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

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ABSTRACT

Searches for the Higgs boson decays $H \to ee$ and $H \to e\mu$ 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 $\mathcal{B}(H \to ee)$ is $3.6 \times 10^{-4}$ ($3.5 \times 10^{-4}$) and on $\mathcal{B}(H \to e\mu)$ is $6.2 \times 10^{-5}$ ($5.9 \times 10^{-5}$). These results represent improvements by factors of about five and six on the previous best limits on $\mathcal{B}(H \to ee)$ and $\mathcal{B}(H \to e\mu)$ respectively.

## 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. In the Standard Model (SM) the fermion masses are generated 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 SM. However, there is currently no evidence of Higgs boson decays into 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 dataset of proton–proton ($pp$) collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV, with an integrated luminosity of 139 fb$^{-1}$. The CMS Collaboration has previously performed searches for $H \to ee$ [16] and $H \to e\mu$ [17] using LHC Run 1 $pp$ data at $\sqrt{s} = 8$ TeV corresponding to an integrated luminosity of 19.7 fb$^{-1}$.

In the SM the $H \to ee$ branching fraction is given by $G_F m_H m_e^2/(4\sqrt{2}\pi\Gamma_H) \simeq 5 \times 10^{-9}$, where $m_H$ and $\Gamma_H$ are the Higgs mass and width respectively. This branching fraction is far below the sensitivity of the LHC experiments. Contributions from diagrams that do not depend on the electron Yukawa coupling $Y_{ee}$ and are non-resonant e.g. $H \to ee\gamma$, are expected to be significantly larger, although still much smaller than present sensitivity.

The LHC offers the best constraint on $Y_{ee}$ [18], which may be larger than predicted by the SM. The SM forbids lepton-flavour-number-violating Higgs boson decays. There are strong indirect constraints on the off-diagonal $Y_{e\mu}$ coupling, the strongest derived from limits on the branching fraction of $\mu \to e\gamma$ and the electric dipole moment of the electron [19]. However, these indirect constraints assume SM values for the as yet unmeasured $Y_{ee}$ and $Y_{\mu\mu}$ Yukawa couplings. Searching for $H \to e\mu$ allows $Y_{e\mu}$ to be constrained directly.

Both analyses presented in this Letter closely follow the search for the SM Higgs boson decay $H \to \mu\mu$ [20]. The signal is separated from the background primarily by identifying a narrow peak in the distribution of the invariant mass of the two leptons $m_{\ell\ell}$ corresponding to the mass of the Higgs boson of 125 GeV [21]. The background in the $ee$ search is dominated by Drell–Yan (DY) $Z/\gamma^*$ production, with smaller contributions from top-quark pair ($t\bar{t}$) and diboson production ($ZZ$, $WZ$ and $WW$). In the $e\mu$ search, a much smaller yield of SM background events is expected. The DY background only contributes through decays of $Z/\gamma^* \to \tau\tau \to e\nu_\tau\nu_e\mu\nu_\tau\nu_\mu$. Thus the production of top quarks, dibosons (mainly through $WW \to e\nu_e\mu\nu_\mu$), $W$+jets and multijet events, with jets misidentified as leptons, are more important than in the $ee$ search.

## 2. ATLAS detector

The ATLAS experiment [22–24] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near $4\pi$ coverage in solid angle.[1] It consists of an

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[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

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inner tracking detector (ID) surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer.

The 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 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 endcap and forward regions are instrumented with LAr calorimeters for both the 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 T m 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 [25]. 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 [26] based on GEANT4 [27]. Higgs boson production via the gluon–gluon fusion (ggF) process was simulated using the POWHEG NNLOPS program [28–35] with the PDF4LHC15 set of parton distribution functions (PDFs) [36]. The Higgs boson rapidity in the simulation was reweighted to achieve next-to-next-to-leading-order (NNLO) accuracy in QCD [37]. Higgs boson production via vector-boson fusion (VBF) and with an associated vector boson ($VH$) were generated at next-to-leading-order (NLO) accuracy in QCD using the POWHEG-BOX program [38–40]. The $ZH$ samples were 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 were processed with PYTHIA8 [41] for the decay of the Higgs bosons into the $ee$ or $e\mu$ final states and to simulate parton showering, hadronisation and the underlying event, using the AZNLO set of tuned parameters [42]. All samples were normalised to state-of-the-art predictions using higher-order QCD and electroweak corrections [43–66]. The effects arising from multiple $pp$ collisions in the same or neighbouring bunch crossings (pile-up) were included in the simulation by overlaying inelastic $pp$ interactions generated with PYTHIA8 using the NNPDF2.3LO set of PDFs [67] and the A3 set of tuned parameters [68]. Events were reweighted such that the distribution of the average number of interactions per bunch crossing matches that observed in data. Simulated events were corrected to reflect the lepton energy scale and resolution, and trigger, reconstruction, identification and isolation efficiencies measured in data.

To evaluate the uncertainty in 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 integrated luminosity of the data. For this sample, $Z/\gamma^* + (0,1)$-jet events were generated inclusively at NLO accuracy using POWHEG-BOX [69] with the CT10 PDF set [70]. Additional $Z/\gamma^* + 2$-jet events were generated with ALPGEN [71] at leading-order accuracy with the CTEQ6L1 PDF set [72]. The events were interfaced to PHOTOS [73] to simulate QED final-state radiation. The effects of pile-up and a fast parameterisation of the response of the detector to electrons and jets, using simple smearing functions, was then applied to the generated events.

## 4. Event selection

Events are recorded using triggers that require either an isolated electron or an isolated muon above a transverse momentum ($p_{\mathrm{T}}$) threshold of 26 GeV [25,74]. Electrons are reconstructed in the range $|\eta| < 2.47$ from clusters of energy deposits in the calorimeter matched to a track in the ID [75]. Muons are reconstructed in the range $|\eta| < 2.5$ by combining tracks in the ID either with tracks in the MS or, for $|\eta| < 0.1$, with calorimeter energy deposits consistent with a muon [76]. The electrons and muons are required to be associated with the primary $pp$ collision vertex, which is defined as the collision vertex with largest sum of $p_{\mathrm{T}}^2$ of tracks, and to be isolated from other tracks [75,76]. Each event must contain either exactly two electrons or an electron and a muon. One lepton must have $p_{\mathrm{T}} > 27$ GeV to ensure a high trigger efficiency and the other must be of opposite charge and have $p_{\mathrm{T}} > 15$ GeV.

Requirements on jets are used in this analysis to suppress background and define a category that has a high sensitivity to signal produced in the VBF production mode. Jets in the range $|\eta| < 4.5$ and $p_{\mathrm{T}} > 30$ GeV are reconstructed from energy deposits in the calorimeter [77], using the anti-$k_t$ algorithm [78,79] with a radius parameter of 0.4. Tracking information is combined using a multivariate likelihood to suppressed jets from pile-up interactions [80].

Backgrounds with top quarks are suppressed by identifying $b$-hadrons and neutrinos in the final state. Jets in the range $|\eta| < 2.5$ containing $b$-hadrons are identified as $b$-jets using a multivariate algorithm that uses calorimeter and tracking information [81]. Events are rejected if there is at least one identified $b$-jet. Different working points are used for the $ee$ and $e\mu$ channels because the latter has a larger top-quark background. For the $ee$ ($e\mu$) channel the $b$-jet identification efficiency is about 60% (85%) with a rejection factor of about 1200 (25) for light-flavour jets [82]. Neutrinos produced in semileptonic top-quark decays escape detection and lead to missing transverse momentum $E_{\mathrm{T}}^{\mathrm{miss}}$, reconstructed as the magnitude of the vector sum of the transverse momenta of all calibrated leptons and jets and additional ID tracks associated with the primary vertex (soft term) [83]. Backgrounds with significant $E_{\mathrm{T}}^{\mathrm{miss}}$ are suppressed by requiring $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}} < 3.5$ (1.75) GeV$^{1/2}$ for the $ee$ ($e\mu$) channel, where $H_{\mathrm{T}}$ is the scalar sum of the transverse momenta of leptons and jets and $\sqrt{H_{\mathrm{T}}}$ is proportional to the $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution.

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

The search is performed in the range of dilepton invariant mass $110 < m_{\ell\ell} < 160$ GeV, which allows the background to be determined with analytic functions constrained by the sidebands to either side of the potential signal.

The event sample passing the basic lepton selection is divided into seven (eight) categories for the $ee$ ($e\mu$) channel that differ in their expected signal-to-background ratios, to improve the overall sensitivity of the search. These categories are based on those

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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 $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

used in Ref. [20], and are found to provide good sensitivity in the present analyses.

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

Events that fail to meet the criteria of the 'Low $p_{\mathrm{T}}^{\ell}$' 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 $p_{\mathrm{T}}^{\ell\ell}$ are considered: 'Low $p_{\mathrm{T}}^{\ell\ell}$' ($p_{\mathrm{T}}^{\ell\ell} \leq 15$ GeV), 'Mid $p_{\mathrm{T}}^{\ell\ell}$' ($15 < p_{\mathrm{T}}^{\ell\ell} \leq 50$ GeV), and 'High $p_{\mathrm{T}}^{\ell\ell}$' ($p_{\mathrm{T}}^{\ell\ell} > 50$ GeV). These categories exploit differences in the dilepton mass resolution, which is better for more central leptons, as well as differences in the expected signal-to-background ratio between the signal and the background processes as function of dilepton transverse momentum and rapidity.

## 5. Signal and background parameterisation

Analytic functions are used to describe the $m_{\ell\ell}$ distributions for both the signal and the background. The $H \to ee$ and $H \to e\mu$ signals considered are narrow resonances with a mass and a width set to the SM values of $m_H = 125$ GeV and 4.1 MeV respectively. The observed signal shapes are thus determined by detector resolution effects and are parameterised as a sum of a Crystal Ball function ($F_{\mathrm{CB}}$) [84] and a Gaussian function ($F_{\mathrm{GS}}$) following Ref. [20]:

$$\begin{aligned} P_{\mathrm{S}}(m_{\ell\ell}) &= f_{\mathrm{CB}} \times F_{\mathrm{CB}}(m_{\ell\ell}|m_{\mathrm{CB}}, \sigma_{\mathrm{CB}}, \alpha, n) \\ &\quad + (1 - f_{\mathrm{CB}}) \times F_{\mathrm{GS}}\left(m_{\ell\ell}|m_{\mathrm{GS}}, \sigma_{\mathrm{GS}}^{\mathrm{S}}\right) . \end{aligned}$$

The parameters $\alpha$ and $n$ define the power-law tail of the $F_{\mathrm{CB}}$ distribution, while $m_{\mathrm{CB}}$, $m_{\mathrm{GS}}$, $\sigma_{\mathrm{CB}}$, and $\sigma_{\mathrm{GS}}^{\mathrm{S}}$ denote the $F_{\mathrm{CB}}$ mean value, $F_{\mathrm{GS}}$ mean value, $F_{\mathrm{CB}}$ width, and $F_{\mathrm{GS}}$ width respectively. The relative normalisation between the terms is governed by the parameter $f_{\mathrm{CB}}$. These parameters are determined by fitting the simulated signal $m_{\ell\ell}$ distribution in each category. In the $ee$ ($e\mu$) channel the signal mass resolution varies between about 2.0 GeV (2.3 GeV) for the central and 2.9 GeV (3.0 GeV) for the non-central categories.

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 ($F_{\mathrm{BW}}$) convolved with a $F_{\mathrm{GS}}$, and an exponential function divided by a cubic function:

$$\begin{aligned} P_{\mathrm{B}}(m_{ee}) &= f \times [F_{\mathrm{BW}}(m_{ee}|m_{\mathrm{BW}}, \Gamma_{\mathrm{BW}}) \otimes F_{\mathrm{GS}}(m_{ee}|\sigma_{\mathrm{GS}}^{\mathrm{B}})] \\ &\quad + (1 - f) \times C e^{A \cdot m_{ee}} / m_{ee}^3 , \end{aligned}$$

where $f$ represents the fraction of the $F_{\mathrm{BW}}$ component when each individual component is normalised to unity and $C$ is a normalisation coefficient. The $\sigma_{\mathrm{GS}}^{\mathrm{B}}$ 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 $F_{\mathrm{BW}}$ parameters are fixed to $m_{\mathrm{BW}} = 91.2$ GeV and $\Gamma_{\mathrm{BW}} = 2.49$ GeV [85]. 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 two is used to parameterise the $m_{e\mu}$ distribution of the background in each of the eight categories in the $e\mu$ channel, with parameters uncorrelated across categories. The choice of background function is validated by an F-test considering Bernstein polynomials of first, second and third degree.

The signal yield, which is allowed to be positive or negative, 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% [86], obtained using the LUCID-2 detector [87] for the primary luminosity measurements. Other sources of experimental uncertainty include the electron and muon trigger, reconstruction, identification and isolation efficiencies [75,76], the $b$-jet identification efficiency [81], the pile-up modelling [88], the determination of the $E_{\mathrm{T}}^{\mathrm{miss}}$ soft term [83], and the jet energy scale and resolution [89]. The uncertainties in the electron energy scale and resolution [75] and in the muon momentum scale and resolution [76] 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, $E_{\mathrm{T}}^{\mathrm{miss}}$ soft term and pile-up effects, and the last two contributions are larger in the $e\mu$ analysis due to the tighter $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ requirement. 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 taken from Ref. [43]. 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 in the acceptance for 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 approximated 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 in the acceptance due to the QCD scales are found to be small. The effects of uncertainties in the parton distribution functions and the value of $\alpha_{\mathrm{S}}$ are estimated using the PDF4LHC15 recommendations [36] 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 by PYTHIA with that of events showered by HERWIG [90, 91]. 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.

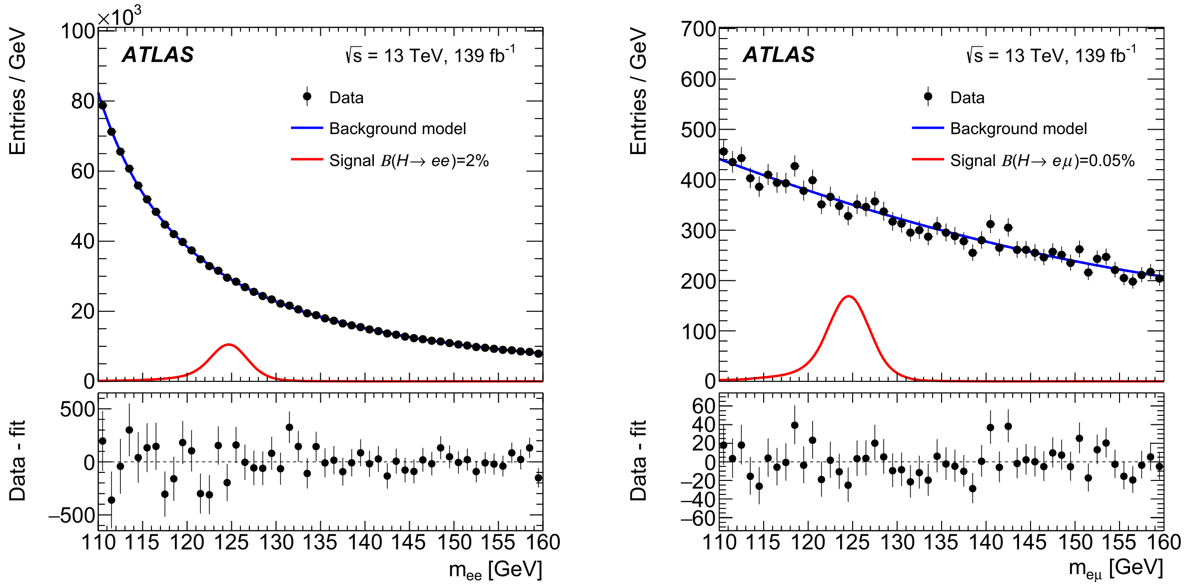

**Fig. 1.** Dilepton invariant mass $m_{\ell\ell}$ for all categories summed together for the $ee$ channel (left) and the $e\mu$ channel (right) compared with the background-only model. The signal parameterisations with branching fractions set to $\mathcal{B}(H \to ee) = 2\%$ and $\mathcal{B}(H \to e\mu) = 0.05\%$ are also shown (red line). The bottom panels show the difference between data and the background-only fit.

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 from the choice of background function is assessed in different ways. In the $ee$ channel the $S + B$ fit is repeated using the high-statistics DY-background fast simulation instead 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 from zero 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 an exponential and evaluating the difference in signal yield compared with the default fit to a sample of simulated background events [92–94]. The effect of this uncertainty on the expected limit is about 1%.

## 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 signal yields are obtained in a simultaneous maximum-likelihood fit. Confidence intervals are based on the profile-likelihood-ratio test statistics [95], assuming asymptotic distributions for the test statistics. The systematic uncertainties affecting the signal normalisation and shape across categories are parameterised 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 are shown in Fig. 1. No evidence of the decay $H \to ee$ 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 statistical uncertainty in the data, 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 $\text{CL}_\text{s}$ method [95,96], at the 95% confidence level, is found to be $3.6 \times 10^{-4}$ $(3.5 \times 10^{-4})$. This result is a significant 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 are shown in Fig. 1. No evidence of the decay $H \to e\mu$ 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 statistical uncertainty in the data, while the largest systematic contribution is from the Higgs boson production cross-section uncertainty. The observed (expected) upper limit at the 95% confidence level is found to be $6.2 \times 10^{-5}$ $(5.9 \times 10^{-5})$. This result is a significant improvement on the previous limit by CMS of $3.5 \times 10^{-4}$ based on the Run 1 dataset [17].

## 8. Conclusion

Searches are performed for the Higgs boson decays $H \to ee$ and $H \to e\mu$ using 139 $\text{fb}^{-1}$ of data collected with the ATLAS detector in $pp$ collisions at $\sqrt{s} = 13$ TeV at the LHC. No evidence of either decay is found and observed (expected) upper limits at the 95% confidence level on the branching fractions of $3.6 \times 10^{-4}$ $(3.5 \times 10^{-4})$ for $\mathcal{B}(H \to ee)$ and $6.2 \times 10^{-5}$ $(5.9 \times 10^{-5})$ for $\mathcal{B}(H \to e\mu)$ are obtained for a Higgs boson with mass 125 GeV. These are the first such searches made by the ATLAS Collaboration and are considerable improvements on previous measurements.

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