# Measurements of Higgs boson production and properties in the ZZ decay channel using the CMS detector

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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.

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## 1. Introduction

The ATLAS and CMS Collaborations first reported the discovery of a new particle in 2012 [1, 2, 3] consistent with the standard model (SM) Higgs boson. Subsequent studies by CMS using the full LHC Run 1 data in various decay channels and production modes, combined measurements from ATLAS and CMS [4, 5] as well as combination of the CMS results with Run 2 data from 2016 showed that the properties of the new boson are so far consistent with expectations for the SM Higgs boson. The $H \to ZZ \to 4\ell$ 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. This study presents measurements of properties of the Higgs boson in the $H \to ZZ \to 4\ell$ decay channel at $\sqrt{s} = 13$TeV using 2017 data recorded with the CMS detector [6]. Several improvements are introduced compared to the previous CMS analysis: 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 [7] is also reported.

## 2. Analysis strategy

The strategy for the extraction of the $H \to 4\ell$ signal primarily relies on ensuring a large efficiency of reconstructing and selecting leptons. Electrons (muons) are reconstructed within the geometrical acceptance defined by $|\eta| < 2.5(2.4)$ and for transverse momenta $p_T > 7(5)$GeV. The scale and resolution of lepton momenta are calibrated in bins of $p_T$ and $\eta$ exploiting known dilepton resonances. Electron identification uses an improved multivariate discriminant which now also includes isolation variables sensitive to presence of other particles in a cone around the electron direction. 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. Efficiencies are measured in simulation and data with the tag-and-probe method, in order to correct the expectations from simulated samples for possible mis-modeling effects.

Four-lepton candidates are built out of two pairs of opposite-sign, same-flavor selected leptons, and are selected with a set of kinematic requirements that enhance the purity of the Higgs boson signal. In order to improve the sensitivity to the Higgs boson production mechanisms, the selected events are classified into seven mutually exclusive categories, the composition of which is shown in Fig. 1.

Irreducible backgrounds to the $H \to 4\ell$ signal arise from ZZ pair production via $q\bar{q}$ annihilation ($q\bar{q} \to ZZ$) or gluon fusion ($gg \to ZZ$), and are estimated using simulation, whereby K-factors are applied to account for missing higher-order corrections. Reducible backgrounds arising from the selection of misidentified or secondary leptons are collectively denoted as $Z + X$ and estimated by two independent methods using separate control samples in data.
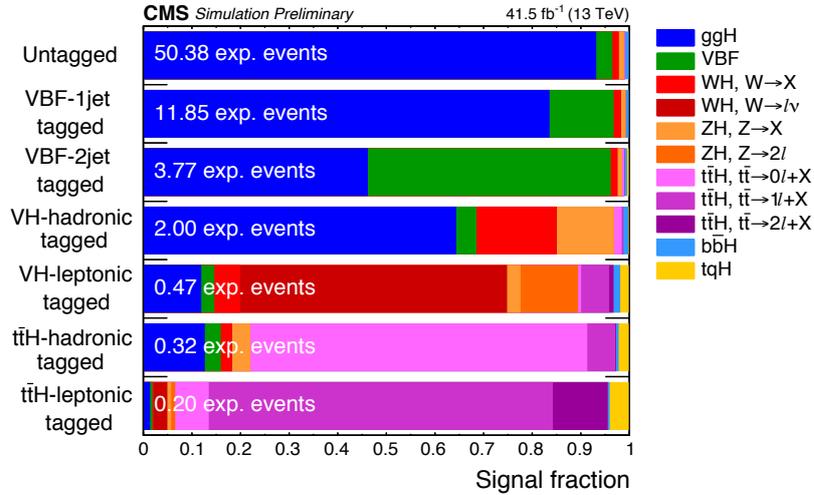
**Figure 1:** Signal relative purity of the seven event categories in terms of the seven main production mechanisms of the Higgs boson in a $118 < m_{4\ell} < 130$ GeV mass window. The WH, ZH and $t\bar{t}$H processes are split according to the decay of associated objects, whereby X denotes anything other than an electron or muon. [8]

## 3. Results

To extract the signal strength for the excess of events observed in the Higgs boson peak region, a two-dimensional unbinned fit that relies on the four-lepton invariant mass $m_{4\ell}$ and the kinematic discriminant $\mathscr{D}_{\text{bkg}}^{\text{kin}}$ based on matrix-element calculations is performed. The kinematic discriminant is different for each category. In VBF-2jet-tagged and VH-hadronic-tagged categories newly developed $\mathscr{D}_{\text{bkg}}^{\text{VBF+dec}}$ and $\mathscr{D}_{\text{bkg}}^{\text{VH+dec}}$ kinematic discriminants sensitive to the VBF and VH production mechanism are used, respectively. In all other event categories a decay only kinematic discriminant is used to separate Higgs signal from the SM background. Based on the seven event categories and the three final states ($4\mu$, $4e$, $2e2\mu$), the distributions of selected events are split into 21 categories.

A simultaneous fit to all categories is performed on 41.5 fb$^{-1}$ of data recorded in 2017 to extract the signal-strength modifier, defined as the ratio of the observed Higgs boson rate in the H $\to$ ZZ $\to 4\ell$ decay channel to the standard model expectation. The combined result is $\mu = \sigma/\sigma_{SM} = 1.10^{+0.14}_{-0.13}(\text{stat})^{+0.13}_{-0.14}(\text{syst}) = 1.10^{+0.19}_{-0.17}$, at $m_{\text{H}} = 125.09$ GeV. This result is compared to five signal-strength modifiers controlling the contribution of the SM Higgs boson production modes in Fig. 2 (left, red lines). Two signal-strength modifiers $\mu_{\text{ggH},t\bar{t}\text{H},b\bar{b}\text{H},tq\text{H}}$ and $\mu_{\text{VBF,VH}}$ 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 leading to the measurements of $\mu_{\text{ggH},t\bar{t}\text{H},b\bar{b}\text{H},tq\text{H}} = 1.11^{+0.23}_{-0.21}$ and $\mu_{\text{VBF,VH}} = 1.00^{+0.96}_{-0.71}$. The 68% and 95% confidence level contours in the $(\mu_{\text{ggH},t\bar{t}\text{H},b\bar{b}\text{H},tq\text{H}}, \mu_{\text{VBF,VH}})$ plane are shown in Fig. 2 (middle, red line). Finally, results for simplified template cross sections are shown in Fig. 2 (right), where the cross section for Higgs boson production is extracted in a simplified fiducial volume defined as $|y_{\text{H}}| < 2.5$ for various sub-processes.

A combined fit of the signal-strength modifiers corresponding to the main SM Higgs boson production modes is performed to a total of 77.4 fb$^{-1}$ of data collected in 2016 and 2017, in the most conservative scenario where experimental and theoretical systematic uncertainties are assumed to be fully correlated. Results are marked with black lines and contours in Fig. 2 (left and middle).
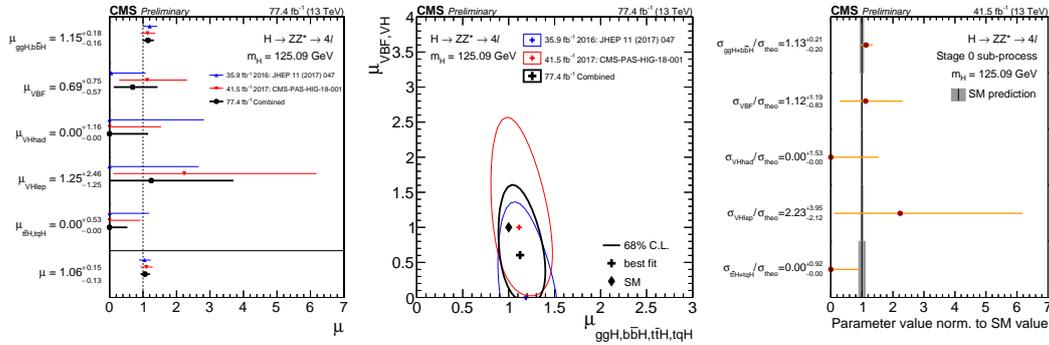


**Figure 2:** (Left) Results of likelihood scans for the signal-strength modifiers corresponding to the main SM Higgs boson production modes, compared to the combined $\mu$ shown as a vertical line. The horizontal bars and the filled band indicate the $\pm 1\sigma$ uncertainties. The uncertainties include both statistical and systematic sources. Results are shown for 2016 data (blue), 2017 data (red), and their combination (black). (Middle) Result of the 2D likelihood scan for the $\mu_{\text{ggH},t\bar{t}H,b\bar{b}H,tqH}$ 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. Results are shown for 2016 data (blue), 2017 data (red), and their combination (black). (Right) Results of the fit for simplified template cross sections for the stage 0 sub-processes, normalized to the SM prediction. [8]

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