Is there room for CP violation in the top-Higgs sector?

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We discuss direct and indirect probes of chirality-flipping couplings of the top quark to Higgs and gauge bosons, considering both CP-conserving and CP-violating observables, in the framework of the Standard Model effective field theory. In our analysis we include current and prospective constraints from collider physics, precision electroweak tests, flavor physics, and electric dipole moments (EDMs). We find that low-energy indirect probes are very competitive, even after accounting for long-distance uncertainties. In particular, EDMs put constraints on the electroweak CP-violating dipole moments of the top that are two to three orders of magnitude stronger than existing limits. The new indirect constraint on the top EDM is given by $|d_t| < 6 \cdot 10^{-20}$ e cm at 90% C.L.

Introduction: The top quark might offer a first gateway to new physics beyond the Standard Model (BSM), due to its large coupling to the Higgs and hence to the electroweak symmetry breaking sector. In fact, in several scenarios, ranging from partial compositeness [1] to supersymmetric models with light stops relevant for electroweak baryogenesis [2], enhanced deviations from the SM are expected in the top sector. Experiments at the Large Hadron Collider (LHC) offer a great opportunity to directly probe non-standard top quark couplings. On the other hand, these same couplings also affect via quantum corrections processes that do not involve a top quark. Such “indirect probes” give very valuable complementary information and in several cases constrain non-standard top couplings more strongly than direct searches.

In this letter we discuss direct and indirect probes of chirality-flipping top-Higgs couplings, including both CP-conserving (CPC) and CP-violating (CPV) interactions, the latter being of great interest in light of Sakharov’s conditions for baryogenesis [3].

Despite the vast literature on top-gluon [4–15], top-photon [16–20], top-W [21–25], top Yukawa [26–27] couplings, and global analyses [28–33], the impact of electric dipole moments (EDMs) has received comparatively little attention [16–20, 28–34]. The central new element of our work is the systematic inclusion of EDM constraints. Even after properly taking into account the hadronic and nuclear uncertainties [34], EDMs dominate the bounds on all the CPV top couplings. Our major new finding is that bounds on the top EDM (weak EDM) are improved by three (two) orders of magnitude over the previous literature. As part of our analysis, we also update indirect constraints from Higgs production and decay.

We work in the linear SM Effective Field Theory (SM-EFT) framework [35–39]. We assume that there is a gap between the scale of new physics $\Lambda$ and the electroweak scale $v = 246$ GeV and keep only the leading terms in $(v/\Lambda)^2$, corresponding to dimension-six operators. We assume that at the high-scale $\Lambda$ the largest non-standard effects appear in the top sector, and hence set to zero all other couplings. We then evolve the non-standard top couplings to lower scales through renormalization group flow and heavy SM particle thresholds. The evolution induces operators that impact a number of high-energy and low-energy phenomena, thus leading to constraints on non-standard top-Higgs couplings at the scale $\Lambda$.

Operator structure and mixing pattern: In this letter we study chirality-flipping couplings of the top quark to Higgs and gauge bosons, leaving the analysis of chirality preserving $LL$ and $RR$ structures to future work. At dimension six, five structures arise: non-standard Yukawa (1), Gluon dipole (1), Electric dipole (1), and Weak dipoles (2). The starting effective Lagrangian of chirality-flipping top-Higgs couplings, including both CP-conserving and CP-violating observables, in the framework of the Standard Model effective field theory (SM-EFT) framework is

$$\mathcal{L}_{\text{eff}}^{\text{BSM}} = \sum_{\alpha \in \{Y, g, \gamma, W_L, W_R\}} C_\alpha O_\alpha + \text{h.c.}$$

with complex couplings $C_\alpha = c_\alpha + i \tilde{c}_\alpha$ and

$$O_Y = -m_t \tilde{t}_L t_R \left( v h + \frac{3}{2} h^2 + \frac{1}{2} h^3 v^2 \right)$$

$$O_\gamma = -\frac{e Q_t}{2} m_t \tilde{t}_L \sigma_{\mu\nu} (F^{\mu\nu} - t_W Z^{\mu\nu}) t_R \left( 1 + \frac{h}{v} \right)$$

$$O_g = -\frac{g_s}{2} m_t \tilde{t}_L \sigma_{\mu\nu} G^{\mu\nu} t_R \left( 1 + \frac{h}{v} \right)$$

$$O_{W_L} = -g m_t \left[ \frac{1}{\sqrt{2}} \tilde{W}_L \sigma^{\mu\nu} t_R W^-_{\mu\nu} + \tilde{t}_L \sigma_{\mu\nu} t_R \left( \frac{1}{2c_W} Z^{\mu\nu} + ig W_{\mu}^- W^+_{\nu} \right) \right] \left( 1 + \frac{h}{v} \right)$$

$$O_{W_R} = -g m_b \left[ \frac{1}{\sqrt{2}} \tilde{W}_R \sigma^{\mu\nu} b_R W^+_{\mu\nu} - \tilde{b}_L \sigma^{\mu\nu} b_R \left( \frac{1}{2c_W} Z^{\mu\nu} + ig W_{\nu}^- W^+_{\mu} \right) \right] \left( 1 + \frac{h}{v} \right),$$

where $Q_t = 2/3$, $t_W = \tan \theta_W$, $c_W = \cos \theta_W$, $b' = V_{tb} + V_{ts} + V_{td}$, and $t' = V_{tb}^* + V_{ts}^* c + V_{td}^* u$. Our operators retain the full constraints of gauge invariance as they
are linear combinations of the explicitly $SU(2) \times U(1)$-invariant operators of Refs. [35, 36], expressed in the unitary gauge. The correspondence to the standard basis is provided in Table I. The couplings $C_{\alpha}$ have mass dimension $[-2]$ and are related to properties of the top quark, such as the electric and magnetic dipole moments ($d_t = (em_t Q_t) c_t$ and $\mu_t = (em_t Q_t) c_t$), their non-abelian gluonic counterparts ($d_t = m_t \tilde{c}_t$ and $\mu_t = m_t \tilde{c}_t$), and the Higgs-top, W-top, and Z-top couplings.

To constrain $c_{\alpha}$ and $\tilde{c}_{\alpha}$ we use both direct and indirect probes. Direct probes involve top quark production (single top, $t\bar{t}$, and $t\bar{t}h$) and decay (W-helicity fractions, lepton angular distributions) at colliders. We include CP effects in the angular distributions of the decay products of a single top [10], while we neglect CPV observables in $t\bar{t}$ and $t\bar{t}h$ production/decay [11] as these are not yet competitive. Indirect probes involve top quarks in quantum loops, affecting both high-energy (Higgs production and decay, precision electroweak tests) and low-energy observables ($b \rightarrow s\gamma$ and EDMs).

Indirect constraints rely on operator-mixing via renormalization group (RG) flow and on threshold corrections arising from integrating out heavy SM particles ($t$, $h$, $W$, $Z$). In Table II we summarize the operators that are generated from Eq. (4) to leading order in the strong, electroweak, and Yukawa couplings. In this extended basis we include only those structures that contribute to high-sensitivity observables, to be used to put strong constraints on the top couplings. These include the light quark electromagnetic and gluonic dipoles (flavor diagonal and the off-diagonal entries relevant to $b \rightarrow s\gamma$), the Weinberg three-gluon operator, and operators mediating non-standard interactions of the Higgs to gauge bosons.

There are several paths to connect the high-scale Wilson coefficients in [11] to the operators in Table II and low-energy observables. These paths are determined by the RG equations

$$\frac{dC_i}{d\ln \mu} = \sum_j \gamma_{j \rightarrow i} C_j \ , \quad (3)$$

and possibly threshold corrections. In Table III we provide a synopsis of the induced low-scale couplings (left column) and the observables they contribute to (right column). Several of these paths have already been analyzed in the literature. Here we briefly recall the dominant paths for each operator, paying special attention to a novel two-step path that connects the top EDM and W-EDMs ($\tilde{c}_t$ and $\tilde{c}_{Wt}$) to low energy. A detailed analysis will be presented in a companion paper [50].

There are three paths that can be used to constrain the top electromagnetic dipole coupling $C_\gamma$ through indirect measurements. First, $C_\gamma$ induces down-type EDMs ($C_\gamma \rightarrow C_{\gamma(d,s)}$) via a flavor-changing W loop, suppressed by the CKM factor $|V_{td,ts}|^2$. Similar one-loop diagrams induce $b \rightarrow s\gamma$ dipole operators $C_{\tilde{c}_t}$ and $C_{\tilde{c}_{Wt}}$. Next, at one loop $C_\gamma$ induces the top gluonic dipole $C_{g_\gamma}$, which in turn at the top threshold generates the three-gluon Weinberg coupling $C_{\tilde{g}_G}$. Finally, there is a new two-step path: first $C_{g_\gamma}$ induces the anomalous couplings of the Higgs to electroweak bosons, namely $C_{\phi_{W}\phi_{B},\phi_{WB}}$ and $C_{\phi_{W},\phi_{B},\phi_{WB}}$ (see top diagrams in Fig. 1). These couplings in turn mix at one loop (see bottom diagrams in Fig. 1) into the electromagnetic dipoles $C_{\gamma(f)}$ ($f = e, u, d, s$) [53, 54]. The relevant anomalous dimensions are

$$\gamma_{C_\gamma \rightarrow C_{\phi_{W},\phi_{B},\phi_{WB}}} = \frac{N_C Q_t m_t^2}{16\pi^2 \alpha} \left\{ 1 - 4Q_t, 0, 1 \right\} \ , \quad (4)$$

$$\gamma_{(C_{\phi_{W},\phi_{B},\phi_{WB}}) \rightarrow \tilde{c}_{\gamma}(f)} = \frac{\alpha}{\pi Q_f s_W^2} \times \left\{ 2T_W^2(T_f^3 - 2Q_f), -2T_f^3, 1 + (8Q_t - 1)T_W^2 \right\} \ , \quad (5)$$

This new “two-step” path leads to light fermion EDMs. For the electron, the approximate solution of (5) reads

$$\tilde{c}_{\gamma}(e) \approx \frac{3N_C Q_t \alpha m_t^2}{64\pi^3 s_W^2 v^5} \left[ 1 + (8Q_t - 1)T_W^2 \right] \left( \log \frac{\Lambda}{m_t} \right)^2 \ , \quad (6)$$

implying $\tilde{c}_{\gamma}(e) / c_{\gamma} \sim 3 \times 10^{-4}$ for $\Lambda = 1$ TeV and thus $|d_e| / c_{\gamma} \sim |C_{\gamma}| \cdot 5 \cdot 10^{-26}$ e cm. While this simple estimate already shows the power of this new path ($|d_e| < 10^{-26}$ e cm).
We use the notation \( \tilde{\text{interactions}} \) in Eq. (1) via RG flow and threshold corrections.

### TABLE II: Dimension-six operators induced by the top-Higgs interactions in Eq. (1)

The weak dipole \( C_{Wt} \) has a mixing pattern similar to \( C_\gamma \). At one loop it generates both top and light quark EDMs, as well as the top chromo-EDM (\( C_g \)). However, the strongest constraints arise again from the two-step path: \( C_{Wt} \rightarrow C_{Wt,Wb,WB} \rightarrow C_{\gamma} \) (\( f = e, u, d, s \)). For \( C_{Wb} \) this path is suppressed by the bottom Yukawa. So the main contribution of \( C_{Wb} \) to EDMs arises from mixing with the \( b \) chromo-EDM, which induces the Weinberg three-gluon operator \( O_{\tilde{G}} \) at the \( m_b \) threshold.

The gluonic dipole coupling \( C_g \) mixes at one loop with the top electromagnetic dipole \( C_\gamma \), the non-standard Yukawa \( C_Y \), and non-standard Higgs-gluon couplings \( C_{\gamma G,GG} \).\footnote{\cite{[54, 57]}} Moreover, at the top threshold \( C_g \) induces the Weinberg three-gluon operator.

Finally, the non-standard top Yukawa coupling \( C_Y \) has no anomalous mixing but it contributes to \( C_g \) all the couplings of the extended effective Lagrangian at lower scale through finite threshold corrections from one-loop diagrams and two-loop Barr-Zee diagrams\footnote{\cite{[60, 65]}}.

### Current and prospective bounds:

As becomes clear from Table II, the high scale top-Higgs couplings can be constrained by a number of CP-even and CP-odd observables. A detailed description of the experimental and theoretical input, as well as the chi-squared function and the treatment of theoretical uncertainties will be presented in Ref. [59]. Here we simply highlight the main features of our analysis: (i) For each observable, we include only contributions linear in the new physics couplings \( C_\alpha \), neglecting quadratic terms that are of higher order in the SM-EFT expansion. We express all the bounds in terms of \( C_\alpha (\Lambda = 1 \text{ TeV}) \). (ii) For low-energy probes (\( b \rightarrow s^+ \))\footnote{\cite{[67, 70]}} and EDMs\footnote{\cite{[54, 71, 72]}} we treat the significant hadronic and nuclear theoretical uncertainties according to the “range-fit” method\footnote{\cite{[73]}} in which the total chi-squared is minimized with respect to the matrix elements (varied in their allowed theoretical range). This procedure allows for cancellations between different contributions to a given observable and thus gives the most conservative bounds on BSM couplings\footnote{\cite{[54]}}. (iii) We use experimental input on top processes at Tevatron\footnote{\cite{[74]}} and the LHC\footnote{\cite{[75, 76, 77]}}, on Higgs production/decay signal strengths\footnote{\cite{[83, 84]}}, on EDMs\footnote{\cite{[55, 88–92]}}; and finally, on neutron,\footnote{\cite{[199, 129, Xe, 225, Ra]}} and electron EDMs\footnote{\cite{[55, 88, 92]}}.

We first focus on the case in which a single operator structure dominates at the high scale, keeping both real (\( c_\alpha \)) and imaginary (\( \tilde{c}_\alpha \)) parts for each coupling. In Figs. 2 and 3 we present the 90% CL bounds on the planes \( v^2 c_\alpha - v^2 \tilde{c}_\alpha \), for the five couplings of Eq. (1). In each case we show the individual most constraining bounds and the combined allowed region. For \( c_\gamma \), \( C_{Wb}, C_{Wt}, C_Y \), and \( c_g \) (direct bounds), our results are compatible with the existing literature. The following features emerge from the plots: (i) Indirect probes are currently more constraining than direct ones, with the exception of \( C_{Wb} \), for which the bound from W helicity fractions in \( t \rightarrow Wb \) competes with \( b \rightarrow s^+ \). In particular, the bound on \( c_g \) from Higgs production is a factor of 5 stronger than the direct bound from \( t\bar{t} \). (ii) EDMs, despite the conservative nature of the range-fit procedure, strongly constrain the CPV couplings, with the electron EDM dominating the bound on \( c_\gamma \) and \( C_{Wb} \), and \( C_Y \) and the neutron EDM leading to the best bound on \( c_g \). In particular EDMs lead to a three (two) orders of magnitude improvement in the bounds on \( c_\gamma \) (\( C_{Wb} \)), see Fig. 2 and a significant one (factor of 5) in \( C_{Wb} \), see Fig. 3. The new bounds on \( c_\gamma \) and \( C_{Wb} \) lie well below the prospected sensitivities of the LHC\footnote{\cite{[17, 20, 25]}} and envisioned\footnote{\cite{[19, 20]}} collider experiments. Note that even for vanishing electron Yukawa coupling the strong bounds from the electron EDM survive, thanks to the WW diagrams in Fig. 1.
In Figs. 2 and 3 we also present projected combined sensitivities for the new physics couplings. These are based on expected improvements in collider searches [33, 34], super-B factory measurements [93, 94], and EDMs experimental sensitivities [97] (one order of magnitude for the electron and two for the neutron).

**Discussion:** The overarching message emerging from our single-operator analysis is that the CPV couplings are very tightly constrained, and out of reach of direct collider searches. A legitimate question is then: how robust are these bounds? One might wonder about the possibility of cancellations due to the new physics simultaneously generating several operators at the scale \( \Lambda \), not necessarily involving top and Higgs fields. In this general case our results can be re-interpreted as a strong correlation between the various couplings: for example a large top EDM \( (\tilde{c}_t) \) is compatible with non-observation of ThO EDM if an electron EDM \( (d_e) \) is also generated at the scale \( \Lambda \), with the right size to cancel the RG effect from \( \tilde{c}_t \), at the level of a few parts in a thousand. This would still be a very powerful constraint on the underlying dynamics and it is just another way to say that the results of our analysis are “naturalness” bounds. Another possibility is that new physics generates all the couplings of Eq. (1) at the matching scale \( \Lambda \). In this case we can quantify the effect of cancellations by performing a global analysis with five free CPV couplings \( \tilde{c}_a(\Lambda) \). We find that with current experimental input, the result depends on how one handles theoretical uncertainties. Fixing the hadronic and nuclear matrix elements to their central values, thanks to the interplay of collider, flavor, and EDMs, bounds on all five CPV couplings survive: 

\[
-0.07 < v^2\tilde{c}_\gamma < 0.1, \quad -0.02 < v^2\tilde{c}_g < 0.04, \quad -0.2 < v^2\tilde{c}_{Wt} < 0.4, \quad -0.1 < v^2\tilde{c}_{Wb} < 0.3, \quad -0.1 < v^2\tilde{c}_Y < 0.3.
\]

While weaker than the single-operator EDM constraints, in most cases these bounds are still stronger than flavor and collider bounds obtained in the single-operator analysis. On the other hand, using the more conserva-
tive range-fit method, unconstrained directions remain in the five-dimensional parameter space. Looking to the future, we have explored which combination of new measurements and theoretical improvements can remove the unbound directions within the range-fit procedure. On the theory side, the major bottleneck arises from uncertainties in the Schiff moment of $^{199}$Hg and the nucleon EDM induced by the Weinberg operator. On the experimental side, a measurement of the $^{225}$Ra at the level of $10^{-26}$ e cm would remove the unconstrained directions, illustrating the importance of complementary probes.

**Conclusions:** In this letter we have highlighted the impact of indirect probes on chirality-flipping top-Higgs couplings, uncovering the dramatic effect of neutron and atomic/molecular EDMs – they improve the bounds on the top EDM by three orders of magnitude ($|d_t| < 6 \cdot 10^{-20}$ e cm at 90\% C.L.). Our results have implications for baryogenesis mechanisms, collider searches, and flavor physics. They further motivate more sensitive EDM searches and improved lattice QCD and nuclear structure calculations of the effect of CPV operators in EDM searches and improved lattice QCD and nuclear and flavor physics. They further motivate more sensitive EDM searches and improved lattice QCD and nuclear structure calculations of the effect of CPV operators in nucleons and nuclei.

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