PROCEEDINGS OF SCIENCE

Higgs boson cross section and couplings measurements in bosonic decays in CMS

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An overview of measurements of the Higgs boson production cross sections and couplings performed by the CMS collaboration is presented. Focus is put on measurements that target bosonic decays of the Higgs boson and exploit the data set collected during Run 2 of the CERN LHC. Measurements in the WW, ZZ, and diphoton decay channels are covered, as well as a measurement targeting the production of the Higgs boson in association with t quarks, which includes decays to WW, ZZ, and $\tau\tau$. Results are presented in the form of cross sections and coupling strengths normalized to their theoretical expectations (modifiers), as well as simplified template cross sections.

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1. Introduction

Since the discovery of the Higgs boson [1–3] at the CERN LHC by the ATLAS [4] and CMS [5] collaborations, the focus of the experiments shifted into measuring the properties of the only fundamental scalar in the Standard Model (SM) with ever increasing precision. The SM predicts that the Higgs boson interacts, directly or indirectly, with every other fundamental particle, making its phenomenology especially rich. Bosonic decays i.e., those to W, Z bosons or photons, are of particular interest at a hadron collider such as the LHC: through a combination of large branching ratios (BR) and final states with leptons and photons, which are more easily distinguishable from the overwhelming QCD-induced background, they provide a tool for precise measurements of to the Higgs boson's properties. This overview covers measurements of cross sections and couplings for the main Higgs boson production modes in the WW [6], $\gamma\gamma$ [7], and ZZ [8] decay modes, as well as a measurement specifically targeting production in association with t quarks [9]. All presented measurements make use of the full data set collected by the CMS experiment during Run 2 of the LHC.

2. Interpretations

Results are presented in three main interpretations. In the signal strength framework, results are provided as signal strength modifiers μ, defined as the ratio of the observed cross section (times the BR, where specified) to its value as predicted by the SM. In the coupling modifier framework, production cross sections and BRs are expressed in terms of coupling modifiers κ [10]. Finally, in the simplified cross section (STXS) framework [11], results are reported as unfolded cross sections in a set of predefined kinematic and production bins (STXS bins). Since the statistical power of the Run 2 data set is not sufficient for individual analyses to be sensitive to the full set of STXS bins, the results are given in coarser sets of STXS bins, which are optimized for each analysis independently.

3. The $\mathrm{H} \to \mathrm{WW}$ decay channel

The WW decay channel leverages the fact that the $\mathrm{H} \to \mathrm{WW}$ BR is the second highest in the SM, while giving access to a leptonic final state, as opposed to the more probable decay into a $b\bar{b}$ quark pair. The high signal yield and the high purity of the final state compensate for the missing kinematic information in the leptonic $\mathrm{H} \to \mathrm{WW} \to 2\ell 2\nu$ decay due to the neutrinos escaping detection, resulting in a sensitivity on the production cross section roughly on par with the ZZ and $\gamma\gamma$ channels. The analysis targets Higgs boson production via gluon fusion (ggH), vector boson fusion (VBF), and in association with a vector boson (VH, where V stands for either W or Z). All target final states are required to have at least two charged leptons, meaning that only $\mathrm{H} \to \mathrm{WW} \to 2\ell 2\nu$ decays are selected for ggH and VBF production, while for VH production semileptonic $\mathrm{H} \to \mathrm{WW} \to \ell\nu\mathrm{qq}'$ decays are also considered. Events are categorized depending on the number and flavor of leptons in the final state, as well as on the number of hadronic jets, to target different production modes. The main discriminating variables used for signal extraction are the invariant mass $m_{\ell\ell}$ of the lepton pair with highest transverse momentum (p_{T}), the invariant mass of the Higgs boson restricted to the plane transverse to the beams $m_{\mathrm{T}}^{\mathrm{H}}$, and various machine-learning (ML) based discriminants. Signal strength modifiers are measured separately for ggH,

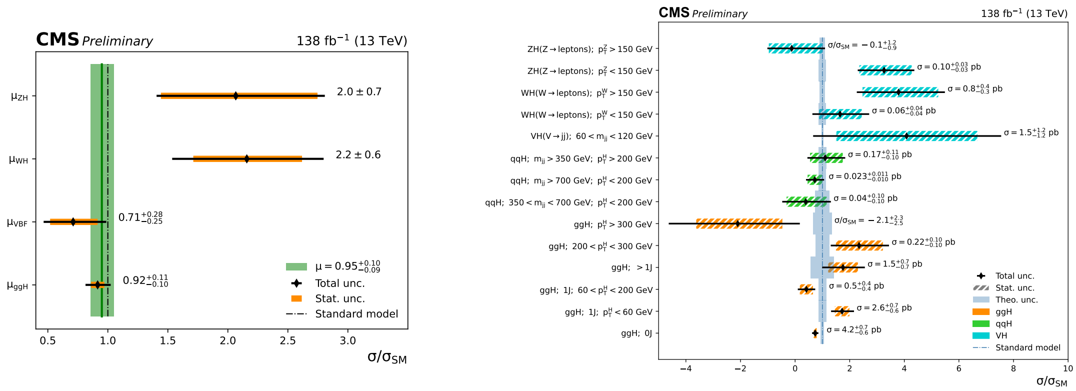

Figure 1: Signal strength modifiers (left) and STXS cross sections (right) measured in the WW decay channel [6].

VBF, WH, and ZH production modes, as shown in Fig. 1 (left). STXS results are provided in 14 kinematic bins, as shown in Fig. 1 (right). Finally, coupling modifiers to vector bosons and fermions are measured at $\kappa_V = 0.99 \pm 0.05$ and $\kappa_f = 0.86^{+0.14}_{-0.11}$, respectively. The overall Higgs boson production signal strength is measured at $\mu = 0.95^{+0.10}_{-0.09}$, showing excellent sensitivity. The STXS measurement achieves similarly good performance, complementing other bosonic channels especially for intermediate values of Higgs boson p_T, a regime in which the the WW decay channel benefits from the higher BR and the limit on the Higgs p_T resolution given by the neutrinos is mitigated.

4. The ttH multilepton channel

The analysis targets Higgs boson production in association with a $t\bar{t}$ quark pair (ttH) or a single t quark (tH). Given the lower predicted cross sections of these processes when compared to production modes discussed above, a wide range of final states are exploited simultaneously to perform the measurement. Specifically, decays of the Higgs boson to pairs of W bosons, Z bosons, and τ leptons are considered. Accounting for different decays of these intermediate state particles, a total of 10 final states are considered. Because of the complexity of tackling such a variety of signatures with different background compositions, the analysis makes heavy use of ML algorithms as discriminating observables for signal extraction. Classifiers are trained both to distinguish signals from various combinations of backgrounds, as well as effectively disentangling ttH from tH events. The latter point is especially relevant, since measuring the two processes independently allows to constrain the sign of the Yukawa coupling to the t quark. The effectiveness of the analysis is evidenced both in the precision reached in measuring the ttH and tH signal strength modifiers, resulting in a value of $\mu_{ttH} = 0.92^{+0.26}_{-0.23}$ and $\mu_{tH} = 5.7^{+4.1}_{-4.0}$, respectively, as well as in simultaneous measurement of the (κ_V, κ_t) coupling modifiers, where the analysis is able to partially resolve the ambiguity on the sign of κ_t. Results pertaining to the ttH signal strength modifier and coupling modifiers are shown in Fig. 2.

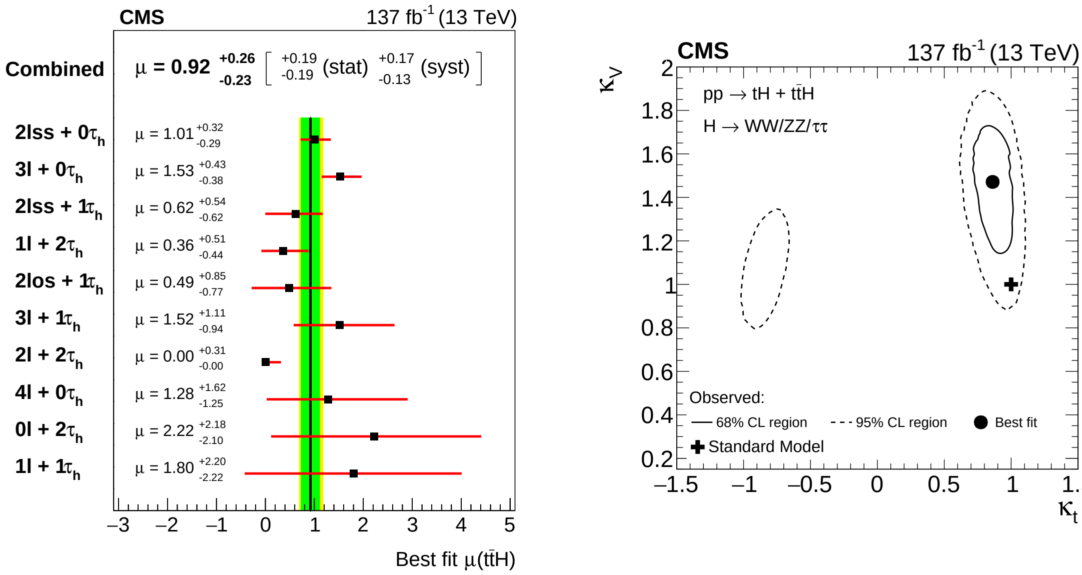

Figure 2: Signal strength (left) and coupling modifiers (right) measured in the ttH multilepton analysis [9].

5. The H $\rightarrow \gamma\gamma$ decay channel

The diphoton decay channel has historically been one of the principal ones for the discovery and characterisation of the Higgs boson. This is primarily due to the outstanding photon reconstruction achieved by the CMS detector, enabling precise kinematic characterization of the final state and overcoming the relatively low BR of the H $\rightarrow \gamma\gamma$ decay. The analysis targets all Higgs boson production modes mentioned thus far down to tH, providing results in the signal strength modifiers, coupling modifiers, and STXS frameworks. The analysis leverages the fact that the kinematics of the diphoton decay are closed to fit the Higgs boson's invariant mass peak over the smooth combinatorial background. Heavy use of ML algorithms is made in key points of the analysis: boosted decision trees are used to separate genuine photons from misreconstructed hadronic jets, assign photons to the correct proton-proton interaction vertex, separate diphoton pairs originating from a Higgs boson from ones originating from other processes, disentangle different Higgs boson production modes, and assign events to corresponding STXS bins. The analysis measures the overall Higgs boson production signal strength at $\mu = 1.12 \pm 0.09$. Coupling modifiers are measured both as effective couplings of the Higgs boson to gluons and photons, as well as assuming a SM-like coupling structure in order to measure couplings to vector bosons and fermions. Finally, STXS results are provided in two binning schemes, targeting the coverage of most STXS bins achievable (27 bins) or better then 100% uncertainty in each bin (17 bins), respectively. Results for the signal strength modifiers and one of the STXS interpretations are shown in Fig. 3.

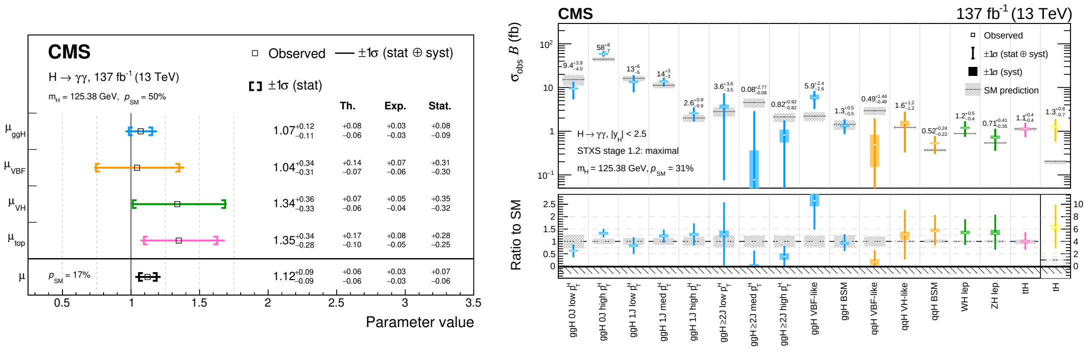

Figure 3: Signal strength modifiers (left) and STXS cross sections (right) measured in the diphoton decay channel [7].

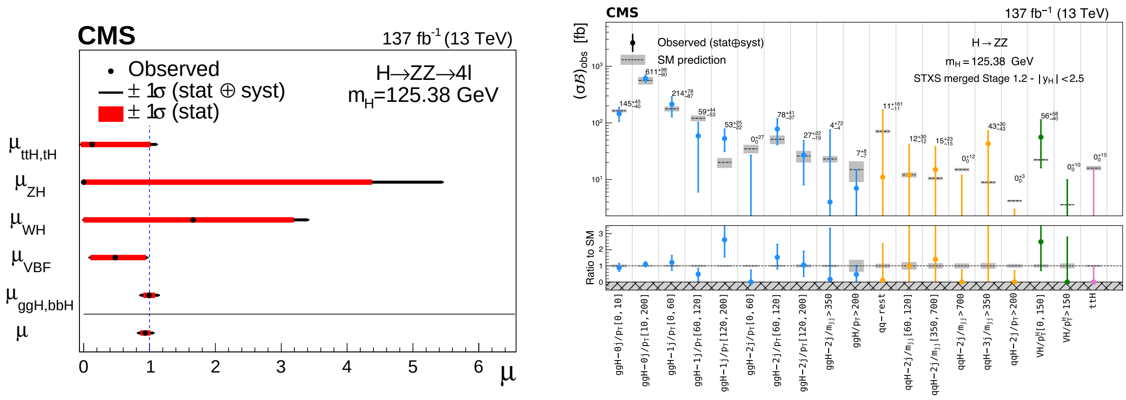

Figure 4: Signal strength modifiers (left) and STXS cross sections (right) measured in the ZZ decay channel [7].

6. The H → ZZ decay channel

Similarly to the diphoton channel discussed previously, the ZZ decay has historically been a driver in experimental Higgs physics. Given the QCD-dominated environment of the LHC, hadronic decays of the Z boson are not useful for this measurement and are thus ignored; focus is put on events in which both Z bosons decay to either a pair of electrons or a pair of muons. This restriction yields a final state with very low background, at the price of a comparably low BR. All three combinations of the aforementioned Z boson decays are considered ($2e2\mu$, $4e$, and 4μ), with the four-muon decay driving the sensitivity. All production modes of the Higgs boson mentioned thus far are targeted, except for tH. Residual backgrounds arise from non-resonant ZZ and Zγ pair production and from misreconstructed leptons. The analysis leverages kinematic discriminants built as ratios of matrix elements evaluated on event kinematics to distinguish signal from background, as well as disentangle different Higgs boson production modes, and the signal is extracted by fitting the invariant mass of the four-lepton system. Results are provided as signal strength modifiers as well as a set of 19 STXS values, both of which are shown in Fig. 4.

7. Conclusions

An overview of the measurements of the Higgs boson production cross section has been given, with focus on analyses targeting bosonic decays of the Higgs boson. All together, these measurement put stringent constraints on the structure of the scalar sector of the SM, showing no significant sign of tension. The increased statistical power of the Run 3 dataset will allow for an even more precise characterization e.g., by allowing the measurement of STXS cross sections in finer bins of phase space, and increasing the experimental sensitivity to rare production modes, such as tH.

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