Implications of large dimuon CP asymmetry in $B_{d,s}$ decays on minimal flavor violation with low $\tan \beta$

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Abstract
The D0 collaboration has recently announced evidence for a dimuon CP asymmetry in $B_{d,s}$ decays of order one percent. If confirmed, this asymmetry requires new physics. We argue that for minimally flavor violating (MFV) new physics, and at low $\tan \beta = v_u/v_d$, there are only two four-quark operators $(Q_{2,3})$ that can provide the required CP violating effect. The scale of such new physics must lie below $260 \text{ GeV} \sqrt{\tan \beta}$. The effect is universal in the $B_s$ and $B_d$ systems, leading to $S_{\psi K} \sim \sin 2\beta - 0.15$ and $S_{\psi f} \sim 0.25$. The effects on $\epsilon_K$ and on electric dipole moments are negligible. The most plausible mechanism is tree-level scalar exchange. MFV supersymmetry with low $\tan \beta$ will be excluded. Finally, we explain how a pattern of deviations from the Standard Model predictions for $S_{\psi f}$, $S_{\psi K}$ and $\epsilon_K$ can be used to test MFV and, if MFV holds, to probe its structure in detail.
1 Introduction

The D0 collaboration has recently announced evidence for new CP violating physics in semileptonic $B$ decays [1]:

\[(a_{SL}^b)_{D0} = (-9.6 \pm 2.5 \pm 1.5) \times 10^{-3}, \quad (1)\]

to be compared with the Standard Model (SM) prediction [2]:

\[(a_{SL}^b)_{SM} = (-0.23^{+0.05}_{-0.06}) \times 10^{-3}. \quad (2)\]

The measured asymmetry is a combination of the asymmetries in $B_d^0$ and $B_s^0$ decays [1]:

\[a_{SL}^b = (0.51 \pm 0.04) a_{SL}^d + (0.49 \pm 0.04) a_{SL}^s. \quad (3)\]

To explain the difference between the experimental result [1] and the SM prediction [2], a new physics contribution to $B_s-\bar{B}_s$ and/or $B_d-\bar{B}_d$ mixing is required that is comparable in size to the SM contribution and carries a new phase of order one.

The fact that, so far, no evidence for new physics in $K$, $D$ and $B_d$ meson decays has been established implies that the flavor structure of new physics at a scale $\lesssim 10^3$ TeV is highly constrained. This situation is suggestive that perhaps such new physics carries no new sources of flavor violation beyond the Yukawa matrices of the SM. This idea, which can be formulated in a rigorous mathematical way [3], became known as minimal flavor violation (MFV) [4, 5, 6].

The MFV hypothesis does not exclude the possibility of new CP violating phases, beyond the Kobayashi-Maskawa phase of the SM [7, 8, 9]. In models with more than a single Higgs doublet, and in particular in the large tan $\beta$ limit, such that the bottom Yukawa coupling is of order one, there is a rather large number of such new phases that could be large. In contrast, in a single Higgs doublet, or even in multi-Higgs doublet models where tan $\beta \ll m_t/m_b$, the situation concerning CP violation is much more constrained. In this work we study the implications of the experimental measurement [1] for the latter class of models.

The plan of this paper is as follows. In Section 2 we introduce the effective four-quark operators of interest, and the flavor suppression factors that accompany them when minimal flavor violation is imposed. In Section 3 we focus our attention on MFV models with tan $\beta \ll m_t/m_b$, find the operators that can account for a large dimuon CP asymmetry and obtain the resulting predictions. In Sections 4 and 5 we show that the effects of the relevant operators on, respectively, CP violation in $K^0 - \bar{K}^0$ mixing and electric dipole moments are negligible. In Section 6 we argue that a large dimuon CP asymmetry would exclude the MFV class of the supersymmetric Standard Model at low tan $\beta$. In Section 7 we explain how the pattern of CP violation in neutral $K$, $B_d$ and $B_s$ meson mixing can be used to test MFV or to probe its detailed structure. We conclude in Section 8.

2 Minimal Flavor Violation

The effects of new physics at a high energy scale ($\Lambda \gg m_W$) on $B_q - \bar{B}_q$ mixing can be studied in an effective operator language. A complete set of four quark operators relevant to $B_s - \bar{B}_s$ transitions is given by

\[
\begin{align*}
Q_{1}^{ab} &= b_{L}^{a} \gamma_{\mu} s_{L}^{b} \bar{b}_{L}^{\gamma} \gamma_{\mu} s_{L}^{b}, \\
Q_{2}^{ab} &= \bar{b}_{L}^{a} s_{L}^{b} \bar{b}_{L}^{\gamma} s_{L}^{b}, \\
Q_{3}^{ab} &= \bar{b}_{R}^{a} s_{L}^{b} \bar{b}_{R}^{\gamma} s_{L}^{b}, \\
Q_{4}^{ab} &= \bar{b}_{R}^{a} s_{L}^{b} \bar{b}_{R}^{\gamma} s_{L}^{b}, \quad (4)
\end{align*}
\]
Here \(d_L(d_R)\) represent \(SU(2)\)-doublets (singlets), and \(\alpha, \beta\) are color-indices. The effective Hamiltonian is given by

\[
H_{eff}^{\Delta B = \Delta S = 2} = \frac{1}{\Lambda^2} \left( \sum_{i=1}^{5} z_i Q_i + \sum_{i=1}^{3} \tilde{z}_i \tilde{Q}_i \right).
\]

For the new physics to give a contribution to the mixing amplitude that is of order 0.22 of the SM one [see Eq. (18)], we need that at least one of the following conditions will be satisfied:

\[
|z_1| \sim 1.2 \times 10^{-5} \left( \frac{\Lambda}{\text{TeV}} \right)^2,
\]

\[
|z_2| \sim 5.5 \times 10^{-6} \left( \frac{\Lambda}{\text{TeV}} \right)^2,
\]

\[
|z_3| \sim 2.0 \times 10^{-5} \left( \frac{\Lambda}{\text{TeV}} \right)^2,
\]

\[
|z_4| \sim 2.0 \times 10^{-6} \left( \frac{\Lambda}{\text{TeV}} \right)^2,
\]

\[
|z_5| \sim 5.3 \times 10^{-6} \left( \frac{\Lambda}{\text{TeV}} \right)^2,
\]

(or a value of \(\tilde{z}_i\) similar to the one given for the corresponding \(|z_i|\)). We thus learn that (11) gives an upper bound on the scale of the relevant new physics:

\[
\Lambda \lesssim 700 \text{ TeV}.
\]

We now impose the MFV principle. Since we are interested in \(B_s\) mesons, we work in the down mass basis:

\[
Y_d = \text{diag}(yd, ys, yb), \quad Y_u = V^\dagger \times \text{diag}(yu, yc, yt),
\]

where \(V\) is the CKM matrix. We further define

\[
A_d \equiv Y_d Y_d^\dagger = \text{diag}(0, 0, y_b^2), \quad A_u \equiv Y_u Y_u^\dagger = V^\dagger \times \text{diag}(0, 0, y_t^2) \times V.
\]

We now write the MFV form of the \(z_i\) coefficients. For each \(z_i\), we include the leading term that does give new CP violation, for \(\tan \beta < m_t/m_b\):

\[
z_1 = r_1^+(A_u)_{32}^2 + r_1^-(A_u)_{32}[A_u, A_d]_{32},
\]

\[
z_{2,3} = r_{2,3}(v^2/\Lambda^2)(Y_d^\dagger A_u)_{32},
\]

\[
z_{4,5} = r_{4,5}^+(Y_d^\dagger A_u)_{32}[A_u, A_d]_{32} + r_{4,5}^+(Y_d^\dagger[A_u, A_d]_{32}(A_u Y_d)_{32}.
\]

The \(\tilde{z}_i\) coefficients are highly suppressed. We introduce a \(v^2/\Lambda^2\) factor into \(z_{2,3}\) to take into account the fact that these two operators break \(SU(2)_L\) as a triplet. The coefficients \(r_{1,4,5}^+\) are real.

Inserting the expressions (8) and (9) into Eq. (10), we obtain

\[
\frac{z_1}{y_t^2(V_{tb}V_{tb}^\dagger)^2} = r_1^+ - r_1^- y_b^2,
\]

\[
\frac{z_{2,3}}{y_t^2(V_{tb}V_{tb}^\dagger)^2} = r_{2,3}(v^2/\Lambda^2)y_b^2,
\]

\[
\frac{z_{4,5}}{y_t^2(V_{tb}V_{tb}^\dagger)^2} = r_{4,5}^+ y_t y_s - r_{4,5}^- y_b^3 y_s.
\]

We make the following conclusions:
1. MFV implies that the $z_i$ coefficients are suppressed by, at least, $(V_{ts}V_{tb}^*)^2 \sim 0.002$. Consequently, Eq. (1) gives an upper bound on the scale of MFV new physics:

$$\Lambda_{MFV} \lesssim 30 \text{ TeV}. \quad (12)$$

2. If $\tan \beta$ is not very large, there is further suppression of the CP violating contributions by a factor $y_b^2$, leading to

$$\Lambda_{MFV} \lesssim 500 \text{ GeV } \tan \beta. \quad (13)$$

3. If $r_i^+ \gtrsim r_i^-$, then the phase provided by any of $Q_{1,4,5}$ is suppressed by at least $y_b^2$.

4. If all $r_i$ are of the same order, then the leading contribution comes from $Q_1$ and (for $\tan \beta$ not large) is approximately CP conserving.

3 Small $\tan \beta$

We now focus our attention on $\tan \beta = \mathcal{O}(1)$. Note that $\tan \beta = 1$ in all single Higgs doublet models.

Barring the possibility that $r_i^+ \ll r_i^-$ which is, first, difficult to realize and, second, implies that $r_i^- \ll 1$, so that the new physics contribution suffers further suppression, the only operators that can give a large CP violating effect in $B_s - \overline{B_s}$ mixing are $Q_{2,3}$. As is evident in Eq. (6), the contribution of $Q_3$ at the low scale is suppressed in comparison to that of $Q_2$. Since these operators share the same MFV structure, Eq. (11), we focus our attention henceforth on $Q_2$.

For $Q_2$ to give a dominant contribution in the MFV case, $z_1$ must be highly suppressed. This is the case when, for example, the new physics contribution comes from scalar exchange. As concerns the competition between $Q_2$ and $Q_4$, the first will dominate if either $r_4 \ll r_2$ or

$$2.7 y_b/y_s \lesssim v^2/\Lambda^2 \quad \Rightarrow \quad \Lambda \lesssim 1 \text{ TeV} \quad (14)$$

where we took into account the relative RGE enhancement of $Q_4$. Given the upper bound of Eq. (13), and taking into account that both $z_2$ and $z_4$ are suppressed more strongly than the $\mathcal{O}(y_t^4 y_b^2 (V_{ts}V_{tb}^*)^2)$ suppression that leads to Eq. (13) (the first by $v^2/\Lambda^2$ and the latter by $y_s/y_b$), we learn that in much of the regime where either $Q_2$ or $Q_4$ contribute to $B_s - \overline{B_s}$ mixing comparably to the SM, we expect $Q_2$ to be comparable to or even dominate over $Q_4$. The condition then for an $\mathcal{O}(0.22)$ CP violating contribution is

$$\Lambda_{Q_2} \lesssim 260 \text{ GeV } \sqrt{\tan \beta}. \quad (15)$$

The $Q_2$ dominance, which is necessary to explain Eq. (1) with low $\tan \beta$ MFV physics, has further interesting consequences. In particular, it implies that the new physics contributions are the same in the $B_d$ and $B_s$ systems [9]. More explicitly, defining

$$M_{12}^{d,s} = (M_{12}^{d,s})_{SM} (1 + h_{d,s} e^{2i\sigma_{d,s}}), \quad (16)$$

the $Q_2$ dominance predicts

$$h_b \equiv h_d = h_s, \quad \sigma_b \equiv \sigma_d = \sigma_s. \quad (17)$$

The viability of such a scenario, taking into account all relevant data about $B_d - \overline{B_d}$ and $B_s - \overline{B_s}$ mixing, was investigated in Ref. [10]. It was found that it can be accommodated by the data, even though it is
It is useful also to rewrite Eq. (18) as
\[
r_{b}^{2}e^{2i\theta_{b}} \equiv 1 + h_{b}e^{2i\sigma_{b}} \approx (1.0 \pm 0.1) \times e^{-(0.22 \pm 0.06)i}.
\]

This is a rather predictive scenario. Its most significant predictions can be derived from the following relations:
\[
\begin{align*}
\Delta m_{q} &= r_{b}^{2}\Delta m_{q}^{SM}, \\
\Delta \Gamma_{q} &= \Delta \Gamma_{q}^{SM} \cos 2\theta_{b}, \\
a_{SL}^{q} &= Im \left[ \Gamma_{12}^{q} / \left( M_{12}^{q} r_{b}^{2}e^{2i\theta_{b}} \right) \right] \approx -(\Gamma_{12}^{q}/M_{12}^{q})^{SM} (\sin 2\theta_{b}/r_{b}^{2}), \\
S_{\psi K} &= \sin (2\beta + 2\theta_{b}), \\
S_{\psi \phi} &= \sin (2\beta_{s} - 2\theta_{b}).
\end{align*}
\]

We obtain:
\[
\begin{align*}
\Delta m_{q} &\approx (1.0 \pm 0.1)\Delta m_{q}^{SM}, \\
\Delta \Gamma_{q} &\approx (0.98^{+0.01}_{-0.02})\Delta \Gamma_{q}^{SM}, \\
a_{SL}^{q} &\approx (0.22 \pm 0.07) (\Gamma_{12}^{q}/M_{12}^{q})^{SM}, \\
S_{\psi K} &\approx 0.65 \pm 0.05, \\
S_{\psi \phi} &\approx 0.25 \pm 0.06.
\end{align*}
\]

For the estimate of $S_{\psi K}$, we used the CKMfitter result \[11\], $\sin 2\beta \approx 0.80 \pm 0.03$. The fact that, for $h_{d} = h_{s}$ and $\sigma_{d} = \sigma_{s}$, a negative shift in $S_{\psi K}$ is correlated with a positive shift in $S_{\psi \phi}$, was first pointed out in Ref. \[12\].

Note that by assuming that the new physics affects only $M_{12}^{q}$, the $B_{s}$-related observables in Eq. (20) automatically satisfy (neglecting $\beta_{s}$) the relation \[13\]
\[
\frac{a_{SL}^{q}}{S_{\psi \phi}/(1 - S_{\psi \phi}^{2})^{1/2}} = \frac{|\Delta \Gamma_{s}|}{\Delta m_{s}}.
\]

4 CP violation in $K^{0} - \overline{K}^{0}$ mixing

Within the MFV framework, the existence of the four-quark term,
\[
\frac{z_{bs}^{2}b_{s}^{2}}{\Lambda^{2}} R^{\alpha \beta}L^{\alpha \beta},
\]
which contributes to CP violation in $B_{s} - \overline{B}_{s}$ mixing, requires the existence of another four-quark term,
\[
\frac{z_{sd}^{2}d_{s}^{2}}{\Lambda^{2}} R^{\alpha \beta}L^{\alpha \beta},
\]
which contributes to CP violation in $K^{0} - \overline{K}^{0}$ mixing. The MFV principle relates $z_{sd}^{2}$ to $z_{bs}^{2}$:
\[
\frac{z_{sd}^{2}}{z_{bs}^{2}} = \frac{g_{s}^{2}}{g_{b}^{2}} \left( \frac{V_{td}V_{ts}^{\ast}}{V_{ts}V_{tb}^{\ast}} \right)^{2}
\]

4
Thus, the ratio between the imaginary parts of the new physics contributions is given by

$$\frac{\text{Im}(z_{sd}^d)}{\text{Im}(z_{bs}^s)} = \frac{y_t^2}{y_b^2} \cdot \left| \frac{V_{td}}{V_{tb}} \right|^2 \frac{\sin(2\sigma_b - 2\beta)}{\sin(2\sigma_b)} \approx 1.4 \times 10^{-8}. \quad (26)$$

For the $z_{bs}^s$ term to provide $h_b$ and $\sigma_b$ of Eq. (18), we need $\text{Im}(z_{bs}^s) \sim 5.5 \times 10^{-6} (\Lambda/\text{TeV})^2$, see Eq. (6). Together with Eq. (26), we obtain

$$\frac{\text{Im}(z_{sd}^d)}{\Lambda^2} \sim 8 \times 10^{-14} \text{TeV}^{-2}. \quad (27)$$

This prediction should be compared to the range allowed by the $\epsilon_K$ constraint [14],

$$\frac{\text{Im}(z_{sd}^d)}{\Lambda^2} \in [-5.1, +9.3] \times 10^{-11} \text{TeV}^{-2}, \quad (28)$$

which corresponds to a maximal new physics contribution to $\epsilon_K$ of order ten percent. We conclude that in our framework, of $Q_2$-dominated CP violation from MFV new physics, the effect on $\epsilon_K$ is of order a permill and therefore negligible.

### 5 Electric Dipole Moments

In this section we investigate whether experimental bounds on electric dipole moments (EDMs) constrain the four-fermi operators that are relevant to our study. We use the results of Ref. [15]. A related recent discussion is given in Ref. [16] which, however, focuses on MFV models where the $B_s$ effects are enhanced over those of $B_d$.

Let us consider four-Fermi operators that play a role in EDMs:

$$\mathcal{L}_{4f} = \sum_{i,j} C_{ij} (\bar{d}_i d_i)(\bar{d}_j i\gamma_5 d_j), \quad (29)$$

where the coefficients $C_{ij}$ are imaginary and of mass dimension $-2$. Their contributions to the Mercury EDM are given by

$$d_{H_\nu} \supset -1.4 \cdot 10^{-5} e \text{ GeV}^2 \left[ 0.5 \frac{C_{11}}{m_d} + 3.3 \kappa \frac{C_{21}}{m_s} + (1 - 0.25\kappa) \frac{C_{31}}{m_b} \right], \quad (30)$$

where $\kappa = 0.5 \pm 0.25$. The experimental bound [17],

$$|d_{H_\nu}| < 3.1 \times 10^{-29} e \text{ cm}, \quad (31)$$

when imposed on each term in (30) independently, gives

$$C_{11} \lesssim 10^{-6} \text{ TeV}^{-2}, \quad C_{21} \lesssim 10^{-5} \text{ TeV}^{-2}, \quad C_{31} \lesssim 10^{-3} \text{ TeV}^{-2}. \quad (32)$$

We now focus on the $Q_2$ operator in the MFV framework. It is convenient to define

$$T_{ij} = V_{ti}^* V_{tj} y_t^2 y_d,$$
Then, in the basis (8), we have
\[ \frac{\mathcal{I}m z_2}{\Lambda^2} = \frac{v^2}{\Lambda^4} \mathcal{I}m(r_2)(T_{23})^2. \] (34)

On the other hand, in the MFV framework,
\[ C_{ij} = \frac{\mathcal{I}m z_2}{\Lambda^2} \frac{T_i T_j}{(T_{23})^2}. \] (35)

The EDM bounds then constrain the \( Q_2 \) contribution (the strongest constraint comes from \( C_{31} \)):
\[ \frac{\mathcal{I}m z_2}{\Lambda^2} \lesssim \frac{10}{\text{TeV}^2}. \] (36)

Comparing to Eq. (6), we conclude that the EDM bounds are far from making a significant constraint on the \( Q_2 \) contribution to CP violation in \( B_s \) mixing. Conversely, in our framework, of \( Q_2 \)-dominated CP violation from MFV new physics, the effect on EDMs is about six orders of magnitude below present bounds.

6 MFV Supersymmetry

Within supersymmetry, one can obtain \( z_2/\Lambda^2 \) in terms of the masses and mixing angles in the squark sector. Alternatively, one can use the average squark mass \( \bar{m} \) and squark mass-insertions \( (\delta^d_{MN})_{23} \), though this is an approximation that is not very precise when the squark spectrum is far from degeneracy.

As argued above, for MFV and low tan \( \beta \), the only operators that can give a large enough CP violating effect in \( B_s \) mixing are \( Q_{2,3} \). In general, the leading contributions come from gluino-mediated box diagrams, giving
\[ \Lambda = \bar{m}, \]
\[ z_2 = -\frac{17}{18} \alpha_s^2 x f_6(x)(\delta^d_{RL})^2_{23}, \]
\[ z_3 = +\frac{1}{6} \alpha_s^2 x f_6(x)(\delta^d_{RL})^2_{23}, \] (38)

where \( m_3 \) is the gluino mass, \( x = m_3^2/\bar{m}^2 \), and \( f_6 \) is a known kinematic function, given by
\[ f_6(x) = \frac{6(1 + 3x) \ln x + x^3 - 9x^2 - 9x + 17}{6(x - 1)^5}. \] (39)

The expressions for \( \tilde{z}_2 \) and \( \tilde{z}_3 \) are obtained from Eq. (37) by replacing the indices \( RL \to LR \). To have \( h_b \sim 0.22 \), we need
\[ (\delta^d_{RL,LR})_{23} \gtrsim 0.11 \left( \frac{\bar{m}}{\text{TeV}} \right). \] (40)

Such a large contribution is excluded by the constraints from \( b \to s\gamma \) and \( b \to s \ell^+ \ell^- \). The gluino-mediated \( (\delta^d_{LR})_{23} \)-related contributions (for an explicit expression, see e.g. Ref. [18]) provide an upper bound which, for \( x = 1 \), reads [19, 20]
\[ |(\delta^d_{LR})_{23}| \lesssim 0.01 \left( \frac{\bar{m}}{\text{TeV}} \right). \] (41)
Table 1: The magnitude of the flavor factors that appear in the $z_i$ coefficients which are relevant to CP violating observables.

| $i$ | $\Im m z_{ib}$ | $\Im m z_{id}/\Im m z_{ib}$ | $\Im m z_{sd}/\Im m z_{ib}$ |
|-----|----------------|-----------------------------|-----------------------------|
| 1   | $y_b y_t V_{tb} V_{ts}$ | $|V_{td}/V_{ts}|^2$ | $(1/y_b)|V_{td}/V_{ts}|^2$ |
| 2.3 | $y_b y_t V_{tb} V_{ts}$ | $|V_{td}/V_{ts}|^2$ | $(y_b y_t)|V_{td}/V_{ts}|^2$ |
| 4.5 | $y_b y_t V_{tb} V_{ts}$ | $|V_{td}/V_{ts}|^2$ | $(y_b y_t|^2)|V_{td}/V_{ts}|^2$ |

Table 2: The size of new MFV effects on CP violating observables.

| $i$ | $S_{\psi \phi}$ | $S_{\psi K}$ | $\epsilon_K$ | $S_{\psi \phi}$ | $S_{\psi K}$ | $\epsilon_K$ |
|-----|----------------|-------------|--------------|----------------|-------------|--------------|
| 1   | small          | small       | large        | small          | small       | large        |
| 2.3 | large          | small       | small        | large          | small       | large        |
| 4.5 | large          | small       | large        | small          | small       | large        |

We conclude that MFV-supersymmetry with $\tan \beta \ll m_t/m_b$ cannot explain a CP asymmetry in semileptonic $B_d$ decays of order a percent.

It is actually well known that in general the supersymmetric Standard Model cannot contribute significantly to $B_s - B_d$ mixing via the $Q_{2,3}$ operators (see e.g. Ref. [21]). This statement is independent of whether the supersymmetric model is MFV or not or whether $\tan \beta$ is large or not. What is novel in our discussion is that we show that in MFV and with low $\tan \beta$, the $Q_{2,3}$ operators are the only potential source of a large effect.

7 Probing MFV with the pattern of CP violation

Our results, when combined with those of Refs. [10] [22], show that there is a surprising variety of scenarios within the MFV framework. Conversely, one can use the pattern of experimental results to test whether MFV holds and, if it does, which are the leading operators. (An investigation similar in spirit to ours, but in the framework of MFV without flavor-diagonal CP violating phases, can be found in Ref. [23].)

Our starting point is the flavor suppression factors of the various $z_i$, presented in Eq. [11]. In Table 1 we rewrite the flavor factors that appear in the ratios between $\Im m (z_{i}^{kd})$, relevant to $S_{\psi K}$, $\Im m (z_{i}^{sd})$, relevant to $\epsilon_K$, and $\Im m (z_{i}^{bd})$, relevant to $S_{\psi \phi}$. Note that for $\Im m z_{i}^{bd}$ the relevant term is the one carrying a new phase, while for $\Im m z_{i}^{sd}$ the relevant term can have no new phase. The reason is that a new physics contribution to $B_s - B_d$ mixing that is aligned in phase with $(V_{td} V_{ts})^2 [V_{td} V_{ts}]^2$ leaves $S_{\psi \phi}$ $[S_{\psi K}]$ unchanged, but a new physics contribution to $K^0 - \bar{K}^0$ mixing that is aligned in phase with $(V_{td} V_{ts})^2$ does change $\epsilon_K$. In what follows we assume that the flavor-less coefficients $r_{1,4,5}^\pm$ and $r_{2,3}$ are of the same order, and do not affect the suppression pattern depicted in Table 1.

By examining Table 1 it should be clear that the pattern of deviations from the SM in $S_{\psi \phi}$, $S_{\psi K}$ and $\epsilon_K$ can tell us whether a new MFV contribution is dominated by $Q_1$, $Q_{2,3}$ or $Q_{4,5}$. The different patterns are presented in Table 2 for large $y_b \sim 1$ (very large $\tan \beta$) and $y_b < 1$ (low $\tan \beta$). For each case we saturate the most restrictive observable (“large”), and estimate whether the effect on the other observables is similarly significant (“large”) or smaller than present sensitivity (“small”).

Note that we restrict ourselves here to scenarios where at least one of the systems gives a convincing
signal of new physics. A-priori, there are seven different patterns among the three systems. We find that three of these – the two where there is a large effect on $S_{\psi K}$ simultaneously with a negligible effect on $S_{\psi \phi}$ (with large or small effect on $\epsilon_K$) [2] and the one with large effects in all three systems cannot be realized in our framework. The other four scenarios can, and each of them directs us to specific scenarios: Large effect in $\epsilon_K$ and small effects in $S_{\psi \phi}, S_{\psi K}$ is possible with $Q_1$-dominance or with $Q_{4,5}$-dominance at low tan $\beta$. Small effect in $\epsilon_K$ and large effects in $S_{\psi \phi}, S_{\psi K}$ is possible with $Q_{2,3}$-dominance. Large effects in $\epsilon_K$ and $S_{\psi \phi}$ with a small effect in $S_{\psi K}$ is possible with $Q_{4,5}$-dominance at very large tan $\beta$.

8 Conclusions

The D0 collaboration has found evidence for CP violation in semileptonic $B_s$ decays at the level of one percent. If confirmed, this result requires new, CP and flavor violating physics [24, 25, 26].

The measurement further provides interesting upper bounds on the scale of new physics. In general, it must be well below $10^3$ TeV. If the new physics is minimally flavor violating (MFV), then its scale must be below about 30 TeV. In MFV single Higgs doublet models the bound is further strengthened to 500 GeV. Within multi-Higgs doublet models with $\tan \beta \sim m_t/m_b$, there is a variety of ways to generate a large CP asymmetry in the semileptonic $B_s$ decays from flavor-diagonal phases [10, 22]. The situation is, however, much more constrained if $y_b \ll 1$. In this case, the only way to generate a phase of order one is via the $Q_{2,3}$ operators defined in Eq. (1). The upper bound on the scale is then still stronger, $\Lambda \lesssim 260$ GeV $\sqrt{\tan \beta}$. Furthermore, the effects in the neutral $B_q$ meson mixing are universal in the $d-s$ flavor space. While the effects on the CP conserving observables $\Delta m_q$ and $\Delta \Gamma_q$ are small, the effects on the CP violating observables are large. It is interesting to note that a CP asymmetry in semileptonic $B_s$ decays that is negative and of order one percent implies that the CP asymmetry in $B \to \psi K S$ is shifted down by about 0.15 from $\sin 2 \beta$, which is consistent with present data.

If the new physics contribution appears at the loop level, we expect a further suppression of $z_2$ by a factor of $1/16\pi^2$. Upper bounds on the scale of new physics, such as the one in Eq. (13), become stronger by a factor of $4\pi$, a dangerously low scale. There is also a need to avoid a situation where $r_1^+ \gtrsim r_2$, because in this case, the new physics phase, $\sigma_b$, will be small. Taking these two points together, we are led to conclude that to explain $a_{\psi K}^0 \sim 0.01$ within MFV models with $y_b \ll 1$, the most likely mechanism is that of tree-level exchange of a scalar. Indeed, such models have been suggested in Refs. [22, 22] to explain the D0 result. Both works study, however, models with very large $\tan \beta$.

Finally, if the evidence from the D0 measurement is confirmed, all MFV versions of the supersymmetric Standard Model with $\tan \beta \ll m_t/m_b$ will be excluded.

Independent of whether the D0 measurement is confirmed, we demonstrate how the measurements of $\epsilon_K, S_{\psi K}$ and $S_{\psi \phi}$ can be used to test the MFV hypothesis. For example, a shift in $S_{\psi K}$ from the SM value is much larger than $S_{\psi \phi}$ will exclude MFV. If the pattern is consistent with MFV, it can be used to probe its detailed structure. For example, large effects on $S_{\psi \phi}$ and on $S_{\psi K}$ and no effect on $\epsilon_K$ will point towards $Q_{2,3}$-dominance, as discussed in this paper, while observable effects on $S_{\psi \phi}$ and $\epsilon_K$ with only small effect on $S_{\psi K}$ will point towards $Q_{4,5}$-dominance and large $\tan \beta$, as discussed in Ref. [22].

Since the announcement of the D0 measurement of $a_{\psi K}^0$, a number of works interpreting the results have appeared. We mentioned above the three works that are most closely related to our study, Refs. [10, 22, 22], which study models where the new physics effect is only in the neutral meson mixing amplitudes and is MFV. The emphasis of all three works is, however, on large $\tan \beta$. Refs. [28, 29] assume that the new physics enters $\Delta B = 1$ processes, while we assume that the new physics affects only the mixing amplitude. Refs. [30, 31, 32, 33, 34] study non-MFV models. (For previous works on non-MFV models, see e.g. [35, 36, 37].)

Note added: When this work was in final stages of writing, several additional works interpreting the D0 result have appeared [38, 39, 40, 41, 42, 43, 44].
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