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Studies of anomalous couplings of the Higgs boson and its CP structure at CMS

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Pinning down the properties of the Higgs boson and its interaction with other particles is one of the main focuses of research at the CERN LHC. Sophisticated analysis techniques are developed to extract the maximum amount of information from data about Higgs boson coupling to other fundamental particles. A number of studies, public as of July 2022, to probe anomalous effects in Higgs boson couplings and their charge-parity structures using 138 fb^{-1} of data collected by the CMS Experiment in proton-proton collisions at a center-of-mass energy of 13 TeV is presented.

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1. Introduction

Since the discovery of the Higgs boson (H) in 2012 [1–3], measurements at the CERN LHC have solidified the standard model (SM) of particle physics. In the last years, LHC experiments have pinned down the properties of H, including its mass, spin-parity quantum number, coupling strength to different gauge bosons and fermions, to an excellent precision [4, 5]. Measurements so far have supported the SM prediction that H is even under charge-parity (CP) inversion while still allowing the possibility of it being an admixture of CP-even and -odd components.If a CP-odd component of H is found in experiments, it might be of paramount interest in explaining the baryon asymmetry of the universe. Similarly, any deviation of H couplings to other particles from the SM prediction, if found, will shed light on the nature of physics beyond the SM (BSM). In the following, a few recent results from studies of anomalous couplings of H and CP structure performed by the Compact Muon Solenoid (CMS) [6] Experiment are reported.

2. Higgs to vector boson couplings

The coupling of H to vector bosons (V) is parameterized by the scattering amplitude:

$$\mathcal{A}(\mathrm{HVV}) \approx \left[a_1 + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{(\Lambda_1^{\mathrm{VV}})^2}\right] m_{\mathrm{V}1}^2 \epsilon_{\mathrm{V}1}^* \epsilon_{\mathrm{V}2}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}, \quad (1)$$

where a_1 is an SM-like coupling, κ_1, κ_2, and a_2 are CP-even anomalous couplings, and a_3 is a CP-odd anomalous coupling. For the effective interaction of H with gluon (g), a_1, κ_1, κ_2 are 0 to maintain gauge invariance. Anomalous coupling contributions are probed experimentally by measuring the cross section fractions defined as:

$$f_{ai} = \frac{|a_i|^2 \sigma_i}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + |\kappa_1|^2\sigma_{\Lambda 1} + \kappa_2|^2\sigma_{\Lambda_{Z\gamma}}} \quad . \quad (2)$$

In general, to probe H to gauge boson couplings, one needs a large number of observables that fully characterize the system of H production followed by its decay. Performing a multidimensional measurement over a large number of independent variables is very difficult due to the limited volume of data currently available. This problem is solved using the matrix element likelihood approach (MELA) [7], which takes kinematic variables describing the H production and decay and builds discriminants sensitive to the pure BSM signature of an anomalous coupling and its interference with other processes, including in the SM. With this approach, one needs to measure a smaller number of observables while retaining most of the information about SM-BSM separation.

2.1 Anomalous Higgs to electroweak vector boson couplings

The presence of anomalous effects in the coupling of H to electroweak vector bosons is probed in H production via electroweak vector boson fusion (VBF) in the $\mathrm{H} \to \tau\tau$ final state [8] as well as in both H production via VBF and decay using the $\mathrm{H} \to \mathrm{ZZ}^* \to 4\ell$ final state [9]. The $\mathrm{H} \to \tau\tau$ analysis targets the final state where at least one of the two τ's decays hadronically, as well as the case where one τ decays to an electron and the other decays to a muon. The production of H in gluon-gluon fusion (ggH) in association with two jets mimics the H production via VBF.

A MELA discriminator, denoted as D_{2jet}^{VBF}, is used to separate these two processes. A neural network (NN) discriminator (D_{NN}) is designed to separate the VBF-like signature from the SM backgrounds excluding the ggH process. A set of MELA discriminators is constructed to separate the pure BSM and SM-BSM interference signature of the CP-even and -odd anomalous couplings. The distributions of MELA variables in observed data, expected background from SM, and BSM predictions are shown in Fig. 1 (top). In the $H \to 4\ell$ analysis, several MELA discriminators are

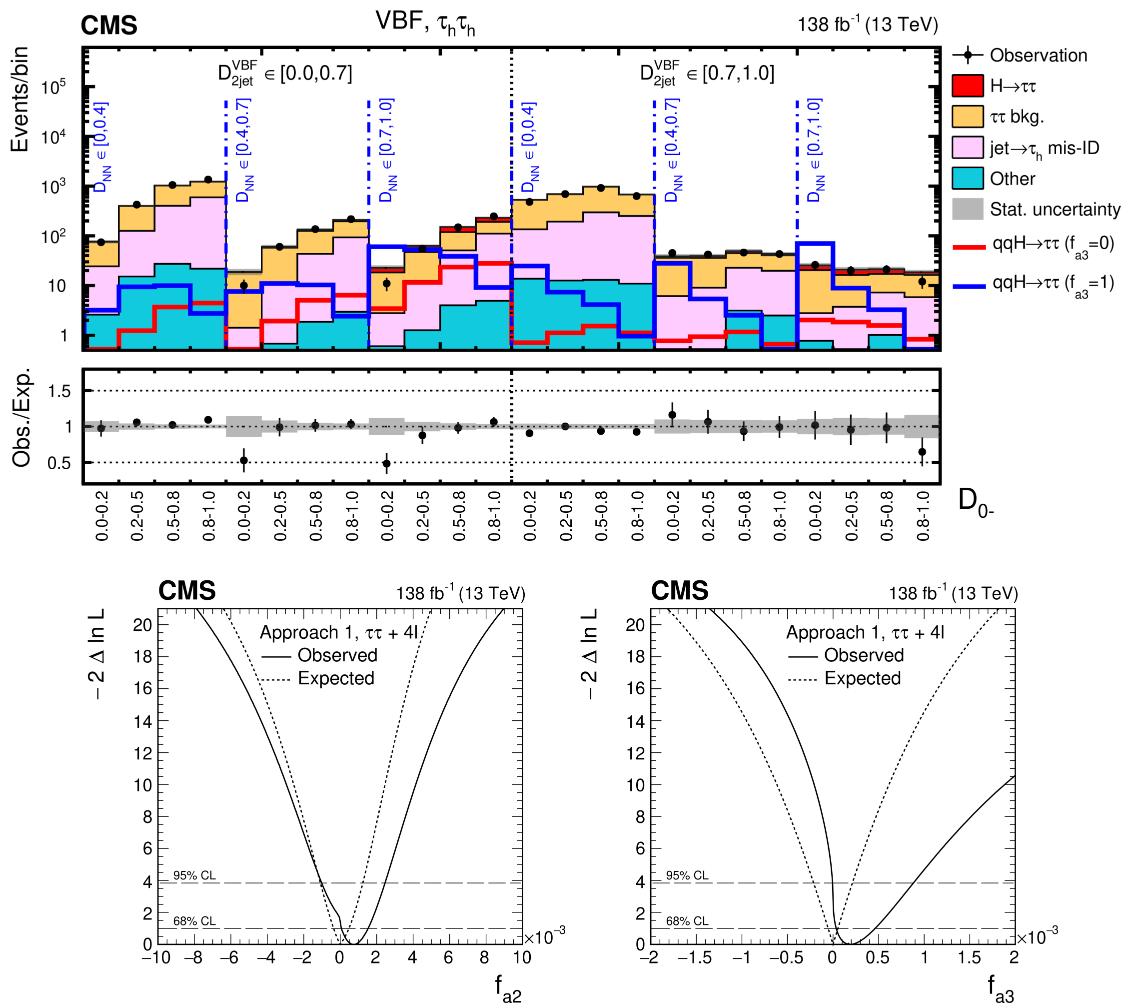

Figure 1: Observed and predicted 3-D distributions of D_{NN}, D_{2jet}^{VBF}, and the MELA discriminator D_{0^-} separating the pure CP-odd anomalous H-V coupling in the final state where both τ leptons decay hadronically (top). Observed and expected negative log-likelihood scans as functions of the cross section fractions of CP-even and -odd anomalous H-V couplings obtained with the combination of results from the $H \to \tau\tau$ and $H \to 4\ell$ analyses (bottom). All figures from Ref. [8].

used to separate different H production modes as well as anomalous coupling signatures. The constraints on cross section fractions due to CP-even and -odd anomalous couplings are obtained after combining results from the $H \to \tau\tau$ and $H \to 4\ell$ analyses and are shown in Fig. 1 (bottom). The sensitivity at small cross section fraction is dominated by the H production in VBF involving a large momentum transfer, and mostly comes from the $H \to \tau\tau$ analysis, whereas the decay information from the $H \to 4\ell$ analysis improves the sensitivity for large values of cross section fractions.

2.2 Higgs to gluon effective couplings

In the analysis targeting the $H \to \tau\tau$ decay, the presence of a CP-odd anomalous coupling in the effective Higgs-to-gluon vertex is probed using another set of MELA variables, where the sensitivity is driven by the separation of two forward jets in azimuthal angle. After combining with the results of the $H \to 4\ell$ analysis, the pure CP-odd H-to-gluon coupling hypothesis is disfavored by the data at the level of 2.4 standard deviations. The combined constraint on the cross section fraction due to the CP-odd anomalous coupling is shown in Fig. 2 (left).

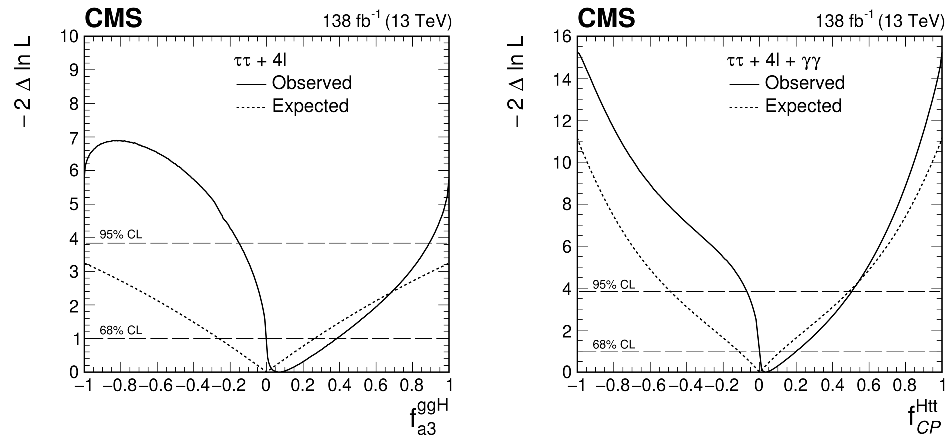

Figure 2: Observed and expected negative log-likelihood scans as a function of cross section fraction of the CP-odd H-g coupling after combining results from the $H \to \tau\tau$ and $H \to 4\ell$ analyses (left) and the CP-odd H-t coupling after combining $H \to 4\ell$, $H \to \gamma\gamma$, and $H \to \tau\tau$ analysis results (right) [8].

3. Anomalous Higgs to fermion couplings

The Lagrangian describing both CP-even and -odd Yukawa couplings of H to fermions, denoted as κ_{f} and $\widetilde{\kappa}_{\mathrm{f}}$, respectively, can be expressed as the following:

$$\mathcal{L}_{\mathrm{Hff}} = -\frac{m_{\mathrm{f}}}{v}\mathrm{H}\bar{\psi}_{\mathrm{f}}\left(\kappa_{\mathrm{f}} + i\gamma_5\widetilde{\kappa}_{\mathrm{f}}\right)\psi_{\mathrm{f}}. \tag{3}$$

In experiments, the presence of a CP-odd component in the H-to-fermion coupling is probed by measuring either the cross section fraction or the mixing angle between κ_{f} and $\widetilde{\kappa}_{\mathrm{f}}$, defined in Eq. 4.

$$f_{\mathrm{CP}}^{\mathrm{Hff}} = \frac{|\widetilde{\kappa}_{\mathrm{f}}|^2}{|\kappa_{\mathrm{f}}|^2 + |\widetilde{\kappa}_{\mathrm{f}}|^2} \quad \alpha^{\mathrm{Hff}} = \tan^{-1}\left(\frac{\widetilde{\kappa}_{\mathrm{f}}}{\kappa_{\mathrm{f}}}\right) \tag{4}$$

3.1 Higgs to top quark couplings

The presence of anomalous interactions in the H to top quark (t) coupling is probed using H production through ggH and in association with a top quark-antiquark pair ($\mathrm{t\bar{t}H}$) or a single t (tH), and final states targeting different H decay modes: $\mathrm{H} \to \gamma\gamma$ [10], $\mathrm{H} \to 4\ell$ [9], and $\mathrm{H} \to \tau\tau$ [8]. In the $\mathrm{H} \to 4\ell$ analysis, MELA discriminators are built targeting the $\mathrm{t\bar{t}H}$ and tH production modes, whereas the $\mathrm{H} \to \gamma\gamma$ analysis distinguishes $\mathrm{t\bar{t}H}$ and background events using boosted decision tree (BDT) based discriminators. Both analyses use MELA discriminators to probe the CP-odd H-t coupling. The $\mathrm{H} \to 4\ell$ analysis combines the results targeting $\mathrm{t\bar{t}H}$ and ggH production modes, assuming top quark dominance in the ggH loop, which results in a large improvement in sensitivity. This is due to the fact that the $\mathrm{t\bar{t}H}$ production cross section increases with increasing CP-odd cross section fraction, whereas the cross section of the ggH process decreases. In the $\mathrm{H} \to \tau\tau$ analysis, the constraints on anomalous effects in the H-g coupling are also reinterpreted as constraints on the H-t coupling. This combined result is shown in Fig. 2 (right).

The CP nature of the H-t coupling is also probed in $\mathrm{t\bar{t}H}$ and tH production in final states with multiple leptons, targeting $\mathrm{H} \to \mathrm{WW}^*$, $\mathrm{H} \to \mathrm{ZZ}^*$, and $\mathrm{H} \to \tau\tau$ decays [11]. Events are categorized depending on the lepton content. A multiclass NN is designed to separate H production via $\mathrm{t\bar{t}H}$ and tH from the SM backgrounds. A BDT discriminator is used in each event category to separate CP-even and -odd H-t coupling scenarios using CP-sensitive variables. The analysis is combined with the analyses targeting $\mathrm{H} \to \gamma\gamma$ and $\mathrm{H} \to 4\ell$ decays [9, 10]. The constraints in the two-dimensional coupling plane (κ_t vs $\widetilde{\kappa}_\mathrm{t}$) is shown in Fig. 3 (left). The data disfavor the pure CP-odd H-t coupling hypothesis at 3.7 standard deviations.

3.2 Search for CP violation in $\mathrm{H} \to \tau\tau$ decay

A search for CP violation in the $\mathrm{H} \to \tau\tau$ decay is performed using the angle between two τ decay planes, denoted as ϕ_{CP} [12]. A NN discriminator is used to separate the $\mathrm{H} \to \tau\tau$ signal from the SM backgrounds. The phase of the ϕ_{CP}-distribution changes depending on the CP-phase of the H-τ coupling. Constraints in the two-dimensional plane of CP-even and -odd H-τ couplings are shown in Fig. 3 (right). The pure CP-odd hypothesis for the H-τ coupling is excluded with 3.0 standard deviations.

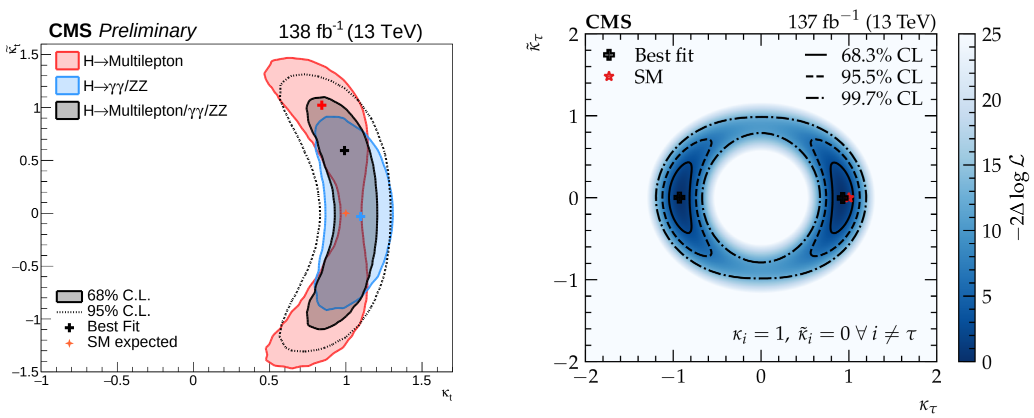

Figure 3: Constraints in the 2-D plane of H-t Yukawa couplings after combining the analyses targeting $\mathrm{H} \to \gamma\gamma$ and $\mathrm{H} \to 4\ell$ decays with the one targeting the multilepton final state (left) [11]. The 2-D negative log-likelihood scan as functions of CP-even and -odd H-τ Yukawa couplings (right) [12].

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4. Conclusion

A number of comprehensive studies are performed by the CMS Experiment to probe the anomalous coupling and CP-structure of the Higgs boson interaction with electroweak vector bosons, gluons, and fermions of the third generation using data collected during Run 2 of the LHC. The knowledge about the nature of the Higgs boson couplings is significantly improved compared to the Run-1 results. This is a result of the larger data set as well as improved analysis techniques.

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] CMS Collaboration, "Observation of a New Boson with Mass Near 125 GeV in *pp* Collisions at $\sqrt{s}$ = 7 and 8 TeV", *JHEP* **06** (2013) 081, doi:10.1007/JHEP06(2013)081, arXiv:1303.4571.

[4] ATLAS Collaboration, "A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery", *Nature* **607** (2022) 52, doi:10.1038/s41586-022-04893-w, arXiv:2207.00092.

[5] 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.

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

[7] A. V. Gritsan, R. Röntsch, M. Schulze, and M. Xiao, "Constraining anomalous Higgs boson couplings to the heavy flavor fermions using matrix element techniques", *Phys. Rev. D* **94** (2016) 055023, doi:10.1103/PhysRevD.94.055023, arXiv:1606.03107.

[8] CMS Collaboration, "Constraints on anomalous Higgs boson couplings to vector bosons and fermions from the production of Higgs bosons using the $\tau\tau$ final state", arXiv:2205.05120.

[9] CMS Collaboration, "Constraints on anomalous Higgs boson couplings to vector bosons and fermions in its production and decay using the four-lepton final state", *Phys. Rev. D* **104** (2021) 052004, doi:10.1103/PhysRevD.104.052004, arXiv:2104.12152.

[10] CMS Collaboration, "Measurements of $\mathrm{t\bar{t}H}$ Production and the CP Structure of the Yukawa Interaction between the Higgs Boson and Top Quark in the Diphoton Decay Channel", *Phys. Rev. Lett.* **125** (2020) 061801, doi:10.1103/PhysRevLett.125.061801, arXiv:2003.10866.

[11] CMS Collaboration, "Search for CP violation in $\mathrm{t\bar{t}H}$ and tH production in multilepton channels at $\sqrt{s}$ = 13 TeV", 2022. http://cds.cern.ch/record/2803420.

[12] CMS Collaboration, "Analysis of the *CP* structure of the Yukawa coupling between the Higgs boson and τ leptons in proton-proton collisions at $\sqrt{s}$ = 13 TeV", *JHEP* **06** (2022) 012, doi:10.1007/JHEP06(2022)012, arXiv:2110.04836.