PROCEEDINGS OF SCIENCE

Higgs couplings combination at CMS

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With the data collected in Run-2, the Higgs boson can be studied in several production processes using a wide range of decay modes. Combining data in these different channels provides a broad picture of the Higgs boson coupling strengths to SM particles. This contribution outlines the latest combination of Higgs boson production and decay modes at CMS to measure the Higgs boson couplings and production cross sections.

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1. Introduction

In July 2012 the ATLAS and CMS Collaborations at the CERN LHC announced the discovery of a scalar particle compatible with the standard model (SM) prediction of the Higgs (H) boson [1–3]. Promptly after the discovery, the two collaborations started to probe in detail the properties of this long sought particle, clearly demonstrating its CP-even structure and measuring its mass to be compatible with 125 GeV. Since the value of m_H is not predicted by the SM, its experimental determination is crucial to ascertain which production modes and decay channels of the H boson are accessible at the LHC. Today, ten years after the discovery of the H boson, m_H is one of the SM quantities measured with the highest precision, and most of the production mechanisms and decay channels have been experimentally observed.

During Run–II (2015–2018), the LHC operated at a center–of–mass energy of $\sqrt{s}$ = 13 TeV, resulting in H boson production cross sections of a factor 2–4 larger than the ones accessible at $\sqrt{s} = 7 - 8$ TeV during Run–I (2009–2013). The CMS experiment collected a substantial amount of data, for about 8 million H bosons produced during the whole Run–II and a total of 138 fb^{-1} of data analysed. This ramping up in the performance of the accelerator opened the doors to the precision physics realm, where the large amount of data collected ensured not only the observation of rarer physics phenomena, but also the possibility of scrutinising in detail the properties of the H boson.

The CMS Collaboration [4] recently presented the results of the combination of several analyses targeting different production and decay mechanisms of the H boson [5], providing a comprehensive characterisation of the H boson profile at the LHC. The following summarises these results, trying to address three questions:

- Do we observe SM yields? That is, how compatible are the production and decay rates of this boson with the SM predictions?
- Do we observe SM couplings? That is, is this particle coupling with fermions and vector bosons as predicted by the SM or do we observe any physics beyond the SM?
- Can we measure the H boson self-coupling to probe in detail the properties of the electroweak symmetry breaking (EWSB) mechanism?

2. Production and decay rate measurements

Already from the time of the discovery, one of the most direct ways to assess the agreement between data and the SM expectations is to measure signal strenght modifiers. These are defined as scalings of the production and/or decay rates with respect to the SM predictions. The most general compatibility test with the SM can be done by introducing and inclusive signal strength modifier that scales simultaneously production and decay rates as $\mu = (\sigma\mathcal{B})_{\text{obs}} / (\sigma\mathcal{B})_{\text{exp}}$. The inclusive signal strength modifier is measured to be:

$$\mu = 1.002 \pm 0.057 = 1.002 \pm 0.036 \text{ (theory)} \pm 0.033 \text{ (exp.)} \pm 0.029 \text{ ((stat.)}, \tag{1}$$

where it is interesting to observe a fourfold improvement in precision with respect to the corresponding measurement at the time of the discovery ($\mu = 0.87 \pm 0.23$). A second feature of this measurement to note is the fact that the statistical uncertainty is at a similar level of the theoretical and systematic uncertainties.

A more detailed characterisation of the H boson profile can be obtained introducing separate signal strength modifiers for production mechanisms (μ_i) and decay channels (μ^f). The results of these measurements are shown in Fig. 1. All the production modes, except for tH, are observed with a significance of 5 standard deviations (SD) or larger. In general, all the results exhibit a good agreement with the SM predictions, with a p–value of 3.1% and 30.1% for μ_i and μ^f, respectively.

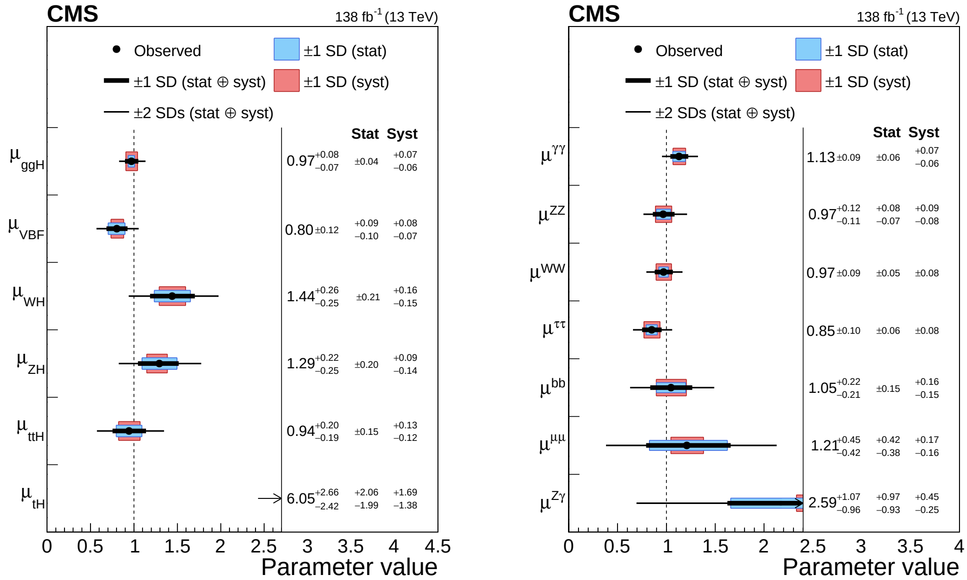

Figure 1: Signal strength modifiers for production, μ_i, (left) and decay, mu^f, (right) of the Higgs boson. The thick (thin) lines define the 1 (2) SD confidence intervals. The vertical dashed line at 1 represents the SM expectation. Figures taken from Ref. [5].

Production and decay rates of the H boson can be compared to the SM in a more granular way by relaxing further the assumptions on the signal strength modifiers and introducing independent parameters μ_i^f for each production channel and decay mode. The results of this measurement are shown in Fig. 2. Also in this case an overall good agreement with the SM prediction is observed, corresponding to a p–value of 5.8%.

3. Coupling strength measurements

The characterisation of the H boson detailed in the previous section can be complemented by measuring the coupling of this particle to vector bosons and fermions and assessing their compatibility with the SM predictions. This is done in the so called κ-framework, where coupling modifiers κ_i are introduced as scalings of the H boson interactions.

A global characterisation of the H boson interactions is performed by introducing only two parameters that scale the inclusive couplings to vector bosons (κ_V) and fermions (κ_f). The result of the two dimensional scan in the (κ_V, κ_f) plane is shown in the left plot of Fig. 3, together with a comparison with the same result at the time of the discovery and at the end of Run–I. A substantial

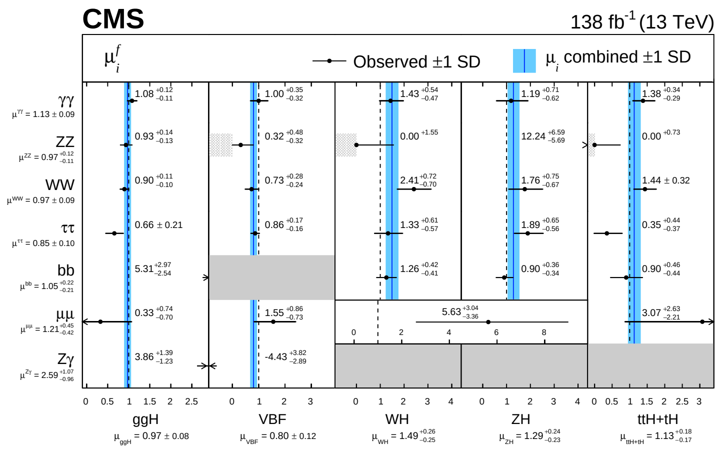

Figure 2: Combined signal strenght modifier, μ_i^f, for all production and decay channels. The hatched gray bands indicate that the signal strength is forced to be positive. The vertical dashed line at 1 represents the SM expectation. Figure taken from Ref. [5].

improvement in the precision of the limits on these couplings is observed, with the current results being in agreement with the SM predictions within 10%.

A "stress test" of the SM can be performed by measuring the couplings of the H boson with individual fermions and vector bosons. The SM predicts the former to scale proportionally with the mass of fermions ($\mathrm{m_f}$) and the latter with the square of the gauge boson mass ($\mathrm{m_V}$). The results of this measurement are shown in the right plot of Fig. 3, where the remarkable agreement with the SM prediction (dashed line in the plot) can be observed. With the large data set available at the end of Run–II, couplings to second generation fermions started to be probed in more detail. In addition, all the other couplings are now measured with excellent precision, with statistical and systematic uncertainties at the same level.

The presence of possible BSM effects can be assessed by introducing modifiers for the effective couplings of the H boson to gluons (κ_g), photons (κ_γ), and Zγ ($\kappa_{Z\gamma}$). The results are shown in the left plot of Fig. 4. The p-value for the compatibility with the SM is 28%. All the couplings are probed at the level of 10%, except for κ_μ and κ_b (20%), and $\kappa_{Z\gamma}$ (40%). An additional degree of freedom can be introduced in the fit allowing invisible and undetected decay modes and setting the SM as upper bound to κ_Z and κ_W and requiring their absolute value to be smaller or equal to 1. The result is shown in the rigth plot of Fig. 4. The p-value with respect to the SM is 33% and all the κs are found to be consistent with the expectations within 1 SD. The branching fractions to invisible and undetected decays of the H boson are found to be compatible with zero, with 95% CL upper limits of $\mathcal{B}_{\mathrm{Undet.}} < 0.16$ and $\mathcal{B}_{\mathrm{Inv.}} < 0.17$.

4. The Higgs boson self-coupling

The measurement of the H boson self-coupling is a cornerstore to understand the properties of the EWSB mechanism in the SM. The strength of the H boson self-interaction can be written as $\lambda = \mathrm{m_H^2}/(2v^2)$, where v is the vacuum expectation value of the H field. In a similar fashion to

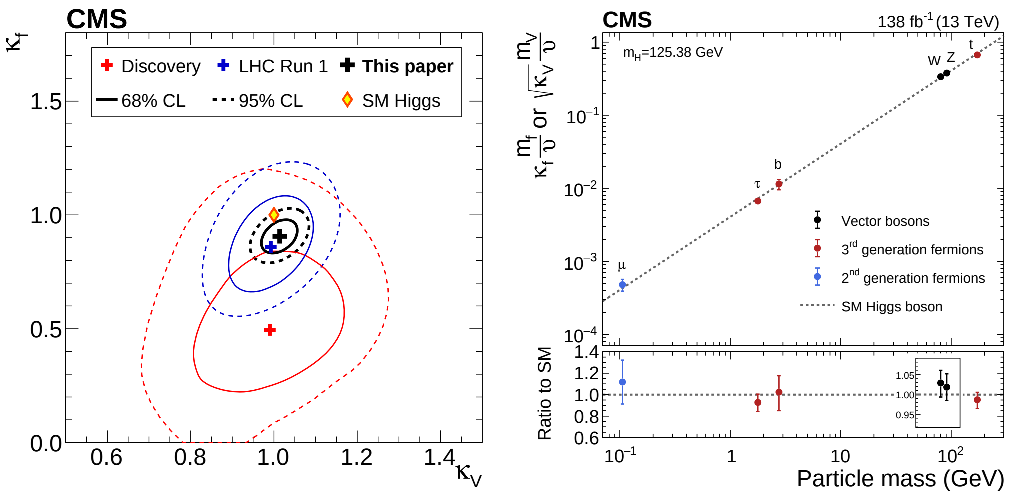

Figure 3: Left: Modifiers of the H boson couplings to vector bosons (κ_V) and fermions (κ_f). Contours are shown at 68% and 95% CL for different data sets: discovery (red), Run–I combination (blue), CMS Run–II combination (black). Right: Measured modifiers of of the H boson couplings to vector bosons and fermions as a function of the mass of the particles. Figures taken from Ref. [5].

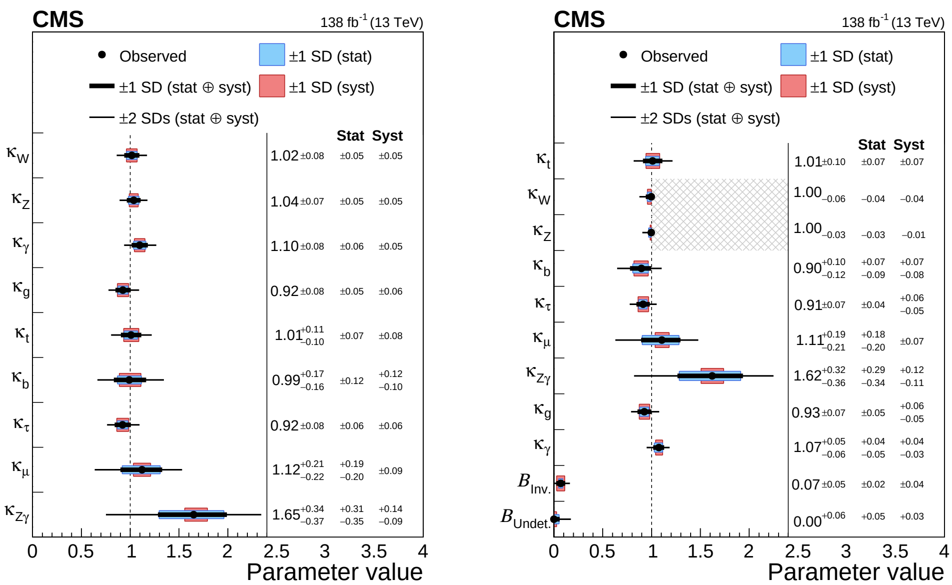

Figure 4: Coupling modifiers measured including loop-induced H boson interactions. In the right plot invisible and undetected decay modes are considered in the fit. Figures taken from Ref. [5].

what is done in the κ–framework, this analysis also sets limits to the coupling modifier for the H boson self-interaction (κ_λ). While constraints on κ_λ are usually set from measurements of H boson pair production, single H boson production and decay are also sensitive to next-to-leading-order quantum corrections due to κ_λ modifications and can be used to set constraints complementary to those from searches for Higgs boson pair production. The results obtained from both single Higgs and H boson pair production are shown in Fig. 5. In both cases a value of κ_λ consistent with 1 is observed.

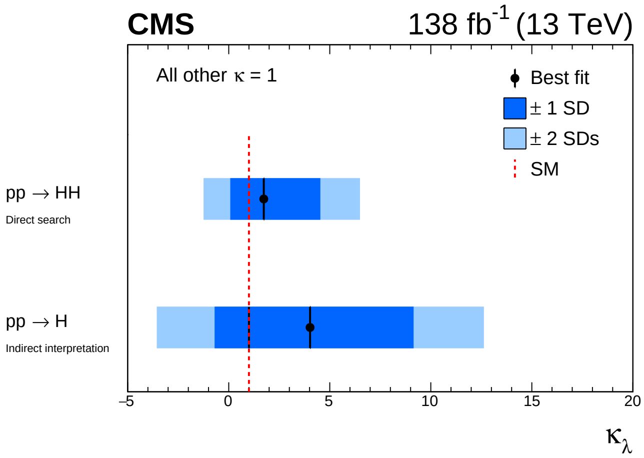

Figure 5: Constraints on the H boson self-coupling obtained directly from H boson pair production and indirect interpretation of single H measurements. Figure taken from Ref. [5].

5. Summary

A long journey in the understanding of the properties of the Higgs boson has been undertaken in the last 10 years, after the announcement of its discovery in July 2012. The full Run–II data set give access to a large amount of production modes and decay channels that can be combined together to achieve a comprehensive characterisation of the Higgs boson profile. This proceeding summarised the results of the latest combined Higgs boson measurement performed by the CMS Collaboration. The results of this analysis confirm that this H boson has production and decay rates and couplings to other particles in agreement with the SM expectations. No clear sign of new physics beyond the SM is found: the branching fraction for Higgs to invisible decays is found to be consistent with zero and a good agreement with unity is observed in the measurement of the self-coupling modifier. Many measurements reported here featured a fourfold improvement in precision if compared to the corresponding results at the time of the Higgs boson discovery. In addition, the full Run–II data set opened the door to the precision physics realm, where many experimental results are starting to have comparable statistical and systematic uncertainties and will be soon limited by the latter.

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