Physics Letters B 781 (2018) 492–498

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Top down electroweak dipole operators

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ARTICLE INFO

Article history:
Received 19 November 2017
Received in revised form 6 March 2018
Accepted 11 April 2018
Available online 13 April 2018
Editor: B. Grinstein

ABSTRACT

We derive present constraints on, and prospective sensitivity to, the electric dipole moment (EDM) of the top quark (d_t) implied by searches for the EDMs of the electron and nucleons. Above the electroweak scale v, the d_t arises from two gauge invariant operators generated at a scale $\Lambda \gg v$ that also mix with the light fermion EDMs under renormalization group evolution at two-loop order. Bounds on the EDMs of first generation fermion systems thus imply bounds on $|d_t|$. Working in the leading log-squared approximation, we find that the present upper bound on $|d_t|$ is 10^{-19} e cm for $\Lambda = 1$ TeV, except in regions of finely tuned cancellations that allow for $|d_t|$ to be up to fifty times larger. Future d_e and d_n probes may yield an order of magnitude increase in d_t sensitivity, while inclusion of a prospective proton EDM search may lead to an additional increase in reach.

1. Introduction

The search for physics beyond the Standard Model (BSM) lies at the forefront of both high- and low-energy physics. The properties of the top quark constitute a particularly interesting meeting ground for the two regimes. Theoretically, top quarks may provide a unique window into BSM physics, given that the top Yukawa coupling is large compared to all other Standard Model (SM) fermions. Experimentally, top quarks can be copiously produced in high energy proton–proton collisions, while their indirect effects – generated via quantum loops – can be pronounced. Indeed, the breaking of custodial SU(2) symmetry by the top quark-bottom quark mass splitting has a significant impact on the interpretation of electroweak precision tests at the loop level. This sensitivity provided an early handle on the value of the top quark mass and, after the discovery of the top quark, an important test of the self-consistency of the SM at the level of quantum corrections.

The CP property of top quark interactions is a topic of on-going interest. In the context of electroweak baryogenesis (EWBG) [1], CP-violating (CPV) interactions of the top quark with an extended scalar sector can yield the observed cosmic baryon asymmetry [2–7]. The presence of BSM CPV in the top quark sector may also appear in the guise of a top electric dipole moments (EDM) and chromo-electric dipole moment (CEDM), two of a number of possible higher dimension top quark operators. Since the top (C)EDM is chirality changing, it can be significantly enhanced compared to light fermion (C)EDMs by the large top Yukawa coupling.

While direct collider probes of the (C)EDM have been studied extensively [8–27], a complementary way to access the top EDM (d_t) and CEDM ($\tilde{d}_t$) is through their indirect effects, such as the resulting, radiatively-induced light fermion EDMs. This possibility has been explored in several studies [28–31]. The most powerful limit on d_t appears to result from the limit on the EDM of the electron $|d_e| < 8.7 \times 10^{-29}$ e cm (90% C.L.) [32] (see also the recent result using HfF$^+$, $|d_e| < 1.3 \times 10^{-28}$ e cm (90% C.L.) [33]), implying $|d_t| < 5.0 \times 10^{-20}$ e cm (90% C.L.) [30,31].

In this study, we focus on d_t. If it is generated by BSM physics at a scale Λ that lies well above the electroweak scale $v = 246$ GeV, then it is likely that two dimension-six CPV dipole operators emerge, coupling respectively to the $U(1)_Y$ and $SU(2)_L$ gauge bosons. We henceforth denote these operators as $\mathcal{O}_{tB}$ and $\mathcal{O}_{tW}$, respectively. Denoting their coefficients as $C_{tB(W)}/\Lambda^2$, we note that the presence of CPV implies that the dimensionless Wilson coefficients $C_{tB(W)}$ are, in general, complex. After electroweak symmetry breaking (EWSB), one linear combination yields d_t at tree-level. The operators $\mathcal{O}_{tB}$ and $\mathcal{O}_{tW}$ will also radiatively generate all other light fermion EDMs at two-loop order. Bounds on d_e as well as on the neutron EDM, d_n, then yield (in principle) complementary constraints on $C_{tB(W)}$, with corresponding implications for d_t.

In what follows, we perform an explicit two-loop computation of the light fermion EDMs induced by $\mathcal{O}_{tB(W)}$, retaining the leading $\ln^2(\Lambda/v)$ contributions. After translating the light quark EDMs into d_n, we derive constraints on the $C_{tB(W)}/\Lambda^2$, along with the corre-

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https://doi.org/10.1016/j.physletb.2018.04.022
0370-2693/

sponding implications for d_t, using the present neutron and electron EDM bounds. We will make no *a priori* assumptions about the relationships between the C_{tB} and C_{tW} at the scale Λ, endeavoring to be as model-independent as possible. In these respects, our analysis complements the earlier studies in Refs. [28–31]. In this context, we also find that there exist regions where cancellations between these two operators can considerably weaken the generic constraints, albeit with some degree of fine-tuning. Looking ahead, we illustrate the potential reach of next generation electron and nucleon EDM searches.

2. Effective operators

To set the conventions for our analysis, we start with the CPV effective Lagrangian generated by BSM physics at the scale Λ [30,31]:

$$\mathcal{L}_{\rm eff} = -\frac{1}{\Lambda^2}\sum_{f=e,u,d,t}\left(\frac{g_1}{\sqrt{2}}C_{fB}\mathcal{O}_{fB} + \frac{g_2}{\sqrt{2}}C_{fW}\mathcal{O}_{fW} + \text{h.c.}\right) + \frac{1}{\Lambda^2}\sum_{X=B,W}C_{H\tilde{X}}\mathcal{O}_{H\tilde{X}} + \frac{1}{\Lambda^2}\sum_{F=L,Q,f=e,d,t}\left(C^{(i)}_{FfF'f'}\mathcal{O}^{(i)}_{FfF'f'} + \text{h.c.}\right), \quad (1)$$

where the first line indicates the dipole operators

$$\begin{aligned}\mathcal{O}_{eB} &= \bar{L}\sigma^{\mu\nu}e_R H B_{\mu\nu},\\ \mathcal{O}_{eW} &= \bar{L}\sigma^{\mu\nu}e_R\tau^A H W^A_{\mu\nu},\\ \mathcal{O}_{tB} &= \bar{Q}\sigma^{\mu\nu}t_R\tilde{H}B_{\mu\nu},\\ \mathcal{O}_{tW} &= \bar{Q}\sigma^{\mu\nu}t_R\tau^A\tilde{H}W^A_{\mu\nu}.\end{aligned} \quad (2)$$

The second and third lines represent gauge-Higgs and 4-fermi operators

$$\begin{aligned}\mathcal{O}_{H\tilde{B}} &= g_1^2 H^\dagger H\tilde{B}_{\mu\nu}B^{\mu\nu},\\ \mathcal{O}_{H\tilde{W}} &= g_2^2 H^\dagger H\tilde{W}^A_{\mu\nu}W^{A\mu\nu},\\ \mathcal{O}_{H\tilde{W}B} &= g_1 g_2 H^\dagger\tau^A H\tilde{W}^A_{\mu\nu}B^{\mu\nu},\end{aligned} \quad (3)$$

and

$$\begin{aligned}\mathcal{O}^{(3)}_{\ell eqt} &= (\bar{L}^a\sigma^{\mu\nu}e_R)\epsilon_{ab}(\bar{Q}^b\sigma_{\mu\nu}t_R),\\ \mathcal{O}^{(1)}_{qtqd} &= (\bar{Q}^a t_R)\epsilon_{ab}(\bar{Q}^b d_R),\\ \mathcal{O}^{(8)}_{qtqd} &= (\bar{Q}^a\tau^A t_R)\epsilon_{ab}(\bar{Q}^b\tau^A d_R).\end{aligned} \quad (4)$$

Here, L and Q are the lepton and quark doublets, e_R (t_R) is the right-handed electron (top quark), τ^A is the Pauli matrix, and H is the Higgs doublet with $\tilde{H} = i\tau^2 H^*$; $B_{\mu\nu}$ and $W^A_{\mu\nu}$ are the $U(1)_Y$ and $SU(2)_L$ field strengths, respectively; and g_1 and g_2 represent their gauge couplings; $\tilde{X}$ is defined as $\epsilon_{\mu\nu\alpha\beta}X^{\alpha\beta}/2$; a and b are the $SU(2)_L$ indices. The dipole operators for the up (down) quark $\mathcal{O}_{uB,uW}$ ($\mathcal{O}_{dB,dW}$) are also given by the same structure as $\mathcal{O}_{tB,tW}$ ($\mathcal{O}_{eB,eW}$). For a listing of the complete set of dimension-six CPV operators, see, *e.g.*, [34,35]. The operators that we employ here are listed in [35].

After EWSB, the dipole operators in Eq. (1) produce the EDMs

$$\mathcal{L}_{\rm eff} \ni -\frac{i}{2}\sum_{f=e,u,d,t} d_f\bar{f}\sigma^{\mu\nu}\gamma_5 f F_{\mu\nu}, \quad (5)$$

with $F_{\mu\nu}$ being the photon field strength tensor. The coupling d_f is related to the Wilson coefficients of the operators

$$\begin{aligned}d_{e(d)} &= \frac{ev}{\Lambda^2}\left\{\text{Im}(C_{e(d)B}) - \text{Im}(C_{e(d)W})\right\},\\ d_{t(u)} &= \frac{ev}{\Lambda^2}\left\{\text{Im}(C_{t(u)B}) + \text{Im}(C_{t(u)W})\right\}.\end{aligned} \quad (6)$$

The opposite relative sign between the C_{fB} and C_{fW} for up- and down-type fermions is due to their isospin projection quantum numbers. To facilitate comparison with the experimental EDM limits, it is useful to express a factor of ev/Λ^2 with units of fm[1]

$$\frac{ev}{\Lambda^2} = \frac{e}{v}\left(\frac{v}{\Lambda}\right)^2 \simeq (7.8\times 10^{-4}\, e\ \text{fm})\left(\frac{v}{\Lambda}\right)^2. \quad (7)$$

In addition to the bounds on $|d_e|$ quoted above,[2] we consider the constrains implied by the light-quark contributions to d_n,[3] whose experimental limit is $|d_n| < 3.0\times 10^{-26}$ e cm (90% C.L.) [37]. As we discuss below, the d_e-contributions from $\mathcal{O}_{tB}$ and $\mathcal{O}_{tW}$ may cancel in some finely-tuned portions of parameter space. Inclusion of the d_n constraints may provide a complementary probe of this "cancellation region". Outside of this region, present EDM limits imply an upper bound on $|d_t| \lesssim 10^{-19}$ e cm, depending on the value of Λ. Looking to the future, next generation EDM searches may reach the levels of sensitivity: $|d_e| < 1.0\times 10^{-29}$ e cm and $|d_n| < 3.0\times 10^{-28}$ e cm [38], implying an order of magnitude increase in the sensitivity to d_t. In addition, efforts are underway to develop storage ring proton EDM search with sensitivity 10^{-29} e cm [39]. For the scenario considered here, the constraints from diamagnetic atom EDM searches, such as that of the ^{199}Hg atom [40] can be comparable to those from d_n. Although the latest ^{199}Hg result yields an upper bound on $|d_n|$ that is roughly two times stronger than the direct limit, we expect the latter to become considerably more stringent with the next generation experiments. Consequently, we will use the direct d_n bounds in what follows.

3. Loop calculations

The existence of the top quark dipole operators in Eq. (1) at a renormalization scale $\mu = \Lambda$ will lead to non-vanishing electron and light-quark dipole operators through the two-loop Barr-Zee diagrams of Fig. 1. This effect corresponds to the electroweak operator mixing in the renormalization group evolution (RGE) from Λ to v, thereby relating the Wilson coefficients of the electron and light quark dipole operators at the EW scale to $C_{tB}(\Lambda)$ and $C_{tW}(\Lambda)$. Below the scale v, we integrate out the heavy SM degrees of freedom (t, W, Z, and h), and the dominant contributions when running to the low-energy scale relevant to experiment involve $SU(3)_C$ interactions. The upper two diagrams induce the up quark EDM, the lower two diagrams yield the electron and down quark EDMs. This assignment can be understood by considering which Higgs field is chosen as an external particle. Each diagram has two opposite fermion flows (corresponding to distinct Wick contractions), as well as topologies involving crossing of the scalar and gauge boson lines.

In addition to the overall logarithmic divergence associated with these diagrams, logarithmically divergent one-loop subgraphs associated with the upper and lower loops in Fig. 1 correspond to mixing between $\mathcal{O}_{tB,W}$ and $\mathcal{O}_{H\tilde{B},\tilde{W},\tilde{W}B}$ and $\mathcal{O}^{(3,1,8)}_{\ell eqt,qtqd}$,

[1] Since our definitions of the dipole operators are accompanied with a factor of $1/\sqrt{2}$, the coefficient of ev/Λ^2 becomes smaller than that in [36].

[2] The limit is obtained by assuming that the ThO EDM does not receive a contribution from semileptonic four-fermion interactions.

[3] Although the EDM of the strange quark and chromo EDMs also contribute to the neutron EDM, we do not include them, here.