function of the mass of the mediator [1]. The advantage of these models is that it can be analysed using 4-body final states, where different decay modes dominate among the mass mediator (m_a) values. Here we cover situations when the mediator decays into muons and b-quarks [8]. This search explores the mass mediator range 16 GeV < m_a < 62 GeV. In that region the b-quark decay mode is the dominant with the largest branching ratio. However, the ATLAS detector does not offer a clean selection of this mode. So, here the selection of the second decay mode takes an important role. ATLAS has a good eficiency selecting muons. This advantage is used in the event selection. A kinematic likelihood fit is used to improve the $m_{bb\mu\mu}$ resolution and this variable maintains $m_{bb} \approx m_{\mu\mu}$. The gain to use this approach is that $m_{\mu\mu}$ has 10 times better resolution compared with m_{bb}. The four body mass is selected to be in the neighborhood of the SM Higgs boson, 110 < $m_{bb\mu\mu}$ < 140 GeV. Since there is no invisible particle involved in the final state it is required that $E_{\mathrm{T}}^{\mathrm{miss}}$ < 60 GeV. Additionally, boosted decision tree (BDT) techniques are used to improve the separation of the signal against the main backgrounds, $t\bar{t}$ and DY+jets productions. The BDT training is optimised in multiple $m_{\mu\mu}$ windows to exploit kinematic differences that depend on m_a. This increases the analysis sensitivity, especially for higher m_a. The analysis is dominated by the statistical uncertainty. The most important systematics arise from jet energy calibration, jet resolution, and b-jet efficiencies. No significant excess of the data above the SM prediction is observed. The lowest local p_0-value of 0.00054 is observed at $m_{\mu\mu}$ = 52 GeV and corresponds to a local significance of 3.3 σ. The global significance of that excess is determined to be 1.7 σ. Upper limits at 95% CL are established compared to previous results from ATLAS with 36 fb^{-1}, these limits are significantly improved [9], as can be seen in Figure 2.

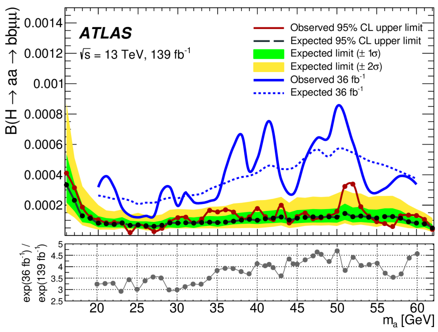

Figure 2: Upper limits on $B(H \to aa \to bb\mu\mu)$ as a function of the signal mass [8]. For comparison, the expected (observed) limits from the 36 fb^{-1} [9] result are shown in dashed (full) blue line.

5. Search of lepton flavor violating Higgs boson decays

LFV decays of the Higgs boson are forbidden in the SM. They are allowed in its many extensions. For instance, supersymmetry (SUSY), multi-Higgs doublet models and many others can introduce LFV Yukawa couplings. In particular, the decay $H \to e\mu$ was recently updated by the ATLAS Collaboration [10]. To select signal events from the background it used a narrow peak in the invariant mass distribution of the two leptons $m_{e\mu}$ corresponding to a decay of the Higgs boson with m_H = 125 GeV. The main backgrounds of the search are $Z \to \tau\tau, \mu\mu$ processes. The event selection divides the events into eight categories, depending on the subleading lepton or dilepton p_{T}. A simultaneous fit using a profile-likelihood-ratio test statistics is performed to the observed electron-muon-mass spectra divided into 50 $m_{e\mu}$ bins in each of the eight categories. The uncertainty is dominated by the data statistics, while the largest systematic contribution is from the Higgs boson production cross-section uncertainty. So far, there is no evidence for the decay of $H \to e\mu$. The observed (median expected) upper limits at the 95% CL on the branching fractions is found to be 6.2×10^{-5} (5.9×10^{-5}). Figure 3 shows the 95% CL upper limits on the branching fractions of the Higgs boson to LFV decays, $H \to e\mu$, $H \to e\tau$ and $H \to \mu\tau$, these last two are from a previous ATLAS analysis [11].

6. Search of lepton flavor violating Z boson decays

LFV has been observed in neutrino oscillations, but the rate of charged-lepton-flavor transitions mediated by neutrino-flavor oscillations is expected to be negligible in the SM. A possible charged-lepton-flavor violation would indicate physics beyond the Standard Model, and searches for such

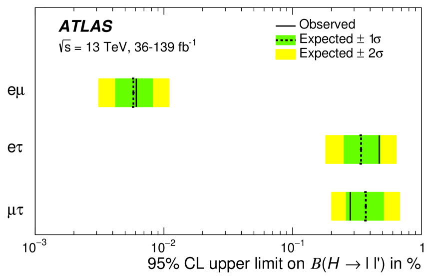

Figure 3: Limits at 95% CL upper limits on the branching fractions of the Higgs boson to various LFV decays in percent. The result for $H \to e\mu$ is from the newest search presented [10] and $H \to e\tau$ and $H \to \mu\tau$ results are taken from a previous analysis [11]. Expected limits are shown as a dashed line with the one and two sigma uncertainty bands in green and yellow.

violations can be used to constrain BSM theories. For all Run 2, around 8×10^9 Z bosons were produced in ATLAS. This high amount allows us to reduce the statistical uncertainty of this search. The decay of $Z \to e\mu$ is presented in this document [12]. The signal region is selected by requiring one electron and one oppositely charged muon with an invariant mass in the window $70 < m_{e\mu} < 110$ GeV. For background estimation events are selected with two opposite-charge electrons (muons) with an invariant mass in the same window. To suppress the top quark background, events are required to have low E_T^{miss} or low p_T, or a b-jet veto. A BDT enhances the signal selection. It is trained using events in a mass window of $85 < m_{e\mu} < 95$ GeV in simulated signal and in $Z \to \mu\mu$ background. In order to reduce the uncertainties, this search is based on normalising the $m_{\ell\ell}$ to $Z \to ee, \mu\mu$ observed yields. The dominant systematic uncertainties are the statistics of the simulated $Z \to \tau\tau, \mu\mu$ backgrounds. The observed distribution of $m_{e\mu}$ is consistent with the SM expectation. Figure 4 shows the distribution of the invariant mass $m_{e\mu}$ of the $Z \to e\mu$ candidates. An upper limit of $\mathcal{B}[Z \to e\mu] < 2.62 \times 10^{-7}$ is set at 95% CL, this last measurement reduces the LEP limit by a factor 6.5 and the previous ATLAS result is reduced by a factor of 3, as can be seen in Table 1 [12–14].

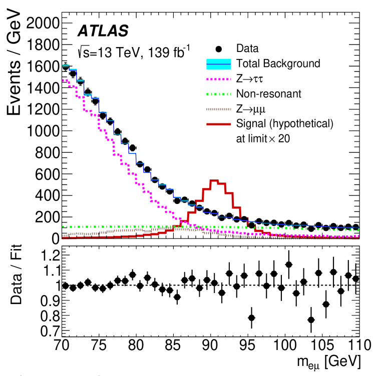

Figure 4: Distribution of the invariant mass $m_{e\mu}$ for data (points) and expected backgrounds (lines) after the background-only likelihood fit. The final total fit is shown with a blue solid line [12].

Table 1: Upper limits of $\mathcal{B}[Z \to e\mu]$ at 95% CL obtained by ATLAS and OPAL.

Upper limit at 95 % CL	$\mathcal{B}[Z \to e\mu]$
ATLAS all Run 2 (139 fb^{-1})	0.26×10^{-6}
ATLAS 2012 data (20 fb^{-1})	0.75×10^{-6}
LEP OPAL (0.126 fb^{-1})	1.7×10^{-6}

7. Summary

Latest results of the ATLAS detector using full Run 2 LHC data (139 fb^{-1}) for exotic decays of the Higgs and Z bosons are presented. A new Z' production, many nonstandard decays of the SM

Higgs boson, and LFV for Z and Higgs bosons have been shown. No significant deviation from the SM background predictions is observed across all searches. Many limits were improved due to a better event selection and the increase of the dataset.

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