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Higgs boson couplings at CMS

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This document presents the measurements of the Higgs boson (H) couplings with the data from proton-proton collisions at a center-of-mass energy of 13 TeV collected by the CMS experiment. After more than ten years since the H discovery, one of the main goals of the LHC physics program is the characterization of this particle, which includes measurements of its mass, decay width, and couplings. In order to perform an extensive test of the standard model (SM) predictions, the measurements of the H cross sections and branching ratios in the most sensitive production and decay channels are statistically combined. The measurements are interpreted in terms of deviations of H couplings to fermions and vector bosons from the SM. No significant deviations are observed. The uncertainty on most of the couplings is better than 10%. Constraints on the H boson trilinear self-coupling constant (λ) are also extracted from the combined H cross section and branching ratio measurements. The H production cross sections and decay branching ratios depend on λ because of electroweak corrections at the next-to-leading order. The results are found consistent with the SM and the constraints on λ are similar to the ones extracted from the searches for the H pair production.

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1. Introduction

More than ten years have passed since the discovery of the Higgs boson (H) at the CMS and ATLAS experiments [1, 2]. Among the primary goals of the LHC physics program is the H characterization. This is fundamental to investigate several open physics questions, such as the reason for the hierarchy of the fermion masses, or the unbalance between matter and antimatter in the universe, as discussed in Ref. [3]. The measurements of the H production cross sections and decay branching ratios provide a fundamental and extensive test of the SM. The main H production mechanisms at the LHC are the gluon-fusion (ggH) and the vector boson fusion (VBF). Other sensitive H production mechanisms are the H associated production with a Z or W boson, which are referred to as ZH and WH, respectively, and the H associated production with a $t\bar{t}$ quark pair ($t\bar{t}$H). The H production in association with a $b\bar{b}$ quark pair, or with one top quark (tH) have not been observed yet. The observed H decay channels are to a pair of $b\bar{b}$ quarks, $\tau^+\tau^-$ leptons, vector bosons, as well as the loop-induced decays to a pair of photons, or to a Z boson and a photon. The H decay channel to a $\mu^+\mu^-$ pair has a higher statistical uncertainty.

The SM also predicts trilinear and quartic H self-interactions. The strength of these couplings is controlled by the Higgs boson trilinear self-coupling constant (λ) parameter. The value of λ normalized by its SM prediction is κ_λ. Constraints on κ_λ can be derived from the searches for the production of H pairs (HH). An alternative way to constrain κ_λ is from the measurements of the cross sections and branching ratios of the H processes. The H cross sections and branching ratios depend on κ_λ because of next-to-leading order electroweak corrections [4, 5].

In Ref. [6], the measurements of the H cross sections in the most sensitive production and decay channels are statistically combined to perform an extensive test of the SM, and to achieve the ultimate precision on the H couplings with the available data. Constraints on the modifiers of the H couplings defined in the κ-framework [7] are also extracted.

2. Input channels and combination procedure

The input channels to the combination are summarized in Table 1. The details about the analysis strategy developed for each channel can be found in the references listed in the table. Most of the input channels use the dataset collected by the CMS experiment [8, 9] between 2016 and 2018, corresponding to an integrated luminosity of about 138 fb^{-1}. The considered input channels cover all the main H production and decay channels. The $t\bar{t}$H(leptons) analysis targets the $t\bar{t}$H events in final state with multiple electrons, muons, or hadronically-decaying tau leptons, from the H$\rightarrow$W$^+$W$^-$ and H$\rightarrow\tau^+\tau^-$ channels.

The statistical combination is based on a combined likelihood method [20]. A likelihood function is built as the product of the probability density functions of signal and backgrounds for the discriminating variables used in each input channel, and of constraints on nuisance parameters. The nuisance parameters are introduced to describe the systematic uncertainties. The parameters of interest, i.e. the signal strengths or coupling modifiers, and the associated confidence intervals are estimated using a profile likelihood ratio [21] as test statistic.

The systematic uncertainties originate from the theoretical predictions or the experimental procedure. The most important theory uncertainties are on the H cross sections predictions. They

Table 1: Analyses considered in the combination and integrated luminosity corresponding to the analyzed data, along with the reference publications.

Analysis	Integrated luminosity (fb^{-1})	References
$H \to ZZ(4\ell)$	138	[10]
$H \to \gamma\gamma$	138	[11]
$H \to W^+W^-$	138	[12]
$t\bar{t}H$(leptons)	138	[13]
$H \to b\bar{b}$	138	[14]
$VH(b\bar{b})$	77	[15, 16]
$t\bar{t}H(b\bar{b})$	36	[17]
$H \to \tau^+\tau^-$	138	[18]
$H \to \mu^+\mu^-$	138	[19]

can be uncertainties in the parton distribution functions, in the H branching ratios, and in the scales of QCD renormalization and factorization. The theory uncertainties on the backgrounds are also considered for those background processes which are estimated from the theory prediction. The theory uncertainties are correlated across all the affected input channels. The experimental uncertainties include the ones on the integrated luminosity, on the jet energy scale and resolution, on the efficiency in the reconstruction and identification of leptons, photons, and heavy-flavour jets. Such uncertainties are correlated among all the affected channels. For each channel, additional analysis-specific systematic uncertainties are considered.

3. Results

The inclusive H signal strength, defined as the ratio between the measured cross section and the SM one, is measured to be 1.002 ± 0.057, thus in good agreement with the expectation. The components of the uncertainty from theoretical and experimental sources are 3.6% and 3.3%, respectively. Those contributions are slightly larger than the statistical one (2.9%). The measurements of the signal strengths per H production or decay channel are shown in Fig. 1. In general, the signal strengths are found in good agreement with the SM. The largest deviations from the SM are observed in the tH production and $H \to Z\gamma$ decay, which are not significant because of the large statistical uncertainties. The proton-proton collision data that the CMS experiment has been collecting since 2022 will be fundamental for more precise measurements of these processes.

Constraints on the H coupling modifiers are extracted and shown in the left panel of Fig. 2. Modifiers of the H couplings to fermions and vector bosons with masses spanning over four orders of magnitude are found in agreement with the SM. For most of the couplings the uncertainty is within $10-15\%$. The right panel of Fig. 2 shows the constraints on κ_λ from the combination of H measurement in comparison to the ones from the combination of HH searches presented in Ref. [6]. These are the first constraints on κ_λ from the data collected by the CMS experiment exploiting the effects of κ_λ on the H cross sections at the differential level. The most stringent constraints are from the searches for the HH process because its cross section depends at the leading order from κ_λ, thus its variation with κ_λ is larger than the one of the H cross sections and branching ratios.

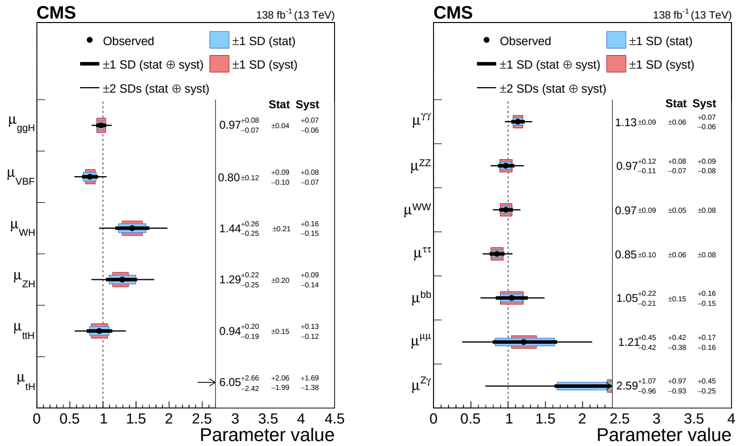

Figure 1: Signal strengths measurements for various H production modes (left) and decay channels (right) from Ref. [6].

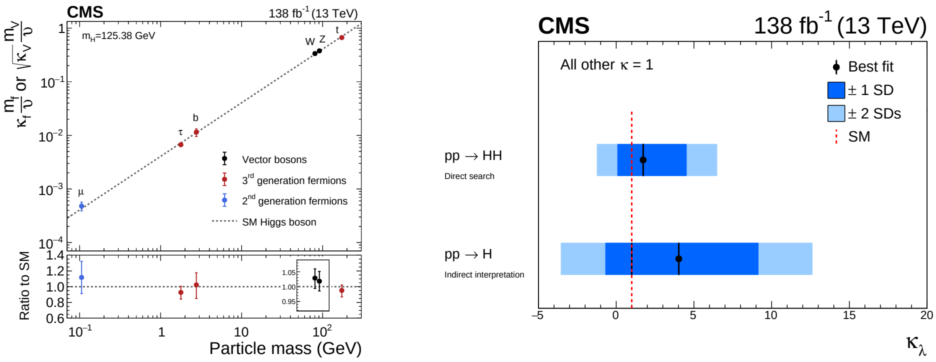

Figure 2: On the left H coupling modifiers as a function of the corresponding particle mass. On the right constraints on κ_λ from the combination of HH searches or H measurements. The figures are from Ref. [6].

4. Summary

The measurements of the Higgs boson (H) cross sections and branching ratios provide a fundamental test of the standard model (SM). A statistical combination of those measurements in the most sensitive production modes and decay channels have been presented. The measurements are based on data from proton-proton collisions at a center-of-mass energy of 13 TeV collected by the CMS experiment, which correspond to up to 138 fb $^{-1}$ of integrated luminosity. No significant deviations from the SM predictions have been observed. For most of the production and decays channels, the statistical uncertainties are found comparable to the systematic ones. Measurements of the modifiers of the H couplings to fermions and vector bosons are performed. For most of them the precision is better than 10%. Constraints on the H trilinear self-coupling are also derived exploiting, for the first time in CMS, the effects of the self-coupling constant on the differential H cross sections.

References

[1] ATLAS Collaboration, "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC", *Phys. Lett. B* **716** (2012) 1, doi:10.1016/j.physletb.2012.08.020, arXiv:1207.7214.

[2] CMS Collaboration, "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC", *Phys. Lett. B* **716** (2012) 30, doi:10.1016/j.physletb.2012.08.021, arXiv:1207.7235.

[3] G. P. Salam, L.-T. Wang, and G. Zanderighi, "The Higgs boson turns ten", *Nature* **607** (2022), no. 7917, 41–47, doi:10.1038/s41586-022-04899-4, arXiv:2207.00478.

[4] G. Degrassi, P. P. Giardino, F. Maltoni, and D. Pagani, "Probing the Higgs self coupling via single Higgs production at the LHC", *JHEP* **12** (2016) 080, doi:10.1007/JHEP12(2016)080, arXiv:1607.04251.

[5] F. Maltoni, D. Pagani, A. Shivaji, and X. Zhao, "Trilinear Higgs coupling determination via single-Higgs differential measurements at the LHC", *Eur. Phys. J. C* **77** (2017) 887, doi:10.1140/epjc/s10052-017-5410-8, arXiv:1709.08649.

[6] CMS Collaboration, "A portrait of the Higgs boson by the CMS experiment ten years after the discovery", *Nature* **607** (2022) 60, doi:10.1038/s41586-022-04892-x, arXiv:2207.00043.

[7] LHC Higgs Cross Section Working Group, "Handbook of LHC Higgs cross sections: 4. Deciphering the nature of the Higgs sector", CERN Report CERN-2017-002-M, 2016. doi:10.23731/CYRM-2017-002, arXiv:1610.07922.

[8] CMS Collaboration, "The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[9] CMS Collaboration, "Development of the CMS detector for the CERN LHC Run 3", arXiv:2309.05466. accepted by JINST (2023).

[10] CMS Collaboration, "Measurements of production cross sections of the Higgs boson in the four-lepton final state in proton-proton collisions at $\sqrt{s} = 13$ TeV", *Eur. Phys. J. C* **81** (2021) 488, doi:10.1140/epjc/s10052-021-09200-x, arXiv:2103.04956.

[11] CMS Collaboration, "Measurements of Higgs boson production cross sections and couplings in the diphoton decay channel at $\sqrt{s} = 13$ TeV", *JHEP* **07** (2021) 027, doi:10.1007/JHEP07(2021)027, arXiv:2103.06956.

[12] CMS Collaboration, "Measurements of the Higgs boson production cross section and couplings in the W boson pair decay channel in proton-proton collisions at $\sqrt{s} = 13$ TeV", *Eur. Phys. J. C* **83** (2023) 667, doi:10.1140/epjc/s10052-023-11632-6, arXiv:2206.09466.

[13] CMS Collaboration, "Measurement of the Higgs boson production rate in association with top quarks in final states with electrons, muons, and hadronically decaying tau leptons at $\sqrt{s} = 13$ TeV", *Eur. Phys. J. C* **81** (2021) 378, doi:10.1140/epjc/s10052-021-09014-x, arXiv:2011.03652.

[14] CMS Collaboration, "Inclusive search for highly boosted Higgs bosons decaying to bottom quark-antiquark pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV", *JHEP* **2012** (2020) 085, doi:10.1007/JHEP12(2020)085, arXiv:2006.13251.

[15] CMS Collaboration, "Observation of Higgs Boson Decay to Bottom Quarks", *Phys. Rev. Lett.* **121** (2018) 121801, doi:10.1103/PhysRevLett.121.121801.

[16] CMS Collaboration, "Evidence for the Higgs boson decay to a bottom quark-antiquark pair", *Physics Letters B* **780** (2018) 501, doi:10.1016/j.physletb.2018.02.050.

[17] CMS Collaboration, "Search for $\mathrm{t\bar{t}H}$ production in the $\mathrm{H} \to \mathrm{b\bar{b}}$ decay channel with leptonic $\mathrm{t\bar{t}}$ decays in proton-proton collisions at $\sqrt{s} = 13$ TeV", *JHEP* **03** (2019) 026, doi:10.1007/JHEP03(2019)026, arXiv:1804.03682.

[18] CMS Collaboration, "Measurements of Higgs boson production in the decay channel with a pair of τ leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV", *Eur. Phys. J. C* **83** (2023) 562, doi:10.1140/epjc/s10052-023-11452-8, arXiv:2204.12957.

[19] CMS Collaboration, "Evidence for Higgs boson decay to a pair of muons", *JHEP* **01** (2021) 148, doi:10.1007/JHEP01(2021)148, arXiv:2009.04363.

[20] ATLAS and CMS Collaborations, and LHC Higgs Combination Group, "Procedure for the LHC Higgs boson search combination in Summer 2011", Technical Report CMS-NOTE-2011-005, ATL-PHYS-PUB-2011-11, 2011.

[21] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, "Asymptotic formulae for likelihood-based tests of new physics", *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727.