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HIGGS BOSON MEASUREMENTS AT CMS[*]

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This report summarizes measurements of the Higgs boson properties performed with the CMS experiment at the CERN LHC. The measurements presented here are based on data from *pp* collisions at the center-of-mass energy of 7, 8, and 13 TeV collected up to the year 2018 and corresponding to integrated luminosity of 5, 20, and 138 fb^{-1}, respectively. These results represent most up-to-date knowledge on the Higgs boson properties. All presented measurements agree with predictions of the Standard Model of particle physics within their uncertainties.

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1. Introduction

Since the discovery of the Higgs boson (H) in 2012 [1–3], its properties have been tested with increasing precision. In this report, we summarize the most up-to-date knowledge on the Higgs boson properties based on measurements performed using *pp* collision data collected with the CMS detector [4] at the LHC in two periods: 2010–2012 (Run 1) and 2015–2018 (Run 2). During Run 1, LHC operated at the center-of-mass energy of 7 and 8 TeV and the CMS experiment collected, respectively, 5 and 20 fb^{-1} of data, while during Run 2, the center-of-mass energy amounted to 13 TeV and integrated luminosity of CMS data to 138 fb^{-1}.

2. Higgs boson mass

The mass of the Higgs boson, m_H, is a free parameter of the Standard Model of particle physics (SM) and, within the SM, its value determines all the other Higgs boson properties.

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Precise measurements of m_H are performed using two fully-reconstructed, high-resolution ($\mathcal{O}(1\%)$) decay channels: $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ (reconstructed invariant mass shown in Fig. 1). The most recent combination of m_H measurements performed by the CMS Collaboration using those two decay channels with Run 1 and 2016 Run 2 data amounts to $m_H = 125.38 \pm 0.14\,[\pm 0.11(\mathrm{stat.}) \pm 0.09(\mathrm{syst.})]$ GeV [5, 6]. The uncertainty of the combined measurement is dominated by its statistical component similarly as for earlier measurements using only Run 1 data. It was achieved thanks to precise calibration of photon energy and lepton momentum. This combined measurement was recently improved by a measurement with the $H \to ZZ \to 4\ell$ channel using the full Run 2 data set which yields $m_H = 125.08 \pm 0.12\,[\pm 0.10(\mathrm{stat.}) \pm 0.05(\mathrm{syst.})]$ GeV [7]. Precision of m_H determination can be further improved by combining measurements with both channels with more data.

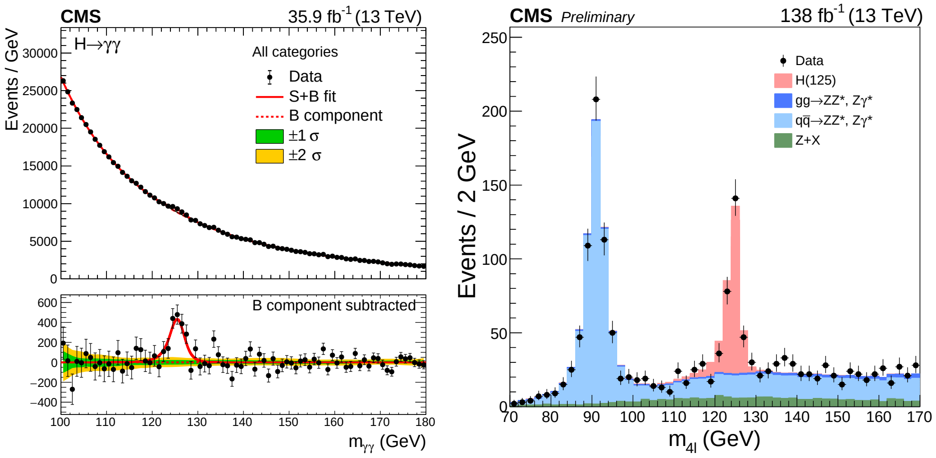

Fig. 1. Distributions of mass of photon pairs, $m_{\gamma\gamma}$ (left) [6] and of four leptons, $m_{4\ell}$ (right) [7].

3. Total width of the Higgs boson

Another important parameter describing the Higgs boson is its total width, Γ_H. In the SM, its value amounts to 4.1 MeV for the observed value of m_H [8]. Deviation from the SM expectation will be a sign of non-SM decays of the H boson. The predicted value of Γ_H is much smaller than the resolution of the CMS detector and direct measurements from the line shape with the $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$ decays give only weak upper limits of around 1 GeV (see *e.g.* Ref. [5]). Therefore, an indirect method was proposed in Refs. [9, 10] where Γ_H is obtained by comparing cross sections of the $H \to VV$ ($V = W, Z$) process on-shell and off-shell as given in Eq. (1)

$$\sigma^{\mathrm{on-shell}}_{gg\to H\to VV} \propto \frac{g^2_{ggH}g^2_{HVV}}{m_H\Gamma_H}\,,$$
$$\sigma^{\mathrm{off-shell}}_{gg\to H^*\to VV} \propto \frac{g^2_{ggH}g^2_{HVV}}{(2m_V)^2}\,. \tag{1}$$

This method was employed by the CMS Collaboration to measure the H total width using a combination of $H \to ZZ \to 4\ell$ process with 2016 data and $H \to ZZ \to 2\ell 2\nu$ with the full Run 2 data set [11]. The value of the H width measured in this analysis amounts to $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV at 68% confidence level (C.L.), in agreement with the SM expectation. The most recent measurement of the H width performed by the CMS Collaboration exploits the $H \to ZZ \to 4\ell$ process with full Run 2 data set [7] and gives $\Gamma_H = 2.9^{+2.3}_{-1.7}$ MeV at 68% C.L. (Fig. 2) which agrees with both previous measurement and the SM prediction. The uncertainties of both measurements are dominated by a statistical component (on off-shell yields) that will decrease with including more data. The measurements will also profit from reducing the uncertainty of the theoretical prediction on the non-resonant production of ZZ pairs which constitute the main irreducible background for the off-shell $H^* \to ZZ$ signal. Both measurements have comparable precision and constitute the most precise measurements of Γ_H to date. The CMS Collaboration is working on combining both measurements for further reduction of uncertainty on Γ_H.

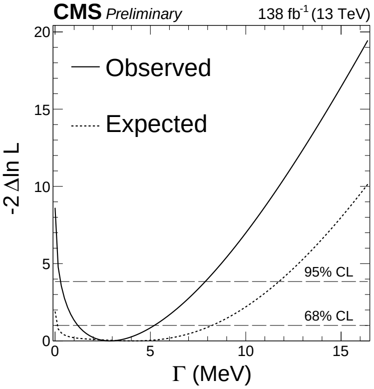

Fig. 2. Profile likelihood projection on the H boson width (Γ_H) measured using the on-shell and off-shell $H \to ZZ \to 4\ell$ production [7].

4. Rates and couplings

The Higgs boson analyses at the LHC measure directly only signal yields for a given combination of production and decay modes. However, the production and decay rates, and then individual couplings can be determined with a combination of those analyses to exploit different correlations between production and decay modes to which the analyses (event categories within them) are sensitive. This combination requires a set of basic theory assumptions which are discussed in Ref. [12].

The CMS Collaboration performed combined measurements exploiting all analyses based on 13 TeV data collected in 2016–2018 [13]. When all the measurements are parameterized with one inclusive ratio of the measured Higgs boson signal yield to the SM expectation, the so-called signal strength, μ, is equal to $\mu = 1.002 \pm 0.057$, in excellent agreement with the SM expectation. In these measurements the theoretical uncertainties on the signal prediction, and the experimental statistical and systematic uncertainties, contribute at a similar level, and they are 0.036, 0.033, and 0.029, respectively.

Production (μ_i) and decay (μ^f) signal strength parameters extracted with the combined analysis are shown in Fig. 3, all in agreement with the SM expectations. The precision of signal strength for the gluon–gluon fusion production mode is better than 10%, while for other main production processes is 10–20%. The signal strength for the main bosonic decay modes ($H \to \gamma\gamma, ZZ, WW$) and for $H \to \tau\tau$ is measured with an uncertainty of about 10%, and about 20% for $H \to b\bar{b}$ decays.

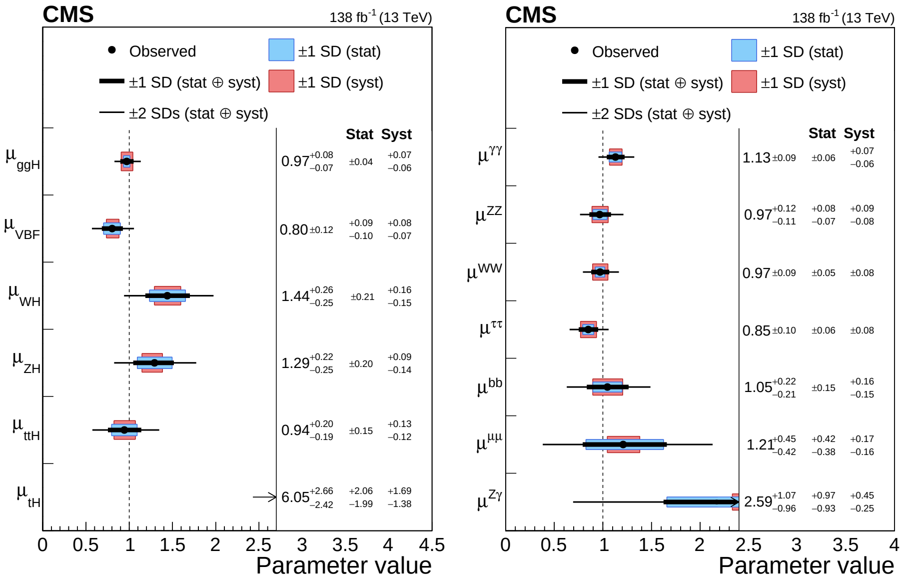

Fig. 3. Signal strength parameters measured for various production modes, μ_i, (left) and various decay channels, μ^f (right) [13].

The measurements can also be parameterized in terms of coupling modifiers, κ, that scale SM couplings of H to other particles [12]. The quantities such as production cross section (σ_i) and decay width (Γ^f) are scaled by κ^2. In the case of loop-mediated processes, *e.g.* $gg \to H$ or $H \to \gamma\gamma$, two ways are considered: they are either treated as effective and parameterized with their own κ modifiers or they are resolved assuming SM-like contributions. By construction, in the SM, all κ values are equal to one. Results of the combined coupling measurement are summarized in Fig. 4 and are in all cases consistent with expectations for the SM Higgs boson.

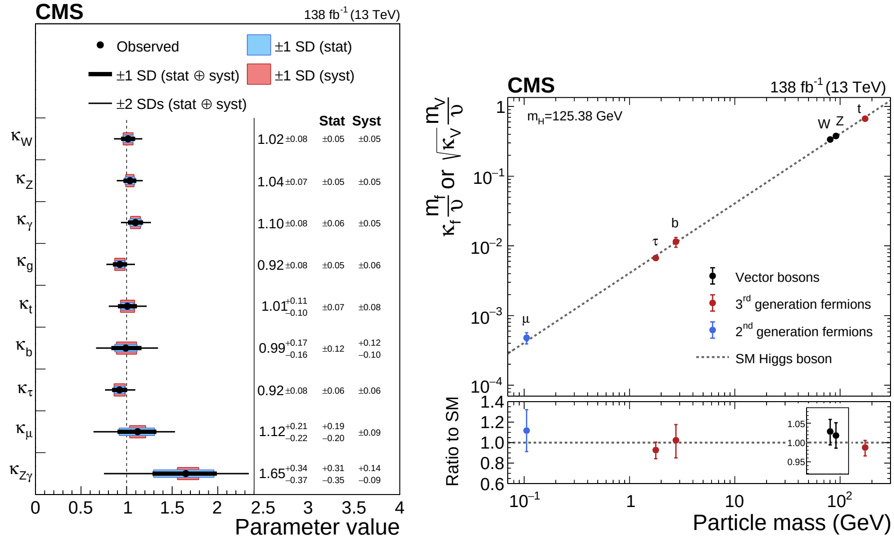

Fig. 4. Individual coupling modifiers (left) and reduced couplings as a function of particle mass (right) [13].

The Higgs boson self-coupling (λ) defines the shape of the Higgs potential. In the SM, its value is determined by m_H and the Fermi constant. The value of λ can be probed directly through the Higgs boson pair production (HH). This process, however, is not yet established experimentally due to the low production cross section which is three orders of magnitude smaller than that of the single-H production. The results of the search for the HH process are therefore expressed as an upper limit on its production cross section that amounts to 3.4 times the SM prediction at 95% C.L. (Fig. 5, left). This result can be translated to an allowed range of the Higgs boson self-interaction coupling modifier (κ_λ) of $-1.24 < \kappa_\lambda < 6.49$ at 95% C.L. The λ coupling can be also extracted from measurements of the single-H production which is sensitive to higher-order corrections involving the exchange of a virtual H boson. This leads to an allowed range of $-3.55 < \kappa_\lambda < 12.61$ at 95% C.L. (Fig. 5, right).

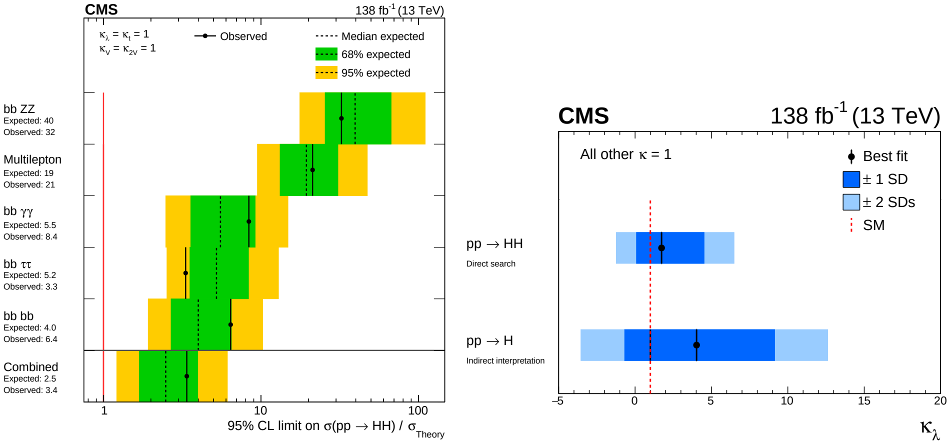

Fig. 5. Exclusion limits on the production of the Higgs boson pairs in searches using different final states and their combination (left), and constraint on the Higgs boson self-coupling from pair and single production (right) [13].

5. Differential cross sections

Measurements of differential cross sections provide more model-independent way to probe the Higgs boson dynamics than global parameterizations discussed in Section 4. The CMS Collaboration performed such measure-

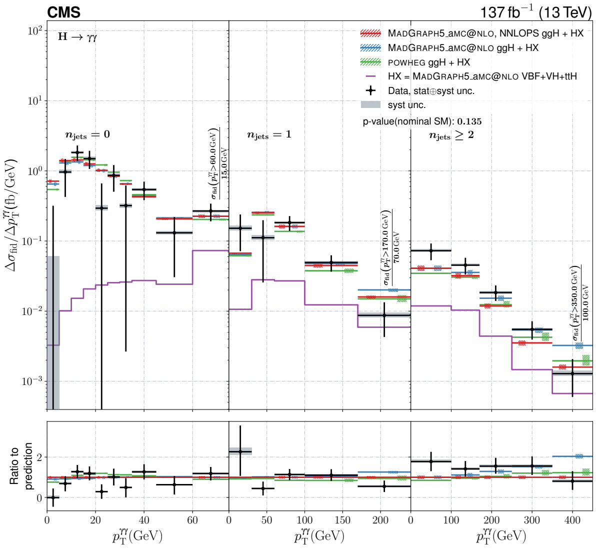

Fig. 6. Double-differential fiducial cross section measured in the $H \to \gamma\gamma$ channel in bins of $p_T^{\gamma\gamma}$ and n_{jets} [14].

ments with various final states using the full Run 2 data set: $H \to \gamma\gamma$ [14], $H \to ZZ \to 4\ell$ [15], $H \to WW \to 2\ell 2\nu$ [16], and $H \to \tau\tau$ [17]. All those measurements were done in fiducial regions different for each final state and defined by detector acceptance for the relevant final state, trigger thresholds, selections used to suppress background, *etc.* An example of double differential cross section measured in the $H \to \gamma\gamma$ channel is shown in Fig. 6. All those measurements are in agreement with the SM predictions. The differential cross-section measurements enable probes beyond SM physics in extreme regions of phase space, *e.g.* at large p_{T} of H that is sensitive to new particles exchanged in the $gg \to H$ loop.

6. Summary

In this report, we summarized measurements of the Higgs boson properties performed using data collected with the CMS detector up to 2018. The obtained results represent the most up-to-date knowledge on the Higgs boson properties. The mass of the Higgs boson (a free parameter of the SM) is measured with a precision of about 0.1%. The observed value of the total width of H (extracted using the on- and off-shell $H \to ZZ$ process) is measured with an uncertainty of about 50% and agrees with the SM prediction. Measured production and decay rates, inclusive and differential cross sections, and extracted couplings to other particles also agree with predictions of the SM within their uncertainties. The CMS Collaboration looks forward to analyzing the full data set of the ongoing Run 3 of the LHC that is expected to more than double the amount of collected data.

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