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Probes of CP-violating Higgs couplings and their impact on baryogenesis

H. Bahl,[a] **E. Fuchs,**[b,c] **M. Hannig,**[b] **S. Heinemeyer,**[d] **J. Katzy,**[c] **M. Menen,**[b,e,*] **K. Peters,**[c] **M. Saimpert**[f] **and G. Weiglein**[c,g]

[a] *ITP, Ruprecht Karls Universität Heidelberg, Philosophenweg 16, Heidelberg, Germany*
[b] *ITP, Leibniz Universität Hannover, Appelstraße 2, Hannover, Germany*
[c] *DESY, Notkestraße 85, Hamburg, Germany*
[d] *IFT, UAM/CSIC, C. Nicolás Cabrera 13-15, Madrid, Spain*
[e] *PTB Braunschweig, Bundesallee 100, Braunschweig, Germany*
[f] *IRFU, CEA, Jardins des Merisiers, Gif-Sur-Yvette, France*
[g] *Inst. Exp. Phys. II, Universität Hamburg, Edmund-Siemers-Allee 1, Hamburg, Germany*

E-mail: h.bahl@thphys.uni-heidelberg.de, elina.fuchs@cern.ch, marc.hannig@stud.uni-hannover.de, sven.heinemeyer@cern.ch, judith.katzy@desy.de, marco.menen@itp.uni-hannover.de, krisztian.peters@desy.de, matthias.saimpert@cern.ch, georg.weiglein@desy.de

We investigate the $\mathcal{CP}$ structure of the Higgs couplings to fermions and gluons by using constraints from LHC measurements and the electric dipole moment of the electron. We further use these constraints to assess how much of the observed baryon asymmetry of the universe can be explained by $\mathcal{CP}$ violation in the Higgs sector. Additionally, our expected limits on the $\mathcal{CP}$ phase of the top-Yukawa coupling from both a global fit and a multivariate approach are stronger than currently existing measurements.

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1. Introduction

In 2012 the ATLAS and CMS collaborations discovered a new particle which properties were in agreement with the predictions from the Standard Model (SM) for the Higgs boson [1, 2]. In the following years a large number of experimental studies was conducted at the LHC which so far showed no strong sign of physics beyond the Standard Model (BSM). One important and so far comparibly unconstrained property of the discovered particle is its $\mathcal{CP}$ nature. While the possibility of a pure $\mathcal{CP}$-odd Higgs was already ruled out experimentally [3, 4], $\mathcal{CP}$ violation in the Yukawa-couplings is still only constrained to $\alpha \lesssim 45°$ @ 95% C.L. in terms of the $\mathcal{CP}$ mixing angle α [5].

Constraints on the $\mathcal{CP}$ structure of the Higgs boson couplings to SM particles can be obtained in multiple complementary ways. The methods used in our works include a global fit to the production and decay rates of the Higgs boson, separation of the $\mathcal{CP}$ states by using kinematic information of specific processes and machine learning techniques, as well as information from the electric dipole moment of the electron (eEDM). Since $\mathcal{CP}$ violation is a necessary ingredient for baryogenesis, we also examine how much of the observed baryon asymmetry of the universe (BAU) can be obtained within the current constraints.

2. Effective model and constraints

In our work, we use the Higgs characterization model [6] which assumes that the Higgs boson at 125 GeV is of a mixed $\mathcal{CP}$ state. The Yukawa couplings can the be written as

$$\mathcal{L}_{\text{yuk}} = -\sum_f \frac{y_f^{\text{SM}}}{\sqrt{2}} \bar{f} \left(c_f + i\gamma_5 \tilde{c}_f \right) f H, \tag{1}$$

with the $\mathcal{CP}$-even coupling modifier c_f and the $\mathcal{CP}$-odd coupling modifier $\tilde{c}_f$. It is also possible to introduce new, effective couplings such as an effective Higgs-gluon coupling via

$$\mathcal{L}_{Hgg} = -\frac{1}{4v} H \left(-\frac{\alpha_s}{3\pi} c_g G^a_{\mu\nu} G^{a,\mu\nu} + \frac{\alpha_s}{2\pi} \tilde{c}_g G^a_{\mu\nu} \widetilde{G}^{a,\mu\nu} \right) \tag{2}$$

where c_g and $\tilde{c}_g$ are the $\mathcal{CP}$-even and $\mathcal{CP}$-odd coupling modifiers, respectively.

In the first part of our work on this topic, we concentrated on the $\mathcal{CP}$ structure of the Yukawa couplings [7]. The modified Yukawa couplings can affect multiple Higgs production and decay rates, such as gluon fusion or the Higgs decay into two fermions. We perform a global fit to all available relevant production and decay rate measurements using the program `HiggsSignals` (version 2.5.0) [8], which has since been incorporated into the `HiggsTools` library [9]. Additional $\mathcal{CP}$ violation beyond the SM typically also leads to enhanced EDMs of fundamental particles. For the eEDM, the leading order contributions come from the so-called Barr-Zee diagrams, which were analytically evaluated in Refs. [10–12]. We use these analytical expressions to assess the relative importance of the different Yukawa couplings. Finally, another "constraint" can be obtained by requiring that the observed BAU should be epxlainable by a given BSM model and within the experimental constraints. For this, we make use of the evaluation of the vev-insertion approximation (VIA) to describe baryogenesis from Refs. [13, 14].

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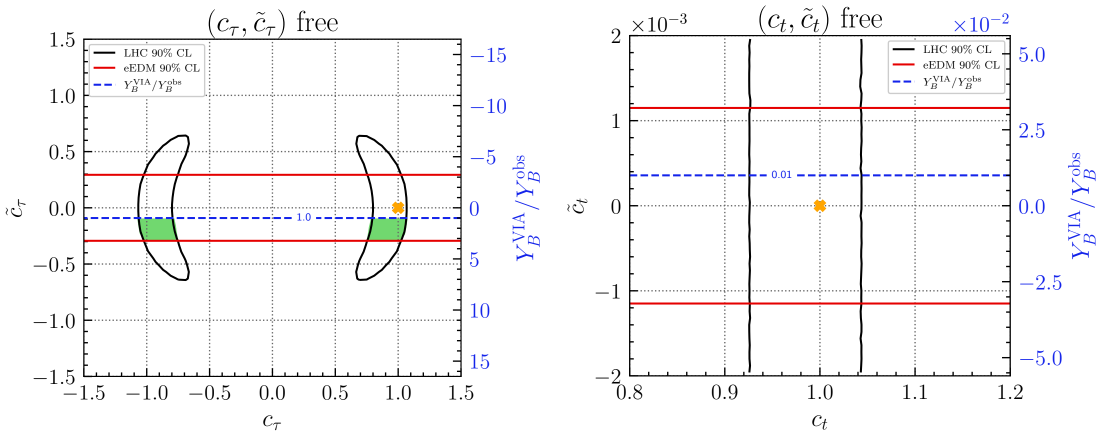
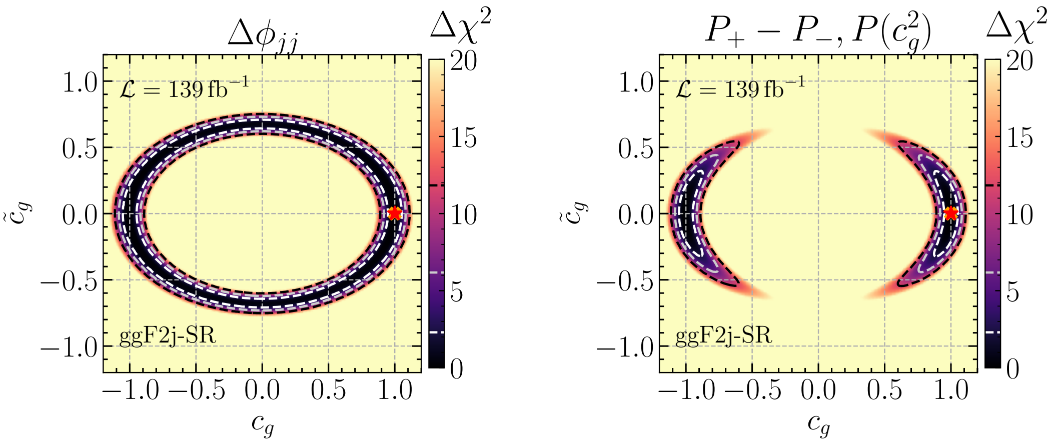


Figure 1: Constraints on the $\mathcal{CP}$-even and $\mathcal{CP}$-odd modifiers of (left) the tau-Yukawa, and (right) the top-Yukawa interactions based on LHC measurements (black), eEDM limits (red), and the ratio $Y_B^{\rm VIA}/Y_B^{\rm obs}$ (blue contours and vertical scale on the right). The green colored areas indicate the parameter regions satisfying the LHC and eEDM constraints for which $Y_B^{\rm VIA}/Y_B^{\rm obs} \geq 1$.

The second part of our work concentrates on the $\mathcal{CP}$ structure of the Higgs-gluon coupling and its connection to the top-Yukawa coupling [15]. For this, we make use of kinematic information in the Higgs production via gluon fusion with two additional jets (ggF2j). The underlying events are generated with `MadGraph5` (version 3.4.0) [16] and are passed on to `Pythia8` (version 8.306) [17] and `Delphes3` (version 3.4.2) [18] for parton showering, hadronisation and detector simulation. The events are split into the signal process ggF2j, and the background processes VBF and VH. The ggF2j events are further split into the three $\mathcal{CP}$ contributions to the total cross section: a squared $\mathcal{CP}$-even, squared $\mathcal{CP}$-odd and interference term. The $\mathcal{CP}$ classification is based on a machine learning approach using the Gradient Boosting Classifier from the `scikit-learn` package [19].

3. Results

The constraints based on our global fit, the eEDM measurement and the explainable amount of the BAU are shown in Fig. 1. The left plot shows the constraints in the case of a free τ-Yukawa coupling, where every other Higgs coupling is fixed to its SM value. The black, solid lines show the constraints from LHC measurement, which include the $H \to \tau^+\tau^-$ decay, as well as a dedicated $\mathcal{CP}$ measurement from CMS [5]. The red, solid lines show the constraints from the 2018 eEDM measurement by the ACME collaboration [20] and the blue, dashed line shows the amount of $\mathcal{CP}$ violation needed in this coupling to explain the observed BAU. The green area corresponds to the allowed region by all three constraints. It should be noted however, that this area is almost completely excluded when incorporating the latest eEDM measurement from 2022 [21]. The right plot of Fig. 1 shows the same contraints but for the top-Yukawa coupling. Here, the eEDM constraint dominates and the blue, dashed line shown in the plot now only corresponds to 1% of the observed BAU. However, lifting the assumption that the e-Yukawa coupling is SM-like leads to greatly enhanced values of the BAU being explainable with just a free top-Yukawa coupling. For more details on this, we refer to Ref. [7].



(a) (b)

Figure 2: Constraints on the $\mathcal{CP}$-even and $\mathcal{CP}$-odd modifiers of the effective Higgs-gluon coupling based on (left) the $\mathcal{CP}$-odd observable $\Delta\phi_{jj}$ and (right) the combined output of a $\mathcal{CP}$-even and a $\mathcal{CP}$-odd classifier. The white, grey and black dashed lines correspond to the 1σ, 2σ and 3σ regions, respectively.

For the constraints on the $\mathcal{CP}$ structure of the effective Higgs-gluon coupling, we compare the constraints from $\Delta\phi_{jj}$, a $\mathcal{CP}$-odd and widely used observable in experimental analysis, to a multivariate approach in which two classifiers, one $\mathcal{CP}$-even and one $\mathcal{CP}$-odd, are trained to distinguish between the two $\mathcal{CP}$ hypotheses. The results can be seen in Fig. 2. On the left, the constraints from $\Delta\phi_{jj}$ are shown which form an ellipse in the c_g, $\tilde{c}_g$ plane, mostly corresponding to the rate information from ggF2j. The combined limits from the two classifiers are plotted on the right and show much tighter constraints, as the ellipse is split into two symmetric regions. In terms of the $\mathcal{CP}$ mixing angle, these results correspond to $\alpha_{Hgg} \lesssim 25°$ @ 95% C.L. for the $\mathcal{CP}$ state of the Higgs-gluon coupling.

Our analysis is designed in a way that the contribution from top-quarks is included in the effective Higgs-gluon coupling and concentrates on a kinematic region in which the infinite top assumption is valid. With the additional assumption that no low-mass colored BSM particle affects the loop in the gluon fusion process, we can set $c_g = c_t$ and $\tilde{c}_g = ctt$ and therefore obtain $\alpha_{ttH} \lesssim 25°$ @ 95% C.L.. The so obtained projected limits for the $\mathcal{CP}$ state of the top-Yukawa coupling are stronger than existing limits based on the ggF2j channel [22, 23] and also stronger than direct searches in top-associated Higgs production [24]. Our global fit approach gives a comparable constraint of $\alpha_{ttH} \lesssim 28°$ @ 95% C.L.. For more details, we refer to Ref. [15].

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. **B716** (2012) 1 [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. **B716** (2012) 30 [1207.7235].

[3] CMS collaboration, *Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV*, Phys. Rev. D **92** (2015) 012004 [1411.3441].

[4] ATLAS collaboration, *Study of the spin and parity of the Higgs boson in diboson decays with the ATLAS detector*, Eur. Phys. J. C **75** (2015) 476 [1506.05669].

[5] 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 [2110.04836].

[6] P. Artoisenet et al., *A framework for Higgs characterisation*, JHEP **11** (2013) 043 [1306.6464].

[7] H. Bahl, E. Fuchs, S. Heinemeyer, J. Katzy, M. Menen, K. Peters et al., *Constraining the $\mathcal{CP}$ structure of Higgs-fermion couplings with a global LHC fit, the electron EDM and baryogenesis*, Eur. Phys. J. C **82** (2022) 604 [2202.11753].

[8] P. Bechtle, S. Heinemeyer, T. Klingl, T. Stefaniak, G. Weiglein and J. Wittbrodt, *HiggsSignals-2: Probing new physics with precision Higgs measurements in the LHC 13 TeV era*, Eur. Phys. J. C **81** (2021) 145 [2012.09197].

[9] H. Bahl, T. Biekötter, S. Heinemeyer, C. Li, S. Paasch, G. Weiglein et al., *HiggsTools: BSM scalar phenomenology with new versions of HiggsBounds and HiggsSignals*, Comput. Phys. Commun. **291** (2023) 108803 [2210.09332].

[10] J. Brod, U. Haisch and J. Zupan, *Constraints on CP-violating Higgs couplings to the third generation*, JHEP **11** (2013) 180 [1310.1385].

[11] W. Altmannshofer, J. Brod and M. Schmaltz, *Experimental constraints on the coupling of the Higgs boson to electrons*, JHEP **05** (2015) 125 [1503.04830].

[12] G. Panico, A. Pomarol and M. Riembau, *EFT approach to the electron Electric Dipole Moment at the two-loop level*, JHEP **04** (2019) 090 [1810.09413].

[13] E. Fuchs, M. Losada, Y. Nir and Y. Viernik, *CP violation from τ, t and b dimension-6 Yukawa couplings - interplay of baryogenesis, EDM and Higgs physics*, JHEP **05** (2020) 056 [2003.00099].

[14] S. Aharony Shapira, *Current bounds on baryogenesis from complex Yukawa couplings of light fermions*, 2106.05338.

[15] H. Bahl, E. Fuchs, M. Hannig and M. Menen, *Classifying the CP properties of the ggH coupling in H+2j production*, 2309.03146.

[16] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, Journal of High Energy Physics **2014** (2014) .

[17] T. Sjostrand, S. Mrenna and P.Z. Skands, *A Brief Introduction to PYTHIA 8.1*, Comput. Phys. Commun. **178** (2008) 852 [0710.3820].

[18] J. de Favereau, C. Delaere, P. Demin, A. Giammanco, V. Lemaître, A. Mertens et al., *DELPHES 3: a modular framework for fast simulation of a generic collider experiment*, Journal of High Energy Physics **2014** (2014) .

[19] F. Pedregosa, G. Varoquaux, A. Gramfort, V. Michel, B. Thirion, O. Grisel et al., *Scikit-learn: Machine learning in Python*, *Journal of Machine Learning Research* **12** (2011) 2825.

[20] ACME collaboration, *Improved limit on the electric dipole moment of the electron*, Nature **562** (2018) 355.

[21] T.S. Roussy, L. Caldwell, T. Wright, W.B. Cairncross, Y. Shagam, K.B. Ng et al., *An improved bound on the electron's electric dipole moment*, Science **381** (2023) 46 [https://www.science.org/doi/pdf/10.1126/science.adg4084].

[22] ATLAS collaboration, *Constraints on Higgs boson properties using $WW^*(\to e\nu\mu\nu)jj$ production in* 36.1 fb^{-1} *of* $\sqrt{s} = 13$ *TeV pp collisions with the ATLAS detector*, Eur. Phys. J. C **82** (2022) 622 [2109.13808].

[23] 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*, Phys. Rev. D **108** (2023) 032013 [2205.05120].

[24] ATLAS collaboration, *CP Properties of Higgs Boson Interactions with Top Quarks in the $t\bar{t}H$ and tH Processes Using $H \to \gamma\gamma$ with the ATLAS Detector*, Phys. Rev. Lett. **125** (2020) 061802 [2004.04545].