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Impact of new experimental data on the C2HDM: the strong interdependence between LHC Higgs data and the electron EDM

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Abstract: The complex two-Higgs doublet model (C2HDM) is one of the simplest extensions of the Standard Model with a source of CP-violation in the scalar sector. It has a $\mathbb{Z}_2$ symmetry, softly broken by a complex coefficient. There are four ways to implement this symmetry in the fermion sector, leading to models known as Type-I, Type-II, Lepton-Specific and Flipped. In the latter three models, there is *a priori* the surprising possibility that the 125 GeV Higgs boson couples mostly as a scalar to top quarks, while it couples mostly as a pseudoscalar to bottom quarks. This "maximal" scenario was still possible with the data available in 2017. Since then, there have been more data on the 125 GeV Higgs boson, direct searches for CP-violation in angular correlations of τ-leptons produced in Higgs boson decays, new results on the electron electric dipole moment, new constraints from LHC searches for additional Higgs bosons and new results on $b \to s\gamma$ transitions. Highlighting the crucial importance of the physics results of LHC's Run 2, we combine all these experiments and show that the "maximal" scenario is now excluded in all models. Still, one can have a pseudoscalar component in $h\tau\bar{\tau}$ couplings in the Lepton-Specific case as large as 87% of the scalar component for all mass orderings of the neutral scalar bosons.

Keywords: Higgs Properties, Multi-Higgs Models, Specific BSM Phenomenology

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Contents

1 Introduction

The discovery of a 125 GeV neutral scalar (h_{125}) by the ATLAS [1] and CMS [2] collaborations at the Large Hadron Collider (LHC) opened a window into the scalar sector. The subsequent Run 2 stage has greatly improved our knowledge, as will become apparent in this article. However, there is still much to uncover, as we start Run 3 and peer into the scalar sector with unprecedented precision.

One interesting example concerns the CP properties of the h_{125}. The early detection of the $h_{125} \to ZZ^*$ decay meant that the Higgs boson could not be a pure CP-odd state [3, 4]. But maybe it can be a mixture of CP-even and CP-odd components. More surprisingly, the h_{125} can couple as mostly CP-even to some states and as mostly CP-odd to others. Consider a two-Higgs doublet model with a $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$ symmetry, softly broken in the potential by a term,

$$V_{\text{soft}} = m_{12}^2 \Phi_1^\dagger \Phi_2 + m_{12}^{2\,*} \Phi_2^\dagger \Phi_1 \,, \tag{1.1}$$

where m_{12}^2 is a complex coefficient. This is known as the complex two-Higgs doublet model (C2HDM). We will denote by "real 2HDM" the model obtained when all coefficients in the scalar potential (including m_{12}^2) are real;[1] for reviews, see refs. [6, 7]. The real 2HDM was introduced by T. D. Lee in order to show that one can have a spontaneous symmetry breaking origin for CP-violation [8]. In contrast, in the C2HDM investigated here the CP-violation appears explicitly in the potential [9, 10].

[1] In ref. [5] it is argued that, since neutral meson observables require explicit complex CP-violating dimension-four Yukawa couplings to quarks, the real 2HDM might not be a fully consistent theory.

Due to the presence of additional sources of CP-violation and the possibility of accommodating a strong first-order electroweak phase transition, the C2HDM is a suitable framework for an explanation of the baryon asymmetry of the Universe by means of electroweak baryogenesis. This model has been studied extensively in the literature; see, for example, refs. [11–40]. In particular, a full analysis was performed of the C2HDM parameter space consistent with the experimental data available at the end of 2017 [26]. The 2017 analysis introduced a new code, `C2HDM_HDECAY`, implementing the C2HDM in the well-known `HDECAY` program [41, 42], and used also:

- Signal strength constraints on h_{125} from the combination of ATLAS and CMS data collected at 7 TeV and 8 TeV [43];
- HiggsBounds 4.3.1 [44], for data from searches for additional scalars;
- The electron electric dipole moment (eEDM) limit of 8.7×10^{-29} e.cm [45];
- The lower bound of 580 GeV on the charged Higgs boson mass, $m_{H^\pm}$, from radiative B-meson decays in the Type-II and Flipped models (introduced below) [46].

Since then, the experimental situation improved considerably on all four fronts. In fact, there are new data on both the properties of the h_{125} (see ref. [47] for a recent summary of the LHC Run 2 results from ATLAS) and the searches for additional scalar states, a factor of roughly 20 improvement on the eEDM, and improved lower bounds on $m_{H^\pm}$ in Type-II and Flipped. In this paper, we analyze the impact of the new experimental data on the parameter space of the C2HDM. Specifically, we address the question whether it is still experimentally viable that the detected Higgs boson at 125 GeV could be coupled to down-type quarks and/or charged leptons as a dominantly CP-odd state.[2] To this end, we confront the model with the following set of recent measurements:

- The latest LHC data on the h_{125} signal strengths, including the full Run 2 data collected at 13 TeV, for the different production and decay modes that have so far been detected. We specifically use the ATLAS results summarized in figure 3 of ref. [53], demanding that the predicted signal rates agree within 2σ with each individual signal-rate measurement. The ATLAS measurements are well in agreement with the corresponding CMS results, such that all our conclusions would remain unchanged if instead the CMS results or a combination of ATLAS+CMS results were used;
- The impact of the latest data of direct searches for CP-violation by CMS using angular correlations in decay planes of τ leptons produced in Higgs boson decays $h_{125} \to \tau\bar{\tau}$ [54], setting an upper limit of $\alpha_{h\tau\tau} < 41^\circ$ on the effective mixing angle between the CP-even and CP-odd τ-Yukawa coupling at the 2σ confidence level (which, as we will show, has a very strong impact on our analysis);[3]

[2]Similar analyses focusing on the LHC Higgs data have been carried out in the past within an effective field theory framework to describe the Higgs-boson couplings, see, e.g. refs. [48–52].

[3]Our analysis uses the CMS results, which was published earlier than the corresponding ATLAS results. ATLAS recently published a similar upper limit of $\alpha_{h\tau\tau} < 34^\circ$ [55]. Our conclusions would remain unchanged if a combined CMS+ATLAS limit would be considered.

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- The impact of new searches for additional scalars, as compiled in `HiggsBounds` 5.7.1 and 5.9.1 [44, 56–58] and in the newest `HiggsTools` 1.1.3 [59], incorporating the newest version 6 of `HiggsBounds`, extending the previous versions by a large set of searches that were performed including the full Run 2 data collected at 13 TeV;

- The recent 90% confidence-level limit on the eEDM of 1.1×10^{-29} e.cm reported by the ACME collaboration [60] and the most recent limit of 4.1×10^{-30} e.cm measured at JILA [61];

- Updated bounds on the mass of the charged Higgs bosons from measurements of radiative B-meson decays (see the discussion in section 3.1).

We note that in the C2HDM the stringent eEDM bounds can only be evaded either close to the CP-conserving limit of the model, or in scenarios where cancellations between diagrams with different neutral scalar particles occur [62–64].[4] Also, henceforth HB stands for `HiggsBounds` and HT for `HiggsTools`.

The paper is organised as follows. In section 2, we describe the parameter space of the model and the couplings of the scalars to fermions and gauge bosons, and we present the theoretical and experimental constraints used in our analysis. In section 3, we discuss the current situation concerning the possibility that the CP-odd components in the couplings of fermions to h_{125} are sizable compared to the respective CP-even components, and thus potentially directly detectable at the LHC. We summarize our conclusions in section 4.

2 The C2HDM

2.1 Physical parameters

We follow closely the notation of ref. [26]. In our notation, the vacuum expectation values (vevs) of the neutral components of the scalar doublets are $\langle \Phi_i^0 \rangle = v_i/\sqrt{2}$ $(i = 1, 2)$, where the parameters v_i can be set to be real and positive without loss of generality due to the freedom of field re-definitions of the doublet fields Φ_i, and $v^2 = v_1^2 + v_2^2 \simeq 246\,\text{GeV}$, $\tan\beta = v_2/v_1$. The mixing of the neutral scalar particles can be described by three angles α_k $(k = 1, 2, 3)$, combined in the mixing matrix

$$R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix}, \tag{2.1}$$

where the short-hand notation $s_k \equiv \sin\alpha_k$ and $c_k \equiv \cos\alpha_k$ has been used, and, without loss of generality,

$$-\pi/2 < \alpha_1 \leq \pi/2, \qquad -\pi/2 < \alpha_2 \leq \pi/2, \qquad -\pi/2 \leq \alpha_3 \leq \pi/2. \tag{2.2}$$

We will make use of a mass-ordered notation in which the neutral scalar masses obey $m_1 < m_2 < m_3$. Following ref. [26], we will describe the scalar sector of the C2HDM in

[4]The contributions from the muon EDM and from non-leptonic EDMs are currently less stringent [26] and will not be considered here.

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terms of 9 independent parameters:

$$v,\ \tan\beta,\ \alpha_1,\ \alpha_2,\ \alpha_3,\ m_{H^\pm},\ m_1,\ m_2,\ \text{and}\ \mathrm{Re}(m_{12}^2)\,. \tag{2.3}$$

With this choice of independent parameters, the mass of the heaviest neutral scalar, m_3, is a dependent parameter, given by

$$m_3^2 = \frac{m_1^2\, R_{13}(R_{12}\, t_\beta - R_{11}) + m_2^2\, R_{23}(R_{22}\, t_\beta - R_{21})}{R_{33}(R_{31} - R_{32}\, t_\beta)}\,, \tag{2.4}$$

with $t_\beta \equiv \tan\beta$. Any of the three neutral scalars, denoted h_1, h_2, h_3 in the following, can in principle coincide with h_{125}; we will thus explore the three possibilities: $m_{h_{125}} = m_1$, $m_{h_{125}} = m_2$, and $m_{h_{125}} = m_3$.

The most general 2HDM suffers from potentially large flavour-changing neutral scalar interactions with quarks, which could contribute to the neutral meson mixing observables at levels much above what is experimentally allowed. This can be cured by the so-called natural flavour conservation mechanism, which uses a $\mathbb{Z}_2$ symmetry, $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$ extended to the fermion sector in such a way that each of the three families of fermions (up-type quarks, down-type quarks, charged leptons) couples to one and only one scalar field [65, 66]. Denoting by Φ_u, Φ_d, and Φ_ℓ the doublet Φ_i $(i = 1, 2)$ that couples to up-type quarks, down-type quarks, and charged leptons, respectively, there are the following four possibilities:[5]

- Type-I: $\Phi_u = \Phi_d = \Phi_\ell \equiv \Phi_2$;
- Type-II: $\Phi_u \equiv \Phi_2 \neq \Phi_d = \Phi_\ell \equiv \Phi_1$;
- Lepton-Specific (LS): $\Phi_u = \Phi_d \equiv \Phi_2 \neq \Phi_\ell \equiv \Phi_1$;
- Flipped $\Phi_u = \Phi_\ell \equiv \Phi_2 \neq \Phi_d \equiv \Phi_1$.

In the fermion and scalar mass bases, the Yukawa Lagrangian for the neutral scalars may be written as

$$\mathcal{L}_Y = -\sum_{i=1}^{3} \frac{m_f}{v} \bar{f} \left[c^e(h_i f\bar{f}) + i c^o(h_i f\bar{f})\gamma_5 \right] f\, h_i\,, \tag{2.5}$$

where f denotes the fermion field with mass m_f. The real coefficients $c^e(h_i f\bar{f})$ and $c^o(h_i f\bar{f})$ describe the CP-even and CP-odd parts of the Yukawa couplings, respectively; we list them in table 1 in terms of the mixing matrix elements R_{ij} (see eq. (2.1)) and the mixing angle β. In the following, $c^e(h_{125} f\bar{f})$ and $c^o(h_{125} f\bar{f})$ are abbreviated by c_f^e and c_f^o, respectively. Moreover, we represent the different families of up-type quarks, down-type quarks and leptons by identifying f with the generic labels t, b and τ, respectively. The effective mixing angle between CP-even and CP-odd τ-Yukawa couplings introduced in section 1 is then given by

$$\alpha_{h\tau\tau} = \tan^{-1} |c_\tau^o| / |c_\tau^e|\,. \tag{2.6}$$

[5]For all four possibilities, the Yukawa coupling matrices of fermions with all neutral scalars are diagonal and proportional to the fermion masses. Thus, besides the parameters for the scalar sector, only fermion masses and the parameters of the Cabibbo-Kobayashi-Maskawa (CKM) matrix (for the coupling to charged scalars) are needed to specify a parameter point.

	u-type	d-type	leptons
Type-I	$\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i2}}{s_\beta} + i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i2}}{s_\beta} + i\frac{R_{i3}}{t_\beta}\gamma_5$
Type-II	$\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i1}}{c_\beta} - it_\beta R_{i3}\gamma_5$	$\frac{R_{i1}}{c_\beta} - it_\beta R_{i3}\gamma_5$
Lepton-Specific	$\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i2}}{s_\beta} + i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i1}}{c_\beta} - it_\beta R_{i3}\gamma_5$
Flipped	$\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i1}}{c_\beta} - it_\beta R_{i3}\gamma_5$	$\frac{R_{i2}}{s_\beta} + i\frac{R_{i3}}{t_\beta}\gamma_5$

Table 1. Yukawa couplings of the Higgs bosons h_i in the C2HDM, divided by the corresponding Standard Model Higgs couplings. The expressions correspond to $[c^e(h_i f\bar{f})+ic^o(h_i f\bar{f})\gamma_5]$ from eq. (2.5).

The LHC signal-rate measurements of h_{125} indicate that the couplings of h_{125} to the massive gauge bosons $V = W, Z$ agree within about 10% with their Standard Model (SM) values [53, 67]. This favors the alignment limit of the 2HDM, in which the couplings of the neutral scalar h_i identified with h_{125}, mimic the ones of the Higgs boson as predicted by the SM. The deviations of the couplings of each neutral scalar h_i from that limit are parameterized by

$$c(h_i VV) = c_\beta R_{i1} + s_\beta R_{i2}\,, \tag{2.7}$$

where in the exact alignment limit one finds $c(h_i VV) = 1$ for one of the three states $h_i = h_{125}$ and $c(h_i VV) = 0$ for the other two $h_i \neq h_{125}$, and outside of the alignment limit $c(h_i VV) < 1$ for all three neutral scalars. We note that enforcing the alignment limit in the (Z_2-symmetric) C2HDM removes all sources of CP-violation in the Higgs sector. Thus, demanding the presence of CP-violation and the alignment limit in the Higgs sector requires an interpretation in a more general 2HDM, see ref. [68] for a recent discussion. For reference, the full set of couplings in the C2HDM using our notation is presented on the web page [69].

2.2 Theoretical and experimental constraints

Our input parameters are chosen as follows. One of the neutral scalars is identified with h_{125}; the masses of the remaining neutral scalars are kept in the interval $30\,\text{GeV} \leq m_i < 1\,\text{TeV}$. As for $m_{H^\pm}$, we implement the bounds on the $m_{H^\pm} - t_\beta$ plane arising from B physics, most notably those implied by the measurements of $B \to X_s\gamma$ [46, 70–74]. We follow ref. [26] in using $80\,\text{GeV} \leq m_{H^\pm} < 1\,\text{TeV}$ for the Type-I and LS models, and $580\,\text{GeV} \leq m_{H^\pm} < 1\,\text{TeV}$ for both Type-II and Flipped models (although we will discuss the impact of the new bounds in the two latter types). As for the remaining input parameters, we also follow ref. [26], by choosing the intervals: $0.8 \leq t_\beta \leq 35$, $-\frac{\pi}{2} \leq \alpha_{1,2,3} < \frac{\pi}{2}$ and $0 \leq \text{Re}(m_{12}^2) < 500000\,\text{GeV}^2$. We then require our points to comply with the measured values of the oblique parameters S, T and U [7] within 2σ of the experimental results quoted in ref. [75], comparing against the theoretically predicted values for the oblique parameters at the one-loop level. Finally, for each plot shown below, we will explicitly mention which LHC constraints on h_{125} are being used (whether those from ref. [43] or those from ref. [53]), which LHC constraints on extra scalars are being used (whether HB-4.3.1 [44], HB-5.9.1 [58] or HT-1.1.3 [59]), which eEDM constraints are being used (whether 8.7×10^{-29} e.cm [45, 76], 1.1×10^{-29} e.cm [60] or 4.1×10^{-30} e.cm [61]), and if the constraint on CP-violating couplings coming from angular

Type	I	II	LS	Flipped
$h_1 = h_{125}$	$\times$	$\times$	✓	✓
$h_2 = h_{125}$	$\times$	✓	✓	$\times$
$h_3 = h_{125}$	$\times$	$\times$	✓	$\times$

Table 2. Results for the possibility of sizable CP-odd components in the couplings of the Higgs boson at 125 GeV from ref. [26]. A checkmark (cross) means that it was (not) possible to have large CP-odd components $|c_f^o| > |c_f^e|$ $(f = b, \tau)$ in the couplings of h_{125}.

correlations in the decays $h_{125} \to \tau\bar{\tau}$ [54] is being used. For the theoretical predictions of the eEDM in the C2HDM, we follow ref. [16].

In all plots, we impose the known theoretical constraints, namely boundedness from below and the non-existence of a lower lying minimum [77] to ensure the absolute stability of the EW vacuum, and we demand perturbative unitarity [78–80], applying an upper limit of 8π on the eigenvalues of the scalar four-point scattering matrix in the high-energy limit.

3 Searching for large CP-odd couplings

We perform an update of ref. [26] of some of the authors of this paper, looking in particular at the possibility that the $h_{125}b\bar{b}$ and/or the $h_{125}\tau\bar{\tau}$ coupling might be mostly CP-odd; that is, $|c_b^o| \gg |c_b^e|$ and/or $|c_\tau^o| \gg |c_\tau^e|$. In ref. [26], we found the situation summarized in table 2.

The impossibility to accommodate mostly CP-odd couplings of h_{125} found in all Type-I cases is easy to understand. As can be seen in the first row of table 1, the CP-odd coupling components in that Type are always proportional to R_{i3}/t_β. Now, on the one hand, the B physics constraints force $t_\beta > 1$. On the other hand, R_{i3} is just a product of sine and cosine of the rotation angles matrix of eq. (2.1), so that $|R_{i3}| \leq 1$. More than this, $|R_{i3}|$ is further constrained by μ_{VV} (the ratio between the new physics and the SM value of the product between Higgs-boson production and its decay to vector bosons); the reason is that $|R_{i3}|$ is a measure of the CP-odd admixture of the state h_i, thus suppressing the couplings to gauge bosons [22]. Finally, since in Type-I all fermions couple as the top quark to the scalars, this Type is precluded from large CP-odd components.[6] As a consequence, in the following discussion we do not consider the Type-I anymore and focus on the other three Yukawa types of the C2HDM.

In the following subsections, we present several figures. In all of them, the light green points are consistent with the old eEDM of 8.7×10^{-29} e.cm, the dark green points with the more recent result 1.1×10^{-29} e.cm and the dark red points with the new result, 4.1×10^{-30} e.cm. Also, the signs of c_f^e and c_f^o have no absolute meaning; they are relative to the sign of $k_V \equiv c(h_{125}VV)$, which is thus also taken into account in the plots by always plotting $\mathrm{sgn}(k_V)c_f^o$ vs. $\mathrm{sgn}(k_V)c_f^e$.

[6] There are also direct measurements on the CP-odd vs. CP-even components of the top coupling coming from $pp \to t\bar{t}(h_{125} \to \gamma\gamma)$ [81], giving rise to $\alpha_{htt} < 43^\circ$ at 95% confidence level, thus directly excluding the maximally CP-odd scenario with $|c_t^o| \gg |c_t^e|$. We also point out that the valid cases shown in table 2 also allowed for the so-called wrong-sign regime, in which the Yukawa coupling is real but has the opposite sign it would have in the SM [19, 82–86].

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3.1 Type-II

Reference [26] found that, in Type-II, it was possible to have sizable CP-odd components in the Yukawa couplings of h_{125} for the case of $h_2 = h_{125}$ (and only in this case). In the following figures, we reproduce this result, and investigate the impact of recent LHC data. We thus assume $h_2 = h_{125}$, and we use the bound of $m_{H^\pm} > 580\,\text{GeV}$ [46] resulting from measurements of $b \to s\gamma$ transitions, which was the limit applied in ref. [26]. Meanwhile, there was an updated NNLO calculation of the inclusive $b \to s\gamma$ branching ratios, giving rise to a limit of $m_{H^\pm} > 800\,\text{GeV}$ [74]. This limit was based on the HFLAV average value $\text{BR}(b \to s\gamma) = (3.32 \pm 0.15) \times 10^{-4}$ from 2019 [87]. The current average value from HFLAV 2022 [88], $\text{BR}(b \to s\gamma) = (3.49 \pm 0.19) \times 10^{-4}$, is slightly larger and has a larger uncertainty.[7] A reanalysis of the impact of this new result by the group that provided the previous limits [46, 74] lowers the limit on the charged Higgs-boson mass to $m_{H^\pm} > 500\,\text{GeV}$ at 2σ confidence level [90]. Since the underlying experimental data has undergone significant changes in recent years, leading to substantial fluctuations in the lower limit on the mass of the charged Higgs bosons, we decided to keep the somewhat stronger limit of $m_{H^\pm} > 580\,\text{GeV}$ [46] applied in the previous analysis [26] to facilitate a better comparison and a more direct analysis of the impact of the other experimental constraints applied in our analysis. We have verified that our conclusions regarding the possibility of accommodating sizable CP-odd components in the couplings of h_{125} in the Type-II and the Flipped Type do not depend on whether a lower limit of 500 GeV or 580 GeV is applied.

Figure 1 shows the allowed parameter space in the plane CP-odd (c_b^o) vs. CP-even (c_b^e) component of the $h_{125}b\bar{b}$ coupling. The left panel considers the 7 and 8 TeV LHC data for h_{125} collected until 2017 [43] and the cross-section limits from BSM scalar searches as implemented in HB-4.3.1 [44], which are the limits that were applied in the previous analysis [26]. The right one considers additionally the 13 TeV LHC data for h_{125} collected during Run 2 [53] and the cross-section limits from BSM scalar searches at 13 TeV as implemented in HT-1.1.3 [59]. The light green points are in agreement with the old eEDM of 8.7×10^{-29} e.cm [45, 76], the dark green points with the more recent result 1.1×10^{-29} e.cm [60]. The dark red points obey the current limit on the eEDM [61]. The considerable reduction of the allowed parameter space in the transition from the left to the right plot is mainly caused by the 13 TeV data on h_{125} collected until 2022 (and to a lesser extend by improved searches for heavier scalars involved in the different versions of HB). The width of the rings is related to the decay width $\Gamma(h_{125} \to b\bar{b}) \propto (c_b^e)^2 + (c_b^o)^2$, which is the largest contribution to the total width and can thus also be responsible for modifications in other decay channels, and the new data reduces the allowed range for $(c_b^e)^2 + (c_b^o)^2$. Note also that the points close to the wrong sign limit in the left panel of figure 1 disappear with the new data, which is mainly related to more precise measurements in the gluon-fusion production channels of h_{125}.[8] Yet, even after applying all current constraints except for the direct limit on the effective mixing angle $\alpha_{h\tau\tau}$ (see discussion below), but including the new limit on the eEDM [61], we find allowed parameter points in the Type-II with a large pseudoscalar component in the couplings of h_{125} to bottom quarks.

[7] Not including the most recent Belle-II measurement [89], the HFLAV 2022 average value is in good agreement with this latest experimental result.

[8] See refs. [91–93] for more detailed discussions about the wrong sign limit in view of the 13 TeV LHC Higgs data.

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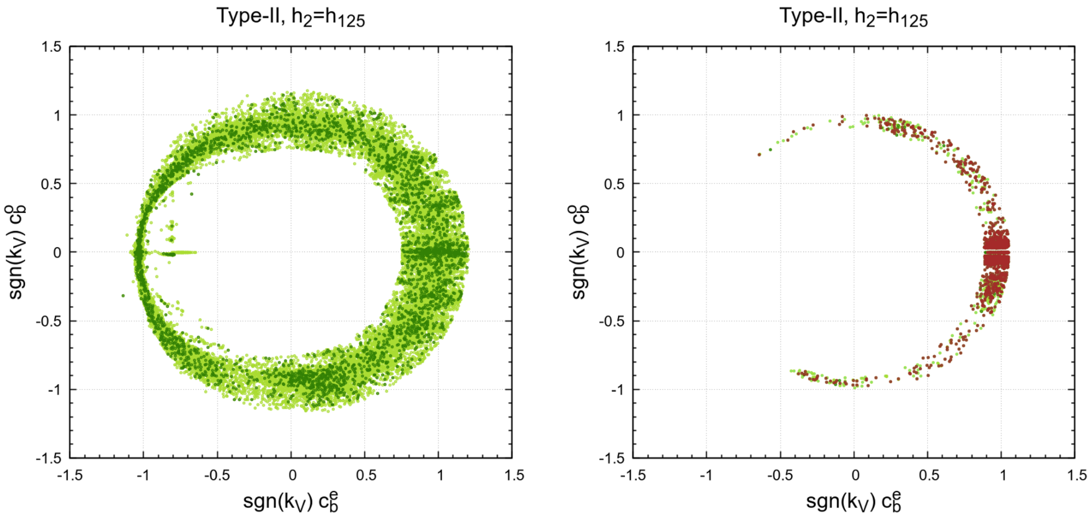

Figure 1. CP-odd vs. CP-even component in the $h_{125}b\bar{b}$ coupling of allowed parameter points in Type-II, assuming $h_2 = h_{125}$. Left panel: LHC 2017 data on h_{125} and constraints from beyond-SM (BSM) scalar searches at 7 and 8 TeV using HB-4.3.1. Right panel: LHC 2022 data on h_{125} and constraints from BSM scalars including 13 TeV data using HT-1.1.3. The light green points are consistent with the old eEDM of 8.7×10^{-29} e.cm [45, 76], the dark green points with the more recent ACME result 1.1×10^{-29} e.cm [60]. The dark red points obey the currently strongest limit on the eEDM 4.1×10^{-30} e.cm reported by JILA [61]. The fermion masses in the loops of diagrams contributing to the eEDM were taken as pole masses. The limit $\alpha_{h\tau\tau} < 41°$ [54] from searches for CP-violation in angular correlations of τ leptons in $h_{125} \to \tau\bar{\tau}$ decays has not been applied in either of the plots in this figure.

So far, we have not yet applied the recent direct bound on a CP-odd coupling component from the angular correlations of τ leptons in $h_{125} \to \tau\bar{\tau}$ decays [54, 55]. In the Type-II model, the down-type quarks are coupled to the neutral scalars in the same way as the charged leptons, such that $c_b^{e,o} = c_\tau^{e,o}$. It follows that, in this type, the recent bound $\alpha_{h\tau\tau} < 41°$ has to be taken into account in the study of the CP properties of $h_{125}b\bar{b}$. The limit on $\alpha_{h\tau\tau}$ has not been applied in either of the plots in figure 1. Requiring that $\alpha_{hbb} < 41°$, with $\alpha_{hbb} = \tan^{-1}|c_b^o|/|c_b^e| = \alpha_{h\tau\tau}$, excludes the possibility of $|c_b^o| \gg |c_b^e|$ in the right panel of figure 1. Nevertheless, the interesting possibility that $|c_b^o| \simeq |c_b^e|$ (and therefore also $|c_\tau^o| \simeq |c_\tau^e|$) would still be allowed.

The above conclusions in the Type-II crucially depend on a significant fine-tuning of the model parameters in order to be compatible with the stringent experimental upper bounds on the eEDM. These limits can be evaded only as a result of a cancellation between different contributions to the eEDM at two-loop level in the perturbative expansion (as discussed in more detail below). This cancellation gives rise to a strong dependence of the predicted eEDM on the model parameters, including the values for the masses of the fermions that appear as virtual particles in the loops of Barr-Zee type diagrams [94]. The corresponding amplitudes are proportional to the mass of the fermion appearing in the loop. Consequently, the numerically relevant contributions stem from diagrams with an internal top quark, bottom quark, or τ lepton. At the two-loop level, it is formally consistent to choose different renomalization

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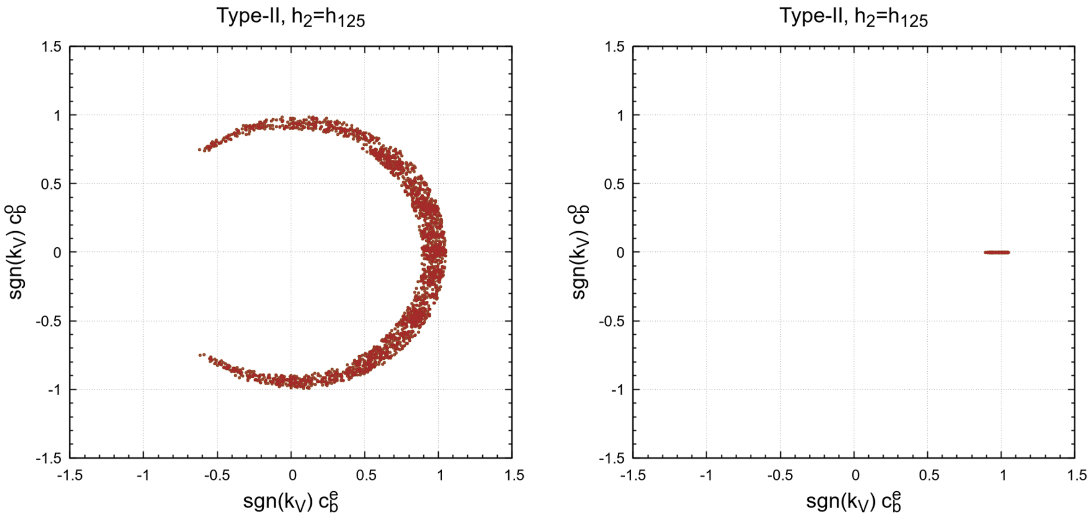

Figure 2. CP-odd vs. CP-even component in the $h_{125}b\bar{b}$ coupling of allowed parameter points in Type-II, assuming $h_2 = h_{125}$. All points obey the current experimental limit on the eEDM [61], where here the masses of the fermions in the loops of diagrams contributing to the eEDM were taken to be the running masses at the M_Z scale (see text for details). Also applied are the constraints from the h_{125} cross section measurements using LHC 2022 data collected at 13 TeV. The left panel does not include the LHC constraints on the extra scalars while in the right panel these constraints are applied including the most recent searches at 13 TeV using HT-1.1.3.

prescriptions for the fermion masses [95], and different approaches have been applied in the literature. The two most common choices have been to use either $\overline{\text{MS}}$ running masses at the scale M_Z ($\overline{m}_t(M_Z), \overline{m}_b(M_Z), \overline{m}_\tau(M_Z)$), see e.g. refs. [16, 33, 96], or pole masses for top quark and τ lepton in combination with the running bottom-quark mass at the scale $\overline{m}_b$ ($m_t, \overline{m}_b(\overline{m}_b), m_\tau$), see e.g. refs. [26, 27, 35, 40, 52]. In the analysis discussed above, we have used the latter possibility for the eEDM predictions. In the following, we will discuss the modifications resulting from choosing the running masses at the scale M_Z.

To this end, we generated a new set of parameter points in the Type-II which all satisfy the current experimental limit on the eEDM with the eEDM computed using the running masses at M_Z. Moreover, the parameter points fulfill the other experimental and theoretical constraints discussed in section 2.2, with the exception of the constraints from BSM scalar searches at the LHC and from direct searches for CP-violation in $h_{125} \to \tau\bar{\tau}$ decays. The resulting parameter points are shown in the plane of CP-odd *vs.* CP-even components of the $h_{125}b\bar{b}$ coupling in the left plot of figure 2. One can see that, before the cross-section limits from the LHC searches are applied, the results are very similar to the case shown in the right plot of figure 1, where the eEDM was computed using the on-shell (OS) prescription for the top-quark and τ-lepton masses in combination with $\overline{m}_b(\overline{m}_b)$. However, after applying the LHC constraints from searches for additional scalars (see the discussion below for details), the only still viable parameter points are situated very close to the alignment limit, as is shown in the right plot of figure 2. Hence, if the eEDM is computed using the running masses at the scale M_Z, we find that it is incompatible to have both sizable CP-odd components in the $h_{125}b\bar{b}$ coupling and agreement with the experimental upper limit on the eEDM and with

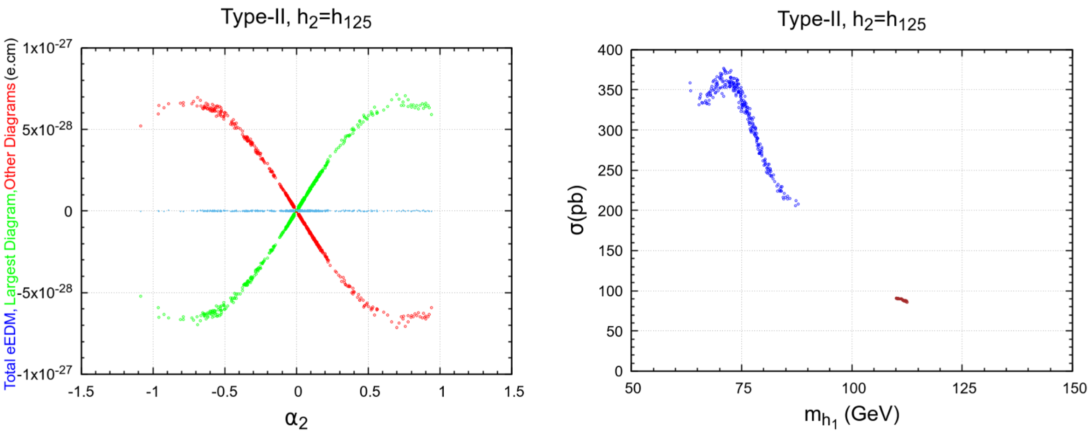

Figure 3. Left panel: individual contributions to the eEDM taken into our account in our analysis. The green points show the contribution from one of the diagrams in the W-loop class, which gives the largest contribution to the eEDM, and the red points show the sum of the remaining contributions. The blue points show the total eEDM (see text for the details). Right panel: LHC 13 TeV cross section for the gluon-fusion production of h_1 as a function of m_{h_1}. Blue and brown points are the subset of the points shown in the right plot of figure 1 and in the left plot of figure 2, respectively, that additionally satisfy the condition $|c_b^e| < 0.1$.

cross-section limits from BSM scalar searches. This is in clear contrast to our observations using pole masses m_t and m_τ in combination with $\overline{m}_b(\overline{m}_b)$ for the eEDM predictions, as becomes apparent by comparing the right plot of figure 2 to the right plot of figure 1.

To gain more insight as to why the conclusions in the Type-II model depend so strongly on the choice of the parameters (such as the precise values for the fermion masses), we investigated the individual Barr-Zee contributions to the eEDM. Following the nomenclature of ref. [16], these can be divided into four classes denoted "fermion loops", "charged Higgs loops", "W loops" and "$H^\mp W^\pm \gamma$ loops". In our scans, we observed that, for parameter points that satisfy the experimental upper limit of $4.1 \cdot 10^{-30}$ e.cm, the contributions from the individual pieces can still be of the order of 10^{-28} e.cm. This is illustrated in the left plot of figure 3, where we show in green the contribution from one of the diagrams in the W-loop class, which typically is the numerically most important piece, and in red the sum of the other three contributions. Finally, we show in blue the total eEDM containing all four pieces, confirming the very significant fine-tuning between the different components.

In our scans, this fine-tuning is achieved by carefully adjusting the parameters of the model. If one changes the fermion masses in the loops (e.g. as a result of choosing different renormalization prescriptions as discussed above), one has to adjust the other parameters of the model in order to maintain the fine-tuning in the eEDM prediction. This concerns mainly the masses of the BSM scalars, which then turns out to have a large impact on the LHC phenomenology and corresponding constraints on the C2HDM. The difference of results in Type-II according to the different prescription of the fermion masses, as discussed above, has its origin in the application of cross-section limits from LHC searches — more specifically, searches for scalar resonances produced via gluon-fusion with subsequent decay in $\tau\bar{\tau}$ final

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states performed by CMS at 13 TeV [97].[9] In the right plot of figure 3, we show the parameter points from the two scans that we have performed in Type-II, with the lightest scalar mass m_{h_1} on the horizontal axis and the gluon-fusion production cross section for h_1 at 13 TeV on the vertical axis. Note that we only show the points that satisfy the additional condition $|c_b^e| < 0.1$, which ensures that, for the shown parameter points, the $h_{125}b\bar{b}$ coupling is mainly CP-odd. The brown points are from the scan in which we used the pole masses m_t and m_τ and the $\overline{\text{MS}}$ mass $\overline{m}_b(\overline{m}_b)$ in the computation of the eEDM (corresponding to a subset of the points depicted in the right plot of figure 1), and the blue points are from the scan in which the running fermion masses at the weak scale were used (corresponding to a subset of the points depicted in the left plot of figure 2). One can see that, for the latter set of parameter points, the masses of the lightest scalar h_1 are lower compared to the points for which the pole masses m_t and m_τ in combination with $\overline{m}_b(\overline{m}_b)$ were used for the eEDM. As a consequence, h_1 has substantially larger production cross sections at the LHC, and would have been observed in searches for low-mass scalar resonances decaying into τ-lepton pairs.[10] The application of the corresponding cross-section limits gives rise not only to the difference between the left and the right plot of figure 2, but also to the different conclusions (regarding the possibility of detectable CP-odd components in the couplings of h_{125}) according to the mass renormalization of the virtual fermions in diagrams contributing to the eEDM.

3.2 Lepton-specific

In the LS model, the down-type quarks are coupled to the scalars in the same way as the up-type quarks. As a consequence, given that (as discussed above) the $h_{125}t\bar{t}$ coupling is measured to be mainly CP-even, one can only find sizable CP-odd components in the LS model in the coupling to leptons, i.e. $|c_\tau^o| \gg |c_\tau^e|$. In the following, we consider the three possible mass hierarchies with the lightest, the second-lightest or the heaviest neutral scalar playing the role of h_{125}. With the 7 and 8 TeV LHC Higgs data collected until 2017 and for the LS case, all placements of h_{125} in the neutral scalar mass orderings were still consistent with a mostly CP-odd $h_{125}\tau\bar{\tau}$ coupling [26].

In view of the discussion in section 3.1, we computed the eEDM in the LS model using the running fermion masses at the M_Z scale. However, we note that, in contrast to the Type-II model, the LS model is such that the fine-tuning of parameters required to satisfy the upper bounds on the eEDM is not very severe. It follows that our findings are unchanged if, instead of the running fermion masses at the M_Z scale, we were to use the pole masses for the top quark and the τ lepton as well as $\overline{m}_b(\overline{m}_b)$ (we verified this explicitly with dedicated scans). The LS model has a further advantage over the Type-II model, which concerns the fact that constraints from collider experiments are less severe. As discussed in section 2.2, in fact, the lower limit $m_{H^\pm} > 580$ GeV on the charged Higgs-boson mass from measurements of $b \to s\gamma$ transitions applicable in Type-II is not valid for the LS model. Moreover, the LS model can realize CP-violating effects only in the couplings of the 125 GeV Higgs boson

[9] The corresponding ATLAS search [98] does not include the mass region below 125 GeV that is relevant in this discussion.

[10] The branching ratios of the decay $h_1 \to \tau\bar{\tau}$ have values in the interval 8.6% to 9.7% for the brown points and 8.6% to 9.2% for the blue points. Therefore, the exclusion comes mainly from the differences in the production cross section.

to leptons, whereas its couplings to quarks can remain at the same time approximately CP-conserving. As a result, the LS model allows for a sizable amount of CP-violation in the couplings of the h_{125} to leptons, without modifications from CP-violating effects to the most important production and decay channels at the LHC. Thus, there is more freedom in this type for the presence of CP-violating couplings in regards to the cross-section measurements of the detected Higgs boson.

In the following, we will analyze separately the three possible mass hierarchies in the LS model.

3.2.1 $h_1 = h_{125}$

The results for the LS model with $h_1 = h_{125}$ are shown in figure 4. This figures takes into account up-to-date constraints from LHC searches for additional Higgs bosons and the signal rate measurements of h_{125}. Whereas in the left panel we exclude the constraints on the CP-violating phase $\alpha_{h\tau\tau}$ coming from direct searches for CP-violation in angular variables of τ leptons in $h_{125} \to \tau\bar{\tau}$ decays, reported by CMS [54], in the right panel we include them. We see that, in the left panel, even though we are including the latest eEDM data, there is still a large allowed parameter region consistent with $|c_\tau^o| \gg |c_\tau^e|$. On the other hand, the right panel shows that the constraints on $\alpha_{h\tau\tau}$ exclude this scenario. Therefore, in the LS type of the C2HDM, the direct LHC measurements of CP-violation in angular variables in $h_{125} \to \tau\bar{\tau}$ decays are able to exclude regions of the parameter space that would otherwise be allowed by all other theoretical and experimental constraints. In particular, we find parameter points which are in agreement with the experimental upper bounds on the eEDM (dark red points in figure 4), and which are excluded only by the LHC measurements of CP-violation in decays of the h_{125} to τ leptons. This demonstrates the complementarity of probing possible CP-violation in extended Higgs-sector models at low-energies in terms of eEDMs and at high-energy at the LHC.

Even though the direct limits on $\alpha_{h\tau\tau}$ substantially restrict the possible amount of CP-violation in the $h_{125}\tau\bar{\tau}$ coupling, they do not exclude the interesting possibility $|c_\tau^o| \simeq |c_\tau^e|$, as can be seen in the right panel of figure 4. This has important consequences for the possibility of explaining the baryon asymmetry of the Universe in the framework of the C2HDM by means of electroweak baryogenesis. It has recently been shown that a sizable amount of CP-violation in the $h_{125}\tau\bar{\tau}$ coupling might be sufficient to accommodate the baryon asymmetry without the presence of additional CP-violation in the other couplings of the h_{125} [52].[11] As such, the LS C2HDM can still be regarded as a possible framework for an explanation of the matter-antimatter asymmetry of the Universe. We note, however, that a successful realization of electroweak baryogenesis also requires a sufficiently strong first-order electroweak phase transition. We leave for future work an analysis of whether the allowed parameter points in our scan sample that feature sizable CP-odd components in the $h_{125}\tau\bar{\tau}$ coupling can additionally accommodate such a phase transition.

[11] Compare, however, also with ref. [35]. Note furthermore that it is still under debate if the amount of generated baryon asymmetry is sufficiently large to be in agreement with the observed value because of large theory uncertainties in the prediction for the baryon asymmetry, which strongly depends on the approach that is used to compute the source term for the baryon asymmetry, see ref. [99] for a recent discussion.

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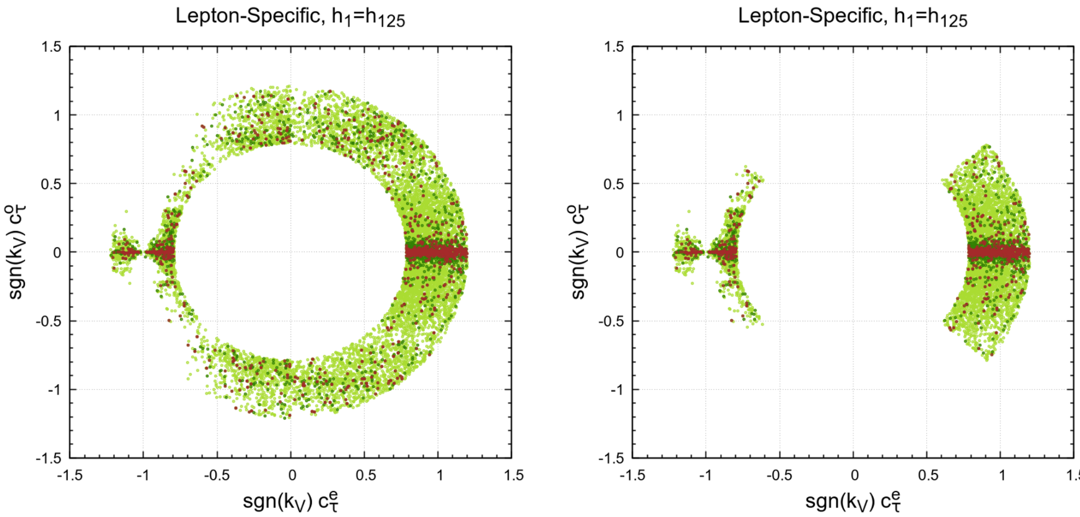

Figure 4. CP-odd vs. CP-even component in the $h_{125}\tau\bar{\tau}$ coupling for the allowed parameter points in the LS model, assuming $h_1 = h_{125}$, using 13 TeV LHC Higgs data on h_{125} collected until 2022 and constraints from BSM scalar searches included in HT-1.1.3. In the left panel, the limit $\alpha_{h\tau\tau} < 41°$ from angular correlations of τ leptons in $h_{125} \to \tau\bar{\tau}$ decays is not applied, whereas the right panel includes this limit. Colour code as in figure 1.

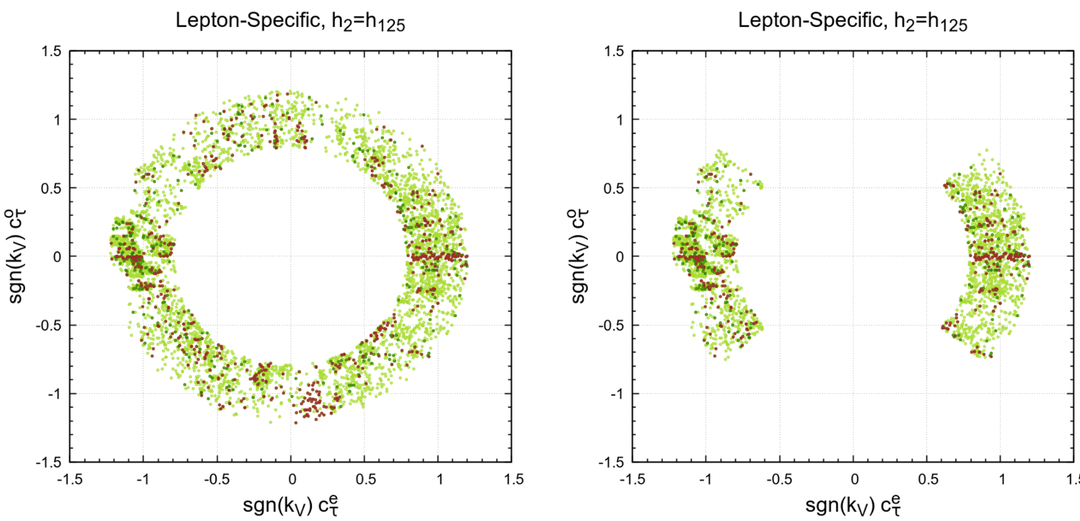

Figure 5. Same as in figure 4, but for $h_2 = h_{125}$.

3.2.2 $h_2 = h_{125}$

The case with the second lightest neutral scalar h_2 acting as h_{125} is similar to the case where $h_1 = h_{125}$, as can be seen in figure 5. Here, we show the same as in figure 4, but now for $h_2 = h_{125}$. As in the previous case, a parameter region with $|c^o_\tau| \gg |c^e_\tau|$ still remains after the application of all current experimental constraints from the LHC and the eEDM. Consequently, also the mass hierarchy with $h_2 = h_{125}$ is subject to new constraints on the parameter space coming from the LHC measurement of CP violating effects in $h_{125} \to \tau\bar{\tau}$ decays, still leaving the interesting possibility of $|c^o_\tau| \simeq |c^e_\tau|$ though.

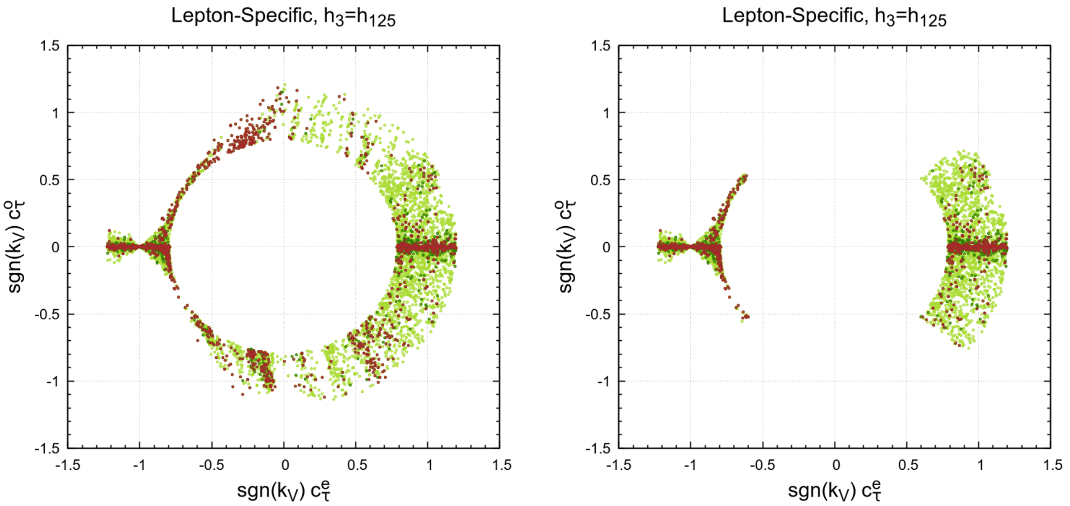

Figure 6. Same as in figure 4, but for $h_3 = h_{125}$.

3.2.3 $h_3 = h_{125}$

The situation for the mass hierarchy with $h_3 = h_{125}$, is shown in figure 6, where the color of the points is defined as in figures 4 and 5. Likewise, the limit on $\alpha_{\tau\tau}$ has been applied in the right plot only, whereas all other constraints have been applied in both plots according to the discussion above. The main conclusions are the same as in the previous two cases. Since all mass hierarchies in the LS model are compatible with CP-odd components in the $h_{125}\tau\bar{\tau}$ coupling that are sufficiently large to be directly observable at the LHC, a possible future detection of CP-violation in $h_{125} \to \tau\bar{\tau}$ decays via angular correlations of the τ leptons would not allow for a distinction between the different mass hierarchies.

3.3 Flipped

We have seen that Higgs data related to μ_{VV} (as well as direct searches [81]) forbid values of $|c_t^0| \gtrsim |c_t^e|$, and that the latest data of searches for CP-violation in angular correlations of the τ leptons in $h_{125} \to \tau\bar{\tau}$ decays precludes $|c_\tau^o| \simeq 1$ [54, 55]. The Flipped type, with $\Phi_u = \Phi_\ell \neq \Phi_d$, might still be a promising candidate for large CP-odd components, as it in principle allows the possibility of large $|c_b^o|$. Moreover, since this type was shown in 2017 (after the 7 and 8 TeV Runs of the LHC) to be able to accommodate sizable CP-odd components with the mass hierarchy in which the detected Higgs boson at 125 GeV is the lightest scalar [26], the impact of the more stringent lower bounds on $m_{H^\pm}$ from $b \to s\gamma$ transitions can be expected to be less severe compared to the situation in Type-II (see discussion in section 3.1).

It turns out that this possibility is now excluded. Indeed, the status of the Flipped type changed significantly with respect to ref. [26]. This is not because of the LHC 2022 data on the signal strengths of h_{125}, but because of the additional constraints imposed by the searches for extra scalars at 13 TeV, as implemented in the most recent version of HB (now incorporated in HT). This is shown in figure 7, which takes $h_1 = h_{125}$. In the left panel, we use the old 2017 data on h_{125} and the old HB-4.3.1 bounds. In the right panel, we use HT-1.1.3 and the latest LHC 2022 data on searches for additional Higgs bosons, as well as the most recent limit on the eEDM [61] (not used with the old data on the left panel). The main impact of taking into account the 13 TeV signal-rate measurements of h_{125} is that it

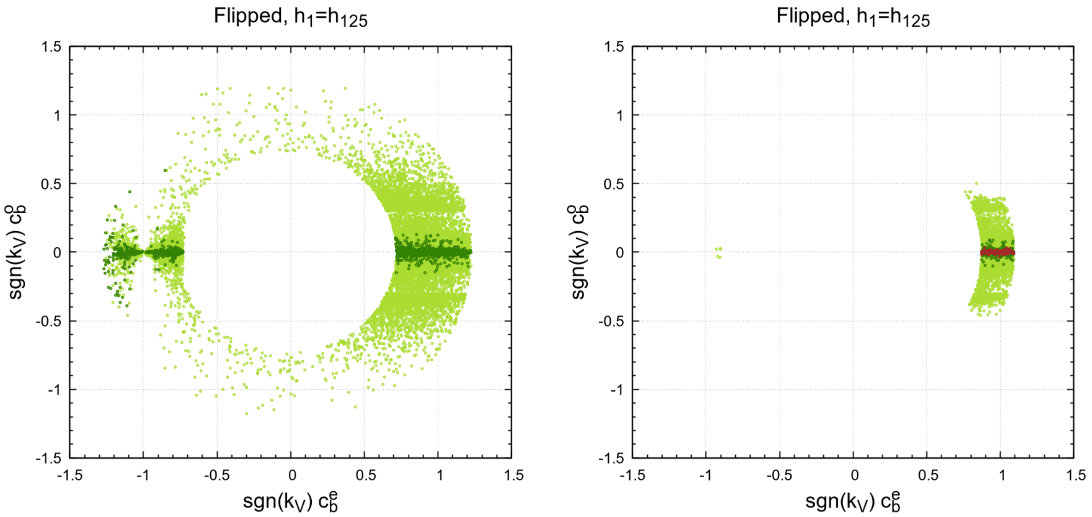

Figure 7. CP-odd vs. CP-even component in the $h_{125}b\bar{b}$ coupling for allowed parameter points in the Flipped model, assuming $h_1 = h_{125}$. Left panel: LHC 2017 data on h_{125} and constraints from BSM scalar searches at 7 and 8 TeV included in HB-4.3.1. Right panel: LHC 2022 data on h_{125}, constraints from BSM scalar searches including searches at 13 TeV using HT-1.1.3 and the latest eEDM limit. Colour code as in figure 1.

decreases the width of the rings on which allowed parameter points can be found. We see a more significant difference between the left and the right plot of figure 7 as a result of new constraints from LHC searches for additional scalars at 13 TeV. In particular, searches for one heavy Higgs boson decaying into a Z and another Higgs boson, both by ATLAS [100] and CMS [101], together with the latest eEDM results — precludes the situation where $c_b^e \simeq 0$, which is thus not visible in the right panel of figure 7. One should note here that, in the CP-conserving limit of the 2HDM with h_{125} predicted to be CP-even as in the SM, the decay $h_i \to Zh_{125}$ is only allowed for a CP-odd state h_i, whereas there is no coupling between a Z boson and two CP-even scalars. If, on the other hand, h_{125} carries a CP-odd admixture, both heavier neutral scalars h_2 and h_3 can decay into a Z boson and h_{125}. It follows that searches for heavier Higgs bosons decaying into the 125 GeV Higgs boson and a Z-boson are exceptionally important if CP-violation is present in the scalar sector (see also refs. [21, 23, 24]). In our case, indeed, they exclude large parts of figure 7 with $|c_b^e| < 1$. This is a confirmation of the important physical insight gained during Run 2 and, in this particular instance, on the crucial new bounds placed on the production of additional Higgs bosons.

As a result of the application of the 13 TeV BSM scalar searches, there is no further impact from the CMS constraints on $\alpha_{h\tau\tau}$ [54]. We observe that, at the current level of experimental precision, the direct limit on $\alpha_{h\tau\tau}$ does not yet play a role in the CP properties of the coupling $h_{125}b\bar{b}$. This is expected by the fact that, in the Flipped type, the $h_{125}\tau\bar{\tau}$ and the $h_{125}b\bar{b}$ couplings are independent parameters, according to $\Phi_u = \Phi_\ell \neq \Phi_d$. In the end, then, the situation that was shown to be possible in ref. [26] (left panel of figure 7) is reduced to almost vanishing CP-odd components, c_b^o. These would not be observable directly at the LHC, due to the combination of the new results from the eEDM (dark red points) and searches for additional scalars at the LHC.

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4 Conclusions

The C2HDM is one of the simplest extensions of the SM with one new CP-violating parameter, which arises from the scalar sector. The experimental data available in 2017, in particular the LHC data collected at 7 and 8 TeV, still allowed for the striking possibility that the CP-odd components (c^o) of the h_{125} couplings to down-type quarks and/or charged leptons were much larger than the corresponding CP-even components (c^e). This was possible for all types, except Type-I [26]. The possible presence of sizable CP-odd coupling components would be a clear indication of physics beyond the SM, and it could give rise to important phenomenological consequences. For instance, the viability of a realization of electroweak baryogenesis in generic extensions of the SM by a second Higgs doublet field relies on additional sources of CP-violation according to the Sakharov conditions [102].

In this paper, we re-analyze the situation in light of the most recent experimental constraints, namely: up-to-date results from LHC's Run 2 at 13 TeV regarding searches for additional scalars and the signal-rate measurements of the Higgs boson at 125 GeV, new eEDM results, data from direct searches for CP-violation in angular correlations of final state τ-leptons in $h_{125} \to \tau\bar{\tau}$ decays in terms of the effective mixing angle $\alpha_{h\tau\tau}$ and, finally, discussing the bounds on $m_{H^\pm}$ coming from the $b \to s\gamma$ constraints. The current situation is summarized in table 3. This can be compared with table 2 summarizing the status in 2017 found in a previous analysis [26]. The most important conclusions of the updated analysis presented here are the following:

Type-II: Previously, the possibility of sizable CP-odd components in the couplings of h_{125}, $|c_b^o| \gg |c_b^e|$, remained experimentally viable for the mass hierarchy with h_{125} being the second lightest neutral scalar ($h_2 = h_{125}$) [26]. This possibility is now practically excluded, as we discussed in section 3.1. This exclusion follows from the combination of stringent eEDM constraints and limits from LHC searches for additional Higgs bosons at 13 TeV, most notably from searches for di-τ resonances below 125 GeV [97]. The only still viable option for sizable $|c_b^o|$ happens if two conditions are verified: first, if the parameters are very fine-tuned, such that cancellations between different contributions to the eEDM occur at (or below) the percent-level; second, if the pole masses for top-quark and τ-lepton and the running bottom-quark mass $\overline{m}_b(\overline{m}_b)$ are used for the computation of the eEDM. If both conditions are met, the LHC measurements of $\alpha_{h\tau\tau}$ exclude otherwise allowed parameter space. If, however, the running fermion masses at the scale M_Z are used for the computation of the eEDM, no parameter points can be found that simultaneously evade the experimental upper bound on the eEDM, and comply with the LHC cross-section limits from BSM scalar searches. This strong dependence on the fermion masses emphasizes that, in order to conclude whether Type-II can accomodate sizable CP-violating Higgs-boson couplings, one needs a proper understanding of which prescription to use for the fermion masses in the calculation of the eEDM.

LS: This Yukawa type is the only one that can still accommodate sizable CP-odd components in the couplings of h_{125} to charged leptons, while being in agreement with all theoretical and experimental constraints. In particular, the possibility of $|c_\tau^o| \simeq |c_\tau^e|$ is still allowed

Type	I	II	LS	Flipped
$h_1 = h_{125}$	$\times$	$\times$	τ	$\underline{\times}$
$h_2 = h_{125}$	$\times$	$\underline{\times}$	τ	$\times$
$h_3 = h_{125}$	$\times$	$\times$	τ	$\times$

Table 3. Current results for the large Yukawa couplings. A cross means that it is not possible to have large CP-odd couplings, i.e. $|c^0| \gtrsim |c^e|$. The notation τ means that c^o/c^e is limited by the direct searches for CP-violating angular correlations of τ leptons in $h_{125} \to \tau\bar{\tau}$ decays [54]. Underlined crosses indicate a change from allowed (✓) to excluded ($\times$) compared to the previous analysis carried out in 2017 [26].

in the LS case, and only in this case. We find values of $\alpha_{h\tau\tau}$ that would be directly observable at the LHC by measurements of angular correlations of final state τ leptons in $h_{125} \to \tau\bar{\tau}$ decays. Consequently, in the LS type, the recently reported 2σ confidence-level limits of $\alpha_{h\tau\tau} < 41°$ from CMS [54] and of $\alpha_{h\tau\tau} < 34°$ from ATLAS [55] give rise to new constraints on the C2HDM parameter space, excluding previously allowed parameter space regions. According to our findings, if in the future a non-vanishing value of $\alpha_{h\tau\tau}$ were measured at the LHC, this would point towards the LS type, allowing to experimentally distinguish this type from the other Yukawa types of the C2HDM. Since all possible mass hierarchies of neutral scalars were shown to be compatible with sizable values of $\alpha_{h\tau\tau}$, a possible future detection of a CP-violating $h_{125}\tau\bar{\tau}$ coupling would not decide whether the detected Higgs boson at 125 GeV would correspond to the lightest, the second-lightest or the heaviest neutral scalar of the C2HDM.

Flipped: In this type, one has $c^o_\tau = c^o_t$. Hence, the circumstance that $|c^o_t|$ is already stringently constrained from signal-rate measurements of h_{125} renders the aforementioned constraints on $\alpha_{h\tau\tau}$ irrelevant. On the other hand, the possibility $|c^o_b| > |c^e_b|$ was previously allowed, assuming that the 125 GeV Higgs boson is the lightest neutral scalar. Here, we demonstrated that this possibility is now also forbidden in this type of the C2HDM, due to the LHC's improved bounds from searches for extra scalars (in combination with the other experimental constraints). The most relevant searches are those involving one heavy Higgs boson decaying into a Z and another Higgs boson, both by ATLAS [100] and CMS [101]. Additionally, the more recent eEDM bounds [61] constrain c^o_b to lie very close to zero.

In summary, we have shown that the possibility of sizable CP-odd components $|c^o| \simeq |c^e|$ in the couplings of the 125 GeV Higgs boson is only allowed in the LS cases (all mass orderings), where the CP-violation appears in the couplings of the Higgs boson to τ leptons. The possible amount of CP-violation is then limited ultimately by the direct searches for CP-violation in angular correlations between τ leptons produced in Higgs boson decays. These measurements have been performed by both ATLAS and CMS utilizing the full Run 2 dataset. The measurements are currently statistically limited. The anticipated future improvements on their experimental precision will be paramount to our understanding of the C2HDM and its phenomenology at the LHC, as well as of the extent to which the shortcomings of the SM can be addressed in this model.

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