B_s mixing and electric dipole moments in the framework of minimal flavor violation

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(Received 23 July 2010; published 29 September 2010)

We analyze the general structure of four-fermion operators capable of introducing CP violation preferentially in B_s mixing within the framework of minimal flavor violation. The effect requires a minimum of $O(Y_u^4 Y_d^4)$ Yukawa insertions, and at this order we find a total of six operators with different Lorentz, color, and flavor contractions that lead to enhanced B_s mixing. We then estimate the impact of these operators and of their close relatives on the possible sizes of electric dipole moments (EDMs) of neutrons and heavy atoms. We identify two broad classes of such operators: those that give EDMs in the limit of vanishing Cabibbo-Kobayashi-Maskawa angles, and those that require quark mixing for the existence of nonzero EDMs. The natural value for EDMs from the operators in the first category is up to an order of magnitude above the experimental upper bounds, while the second group predicts EDMs well below the current sensitivity level. Finally, we discuss plausible UV completions for each type of operator.

DOI: 10.1103/PhysRevD.82.054033 PACS numbers: 13.25.Hw

I. INTRODUCTION

Studies of the B_d mesons in the last decade [1] have confirmed the economical Cabibbo-Kobayashi-Maskawa (CKM) mechanism of flavor- and CP-violation implicit in the standard model (SM), described entirely by three mixing angles and a single phase. Despite a continuing improvement in precision, a practical question arises as to the best strategy to look for new flavor/CP-violating effects in B systems. One formidable opportunity is presented by the B_s system, where the CP violation due to the SM CKM phase is naturally small, so that a large amount of CP violation would necessarily be attributable to a new physics (NP) source. In other words, CP violation in the B_s system belongs to the same CKM-background-free category of tests as electric dipole moments (EDMs) of neutrons and heavy atoms.

It is therefore intriguing that recent tests of CP violation in the decays of B mesons at the Tevatron experiments show a deviation from the predictions of the SM. Specifically, both the CDF and D0 experiments have reported correlated measurements of the width difference $\Delta\Gamma_s$ and CP-violating phase $\phi_s^{J/\psi\phi}$ from an analysis of the angular distributions of the flavor-tagged decays $B_s^0 \to J/\psi\phi$. Early results [2,3] showed a deviation with the SM at the 2.1σ level [4], while a more recent preliminary measurement [5] is consistent with the SM, albeit still with relatively large error bars. More recently, the D0 Collaboration announced [6] the measurement of the same-sign dimuon asymmetry in B decays:

$$A_{\rm sl}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}} = -(9.57 \pm 2.51 \pm 1.46) \times 10^{-3}, \tag{1}$$

where N_b^{++} is the number of events in which two antimuons are produced from the decays of a B and a $\bar{B}$ meson, i.e. $b\bar{b} \to \mu^+\mu^+ X$. This is to be compared to the SM prediction, $A_{\rm sl}^b({\rm SM}) = (2.3^{+0.5}_{-0.6}) \times 10^4$ [7,8], and thus shows a 3.2σ deviation from the predicted value. Given the tighter constraints in the well-studied B_d system, this measurement therefore also hints at a NP source of CP violation in B_s mixing.[1] Indeed, interpreted at face value, the D0 result [6] implies the presence of a CP-violating part of the B_s-$\bar{B}_s$,

$${\rm Im}\,(\Delta M_{12}) \sim O(|M_{12}^{\rm SM}|) \sim O(10\ {\rm psec}^{-1}). \tag{2}$$

We refer the reader to the detailed numerical fits of the data recently performed in Refs. [9,10]. We focus on NP contributions to ΔM_{12}, but see [11] for a recent analysis of the possible NP contributions to Γ_{12}. Perhaps the ultimate test of CP in B_s systems will be delivered by the LHCb experiment in the near future.

If these recent measurements from the Tevatron experiments are to be ascribed to a NP source of CP violation, a natural question is how such NP contributes to EDMs. On the experimental front, significant progress has been achieved in the measurement of ^{199}Hg EDM, where the upper bound has been improved by a factor of 7 [12],

$$|d_{\rm Hg}| < 3.1 \times 10^{-29}\ e\,{\rm cm}. \tag{3}$$

This considerably tightens all bounds on flavor-conserving hadronic and semileptonic CP-violating operators, and, in

[1]Current data still allow for a sizable $O(20\%)$ NP contribution to CP violation in the B_d system, which may be partially responsible for the recent experimental anomalies. For a detailed discussion of this possibility, see Refs. [9,10].

particular, implies rather strong bounds on the color EDMs of quarks.

In this paper we investigate a possible connection between CP violation in B_s mixing and EDMs within the framework of minimal flavor violation (MFV) [13,14]. This framework assumes that NP, should it induce flavor change, preserves the reparametrization independence of the SM flavor physics. In other words, the flavor transitions are governed by the CKM matrix $V_{\rm CKM}$ and the eigenvalues of the Yukawa couplings, but new CP-violating phases introduced in a flavor-universal way are allowed [15,16]. We identify all $\Delta F = 2$ four-fermion operators leading to the preferential introduction of CP violation in the B_s system. To leading order in Yukawa insertions, the required operators arise at $O(Y_u^4 Y_d^4)$. These are specific realizations of the class of operators pointed out in Ref. [17], where the general consequences of Yukawa insertions at any order were investigated. The origin of CP violation is flavor blind, and the enhancement of its effect in B_s relative to B_d is governed by the ratio of Yukawa couplings y_s/y_d [17]. Notice that despite the fact that the total number of Yukawa insertions is rather large, the effect is not necessarily hopelessly small simply because the scale of the Yukawa coupling in the down-type sector is very uncertain. In particular, the Yukawa couplings of b quarks may not lead to any suppression at all, $y_b \sim O(1)$, as happens in large $\tan\beta$ two-Higgs doublet models (2HDMs). An example of a model in this category would be the large $\tan\beta$ supersymmetric model, where even in the limit of very heavy superpartners the Higgs exchange leads to important effects both in flavor physics [18] and EDMs [19,20]. For an MFV vs EDM discussion, see [21]. See also Ref. [22] for an early study of SUSY effects on lepton asymmetries in B systems.

Normalizing the size of these CP-violating four-fermion operators to a putative signal in B_s decays, i.e. to the maximal size consistent with the mass splitting, we next address the question of EDMs. We point out that all these operators and their close relatives can be further subdivided into two broad classes. The first class contains the scalar-pseudoscalar Lorentz structure $S \times P$ and survives in the limit of $V_{\rm CKM} \to 1$. The neutron EDM is predicted typically close to experimental bounds, and the natural size of the mercury EDM is up to 1 order of magnitude above the experimental limits. The second class of operators has the structure of left-handed times right-handed vector current, $(V - A) \times (V + A)$. To have CP violation, this class of operators requires more than one generation, and as a result all EDMs acquire additional suppression by V_{ts}^2 or V_{td}^2, bringing them well below the sensitivity of modern EDM experiments. We provide examples of possible UV completions for both types of operators.

In Sec. II we present a detailed classification of these operators, along with the estimate of their plausible size that makes them detectable in the B_s mixing. Section III provides some background information on EDMs and estimates the contribution from each operator to $d_{\rm Hg}$ and d_n. Finally, Sec. IV contains a discussion of possible UV completions and presents our conclusions.

II. *CP*-VIOLATING MFV OPERATORS FOR THE B_s MIXING

The rules of the game in MFV are defined by the requirement to retain the existing flavor reparametrization freedom of the SM. Since the right-handed rotations remain unphysical, we use this freedom to put all Yukawa couplings to the Hermitian form

$$Y_u^\dagger = Y_u, \qquad Y_d^\dagger = Y_d, \tag{4}$$

which allows for shorter expressions.

A four-fermion operator relevant for B_s mixing can be written in the following general form,

$$O = (\bar{b}\Gamma_A s)(\bar{b}\Gamma'_A s), \tag{5}$$

where $\Gamma_A^{(\prime)}$ stands for all possible Lorentz and color contractions. Lifting such operators to the flavor space according to the MFV rules, one encounters two types of MFV operators: those that give identical CP-violating NP contributions in both B_d and B_s mixing in comparison to their SM values, and those that are enhanced in B_s mixing [17]. We are interested in the latter, and therefore specify the following criteria for selecting the operators:

(1) O violates CP and contains $\Delta F = 2$ transitions.
(2) The contribution of O to the mixing in B_s is enhanced over B_d by y_s/y_d.
(3) O survives the limit of y_c^2, $y_u^2 \to 0$, and involves no more than one power of y_s or y_d.
(4) O is a local Lorentz scalar mediated by the exchange of particles heavier than m_B.
(5) The total number of Yukawa insertions in O is minimized.

Needless to say, we also require an overall electric and color neutrality of O, but do not impose any $SU(2) \times U(1)$ requirements, as those can be easily satisfied by an appropriate number of Higgs insertions. While the first four conditions on the list are crucial for our discussion, the last one is for bookkeeping purposes only, as any Y_u^2 insertions can be taken as $(Y_u^2)^n$, resulting in a proliferation of powers of top quark Yukawas, but not bringing any additional numerical smallness. The condition of locality explicitly forbids a situation where the B mixing is mediated by a neutral particle with a mass close to m_{B_s} or m_{B_d}, which can enhance the mixing in either of these two systems via a resonance, with a possibility of distorting MFV relations.

When generalizing (5) to the full flavor space, one has to remember that flavor indices can be contracted outside of a quark pair that has its Lorentz/color indices contracted. We choose to eliminate such operators using completeness in the flavor sector, but then have to account for all possible

Lorentz and color structures. Calling the left- and right-handed down quarks Q and D, with the above guiding conditions at hand, we arrive at the following set $\{O_s\}$ of the effective CP-violating operators:

$$\begin{aligned} O_1 &= i(\bar{Q}^k Y_u^2 Y_d D^k)(\bar{D}^l Y_d [Y_d^2, Y_u^2] Q^l) + (\text{H.c.}),\\ O_2 &= i(\bar{Q}^k Y_u^2 Y_d D^l)(\bar{D}^l Y_d [Y_d^2, Y_u^2] Q^k) + (\text{H.c.}),\\ O_3 &= i(\bar{D}^k Y_d [Y_d^2, Y_u^2] Y_d \gamma_\mu D^k)(\bar{Q}^l Y_u^2 \gamma_\mu Q^l),\\ O_4 &= i(\bar{D}^k Y_d [Y_d^2, Y_u^2] Y_d \gamma_\mu D^l)(\bar{Q}^l Y_u^2 \gamma_\mu Q^k),\\ O_5 &= i(\bar{D}^k Y_d Y_u^2 Y_d \gamma_\mu D^k)(\bar{Q}^k [Y_d^2, Y_u^2] \gamma_\mu Q^l),\\ O_6 &= i(\bar{D}^k Y_d Y_u^2 Y_d \gamma_\mu D^l)(\bar{Q}^l [Y_d^2, Y_u^2] \gamma_\mu Q^k). \end{aligned} \tag{6}$$

In these expressions, $[,]$ denote commutators in the flavor space, superscripts k and l show the contraction of color $SU(3)$ indices, while the Lorentz and flavor indices are contracted within each set of parentheses. From the point of view of $\Delta F = 2$ flavor transitions, the set $\{O_s\}$ is clearly overcomplete. Indeed, e.g. to leading order in the strange quark Yukawa coupling, several of them lead to the same $(\bar{b}_L s_R)(\bar{b}_R s_L)$ or $(\bar{b}_L \gamma_\mu s_L)(\bar{b}_R \gamma_\mu s_R)$ operators. However, we should not count these operators as *a priori* redundant, as they might contain differences in $\Delta F = 0$ channels and thus have different manifestations in the EDMs. All of these operators contain commutators in the flavor space and therefore vanish in the limit of $V_{\text{CKM}} \to 1$. While the flavor structures in O_3–O_6 are clearly dictated by the properties of Hermiticity, the choice of flavor structure in O_1 and O_2 is not unique. One can take, for example, $i(\bar{Q}^k Y_u^2 Y_d D^k)(\bar{D}^l Y_d^3 Y_u^2 Q^l)$, which also leads to CP violation in B_s mixing. However, this can be reduced to O_1 since a structure analogous to O_1 with an anticommutator instead of a commutator gives a vanishing contribution to $\Delta F = 2$ operators.

Choosing the normalization constant to be $G_F/\sqrt{2}$, we combine these operators into an effective CP-odd Lagrangian weighted with dimensionless coefficients c_i:

$$\mathcal{L}^{CP} = \frac{G_F}{\sqrt{2}} \sum_{i=1...6} c_i O_i. \tag{7}$$

Next, we reduce Eq. (7) to the subset of operators leading to $\Delta F = 2$ transitions for B mesons, finding two independent structures for each light flavor:

$$\mathcal{L}^{CP}_{\Delta F=2} = i \frac{G_F}{\sqrt{2}} y_t^4 y_b^3 V_{tb}^{*2} \sum_{q=d,s} y_q V_{tq}^2 [C_{SLR} (\bar{b}_L q_R)(\bar{b}_R q_L) + C_{VLR} (\bar{b}_L \gamma_\mu q_L)(\bar{b}_R \gamma_\mu q_R)] + (\text{H.c.}), \tag{8}$$

where the Wilson coefficients are related to the original classification as follows:

$$C_{SLR} = 2(c_1 - c_4 - c_6); \qquad C_{VLR} = c_3 + c_5 - c_2. \tag{9}$$

These operators should be evolved using perturbative QCD from the scale where they are generated to the B-meson energy scale. It is hard to do this, in general, since we do not know the actual scale at which these operators are generated. A reasonable assumption is that this scale is rather large, comparable to the electroweak scale, in which case we can directly use the results of QCD evolution and the calculated matrix elements already present in the literature (see e.g. [23]). This produces the following estimate of the CP-odd mixing part of B_s.

$$\begin{aligned} \text{Im}(M_{12}) &\simeq \frac{G_F}{\sqrt{2}} \frac{m_{B_s} F_{B_s}^2}{3} y_t^4 y_b^3 y_s |V_{tb}^* V_{ts}|^2 \\ &\quad \times (P_1 C_{VLR} + P_2 C_{SLR}) \\ &\simeq (10\ \text{psec}^{-1}) \times \frac{y_b^3 y_s}{10^{-3}} [c_1 - c_4 - c_6 \\ &\quad + 0.33(c_2 - c_3 - c_5)], \end{aligned} \tag{10}$$

where $P_1 \simeq -1.62$ and $P_2 \simeq 2.46$ are from Ref. [23]. The eigenvalues of Yukawa matrices are normalized at a high-energy scale. We have disregarded the small complex phase of $V_{tb}^* V_{ts}$, and taken this product to be equal to 0.04, and $y_t \simeq 1$. The overall coefficient in (10) is chosen to be very close to half of the measured absolute value of ΔM_{B_s}.

Besides the presence of six unknown Wilson coefficients, an additional uncertainty in the estimate (10) is the value of the combination of Yukawa couplings from the down-quark sector. In the SM such a combination is hopelessly small, but at large $\tan\beta$ this combination can be as large as 10^{-2}, so that (10) will cause a large effect in B_s mixing. It should also be said that at very large $\tan\beta$ the relation between measured masses and eigenvalues of the Yukawa couplings, e.g. $y_s/y_b \simeq m_s/m_b$, weakens considerably because of the possibility of very large corrections to the mass operator [24]. The result (10) shows that there is some room for the generation of $\{O_s\}$ at the weak scale with nearly maximal $\tan\beta$, a point emphasized recently in Ref. [25].

We equate the imaginary part of the NP contribution to $\Delta m_{B_s}/2 \simeq 10\ \text{psec}^{-1}$ as suggested by the D0 dimuon asymmetry [6] and the recent fits in Refs. [9,10]. This benchmark fixes the combination of $y_b^3 y_s$ times the linear combination of Wilson coefficients. We shall now use this as an approximate input for the estimates of the natural size of EDMs in this framework.

III. NATURAL SIZE OF EDMS FROM $\{O_s\}$ AND ITS EXTENSIONS

Electric dipole moments of heavy atoms and neutrons (see Refs. [26,27] for reviews) are a powerful probe of new CP-violating physics at and above the weak scale. EDMs do not require flavor transition and therefore may be induced by NP even in the limit of $V_{\text{CKM}} \to 1$. It is remarkable that despite the fact that MFV has extra flavor-universal CP-violating phases, *all* operators in the set $\{O_s\}$ vanish at $V_{\text{CKM}} \to 1$. Moreover, it turns out that operators

O_1 and O_2 do not contain CP-violating terms for $\Delta F = 0$ processes. Indeed, the flavor commutator requires the presence of quarks from two different generations, e.g. s and b, which makes such operators $\propto (\bar{b}_L s_R)(\bar{s}_R b_L)$. These in turn can be Fierz-transformed to the products of s- and d-vector and axial vector currents, $(\bar{s}_R \gamma_\mu s_R)(\bar{b}_L \gamma_\mu b_L)$, that always conserve CP. Retaining only $y_b^3 y_{s(d)}$-proportional contributions, we choose to eliminate all $(V-A)\times(V+A)$ operators with Fierz transformations, arriving at the following $\Delta F = 0$ component of the effective Lagrangian (7):

$$\mathcal{L}^{CP}_{\Delta F=0} = i\frac{G_F}{\sqrt{2}} y_t^4 y_b^3 \sum_{q=d,s} 2y_q |V_{tb}V_{tq}|^2 [(c_4 - c_6)(\bar{b}_L^k b_R^k) \times (\bar{q}_R^l q_L^l) + (c_3 - c_5)(\bar{b}_L^k b_R^l)(\bar{q}_R^l q_L^k)] + (\text{H.c.}). \quad (11)$$

Thus, even before estimating the actual size of the EDMs, we can conclude that there exist natural choices of operators within MFV, such as O_1 and O_2, that contribute to CP violation in B_s but do not lead to EDMs.

Turning to the actual size of the EDMs induced by (11), we expect them to be very small on account of the additional suppression by $|V_{td}|^2 \sim 10^{-4}$. There are several pathways for the Lagrangian (11) to contribute to EDM observables. Integrating out the b quark induces EDMs d_q and color EDMs $\tilde{d}_q$ of light quarks that in turn lead to a neutron EDM, as well as CP-odd nuclear forces that manifest in d_{Hg}.

A good proxy for the strength of CP-odd nuclear forces is given by the CP-odd pion-nucleon and η-nucleon coupling constants. Besides being induced by the two-loop $\tilde{d}_q$, these couplings also receive a more direct contribution from (11) [19,28] via the "heavy quark content" of a nucleon, $\langle N|m_b \bar{b}b|N\rangle \simeq 65$ MeV. Taking the $\bar{b}b\bar{d}i\gamma_5 d$ part of $\mathcal{L}^{CP}_{\Delta F=0}$, we estimate the strength of the pion-nucleon coupling constant to be

$$g_{\pi NN} = (c_4 - c_6)\frac{G_F}{\sqrt{2}}|V_{tb}V_{tq}|^2 y_t^4 y_b^3 y_d \times \frac{\eta_{\text{QCD}} R_{\text{QCD}}}{f_\pi}, \quad (12)$$

where R_{QCD} is a factorized combination of QCD condensates and nucleon matrix elements of quark bi-linears:

$$R_{\text{QCD}} = \langle N|\bar{b}b|N\rangle\langle 0|\bar{d}d|0\rangle - \langle N|\bar{d}d|N\rangle\langle 0|\bar{b}b|0\rangle \sim 5\times 10^{-4}\ (\text{GeV})^3. \quad (13)$$

The numerical value of R_{QCD} is obtained assuming the following values of the quark condensates and matrix elements: $\langle N|\bar{b}b|N\rangle \sim 1.35\times 10^{-2}$, $\langle 0|\bar{b}b|0\rangle = -\langle G^{a2}_{\mu\nu}\rangle \alpha_s/(12\pi m_b) \sim -(55\ \text{MeV})^3$, $\langle N|\bar{d}d|N\rangle \sim 4$, and $\langle 0|\bar{d}d|0\rangle \sim -(250\ \text{MeV})^3$. There is also an enhancement coefficient $\eta_{\text{QCD}} \sim 2.5$ due to QCD running of the $\bar{b}_L b_R \bar{d}_R d_L$ operator from the UV scale down to the scale m_b. All of these steps produce the following estimate of the pion-nucleon coupling constant:

$$g_{\pi NN} \sim 5\times 10^{-16} \times \frac{y_b^3 y_s}{10^{-3}}(c_4 – c_6), \quad (14)$$

where we also used $y_d/y_s \sim 0.04$.

It is easy to see that $\mathcal{L}^{CP}_{\Delta F=0}$ induces nonzero d_q and $\tilde{d}_q$ only at two-loop level. The results for the color EDMs can be obtained by "recycling" the calculations of the Barr-Zee diagrams for the 2HDM in the limit of $m_b^2 \ll m^2_{\text{Higgs}}$ [29–31]:

$$\tilde{d}_d^{\text{2-loop}} = \frac{\alpha_s m_b}{16\pi^3}\frac{G_F}{\sqrt{2}}|V_{tb}V_{tq}|^2 y_t^4 y_b^3 y_d \times \ln\frac{\Lambda_{\text{UV}}}{m_b} \times \left(c_4 - c_6 + \frac{7}{6}(c_3 - c_5)\right) \simeq \frac{y_b^3 y_s}{10^{-3}}\left(c_4 - c_6 + \frac{7}{6}(c_3 - c_5)\right) \times 5\times 10^{-30}\ \text{cm}. \quad (15)$$

In the second relation we also used $\Lambda_{\text{UV}} \sim G_F^{-1/2}$ and chose $\alpha_s \sim 0.15$. This result should be compared with the limit on the CP-odd pion-nucleon coupling in the isospin $= 1$ channel extracted from the mercury EDM [12] and the implied limit on color EDMs of quarks [12,26,32]:

$$|g^1_{\pi NN}| < 10^{-12}; \qquad |\tilde{d}_d - \tilde{d}_u| < 6\times 10^{-27}\ \text{cm}. \quad (16)$$

It shows that the choice $y_b^3 y_s c_i \sim O(10^{-3})$ motivated by maximal CP violation in B_s mixing (10) yields EDMs that are 3 orders of magnitude below the experimental bounds. Even taking into account significant theoretical uncertainties involved in estimates (12) and (15) as well as nuclear/QCD uncertainties in extracting (16) from d_{Hg}, one can conclude that the EDMs induced by operators from $\{O_s\}$ are well below current levels as well as anticipated future experimental sensitivity benchmarks.

One of the main reasons why the results (12) and (15) are so small is the strong suppression coming from the factor $|V_{td}|^2 \simeq 10^{-4}$, which is a consequence of the commutators in flavor space present in every member of $\{O_s\}$. In this respect, it is reasonable to investigate whether close "flavor relatives" of O_i give EDMs in the limit $V_{\text{CKM}} \to 1$. We define a flavor relative as a modification of an operator O_i where some flavor structure is added/removed within each quark pair in a way consistent with MFV. For example, a "minimal" flavor relative of O_1 would be the operator $(\bar{Q}^k Y_d D^k)(\bar{D}^l Y_d Q^l)$. It is easy to see that all operators O_3–O_6 that involve a product of left- and right-handed currents do not have flavor relatives that give large EDMs. Indeed, removing any of the Y_u^2 or Y_d^2 insertions leads to operators that conserve CP. Therefore, flavor relatives of O_3–O_6 always require $V_{\text{CKM}} \neq 1$ to induce EDMs, and these EDMs are small according to (12) and (15). On the contrary, there exist flavor relatives of O_1 and O_2 that do give EDMs in the limit of $V_{\text{CKM}} \to 1$:

$$O_{1,2} \to i(\bar{Q}^k Y_d^3 D^k)(\bar{D}^l Y_d Q^l) + (\text{H.c.})$$
$$\to i y_b^3 y_d (\bar{b}_L b_R)(\bar{d}_R d_L) + (\text{H.c.}). \quad (17)$$

If UV physics generates these relatives of O_1 and O_2 with similar-size Wilson coefficients, the resulting EDMs are 4 orders of magnitude above (12) and (15), on the order of $\tilde{d}_d \sim 5 \times 10^{-26}$ cm. This corresponds to EDMs right at the current level of experimental sensitivity for the neutron [33] and about 1 order of magnitude above the current bounds for mercury. The effective field theory approach does not allow one to make a more refined statement before the UV physics is specified.

As a final comment in this section, it may still be possible that D0 same-sign dimuon asymmetry [6] has a non-negligible contribution from a NP source that does not differentiate between B_s and B_d by an extra factor of y_s/y_d, and for whatever reason, the presence of NP in B_d has not been detected elsewhere. In this case, the spectrum of CP-violating operators broadens rather considerably. Some of these operators, such as pure left-handed type $i(\bar{Q}[Y_u^2, Y_d^2]\gamma_\mu Q)(\bar{Q}Y_u^2\gamma_\mu Q)$ and its flavor relatives, cannot induce large EDMs. Others involve the chirality flip, $(\bar{Q}Y_u^2 Y_d D)(\bar{Q}Y_u^2 Y_d D)$, and their flavor/Lorentz relatives may induce significant EDMs even at one-loop level:

$$i(\bar{Q}Y_d\sigma_{\mu\nu}D)(\bar{Q}Y_d\sigma_{\mu\nu}D) \to i y_b y_d (\bar{b}_L\sigma_{\mu\nu}b_R)(\bar{d}_L\sigma_{\mu\nu}d_R)$$
$$\to d_d^{\text{1-loop}}. \quad (18)$$

If the combination $y_b y_d$ corresponds to a choice of maximal $\tan\beta$, such one-loop EDMs will be very large, being enhanced relative to (15) by $O(100 \times V_{td}^{-2}) \sim 10^6$, and indeed several orders of magnitude above all EDM bounds. A detailed analysis of such operators falls outside the scope of the present paper.

IV. DISCUSSION

In this paper we have presented the explicit form of the CP-odd $\Delta B = 2$ MFV operators that predominantly contribute to the CP violation of B_s mesons [17]. Since the CP-violating properties are governed by the flavor-universal phase in front of these operators, one might have expected large effects for EDMs. On the contrary, we have found that $\{O_s\}$ requires nonzero CKM mixing matrix elements for the EDMs to exist. This extra $|V_{td}|^2$ suppression places EDMs directly induced by $\{O_s\}$ well below the experimental bounds. At the same time "close flavor relatives" of scalar operators O_1 and O_2 give EDMs on the order of 10^{-26} cm, comparable or even somewhat larger than the current best limits [12]. On the other hand, operators of the type O_3–O_6 that involve the product of left- and right-handed currents $(V - A) \times (V + A)$ *do not have* flavor relatives that generate EDMs in the limit $V_{\text{CKM}} \to 1$. Our general analysis has implications for the specific UV completion schemes that may be responsible for generating operators O_i that lead to preferential CP violation in the B_s system.

2HDM, minimal supersymmetric standard model, and color-octet scalars.—The exchange of MFV scalars [9,34] can generate O_1 and/or O_2 operators and their flavor relatives, and there is no good argument why EDMs should be small. In the minimal supersymmetric standard model, Higgs exchange at large $\tan\beta$ combined with SUSY radiative corrections to the mass sector of down-type quarks can be a significant source of $\Delta F = 2$ operators. If CP violation is introduced in a MFV-like fashion, it has to be sourced by the relative phase of the μ parameter in the superpotential and the gluino mass parameter. To have an effect on B_s, this phase would have to be nearly maximal. Besides the effects induced by O_1 and O_2 discussed in this paper, there will be of course the one-loop $\tan\beta$-enhanced EDMs that will be sensitive to the scale of the light scalar quark and lepton masses in excess of $\sim$5 TeV. With the necessity to keep heavy Higgs masses under a TeV, the model would require a number of fine-tunings of different mass/phase parameters to survive the EDM constraints. If, however, all these tuning requirements are met and mass scales in the squark/slepton sector are pushed into multi-TeV range, while $m_{A(H)}$ are kept under a TeV, there are still nonvanishing contributions to atomic EDMs on account of hadronic and semileptonic four-fermion operators, e.g. $\bar{q}q\bar{e}i\gamma_5 e$ [19]. Given the analysis of this paper and of Ref. [19], such EDMs will be at the current limits of experimental observability (or even slightly above current bounds). It would be interesting to investigate CP violation in the B_s system and EDMs in SUSY models extended by neutral chiral superfields on account of possibly light mediators and new sources for the CP-violating phases.

Vector and pseudoscalar exchange.—The exchange by neutral vector particles such as Z bosons (or hypothetical Z') is the most relaxed possibility with respect to the EDM constraints because it results only in O_3–O_6 operators. The Z boson, of course, does not have any flavor-changing couplings, and those would have to be generated by integrating out NP. An explicit example of such couplings consistent with MFV was given recently in models with extra vectorlike quarks [35]. These models may also have additional, and not necessarily small, effects in B_d and K mesons from pure left-handed operators, $\bar{Q}Y_u^2 Q\bar{Q}Y_u^2 Q$, and the associated CKM phase. The derivatively coupled pseudoscalar particles, with couplings $f_a^{-1}\partial_\mu a\bar{D}\gamma_\mu D$ and alike, are, in principle, capable of inducing similar effects if f_a is under a TeV but, on account of the extra derivative, would necessarily have to be relatively light, $m_a \sim m_B$.

Exchange by particles transforming nontrivially under flavor.—Lastly, the exchange by particles that transform nontrivially under flavor rotations (see e.g. Refs. [35,36]) is also capable of inducing $\{O_s\}$. In this case, however, the correspondence between the spin of the mediators and our operator classification may be different than in the case of the mediators that transform trivially under flavor. For example, exchange by scalars that transform as $(3, \bar{3})$ under the $SU(3)_Q$ and $SU(3)_D$ would generate operators $\bar{Q}^f D^j \bar{D}^j Q^f$, where j, f are flavor indices. After a Fierz transformation, this operator obtains the $(V-A)\times(V+A)$ structure and therefore requires additional CKM suppression to induce EDMs.

ACKNOWLEDGMENTS

M. P. would like to thank the participants of the JHU workshop for a number of useful discussions. The work of M. P. is supported in part by NSERC, Canada, and research at the Perimeter Institute is supported in part by the Government of Canada through NSERC and by the Province of Ontario through MEDT.

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