Measurements of properties of the Higgs boson in the four-lepton final state at $\sqrt{s} = 13$ TeV

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Abstract

Properties of the Higgs boson are measured in the $H \rightarrow ZZ \rightarrow 4\ell$ ($\ell = e, \mu$) decay channel. A data sample of proton-proton collisions at a center-of-mass energy of 13 TeV is used, corresponding to an integrated luminosity of 41.5 fb$^{-1}$ recorded in 2017 by the CMS detector at the LHC. The signal-strength modifier $\mu$, defined as the ratio of the observed Higgs boson rate in the $H \rightarrow ZZ \rightarrow 4\ell$ decay channel to the standard model expectation, is measured to be $\mu = 1.10^{+0.19}_{-0.17}$ at $m_H = 125.09$ GeV, the combined ATLAS and CMS measurement of the Higgs boson mass. The signal-strength modifiers for the main Higgs boson production modes are also constrained. Combination with data recorded in 2016 by the CMS detector at a center-of-mass energy of 13 TeV corresponding to an integrated luminosity of 35.9 fb$^{-1}$ is reported. All results are found to be compatible with the standard model predictions.
1 Introduction

The ATLAS and CMS Collaborations first reported the discovery of a new particle in 2012 [1, 2] consistent with the standard model (SM) Higgs boson [3–8]. Subsequent studies by CMS using the full LHC Run 1 data in various decay channels and production modes, combined measurements from ATLAS and CMS as well as combination of the CMS results with Run 2 data from 2016 [9–13] showed that the properties of the new boson are so far consistent with expectations for the SM Higgs boson.

The $H \rightarrow ZZ \rightarrow 4\ell$ decay channel ($\ell = e, \mu$) has a large signal-to-background ratio due to the complete reconstruction of the final state decay products and excellent lepton momentum resolution. This makes it one of the most important channels for studies of the Higgs boson’s properties. Measurements performed using this decay channel and the Run 1 and Run 2 data set include the determination of the mass and spin-parity of the new boson [14–16], its width [17, 18] and fiducial cross sections [19, 20], and the tensor structure of its interaction with a pair of neutral gauge bosons [16, 18, 21].

This note presents measurements of properties of the Higgs boson in the $H \rightarrow ZZ \rightarrow 4\ell$ decay channel at $\sqrt{s} = 13$ TeV using 2017 data. Several improvements are introduced compared to the previous CMS analysis [20]: a new multivariate tool enhancing the selection of electrons, new kinematic discriminants developed to better extract the signal produced via vector boson fusion or in association with a vector boson and new categories targeting the production of Higgs boson in association with top quarks. A combination with 2016 data is also reported.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. An entirely new pixel detector has been installed in 2016, featuring a full silicon device with 4 layers in the barrel and 3 disks in the endcaps [22], providing a four hits coverage system and reduced material budget in front of the calorimeters. Forward calorimeters extend the pseudorapidity ($\eta$) coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [23].

3 Data and simulated samples

This analysis makes use of pp collision data recorded in 2017 by the CMS detector corresponding to an integrated luminosity of 41.5 fb$^{-1}$. Collision events are selected by high-level trigger algorithms that require the presence of leptons passing loose identification and isolation requirements. The main triggers of this analysis select either a pair of electrons or muons, or an electron and a muon. The minimal transverse momentum of the leading electron (muon) is 23(17) GeV, while that of the subleading lepton is 12(8) GeV. To maximize the coverage of the $H \rightarrow 4\ell$ phase space, triggers requiring three leptons with relaxed $p_T$ thresholds and no isolation requirement are also used, as are isolated single-electron and single-muon triggers with thresholds of 35 GeV and 27 GeV, respectively. The overall trigger efficiency for simulated
signal events that pass the full selection chain of this analysis is larger than 99%. The trigger efficiency is measured in data using a sample of 4ℓ events collected by the single-lepton triggers and is found to be in agreement with the expectation from simulation.

Monte Carlo (MC) simulation samples for the signals and the relevant background processes are used to estimate backgrounds, optimize the event selection, and evaluate the acceptance and systematic uncertainties. The SM Higgs boson signals are generated at next-to-leading order (NLO) in perturbative QCD (pQCD) with the **POWHEG 2.0** [24–26] generator for the five main production modes: gluon fusion (ggH), vector boson fusion (VBF) and associated production (WH, ZH and t¯tH). For WH and ZH the **MINLO HVJ** [27] extension of **POWHEG 2.0** is used. The cross section for the dominant gluon fusion production mode is taken from Ref. [28]. Two other production modes, bbH and tqH, are generated using **JHUGEN** [29–32]. In all cases, the decay of the Higgs boson to four leptons is modeled with **JHUGEN** [29, 30].

The SM ZZ background contribution from quark-antiquark annihilation is generated at NLO pQCD with **POWHEG 2.0**, while the gg → ZZ process is generated at leading order (LO) with **MCFM** [33]. Reducible background is estimated from data as described in section 7.2.

The default parton distribution functions (PDF) used are NNPDF31nlo_hessian_pdfs and NNPDF31_lo_as_0130 [34] for NLO and LO simulations, respectively. All signal and background event generators are interfaced with **PYTHIA 8** [35] tune CUETP8M1 [36] to simulate the multi-parton interaction and hadronization effects. The generated events are processed through a detailed simulation of the CMS detector based on **GEANT4** [37, 38] and are reconstructed with the same algorithms that are used for data. The simulated events include overlapping pp interactions (pileup) and have been reweighted so that the distribution of the number of interactions per LHC bunch crossing in simulation matches that observed in data.

### 4 Event reconstruction and selection

The particle-flow algorithm [39] aims to reconstruct and identify each individual particle in an event, with an optimized combination of information from the various elements of the CMS detector. The energy of photons is directly obtained from the ECAL measurement, corrected for zero-suppression effects. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energy.

Muons within the geometrical acceptance |ηµ| < 2.4 and pTµ > 5 GeV are reconstructed by combining information from the silicon tracker and the muon system [40]. The matching between the inner and outer tracks proceeds either outside-in, starting from a track in the muon system, or inside-out, starting from a track in the silicon tracker. Tracker tracks that match track segments in only one or two stations of the muon system are also considered in the analysis to collect very low-pT muons that may not have sufficient energy to penetrate the entire muon system. The muons are selected among the reconstructed muon track candidates by applying minimal requirements on the track in both the muon system and inner tracker system, and taking into account compatibility with small energy deposits in the calorimeters.
To discriminate prompt muons from Z boson decay from those arising from electroweak decays of hadrons within jets, an isolation requirement of $I^\mu < 0.35$ is imposed, where the relative isolation is defined as

$$I^\mu \equiv \left( \sum p_T^{\text{charged}} + \max \left[ 0, \sum p_T^{\text{neutral}} + \sum p_T^{\gamma_i} - p_T^{\text{PU}}(\mu) \right] \right) / p_T^{\mu}. \quad (1)$$

In Eq. 1, $\sum p_T^{\text{charged}}$ is the scalar sum of the transverse momenta of charged hadrons originating from the chosen primary vertex of the event. The $\sum p_T^{\text{neutral}}$ and $\sum p_T^{\gamma_i}$ are the scalar sums of the transverse momenta for neutral hadrons and photons, respectively. Since the isolation variable is particularly sensitive to undesirable energy deposits from pileup interactions, a $p_T^{\text{PU}}(\mu)$ contribution is subtracted. We define $p_T^{\text{PU}}(\mu) \equiv 0.5 \sum p_T^{\text{PU},i}$ where $i$ runs over the momenta of the charged hadron PF candidates not originating from the primary vertex, and the factor of 0.5 corrects for the different fraction of charged and neutral particles in the cone. The isolation sums involved are all restricted to a volume bounded by a cone of angular radius $\Delta R = 0.3$ around the muon direction at the primary vertex, where the angular distance between two particles $i$ and $j$ is $\Delta R(i,j) = \sqrt{(\eta^i - \eta^j)^2 + (\phi^i - \phi^j)^2}$. An algorithm is used to collect the final-state radiation (FSR) of leptons. Photons which are selected are excluded from the isolation computation of selected muons in the event.

Electrons are reconstructed within the geometrical acceptance defined by pseudorapidity $|\eta^e| < 2.5$ and for transverse momentum $p_T^e > 7$ GeV with an algorithm that combines information from the ECAL and the tracker [41]. Electrons are identified using a multivariate discriminant which includes observables sensitive to the presence of bremsstrahlung along the electron trajectory, the geometrical and momentum-energy matching between the electron trajectory and the associated cluster in the ECAL, the shape of the electromagnetic shower in the ECAL, and variables that discriminate against electrons originating from photon conversions. It now also includes the isolation sums described above ($\sum p_T^{\text{charged}}, \sum p_T^{\text{neutral}},$ and $\sum p_T^{\gamma_i}$) but computed around the electron direction. It helps suppressing electrons originating from electroweak decays of hadrons within jets [42]. The reduced material budget induced by the upgrade of the pixel detector impacts the electron profile in the endcaps, with less radiated photons and less electrons from photon conversion. This, together with the improved multivariate discriminant strongly diminish the misidentification of electrons.

The training and optimization of the multivariate discriminant used for electron identification are performed using simulation and are divided into six regions formed from two transverse momentum ranges (7–10 GeV and >10 GeV) and three pseudorapidity regions: central barrel ($|\eta^e| < 0.8$), outer barrel ($0.8 < |\eta^e| < 1.479$), and endcaps ($1.479 < |\eta^e| < 2.5$).

In order to suppress muons originating from in-flight decays of hadrons and electrons from photon conversions, we require each lepton track to have a 3D impact parameter significance with respect to the primary vertex less than 4. The reconstructed vertex with the largest value of summed physics-object $p_T^2$ is taken to be the primary pp interaction vertex. The physics objects are the jets, clustered using the jet finding algorithm [43, 44] with the tracks assigned to the vertex as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the $p_T$ of those jets.

The momentum scale and resolution of electrons and muons are calibrated in bins of $p_T^\ell$ and $\eta^\ell$ using the decay products of known dilepton resonances. The lepton momentum scale in data is corrected with a $Z \rightarrow \ell^+\ell^-$ sample, by matching the peak of the reconstructed dilepton mass spectrum to the known value of $m_{Z}$, and a pseudorandom Gaussian smearing is applied to lepton energies in simulation to make the $Z \rightarrow \ell^+\ell^-$ mass resolution in simulation match...
the one in data.

A “tag and probe” technique using samples of Z boson events in data and simulation is used to measure the efficiency of the reconstruction and selection for prompt electrons and muons in several bins of $p_T^\ell$ and $\eta^\ell$. The difference in the efficiencies measured in simulation and data is used to rescale the yields of selected events in the simulated samples.

For each event, hadronic jets are clustered from the reconstructed particles using the infrared and collinear safe anti-$k_T$ algorithm [43, 44] with a distance parameter of 0.4. The jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be within 5 to 10% of the true momentum over the whole $p_T$ spectrum and detector acceptance. Additional proton-proton interactions within the same or nearby bunch crossings can contribute additional tracks and calorimetric energy depositions to the jet momentum. To mitigate this effect, tracks identified to be originating from pileup vertices are discarded and an offset correction is applied to correct for remaining contributions. Jet energy corrections are derived from simulation to bring measured response of jets to that of particle level jets on an average. In situ measurements of the momentum balance in dijet, photon + jet, $Z + \text{jet}$, and multijet events are used to account for any residual differences in jet energy scale in data and simulation [45]. The jet energy resolution amounts typically to 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV. Additional selection criteria are applied to each jet to remove jets potentially dominated by anomalous contributions from various subdetector components or reconstruction failures. To be considered in the analysis, jets must satisfy $p_T^\text{jet} > 30$ GeV and $|\eta^\text{jet}| < 4.7$, and be separated from all selected lepton candidates and any selected FSR photons by $\Delta R(\ell/\gamma, \text{jet}) > 0.4$. Jets are also requested to pass tight cut-based jet identification with efficiency > 99% and to pass tight working point of pileup jet identification [46].

For event categorization, jets are tagged as b-jets using the DeepCSV algorithm [47] which combines information about impact parameter significance, the secondary vertex, and jet kinematics. Data to simulation scale factors for the b-tagging efficiency are applied as a function of jet $p_T$, $\eta$ and flavor.

The event selection is designed to extract signal candidates from events containing at least four well-identified and isolated leptons, each originating from the primary vertex and possibly accompanied by an FSR photon candidate. In what follows, unless otherwise stated, FSR photons are included in invariant mass computations.

First, Z candidates are formed with pairs of leptons of the same flavor and opposite-charge ($e^+e^-, \mu^+\mu^-$) and required to pass $12 < m_{\ell^+\ell^-} < 120$ GeV. They are then combined into ZZ candidates, wherein we denote as $Z_1$ the Z candidate with an invariant mass closest to the nominal Z boson mass [48], and as $Z_2$ the other one. The flavors of involved leptons define three mutually exclusive subchannels: 4e, 4$\mu$ and 2e2$\mu$.

To be considered for the analysis, ZZ candidates have to pass a set of kinematic requirements that improve the sensitivity to Higgs boson decays. The $Z_1$ invariant mass must be larger than 40 GeV. All leptons must be separated in angular space by at least $\Delta R(\ell_i, \ell_j) > 0.02$. At least two leptons are required to have $p_T > 10$ GeV and at least one is required to have $p_T > 20$ GeV. In the 4$\mu$ and 4e subchannels, where an alternative $Z_0Z_0$ candidate can be built out of the same four leptons, we discard candidates with $m_{Z_b} < 12$ GeV if $Z_0$ is closer to the nominal Z boson mass than $Z_1$ is. This protects against events that contain an on-shell Z and a low-mass dilepton resonance. To further suppress events with leptons originating from hadron decays in jet fragmentation or from the decay of low-mass resonances, all four opposite-charge lepton pairs that can be built with the four leptons (irrespective of flavor) are required.
to satisfy $m_{\ell^+\ell^-} > 4$ GeV, where selected FSR photons are disregarded in the invariant mass computation. Finally, the four-lepton invariant mass $m_{4\ell}$ must be larger than 70 GeV, which defines the mass range of interest for the subsequent steps of the analysis.

In events where more than one ZZ candidate passes the above selection, the candidate with the highest value of $D_{\text{kin}}^b$ (defined in Section 5) is retained, except if two candidates consist of the same four leptons in which case the candidate with the $Z_1$ mass closest to the nominal Z boson mass is retained.

## 5 Kinematic discriminants

The full kinematic information from each event using either the Higgs boson decay products or associated particles in its production is extracted using matrix element calculations and used to form several kinematic discriminants. These computations rely on the MELA package [1, 29–31] and use JHUGEN matrix elements for the signal and MCFM matrix elements for the background. Both H boson decay kinematics and kinematics of associated production of H+jet, H+2 jets, VBF, ZH, WH are explored in this analysis. The full event kinematics is described by decay observables $\vec{\Omega}_{H \rightarrow 4\ell}$ or observables describing associated production $\vec{\Omega}_{H+JJ}$.

The discriminant sensitive to the $gg/q\bar{q} \rightarrow 4\ell$ kinematics is calculated as [1, 16]

$$D_{\text{kin}}^b = \left[ 1 + \frac{P_{\text{bkg}}^{s|f} (\vec{\Omega}_{H \rightarrow 4\ell}|m_{4\ell})}{P_{\text{sig}}^{s|f} (\vec{\Omega}_{H \rightarrow 4\ell}|m_{4\ell})} \right]^{-1},$$

where $P_{\text{sig}}^{s|f}$ is the probability for the signal and $P_{\text{bkg}}^{s|f}$ is the probability for the dominant $q\bar{q} \rightarrow 4\ell$ background process, all calculated either with the JHUGEN or MCFM matrix elements within the MELA framework.

In VBF and VH-hadronic categories, the contamination from gluon fusion process is still significant. The new dedicated production-dependent $D_{\text{bkg}}$ discriminants used in the VBF-2jet tagged and hadronic VH tagged categories are then defined as:

$$D_{\text{VBF+dec}} = \frac{P_{\text{VBF+VH+dec}} (\vec{\Omega})}{P_{\text{VBF+VH+dec}} (\vec{\Omega}) + c_{\text{VBF2jet}} (m_{4\ell}) \times (P_{\text{VBS+VVV}} (\vec{\Omega}) + P_{\text{QCD+dec}} (\vec{\Omega}))},$$

$$D_{\text{VH+dec}} = \frac{P_{\text{VBF+VH+dec}} (\vec{\Omega})}{P_{\text{VBF+VH+dec}} (\vec{\Omega}) + c_{\text{had.VH}} (m_{4\ell}) \times (P_{\text{VBS+VVV}} (\vec{\Omega}) + P_{\text{QCD+dec}} (\vec{\Omega}))},$$

where $P_{\text{VBF+VH+dec}}$ is the probability for VBF and VH signal, $P_{\text{VBS+VVV}}$ is the probability for vector boson scattering and tri-boson background, $P_{\text{QCD+dec}}$ is the probability for QCD production and $c^p (m_{4\ell})$ for category $p$ is the $m_{4\ell}$-dependent constant to calibrate the distribution.

A test of new discriminants was performed, running the full statistical analysis. The likelihood scans for the expected signal strength modifiers corresponding to the five main Higgs production modes were computed using $D_{\text{kin}}^b$ as a second dimension in all categories and using new kinematic discriminants with jet information in their dedicated categories instead. An improvement in sensitivity of about 10 to 15% was observed.

Four discriminants calculated following prescription in Ref. [18, 49] are used to enhance the purity of event categories as described in Section 6. The discriminant sensitive to the VBF
signal topology with two associated jets, the VBF signal topology with one associated jet, and to the VH (either ZH or WH) signal topology with two associated jets are

\[ D_{2\text{jet}} = \left[ 1 + \frac{\mathcal{P}_{\text{HJJ}}(\bar{Q}^{H+\text{JJ}}|m_{4\ell})}{\mathcal{P}_{\text{VBF}}(\bar{Q}^{H+\text{JJ}}|m_{4\ell})} \right]^{-1} \]

\[ D_{1\text{jet}} = \left[ 1 + \frac{\mathcal{P}_{\text{HJJ}}(\bar{Q}^{H+\text{JJ}}|m_{4\ell})}{\mathcal{P}_{\text{VH}}(\bar{Q}^{H+\text{JJ}}|m_{4\ell})} \right]^{-1} \]

\[ D_{\text{VH}} = \left[ 1 + \frac{\mathcal{P}_{\text{HJJ}}(\bar{Q}^{H+\text{JJ}}|m_{4\ell})}{\mathcal{P}_{\text{VH}}(\bar{Q}^{H+\text{JJ}}|m_{4\ell})} \right]^{-1} \]

\[ D_{\text{ZH}} = \left[ 1 + \frac{\mathcal{P}_{\text{HJJ}}(\bar{Q}^{H+\text{JJ}}|m_{4\ell})}{\mathcal{P}_{\text{ZH}}(\bar{Q}^{H+\text{JJ}}|m_{4\ell})} \right]^{-1} \]

where \( \mathcal{P}_{\text{VBF}}, \mathcal{P}_{\text{HJJ}}, \mathcal{P}_{\text{HJ}} \) and \( \mathcal{P}_{\text{VH}} \) are probabilities obtained from the JHUGEN matrix elements for the VBF process, the gluon fusion (technically combination of gg/qg/qq’ parton collisions) in association with two jets (H + 2jets), the gluon fusion in association with one jet (H + 1jet), and the VH process. The \( \int d\eta \mathcal{P}_{\text{VBF}} \) is the integral of the two-jet VBF matrix element probability discussed above over the \( \eta \) values of the unobserved jet with the constraint that the total transverse momentum of the H + 2jets system is zero.

### 6 Event categorization

In order to improve the sensitivity to the Higgs boson production mechanisms, the selected events are classified into mutually exclusive categories. Category definitions exploit the multiplicity of jets, b-tagged jets and additional leptons (defined as leptons that are not involved in the ZZ candidate selection and that pass identification, vertex compatibility, and isolation requirements), and requirements on the kinematic discriminants described in Section 5.

Seven categories are defined, using the following criteria applied in this exact order (i.e. an event is considered for the subsequent category only if it does not satisfy the requirements of the previous category):

- **VBF-2jet-tagged category** requires exactly 4 leptons. In addition there must be either 2 or 3 jets of which at most 1 is b-tagged, or at least 4 jets and no b-tagged jets. Finally, \( D_{2\text{jet}} > 0.5 \) is required.
- **VH-hadronic-tagged category** requires exactly 4 leptons. In addition there must be 2 or 3 jets, or at least 4 jets and no b-tagged jets. Finally, \( D_{\text{VH}} \equiv \max(D_{\text{ZH}}, D_{\text{WH}}) > 0.5 \) is required.
- **VH-leptonic-tagged category** requires no more than 3 jets and no b-tagged jets in the event, and exactly 1 additional lepton or 1 additional pair of opposite sign same flavor leptons. This category also includes events with no jets and at least 1 additional lepton.
- **t\bar{t}H-hadronic-tagged category** requires at least 4 jets of which at least 1 is b-tagged and no additional leptons.
- **t\bar{t}H-leptonic-tagged category** requires at least 1 additional lepton in the event.
- **VBF-1jet-tagged category** requires exactly 4 leptons, exactly 1 jet and \( D_{1\text{jet}} > 0.5 \).
- **Untagged category** consists of the remaining events.

Figure 1 shows the signal relative purity of the seven event categories in terms of Higgs boson production processes. The VBF-1jet-tagged and VH-hadronic-tagged categories are expected to have substantial contamination from gluon fusion, while the purity of the VBF process in the VBF-2jet-tagged category is expected to be about 49%. The purity of the t\bar{t}H process in the t\bar{t}H-leptonic-tagged category is expected to be about 87%.
7. Background estimation

7.1 Irreducible backgrounds

The irreducible background to the Higgs boson signal in the 4\ell channel, which come from the production of ZZ via q\bar{q} annihilation or gluon fusion, is estimated using simulation. The fully differential cross section for the q\bar{q} \rightarrow ZZ process has been computed at NNLO [50], and the NNLO/NLO K factor as a function of m_{ZZ} has been applied to the POWHEG sample. This K factor varies from 1.0 to 1.2 and is 1.1 at m_{ZZ} = 125 GeV. Additional NLO electroweak corrections which depend on the initial state quark flavor and kinematics are also applied in the region m_{ZZ} > 2m_{Z} where the corrections have been computed [51].

The production of ZZ via gluon fusion contributes at NNLO in pQCD. It has been shown [52] that the soft collinear approximation is able to describe the background cross section and the interference term at NNLO. Further calculations also show that the K factors are very similar at NLO for the signal and background [53] and at NNLO for the signal and interference terms [54]. Therefore, the same K factor is used for the signal and background [55]. The NNLO K factor for the signal is obtained as a function of m_{ZZ} using the HNNLO v2 program [56–58] by calculating the NNLO and LO gg → H → 2\ell 2\ell' cross sections at the small H boson decay width of 4.07 MeV and taking their ratios. The NNLO/LO K factor for gg → ZZ varies from 2.0 to 2.6 and is 2.27 at m_{ZZ} = 125 GeV, and a systematic uncertainty of 10% on its determination when applied to the background process is used in the analysis.

7.2 Reducible backgrounds

Additional backgrounds to the Higgs boson signal in the 4\ell channel arise from processes in which heavy-flavor jets produce secondary leptons, and also from processes in which decays of heavy-flavor hadrons, in-flight decays of light mesons within jets, or (for electrons) the decay of...
charged hadrons overlapping with $\pi^0$ decays are misidentified as leptons. The main processes producing these backgrounds are $Z + \text{jets}$, $t\bar{t} + \text{jets}$, $Z\gamma + \text{jets}$, $WW + \text{jets}$, and $WZ + \text{jets}$. We denote these reducible backgrounds as “Z+X” since they are dominated by the $Z + \text{jets}$ process. The contribution from the reducible background is estimated using two independent methods having dedicated control regions in data. The control regions are defined by a dilepton pair satisfying all the requirements of a $Z_1$ candidate and two additional leptons, opposite sign (OS) or same sign (SS), satisfying certain relaxed identification requirements when compared to those used in the analysis. These four leptons are then required to pass the analysis ZZ candidate selection. The event yield in the signal region is obtained by weighting the control region events by the lepton misidentification probability $f$, defined as the fraction of non-signal leptons which are identified by the analysis selection criteria. A detailed description of both methods can be found in Ref. [20].

The lepton misidentification rates $f_e$ and $f_\mu$ are measured by forming a sample which includes a $Z_1$ candidate consisting of a pair of leptons, both passing the selection requirements used in the analysis, and exactly one additional lepton passing the relaxed selection. For the OS method, the mass of the $Z_1$ candidate is required to satisfy $|Z_1 - m_Z| < 7$ GeV in order to reduce the contribution of (asymmetric) photon conversions which is estimated separately. In the SS method, the contribution of photon conversions to the misidentification rate is estimated with dedicated samples and corrected for. Furthermore, the $p_T^{\text{miss}}$ is required to be less than 25 GeV in order to suppress contamination from WZ and $t\bar{t}$ processes.

### 7.2.1 Prediction and uncertainties

The predicted yield in the signal region of the reducible background from the two methods are in agreement within their statistical uncertainties, and since they are mutually independent, the results of the two methods are combined. The shape of the $m_4\ell$ distribution for the reducible background is obtained by combining the prediction from the OS and SS methods and fitting the distributions with empirical functional forms built from Landau [59] and exponential distributions.

The dominant systematic uncertainty on the reducible background estimation arises from the limited number of events in the control regions as well as in the region where the misidentification rates are computed. Additional sources of systematic uncertainty arise from the difference in the composition of the sample from which the misidentification rate is computed and the control regions of the two methods where the misidentification rate is applied.

### 8 Signal modeling

In order to generate an accurate signal model, the $p_T$ spectrum of the Higgs ($p_T(H)$) boson was tuned in the POWHEG simulation of the dominant gluon fusion production mode to better match predictions from full phase space calculations implemented in the HRES 2.3 generator [58, 60, 61].

In order to take advantage of the most accurate simulation of ggH available, a reweighting is defined. Gluon fusion events are separated into 0, 1, 2, and $\geq 3$ jet bins, where the jets used for counting are clustered from all stable particles, excluding the decay products of the Higgs boson or associated vector bosons, and have $p_T > 30$ GeV. The sum of weights in each sample are first normalized to the inclusive cross section. The ratio of the $p_T(H)$ distribution from the NNLOPS generator [62] to that from the POWHEG generator in each jet bin is applied to the ggH signal samples.
9. Systematic uncertainties

The signal lineshape of a narrow resonance around \( m_H \sim 125 \text{ GeV} \) is parametrized using a double-sided Crystal Ball function \([14]\). In addition, a Landau function is also added in the total probability density function for the non-resonant part of the signal for the case of WH, ZH and \( t\bar{t}H \) production modes. The signal lineshape is parametrized as a function of \( m_H \) by performing a simultaneous fit of several mass points for ggH production in mass range from 105 GeV to 140 GeV. Each parameter of the double-sided Crystal Ball function is given a linear dependence on \( m_H \) for a total of 12 free parameters. The correlation amongst these 12 parameters is checked and parameters are dropped to remove large correlations, or if they are constant within the uncertainty.

9 Systematic uncertainties

The experimental uncertainties common to all final states include the uncertainty in the integrated luminosity (2.3%) and the uncertainty in the lepton identification and reconstruction efficiency (ranging from 3 to 12.5% on the overall event yield for the 4\( \mu \) and 4\( e \) channels, respectively), which affect both signal and background. Experimental uncertainties in the reducible background estimation, described in Section 7.2, originating from the background composition and fake rate uncertainty vary between 31 and 43% depending on the final state and category.

The uncertainty in the lepton energy scale is determined by considering the \( Z \to \ell\ell \) mass distributions in data and simulation. Events are separated into categories based on the \( p_T \) and \( \eta \) of one of the two leptons, determined randomly, and integrating over the other. The dilepton mass distributions are then fit by a Breit-Wigner parameterization convolved with a double-sided Crystal Ball function.

Theoretical uncertainties which affect both the signal and background estimation include uncertainties from the renormalization and factorization scale and choice of PDF set. The uncertainty from the renormalization and factorization scale is determined by varying these scales between 0.5 and 2 times their nominal value while keeping their fraction between 0.5 and 2. The uncertainty from the PDF set is determined by taking the root mean square of the variation when using different replicas of the default NNPDF set. An additional uncertainty of the 10% in the K factor used for the gg \( \to ZZ \) prediction is applied as described in Section 7.1. A systematic uncertainty of 2\% [63] in the branching fraction of H \( \to 4\ell \) only affects the signal yield. The theoretical uncertainties on the background yield are included for all measurements, while the theoretical uncertainties on the overall signal yield are not included in the measurement uncertainties when cross sections, rather than signal strengths, are extracted.

The ggH cross section uncertainty scheme has been updated to the one proposed in Ref. [63]. This uncertainty scheme includes 9 nuisance parameters accounting for uncertainties in the cross section prediction for exclusive jet bins (including the migration between the 0 and 1-jet, as well as between the 1 and \( \geq 2 \)-jet bins), the 2 jet and \( \geq 3 \) jet VBF phase spaces, different \( p_T (H) \) regions, and the uncertainty in the \( p_T (H) \) distribution due to missing higher order finite top quark mass corrections.

All experimental and theoretical uncertainties which account for possible migration of signal and background events between categories are included. The main sources of uncertainty on the event categorization include the renormalization and the factorization scales, the choice of the PDF set, and the modeling of hadronization and the underlying event. These uncertainties amount to between 2 and 40% for main production modes depending on the category. The lower range corresponds to the VBF and VH processes in their dedicated categories and the upper range corresponds to the ggH process yield in the VBF-2jet-tagged category. Additional uncertainties come from the imprecise knowledge of the jet energy scale (from 2% for the ggH...
yield in the untagged category to 22% for ggH yield in the VBF-2jet-tagged category) and b-
tagging efficiency and light quarks (u, d, s, c) and gluon jet mistag rate (up to 11% in the ttH-hadronic-tagged category).

10 Results

The reconstructed four-lepton invariant mass distribution is shown in Fig. 2 for the sum of the 4e, 4μ and 2e2μ subchannels, and compared with the expectations from signal and background processes. The error bars on the data points correspond to the so-called Garwood confidence intervals at 68% confidence level (CL) [64]. The observed distribution agrees with the expectation within the statistical uncertainties over the whole spectrum. In Fig. 3, the reconstructed four-lepton invariant mass distributions are split by event category, for the low-mass range.

Figure 2: Distribution of the four-lepton reconstructed invariant mass \( m_{4\ell} \) in the full mass range (left) and the low-mass range (right). Points with error bars represent the data and stacked histograms represent expected distributions of the signal and background processes. The SM Higgs boson signal with \( m_H = 125 \text{ GeV} \), denoted as H(125), and the ZZ backgrounds are normalized to the SM expectation, the Z+X background to the estimation from data. The order in perturbation theory used for the normalization of the irreducible backgrounds is described in Section 7.1. No events are observed with \( m_{4\ell} > 1.1 \text{ TeV} \).

The number of candidates observed in data and the expected yields for the backgrounds and Higgs boson signal after the full event selection are reported in Table 1 for the full range of \( m_{4\ell} \). Table 2 shows the expected and observed yields for each of the seven event categories.

The reconstructed dilepton invariant masses selected as Z1 and Z2 are shown in Fig. 4 for 118 < \( m_{4\ell} \) < 130 GeV, with their correlation. The distribution of the discriminants used for event categorization along with the corresponding working point values are shown in Fig. 5. The correlation of the kinematic discriminants \( D_{\text{kin}} \), \( D_{\text{VBF}+\text{dec}} \) and \( D_{\text{VH}+\text{dec}} \) with the four-lepton invariant mass is shown in Fig. 6. Their distributions for 118 < \( m_{4\ell} \) < 130 GeV are shown in Fig. 7.

10.1 Signal strength

To extract the signal strength for the excess of events observed in the Higgs boson peak region, we perform a multi-dimensional fit that relies on two variables: the four-lepton invariant mass
Figure 3: Distribution of the four-lepton reconstructed mass in the seven event categories for the low-mass range. (a) untagged category (b) VBF-1jet-tagged category (c) VBF-2jet-tagged category (d) VH-hadronic-tagged category (e) VH-leptonic-tagged category (f) tH-hadronic-tagged category (g) tH-leptonic-tagged category. Points with error bars represent the data and stacked histograms represent expected distributions of the signal and background processes. The SM Higgs boson signal with \( m_H = 125 \) GeV, denoted as H(125), and the ZZ backgrounds are normalized to the SM expectation, the Z+X background to the estimation from data. For the categories other than the untagged category, the SM Higgs boson signal is separated into two components: the production mode that is targeted by the specific category, and other production modes, where the gluon fusion process dominates. The order in pertubation theory used for the normalization of the irreducible backgrounds is described in Section 7.1.
Table 1: The number of expected background and signal events and number of observed candidates after full analysis selection, for each final state, for the full mass range $m_4\ell > 70$ GeV and for an integrated luminosity of 41.5 fb$^{-1}$. Signal and ZZ backgrounds are estimated from Monte Carlo simulation, Z+X is estimated from data. The uncertainties include both statistical and systematic sources.

<table>
<thead>
<tr>
<th>Channel</th>
<th>4e</th>
<th>4µ</th>
<th>2e2µ</th>
<th>4ℓ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q\bar{q} \to ZZ$</td>
<td>$235^{+32}_{-26}$</td>
<td>$443^{+36}_{-40}$</td>
<td>$572^{+50}_{-53}$</td>
<td>$1250^{+104}_{-114}$</td>
</tr>
<tr>
<td>$gg \to ZZ$</td>
<td>$49.1^{+8.7}_{-8.8}$</td>
<td>$81.8^{+11.2}_{-12.7}$</td>
<td>$121.5^{+13.1}_{-16.3}$</td>
<td>$252.4^{+33.5}_{-21.3}$</td>
</tr>
<tr>
<td>$Z + X$</td>
<td>$17.1^{+6.4}_{-6.1}$</td>
<td>$35.4^{+11.4}_{-11.4}$</td>
<td>$47.8^{+16.4}_{-15.8}$</td>
<td>$100.3^{+20.6}_{-20.6}$</td>
</tr>
<tr>
<td>Sum of backgrounds</td>
<td>$301^{+30}_{-33}$</td>
<td>$560^{+43}_{-47}$</td>
<td>$741^{+62}_{-65}$</td>
<td>$1602^{+126}_{-135}$</td>
</tr>
<tr>
<td>Signal ($m_H = 125$ GeV)</td>
<td>$13.9^{+1.9}_{-2.1}$</td>
<td>$28.9^{+2.3}_{-2.6}$</td>
<td>$35.8 \pm 3.3$</td>
<td>$78.5^{+7.7}_{-7.1}$</td>
</tr>
<tr>
<td>Total expected</td>
<td>$315^{+41}_{-45}$</td>
<td>$589^{+45}_{-49}$</td>
<td>$777^{+67}_{-69}$</td>
<td>$1681^{+131}_{-140}$</td>
</tr>
<tr>
<td>Observed</td>
<td>307</td>
<td>602</td>
<td>797</td>
<td>1706</td>
</tr>
</tbody>
</table>

Figure 4: Distribution of the $Z_1$ (left) and $Z_2$ (center) reconstructed invariant masses and correlation between the two (right) in the mass region $118 < m_4\ell < 130$ GeV. The stacked histograms and the gray scale represent expected distributions of the signal and background processes, and points represent the data. The SM Higgs boson signal with $m_H = 125$ GeV, denoted as H(125), and the ZZ backgrounds are normalized to the SM expectation, the Z+X background to the estimation from data. The order in perturbation theory used for the normalization of the irreducible backgrounds is described in Section 7.1.

$m_{4\ell}$ and the $D_{bkg}^{\text{kin}}$ discriminant. We define the two-dimensional likelihood function as:

$$L_{2D}(m_{4\ell}, D_{bkg}^{\text{kin}}) = L(m_{4\ell})L(D_{bkg}^{\text{kin}} | m_{4\ell}).$$

(5)

The kinematic discriminant is different for each category. In VBF-2jet-tagged category we use $D_{bkg}^{\text{VBF+dec}}$ which is sensitive to the VBF production mechanism. Similarly, in VH-hadronic-tagged the $D_{bkg}^{\text{VH+dec}}$ discriminant is used. In all other categories we use a decay only kinematic discriminant to separate Higgs signal from the SM background. The mass dimension is unbinned and uses the model described in Section 8. The conditional 2D term is implemented by creating a two-dimensional template of $m_{4\ell}$ vs. $D_{bkg}^{\text{kin}}$ normalized to 1 for each bin of $m_{4\ell}$. Gluon fusion, VBF, WH and ZH samples are used to build different templates for each of the corresponding production modes. For all other production modes gluon fusion templates are used. Based on the seven event categories and the three final states ($4\mu$, $4e$, $2e2\mu$), the ($m_{4\ell}, D_{bkg}^{\text{kin}}$) unbinned distributions of selected events are split into 21 categories.
Table 2: The number of expected background and signal events and number of observed candidates after full analysis selection, for each event category, for the mass range 118 < m_{H} < 130 GeV and for an integrated luminosity of 41.5 fb^{-1}. The yields are given for the different production modes. Signal and ZZ backgrounds are estimated from Monte Carlo simulation, Z+X is estimated from data. The uncertainties include both statistical and systematic sources.

<table>
<thead>
<tr>
<th>Event Category</th>
<th>Untagged</th>
<th>VBF-1j</th>
<th>VBF-2j</th>
<th>VH-lept.</th>
<th>VH-hadr.</th>
<th>ttH-lept.</th>
<th>ttH-hadr.</th>
<th>Inclusive</th>
</tr>
</thead>
<tbody>
<tr>
<td>q\bar{q} → ZZ</td>
<td>22.72</td>
<td>1.91</td>
<td>0.13</td>
<td>0.23</td>
<td>0.19</td>
<td>0.00</td>
<td>0.01</td>
<td>25.19</td>
</tr>
<tr>
<td>gg → ZZ</td>
<td>1.93</td>
<td>0.30</td>
<td>0.03</td>
<td>0.04</td>
<td>0.02</td>
<td>0.00</td>
<td>0.00</td>
<td>2.32</td>
</tr>
<tr>
<td>Z + X</td>
<td>9.60</td>
<td>0.80</td>
<td>0.56</td>
<td>0.17</td>
<td>0.56</td>
<td>0.04</td>
<td>0.15</td>
<td>11.87</td>
</tr>
<tr>
<td>Sum of backgrounds</td>
<td>34.25</td>
<td>3.00</td>
<td>0.72</td>
<td>0.44</td>
<td>0.77</td>
<td>0.04</td>
<td>0.16</td>
<td>39.38</td>
</tr>
<tr>
<td>Uncertainties</td>
<td>+2.79</td>
<td>+0.30</td>
<td>+0.14</td>
<td>+0.04</td>
<td>+0.12</td>
<td>-0.01</td>
<td>-0.10</td>
<td>+3.29</td>
</tr>
</tbody>
</table>

| | ggH | 46.94 | 9.90 | 1.74 | 0.06 | 1.29 | < 0.01 | 0.04 | 59.96 |
| q\bar{q} → q\bar{q}H | 1.68 | 1.57 | 1.89 | 0.01 | 0.08 | < 0.01 | 0.01 | 5.24 |
| WH-lep | 0.18 | 0.02 | 0.01 | 0.28 | 0.01 | 0.01 | < 0.01 | 0.50 |
| WH-had | 0.48 | 0.16 | 0.05 | 0.00 | 0.32 | < 0.01 | 0.01 | 1.02 |
| ZH-lep | 0.29 | 0.02 | 0.01 | 0.07 | 0.03 | < 0.01 | < 0.01 | 0.43 |
| ZH-had | 0.32 | 0.10 | 0.03 | 0.00 | 0.23 | < 0.01 | 0.01 | 0.69 |
| t\bar{t}H | 0.11 | < 0.01 | 0.02 | 0.03 | 0.04 | 0.18 | 0.25 | 0.65 |
| bbH | 0.48 | 0.10 | 0.02 | 0.01 | 0.02 | < 0.01 | < 0.01 | 0.63 |
| t\bar{t}H | 0.03 | < 0.01 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.09 |
| Signal | 50.51 | 11.87 | 3.79 | 0.47 | 2.03 | 0.20 | 0.33 | 69.21 |
| Uncertainties | +6.88 | +1.41 | +0.68 | +0.04 | +0.28 | +0.03 | +0.05 | +6.13 |

| | Total expected | 84.76 | 14.87 | 4.51 | 0.91 | 2.80 | 0.24 | 0.49 | 108.58 |
| Uncertainties | +6.52 | +1.59 | +0.74 | +0.07 | +0.32 | +0.03 | +0.11 | +8.21 |
| Observed | 103 | 14 | 5 | 2 | 2 | 0 | 0 | 126 |

Figure 5: Distribution of categorization discriminants in the mass region 118 < m_{H} < 130 GeV: (left) D_{2jet}, (middle) D_{1jet}, (right) D_{VH} = max(D_{WH}, D_{ZH}). Points with error bars represent the data and stacked histograms represent expected distributions of the signal and background processes. The SM Higgs boson signal with m_{H} = 125 GeV, denoted as H(125), and the ZZ backgrounds are normalized to the SM expectation, the Z+X background to the estimation from data. The vertical gray dashed lines denote the working points used in the event categorization. The SM Higgs boson signal is separated into two components: the production mode which is targeted by the specific discriminant, and other production modes, where the gluon fusion process dominates. The order in perturbation theory used for the normalization of the irreducible backgrounds is described in Section 7.1.
Figure 6: Distribution of three different kinematic discriminants versus $m_{4\ell}$: $D_{\text{kin}}^{bkg}$ (left), $D_{\text{VBF+dec}}^{bkg}$ (middle) and $D_{\text{VH+dec}}^{bkg}$ (right) shown in the mass region $100 < m_{4\ell} < 170\,\text{GeV}$. The gray scale represents the expected total number of ZZ and Z+X background and SM Higgs boson signal events for $m_H = 125\,\text{GeV}$. The points show the data and the horizontal bars represent the measured event-by-event mass uncertainties. Different marker styles are used to denote the categorization of the events.

Figure 7: Distribution of kinematic discriminants in the mass region $118 < m_{4\ell} < 130\,\text{GeV}$: (left) $D_{\text{kin}}^{bkg}$, (middle) $D_{\text{VBF+dec}}^{bkg}$, (right) $D_{\text{VH+dec}}^{bkg}$. Points with error bars represent the data and stacked histograms represent expected distributions of the signal and background processes. The SM Higgs boson signal with $m_H = 125\,\text{GeV}$, denoted as H(125), and the ZZ backgrounds are normalized to the SM expectation, the Z+X background to the estimation from data. The SM Higgs boson signal is separated into two components: the production mode which is targeted by the specific discriminant, and other production modes, where the gluon fusion process dominates.

A simultaneous fit to all categories is performed to extract the signal-strength modifier, defined as the ratio of the observed Higgs boson rate in the $H \rightarrow ZZ \rightarrow 4\ell$ decay channel to the standard model expectation. At $m_H = 125.09\,\text{GeV}$, the combined result is $\mu = \sigma/\sigma_{\text{SM}} = 1.10^{+0.14}_{-0.13}\text{(stat)} + 0.13\text{(syst)} = 1.10^{+0.19}_{-0.17}$, which is compared to the results for each of the seven event categories in Fig. 8 (top left). The observed values are consistent with 1 within the uncertainties. The dominant experimental sources of systematic uncertainty are the uncertainties in the lepton identification efficiencies and luminosity measurement, while the dominant theoretical sources are the uncertainty in the total gluon fusion cross section as well as the uncertainty in the category migration for the gluon fusion process. The contributions to the total uncer-
10. Results

A fit is performed for five signal-strength modifiers \(\mu_{ggH,b\bar{b}H,t\bar{t}H,tqH} \) controlling the contribution of the main SM Higgs boson production modes. The WH and ZH processes are merged, and then split based on the decay of the associated V into either VH hadronic decays or VH lepton decays. Contributions of the bbH and tqH production modes are also taken into account in the fit. The bbH contribution is floated together with gluon fusion and tqH production mode is floated with ttH.

The results are reported in Fig. 8 (top right) and compared to the expected signal-strength modifiers in Table 3.

<table>
<thead>
<tr>
<th></th>
<th>Inclusive</th>
<th>(\mu_{ggH,b\bar{b}H})</th>
<th>(\mu_{VBF})</th>
<th>(\mu_{VH\text{had}})</th>
<th>(\mu_{VH\text{lep}})</th>
<th>(\mu_{t\bar{t}H,tqH})</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Expected</strong></td>
<td>(1.00^{+0.14}_{-0.13})</td>
<td>(1.00^{+0.22}_{-0.20})</td>
<td>(1.00^{+1.19}_{-0.79})</td>
<td>(1.00^{+3.24}_{-1.00})</td>
<td>(1.00^{+3.36}_{-1.00})</td>
<td>(1.00^{+2.47}_{-1.00})</td>
</tr>
<tr>
<td><strong>Observed</strong></td>
<td>(1.10^{+0.24}_{-0.13})</td>
<td>(1.14^{+0.23}_{-0.20})</td>
<td>(1.12^{+1.19}_{-0.83})</td>
<td>(0.00^{+0.00}_{-0.00})</td>
<td>(2.23^{+2.12}_{-1.00})</td>
<td>(0.93^{+0.93}_{-0.00})</td>
</tr>
</tbody>
</table>

Two signal-strength modifiers \(\mu_{ggH,t\bar{t}H,b\bar{b}H,tqH}\) and \(\mu_{VBF,VH}\) are introduced as scale factors for the fermion and vector-boson induced contribution to the expected SM cross section. A two-dimensional fit is performed assuming a mass of \(m_H = 125.09\) GeV leading to the measurements of \(\mu_{ggH,t\bar{t}H,b\bar{b}H,tqH} = 1.11^{+0.23}_{-0.21}\) and \(\mu_{VBF,VH} = 1.00^{+0.06}_{-0.13}\). The 68% and 95% CL contours in the \((\mu_{ggH,t\bar{t}H,b\bar{b}H,tqH},\mu_{VBF,VH})\) plane are shown in Fig. 8 (bottom left).

We also present the results for simplified template cross sections, a measurement strategy detailed in the CERN Yellow Report 4 of the LHC-HXSWG [63]. In this measurement, the cross section for Higgs boson production in a simplified fiducial volume defined as \(|y_H| < 2.5\) for various sub-processes is extracted. The theoretical uncertainties on the overall signal cross sections are removed, while the theoretical uncertainties which can cause migration of events between the various categories are kept. The measured cross sections, normalized to the SM prediction (including the \(|y_H| < 2.5\) requirement) are also shown in Fig. 8 (bottom right). The dominant experimental sources of systematic uncertainty are the same as in the measurement of the signal strength, while the dominant theoretical source is the uncertainty in the category migration for the gluon fusion process.

10.2 Combination of 2016 and 2017 data

A combined fit of the signal-strength modifiers corresponding to the main SM Higgs boson production modes is performed. The most conservative scenario is taken under consideration where experimental and theoretical systematic uncertainties are assumed to be fully correlated between 2016 and 2017.

The reconstructed four-lepton invariant mass distribution combining 2016 and 2017 datasets is shown in Fig. 9 for the sum of the 4e, 4\(\mu\) and 2e2\(\mu\) subchannels, and compared with the expectations from signal and background processes.

The results for five signal-strength modifiers are reported in Fig. 10 (right) and compared to the expected signal-strength modifiers in Table 4. A two-dimensional fit is performed assuming a mass of \(m_H = 125.09\) GeV leading to the measurements of \(\mu_{ggH,t\bar{t}H,b\bar{b}H,tqH} = 1.12^{+0.16}_{-0.18}\) and \(\mu_{VBF,VH} = 0.60^{+0.62}_{-0.49}\). The 68% CL contours in the \((\mu_{ggH,t\bar{t}H,b\bar{b}H,tqH},\mu_{VBF,VH})\) plane are shown in Fig. 10 (left) for results with 2016, 2017 data and their combination.
Figure 8: (Top left) Observed values of the signal strength $\mu = \sigma / \sigma_{\text{SM}}$ for the seven event categories, compared to the combined $\mu$ shown as a vertical line with a filled band representing the uncertainty. The horizontal bars indicate the one standard deviation uncertainties. (Top right) Results of likelihood scans for the signal-strength modifiers corresponding to the main SM Higgs boson production modes, compared to the combined $\mu$ shown as a vertical line. The horizontal bars and the filled band indicate the $\pm 1\sigma$ uncertainties. The uncertainties include both statistical and systematic sources. (Bottom left) Result of the 2D likelihood scan for the $\mu_{\text{ggH, t}t\text{H},b\bar{b}\text{H},tt\text{H}}$ and $\mu_{\text{VBF,VH}}$ signal-strength modifiers. The solid and dashed contours show the 68% and 95% CL regions, respectively. The cross indicates the best-fit value, and the diamond represents the expected value for the SM Higgs boson. (Bottom right) Results of the fit for simplified template cross sections for the stage 0 sub-processes, normalized to the SM prediction.
11. Summary

Several measurements of Higgs boson production in the four-lepton final state at $\sqrt{s} = 13$ TeV have been presented, using data samples corresponding to an integrated luminosity of 41.5 fb$^{-1}$. The measured signal strength modifier is $\mu = 1.10^{+0.19}_{-0.17}$, and the measured signal strength modifiers associated with fermions and vector bosons are $\mu_{ggH, t\bar{t}H, bbH, tqH} = 1.11^{+0.23}_{-0.21}$ and $\mu_{VBF,VH} = 1.00^{+0.96}_{-0.71}$ respectively. Results based on data collected in 2016 and 2017 are combined and the measured signal strength modifier is $\mu = 1.06^{+0.15}_{-0.13}$. All results are consistent, within their uncertainties, with the expectations for the SM Higgs boson.

| Table 4: Expected and observed signal-strength modifiers for combined 2016 and 2017 data. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                 | $\mu_{ggH,bbH}$ | $\mu_{VBF}$    | $\mu_{VH,bbH}$ | $\mu_{VHF}$    | $\mu_{HT}$     |
| Expected        | 1.00 ± 0.10(stat) ±0.08(exp. syst) ±0.03(th. syst) | 1.00 ± 0.16 | 1.00 ± 0.26 | 1.00 ± 0.16 | 1.00 ± 0.16 | 1.00 ± 0.16 |
| Observed        | 1.06 ± 0.10(stat) ±0.08(exp. syst) ±0.06(th. syst) | 1.15 ± 0.18 | 0.69 ± 0.75 | 0.00 ± 0.16 | 1.25 ± 1.25 | 0.00 ± 0.00 |
Figure 10: (Left) Result of the 2D likelihood scan for the $\mu_{ggH,tH,b\bar{b}H,tqH}$ and $\mu_{VBF,VH}$ signal-strength modifiers. The solid contours show the 68% CL regions. The cross indicates the best-fit value, and the diamond represents the expected value for the SM Higgs boson. (Right) Results of likelihood scans for the signal-strength modifiers corresponding to the main SM Higgs boson production modes, compared to the SM expectation shown as a vertical dashed line. The horizontal bars indicate the $\pm 1\sigma$ uncertainties. The uncertainties include both statistical and systematic sources. The measurements of the global signal strength $\mu$ are also shown.
References


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