

V-associated production and vector boson fusion as an LHC signature of CP violation

R. Capucha^{1,*}, Á. Lozano-Onrubia^{2,3,†}, L. Merlo^{2,3,‡}, J. M. No^{2,3,§} and R. Santos^{1,4,||}

¹*Centro de Física Teórica e Computacional, Faculdade de Ciências Universidade de Lisboa, Campo Grande, Edifício C8 1749-016 Lisboa, Portugal*

²*Instituto de Física Teórica, IFT-UAM/CSIC, Cantoblanco, 28049, Madrid, Spain*

³*Departamento de Física Teórica, Universidad Autónoma de Madrid, Cantoblanco, 28049, Madrid, Spain*

⁴*ISEL—Instituto Superior de Engenharia de Lisboa, Instituto Politécnico de Lisboa 1959-007 Lisboa, Portugal*



(Received 18 July 2025; accepted 13 October 2025; published 7 November 2025)

We investigate the role of vector boson fusion (VBF) and associated production with an electroweak boson (V-AP) of beyond-the-Standard-Model Higgs bosons at the LHC in probing CP violation in extended Higgs sectors. Resonant production of a new Higgs boson through V-AP and VBF subsequently decaying into a Z boson and a 125 GeV Higgs boson h would be a robust sign of CP violation, since h has been measured to be (predominantly) a CP -even state. After identifying this and other sets of signatures which rely on V-AP and VBF to jointly uncover CP violation, we analyze the prospects to measure CP violation in this way for the complex two-Higgs-doublet model at the High-Luminosity LHC.

DOI: [10.1103/3s5k-h11w](https://doi.org/10.1103/3s5k-h11w)

I. INTRODUCTION

Charge parity (CP) is an approximate symmetry of nature, broken in the Standard Model (SM) only by mixing in the fermion sector and the presence of three families of quarks and/or leptons [1,2]. The presence of CP violation in the early Universe, together with baryon number violation (which occurs at high temperature in the SM [3] via sphaleron processes) and a departure from thermal equilibrium, is required to generate the observed baryon asymmetry of the Universe [4–8]. Yet the amount of CP violation present in the SM is well known to be insufficient for the generation of this asymmetry at the electroweak (EW) scale [9–11], such that new sources of CP violation beyond the SM are needed.

A well-motivated scenario is that such new sources of CP violation reside in a nonminimal Higgs sector—the Higgs sector of the SM is CP conserving by construction. LHC searches then offer a promising avenue to probe

experimentally the effects of CP violation in Higgs physics (see, e.g., [12–18]), complementary to experimental searches of electric dipole moments (EDMs) [19–22]. As opposed to EDMs, LHC searches may provide direct insight on the details of the CP -violating source.

The possibility of a CP -violating Higgs sector is actively investigated at the LHC through the study of the 125 GeV Higgs boson properties, e.g., via its decay $h \rightarrow \tau\tau$ [23–26] or $h \rightarrow ZZ^* \rightarrow 4\ell$ [27,28] (with $\ell = e, \mu$) or its production in association with two jets [29] or a $t\bar{t}$ pair [30–32]. At the same time, LHC searches for beyond-the-Standard-Model (BSM) scalars can yield a direct test of CP violation in extended Higgs sectors via the combination of different decay modes [33,34], which would make inconsistent any possible assignment of CP quantum numbers for the scalars involved. In this work, we investigate a new avenue to probe CP violation within extended Higgs sectors at the LHC, by means of BSM Higgs boson production either in association with an EW gauge boson $V = W^\pm, Z$ or via vector boson fusion [35] (VBF). A prime example of such a signature would be $pp \rightarrow VH_a, H_a \rightarrow Zh$, with H_a a BSM Higgs boson (see Fig. 1, left): The V-associated production (V-AP) of H_a occurs through a $g_{H_a VV}$ coupling (other contributions to V-AP of H_a are proportional to the light fermion masses in the initial state of the partonic process and, thus, negligible); the decay $H_a \rightarrow Zh$ requires a $g_{H_a Zh}$ coupling. Then, H_a can be neither purely CP even nor CP odd for both $g_{H_a VV}$ and $g_{H_a Zh}$ couplings to be present simultaneously, since the 125 GeV Higgs boson h has been experimentally established as a predominantly CP -even

* Contact author: rscapucha@fc.ul.pt

† Contact author: alvaro.lozano.onrubia@csic.es

‡ Contact author: luca.merlo@uam.es

§ Contact author: josemiguel.no@uam.es

|| Contact author: rasantos@fc.ul.pt

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International](https://creativecommons.org/licenses/by/4.0/) license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

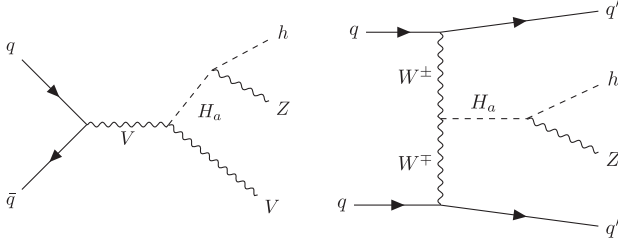


FIG. 1. Feynman diagram for the CP -violating processes with V -AP production (left) and VBF production (right) with the subsequent $H_a \rightarrow Zh$ decay.

state [25,30,31,36,37]. A similar argument can be made for VBF production of H_a followed by the decay $H_a \rightarrow Zh$ (see Fig. 1, right).

The above showcases that both V -AP and VBF production of BSM scalars H_a may be key ingredients in establishing scalar CP violation at the LHC. In the following, we identify sets of processes (without attempting an exhaustive classification), each set including V -AP and/or VBF of BSM Higgs boson(s), and for which the joint observation of all processes within a set would establish CP violation in a model-independent fashion. We then analyze the present LHC constraints on such CP -violating process combinations, together with the prospects for probing them at the high-luminosity (HL) phase of the LHC in a concrete model: the complex two-Higgs-doublet model (C2HDM) with a softly broken $\mathbb{Z}_2$ symmetry, which constitutes a minimal CP -violating Higgs sector.

II. LHC JOINT SIGNATURES OF CP VIOLATION

Considering BSM neutral Higgs bosons H_a and H_b (with masses $m_{H_a} > m_{H_b}$), together with the 125 GeV Higgs h and the EW gauge bosons W and Z , specific sets of joint LHC measurements that would yield unambiguous Higgs sector CP violation (H -CPV) and include V -AP and/or VBF of BSM Higgs bosons, are

- (i) $pp \rightarrow VH_a$, $H_a \rightarrow Zh$;
- (ii) VBF production of H_a , $H_a \rightarrow Zh$;
- (iii) $pp \rightarrow VH_a$, $H_a \rightarrow ZH_b$ together with $pp \rightarrow VH_b$;
- (iv) VBF production of H_a , $H_a \rightarrow ZH_b$ together with VBF production of H_b ;
- (v) gluon fusion (ggF) production of H_a , decaying via $H_a \rightarrow ZH_b$, together with both $pp \rightarrow VH_a$ and $pp \rightarrow VH_b$ (or VBF production of both H_a and H_b);
- (vi) ggF production of H_a , decaying via both $H_a \rightarrow ZH_b$ and $H_a \rightarrow H_b H_b$ (or $H_a \rightarrow VV$), together with $pp \rightarrow VH_b$ (or VBF production of H_b);
- (vii) ggF production of H_a , decaying via $H_a \rightarrow Zh$, together with $pp \rightarrow VH_a$ (or VBF production of H_a), since h is (predominantly) CP even.

We view the above sets as defining potentially promising avenues to test H -CPV at future runs of the LHC. In all

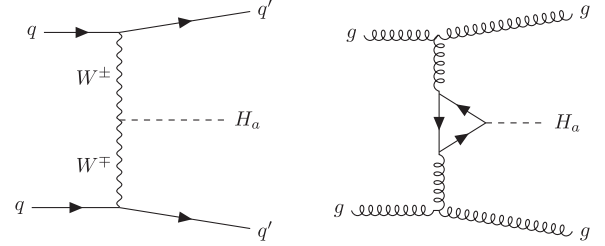


FIG. 2. Left: Feynman diagram for VBF production of H_a . Right: Feynman diagram for ggF production of H_a with two jets. In both cases, the final-state LHC signature is $H_a + jj$.

cases (i)–(vii) above, the V -AP or VBF of either H_a or H_b is needed to establish its coupling to EW gauge bosons ($g_{H_a VV}$ and/or $g_{H_b VV}$). For V -AP, this is essentially granted, as the EW gauge boson can be measured as a final state of the process. This is fairly direct for leptonic decays of V . In contrast, for VBF, the situation is much more subtle: The experimental signature of VBF is the production, e.g., of H_a , together with two (quark) jets—see Fig. 2, left—with a very large dijet invariant mass m_{jj} and a large rapidity gap $\Delta\eta_{jj}$ [38,39]. Yet, the ggF production of H_a with two extra (gluon) jets—see Fig. 2, right—can also produce such a $H_a + jj$ signature, yielding a potential contamination to VBF. ggF production of H_a does not provide *a priori* information on the CP properties of H_a , so this ggF leakage would hinder the possibility to use VBF as a probe of H -CPV. The existence of this ggF contamination is well known for the case of the SM Higgs boson [40], where a combination of cuts [39,41,42] that define VBF-enriched *simplified template cross section* (STXS) regions is able to reduce the contamination of ggF into VBF to $\sim 10\%$ – 20% of the measured VBF cross section depending on the specific STXS region (see, e.g., Refs. [43–45]). While these cuts could significantly reduce the ggF contamination also in BSM scenarios, the ratio of ggF to VBF production cross section of H_a depends on the BSM model parameters and is *a priori* unknown. As a result, this prevents us from disentangling VBF from ggF in an experimental $H_a + jj$ sample, as their initial cross section ratio is not known. Thus, the ggF contamination constitutes a serious hurdle to the use of VBF as part of a H -CPV identification strategy.

A would-be solution to this problem stems from the fact that, for $pp \rightarrow H_a + jj$ production via VBF, the jets are quark initiated, whereas for $pp \rightarrow H_a + jj$ via ggF the jets are (dominantly) gluon initiated. Thus, efficient quark-gluon jet tagging [46,47] would allow one to significantly reduce the ggF contamination to VBF, potentially resolving this issue. However, present quark-gluon jet tagging algorithms are not good enough for this purpose, and one would have to rely on potential future improvements of these algorithms. For this reason, in the rest of this work we choose to leave aside VBF processes to focus on V -AP and, consequently, on sets (i), (iii), and (v)–(vii) above.

At the same time, we must bear in mind that the Z -AP of H_a and/or H_b may receive a (potentially dominant) contribution from ggF production of a heavier scalar (e.g., $gg \rightarrow H_a \rightarrow ZH_b$ in the case of $pp \rightarrow ZH_b$), which would mask the presence of CP violation. This prompts us to rely on W -AP of BSM Higgs bosons as core process within our strategy to measure H -CPV, for which such masking is absent.¹

In the next section, we analyze the possibility of probing H -CPV by means of W -AP, within the minimal CP -violating version of the two-Higgs-doublet model: the softly broken $\mathbb{Z}_2$ -symmetric C2HDM [48]. The model is described in detail in Appendix A. In order to avoid scalar flavor-changing neutral currents at tree level, the $\mathbb{Z}_2$ symmetry is extended to the Yukawa sector, leading to four Yukawa types. We chose to work with the less constrained, the so-called type I, where only one doublet couples to all fermions. Although this analysis does not exhaustively study the whole parameter space of a type-I C2HDM, it represents a proof of concept for such multi-channel searches. Moreover, notice that higher-order processes induced at loop level may, in general, affect the precise determination of cross sections and branching ratios. In our case, however, we expect the results illustrated in the following to hold even including these quantum effects, as the parameter space identified is very close to the alignment limit; that is, the Higgs couplings are very much SM-like.

III. H -CPV IN THE C2HDM

The C2HDM scalar potential for the two Higgs doublets Φ_1 and Φ_2 is given by (see, e.g., [49])

$$V = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{H.c.}) + \frac{\lambda_1}{2} |\Phi_1|^4 + \frac{\lambda_2}{2} |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left[\frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + \text{H.c.} \right]. \quad (1)$$

This potential implements a $\mathbb{Z}_2$ symmetry $\Phi_1 \rightarrow \Phi_1$, $\Phi_2 \rightarrow -\Phi_2$, softly broken by the m_{12}^2 term, and allows for both λ_5 and m_{12}^2 to be complex. CP violation in this model is determined by *one* independent parameter, namely, $\delta \equiv \text{Arg}[(m_{12}^2)^2 \lambda_5^*]$. In the CP -conserving limit, $\delta = 0, \pi$, the physical spectrum of the C2HDM has two charged scalars $H^\pm$, a neutral CP -odd scalar A_0 , and two neutral CP -even scalars H_0 and h_0 (see, e.g., [50] for details), one of which is identified with the 125 GeV Higgs boson. In the presence of CP violation, A_0 mixes with H_0

and h_0 , yielding three neutral mass eigenstates H_1, H_2 , and H_3 , with $m_{H_1} \leq m_{H_2} \leq m_{H_3}$. The rotation angles from the original basis of neutral components of Φ_1 and Φ_2 to the physical basis of $H_{1,2,3}$ are denoted by $\alpha_{1,2,3}$ (with ranges $-\pi/2 < \alpha_i \leq \pi/2$). The corresponding rotation matrix R , parametrized in terms of $(s_i, c_i) = (\sin \alpha_i, \cos \alpha_i)$ with $i = 1, 2, 3$ [49,51–53], is given explicitly in Eq. (A15) in Appendix A, where further details on the C2HDM can be found.

The (input) C2HDM parameters can then be chosen to be $m_{H_1}, m_{H_2}, m_{H^\pm}, \text{Re}(m_{12}^2), \alpha_1, \alpha_2, \alpha_3, \tan \beta$, and $v = 246$ GeV (for such choice of input parameters, the value of m_{H_3} is a derived quantity; see Appendix A for more details). This parameter choice is convenient, as it allows us to directly perform a large scan of C2HDM parameter points with ScannerS [54–58] that satisfies present experimental constraints—as computed via HiggsTools [59–70] (the details on the specific implementation of experimental limits are discussed in Appendix A). We pay attention to the effect of the latest EDM constraints [22] but do not consider them as strict bounds, as these are indirect probes of CP violation and other potential BSM sources of CP violation unrelated to H -CPV would also contribute to EDMs. This also allows one to better explore the complementarity between EDMs and LHC probes of CP violation.

We perform two different scans of the C2HDM parameter space—labeled S_1 and S_2 —with the 125 GeV Higgs boson h corresponding, respectively, to the mass eigenstate H_1 and H_2 . We have chosen the following regions for the input parameters of the C2HDM: $0.8 < \tan \beta < 35$, $-\pi/2 < \alpha_{1,2,3} < \pi/2$, $0.1 \text{ GeV}^2 < \text{Re}(m_{12}^2) < 10^5 \text{ GeV}^2$, and $70 \text{ GeV} < m_{H^\pm} < 500 \text{ GeV}$, and for S_1 $m_{H_1} = 125.09 \text{ GeV}$ and $130 \text{ GeV} < m_{H_2} < 500 \text{ GeV}$, while for S_2 we chose $40 \text{ GeV} < m_{H_1} < 120 \text{ GeV}$ and $m_{H_2} = 125.09 \text{ GeV}$. Besides the use of HiggsTools, we further filter our scan points by requiring that they satisfy 2σ bounds from the CMS analysis [71] on the gauge and fermion coupling modifiers $c_{hVV} \equiv g_{hVV}/g_{h_{\text{SM}}VV}$ and $c_{hff} \equiv y_{hff}/y_{h_{\text{SM}}ff}$. Concretely, we define $y_{hff} = \sqrt{(y_{hff}^R)^2 + (y_{hff}^I)^2}$ (with y_{hff}^R and y_{hff}^I , respectively, the scalar and pseudoscalar parts of the 125 GeV Higgs boson Yukawa couplings to SM fermions) and demand that the scan points lie within the (c_{hff}, c_{hVV}) 2σ ellipse in Ref. [71] from a combined Higgs signal strength fit with observed best-fit value $(c_{hff}, c_{hVV}) = (0.906, 1.014)$. We emphasize that the results of this latter fit apply only to a 2HDM of type I (addressed in this work), as all SM fermions couple only to one doublet and, thus, the Yukawa coupling modifiers are universal.

Throughout this work, the W -AP cross sections of the BSM scalars are calculated at leading order for $\sqrt{s} = 14 \text{ TeV}$ at the LHC via MadGraph5_aMC@NLO 2.9.14 [72],

¹While in extended scalar sectors there can be an s -channel contribution with a charged scalar $H^\pm$ which also contributes to W -AP of neutral states, such a contribution is, in general, suppressed by the light quark masses and, thus, very small.

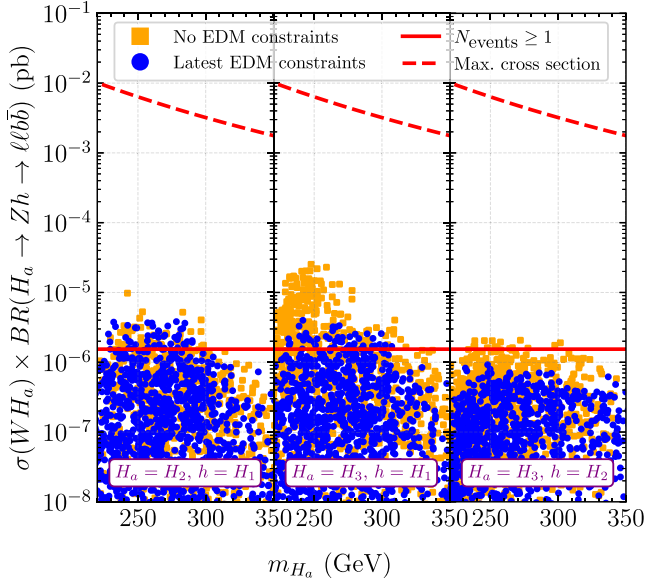


FIG. 3. W -AP cross sections (in picobarns) for H_a —with $H_a \rightarrow Zh \rightarrow \ell\ell b\bar{b}$ —at $\sqrt{s} = 14$ TeV for the C2HDM scans S_1 (left and central panels) and S_2 (right panel), as a function of m_{H_a} . Left panel: $H_a = H_2$. Central and right panels: $H_a = H_3$. We also depict the theoretical upper bound on the cross section (dashed red line; see the text for details) and the cross section yielding one event (including the decay of the W boson) at the HL-LHC (solid red line).

whereas the ggF cross sections (at $\sqrt{s} = 14$ TeV) and the branching fractions of the BSM scalars are obtained from ScannerS (see [58] for further details).

We show the cross sections for $pp \rightarrow WH_a$, $H_a \rightarrow Zh \rightarrow \ell\ell b\bar{b}$ as a function of m_{H_a} in Fig. 3, with $H_a = H_2$ (left) and $H_a = H_3$ (central) for scan S_1 and $H_a = H_3$ for scan S_2 (right). This process corresponds to avenue (i) to establish H -CPV. The theoretical upper bound on this cross section [given by $c_{H_a WW} \equiv g_{H_a WW}/g_{h_{SM} WW} = 1$ and $\text{BR}(H_a \rightarrow Zh) = 1$] is shown as a dashed red line in Fig. 3. It is immediately apparent that the cross sections for this process in the C2HDM with a softly broken $\mathbb{Z}_2$ symmetry are very suppressed and impossible to probe at the HL-LHC with 3 ab^{-1} of integrated luminosity.² We leave a study of this signature in other models—e.g., the C2HDM without the (softly broken) $\mathbb{Z}_2$ symmetry—for future investigation.

The remaining H -CPV sets—except for (vii)—in our analysis require the measurement of W -associated production of a light BSM Higgs boson H_b , with $H_b = H_2$ ($H_b = H_1$) for scan S_1 (S_2), respectively. There exist current experimental limits on this process by CMS [73]

²Considering the leptonic decay $W \rightarrow \ell\nu$, we expect at most $\mathcal{O}(1)$ signal events for the points of scan S_2 at the HL-LHC and $\mathcal{O}(10)$ signal events for the points of scan S_1 , with perfect (unrealistic) final-state reconstruction efficiencies in both cases.

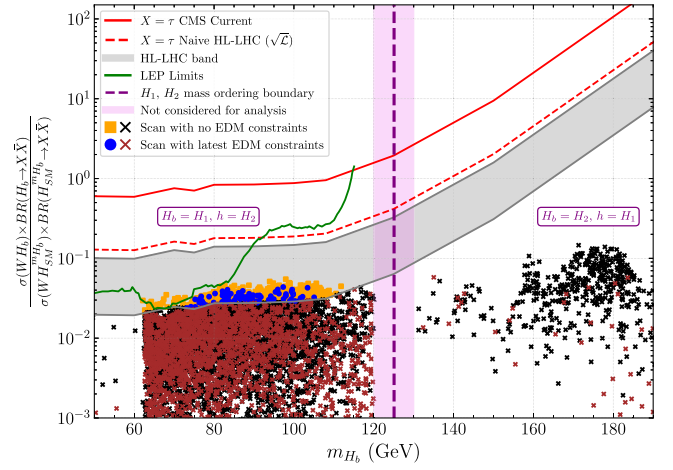


FIG. 4. Current (solid red line) and projected HL-LHC (dashed red line, gray band) sensitivity lines of $pp \rightarrow WH_b$ production at $\sqrt{s} = 14$ TeV normalized to the SM associated production σ_{SM}^{W-AP} of a SM Higgs of mass m_{H_b} as a function of m_{H_b} ; see the text for details. Orange squares (black crosses) correspond to HL-LHC observable (unobservable) C2HDM scan points when no EDM constraints are applied, and blue circles (red crosses) when EDM bounds are strictly imposed, respectively, for scan S_1 (for $m_{H_b} > 125$ GeV) and S_2 (for $m_{H_b} < 125$ GeV). Also shown (solid green line) are the LEP limits on $\sigma(WH_b)/\sigma(WH_{SM}^{m_{H_b}})$ assuming $c_{H_b ZZ} = c_{H_b WW}$.

for $\sqrt{s} = 13$ TeV and an integrated luminosity $\mathcal{L} = 138 \text{ fb}^{-1}$, targeting a $H_b \rightarrow \tau\tau$ final state. These limits, normalized to the SM production cross section $\sigma_{SM}^{W-AP} = \sigma(pp \rightarrow WH_{SM}^{m_{H_b}}, H_{SM}^{m_{H_b}} \rightarrow \tau\tau)$ with $H_{SM}^{m_{H_b}}$ a SM Higgs boson of mass m_{H_b} , are shown in Fig. 4. To estimate the sensitivity achievable at the HL-LHC for $pp \rightarrow WH_b$, we first perform a naive “statistical” $\sqrt{\mathcal{L}}$ extrapolation of the current expected sensitivity of the CMS search [73] by $\sqrt{138/3000}$, also depicted in Fig. 4. Yet, such naive $\sqrt{\mathcal{L}}$ sensitivity scaling has been found to be rather pessimistic in many existing experimental ATLAS and CMS analyses, as discussed in Ref. [74]. Among other things, the $\sqrt{\mathcal{L}}$ scaling does not account for the possible inclusion of further decay modes as $\mathcal{L}$ increases and does not exploit kinematic regions (e.g., high- p_T configurations) that do not appreciably contribute to the present sensitivity but would very much do for larger $\mathcal{L}$. We take inspiration from the experimental sensitivity increase observed between $\mathcal{L} \simeq 36$ and $\simeq 140 \text{ fb}^{-1}$ in various ATLAS and CMS searches performed for 13 TeV LHC—specifically, $pp \rightarrow t\bar{t}t\bar{t}$ [75,76], $pp \rightarrow Vh$ with $h \rightarrow b\bar{b}$ [77,78], EW vector boson scattering $pp \rightarrow ZZ + jj$, $ZZ \rightarrow \ell\ell\ell'\ell'$ (with $\ell, \ell' = e, \mu$) [79,80], and di-Higgs production $pp \rightarrow hh \rightarrow b\bar{b}\tau\tau$ [81,82]. In all these searches, the sensitivity increase exceeds the naive $\sqrt{\mathcal{L}}$ extrapolation, albeit by different amounts. We then develop an “improved” HL-LHC sensitivity extrapolation band as the envelope of the sensitivity

increases of the respective ATLAS and CMS analyses above, extrapolated to $\mathcal{L} = 3000 \text{ fb}^{-1}$. Further details of this improved sensitivity extrapolation are given in Appendix B. This band is shown in gray in Fig. 4. The *strongest* HL-LHC sensitivity we use in the following discussion corresponds to the lower edge of such a HL-LHC extrapolation band.

We then show in Fig. 4 the results of the C2HDM scans S_1 and S_2 , depicting the value of the $pp \rightarrow WH_b$ production cross section in the final state $H_b \rightarrow \tau\tau$, normalized to the SM value (with $m_{h_{\text{SM}}} = m_{H_b}$), and excluding the $\pm 5 \text{ GeV}$ mass window around the observed 125 GeV Higgs boson. This is a key search for the H -CPV scenarios (iii), (v), and (vi). We see that, for scan S_2 (with $H_b = H_1$), a sizable number of C2HDM points (in orange) lie above the lower end of the gray band, thus representing potentially observable signals at the HL-LHC, including parameter space points that satisfy the latest EDM constraints [22] (in blue). At the same time, for scan S_1 , there are no potentially observable points (with $H_b = H_2$) at the HL-LHC via this signature. We also depict in Fig. 4 the indirect limits from LEP [83] (green line) which assume $c_{H_bZZ} = c_{H_bWW}$ and $\text{BR}(H_b \rightarrow X\bar{X}) = \text{BR}(h_{\text{SM}} \rightarrow X\bar{X})$, the latter computed for $m_{h_{\text{SM}}} = m_{H_b} < 125 \text{ GeV}$. These limits show the approximate suppression required for the H_b -gauge coupling at low masses. We also note that, for $m_{H_b} < m_h/2 \simeq 62 \text{ GeV}$, there are very few experimentally allowed C2HDM scan points (and no HL-LHC observable points via $pp \rightarrow WH_b$), since the stringent limits from LHC Higgs signal strengths on exotic Higgs branching fractions [71,84]—here, $\text{BR}(h \rightarrow H_b H_b)$ —apply.

For the potentially observable C2HDM points from scan S_2 in Fig. 4 (in orange and blue), we show the cross section for W -AP of H_3 followed by its on-shell decay $H_3 \rightarrow ZH_1$ (with $Z \rightarrow \ell\ell$) in Fig. 5. Observing these points would establish H -CPV through set (iii). While, to the best of our knowledge, there are no existing dedicated experimental LHC searches for this process, searches for $pp \rightarrow H_3 \rightarrow ZH_1$ by ATLAS and CMS do exist (see, e.g., [85–88]), focusing on ggF production of H_3 . Present CMS limits on $gg \rightarrow H_3 \rightarrow ZH_1 \rightarrow \ell\ell b\bar{b}$ [assuming $\text{BR}(H_1 \rightarrow b\bar{b}) = 1$] with an integrated luminosity of 35.9 fb^{-1} from Ref. [85] and the potential extrapolated HL-LHC strongest reach (for a reference value $m_{H_1} = 70 \text{ GeV}$) are also depicted in Fig. 5, showing that even the largest C2HDM cross sections in Fig. 5—of $\mathcal{O}(0.1) \text{ fb}$ —lie well below the depicted HL-LHC reach. Despite the fact that these limits and projections do not fully apply to our case (as W -AP is a different H_3 production mode³), this indicates that H -CPV via set (iii) will be challenging to probe at the HL-LHC.

³As a result, the corresponding signal acceptances would differ from those of Ref. [85]. Additionally, the extra W boson in the final state would provide new signal discrimination opportunities, which can hopefully enhance the sensitivity of the search.

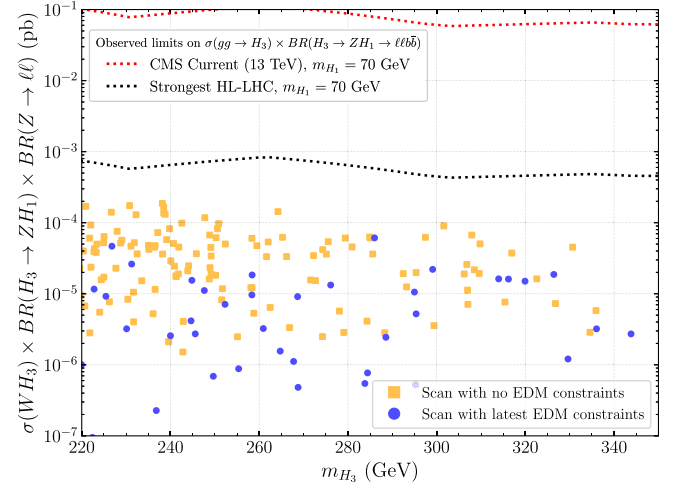


FIG. 5. $pp \rightarrow WH_3$ cross section times branching fraction $\text{BR}(H_3 \rightarrow ZH_1) \times \text{BR}(Z \rightarrow \ell\ell)$ for S_2 scan points within the HL-LHC gray band of Fig. 4. In dotted red (dotted black), we show the current CMS (HL-LHC strongest projection) limits from $pp \rightarrow H_3 \rightarrow ZH_1 \rightarrow \ell\ell b\bar{b}$ [85]; see the text for details.

In fact, the aforementioned signature $gg \rightarrow H_3 \rightarrow ZH_1$ is a required ingredient to establish H -CPV within sets (v) and (vi). For the orange and blue points in Fig. 4 from scan S_2 that fulfill $m_{H_3} > m_{H_1} + m_Z$, we show in Fig. 6 the corresponding C2HDM cross section for ggF production of

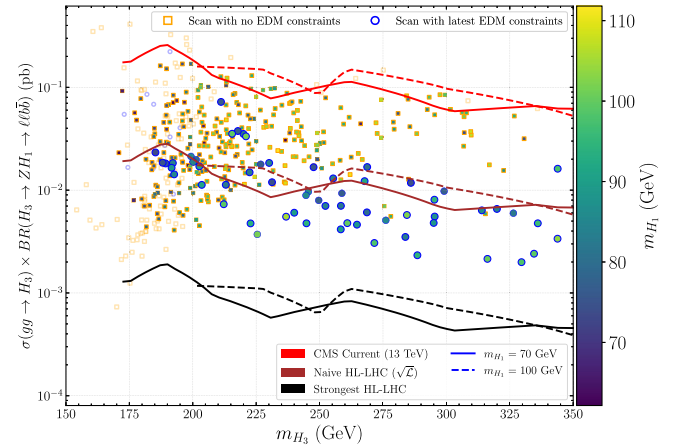


FIG. 6. Cross sections for $gg \rightarrow H_3 \rightarrow ZH_1 \rightarrow \ell\ell b\bar{b}$ for the S_2 scan points within the HL-LHC gray band in Fig. 4, as a function of m_{H_3} . Squares (circles) correspond to scan points without (with) the latest EDM constraints applied. Present $\sqrt{s} = 13 \text{ TeV}$ CMS limits from Ref. [85] for benchmark values $m_{H_1} = 70 \text{ GeV}$ (solid line) and $m_{H_1} = 100 \text{ GeV}$ (dashed line) are shown in red. Sensitivity projections for HL-LHC with 3000 fb^{-1} of integrated luminosity are shown assuming a naive $\sqrt{\mathcal{L}}$ extrapolation of the present CMS limits (brown) as well as a strongest extrapolation (black); see Appendix B for details. Filled scan points are within reach of HL-LHC (and not excluded by present CMS constraints), with filling color indicating the corresponding value of m_{H_1} .

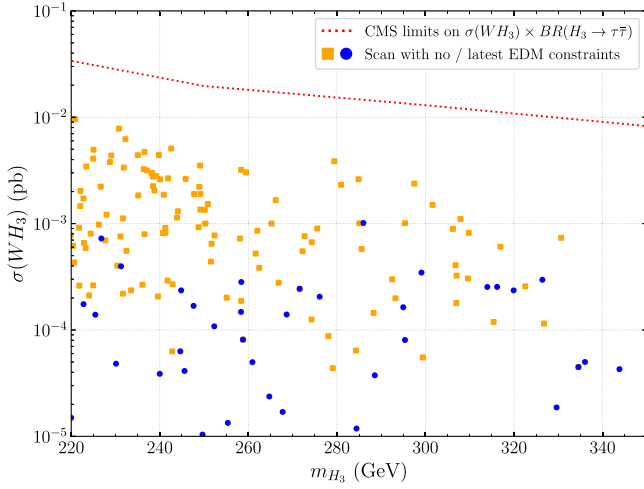


FIG. 7. Values of the $pp \rightarrow WH_3$ production cross section as a function of m_{H_3} for the scan points potentially within reach of HL-LHC in Fig. 6. Also shown is the current CMS 95% CL bound for the $H_3 \rightarrow \tau\tau$ final state [73], for reference.

H_3 in the $H_3 \rightarrow ZH_1$, $Z \rightarrow \ell\ell$, $H_1 \rightarrow b\bar{b}$ final state. We overlay, for two reference mass values $m_{H_1} = 70$ and 100 GeV, the present $\sqrt{s} = 13$ TeV limits (red) from the CMS search [85] (obtained from the data in Ref. [89], with an integrated luminosity of 35.9 fb^{-1}) and the extrapolated HL-LHC reach both in the $\sqrt{\mathcal{L}}$ increase case (brown) and in the strongest case (black) as already employed in Fig. 4 and derived in Appendix B. Figure 6 clearly shows that a large fraction of the S_2 scan points potentially accessible via $pp \rightarrow WH_b$ searches—recall Fig. 4—may also be within reach of future $gg \rightarrow H_3 \rightarrow ZH_1$ LHC searches.

To determine the possibility of establishing H -CPV via set (v), we further collect the S_2 scan points in Fig. 6 that could be probed at the HL-LHC via $gg \rightarrow H_3 \rightarrow ZH_1$ (using the strongest sensitivity projection) and show in Fig. 7 the corresponding values of the $pp \rightarrow WH_3$ cross section for these points, which can be as large as 10 fb. Existing searches for this BSM signature exist in the $H_a \rightarrow \tau\tau$ final state [73] (already discussed in this work and whose limits we show in Fig. 7 for reference), yet the $H_a \rightarrow \tau\tau$ branching fraction for these scan points lies well below 10^{-3} , so that this final state would not allow one to probe H -CPV in this context. Another possibility is the $H_a \rightarrow WW$ final state (with branching fractions that can exceed 10% in our scan), for which a search by ATLAS [90] using same-sign dileptons has been performed. Yet, the model interpretations shown in the ATLAS analysis do not apply to our scenario, and a robust sensitivity assessment is not possible. In particular, the results of Ref. [90] are interpreted in an effective field theory framework with higher-dimensional operators, where the limits provided depend on anomalous couplings that vanish in our model. We leave such a potential study for the future.

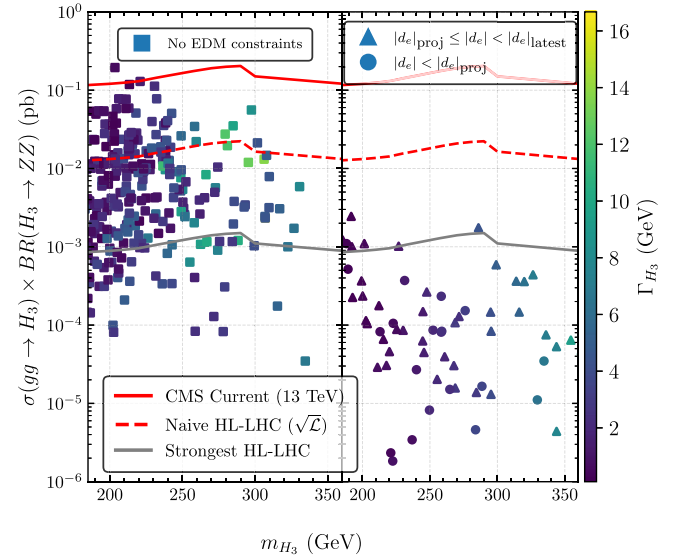


FIG. 8. ggF -mediated $pp \rightarrow H_3 \rightarrow ZZ$ cross sections for the S_2 scan points above the strongest HL-LHC sensitivity extrapolation in both Figs. 4 and 6 (and satisfying $m_{H_3} > 2m_Z$), with the total width Γ_{H_3} for each point depicted in color. Left (right) panels correspond to disregarding (including) the latest EDM constraints (triangles) and their projections $|d_e|_{\text{proj}} = 1.0 \times 10^{-30} e \cdot \text{cm}$ (circles); see the text for details. Also shown are the current 95% CL limits on the $pp \rightarrow H_3 \rightarrow ZZ$ signature (solid red line) from CMS [91]—fixing $\Gamma_{H_3} = 10$ GeV (the experimental limits depend very weakly on the width as long as the resonance is narrow)—and the naive ($\sqrt{\mathcal{L}}$; dashed red line) and strongest (solid gray line) HL-LHC sensitivity extrapolations.

For the C2HDM scan points in Fig. 6 above the HL-LHC (strongest) sensitivity, H -CPV through set (vi) would require these scan points to also be visible via the processes $pp \rightarrow H_3 \rightarrow VV$ and/or $pp \rightarrow H_3 \rightarrow H_1H_1$. We find that the most promising search in such case corresponds to $pp \rightarrow H_3 \rightarrow ZZ$ and show in Fig. 8 the cross section values $\sigma(pp \rightarrow H_3) \times \text{BR}(H_3 \rightarrow ZZ)$ for these points as a function of m_{H_3} (for $m_{H_3} > 2m_Z$), respectively, disregarding (including) the latest EDM constraints and their projections $|d_e|_{\text{proj}}$ in the left (right) panels. We depict the current $\sqrt{s} = 13$ TeV limits from CMS [91,92] (for a fixed total width $\Gamma_{H_3} = 10$ GeV; the limits depend weakly on the specific value of the width), together with the two HL-LHC sensitivity extrapolations used throughout this work (naive $\sqrt{\mathcal{L}}$ and strongest). Figure 8 highlights that, for the parameter space in which $m_{H_b} < m_h = 125$ GeV, set (vi)—through the combination of $pp \rightarrow WH_b$, $pp \rightarrow H_a \rightarrow ZH_b$, and $pp \rightarrow H_a \rightarrow ZZ$ signatures—does constitute a viable avenue to probe H -CPV in the C2HDM, if EDM bounds are not considered at face value. We considered $|d_e|_{\text{proj}} = 1.0 \times 10^{-30} e \cdot \text{cm}$, since the next-generation ACME III experiment is expected to improve the statistical sensitivity to the electron EDM by at least an

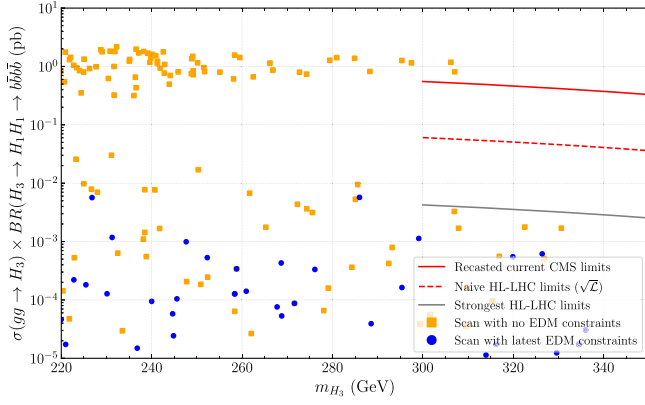


FIG. 9. ggF-mediated $pp \rightarrow H_3 \rightarrow H_1 H_1 \rightarrow b\bar{b}b\bar{b}$ cross sections for the S_2 scan points within HL-LHC reach from Fig. 6. Blue (orange) points correspond to the inclusion (not inclusion) of the latest EDM constraints. Also shown are the recast $pp \rightarrow H_3 \rightarrow H_1 H_1 \rightarrow b\bar{b}b\bar{b}$ 95% CL limits from [95] for 35.9 fb^{-1} (solid red line) and the naive ($\sqrt{\mathcal{L}}$; dashed red line) and strongest (solid gray line) HL-LHC sensitivity extrapolations, all for benchmark value $m_{H_1} = 100 \text{ GeV}$.

order of magnitude, and potentially by a factor of 30 [93,94], compared to the current best limit from ACME II [20]. If we were to take $|d_e|_{\text{proj}} = 0.3 \times 10^{-30} e \cdot \text{cm}$, we would be left with no points above the strongest HL-LHC line depicted in Fig. 8.

Besides $pp \rightarrow H_3 \rightarrow ZZ$, another promising signature which may be used to complete the H -CPV set (vi) is $pp \rightarrow H_3 \rightarrow H_1 H_1 \rightarrow b\bar{b}b\bar{b}$. The $pp \rightarrow H_3 \rightarrow H_1 H_1 \rightarrow b\bar{b}b\bar{b}$ cross section for the S_2 scan points in Fig. 6 potentially within HL-LHC reach are then depicted in Fig. 9, exceeding in some cases 1 pb. While there is no existing LHC experimental search for such a signature, a sensitivity study has been performed in Ref. [95] through the recasting of CMS resonant di-Higgs searches in the $pp \rightarrow H_3 \rightarrow hh \rightarrow b\bar{b}b\bar{b}$ final state with 35.9 fb^{-1} of integrated luminosity [96]. These CMS recast sensitivities are depicted in Fig. 9 for a benchmark value $m_{H_1} = 100 \text{ GeV}$ (solid red line), together with both the naive ($\sqrt{\mathcal{L}}$; dashed red line) and strongest (solid gray line) HL-LHC sensitivity extrapolations. The recast sensitivities from Ref. [95] apply only to $m_{H_3} > 300 \text{ GeV}$, yet a potential ATLAS or CMS search would surely be able to probe lower masses, providing a complementary way to test H -CPV within set (vi).

Finally, we discuss H -CPV via set (vii), which is independent of the results in Fig. 4. We show the ggF $pp \rightarrow H_a \rightarrow Zh \rightarrow \ell\ell b\bar{b}$ cross sections in Fig. 10 for both S_1 (left and center) and S_2 (right) scans (with either $H_a = H_3$ or $H_a = H_2$ depending on the scan). We also depict the present strongest LHC limits from the ATLAS search [97] (solid red line) as well as the HL-LHC naive ($\sqrt{\mathcal{L}}$; dashed red line) sensitivity extrapolation from the present ATLAS

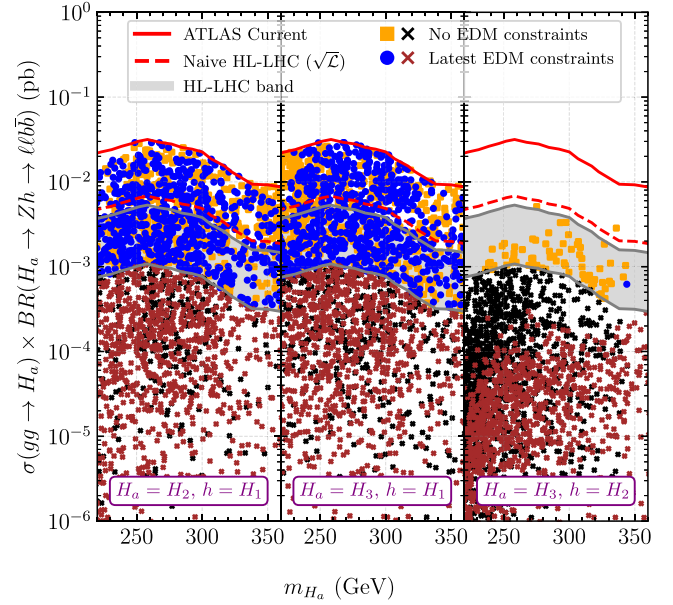


FIG. 10. ggF production $pp \rightarrow H_a \rightarrow Zh \rightarrow \ell\ell b\bar{b}$ cross sections at $\sqrt{s} = 14 \text{ TeV}$ for scans S_1 (left and center panels) and S_2 (right panel), as a function of m_{H_a} . We show the current (solid red line) and projected HL-LHC (dashed red line, gray band) sensitivity lines of this search; see the text for details. Orange squares (black crosses) correspond to HL-LHC observable (unobservable) C2HDM scan points when no EDM constraints are applied, and blue circles (red crosses) when EDM bounds are strictly imposed.

search and the improved HL-LHC (solid gray band) sensitivity extrapolation discussed in Appendix B. For scan S_1 , the C2HDM $pp \rightarrow H_3 \rightarrow Zh \rightarrow \ell\ell b\bar{b}$ cross sections can saturate the current ATLAS bounds both including (blue points) and disregarding (orange points) the latest EDM constraints. For scan S_2 , the cross sections are significantly lower, yet there are many points within potential reach of the HL-LHC if EDM constraints are not taken into account. For the S_1 and S_2 scan points above the strongest HL-LHC sensitivity extrapolation in Fig. 10, we then show in Fig. 11 the resulting cross sections for $pp \rightarrow WH_a$. These cross sections can reach $\sim 10 \text{ fb}$, and—as already emphasized in the discussion around Fig. 7—the possibility of probing W -AP of H_a at the HL-LHC in the $H_a \rightarrow WW$ decay mode seems promising. The recent search by ATLAS [90] provides an important step in this direction, but the model interpretations do not encompass our scenario. The possibility to establish H -CPV via set (vii) then remains an open question.

Before concluding, we stress that, while all our S_1 and S_2 benchmark points satisfy present constraints from 125 GeV Higgs signal strength measurements on the properties of h , it is foreseeable that the future sensitivity on 125 GeV Higgs couplings of the HL-LHC will probe a significant fraction of the scan points for which H -CPV can be established via our various sets (i)–(vii). Focusing for

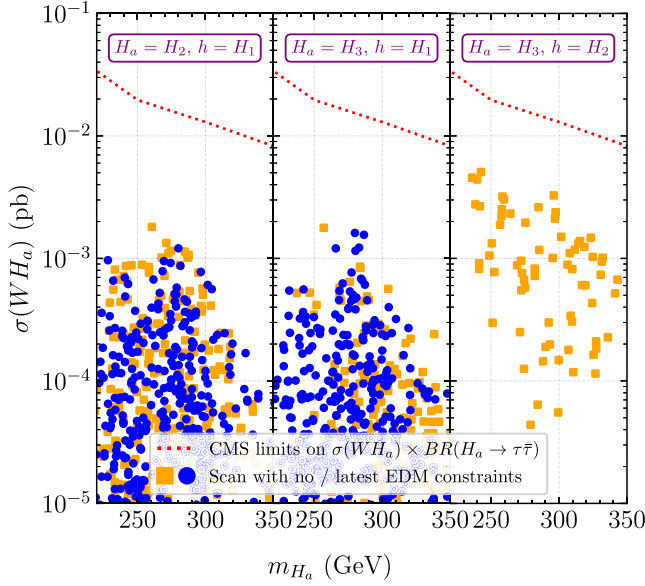


FIG. 11. Values of the $pp \rightarrow WH_a$ production cross section as a function of m_{H_a} for the observable scan points in Fig. 10. Also shown is the current CMS 95% CL bound for the $H_a \rightarrow \tau\tau$ final state [73], for reference.

simplicity only on set (vi), which has been shown to be the most promising avenue analyzed in this work to test H -CPV within the C2HDM with a softly broken $\mathbb{Z}_2$ symmetry, we show in Fig. 12 the value of c_{hVV} for the

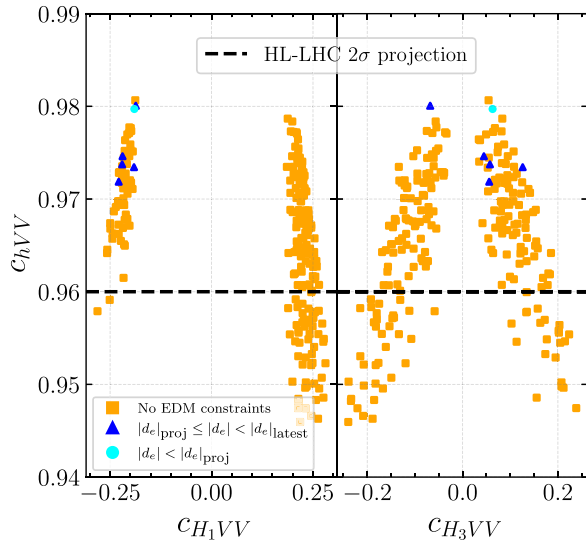


FIG. 12. Values of the Higgs-gauge couplings c_{H_1VV} , c_{hVV} , and c_{H_3VV} for the scan points passing the constraints of set (vi) (for scan S_2). The dashed black line showcases the CMS HL-LHC 2σ sensitivity projection on c_{hVV} from Ref. [71]. Points without EDM constraints are shown as orange squares, those satisfying the latest EDM constraints as blue triangles, and those fulfilling the projected limit $|d_e|_{\text{proj}}$ as cyan circles. The projected eEDM limit is $|d_e|_{\text{proj}} = 1 \times 10^{-30} e \cdot \text{cm}$, the same value used in Fig. 8.

scan points for which H -CPV can potentially be established at the HL-LHC (all belonging to scan S_2), together with their correlation with the values of c_{H_1VV} and c_{H_3VV} . The HL-LHC projection on the sensitivity to c_{hVV} as obtained from Ref. [71] is also depicted (dashed black line), highlighting that a sizable fraction of the C2HDM scan points featuring observable H -CPV through the strategy investigated in this work would, however, not lead to deviations in 125 GeV Higgs boson couplings measurable at HL-LHC.

We end this section with two important remarks on higher-order processes. First of all, in a CP -conserving 2HDM, the decay $A \rightarrow ZZ$ is a fermionic loop-induced process and, therefore, very small. In this work, we have been discussing a CP -violating 2HDM. However, if the CP -violating couplings were so small that they would become comparable with loop-induced processes, the particle CP numbers would have to be investigated in more detail [98]. Yet, the values of c_{H_1VV} and c_{H_3VV} shown in Fig. 12 suggest that this would not be an issue for our scan points with observable H -CPV at the HL-LHC. As a second comment, higher-order corrections can modify the branching ratios of the Higgs decays and, in particular, the ones to other Higgs bosons [99,100], although a dedicated analysis is beyond the scope of this paper.

IV. CONCLUSIONS AND OUTLOOK

In a scenario where CP violation has its origin in a P -even, C -violating sector, three independent processes are needed to reach a contradiction on the CP numbers of the scalars involved. It follows that the identification of a genuine CPV effect can be made explicit only by checking off a combination of processes. We have identified several combinations of such processes where either the three neutral scalars from a C2HDM are present or just two scalars together with the fact that the 125 GeV Higgs boson has been experimentally shown to contain a CP -even admixture. All these multiple signal strategies, listed in sets (i)–(vii) of our manuscript, include VBF or V -associated production of BSM Higgs bosons as a core process, highlighting the potential key role of these processes in probing CP violation within an extended Higgs sector. In particular, W -AP of BSM Higgs bosons is a key channel for probing H -CPV at the HL-LHC, which we believe is currently underexplored by the ATLAS and CMS Collaborations. After taking into account the present constraints coming from collider searches, we have investigated all the proposed sets to understand if they could give us a hint of a CPV model at the HL stage of the LHC. We have concluded that set (vi) is the most promising and that there are good chances to find CPV in the type-I version of the C2HDM. We note that the analysis can be performed not only to any Yukawa types, but also to more general classes of models where new sources of CPV have their origin in the scalar sector.

It is possible that, to attain a stronger probe of such a CPV scenario, one would probably need the cleaner environment of a multi-TeV lepton collider. This, in turn, would provide decisive information about the nature of the extended scalar sector.

ACKNOWLEDGMENTS

The authors thank Mia Tosi and Jorge Fernández de Trocóniz for useful communications. A. L.-O. thanks Marta F. Zamoro and Samuel Rosende Herrero for useful discussions. R. C. thanks Daniel Neascu for help in the implementation of the C2HDM. The authors thank Arturo de Giorgi for participation in early discussions of the project. A. L.-O., L. M., and J. M. N. acknowledge partial financial support by the Spanish Research Agency (Agencia Estatal de Investigación) through the grant IFT Centro de Excelencia Severo Ochoa CEX2020-001007-S and Grants No. PRE2022-105383, No. PID2022-137127NB-I00, and No. PGC2018-096646-A-I00 funded by MCIN/AEI/10.13039/501100011033/FEDER, UE, and by the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie Grant Agreement No. 860881-HIDDeN and No. 101086085-ASYMMETRY. The work of J. M. N. is supported by the Ramón y Cajal Fellowship Contract No. RYC-2017-22986. R. S. and R. C. are partially supported by the Portuguese Foundation for Science and Technology (FCT) under CFTC: UIDB/00618/2020 and UIDP/00618/2020, and through the PRR (Recovery and Resilience Plan), within the scope of the investment “RE-C06-i06—Science Plus Capacity Building”, measure “RE-C06-i06.m02—Reinforcement of financing for International Partnerships in Science, Technology and Innovation of the PRR”, under the project with Reference No. 2024.03328.CERN. R. C. is additionally supported by FCT with a Ph.D. Grant No. 2020.08221.BD. The authors acknowledge support from the COMETA COST Action CA22130. Feynman diagrams were drawn using TikZFeynman [101].

DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX A: DETAILS ON THE C2HDM

1. The model

The C2HDM is one of the simplest scalar sector extensions of the SM to include new sources of CP violation and has been the subject of many studies; see, for instance, Refs. [33,49,52,53,102–130].

The scalar potential of the C2HDM, given in Eq. (1), contains six real parameters, $m_{11}^2, m_{22}^2, \lambda_1, \lambda_2, \lambda_3$, and λ_4 , as well as two complex parameters, λ_5 and m_{12}^2 . Because of the Hermiticity of the potential, only these two parameters can be complex.

The Higgs potential is explicitly CP violating, since no choice of basis exists in which all the Higgs potential parameters are simultaneously real. Its properties can be studied in a charge-conserving vacuum by expanding the doublets around the vacuum expectation values (VEVs) v_1 and v_2 as

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1 + \rho_1 + i\eta_1}{\sqrt{2}} \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2 + \rho_2 + i\eta_2}{\sqrt{2}} \end{pmatrix}, \quad (\text{A1})$$

where ϕ_i^+ denotes the charged and ρ_i and η_i the neutral scalar fields of the respective ($i = 1, 2$) doublets. Employing the conventional definition

$$\lambda_{345} \equiv \lambda_3 + \lambda_5 + \text{Re}(\lambda_5), \quad (\text{A2})$$

the potential is minimized for

$$m_{11}^2 v_1 + \frac{\lambda_1}{2} v_1^3 + \frac{\lambda_{345}}{2} v_1 v_2^2 = \text{Re}(m_{12}^2) v_2, \quad (\text{A3})$$

$$m_{22}^2 v_2 + \frac{\lambda_2}{2} v_2^3 + \frac{\lambda_{345}}{2} v_1^2 v_2 = \text{Re}(m_{12}^2) v_1, \quad (\text{A4})$$

$$2 \text{Im}(m_{12}^2) = v_1 v_2 \text{Im}(\lambda_5). \quad (\text{A5})$$

The last condition is the reason why, despite the two complex phases, CP violation in this model is determined by *one* independent parameter. As long as $\text{Arg}[\lambda_5] \neq 2\text{Arg}[m_{12}^2]$, the two phases cannot be removed simultaneously. However, if $\text{Arg}[\lambda_5] = 2\text{Arg}[m_{12}^2]$ and the VEVs of Φ_1 and Φ_2 are real, we are in the CP -conserving limit of the model.

It is convenient to visualize this model in the Higgs basis, wherein the SM VEV and the Goldstone bosons are located in one of the doublets. To this aim, one rotates the original the doublets as

$$\begin{pmatrix} \mathcal{H}_1 \\ \mathcal{H}_2 \end{pmatrix} = R_H^T \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} \equiv \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix}. \quad (\text{A6})$$

The rotation angle β measures the ratio of the VEVs as

$$\tan \beta \equiv \frac{v_2}{v_1}. \quad (\text{A7})$$

In this basis, the doublets are reexpressed as

$$\mathcal{H}_1 = \left(\frac{G^\pm}{\frac{1}{\sqrt{2}}(v + H^0 + iG^0)} \right), \quad \mathcal{H}_2 = \left(\frac{H^\pm}{\frac{1}{\sqrt{2}}(R_2 + iI_2)} \right), \quad (\text{A8})$$

where we have defined the total (SM) VEV as

$$v = \sqrt{v_1^2 + v_2^2}. \quad (\text{A9})$$

For a study of the spectrum of neutral states, it is convenient to work in the mass basis. Denoting the mass eigenstates as H_i for $i \in \{1, 2, 3\}$, this is achieved by appropriate rotations

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = R \tilde{R}_H \begin{pmatrix} H^0 \\ R_2 \\ I_2 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \end{pmatrix}, \quad (\text{A10})$$

where we fix $\rho_3 = I_2$ and have embedded the Higgs-to- Φ -basis rotation matrix R_H into

$$\tilde{R}_H = \begin{pmatrix} R_H & 0 \\ 0 & 1 \end{pmatrix}. \quad (\text{A11})$$

Given the Hessian of the potential with respect to the neutral states in the Φ basis

$$(\mathcal{M}^2)_{ij} = \left\langle \frac{\partial^2 V}{\partial \rho_i \partial \rho_j} \right\rangle, \quad (\text{A12})$$

the masses of the neutral scalar eigenstates are obtained as

$$R \mathcal{M}^2 R^T = \text{diag}(m_{H_1}^2, m_{H_2}^2, m_{H_3}^2), \quad (\text{A13})$$

where a hierarchy $m_{H_1} \leq m_{H_2} \leq m_{H_3}$ is assumed.

Using the standard trigonometric notation $(s_i, c_i) = (\sin \alpha_i, \cos \alpha_i)$ and the ranges

$$-\pi/2 < \alpha_i \leq \pi/2, \quad (\text{A14})$$

for $i = 1, 2, 3$, the rotation matrix R can be parametrized as [49,51–53]

$$\begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix}. \quad (\text{A15})$$

After fixing all parameter relations, the potential possesses nine free parameters that can be traded for nine physical input parameters, namely, m_{H_1} , m_{H_2} , $m_{H^\pm}$, $\text{Re}(m_{12}^2)$, α_1 , α_2 , α_3 , v , and $\tan \beta$. In particular, the above choices imply the following relation for the mass of the remaining neutral eigenstate:

TABLE I. The four Yukawa types of the softly broken $\mathbb{Z}_2$ -symmetric 2HDM.

	u -type	d -type	Leptons
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

$$m_{H_3}^2 = \frac{m_{H_1}^2 R_{13}(R_{12} t_\beta - R_{11}) + m_{H_2}^2 R_{23}(R_{22} t_\beta - R_{21})}{R_{33}(R_{31} - R_{32} t_\beta)} \quad (\text{A16})$$

with the restriction $m_{H_3} > m_{H_2}$.

The Higgs couplings to the massive gauge bosons $V = W, Z$ are given by

$$i g_{\mu\nu} c_{H_i V V} g_{h V V}, \quad (\text{A17})$$

where $g_{h V V}$ denotes the corresponding SM Higgs coupling, given by

$$g_{h V V} = \begin{cases} g M_W & V = W, \\ g M_Z / \cos \theta_W & V = Z, \end{cases} \quad (\text{A18})$$

where g is the $SU(2)$ gauge coupling and θ_W is the Weinberg angle. The effective couplings can be written as

$$c_{H_i V V} = c_\beta R_{i1} + s_\beta R_{i2}. \quad (\text{A19})$$

The Yukawa sector is built by extending the $\mathbb{Z}_2$ symmetry to the fermion fields such that flavor-changing neutral currents are absent at tree level [131,132]. There are four possible $\mathbb{Z}_2$ charge assignments and, therefore, four different types of 2HDMs described in Table I.

The Yukawa Lagrangian has the form

$$\mathcal{L}_Y = - \sum_{i=1}^3 \frac{m_f}{v} \bar{\psi}_f [c_{H_i f f}^e + i c_{H_i f f}^o \gamma_5] \psi_f H_i, \quad (\text{A20})$$

where ψ_f denotes the fermion fields with mass m_f . The coefficients of the CP -even and of the CP -odd part of the Yukawa coupling, $c_{H_i f f}^e$ and $c_{H_i f f}^o$, respectively, are presented in Table II. A longer list of the interactions between the Higgs bosons and the remaining SM fields can be found in Ref. [49].

2. Theoretical and experimental constraints

In this section, we briefly summarize the main theoretical and experimental restrictions that we considered in the C2HDM scans (for more details about these constraints, see, for instance, Refs. [49,130]). The C2HDM was implemented in *ScannerS* [54,58]. The most relevant

TABLE II. Yukawa couplings of the Higgs bosons H_i in the C2HDM, divided by the corresponding SM Higgs couplings. The expressions correspond to $[c_{H_i ff}^e + ic_{H_i ff}^o \gamma_5]$ from Eq. (A20).

	u -type	d -type	Leptons
Type I	$\frac{R_{12}}{s_\beta} - i \frac{R_{13}}{t_\beta} \gamma_5$	$\frac{R_{12}}{s_\beta} + i \frac{R_{13}}{t_\beta} \gamma_5$	$\frac{R_{12}}{s_\beta} + i \frac{R_{13}}{t_\beta} \gamma_5$
Type II	$\frac{R_{12}}{s_\beta} - i \frac{R_{13}}{t_\beta} \gamma_5$	$\frac{R_{11}}{c_\beta} - it_\beta R_{13} \gamma_5$	$\frac{R_{11}}{c_\beta} - it_\beta R_{13} \gamma_5$
Lepton-specific	$\frac{R_{12}}{s_\beta} - i \frac{R_{13}}{t_\beta} \gamma_5$	$\frac{R_{12}}{s_\beta} + i \frac{R_{13}}{t_\beta} \gamma_5$	$\frac{R_{11}}{c_\beta} - it_\beta R_{13} \gamma_5$
Flipped	$\frac{R_{12}}{s_\beta} - i \frac{R_{13}}{t_\beta} \gamma_5$	$\frac{R_{11}}{c_\beta} - it_\beta R_{13} \gamma_5$	$\frac{R_{12}}{s_\beta} + i \frac{R_{13}}{t_\beta} \gamma_5$

theoretical and experimental bounds are either built in the code or accessible via interfaces with other codes. We have imposed the following constraints on the scans that were performed.

- (i) The theoretical bounds include boundedness from below and perturbative unitarity [133–135], as well as vacuum stability, which can be accomplished by forcing the minimum to be global [136].
- (ii) The points generated are required to comply with the measured values of the oblique parameters S , T , and U [50], within 2σ of the experimental results from [137].
- (iii) The most constraining bounds on the charged sector of the C2HDM come from the measurements of $B \rightarrow X_s \gamma$ [138–143], which translate into 2σ exclusion bounds on the $m_{H^\pm} - t_\beta$ plane. We follow [49] in using $80 \text{ GeV} \leq m_{H^\pm} < 1 \text{ TeV}$ and $0.8 \leq t_\beta \leq 35$ for the type-I model that was considered in this work. Notice, however, that for type-II and flipped models, the bounds are much more severe, forcing $m_{H^\pm} > 580 \text{ GeV}$ almost independently of $\tan\beta$.
- (iv) The most recent limit of $4.1 \times 10^{-30} \text{ e.cm}$ measured at JILA [22] for the eEDM is considered. This limit was not applied to all the points. In the text and in the figures, we indicate when the eEDM limit was applied in our scans.
- (v) Compatibility with new searches for additional scalars and LHC constraints on the discovered Higgs boson at the LHC are checked via the interface to the code HiggsTools [59]. As mentioned in the main text, we apply an additional filtering to our scan points by requiring that they lie within the (c_{hff}, c_{hVV}) 2σ ellipse in Ref. [71] from a combined Higgs signal strength fit with observed best-fit value $(c_{hff}, c_{hVV}) = (0.906, 1.014)$.

APPENDIX B: HL-LHC SENSITIVITIES

As outlined in the main text, the naive “statistical” $\sqrt{\mathcal{L}}$ extrapolation of the current experimental sensitivity of

ATLAS and CMS analyses to the HL-LHC could turn out to be rather pessimistic in many cases, as discussed in detail in Ref. [74]. Such an extrapolation does not account for several ingredients that would presumably increase the future LHC sensitivity with respect to a $\sqrt{\mathcal{L}}$ projection:

- (i) the possible inclusion of further decay modes in analyses already targeting a specific decay channel as $\mathcal{L}$ increases;
- (ii) the exploitation of kinematic regions (e.g., high- p_T configurations) that do not appreciably contribute to the present sensitivity but would very much do for larger $\mathcal{L}$;
- (iii) the development of new (e.g., artificial-intelligence-based) analysis strategies; and
- (iv) the (obvious) increase in center-of-mass energy $\sqrt{s}$ from LHC run II to HL-LHC, which will increase the sensitivity (albeit not in a dramatic way) of many BSM searches.

A robust estimate of the sensitivity increase at the HL-LHC with respect to the present ATLAS and CMS searches that we have analyzed lies beyond the scope of this work and may not even be possible in some cases (e.g., if new, machine-learning-based analysis tools were to be used in future searches). Yet, the sensitivity evolution of several ATLAS and CMS searches up to their current status offers a way to ascertain the possibility of improving over the $\sqrt{\mathcal{L}}$ extrapolation. Specifically, we parametrize the experimental sensitivity increase observed between an integrated luminosity $\simeq 36$ and $\simeq 140 \text{ fb}^{-1}$ in different ATLAS and CMS SM searches performed for $\sqrt{s} = 13 \text{ TeV}$ LHC,⁴ as an $\mathcal{L}^x$ function of the luminosity increase $\mathcal{L} \simeq 140/36$ (with $x = 0.5$ corresponding to the “statistical” sensitivity increase). The searches we consider are $pp \rightarrow t\bar{t}t\bar{t}$ [75,76], for which the sensitivity increase yields $x = 0.86$; $pp \rightarrow Vh$ with $h \rightarrow b\bar{b}$ [77,78], for which the sensitivity increase yields $x = 0.60$; EW vector boson scattering $pp \rightarrow ZZ + jj$, $ZZ \rightarrow \ell\ell\ell'\ell'$ (with $\ell, \ell' = e, \mu$) [79,80], for which the sensitivity increase yields $x = 0.58$; and di-Higgs production $pp \rightarrow hh \rightarrow b\bar{b}\tau\tau$ [81,82], for which the sensitivity increase yields $x = 1.11$. We note that all these searches yield a sensitivity increase from 36 to 140 fb^{-1} , which exceeds the $\sqrt{\mathcal{L}}$ scaling. Then, as an “optimistic” projection of the sensitivity of the various searches we discuss in this work to the HL-LHC with 3000 fb^{-1} of integrated luminosity, we use an $\mathcal{L}^x$ scaling, with $x \in [0.58, 1.11]$ rather than the naive $\sqrt{\mathcal{L}}$ scaling. This defines the “improved” HL-LHC extrapolated sensitivity band shown in gray in Fig. 4.

⁴Avoiding the sensitivity comparison with $\sqrt{s} = 8 \text{ TeV}$ data allows one to drop out of the discussion the sensitivity gain in going from $\sqrt{s} = 8 \text{ TeV}$ to $\sqrt{s} = 13 \text{ TeV}$ LHC c.m. energy.

- [1] N. Cabibbo, *Phys. Rev. Lett.* **10**, 531 (1963).
- [2] M. Kobayashi and T. Maskawa, *Prog. Theor. Phys.* **49**, 652 (1973).
- [3] V. A. Kuzmin, V. A. Rubakov, and M. E. Shaposhnikov, *Phys. Lett.* **155B**, 36 (1985).
- [4] A. D. Sakharov, *Pis'ma Zh. Eksp. Teor. Fiz.* **5**, 32 (1967).
- [5] A. G. Cohen, D. B. Kaplan, and A. E. Nelson, *Annu. Rev. Nucl. Part. Sci.* **43**, 27 (1993).
- [6] M. Trodden, *Rev. Mod. Phys.* **71**, 1463 (1999).
- [7] D. E. Morrissey and M. J. Ramsey-Musolf, *New J. Phys.* **14**, 125003 (2012).
- [8] T. Konstandin, *Phys. Usp.* **56**, 747 (2013).
- [9] M. B. Gavela, P. Hernandez, J. Orloff, and O. Pene, *Mod. Phys. Lett. A* **9**, 795 (1994).
- [10] M. B. Gavela, M. Lozano, J. Orloff, and O. Pene, *Nucl. Phys.* **B430**, 345 (1994).
- [11] M. B. Gavela, P. Hernandez, J. Orloff, O. Pene, and C. Quimbay, *Nucl. Phys.* **B430**, 382 (1994).
- [12] F. Ferreira, B. Fuks, V. Sanz, and D. Sengupta, *Eur. Phys. J. C* **77**, 675 (2017).
- [13] J. Brehmer, F. Kling, T. Plehn, and T. M. P. Tait, *Phys. Rev. D* **97**, 095017 (2018).
- [14] F. U. Bernlochner, C. Englert, C. Hays, K. Lohwasser, H. Mildner, A. Pilkington, D. D. Price, and M. Spannowsky, *Phys. Lett. B* **790**, 372 (2019).
- [15] V. Cirigliano, A. Crivellin, W. Dekens, J. de Vries, M. Hoferichter, and E. Mereghetti, *Phys. Rev. Lett.* **123**, 051801 (2019).
- [16] C. Englert, P. Galler, A. Pilkington, and M. Spannowsky, *Phys. Rev. D* **99**, 095007 (2019).
- [17] E. Fuchs, M. Losada, Y. Nir, and Y. Viernik, *J. High Energy Phys.* **05** (2020) 056.
- [18] H. Bahl, E. Fuchs, S. Heinemeyer, J. Katzy, M. Menen, K. Peters, M. Saimpert, and G. Weiglein, *Eur. Phys. J. C* **82**, 604 (2022).
- [19] W. C. Griffith, M. D. Swallows, T. H. Loftus, M. V. Romalis, B. R. Heckel, and E. N. Fortson, *Phys. Rev. Lett.* **102**, 101601 (2009).
- [20] V. Andreev *et al.* (ACME Collaboration), *Nature (London)* **562**, 355 (2018).
- [21] C. Abel *et al.* (nEDM Collaboration), *Phys. Rev. Lett.* **124**, 081803 (2020).
- [22] T. S. Roussy *et al.*, *Science* **381**, adg4084 (2023).
- [23] R. Harnik, A. Martin, T. Okui, R. Primulando, and F. Yu, *Phys. Rev. D* **88**, 076009 (2013).
- [24] S.-F. Ge, G. Li, P. Pasquini, and M. J. Ramsey-Musolf, *Phys. Rev. D* **103**, 095027 (2021).
- [25] A. Tumasyan *et al.* (CMS Collaboration), *J. High Energy Phys.* **06** (2022) 012.
- [26] W. Esmail, A. Hammad, M. Nojiri, and C. Scherb, *J. High Energy Phys.* **04** (2025) 083.
- [27] S. Bolognesi, Y. Gao, A. V. Gritsan, K. Melnikov, M. Schulze, N. V. Tran, and A. Whitbeck, *Phys. Rev. D* **86**, 095031 (2012).
- [28] G. Aad *et al.* (ATLAS Collaboration), *Eur. Phys. J. C* **75**, 476 (2015); **76**, 152(E) (2016).
- [29] M. J. Dolan, P. Harris, M. Jankowiak, and M. Spannowsky, *Phys. Rev. D* **90**, 073008 (2014).
- [30] G. Aad *et al.* (ATLAS Collaboration), *Phys. Rev. Lett.* **125**, 061802 (2020).
- [31] A. M. Sirunyan *et al.* (CMS Collaboration), *Phys. Rev. Lett.* **125**, 061801 (2020).
- [32] A. Tumasyan *et al.* (CMS Collaboration), *J. High Energy Phys.* **07** (2023) 092.
- [33] D. Fontes, J. C. Romão, R. Santos, and J. a. P. Silva, *Phys. Rev. D* **92**, 055014 (2015).
- [34] H. E. Haber, V. Keus, and R. Santos, *Phys. Rev. D* **106**, 095038 (2022).
- [35] D. R. T. Jones and S. T. Petcov, *Phys. Lett.* **84B**, 440 (1979).
- [36] G. Aad *et al.* (ATLAS Collaboration), *Eur. Phys. J. C* **83**, 563 (2023).
- [37] G. Aad *et al.* (ATLAS Collaboration), *Phys. Lett. B* **849**, 138469 (2024).
- [38] J. D. Bjorken, *Phys. Rev. D* **47**, 101 (1993).
- [39] N. Kauer, T. Plehn, D. L. Rainwater, and D. Zeppenfeld, *Phys. Lett. B* **503**, 113 (2001).
- [40] V. Del Duca, W. Kilgore, C. Oleari, C. Schmidt, and D. Zeppenfeld, *Phys. Rev. Lett.* **87**, 122001 (2001).
- [41] V. D. Barger, K. Cheung, T. Han, and D. Zeppenfeld, *Phys. Rev. D* **44**, 2701 (1991); **48**, 5444(E) (1993).
- [42] D. L. Rainwater, D. Zeppenfeld, and K. Hagiwara, *Phys. Rev. D* **59**, 014037 (1998).
- [43] G. Aad *et al.* (ATLAS Collaboration), *Phys. Rev. D* **108**, 032005 (2023).
- [44] G. Aad *et al.* (ATLAS Collaboration), *J. High Energy Phys.* **07** (2023) 088.
- [45] G. Aad *et al.* (ATLAS Collaboration), *J. High Energy Phys.* **08** (2022) 175.
- [46] Constituent-based quark gluon tagging using transformers with the ATLAS detector, technical report, CERN, Geneva, 2023.
- [47] G. Aad *et al.* (ATLAS Collaboration), *Chin. Phys. C* **48**, 023001 (2024).
- [48] I. F. Ginzburg, M. Krawczyk, and P. Osland, in *Proceedings of the International Workshop on Linear Colliders (LCWS 2002)* (2002), pp. 703–706, [arXiv:hep-ph/0211371](#).
- [49] D. Fontes, M. Muhlleitner, J. C. Romao, R. Santos, J. P. Silva, and J. Wittbrodt, *J. High Energy Phys.* **02** (2018) 073.
- [50] G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. Sher, and J. P. Silva, *Phys. Rep.* **516**, 1 (2012).
- [51] E. Accomando *et al.* (2006), [10.5170/CERN-2006-009](#),
- [52] W. Khater and P. Osland, *Nucl. Phys.* **B661**, 209 (2003).
- [53] A. W. El Kaffas, P. Osland, and O. M. Ogreid, *Nonlin. Phenom. Complex Syst.* **10**, 347 (2007).
- [54] R. Coimbra, M. O. P. Sampaio, and R. Santos, *Eur. Phys. J. C* **73**, 2428 (2013).
- [55] P. M. Ferreira, R. Guedes, M. O. P. Sampaio, and R. Santos, *J. High Energy Phys.* **12** (2014) 067.
- [56] R. Costa, M. Muhlleitner, M. O. P. Sampaio, and R. Santos, *J. High Energy Phys.* **06** (2016) 034.
- [57] M. Muhlleitner, M. O. P. Sampaio, R. Santos, and J. Wittbrodt, *J. High Energy Phys.* **03** (2017) 094.
- [58] M. Muhlleitner, M. O. P. Sampaio, R. Santos, and J. Wittbrodt, *Eur. Phys. J. C* **82**, 198 (2022).
- [59] H. Bahl, T. Biekotter, S. Heinemeyer, C. Li, S. Paasch, G. Weiglein, and J. Wittbrodt, *Comput. Phys. Commun.* **291**, 108803 (2023).

- [60] P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein, and K. E. Williams, *Comput. Phys. Commun.* **181**, 138 (2010).
- [61] P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein, and K. E. Williams, *Comput. Phys. Commun.* **182**, 2605 (2011).
- [62] P. Bechtle, O. Brein, S. Heinemeyer, O. Stal, T. Stefaniak, G. Weiglein, and K. Williams, *Proc. Sci., CHARGED2012* (**2012**) 024 [arXiv:1301.2345].
- [63] P. Bechtle, O. Brein, S. Heinemeyer, O. Stal, T. Stefaniak, G. Weiglein, and K. E. Williams, *Eur. Phys. J. C* **74**, 2693 (2014).
- [64] P. Bechtle, S. Heinemeyer, O. Stal, T. Stefaniak, and G. Weiglein, *Eur. Phys. J. C* **75**, 421 (2015).
- [65] P. Bechtle, D. Dercks, S. Heinemeyer, T. Klingl, T. Stefaniak, G. Weiglein, and J. Wittbrodt, *Eur. Phys. J. C* **80**, 1211 (2020).
- [66] H. Bahl, V. M. Lozano, T. Stefaniak, and J. Wittbrodt, *Eur. Phys. J. C* **82**, 584 (2022).
- [67] P. Bechtle, S. Heinemeyer, O. Stal, T. Stefaniak, and G. Weiglein, *Eur. Phys. J. C* **74**, 2711 (2014).
- [68] O. Stal and T. Stefaniak, *Proc. Sci., EPS-HEP2013* (**2013**) 314 [arXiv:1310.4039].
- [69] P. Bechtle, S. Heinemeyer, O. Stal, T. Stefaniak, and G. Weiglein, *J. High Energy Phys.* **11** (2014) 039.
- [70] P. Bechtle, S. Heinemeyer, T. Klingl, T. Stefaniak, G. Weiglein, and J. Wittbrodt, *Eur. Phys. J. C* **81**, 145 (2021).
- [71] A. Tumasyan *et al.* (CMS Collaboration), *Nature (London)* **607**, 60 (2022); **623**, E4 (2023).
- [72] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, *J. High Energy Phys.* **07** (2014) 079.
- [73] A. Tumasyan *et al.* (CMS Collaboration), *Phys. Rev. D* **110**, 012013 (2024).
- [74] A. Belvedere, C. Englert, R. Kogler, and M. Spannowsky, *Eur. Phys. J. C* **84**, 715 (2024).
- [75] A. M. Sirunyan *et al.* (CMS Collaboration), *Eur. Phys. J. C* **78**, 140 (2018).
- [76] A. Hayrapetyan *et al.* (CMS Collaboration), *Phys. Lett. B* **847**, 138290 (2023).
- [77] M. Aaboud *et al.* (ATLAS Collaboration), *J. High Energy Phys.* **12** (2017) 024.
- [78] G. Aad *et al.* (ATLAS Collaboration), *Eur. Phys. J. C* **81**, 178 (2021).
- [79] A. M. Sirunyan *et al.* (CMS Collaboration), *Phys. Lett. B* **774**, 682 (2017).
- [80] A. M. Sirunyan *et al.* (CMS Collaboration), *Phys. Lett. B* **812**, 135992 (2021).
- [81] M. Aaboud *et al.* (ATLAS Collaboration), *Phys. Rev. Lett.* **121**, 191801 (2018); **122**, 089901(E) (2019).
- [82] G. Aad *et al.* (ATLAS Collaboration), *Phys. Rev. D* **110**, 032012 (2024).
- [83] R. Barate *et al.* (LEP Working Group for Higgs boson searches, ALEPH, DELPHI, L3, OPAL Collaborations), *Phys. Lett. B* **565**, 61 (2003).
- [84] G. Aad *et al.* (ATLAS Collaboration), *Nature (London)* **607**, 52 (2022); **612**, E24 (2022).
- [85] A. M. Sirunyan *et al.* (CMS Collaboration), *J. High Energy Phys.* **03** (2020) 055.
- [86] V. Khachatryan *et al.* (CMS Collaboration), *Phys. Lett. B* **759**, 369 (2016).
- [87] M. Aaboud *et al.* (ATLAS Collaboration), *Phys. Lett. B* **783**, 392 (2018).
- [88] G. Aad *et al.* (ATLAS Collaboration), *Eur. Phys. J. C* **81**, 396 (2021).
- [89] A. M. Sirunyan *et al.* (CMS Collaboration), Search for new neutral Higgs bosons through the $H \rightarrow ZA \rightarrow \ell^+ \ell^- b \bar{b}$ process in pp collisions at $\sqrt{s} = 13$ TeV, 10.17182/hepdata.90710 (2020) (accessed: 2025-04-10).
- [90] G. Aad *et al.* (ATLAS Collaboration), *J. High Energy Phys.* **07** (2023) 200.
- [91] A. M. Sirunyan *et al.* (CMS Collaboration), *J. High Energy Phys.* **06** (2018) 127; **03** (2019) 128(E).
- [92] C. B. group, CMS beyond sm particles decaying 2(to) Higgs, top and gauge bosons (b2g) public physics results, <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G> (2025) (accessed: 2025-05-13).
- [93] D. G. Ang, C. Meisenholder, C. D. Panda, X. Wu, D. DeMille, J. M. Doyle, and G. Gabrielse, *Phys. Rev. A* **106**, 022808 (2022).
- [94] X. Wu, P. Hu, Z. Han, D. G. Ang, C. Meisenholder, G. Gabrielse, J. M. Doyle, and D. DeMille, *New J. Phys.* **24**, 073043 (2022).
- [95] D. Barducci, K. Mimasu, J. M. No, C. Vernieri, and J. Zurita, *J. High Energy Phys.* **02** (2020) 002.
- [96] A. M. Sirunyan *et al.* (CMS Collaboration), *J. High Energy Phys.* **08** (2018) 152.
- [97] G. Aad *et al.* (ATLAS Collaboration), *J. High Energy Phys.* **06** (2023) 016.
- [98] A. Arhrib, R. Benbrik, J. El Falaki, M. Sampaio, and R. Santos, *Phys. Rev. D* **99**, 035043 (2019).
- [99] M. Krause, M. Muhlleitner, R. Santos, and H. Ziesche, *Phys. Rev. D* **95**, 075019 (2017).
- [100] J. Braathen and S. Kanemura, *Phys. Lett. B* **796**, 38 (2019).
- [101] J. Ellis, *Comput. Phys. Commun.* **210**, 103 (2017).
- [102] B. Grzadkowski and P. Osland, *Phys. Rev. D* **82**, 125026 (2010).
- [103] A. Arhrib, E. Christova, H. Eberl, and E. Ginina, *J. High Energy Phys.* **04** (2011) 089.
- [104] A. Barroso, P. M. Ferreira, R. Santos, and J. P. Silva, *Phys. Rev. D* **86**, 015022 (2012).
- [105] T. Abe, J. Hisano, T. Kitahara, and K. Tobioka, *J. High Energy Phys.* **01** (2014) 106 (2014); **04** (2016) 161(E) (2016).
- [106] S. Inoue, M. J. Ramsey-Musolf, and Y. Zhang, *Phys. Rev. D* **89**, 115023 (2014).
- [107] K. Cheung, J. S. Lee, E. Senaha, and P.-Y. Tseng, *J. High Energy Phys.* **06** (2014) 149.
- [108] D. Fontes, J. C. Romão, and J. P. Silva, *J. High Energy Phys.* **12** (2014) 043.
- [109] G. Dorsch, S. Huber, T. Konstandin, and J. No, *J. Cosmol. Astropart. Phys.* **05** (2017) 052.
- [110] R. Grober, M. Muhlleitner, and M. Spira, *Nucl. Phys. B* **925**, 1 (2017).
- [111] D. Fontes, J. C. Romão, R. Santos, and J. P. Silva, *J. High Energy Phys.* **06** (2015) 060.
- [112] C.-Y. Chen, S. Dawson, and Y. Zhang, *J. High Energy Phys.* **06** (2015) 056.
- [113] C.-Y. Chen, H.-L. Li, and M. Ramsey-Musolf, *Phys. Rev. D* **97**, 015020 (2018).

- [114] M. Mühlleitner, M. O. P. Sampaio, R. Santos, and J. Wittbrodt, *J. High Energy Phys.* **08** (2017) 132.
- [115] P. Basler, M. Mühlleitner, and J. Wittbrodt, *J. High Energy Phys.* **03** (2018) 061.
- [116] M. Aoki, K. Hashino, D. Kaneko, S. Kanemura, and M. Kubota, *Prog. Theor. Exp. Phys.* **2019**, 053B02 (2019).
- [117] P. Basler, M. Mühlleitner, and J. Müller, *J. High Energy Phys.* **05** (2020) 016.
- [118] X. Wang, F. P. Huang, and X. Zhang, *Phys. Rev. D* **101**, 015015 (2020).
- [119] R. Boto, T. V. Fernandes, H. E. Haber, J. C. Romão, and J. a. P. Silva, *Phys. Rev. D* **101**, 055023 (2020).
- [120] K. Cheung, A. Jueid, Y.-N. Mao, and S. Moretti, *Phys. Rev. D* **102**, 075029 (2020).
- [121] W. Altmannshofer, S. Gori, N. Hamer, and H. H. Patel, *Phys. Rev. D* **102**, 115042 (2020).
- [122] D. Fontes and J. C. Romão, *J. High Energy Phys.* **06** (2021) 016; **12** (2021) 5.
- [123] P. Basler, L. Biermann, M. Mühlleitner, and J. Müller, *Eur. Phys. J. C* **83**, 57 (2023).
- [124] M. Frank, E. G. Fuakye, and M. Toharia, *Phys. Rev. D* **106**, 035010 (2022).
- [125] H. Abouabid, A. Arhrib, D. Azevedo, J. E. Falaki, P. M. Ferreira, M. Mühlleitner, and R. Santos, *J. High Energy Phys.* **09** (2022) 011.
- [126] D. Fontes and J. C. Romão, *J. High Energy Phys.* **03** (2022) 144.
- [127] A. de Giorgi, F. Koutroulis, L. Merlo, and S. Pokorski, *Nucl. Phys.* **B994**, 116323 (2023).
- [128] D. Azevedo, T. Biekötter, and P. M. Ferreira, *J. High Energy Phys.* **11** (2023) 017.
- [129] D. Gonçalves, A. Kaladharan, and Y. Wu, *Phys. Rev. D* **108**, 075010 (2023).
- [130] T. Biekötter, D. Fontes, M. Mühlleitner, J. C. Romão, R. Santos, and J. P. Silva, *J. High Energy Phys.* **05** (2024) 127.
- [131] S. L. Glashow and S. Weinberg, *Phys. Rev. D* **15**, 1958 (1977).
- [132] E. A. Paschos, *Phys. Rev. D* **15**, 1966 (1977).
- [133] S. Kanemura, T. Kubota, and E. Takasugi, *Phys. Lett. B* **313**, 155 (1993).
- [134] A. G. Akeroyd, A. Arhrib, and E.-M. Naimi, *Phys. Lett. B* **490**, 119 (2000).
- [135] I. F. Ginzburg and I. P. Ivanov, *arXiv:hep-ph/0312374*.
- [136] I. P. Ivanov and J. P. Silva, *Phys. Rev. D* **92**, 055017 (2015).
- [137] M. Baak, J. Cuth, J. Haller, A. Hoecker, R. Kogler, K. Monig, M. Schott, and J. Stelzer (Gfitter Group Collaboration), *Eur. Phys. J. C* **74**, 3046 (2014).
- [138] O. Deschamps, S. Descotes-Genon, S. Monteil, V. Niess, S. T’Jampens, and V. Tisserand, *Phys. Rev. D* **82**, 073012 (2010).
- [139] F. Mahmoudi and O. Stal, *Phys. Rev. D* **81**, 035016 (2010).
- [140] T. Hermann, M. Misiak, and M. Steinhauser, *J. High Energy Phys.* **11** (2012) 036.
- [141] M. Misiak *et al.*, *Phys. Rev. Lett.* **114**, 221801 (2015).
- [142] M. Misiak and M. Steinhauser, *Eur. Phys. J. C* **77**, 201 (2017).
- [143] M. Misiak, A. Rehman, and M. Steinhauser, *J. High Energy Phys.* **06** (2020) 175.