Measurement of the CP properties and anomalous couplings of the Higgs boson with the CMS experiment

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Summary. — In many beyond the Standard Model (BSM) theories, anomalous couplings of the Higgs boson with the W and Z vector bosons, or with fermions, are possible and can potentially violate CP symmetry. BSM couplings between the Higgs boson and the top quark, as well as with particles not yet observed, could generate CP violation in the interactions between the Higgs boson and gluons, the dominant process in production at the LHC. Studies of CP violation and anomalous couplings of the Higgs boson to vector bosons (HVV) and fermions (Hff) conducted by the CMS experiment, utilizing the complete Run 2 datasets, are presented. We focus on measurements where the Higgs boson is produced on-shell. The data corresponds to an integrated luminosity of 138 fb^{-1} at a proton-proton collision energy of 13 TeV. The kinematic distributions of the final states are sensitive to the Higgs boson's quantum numbers, and various production and decay channels are used for these studies. Matrix element techniques and multivariate algorithms are employed to identify the production mechanisms and enhance sensitivity to the Higgs boson's tensor structure in the interactions.

1. – Introduction

The discovery of the Higgs boson (H) by the ATLAS [1] and CMS [2, 3] experiments at the LHC has opened a new era for particle physics, where the characterization of this new boson is of crucial importance. The H boson serves both as a test of the Standard Model (SM) and as a gateway to exploring new physics. The properties of the H boson have been found to be consistent with those of the SM Higgs boson. In particular, nonzero spin assignments for the H boson have been excluded, and its spin-parity quantum numbers are consistent with what predicted by the SM $J^{PC} = 0^{++}$. However, the limited precision of current studies still allows for small anomalous couplings of the H boson to two electroweak gauge bosons (HVV). These couplings are expected to be suppressed by loop effects and therefore to be relatively small. On the other hand, anomalous Higgs boson couplings to fermions, which might also indicate CP violation, may appear at tree level and may not suffer from loop suppression. To fully exploit different possible deviations from the SM expectation that may arise in different couplings, it is essential to study the various decay and production channels of the Higgs boson.

2. – Phenomenology of the CP structure in HVV and Hff interaction vertices

The most general form of the scattering amplitude between a spin-0 H boson with two spin-1 gauge bosons VV, is parametrized with three tensor structures and expansion of coefficients up to (q^2/Λ_1^2)

$$A(HVV) \sim \left[a_1^{VV} + \frac{k_1^{VV} q_1^2 + k_2^{VV} q_2^2}{(\Lambda_1^{VV})^2} \right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu} \quad (1)$$

where q_i, ϵ_{Vi}, and m_{V1} are the 4-momentum, polarization vector, and the mass of the vector boson, indexed by i = 1, 2. $f^{(i)\mu\nu} = \epsilon_{Vi}^{\mu} q_i^{\nu} - \epsilon_{Vi}^{\nu} q_i^{\mu}$ is the gauge boson's field strength tensor and $\tilde{f}_{\mu\nu}^{i} =$

$(1/2)\epsilon_{\mu\nu\rho\sigma}f^{(i)\rho\sigma}$ is the dual field strength tensor defined using the Levi-Civita symbol in four dimension ($\epsilon_{\mu\nu\rho\sigma}$). a_i^{VV} are the coupling coefficients. $k_i^{VV}/(\Lambda_1^{VV})^2$ multiply the next term in the q^2 expansion. Λ_1 is the scale of beyond the SM (BSM) physics.

In Eq. 1, the only nonzero SM contributions at tree level are a_1^{WW} and a_1^{ZZ}. All other ZZ and WW couplings are considered anomalous contributions, which are either due to BSM physics or small contributions arising in the SM due to loop effects and are not accessible with the current experimental precision. The parity-violating interaction of a pseudoscalar (CP-odd state) corresponds to the a_3 terms, while the other terms describe the parity-conserving interaction of a scalar (CP-even state). Due to the fact that kinematics of the H boson production in WW fusion and in ZZ fusion are very similar it is assumed that $a_i^{WW} = a_i^{ZZ} = a_i$ and $k_1^{WW}/(\Lambda_1^{WW})^2 = k_1^{ZZ}/(\Lambda_1^{ZZ})^2 = a_{\Lambda_1}$.

Among the anomalous contributions, considerations of symmetry and gauge invariance require $k_1^{ZZ} = k_2^{ZZ} = -exp(i\phi_{\Lambda_1}^{ZZ})$, $k_1^{\gamma\gamma} = k_2^{\gamma\gamma} = 0$, $k_1^{gg} = k_2^{gg} = 0$, $k_1^{Z\gamma} = 0$ and $k_2^{i\phi_{\Lambda 1}^{Z\gamma}}$, where $\phi_{\Lambda 1}^{Z\gamma}$ is the phase of the corresponding coupling.

It should be noted that other approaches to analysis are possible and have been undertaken. For example, one can choose the SMEFT (Standard Model Effective Field Theory) formulation, in which the SU(2)×U(1) symmetry is assumed. However, in this paper, we will focus on the first approach.

The purpose of the analysis is to constrain the three sets of couplings (a_2, a_3 and a_{Λ_1}). The results are expressed in terms of cross sections, or equivalently, signal strengths $\mu_j = \sigma_j/\sigma_{SM}$, and the fractional contributions f_i of the couplings a_i to cross sections The effective cross section f_{ai} and phase ϕ_{ai} are defined as follows:

$$f_{ai} = \frac{|a_i|^2\sigma_i}{\sum_{j=1,2,3,\Lambda_1}|a_j|^2\sigma_j}, \quad \phi_{a_i} = \arg\left(\frac{a_i}{a_1}\right) \tag{2}$$

Where the fraction $f_{a1} = 1 - f_{\Lambda_1} - f_{a2} - f_{a3}$ is the SM tree-level contribution.
$f_{ai} = 0$ indicates a pure SM Higgs boson, f_{ai}= 1 gives a pure BSM particle and $f_{ai} = 0.5$ means that the two couplings contribute equally to the process.

This formulation with f_{ai} allows the presentation of experimental results in the most direct way, with a minimal and complete set of parameters describing the given processes. This approach has several convenient features. The cross sections and their ratios are invariant with respect to the coupling convention. The cross section fractions f_{ai} reflect kinematic features in either production or decay in a direct way. They are conveniently bounded between -1 and +1, and the systematics that affect the normalization of the signal processes cancel out in the ratio.

Anomalous effects in the H boson couplings to fermions can be parameterized with the amplitude :

$$A(Hff) = -\frac{m_f}{v}\bar{\phi}_t(k_f + i\tilde{k_f}\gamma_5)\phi_t \tag{3}$$

where ϕ_f and $\bar{\phi}_f$ are the Dirac spinors, m_f is the fermion mass, v is the SM H field vacuum expectation value, and k_f and $\tilde{k_f}$ are the CP-even and CP-odd Yukawa couplings. In the SM $k_f = 1$ and $\tilde{k_f} = 1$. As for the HVV coupling is more convinient to measure the CP structure with

$$f_{CP}^{Hff} = \frac{|\tilde{k_t}|^2}{|k_t|^2 + |\tilde{k_t}|^2} sign(\tilde{k_t}/k_t) \tag{4}$$

3. – CP structure of the Yukawa interactions with ttH production and diphoton decay

The tree-level top quark Yukawa (Htt) coupling and its CP structure can be tested by studying H production in association with a top quark-antiquark pair (ttH). One of the most sensitive channels for probing the ttH process is $H \to \gamma\gamma$.

In the ttH analysis in which the Higgs boson decay in to two photons, H candidates are built from pairs of photon, which are reconstructed from energy clusters in the ECAL not linked to charged-particle tracks (with the exception of converted photons). The photon energies are corrected for the containment of electromagnetic showers in the clustered crystals and the energy losses of converted photons with a multivariate regression technique based on simulation. Photons are further required to satisfy a loose identification criterion based on a boosted decision tree (BDT). After the preselection described above,it is required that $100 < m_{\gamma\gamma} < 180$ GeV, $p_T/m_{\gamma\gamma} > 1/3$ and $1/4$ for the leading (in p_T) and subleading

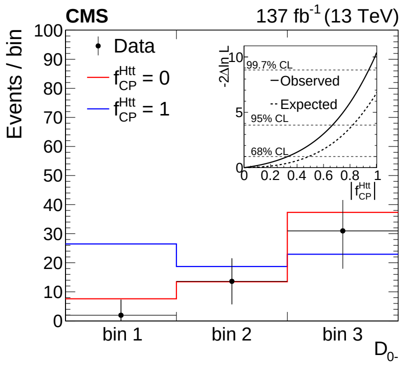

Fig. 1. – The distribution of events weighted by S/(S + B) (S = Signal, B = Background) in three bins of the D_{0-} discriminant. In this display, leptonic/hadronic channels and BDT-bkg categories are combined in the mass range $115 < m_{\gamma\gamma} < 135$ GeV and the background contribution, as determined in the fit to data, is subtracted. The inner panel shows the likelihood scan for $|f_{CP}^{Htt}|$ [4].

photons respectively and then divide events into two channels. The leptonic channel is aimed at selecting events where at least one top quark decays leptonically. The hadronic channel targets $t\bar{t}$ hadronic decays by requiring at least three jets, at least one b-tagged jet, and no isolated leptons (electron or muon). A dedicated BDT discriminant ("BDT-bkg") is employed in each channel to distinguish between ttH and background events. A BDT is trained to distinguish CP-even and CP-odd contributions. The output of the BDT is the D_0^- observable. Simulation shows that D_0^- has negligible correlation with the BDT-bkg discriminant. The events selected for the cross section measurements are split into 12 categories, leptonic or hadronic, two BDT-bkg categories and three D_0^- bins. Fig. 1 shows the distribution of events in three bins of the D_{0-}. The data disfavor the pure CP-odd model of the Htt coupling at 3.2 σ, and a possible fractional CP-odd contribution is measured to be $f_{CP}^{Htt} = 0.00 \pm 0.33$.

4. – Anomalous couplings using the four-leptons final state

In the analysis H $\to$ ZZ $\to$ 4l, three mutually exclusive channels: H $\to$ 4e, 4μ, and 2e2μ are considered. This analysis is of particular importance as it is sensitive to various types of couplings. The ttH and gluon-fusion production modes (under the assumption that the gluon gluon fusion loop is dominated by top quarks) can be utilized to investigate the anomalous coupling between the Higgs boson and fermions. Additionally, the HVV coupling can be studied both in production (e.g., Higgs production through Vector Boson Fusion) and in decay, thus providing access to different phase spaces.

At least two leptons are required to have $p_T > 10$ GeV, and at least one is required to have $p_T > 20$ GeV. All four pairs of oppositely charged leptons that can be built with the four leptons are required to satisfy $m_{l^+l^-} > 4$ GeV regardless of lepton flavor. The Z candidates are required to satisfy the condition $12 < m_{l^+l^-} < 120$ GeV, where the invariant mass of at least one of the Z candidates must be larger than 40 GeV. The region between 105 and 140 GeV in the four-lepton invariant mass (m_{4l}) is considered in this analysis. Kinematic distributions of particles produced in the H boson decay or in the associated production with other particles are sensitive to the quantum numbers and anomalous couplings of the Higgs boson. The full kinematic information from each event using either the Higgs boson decay or associated particles in its production is extracted using discriminants from matrix element calculations. The discriminants used in this study are computed using the MELA [6] package which is designed to reduce the number of observables to a minimum, while retaining all essential information. Two categorization schemes are employed in this analysis, one designed to study Htt and Hgg and the other designed to study HVV anomalous couplings. To increase the sensitivity of the analysis the events are categorized to better distinguish between different production modes and different couplings.

In the analysis of HVV couplings, two different fitting methods were applied: the first method ("fix others") allows only one anomalous coupling to vary while fixing the others at zero, whereas in the second method ("float others"), all anomalous couplings are allowed to vary during the fit. The results for the different couplings are shown in Table I. As expected, the first method achieves better sensitivity for the parameters but makes the result more model-dependent than the first. The combination of the $H \to 4l$ and $\gamma\gamma$ channels with ttH, tH, and ggH processes is performed and the result related to f_{a3} and f_{CP}^{Htt} are shown in Fig. 2

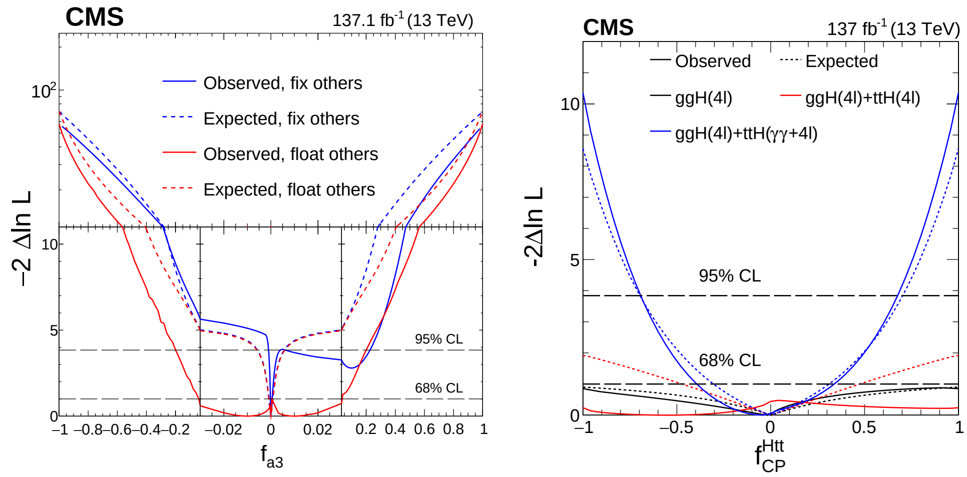

Fig. 2. – On the left, observed (solid) and expected (dashed) likelihood scans of f_{a3}. The results are shown for each coupling fraction fit separately with the other three either set to zero or left unconstrained in the fit. In all cases, the signal strength parameters have been left unconstrained. The dashed horizontal lines show the 68 and 95% CL regions. On the right, constraints on the anomalous H boson couplings to top quarks in the ttH, tH, and ggH processes combined, assuming top quark dominance in the gluon fusion loop, using the $H \to 4l$ and gg decays. Observed (solid) and expected (dashed) likelihood scans of f_{Htt} CP are shown in the ggH process with $H \to 4l$ (black), ttH, tH, and ggH processes combined with $H \to 4l$ (red), and in the ttH, tH, and ggH processes with $H \to 4l$ and the ttH and tH processes with gg combined (blue). Combination is done by relating the signal strengths in the three processes through the couplings in the loops in both production and decay [5].

parameter	method	Observed	[68% CL]
f_{a3}	fix others $f_{a2} = f_{\Lambda_1} = f_{\Lambda_1}^{Z\gamma} = 0$	0.00004	[-0.00007,0.00044]
f_{a3}	floating others	-0.00805	(-0.00010,0.00061]
f_{a2}	fix others $f_{a3} = f_{\Lambda_1} = f_{\Lambda_1}^{Z\gamma} = 0$	0.00020	[-0.00010, 0.00109]
f_{a2}	floating others	-0.24679	[-0.41087, -0.15149] U[-0.00008, 0.00065]
f_{Λ_1}	fix others $f_{a3} = f_{a_2} = f_{\Lambda_1}^{Z\gamma} = 0$	0.00004	[-0.00002, 0.00022]
f_{Λ_1}	floating others	0.18629	[-0.00002, 0.00019]
$f_{\Lambda_1}^{Z\gamma}$	fix others $f_{a3} = f_{a_2} = f_{\Lambda_1} = 0$	-0.00001	[-0.00099,0.00057]
$f_{\Lambda_1}^{Z\gamma}$	floating others	-0.02884	[-0.09000, - 0.00534]U[-0.00068, 0.00078]

TABLE I. – *Allowed 68% CL (central values with uncertainties) intervals on anomalous HVV coupling parameters using the $H \to 4l$ decay channel [5].*

5. – Constraints on anomalous Higgs boson couplings using the $H \to \tau\tau$ final state

The study uses Higgs boson candidates produced mainly in electroweak vector boson or gluon fusion that subsequently decay to a pair of τ leptons. Selected events are classified according to four decay channels, $e\mu$, $e\tau_h$, $\mu\tau_h$, and $\tau_h\tau_h$. The resulting event samples are made mutually exclusive by discarding events that have additional loosely identified and isolated electrons or muons. The largest irreducible source of background is Drell-Yan production of $Z \to \tau\tau$, while the dominant background sources with jets misidentified as leptons are QCD multijet and W+jets.

Event categories are designed to increase the sensitivity to the signal by isolating regions with large signal-to-background ratios, and to provide sensitivity to the Hgg and HVV parameters Using the same methodology as the previous analysis, the MELA package is once again employed to categorize the data in this case.

The results are combined with those from the $H \to 4l$ and $H \to \gamma\gamma$ decay channels to yield the most stringent constraints on anomalous Higgs boson couplings to date as shown in Fig. 3 and table II

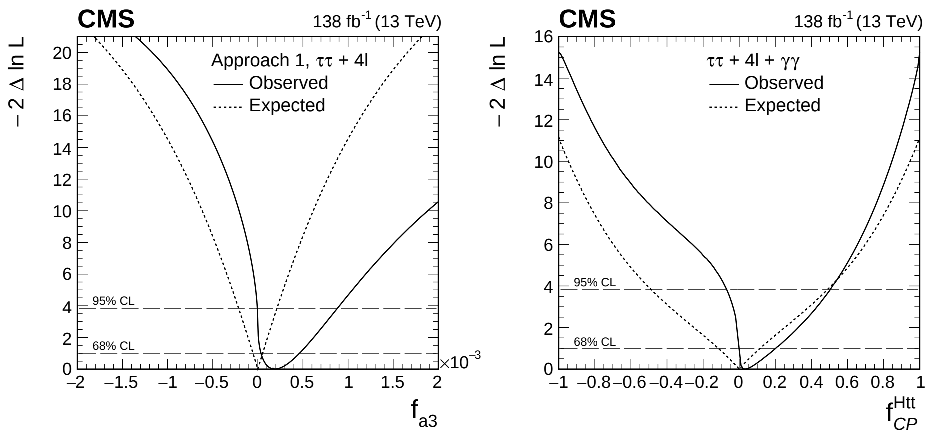

Fig. 3. – On the left: observed (solid) and expected (dashed) likelihood scans of f_{a_3} (left) and f_{CP}^{Htt} (right) obtained with the combination of results using the $H \to \tau\tau$ and $H \to 4l$ decay channels [7].

parameter	Observed/10^{-3} [68% CL]	Expected/10^{-3} [68% CL]
f_{a3}	$0.20^{+0.26}_{-0.16}$	$0.00^{+0.05}_{-0.05}$
f_{a2}	$0.7^{+0.8}_{-0.6}$	$0.00^{+0.5}_{-0.4}$
f_{Λ_1}	$-0.04^{+0.04}_{-0.08}$	$0.00^{+0.11}_{-0.04}$
$f_{\Lambda_1}^{Z\gamma}$	$-0.7^{+1.6}_{-1.3}$	$0.00^{+1.0}_{-1.0}$
f_{CP}^{Htt}	$0.28^{+0.39}_{-0.23}$	$0.00^{+0.08}_{-0.08}$

TABLE II. – *Allowed 68% CL (central values with uncertainties) intervals on anomalous coupling parameters using the $H \to \tau\tau$ $H \to 4l$ decay channel [7].*

6. – Conclusion

The study of the spin and parity properties of the Higgs boson is a crucial area for exploring physics beyond the Standard Model. Investigating potential signs of CP violation in Higgs couplings has been a primary research focus. This field is rapidly expanding, with recent advancements offering new interpretative possibilities. Moreover those analyses are limited by statistical uncertainties, so we expect improvements from the increase in data.

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