PROCEEDINGS OF SCIENCE

Higgs measurements from CMS

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Ten years after the discovery of the Higgs boson in 2012, the data collected by CMS during the LHC Run 2 allows measuring many of the properties of this particle. A review of the recent Higgs results from CMS is presented in this report. They include mass, width, and differential cross-section measurements, together with coupling and charge-parity measurements. Additionally, the latest measurements of di-Higgs production are shown. Finally, a few results showing an excess of data over the predictions are illustrated.

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1. Introduction

Ten years after its discovery [1–3] by the ATLAS and CMS collaborations [4, 5], the Higgs boson (H) can now be measured precisely. About 7.7 million Higgs bosons have been produced at the CMS interaction point during the Run 2 of the LHC. The large data set means the Higgs boson mass can be measured with unprecedented precision, and that the main production modes and final states can be studied in detail. Additionally, results are also presented in the simplified template cross-section (STXS) framework [6] to increase the re-interpretability and minimize the theory dependence with respect to inclusive measurements. Beyond that, rare decays as the decay to a Z boson and a photon ($H \to Z\gamma$), couplings to second-generation fermions, and CP properties can be targeted. Finally, a significant step forward has been made in the study of Higgs boson pair production, a fundamental process to understand the Higgs self-coupling and the structure of the scalar Higgs field potential.

2. Higgs mass, width, and STXS measurements

The Higgs boson mass is measured using the two discovery channels ($H \to \gamma\gamma$ and $H \to ZZ$), as they provide the best invariant mass resolution together with a good signal-to-background ratio around the Higgs boson mass peak. Energy and momentum calibrations are key elements in these analyses and rely on precise detector calibration and alignment. The latest result from CMS [7] combines data from 2016 with those from Run 1 and provides the most accurate results so far: $m_H = 125.38 \pm 0.14$ GeV, with an uncertainty of 0.11%.
The direct measurement of the Higgs boson mass is not sensitive to its intrinsic width, which is much smaller than the typical invariant mass resolution of the CMS experiment. Indirect measurements

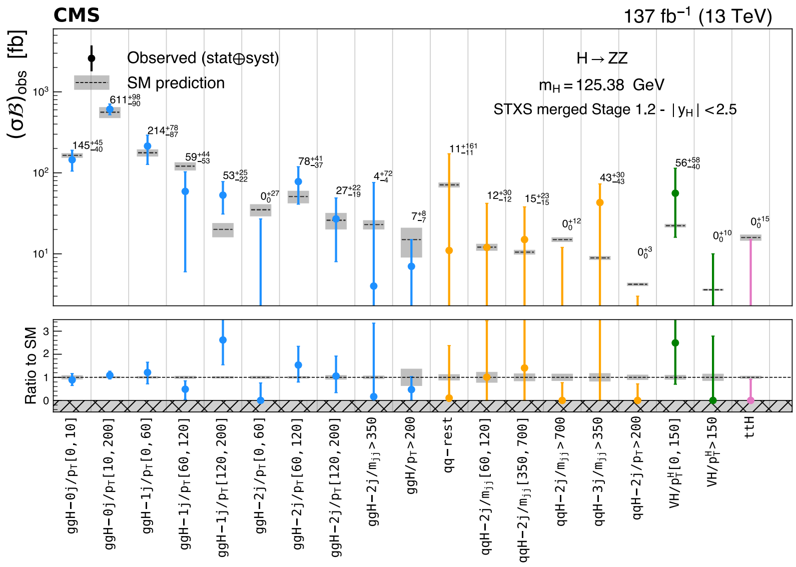
exploit the fact that the ratio between the off-shell and on-shell productions of a resonance is proportional to its width:

$$\sigma^{\mathrm{on-shell}} \propto \frac{g_p^2 g_d^2}{\Gamma_{\mathrm{H}}} \propto \mu_p, \sigma^{\mathrm{off-shell}} \propto g_p^2 g_d^2 \propto \mu_p \Gamma_{\mathrm{H}}, \tag{1}$$

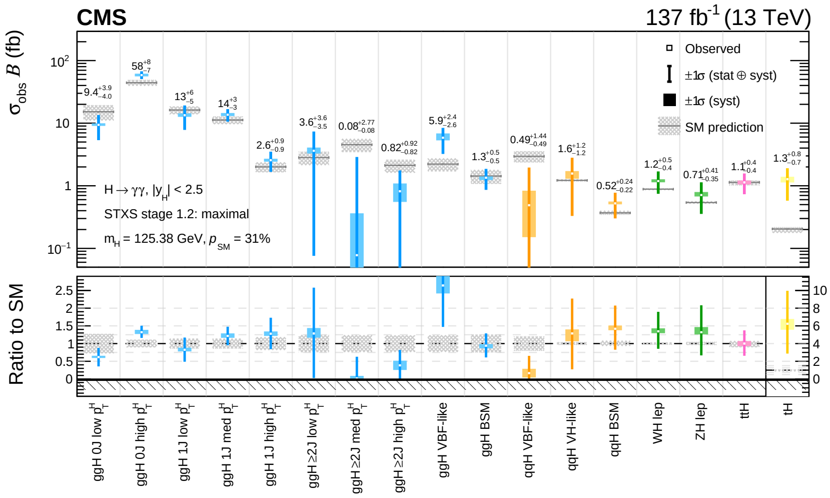
where g_p and g_d are the couplings associated with the H boson production and decay modes, respectively, and μ_p is the on-shell Higgs boson signal strength. CMS targeted this measurement using the full Run 2 data set and the H $\rightarrow$ ZZ final state [8], which resulted in the evidence of the off-shell Higgs boson production and a measurement of the Higgs boson width of $\Gamma_{\mathrm{H}} = 3.2^{+2.4}_{-1.7}$ MeV, compatible with the standard model expectation of 4.1 MeV.
CMS also performed differential measurements of the Higgs boson production cross-section, targeting several production and decay modes. We highlight two measurements carried out following the STXS prescriptions in the H $\rightarrow$ ZZ [9] and H $\rightarrow \gamma\gamma$ [10] final states. The results are shown in Figure 1, and include measurements of the production cross section of rare production modes such as the production of a Higgs boson in association with a top quark. All measured cross sections are found to be compatible with the standard model expectations.

3. Higgs rare decays and CP properties

The statistical power of the Run 2 data set allows us to inspect rare decays and study the CP properties of the Higgs boson couplings.
The H $\rightarrow$ Zγ process is particularly sensitive to new physics. The branching fraction $\mathcal{B}$(H $\rightarrow$ Zγ) value is $(1.57\pm0.09)\times10^{-3}$, slightly smaller that of $\mathcal{B}$(H $\rightarrow \gamma\gamma$) in the standard model. On the other hand, the two decay channels may be affected in different ways by new physics, making the ratio of the two a sensitive observable. The CMS result exploiting the full Run 2 data set measured a signal strength for the H $\rightarrow$ Zγ decay of 2.4 ± 0.9, corresponding to an excess over the background-only hypothesis with a significance of 2.7 standard deviations (σ) [11].
Other final states with small branching fractions include the H $\rightarrow \mu\mu$ and H $\rightarrow$ cc decay channels, that allow to test the couplings to second-generation fermions.
In the H $\rightarrow \mu\mu$ final state, the signal is extracted using a fit to data to distinguish the signal peak above the dominant Z $\rightarrow \mu\mu$ background, whose invariant mass distribution is smoothly falling. In addition, the vector boson fusion category uses a template-based approach to enhance the sensitivity and employ a deep neural network. The measured signal strength is $1.19\,^{+0.40}_{-0.39}(\mathrm{stat})^{+0.15}_{-0.14}(\mathrm{syst})$, corresponding to a 3 σ excess with respect to the background-only hypothesis [13].
The study of the H $\rightarrow$ cc final state instead targets V associated production (VH) to trigger on the associated vector boson and suppress the leading multi-jet background. A state-of-the-art graph neural network has been developed to target the boosted H $\rightarrow$ cc topology, where the two jets from the c quarks are merged in a single large-radius-jet, as shown in Figure 2a. The same approach is used in the VZ (Z $\rightarrow$ cc) channel, allowing the first observation of the Z $\rightarrow$ cc process at a hadron collider. The H $\rightarrow$ cc results are interpreted as upper limits on the VH signal strength. $\mu_{\mathrm{VH(H\rightarrow cc)}}$, These limits are set at 14.4 times the standard model prediction at 95% confidence level, corresponding to a confidence interval on the Higgs boson coupling to the c quark of $1.1 < |\kappa_c| < 5.5$ [14].
To measure the CP properties of the Higgs boson couplings, an effective Lagrangian can be written



(a)



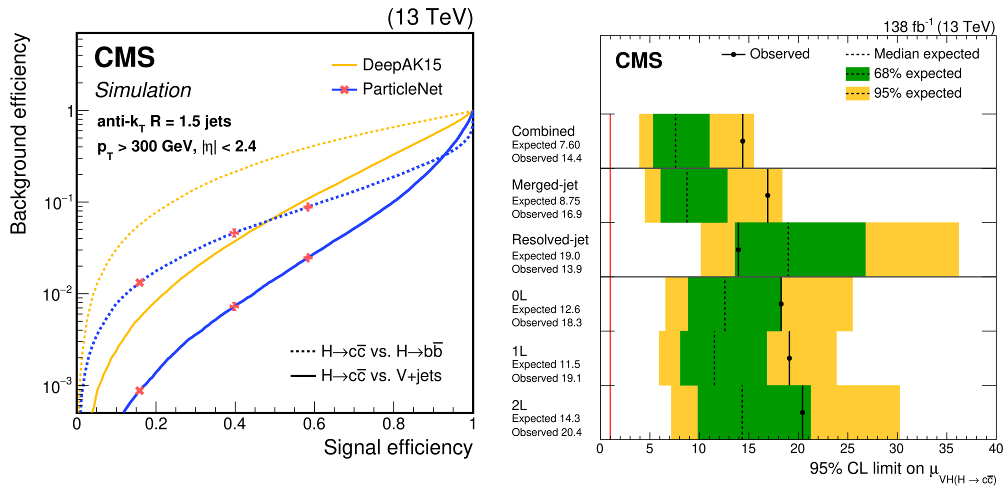
(b)

Figure 1: Results of the H $\rightarrow$ ZZ [9] (a) and H $\rightarrow \gamma\gamma$ [10] (b) STXS measurements.

and parametrized by a CP-even and a CP-odd components:

$$\mathcal{L}_{xxH} = \frac{m_x}{v}\bar{\psi}_x(\kappa_x + i\gamma_5\tilde{\kappa_x})\psi_x \mathrm{H} \tag{2}$$

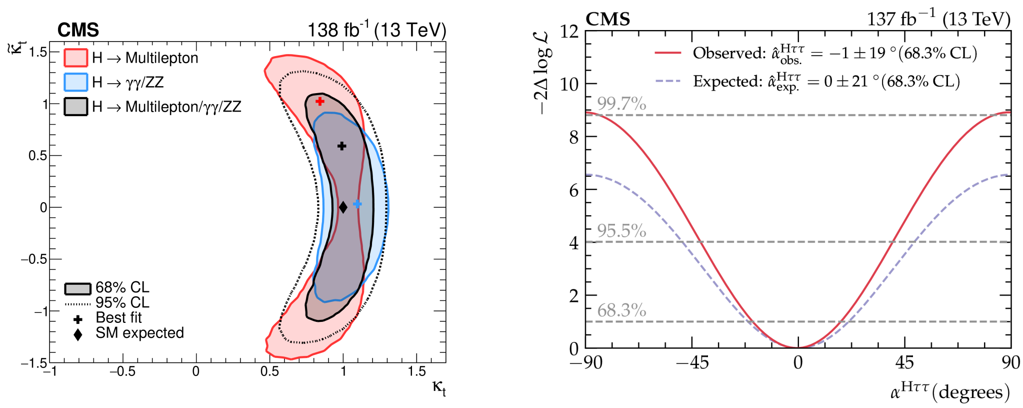
where x is the particle that couples to the Higgs: in the following, the top quark or the τ lepton. Similarly, a mixing angle α between the even and odd components can be introduced, with a value of $\alpha = 90°$ indicating a purely CP-odd scenario and $\alpha = 0°$ or $180°$ a purely CP-even scenario.
The ttH production mode is exploited to measure the parameters of the top quark Yukawa coupling. The results obtained combining the results of the multilepton (i.e., $\tau\tau$ and leptonic WW), $\gamma\gamma$, and ZZ final states are shown in Figure 3a. They measure $|\sin^2\alpha|$ to be 0.28, with an interval of



(a) **(b)**

Figure 2: Performance of the graph neural network (ParticleNet) in discriminating H → cc events versus H → bb or V+jets events (a) and 95% confidence level upper limits on the H → cc signal strength (b) [14].

$|\sin^2\alpha| < 0.55$ at 68% confidence level, excluding pure CP-odd coupling at 3.7 σ [15]. Similarly, the H $\to \tau\tau$ final state is sensitive to the τ Yukawa CP structure. The results are shown in Figure 3b, and allow to exclude a pure CP-odd H$\tau\tau$ coupling at 3 σ [16].

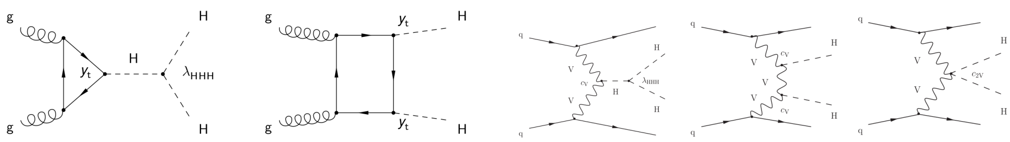


(a) **(b)**

Figure 3: Results of the ttH CP measurement, in terms of the κ and $\tilde{\kappa}$ parameters (a) [15] and results of the H $\to \tau\tau$ CP measurement, in terms of the mixing angle $\alpha^{H\tau\tau}$ (b) [16].

4. Double Higgs

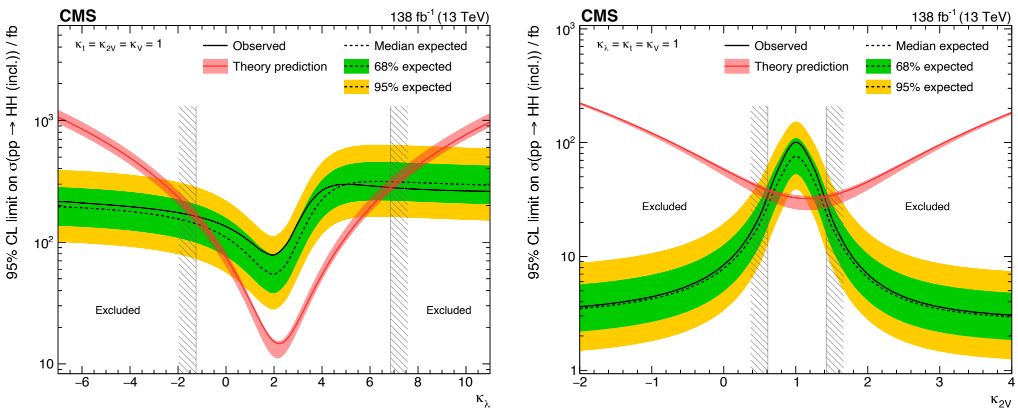
The double Higgs production opens the possibility of measuring the Higgs self-coupling (λ_{HHH}) and the couplings with two vector bosons (c_{2V}). To ease the interpretation of the results, the couplings values are usually presented in terms of their ratios with respect to the standard model expectations, defined as κ_λ and κ_{2V}. The di-Higgs production modes at the LHC are shown in



(a) **(b)**

Figure 4: Feynman diagrams for the double Higgs production through gluon-gluon fusion (a) and for the double Higgs production through vector-boson fusion (b).

Figure 4. The main challenge in studying this process is the low production cross-section, three orders of magnitude lower than that of single-Higgs production, meaning that the results are still limited by the statistical power of the data set. The analyses focus on final states with at least one Higgs boson decaying to a pair of b quarks, profiting from the large $H \to bb$ branching fraction (58%). The combination of the results of several final states, shown in Figure 5, allows to constrain the parameter κ_λ to $(-1.24, 6.49)$, and the parameter κ_{2V} to $(0.67, 1.38)$, excluding $\kappa_{2V} = 0$ with a significance of 6.6 σ [17].

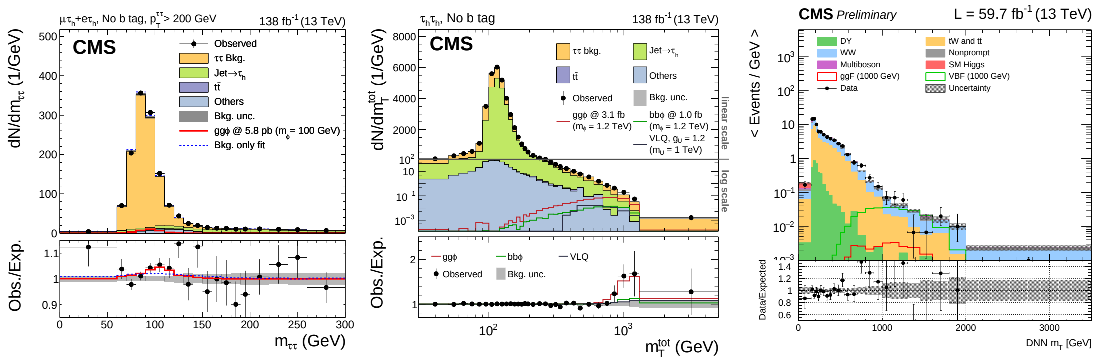


(a) **(b)**

Figure 5: Combined expected and observed 95% CL upper limits on the HH production cross-section for different values of κ_λ (a) and κ_{2V} (b) [17].

5. Is everything really as expected?

As we have shown, many CMS results agree with the hypothesis that the Higgs boson is the one predicted by the standard model. However, in several corners of the phase space, excesses of data with respect to the expectations have been observed [18, 19]. Some of them are shown in Figure 6, together with possible signals compatible with the observations, among them leptoquarks or additional high-mass Higgs bosons. These results do not allow a claim of evidence of new physics, but prove that the standard model does not always perfectly describe the experimental observations.



(a) **(b)** **(c)**

Figure 6: Some of the excesses observed by CMS. Possible signals compatible with the excesses include leptoquarks (a,b) [18] or a heavier Higgs boson (c) [19].

6. Conclusions

Ten years after the discovery of the Higgs boson, precise measurements of its properties are in reach. The mass and width are known with uncertainties of the order of the MeV, and the available data set is large enough to perform differential measurements. Also, dedicated analysis techniques allowed us to perform measurements sensitive to the coupling to second-generation fermions and CP properties and make significant progress in the measurement of the di-Higgs production properties. Despite many results agreeing with the standard model predictions, a few discrepancies have been observed, leaving room for new physics.

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