Search for the decays of the Higgs boson $H \rightarrow ee$ and $H \rightarrow e\mu$ in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

Searches for the decay of the Higgs boson $H \rightarrow ee$ and $H \rightarrow e\mu$ are performed using data corresponding to an integrated luminosity of 139 fb$^{-1}$ collected with the ATLAS detector in $pp$ collisions at $\sqrt{s} = 13$ TeV at the LHC. No significant signals are observed, in agreement with the Standard Model expectation. For a Higgs boson mass of 125 GeV the observed (expected) upper limit at the 95% confidence level on the branching fraction of $H \rightarrow ee$ is $3.6 \times 10^{-4}$ ($3.5 \times 10^{-4}$) and on $H \rightarrow e\mu$ is $6.1 \times 10^{-5}$ ($5.8 \times 10^{-5}$). These results represent an improvement of a factor of about 5 and 6 on the previous best limits on the branching fractions of $H \rightarrow ee$ and $H \rightarrow e\mu$, respectively.

© 2019 CERN for the benefit of the ATLAS Collaboration.
Reproduction of this article or parts of it is allowed as specified in the CC-BY-4.0 license.
1 Introduction

The discovery of a heavy scalar particle by ATLAS and CMS [1, 2] provided experimental confirmation of the Englert-Brout-Higgs mechanism [3–8], which spontaneously breaks electroweak (EW) gauge symmetry and generates mass terms for the $W$ and $Z$ gauge bosons. The fermion masses are generated in the Standard Model via Yukawa interactions. The Yukawa couplings to third generation fermions were determined by measurements of Higgs boson production and decays [9–15], and found to be in agreement with the expectations of the Standard Model. However, there is currently no evidence of Higgs boson decays to first or second generation quarks or leptons.

This letter presents the first ATLAS searches for $H \to ee$ and for the lepton flavour violating decay $H \to e\mu$ using the full Run 2 data set with an integrated luminosity of $139 \, \text{fb}^{-1}$ based on proton-proton collisions at a centre of mass energy of $\sqrt{s} = 13$ TeV. The CMS Collaboration has previously performed searches for $H \to ee$ [16] and $H \to e\mu$ [17] using the LHC Run 1 data of $19.7 \, \text{fb}^{-1}$ at $\sqrt{s} = 8$ TeV.

Searching for these processes probes the structure of the Yukawa sector of the Standard Model (SM). The SM predicts a $H \to ee$ branching fraction far below the sensitivity of the LHC experiments and forbids lepton-flavour-number violating Higgs boson decays. The LHC offers the best constraint on the electron Yukawa coupling $Y_{ee}$ [18]. There are strong indirect constraints on the off-diagonal $Y_{e\mu}$ coupling, the strongest coming from limits on the branching fraction of $\mu \to e\gamma$ and the electron electric dipole moment [19]. However, these indirect constraints assume Standard Model values for the as yet unmeasured $Y_{ee}$ and $Y_{\mu\mu}$ Yukawa couplings.

Both analyses presented in this paper closely follow the search for the Standard Model Higgs boson decay $H \to \mu\mu$ [20]. The signal is separated from the background primarily by identifying a narrow peak in the invariant mass distribution of the two leptons $m_{\ell\ell}$ corresponding to the mass of the Higgs boson of 125 GeV [21]. The background for the $ee$ search is dominated by $Z/\gamma^* \to \tau\tau \to e\nu\tau\nu\tau\nu$, and $Z$ and $W$ pair production. In the $e\mu$ search, a much smaller yield of SM background events is expected. The DY background only contributes through decays of $Z/\gamma^* \to \tau\tau \to e\nu\tau\nu\tau\nu$, and $W+\text{jets}$ and multijet, with jets misidentified as leptons, are more important than in the $ee$ search.

2 ATLAS detector

The ATLAS experiment [22, 23] at the LHC is a multi-purpose particle detector with a forward-backward symmetric cylindrical geometry and a near $4\pi$ coverage in solid angle. It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer incorporating three large superconducting toroid magnets.

The inner tracking detector (ID) covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling

---

1 ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the $z$-axis along the beam pipe. The $x$-axis points from the IP to the centre of the LHC ring, and the $y$-axis points upwards. Cylindrical coordinates $(r, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the $z$-axis. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = - \ln \tan(\theta/2)$. Angular distance is measured in units of $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$.
calorimeters provide electromagnetic (EM) energy measurements with high granularity. A steel/scintillator-tile calorimeter in the central pseudorapidity range $|\eta| < 1.7$ measures the energies of hadrons. The end-cap and forward regions are instrumented with LAr calorimeters for both EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer (MS) surrounds the calorimeters up to $|\eta| = 2.7$ and is based on three large air-core toroidal superconducting magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 Tm across most of the detector. The muon spectrometer includes a system of precision tracking chambers and fast detectors for triggering.

A two-level trigger system is used to select events [24]. It consists of a first-level trigger implemented in hardware and using a subset of the detector information to reduce the event rate to 100 kHz. This is followed by a software-based high-level trigger that employs algorithms similar to those used offline and reduces the rate of accepted events to 1 kHz.

3 Simulated Event Samples

Samples of simulated signal events with a Higgs boson mass of $m_H = 125$ GeV were generated as described below and processed through the full ATLAS detector simulation [25] based on GEANT4 [26]. Higgs boson production in the gluon fusion process (ggF) is simulated using the POWHEG NNLOPS program [27–34] with the PDF4LHC15 set of parton distribution functions (PDFs) [35]. The Higgs boson rapidity in the simulation is reweighted to achieve next-to-next-to-leading-order (NNLO) accuracy in QCD [36]. Higgs boson production via vector-boson fusion (VBF) and with an associated vector-boson ($VH$) are generated at NLO accuracy in QCD using the POWHEG-Box program [37–39]. The $ZH$ samples are simulated for processes with quark–quark initial states and the small contribution from gluon–gluon initial states is accounted for in the normalisation of the $ZH$ cross section. The parton-level events are processed with PYTHIA8 [40] for the decay of the Higgs bosons into the $ee$ or $e\mu$ final states and to provide parton showering, hadronisation and underlying event, using the AZNLO set of tuned parameters [41]. All samples are normalised to state-of-the-art predictions using higher-order QCD and electroweak corrections [42–65]. The effects arising from multiple $pp$ collisions in the same or neighbouring bunch crossings (pileup) are included in the simulation by overlaying inelastic $pp$ interactions produced using PYTHIA8 using the NNPDF2.3LO set of PDFs [66] and the A3 tune [67]. Events are reweighted such that the distribution of the average number of interactions per bunch crossing matches that observed in data. Simulated events are corrected to reflect the lepton energy scale and resolution and trigger, reconstruction, identification and isolation efficiencies measured in data.

To evaluate the uncertainty on the background modelling in the $ee$ channel, a dedicated fast simulation for the dominant DY background was used to produce a sample of $10^9$ events, equivalent to 40 times the data luminosity. For this sample $Z/\gamma^* + 0, 1$ jet events are generated inclusively at NLO accuracy using POWHEG [68] with the CT10 PDF set [69]. Additional $Z/\gamma^* + 2$ jet events are generated with ALPGEN [70] at LO accuracy with the CTEQ6L1 PDF set [71]. The events are interfaced to Photos [72] to simulate QED FSR. A fast parameterisation of the effect of the detector on electrons and jets, including the effects of pileup, is then applied to the generated events.
4 Event Selection

Events are recorded using triggers that require either an isolated electron or an isolated muon with a transverse momentum ($p_T$) threshold of about 26 GeV [24]. Electrons are reconstructed in the range $|\eta| < 2.47$ from clusters of energy deposits in the calorimeter matched to a track in the inner detector [73, 74]. Muons are reconstructed in the range $|\eta| < 2.5$ either by combining tracks in the ID with tracks in the MS or for $|\eta| < 0.1$ with calorimeter deposits consistent with a muon [75]. The electrons and muons are required to be associated with the primary $pp$ collision vertex, which is defined as that with largest sum of $p_T^2$ of tracks, and to be isolated from other tracks [74, 75]. Each event must contain either exactly two electrons or an electron and a muon. One lepton must have $p_T > 27$ GeV to ensure a high trigger efficiency and the other must be of opposite charge and have $p_T > 15$ GeV.

Selections on jets are used in this analysis to suppress backgrounds and define a category that has a high sensitivity to signal produced in the vector boson fusion (VBF) production mode. Jets are reconstructed in the range $|\eta| < 4.5$ and $p_T > 30$ GeV, using the anti-$k_t$ algorithm [76, 77] with a radius parameter of 0.4. Jets from pileup interactions are suppressed using a multivariate likelihood that combines tracking information [78].

Backgrounds with top quarks are suppressed by identifying $b$-hadrons and neutrinos in the final state. Jets containing $b$-hadrons in the range $|\eta| < 2.5$ are identified as $b$-jets using a multivariate algorithm [79]. Events are rejected if there is at least one $b$-tagged jet. A different working point is used for the $e\mu$ channel due to the larger top-quark background; for the $ee$ ($e\mu$) channel the $b$-jet tagging efficiency is about 60% (85%) with a rejection factor of about 1200 (30) for light-flavour jets [80]. Neutrinos produced in semi-leptonic top-quark decays escape detection and lead to missing transverse momentum $E_{\text{miss}}^T$, reconstructed as the magnitude of the vectorial sum of the transverse momenta of all calibrated leptons and jets and additional ID tracks associated with the primary vertex (soft term) [81]. Backgrounds with significant $E_{\text{miss}}^T$ are suppressed by requiring $E_{\text{miss}}^T/\sqrt{H_T} < 3.5(1.75)$ GeV$^{1/2}$ for the $ee$ ($e\mu$) channel, where $H_T$ is the scalar sum of the transverse momenta of leptons and jets and $\sqrt{H_T}$ is proportional to the $E_{\text{miss}}^T$ resolution.

Background from the process $H \to \gamma\gamma$, where the photons are misreconstructed as electrons, was studied with simulated Monte Carlo events and found to contribute about 0.07% in the $ee$ channel for a signal branching fraction at the expected limit. It is therefore neglected in the rest of the analysis.

The search is performed in the range of invariant mass of the two leptons in the range $m_{\ell\ell} = 110$–160 GeV, which allows to determine the background with analytical functions constrained by the sidebands to 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 that differ in their expected signal-to-background ratios to improve the overall sensitivity of the search. These categories are based on those used in Ref. [20], and are found to provide good sensitivity for the present analyses.

Firstly, a low $p_T$ lepton category “Low $p_T^\ell$” is defined in the $e\mu$ channel with events in which the subleading lepton has $p_T < 27$ GeV. This region has a significant fraction of events in which either reconstructed lepton is of non-prompt origin or a misidentified photon or hadron, called fake lepton hereafter. These events are not separated out in the $ee$ channel due to the smaller relative contribution from fake leptons. A category enriched in events from vector-boson fusion production “VBF” is defined from the remaining events by
selecting those containing two opposite hemisphere jets with a pseudorapidity separation $|\Delta \eta_{jj}| > 3$ and dijet invariant mass $m_{jj} > 500$ GeV.

Events that fail the selections of the “Low $p_T^{\ell\ell}$” and “VBF” categories are classified as “Central” if the pseudorapidities of both leptons are $|\eta^{\ell}| < 1$ or as “Non-central” otherwise. For each of these two categories three ranges in the dilepton transverse momentum $p_{T}^{\ell\ell}$ are considered: “Low $p_{T}^{\ell\ell}$” ($p_{T}^{\ell\ell} \leq 15$ GeV), “Mid $p_{T}^{\ell\ell}$” ($15 < p_{T}^{\ell\ell} \leq 50$ GeV), and “High $p_{T}^{\ell\ell}$” ($p_{T}^{\ell\ell} > 50$ GeV).

5 Signal and Background Parameterisation

Analytical functions are used to describe the $m_{\ell\ell}$ distributions for both the signal and the background. The $H \rightarrow ee$ and $H \rightarrow e\mu$ signals considered are narrow resonances with a SM-like width of 4.1 MeV and a mass of $m_H = 125$ GeV. The observed signal shapes are thus determined by detector resolution effects and are parameterised as a sum of a Crystal Ball (CB) [82] and a Gaussian (GS) following Ref. [20]:

$$P_S(m_{\ell\ell}) = f_{CB} \times CB(m_{\ell\ell}|m_{CB}, \sigma_{CB}, \alpha, n) + (1 - f_{CB}) \times GS(m_{\ell\ell}|m_{GS}, \sigma_{GS}),$$

The parameters $\alpha$ and $n$ define the power-law tail of the CB distribution, while $m_{CB}$, $m_{GS}$, $\sigma_{CB}$, and $\sigma_{GS}$ denote the CB mean value, GS mean value, CB width, and GS width, respectively; the relative normalisation between the terms is governed by the parameter $f_{CB}$. These parameters are determined by fitting the simulated signal $m_{\ell\ell}$ distribution in each category.

The background parameterisation for the $ee$ channel follows Ref. [20] as the background is very similar. The $m_{ee}$ distributions in each category are described by a sum of a Breit-Wigner function (BW) convolved with a GS, and an exponential function divided by a cubic function:

$$P_B(m_{ee}) = f \times [BW(m_{BW}, \Gamma_{BW}) \otimes GS(\sigma_{GS}^B)](m_{ee}) + (1 - f) \times C e^A m_{ee} / m_{ee}^3,$$

where $f$ represents the fraction of the BW component when each individual component is normalised to unity and $C$ is an overall normalisation coefficient. The $\sigma_{GS}^B$ parameter in each category is fixed to the corresponding average $m_{\ell\ell}$ resolution as determined from simulated signal events. For all the categories, the BW parameters are fixed to $m_{BW} = 91.2$ GeV and $\Gamma_{BW} = 2.49$ GeV [83]. The parameters $f$ and $A$ and the overall normalisation are left free to be determined in the fit and uncorrelated between different categories.

A Bernstein polynomial of degree 2 is used to parameterise the $m_{\ell\ell}$ distribution of the background in each of the eight categories in the $e\mu$ channel, with parameters uncorrelated across categories. The background function choice is validated by an F-test considering Bernstein polynomials of first, second and third degree.

The signal yield is constrained using separate binned maximum-likelihood fits to the observed $m_{\ell\ell}$ distributions in the range $110 < m_{\ell\ell} < 160$ GeV in the two channels. The fits are performed using the sum of the signal and background models (“$S + B$ model”) and are performed simultaneously in all the categories. In addition to the background model parameters described earlier, the background normalisation in each category and the branching fraction of the signal are free parameters in the fit.
6 Systematic Uncertainties

The signal expectation is subject to experimental and theoretical uncertainties, which are correlated across the categories.

The uncertainty in the combined 2015–2018 integrated luminosity is 1.7% [84], obtained using the LUCID-2 detector [85] for the primary luminosity measurements. Other sources of experimental uncertainty include the electron and muon trigger, reconstruction, identification and isolation efficiencies [73–75], the b-tagging efficiency [79], the pileup modelling [86], the determination of the $E_T^{\text{miss}}$ soft term [81], and the jet energy scale and resolution [87]. The uncertainties in the electron energy scale and resolution [74, 88] and in the muon momentum scale and resolution [75] affect the shape of the signal distribution as well as the signal acceptance.

The total experimental uncertainty in the predicted signal yield in each ggF category is between 2% and 3% for the ee channel and between 4% and 6% for the $e\mu$ channel. It is dominated by the luminosity, $E_T^{\text{miss}}$ soft term and pileup effects and the latter contributions are larger in the $e\mu$ analysis due to the tighter $E_T^{\text{miss}}/\sqrt{H_T}$ selection. The experimental uncertainty in the VBF category is between 7% and 15% for the ee channel and between 6% and 22% for the $e\mu$ channel, due to larger contributions from the jet energy scale and resolution.

The theoretical uncertainties in the production cross section of the Higgs boson are set according to Ref. [42]. In addition, theoretical modelling uncertainties affecting the acceptance for the signals are calculated separately for the ggF and VBF Higgs boson production processes in each analysis category. The uncertainty on the acceptance from the $VH$ process is neglected. The effects of missing higher-order terms in the perturbative QCD calculations are estimated by varying the renormalisation and factorisation scales. For the ggF process the uncertainties are derived from the largest scale variations and treated as two correlated sources that range from around 1% to 11% for the different analysis categories in both channels. For the VBF process the uncertainties on the acceptance due to the QCD scales are found to be small. The uncertainties in the parton distribution functions and the value of $\alpha_S$ are estimated using the PDF4LHC15 recommendations [35] and found to be very small. The uncertainty in the modelling of the parton shower, underlying event, and hadronisation is assessed by comparing the acceptance of signal events showered with PYTHIA to that of events showered with HERWIG [89, 90]. The total variations due to these uncertainties range from less than 1% to 11% for the ggF signal process and from 1% to 8% for the VBF signal process depending on the analysis category.

Due to the very different yields and composition of the backgrounds in the ee and $e\mu$ channels, the potential bias on the measured signal due to the choice of background function is assessed in different ways. In the ee channel the $S + B$ fit is repeated using the high statistics fast DY background simulation in the place of the data. The number of signal events in each category obtained from the fit is used as a systematic uncertainty following the method of Ref. [1]. To be conservative the maximum absolute deviation for a signal mass between 120 and 130 GeV is taken. The uncertainty is treated as uncorrelated between categories. The background modelling uncertainty is implemented as a set of additional nuisance parameters acting on the signal normalisation in each category. The effect of this uncertainty on the expected limit is about 8%. In the $e\mu$ channel the background modelling uncertainty is estimated by changing the fit function to a standard polynomial and evaluating the difference in signal yield compared with the default $S + B$ fit to a sample of simulated Monte Carlo background events. The effect of this uncertainty on the expected limit is less than 1%.
Figure 1: All categories summed together for the $ee$ channel (left) and the $e\mu$ channel (right) compared with the background only model. The signal parameterisations with branching fractions (BF) set to $\mathcal{B}(H \rightarrow ee) = 2\%$ and $\mathcal{B}(H \rightarrow e\mu) = 0.05\%$ are also shown (red line). The bottom panels show the difference between data and fit.

7 Results

In the $ee$ channel, the observed dielectron-mass spectra are divided into 200 $m_{ee}$ bins in each of the seven categories and then fitted simultaneously using a profile-likelihood-ratio test statistic [91]. The systematic uncertainties affecting the signal normalisation and shape across categories are parametrised by making the likelihood function depend on dedicated nuisance parameters, constrained by additional Gaussian or log-normal probability terms. The Higgs boson production cross sections are assumed to be as predicted in the Standard Model. The data and expectation for all categories summed together is shown in Fig. 1. No evidence for the decay $H \rightarrow ee$ is observed. The best fit value of the branching fraction is $(0.0 \pm 1.7 \text{ (stat.)} \pm 0.6 \text{ (syst.)}) \times 10^{-4}$. The uncertainty is dominated by the data statistics, while the largest systematic contribution is from the background modelling uncertainty. The observed (expected) upper limit on the branching fraction, computed using a modified frequentist CL$_s$ method [91, 92], at the 95% confidence level, is found to be $3.6 \times 10^{-4}$ ($3.5 \times 10^{-4}$). This result is a large improvement on the previous limit by CMS of $1.9 \times 10^{-3}$ based on the Run 1 dataset [16].

In the $e\mu$ channel, a similar fit is performed to the observed electron-muon-mass spectra divided into 50 $m_{e\mu}$ bins in each of the eight categories. The data and expectation for all categories summed together is shown in Fig. 1. No evidence for the decay $H \rightarrow e\mu$ is observed with a best fit value of the branching fraction of $(0.4 \pm 2.9 \text{ (stat.)} \pm 0.3 \text{ (syst.)}) \times 10^{-5}$. The uncertainty is dominated by the data statistics, while the largest systematic contribution is from Higgs boson production cross section uncertainty. The observed (expected) upper limit at the 95% confidence level is found to be $6.1 \times 10^{-5}$ ($5.8 \times 10^{-5}$). This result is a large improvement on the previous limit by CMS of $3.5 \times 10^{-4}$ based on the Run 1 dataset [17].
8 Conclusion

Searches have been performed for the Higgs boson decays \( H \rightarrow ee \) and \( H \rightarrow e\mu \) using 139 fb\(^{-1}\) of data collected with the ATLAS detector in \( pp \) collisions at \( \sqrt{s} = 13 \) TeV at the LHC. No evidence for either decay is found and observed (expected) upper limits at the 95\% confidence level for a Higgs boson with mass 125 GeV of \( 3.6 \times 10^{-4} \) (\( 3.5 \times 10^{-4} \)) for \( \mathcal{B}(H \rightarrow ee) \) and \( 6.1 \times 10^{-5} \) (\( 5.8 \times 10^{-5} \)) for \( \mathcal{B}(H \rightarrow e\mu) \) are obtained. These are the first such searches made by the ATLAS Collaboration and are considerable improvements on previous measurements.

References


Appendix

Table 1: Expected signal ($S$) and background ($B$), their ratio ($S/B$), and observed data events in each category of the $ee$ analysis for $120 < m_{e e} < 130$ GeV. The number of background events is obtained from the background only likelihood fit to the data. The signal is shown for a branching fraction of $\mathcal{B}(H \rightarrow ee) = 0.1\%$.

<table>
<thead>
<tr>
<th>Category</th>
<th>$S$</th>
<th>$B$</th>
<th>$S/B$</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Low $p_T^{\ell\ell}$</td>
<td>230</td>
<td>39200</td>
<td>0.0057</td>
<td>39872</td>
</tr>
<tr>
<td>Forward Low $p_T^{\ell\ell}$</td>
<td>390</td>
<td>98500</td>
<td>0.0039</td>
<td>100844</td>
</tr>
<tr>
<td>Central Medium $p_T^{\ell\ell}$</td>
<td>420</td>
<td>30700</td>
<td>0.014</td>
<td>31182</td>
</tr>
<tr>
<td>Forward Medium $p_T^{\ell\ell}$</td>
<td>710</td>
<td>74900</td>
<td>0.0095</td>
<td>76477</td>
</tr>
<tr>
<td>Central High $p_T^{\ell\ell}$</td>
<td>380</td>
<td>13400</td>
<td>0.028</td>
<td>13625</td>
</tr>
<tr>
<td>Forward High $p_T^{\ell\ell}$</td>
<td>590</td>
<td>29900</td>
<td>0.020</td>
<td>30164</td>
</tr>
<tr>
<td>VBF</td>
<td>120</td>
<td>2530</td>
<td>0.049</td>
<td>2561</td>
</tr>
</tbody>
</table>

Table 2: Expected signal ($S$) and background ($B$), their ratio ($S/B$), and observed data events in each category of the $e\mu$ analysis for $120 < m_{e\mu} < 130$ GeV. The number of background events is obtained from the background only likelihood fit to the data. The signal is shown for a branching fraction of $\mathcal{B}(H \rightarrow e\mu) = 0.1\%$.

<table>
<thead>
<tr>
<th>Category</th>
<th>$S$</th>
<th>$B$</th>
<th>$S/B$</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Low $p_T^{\ell\ell}$</td>
<td>210</td>
<td>150</td>
<td>1.35</td>
<td>171</td>
</tr>
<tr>
<td>Forward Low $p_T^{\ell\ell}$</td>
<td>400</td>
<td>560</td>
<td>0.72</td>
<td>532</td>
</tr>
<tr>
<td>Central Medium $p_T^{\ell\ell}$</td>
<td>250</td>
<td>290</td>
<td>0.86</td>
<td>277</td>
</tr>
<tr>
<td>Forward Medium $p_T^{\ell\ell}$</td>
<td>450</td>
<td>830</td>
<td>0.54</td>
<td>854</td>
</tr>
<tr>
<td>Central High $p_T^{\ell\ell}$</td>
<td>180</td>
<td>280</td>
<td>0.65</td>
<td>299</td>
</tr>
<tr>
<td>Forward High $p_T^{\ell\ell}$</td>
<td>300</td>
<td>700</td>
<td>0.43</td>
<td>707</td>
</tr>
<tr>
<td>VBF</td>
<td>83</td>
<td>100</td>
<td>0.82</td>
<td>102</td>
</tr>
<tr>
<td>Low $p_T^{\ell}$</td>
<td>89</td>
<td>600</td>
<td>0.15</td>
<td>558</td>
</tr>
</tbody>
</table>
Figure 2: Likelihood fits to the $m_{ee}$ distribution in data (points) using the background model (blue line) for all categories. A goodness of fit is tested by evaluating a $\chi^2$ value for each category based on statistical errors only. The signal parameterisation with a branching fraction (BF) set to $\mathcal{B}(H \rightarrow ee) = 2\%$ is also shown (red line). The bottom panels show the difference between the data and fit.
signal parameterisation with a branching fraction (BF) set to categories. A goodness of fit is tested by evaluating a Figure 3: Likelihood fits to the \( m_{ll} \) distribution in data (points) using the background model (blue line) for all categories. A goodness of fit is tested by evaluating a \( \chi^2 \) value for each category based on statistical errors only. The signal parameterisation with a branching fraction (BF) set to \( \mathcal{B}(H \to e\mu) = 0.05\% \) is also shown (red line). The bottom panels show the difference between the data and fit.
Figure 4: CL$_{s}$ scans in the $ee$ (left) and $e\mu$ (right) channels.
Figure 5: Constraints on the flavour violating Yukawa couplings $Y_{e\mu}$ and $Y_{\mu e}$ that are related to the branching ratio of the LFV Higgs boson decay $\mathcal{B}(H \rightarrow e\mu)$ following Ref. [19] as $|Y_{e\mu}|^2 + |Y_{\mu e}|^2 = 8\pi\Gamma_{H}^{\text{SM}}/m_{H} \cdot \mathcal{B}(H \rightarrow e\mu)/(1 - \mathcal{B}(H \rightarrow e\mu))$, where $m_{H} = 125.09$ GeV and $\Gamma_{H}^{\text{SM}} = 4.07$ MeV are the mass and SM width of the Higgs boson. The expected (red dashed line) and observed (blue solid line) limits are derived from the limits on $\mathcal{B}(H \rightarrow e\mu)$ from the present analysis. The green (yellow) band indicates the range that is expected to contain $68\%$ ($95\%$) of all observed limit excursions. The shaded regions show the indirect constraints derived using the model calculations of Ref. [19] from null searches for $\mu \rightarrow e\gamma$ [93], $\mu \rightarrow 3e$ [94] and $\mu \rightarrow e$ conversions on gold nuclei [95]. For these calculations the flavour diagonal Yukawa couplings are taken to be the SM values. The diagonal line indicates the so-called naturalness limit $|Y_{e\mu}Y_{\mu e}| < m_{e}m_{\mu}/v^{2}$, where $v = 246$ GeV is the vacuum expectation value of the Higgs field.
Figure 6: Limits at 95% CL upper limits on the branching ratios of the Higgs boson to various lepton flavour violating decays in percent. The results for $H \rightarrow e\mu$ are from the presented analysis and the $H \rightarrow e\tau$ and $H \rightarrow \mu\tau$ results are taken from Ref. [96]. Expected limits are shown as a dashed line with the one- and two-sigma uncertainty bands in green and yellow.