CP Violation in Higgs-Gauge Interactions: From Tabletop Experiments to the LHC

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We investigate the interplay between the high- and low-energy phenomenology of *CP*-violating interactions of the Higgs boson with gauge bosons. For this purpose, we use an effective field theory approach and consider all dimension-six operators arising in so-called universal theories. We compute their loop-induced contributions to electric dipole moments and the *CP* asymmetry in $B \to X_s \gamma$ and compare the resulting current and prospective constraints to the projected sensitivity of the LHC. Low-energy measurements are shown to generally have a far stronger constraining power, which results in highly correlated allowed regions in coupling space—a distinctive pattern that could be probed at the high-luminosity LHC.

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Introduction.—To generate the observed matter-antimatter asymmetry in the Universe, the Sakharov conditions [1] have to be satisfied. One of them requires that charge-parity (*CP*) symmetry be violated. *CP* symmetry is broken in the standard model (SM) of particle physics with three generations of quarks but only by the phase of the Cabibbo-Kobayashi-Maskawa matrix and, potentially, the QCD θ term. The resulting amount of *CP* violation is, however, far too small to explain the observed matter-antimatter asymmetry [2–7]. Scenarios of electroweak (EW) baryogenesis [8–11] demand new sources of *CP* violation not too far above the EW scale.

It has long been recognized that the required new *CP*-violating couplings can generate observable effects in both Higgs production and decay rates, i.e., *CP*-even observables [12–24], as well as genuinely *CP*-odd signatures at the Large Hadron Collider (LHC) [25–37]. Moreover, the interplay with low-energy *CP*-violating observables such as electric dipole moments (EDMs) has been explored, in either specific models [19,38] or SM effective field theory (SMEFT) [12–14,16,19–24], taking into account only subsets of the dimension-six *CP*-odd operators.

Here we take a novel point of view and focus on the *CP*-violating sector of so-called universal theories, originally introduced as the broad class of SM extensions in which beyond-the-SM (BSM) particles couple to SM bosons and/or to SM fermions only through the gauge and Yukawa currents [39], placing the analysis of the oblique EW corrections [40,41] and EW precision tests (EWPTs) in a more general and consistent framework.

With the forthcoming high-luminosity (HL) LHC upgrade, EWPTs involving triple-gauge-boson and gauge-boson–Higgs couplings will be an important thrust and will probe universal theories beyond the level reached with large electron-positron collider/stanford linear collider (LEP/SLC) data [42–44]. In this context, both for completeness and in connection with baryogenesis, it is timely to study the *CP*-violating sector of such theories and to investigate *quantitatively* the complementarity of collider and low-energy measurements.

To address this problem, we work within SMEFT, which relies on assuming a gap between the scale Λ of BSM physics and the EW scale. Universal theories induce, modulo field redefinitions, only bosonic operators at the scale Λ [45]. The SMEFT setup for the *CP*-conserving sector of universal theories and the effect of nonuniversal operators generated by the renormalization group (RG) flow have been studied in Refs. [45,46]. We find that the *CP*-violating sector of universal theories is characterized by six dimension-six operators, which in the Warsaw basis [47,48] read

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$$\mathcal{L} = -g^2 C_{\varphi\tilde{W}} \varphi^\dagger \varphi \tilde{W}^i_{\mu\nu} W_i^{\mu\nu} - g'^2 C_{\varphi\tilde{B}} \varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu} - g g' C_{\varphi\tilde{W}B} \varphi^\dagger \tau^i \varphi \tilde{W}^i_{\mu\nu} B^{\mu\nu} - g_s^2 C_{\varphi\tilde{G}} \varphi^\dagger \varphi G^a_{\mu\nu} \tilde{G}_a^{\mu\nu} + \frac{C_{\tilde{G}}}{3} g_s f_{abc} \tilde{G}^a_{\mu\nu} G_b^{\nu\rho} G_\rho^{c\mu} + \frac{C_{\tilde{W}}}{3} g \epsilon_{ijk} \tilde{W}^i_{\mu\nu} W_j^{\nu\rho} W_\rho^{k\mu}, \tag{1}$$

where φ is the Higgs doublet with $\langle\varphi\rangle = v/\sqrt{2}$, $v \simeq 246$ GeV, g_s, g, and g' are the $SU(3)_c$, $SU(2)_L$, and $U(1)_Y$ couplings, respectively, and $G_{\mu\nu}$, $W_{\mu\nu}$, and $B_{\mu\nu}$ the corresponding field strength tensors. We define $\tilde{X}^{\mu\nu} = \epsilon^{\mu\nu\alpha\beta} X_{\alpha\beta}/2$, $\epsilon^{0123} = +1$. The Wilson coefficients $C_{\varphi\tilde{X},\tilde{X}}$ encode contributions from BSM physics scaling as $1/\Lambda^2$.

This scenario has additional desirable features: It provides a natural arena to study CP-violating Higgs-gauge interactions in the SMEFT context, as those arise, together with the triple-gauge-boson, as the dominant CP-violating couplings. Furthermore, the BSM scale Λ can be relatively low (as minimal flavor violation [49,50] is satisfied and CP-violating fermionic dipoles are generated only through RG flow), a welcome feature for the viability of weak-scale baryogenesis.

The operators in Eq. (1) affect the cross sections of processes such as Higgs production via gluon or vector-boson fusion, Higgs production in association with EW gauge bosons, and Higgs decays through noninterfering contributions quadratic in $C_{\varphi\tilde{X}}$ and are thus suppressed by $(v/\Lambda)^4$. Such dimension-eight contributions, however, still lead to significant constraints [27,32]. The Higgs-gauge operators contribute at $\mathcal{O}(v^2/\Lambda^2)$ to CP-odd observables, such as the CP asymmetry in $pp \to h + 2j$ [28–30,34], angular distributions in associated HW and HZ production [27,31,32], or in $h \to 4l$ [25,33,34], while $C_{\tilde{W}}$ and $C_{\varphi\tilde{W}B}$ contribute to CP-odd observables in diboson production [27,35]. $C_{\tilde{G}}$ gives tree-level corrections to $pp \to h + 2j$ and to multijet production [36]. In addition to these tree-level effects in collider observables, all coefficients contribute to low-energy CP-violating observables, such as EDMs and the CP asymmetry in $B \to X_s\gamma$, at the loop level. In this Letter, we set up the framework to include low-energy CP-violating probes and demonstrate that they put severe constraints on the CP-violating sector of universal theories. To establish the connection to existing collider bounds [30,37], we first concentrate the phenomenological analysis on the operators that involve the Higgs coupling and later discuss the low- and high-energy input necessary for an analysis of all six parameters simultaneously.

Renormalization group evolution.—When the Higgs field acquires its vacuum expectation value, the operators in Eq. (1) generate θ-like terms by means of $\varphi^\dagger\varphi \to v^2/2 + \cdots$, $\varphi^\dagger\tau^i\varphi \to -\delta^{i3}v^2/2 + \cdots$, where the dots denote terms that contain the Higgs scalar boson h. The parts of the operators in Eq. (1) that do not involve h can be absorbed in the SM θ terms. The $U(1)_Y$ and $SU(2)_L$ θ terms are unphysical, because they can be removed by field rotations [51–53]. The gluonic operator effectively shifts the QCD θ term $\theta \to \theta - 16\pi^2 v^2 C_{\varphi\tilde{G}}$, which is strongly constrained by the neutron EDM [54,55]. However, we will assume the presence of a Peccei-Quinn mechanism [56] under which the total θ term vanishes dynamically.

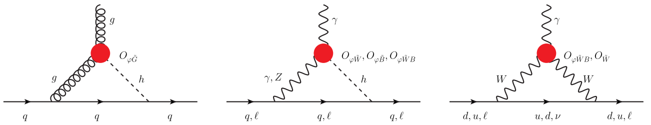

FIG. 1. One-loop diagrams involving Higgs-gauge operators that contribute to (gluonic) dipole operators. The red circles denote insertions of the SMEFT operators. The diagram on the right side also generates threshold corrections to flavor-violating dipole operators.

Below the EW scale, the Lagrangian contains flavor-conserving operators that induce leptonic and hadronic EDMs [fermion EDMs, quark chromo EDMs (CEDMs), and the Weinberg operator] as well as $\Delta B = \Delta S = 1$ operators that contribute to $B \to X_s\gamma$, through the diagrams shown in Fig. 1. These diagrams provide both finite matching contributions at the EW scale, $\mu = \mu_t$, and contributions to the anomalous dimensions that determine the RG evolution between the BSM scale, $\mu = \Lambda$, and the EW scale. We then evolve the low-energy operators to the scale where QCD becomes nonperturbative, $\mu = \Lambda_\chi = 2$ GeV, and take into account the bottom, charm, and strange thresholds where additional matching contributions are generated. More details about the evolution from the high- to low-energy scale are given in Ref. [57] (including Refs. [58–67]).

A key outcome of the RG analysis is that the weak operators $C_{\varphi\tilde{B}}$, $C_{\varphi\tilde{W}}$, $C_{\varphi\tilde{W}B}$, and $C_{\tilde{W}}$ contribute to the fermion EDMs almost exclusively via two combinations, proportional to the third component of the weak isospin, T^3_f, and the electric charge, Q_f. For this reason, present and future EDM experiments constrain at most four directions in the parameter space of Eq. (1), up to small subleading effects.

Low-energy observables.—Next, we discuss the connection to the most sensitive low-energy observables, starting with EDMs. The most stringent limits are set by the neutron and ^{199}Hg atom and by measurements on the polar molecule ThO. For the operators in Eq. (1), the ThO measurement [68,69] can be interpreted as a probe of the electron EDM, with a small theoretical uncertainty [70,71]. In contrast, nucleon, nuclear, and diamagnetic EDMs receive contributions from several operators, with varying levels of theoretical uncertainties. We provide the full expressions in Ref. [72] (including Refs. [73–91]).

Matrix elements connecting quark EDMs to nucleon EDMs are relatively well known [73], but contributions from quark CEDMs and the Weinberg operator suffer from larger uncertainties. In addition to nucleon EDMs, nuclear

TABLE I. Current limits on the electron [68], neutron [54,55], mercury [92,93], xenon [94,95], and radium [96,97] EDMs in units of e cm (90% C.L.). The result for the CP asymmetry, $A_{B\to X_s\gamma} = 0.015(20)$, is taken from Refs. [98–100].

d_e	d_n	$d_{\rm Hg}$	$d_{\rm Xe}$	$d_{\rm Ra}$
1.1×10^{-29}	3.0×10^{-26}	6.2×10^{-30}	3.9×10^{-27}	1.2×10^{-23}

TABLE II. Central and Rfit low-energy constraints (at 95% C.L.), assuming one of the couplings, C_α, is present at the scale $\Lambda = 1$ TeV. For comparison, we show current collider limits from Refs. [33,34] (for $C_{\varphi\tilde{B}}$), Refs. [35,107] (for $C_{\varphi\tilde{W}B}$ and $C_{\tilde{W}}$), and Ref. [30] (for all other couplings).

	Central	Rfit	LHC
$v^2C_{\varphi\tilde{B}}$	$[-5.1,5.1]\times10^{-6}$	$[-5.1,5.1]\times10^{-6}$	$[-28,10]$
$v^2C_{\varphi\tilde{W}}$	$[-4.7,4.7]\times10^{-6}$	$[-4.7,4.7]\times10^{-6}$	$[-2.3,0.43]$
$v^2C_{\varphi\tilde{W}B}$	$[-2.2,2.2]\times10^{-6}$	$[-2.2,2.2]\times10^{-6}$	$[-0.57,0.57]$
$v^2C_{\varphi\tilde{G}}$	$[-5.3,5.3]\times10^{-5}$	$[-1.2,1.2]\times10^{-3}$	$[-1.3,8.1]\times10^{-3}$
$v^2C_{\tilde{G}}$	$[-2.4,2.4]\times10^{-6}$	$[-3.4,3.4]\times10^{-5}$	$\cdots$
$v^2C_{\tilde{W}}$	$[-4.8,4.8]\times10^{-5}$	$[-4.8,4.8]\times10^{-5}$	$[-3.1,3.1]\times10^{-2}$

and diamagnetic EDMs are generated by CP-odd nuclear forces that, for the operators under consideration, are dominated by CP-odd one-pion exchange between nucleons. The sizes of the associated low-energy constants have been calculated with QCD sum rules [80], with $\mathcal{O}(100\%)$ hadronic uncertainty. In addition, the nuclear many-body matrix elements that determine diamagnetic EDMs involve sizable nuclear uncertainties.

Current experimental limits are summarized in Table I, which also shows the limits on systems that are not yet competitive but could provide interesting constraints in the future. EDM experiments on ^{225}Ra and ^{129}Xe atoms have already provided limits [94–96] and are quickly improving. Plans exist to measure the EDMs of charged nuclei such as the proton and deuteron in electromagnetic storage rings [101]. The EDM measurements of light nuclei can be more reliably interpreted in terms of BSM operators than is the case for $d_{\rm Hg}$, as the nuclear theory is under solid theoretical control [81,102].

The operators $O_{\tilde{W}}$ and $O_{\varphi\tilde{W}B}$ contribute to the CP asymmetry in $B\to X_s\gamma$ and to CP-odd triple-gauge couplings that were probed at LEP. Concerning the $B\to X_s\gamma$ asymmetry, we employ the expressions derived in Ref. [91] and take the required SM Wilson coefficients, as well as the hadronic parameters, from the same work. The triple-gauge vertices induced by $O_{\tilde{W}}$ and $O_{\varphi\tilde{W}B}$ are of the form $W^+W^-\gamma$ and W^+W^-Z, which were constrained using angular distributions in $e^+e^-\to W^+W^-$ [103,104]. In the notation of Ref. [105], we have $\tilde{\lambda}_Z = \tilde{\lambda}_\gamma = -2m_W^2 C_{\tilde{W}}$ and $\tilde{\kappa}_Z = -t_w^2\tilde{\kappa}_\gamma = 4t_w^2 m_W^2 C_{\varphi\tilde{W}B}$, $t_w = \tan\theta_w$, which leads to [106]

$$v^2C_{\varphi\tilde{W}B} = -0.93^{+0.47}_{-0.31}, \qquad v^2C_{\tilde{W}} = 0.42(33). \tag{2}$$

As shown in Table II, these constraints have already been improved by the study of the W^+W^- cross section at the LHC [107] and are likely to improve further in the context of EWPTs anticipated at the HL-LHC [42–44].

Analysis.—To constrain the Higgs-gauge operators, we use EDM limits and the CP asymmetry in $B\to X_s\gamma$ as listed in Table I, as well as the LEP constraints on triple-gauge couplings given in Eq. (2). Nuclear and hadronic EDMs as well as the CP asymmetry are affected by significant theoretical uncertainties. We follow Ref. [23] and present limits in a variety of cases: (i) the "central" scenario, in which we neglect all hadronic and nuclear uncertainties, (ii) the "Rfit" strategy, in which all hadronic and nuclear matrix elements are varied within their allowed ranges to minimize the χ^2 value, and (iii) the "Gaussian" strategy, in which the theoretical errors are treated in the same way as statistical errors are. This last strategy provides a realistic estimate of the impact of the theoretical errors when these are under control. We start by discussing the limits derived in the central case, which reflects the maximal constraining power of the low-energy measurements, assuming a single operator is present at the scale $\mu = \Lambda$. We subsequently consider the impact of the theoretical uncertainties in the Rfit scenario, as well as a scenario in which multiple Higgs-gauge operators appear at the scale Λ.

Turning on a single operator at the scale Λ, we see from Table II that the low-energy limits are very stringent. The bounds on the operators with EW gauge bosons are dominated by the electron EDM, which constrains $v^2C_{\varphi\tilde{W},\varphi\tilde{B},\varphi\tilde{W}B,\tilde{W}}$ to be $\mathcal{O}(10^{-6})$, corresponding to a BSM scale of ~100 TeV, assuming $C_i = 1/\Lambda^2$, or 10 TeV, including a loop factor, $C_i = 1/(4\pi\Lambda)^2$. The constraints from the neutron and ^{199}Hg EDMs are weaker, at the permille level for $v^2C_{\varphi\tilde{W}}$ and $v^2C_{\varphi\tilde{W}B}$ and at the percent level for $v^2C_{\varphi\tilde{B},\tilde{W}}$. The bounds on $C_{\varphi\tilde{G}}$ and $C_{\tilde{G}}$ are dominated by the mercury EDM in the central case. For both operators, the large uncertainties on the matrix element of the Weinberg operator imply that the constraints weaken by an order of magnitude and become dominated by the neutron EDM when moving from the central to the Rfit strategy. In contrast, the limits on the EW operators are very similar when using the Rfit strategy, as they are dominated by the ThO measurement. The fourth column in Table II shows the current collider limits for comparison [Here we considered only limits arising from genuine dimension-six contributions to CP-violating observables (more information on the CMS limits [33,34] is provided in Ref. [108]). Constraints on $v^2C_{\tilde{G}}$ stemming from dimension-eight contributions to jet cross sections were considered in Ref. [36] and estimated to be $\mathcal{O}(10^{-2})$]. These high-energy probes are less sensitive by 4–6 orders of magnitude for most of the couplings, while they are competitive with the EDM constraints on $v^2 C_{\varphi\tilde{G}}$ in the Rfit approach.

To see the effects of turning on multiple operators at the scale Λ, we investigate a scenario in which all Higgs-gauge couplings are present at $\mu = \Lambda$, while keeping $C_{\tilde{G},\tilde{W}}(\Lambda) = 0$. This allows us to directly compare the low-energy limits to those of Ref. [30]. In this case, there is one free direction left unconstrained by EDM measurements, even when neglecting theoretical uncertainties. For our choice of $\mu_0 = 1$ TeV, this combination of couplings is given by $\sim 0.17 C_{\varphi\tilde{B}} + 0.86 C_{\varphi\tilde{W}} + 0.48 C_{\varphi\tilde{W}B}$. EDM measurements are not sufficient to constrain all four dimension-six operators simultaneously, and the *CP* asymmetry in $B \to X_s\gamma$ and LEP observables are needed to close the free direction. When treating the theoretical uncertainties in the Rfit or Gaussian approach, the constraints from d_{Hg} and d_n are degenerate, leading to another free direction. These free directions can be closed by reducing the errors on the theoretical predictions of matrix elements or by considering improved constraints on the EDMs in Table I and bounds on the EDMs of additional systems, such as the proton or deuteron. Improvements on these three fronts are expected on the same timescale as the LHC run III and the HL-LHC, for which the limits in Ref. [30] were derived.

We therefore consider improved determinations of the matrix elements that were set as targets for the future in Ref. [21]. We assign 25% uncertainties to the nucleon EDM induced by the *u*- and *d*-quark CEDMs and 50% uncertainties on the nucleon EDM from $C_{\tilde{G}}$, the *CP*-odd pion-nucleon couplings, and the nuclear structure matrix elements. These uncertainty goals are by no means unrealistic considering recent lattice and nuclear-theory efforts [109–112] and in some cases have already been attained [90]. On the experimental side, we assume $|d_n| < 1.0 \times 10^{-27}$ e cm, which will be probed at the PSI and LANL neutron EDM experiments [113,114], and $|d_{\mathrm{Ra}}| < 10^{-27}$ e cm, well within reach of the Argonne National Laboratory radium EDM experiment [97]. On a longer timescale, storage ring searches of the EDMs of light ions have the potential to compete with the neutron EDM [101], and we assume d_p, $d_d < 1.0 \times 10^{-27}$ e cm. For the *CP* asymmetry in $B \to X_s\gamma$, Belle II will be sensitive to subpercent values, $|A_{B\to X_s\gamma}| < 4 \times 10^{-3}$ [115].

A comparison of the projected limits of Ref. [30] to the combination of future EDM and $B \to X_s\gamma$ limits in the $C_{\varphi\tilde{W}}$–$C_{\varphi\tilde{G}}$ and $C_{\varphi\tilde{W}}$–$C_{\varphi\tilde{B}}$ planes is shown in Fig. 2 and in Table III. The nonzero central values for the low-energy curves are driven by the LEP bound (2) on $C_{\varphi\tilde{W}B}$, which deviates from zero by $\sim 2\sigma$. The gray, orange, and purple bands assume the proposed differential measurements in $pp \to h + 2j$ have been performed on 36, 300, and 3000 fb^{-1} of integrated luminosity, respectively, while the red band shows the limits from low-energy experiments. The figure shows that the collider observables could, in principle, probe the $C_{\varphi\tilde{W}}$ and $C_{\varphi\tilde{B}}$ couplings at a comparable level as the low-energy limits with 36 and 3000 fb^{-1} of data, respectively, but become relevant only when delicate cancellations between different couplings occur. The low-energy constraints on the gluonic operator $C_{\varphi\tilde{G}}$ are expected to be more stringent than the projected limits from the HL-LHC by roughly 2 orders of magnitude; see Table III.

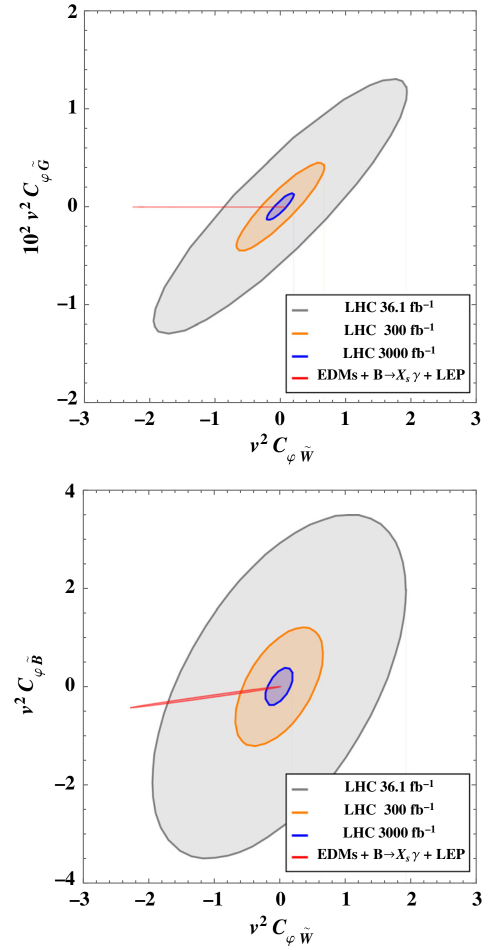

FIG. 2. Projected 95% C.L. constraints from EDM and $B \to X_s\gamma$ as well as collider signatures [30] in the $C_{\varphi\tilde{W}}$–$C_{\varphi\tilde{G}}$ and $C_{\varphi\tilde{W}}$–$C_{\varphi\tilde{B}}$ planes. The remaining couplings are marginalized over, and the Gaussian strategy for the matrix elements is used.

The strong constraints that EDM experiments put on the parameter space will manifest themselves in correlations between observables at the LHC. For example, the electron EDM bound establishes correlations between $C_{\varphi\tilde{W}B}$, $C_{\varphi\tilde{W}}$, and $C_{\varphi\tilde{B}}$, as can be seen from the lower panel in Fig. 2. An observation of large *CP* violation in the Higgs-gauge sector, of the size of the right column in Table III, would then require a nonzero value for $C_{\varphi\tilde{W}B}$. In such a scenario, one would therefore expect large effects in diboson production, induced by $C_{\varphi\tilde{W}B}$, to be consistent with EDM experiments.

TABLE III. Comparison of projected collider and low-energy limits. The LHC limits were taken from Ref. [30], while the low-energy limits assume improved matrix elements and future EDM measurements as described in the text. All four couplings were turned on at the scale $\Lambda = 1$ TeV, and the low-energy limits were obtained using the Gaussian strategy for the theoretical uncertainties.

	Low energy	LHC (3000 fb^{-1})
$v^2 C_{\varphi\tilde{B}}$	$[-0.4, 0.00]$	$[-0.3, 0.3]$
$v^2 C_{\varphi\tilde{W}}$	$[-2.3, 0.02]$	$[-0.17, 0.17]$
$v^2 C_{\varphi\tilde{W}B}$	$[-1.3, 0.01]$	$[-0.39, 0.39]$
$v^2 C_{\varphi\tilde{G}}$	$[-1.3, 1.3] \times 10^{-5}$	$[-9.0, 9.0] \times 10^{-4}$

We can finally relax the assumption $C_{\tilde{W},\tilde{G}}(\Lambda) = 0$ and consider all the *CP*-violating operators expected in the framework of universal theories. As argued above, the dominant EDM constraints are sensitive only to two linear combinations of the weak couplings $C_{\varphi\tilde{B}}$, $C_{\varphi\tilde{W}}$, $C_{\varphi\tilde{W}B}$, and $C_{\tilde{W}}$, so that EDM experiments could, in total, provide four independent constraints on the six operators in Eq. (1). One possible strategy to close the open directions in parameter space relies on the *CP* asymmetry in $B \to X_s\gamma$ and/or LEP observables, but, of course, complementary LHC measurements would also provide the remaining two constraints. In either case, one again expects strong correlations between *CP*-violating observables in the Higgs and weak boson sectors, which illustrates the enormous potential of the low-energy probes in constraining the *CP*-odd sector of universal theories.

Conclusions.—In this Letter, we have analyzed the complementarity of LHC searches and low-energy experiments in constraining or discovering *CP* violation in Higgs-gauge interactions, in the context of universal theories. In particular, we studied *quantitatively* the impact of EDMs on the allowed parameter space. Our work shows that, despite the loop suppression, EDMs cannot be neglected (as in recent LHC analyses)—in fact, in a single-operator analysis, there is very little room for observing *CP* violation in the Higgs sector at the LHC. In a global analysis, flat or weakly bound directions from low-energy constraints are still possible, defining which additional operator combinations are most useful to be constrained by the (HL-)LHC, via the observables considered in Refs. [30,33–35] and, potentially, EWPTs. Several lessons from our analysis extend beyond universal theories, where more *CP*-violating effective couplings appear. In this case, EDMs enforce strong correlations among Higgs-gauge and other *CP*-violating couplings, which require either intricate cancellations and therefore insight on the new sources of *CP* violation or strong bounds on all the individual couplings.

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