

# HIGGS CROSS-SECTION MEASUREMENTS IN THE FOUR-LEPTON FINAL STATE AT CMS\*

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Cross sections of the Higgs ( $H$ ) boson are measured in the  $H \rightarrow ZZ \rightarrow 4\ell$  ( $\ell = e, \mu$ ) decay channel. The full data sample of proton–proton collisions at a center-of-mass energy of 13 TeV is used, corresponding to an integrated luminosity of  $137.1 \text{ fb}^{-1}$  recorded in 2016, 2017, and 2018 by the CMS detector at the LHC. The results include signal-strength modifier  $\mu$ , simplified template cross-sections and fiducial cross-sections (inclusive and differential) measurements. All results are found to be compatible with the SM predictions, within the measurements precision.

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## 1. Introduction

The CMS experiment [1] using the LHC Run 1 and Run 2 data has shown that the properties of the observed  $H$  boson are so far consistent with expectations for the SM  $H$  boson. A brief insight into properties of  $H$  measured with the full Run 2 CMS data are presented in this manuscript [2].

The  $H \rightarrow ZZ \rightarrow 4\ell$  ( $\ell = e, \mu$ ) decay channel 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 a most important channel for studies of the  $H$  boson’s properties.

In the following, the techniques used to analyze the data collected in 2018 ( $59.7 \text{ fb}^{-1}$ ) with the CMS detector are described. The analysis for previously published results using 2016 [3] and 2017 [4] data remain unchanged except the selected events to improve the sensitivity to the Simplified Template Cross Section (STXS).

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## 2. Data and simulated samples

This analysis makes use of  $pp$  full Run 2 collision data recorded by the CMS detector. For the year 2018, it corresponds to  $59.7 \text{ fb}^{-1}$ , where the collision events are selected by high-level trigger algorithms that require the presence of leptons passing loose identification and isolation requirements.

Monte Carlo (MC) simulation samples for the signals and the relevant background processes are generated with different MC generators and used to estimate backgrounds, optimize the event selection, and evaluate the acceptance and systematic uncertainties.

## 3. Event reconstruction and selection

Event selection criteria are described in Ref. [2], where the procedure of selection of leptons,  $Z$ ,  $ZZ$  and then signal candidates is explained.

## 4. Kinematic discriminants and event categorization

The full kinematic information from each event particles in its production is extracted using matrix element calculations and used to form several kinematic discriminants which can further be used to categorize the events. These computations rely on the MELA package [5] and use JHUGen matrix elements for the signal and MCFM matrix elements for the background.

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

$$\mathcal{D}_{\text{bkg}}^{\text{kin}} = \left[ 1 + \frac{\mathcal{P}_{\text{bkg}}^{q\bar{q}} \left( \vec{\Omega}^{H \rightarrow 4\ell} | m_{4\ell} \right)}{\mathcal{P}_{\text{sig}}^{gg} \left( \vec{\Omega}^{H \rightarrow 4\ell} | m_{4\ell} \right)} \right]^{-1}, \quad (1)$$

where  $\mathcal{P}_{\text{sig}}^{gg}$  is the probability for the signal and  $\mathcal{P}_{\text{bkg}}^{q\bar{q}}$  is the probability for the dominant  $q\bar{q} \rightarrow 4\ell$  background process, all calculated within the MELA framework.

The event categorization is primarily designed to separate  $ggH$ ,  $VBF$ ,  $VH$ , and  $t\bar{t}H$ . In addition, the events are further binned within the three main production mechanisms ( $ggH$ ,  $VBF$ , and  $VH$ ) in order to study deeper structure within each production mechanism, following the so-called Simplified Template Cross Sections (STXS) approach (Stage 0 and 1.1). The Bins in the STXS approach are identified at generator level using truth information in the MC simulation. The procedural details can be seen in [2].

## 5. Background estimation

The irreducible background to the  $H$ -boson signal in the  $4\ell$  channel, which comes 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, and the NNLO/NLO  $K$  factor as a function of  $m_{ZZ}$  has been applied to the POWHEG sample. Additional NLO electroweak corrections which depend on the initial-state quark flavor and kinematics are also applied in the region of  $m_{ZZ} > 2m_Z$ .

The production of  $ZZ$  via gluon fusion contributes at NNLO in pQCD. The NNLO  $K$  factor for the signal is obtained as a function of  $m_{ZZ}$  using the hnnlo v2 program by calculating the NNLO and LO  $gg \rightarrow H \rightarrow 2\ell 2\ell'$  cross sections at the small  $H$  boson decay width of 4.07 MeV and taking their ratios. More details are described in [2].

Additional backgrounds 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 [3]. The results of the two methods are combined for the final estimation.

## 6. Systematic uncertainties

The experimental uncertainties include the uncertainty in the integrated luminosity and the uncertainty in the lepton identification and reconstruction efficiency which affect both the signal and background. Other uncertainties are from the reducible background estimation and lepton energy scale.

Theoretical uncertainties are mainly from the renormalization, factorization scale and uncertainty from the PDF set. Additional uncertainties on the  $K$  factor used for the  $gg \rightarrow ZZ$  prediction and the branching fraction of  $H \rightarrow 4\ell$  are also included.

The updated  $ggH$  cross-section uncertainty and the uncertainty in the  $p_T(H)$  distribution due to the missing higher order finite top-quark mass corrections are included. All uncertainties which account for possible migration of signal and background events between categories are included.

In the combination of the three data-taking periods, the theoretical uncertainties as well as the experimental ones related to leptons or jets are treated as correlated, while all other ones from experimental sources are taken as uncorrelated [2].

## 7. Results and conclusion

The reconstructed four-lepton invariant mass distribution for full Run 2 is shown in Fig. 1 (left). The error bars on the data points correspond to the so-called Garwood confidence intervals at 68% confidence level (C.L.) [6]. The correlation of the kinematic discriminants  $\mathcal{D}_{\text{bkg}}^{\text{kin}}$  with the four-lepton invariant mass is also shown in the same figure.

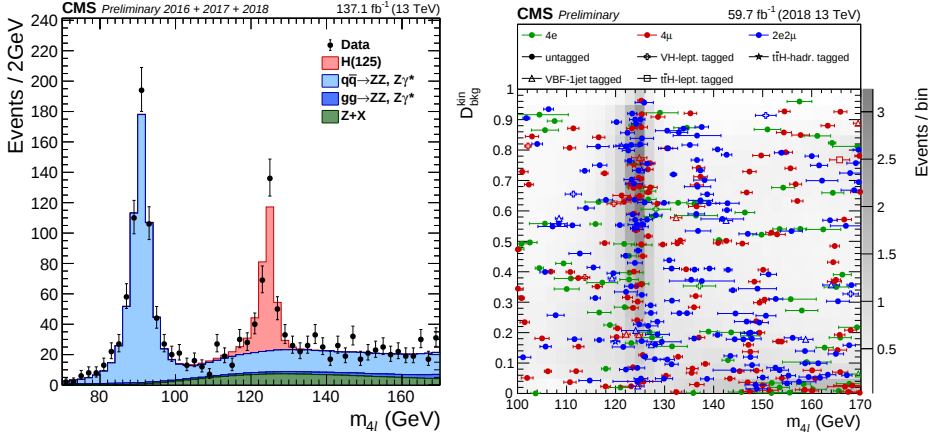


Fig. 1. Left: Distribution of the reconstructed four-lepton invariant mass (left) in the low-mass range with full Run 2 data shown. Right: Distribution of kinematic discriminants ( $\mathcal{D}_{\text{bkg}}^{\text{kin}}$ ) versus  $m_{4\ell}$ , with 2018 data [2].

### 7.1. Signal strength and Simplified Template Cross Section (STXS)

In each production mode, the extracted signal strength for the excess of events observed in the  $H$  boson peak region is shown in Fig. 2 (left). We perform a multi-dimensional fit that relies on two variables: the four-lepton invariant mass  $m_{4\ell}$  and the  $\mathcal{D}_{\text{bkg}}^{\text{kin}}$  discriminant. The two-dimensional likelihood function is defined as

$$\mathcal{L}_{2D} \left( m_{4\ell}, \mathcal{D}_{\text{bkg}}^{\text{kin}} \right) = \mathcal{L}(m_{4\ell}) \mathcal{L} \left( \mathcal{D}_{\text{bkg}}^{\text{kin}} | m_{4\ell} \right). \quad (2)$$

The previous Run 2 analysis has reported the measured Stage 0 results [4]. With full Run 2 data, this analysis targets the finer Stage 1.1 Bins. The measured STXSs, normalized to the SM prediction are shown in Fig. 2 (right).

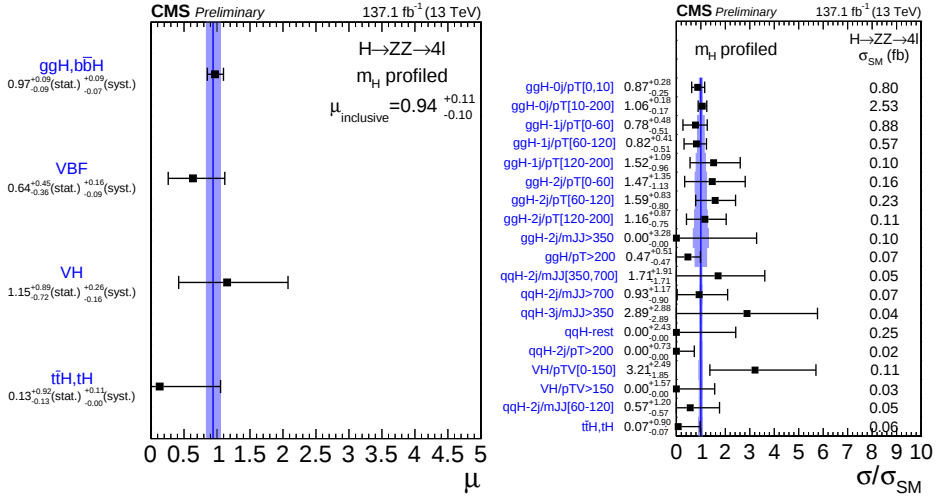


Fig. 2. Left: Results of likelihood scans for the signal-strength modifiers corresponding to the main SM Higgs boson production modes, compared to the combined  $\mu$  shown as a vertical line. Right: The ratios between measured cross sections and the SM prediction for Stage 1.1 Bins with  $m_H$  profiled in the fit [2].

## 7.2. Fiducial cross-section measurement

The measurement of the fiducial cross section for the production and decay  $pp \rightarrow H \rightarrow 4\ell$  is done within a fiducial volume defined (similar to Ref. [7]) to match closely the reconstruction level selection. This measurement has a minimal dependence on the assumptions of the relative fraction or kinematic distributions of the separate production modes.

A maximum likelihood fit of the signal and background parameterizations to the observed  $4\ell$  mass distribution,  $N_{\text{obs}}(m_{4\ell})$ , is performed to extract the integrated fiducial cross section for  $pp \rightarrow H \rightarrow 4\ell$  ( $\sigma_{\text{fid}}$ ). The fit is done inclusive which does not use the  $\mathcal{D}_{\text{bkg}}^{\text{kin}}$  observable in order to minimize the model dependence.

Measurement procedure accounts for the unfolding of detector effects from the observed distributions and is the same as in Ref. [7].

The integrated fiducial cross section is measured to be  $\sigma_{\text{fid}} = 2.73^{+0.30}_{-0.29} = 2.73^{+0.23}_{-0.22}(\text{stat.})^{+0.24}_{-0.19}(\text{syst.})$  fb at  $m_H = 125.09$  GeV. This can be compared to the SM expectation  $\sigma_{\text{fid}}^{\text{SM}} = 2.76 \pm 0.14$  fb. The integrated fiducial cross section as a function of center-of-mass energy is also shown in Fig. 3. The measured differential cross-section results for  $p_T(H)$ ,  $|y(H)|$ ,  $N(\text{jets})$ , and  $p_T(\text{jet})$  can also be seen in Fig. 3. All the measurements on Higgs cross sections are found to be consistent, within their uncertainties, with the expectations for the Standard Model  $H$  boson.

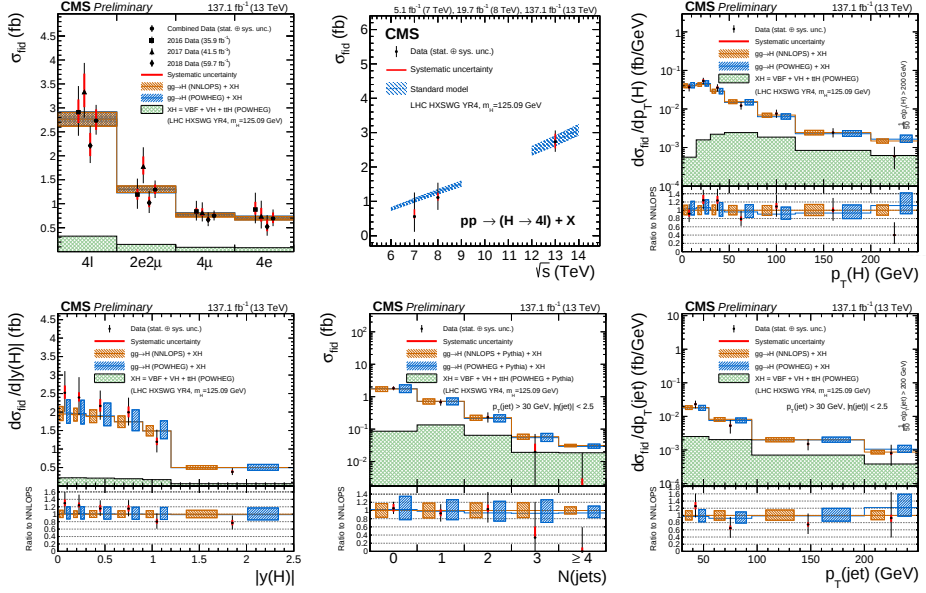


Fig. 3. The measured inclusive fiducial cross section in different final states (top left) and as a function of  $\sqrt{s}$  (top center). The results of the differential cross-section measurement for  $p_T(H)$  (top right),  $|y(H)|$  (bottom left) and  $N(\text{jets})$  (bottom center),  $p_T$  of the leading jet (bottom right). The acceptance and theoretical uncertainties in the differential bins are calculated using POWHEG [2].

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