

## Implications of the Dimuon $CP$ Asymmetry in $B_{d,s}$ Decays

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The D0 Collaboration reported a  $3.2\sigma$  deviation from the standard model (SM) prediction in the like-sign dimuon asymmetry. Assuming that new physics contributes only to  $B_{d,s}$  mixing, we show that the data can be analyzed without using the theoretical calculation of  $\Delta\Gamma_s$ , allowing for robust interpretations. We find that this framework gives a good fit to all measurements, including the recent CDF Collaboration  $S_{\psi\phi}$  result. The data allow universal new physics with similar contributions relative to the SM in the  $B_d$  and  $B_s$  systems, but favors a larger deviation in  $B_s$  than in  $B_d$  mixing. The general minimal flavor violation framework with flavor diagonal  $CP$  violating phases can account for the former case and remarkably even for the latter case. This observation makes it simpler to speculate about which extensions with general flavor structure may also fit the data.

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In the past decade an immense amount of measurements determined that the standard model (SM) is responsible for the dominant part of flavor and  $CP$  violation in meson decays. However, in some processes, mainly related to  $B_s$  decays, possible new physics (NP) contributions are still poorly constrained, and motivated NP scenarios predict sizable deviations from the SM. Recently the D0 Collaboration reported a measurement of the like-sign dimuon charge asymmetry in semileptonic  $b$  decay with improved precision [1],

$$a_{\text{SL}}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}} = -(9.57 \pm 2.51 \pm 1.46) \times 10^{-3}, \quad (1)$$

where  $N_b^{++}$  is the number of  $b\bar{b} \rightarrow \mu^+\mu^+X$  events (and similarly for  $N_b^{--}$ ). This result is  $3.2\sigma$  from the quoted SM prediction,  $(a_{\text{SL}}^b)^{\text{SM}} = (-2.3_{-0.6}^{+0.5}) \times 10^{-4}$  [2]. At the Tevatron both  $B_d^0$  and  $B_s^0$  are produced, and hence  $a_{\text{SL}}^b$  is a linear combination of the two asymmetries [1]

$$a_{\text{SL}}^b = (0.506 \pm 0.043)a_{\text{SL}}^d + (0.494 \pm 0.043)a_{\text{SL}}^s. \quad (2)$$

The above result should be interpreted in conjunction with three other measurements: (i) the  $B_d$  semileptonic asymmetry, measured by the  $B$  factories,  $a_{\text{SL}}^d = -(4.7 \pm 4.6) \times 10^{-3}$  [3]; (ii) the flavor specific asymmetry measured from time dependence of  $B_s^0 \rightarrow \mu^+D_s^-X$  decay and its  $CP$  conjugate,  $a_{\text{fs}}^s = -(1.7 \pm 9.1 \pm 1.5) \times 10^{-3}$  [4]; and (iii) the measurements of  $\Delta\Gamma_s$  and  $S_{\psi\phi}$  (the  $CP$  asymmetry in the  $CP$ -even part of the  $\psi\phi$  final state in  $B_s$  decay) [5–8]. Here  $\Delta\Gamma_s = \Gamma_L - \Gamma_H$  is the width difference of the heavy and light  $B_s$  mass eigenstates. If  $CP$  violation is negligible in the relevant tree-level decays,

then  $a_{\text{fs}}^s = a_{\text{SL}}^s$ . The SM predictions for the asymmetries  $a_{\text{SL}}^d$  and  $a_{\text{SL}}^s$  are negligibly small, beyond the reach of the Tevatron experiments [9–11]. If the evidence for the sizable dimuon charge asymmetry in Eq. (1) is confirmed, it would unequivocally point to  $CP$  violation beyond the Cabibbo-Kobayashi-Maskawa (CKM) mechanism of the SM. The present experimental uncertainties of  $a_{\text{SL}}^d$  and  $a_{\text{SL}}^s$  separately are larger than that of their combination,  $a_{\text{SL}}^b$ . Thus, from Eq. (1) alone it is not clear if the tension with the SM is in the  $B_d$  or in the  $B_s$  system. Bounds from other observables imply (see below) that new physics contributions in  $B_d$  mixing with a generic weak phase cannot exceed roughly 20% of the SM, while in  $B_s$  mixing much larger NP contributions are still allowed.

We focus on interpreting the data *assuming* that the above measurements are associated with new  $CP$  violating physics which contributes to  $B_{d,s}$  mixing, while its contribution to  $CP$  violation in tree-level decay amplitudes is negligible. Under this assumption the D0 result in Eq. (1) is correlated with the Tevatron measurements of  $S_{\psi\phi}$  [12] (and  $\Delta\Gamma_s$ ). These measurements provide nontrivial tests of our hypothesis (see [13] for relaxing these assumptions). Neglecting the small SM contribution to  $S_{\psi\phi}$ , the following relation holds between experimentally measurable quantities [14]

$$a_{\text{SL}}^s = -\frac{|\Delta\Gamma_s|}{\Delta m_s} S_{\psi\phi} / \sqrt{1 - S_{\psi\phi}^2}, \quad (3)$$

where  $\Delta m_s \equiv m_H - m_L$ . Using the new measurement in Eq. (1) together with Eq. (2), the above relation implies

$$|\Delta\Gamma_s| \simeq -\Delta m_s (2.0a_{\text{SL}}^b - 1.0a_{\text{SL}}^d) \sqrt{1 - S_{\psi\phi}^2} / S_{\psi\phi}. \quad (4)$$

For simplicity we do not display the  $\mathcal{O}(10\%)$  uncertainties of the two numerical factors. The CDF and D0 time-dependent  $B_s \rightarrow \psi\phi$  analyses provide a measurement of  $\Delta\Gamma_s$  vs  $S_{\psi\phi}$ . Hence all quantities in Eq. (4) are constrained, and our analysis can be performed without the theoretical prediction of  $\Delta\Gamma_s$  [15], using its determination from data instead.

Using the measured values of  $\Delta m_s$  and  $a_{\text{SL}}^{b,d}$ , we find

$$|\Delta\Gamma_s| \sim [(0.28 \pm 0.15) \text{ ps}^{-1}] \sqrt{1 - S_{\psi\phi}^2} / S_{\psi\phi}. \quad (5)$$

The recent CDF [8] and D0 [5] results give best fit values around  $(\Delta\Gamma_s, S_{\psi\phi}) \sim (\pm 0.15 \text{ ps}^{-1}, 0.5)$ . This shows that the new  $a_{\text{SL}}^b$  measurement in Eq. (1) is consistent with the data on  $\Delta\Gamma_s$  and  $S_{\psi\phi}$ . This consistency is a nontrivial test of the assumption that NP contributes only to neutral meson mixing.

New physics in the mixing amplitudes of the  $B_{d,s}$  mesons can in general be described by four real parameters, two for each neutral meson system,

$$M_{12}^{d,s} = (M_{12}^{d,s})^{\text{SM}} (1 + h_{d,s} e^{2i\sigma_{d,s}}). \quad (6)$$

We denote by  $M_{12}^q$  ( $\Gamma_{12}^q$ ) the dispersive (absorptive) part of the  $B_q^0 - \bar{B}_q^0$  mixing amplitude, and SM superscripts denote the SM values (for quantities not explicitly defined here, see Ref. [16]). The modification to the SM predictions for the relevant observables in terms of  $h_q$  and  $\sigma_q$  is straightforward [12].

As already discussed, the new D0 measurement directly correlates the possible NP contributions in the  $B_d$  and  $B_s$  systems [see Eq. (2)]. In order to quantitatively assess our NP hypothesis, we perform a global fit using the CKMFITTER package [17] to determine simultaneously the NP parameters  $h_{d,s}$  and  $\sigma_{d,s}$ , as well as the  $\bar{\rho}$  and  $\bar{\eta}$  parameters of the CKM matrix.

The results presented here use the post-Beauty2009 CKMFITTER input values [17], except for the lattice input parameters where we use [18], and the most recent experimental data. For  $S_{\psi\phi}$  vs  $\Delta\Gamma_s$ , we use the  $2.8 \text{ fb}^{-1}$  2D likelihood of D0 [5] and the  $5.2 \text{ fb}^{-1}$  1D likelihood of the recent CDF measurement [8] (the 2D likelihood is not available); these fits are done without assumptions on the strong phases. As already mentioned, neither the CDF nor the D0 result gives a significant tension in the fit, so we expect that a real 2D Tevatron combination of the ICHEP 2010 results [8,19] will not alter our results significantly. For the results presented here, we marginalize over  $|\Gamma_{12}^s|$  in the range  $0-0.3 \text{ ps}^{-1}$ , finding that the data prefer values for  $\Delta\Gamma_s$  about 2.5 times larger than the prediction [2]. If we use the theory prediction, our conclusions about NP do not change substantially, but the goodness of fit is reduced significantly.

Figure 1 shows the results of the global fit projected onto the  $h_d - h_s$  plane with  $1\sigma$  (solid lines),  $2\sigma$  (dashed lines), and  $3\sigma$  (dotted lines) contours. We find that the data show evidence for disagreement with the SM or, differently

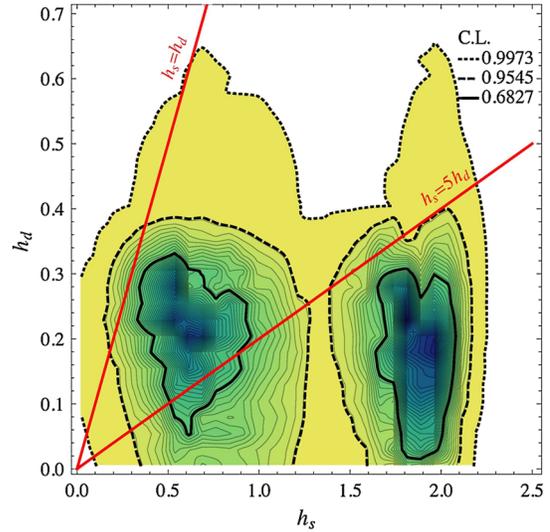


FIG. 1 (color online). The allowed range of  $h_s$  and  $h_d$  from the combined fit. The solid, dashed, and dotted contours show  $1\sigma$ ,  $2\sigma$ , and  $3\sigma$ , respectively.

stated, the no NP hypothesis  $h_s = h_d = 0$  is disfavored at the  $3.3\sigma$  level. Figure 2 shows the  $h_s - \sigma_s$  and  $h_d - \sigma_d$  fits. The two best fit regions are for  $h_s \sim 0.5$  and  $h_s \sim 1.8$  with sizable NP phases,  $\sigma_s \sim 120^\circ$  and  $\sigma_s \sim 100^\circ$ , respectively. Here the point  $h_s = 0$  is disfavored at only  $2.6\sigma$ , since  $h_s$  and  $h_d$  are correlated. In the  $h_d - \sigma_d$  case the data are consistent with no new physics contributions in  $B_d - \bar{B}_d$  mixing ( $h_d = 0$ ) below the  $2\sigma$  level.

To interpret the pattern of the current experimental data in terms of NP models, one should investigate if NP models that respect the SM approximate  $SU(2)_q$  symmetry are favored (in the SM this is due to the smallness of the masses in the first two generations and the smallness of the mixing with the third generation quarks), or if a hierarchy, such as  $h_s \gg h_d$ , is required. In Fig. 1 we show the  $h_d = h_s$  line, which makes it evident that while  $h_d = h_s$  is not disfavored, most of the favored parameter space has  $h_s > h_d$ . Actually, a non-negligible fraction of the allowed parameter space corresponds to  $h_s \gg h_d$ , as indicated by the  $h_s = 5h_d$  line in Fig. 1.

A particularly interesting NP scenario is to assume  $SU(2)_q$  universality ( $q = s, d$ ), defined as

$$h_b \equiv h_d = h_s, \quad \sigma_b \equiv \sigma_d = \sigma_s. \quad (7)$$

The relevant  $h_b - \sigma_b$  plane is shown in Fig. 3. The best fit region, near  $h_b \sim 0.25$  and  $\sigma_b \sim 120^\circ$ , is obtained as a compromise between the BABAR and Belle bounds in the  $B_d$  system and the tensions in the Tevatron  $B_s$  data with the SM predictions. This compromise mostly arises from the different magnitudes of  $h_{d,s}$ : while the best fit  $h_d$  value is a few times smaller than the best fit  $h_s$  value, the best fit values of the phases  $\sigma_{d,s}$  are remarkably close to each other, as can be seen in Fig. 2. Note that while the SM limit,  $h_b = 0$ , is obtained at less than  $3\sigma$  C.L., the goodness of the fit is significantly degraded compared with the nonuniversal case.

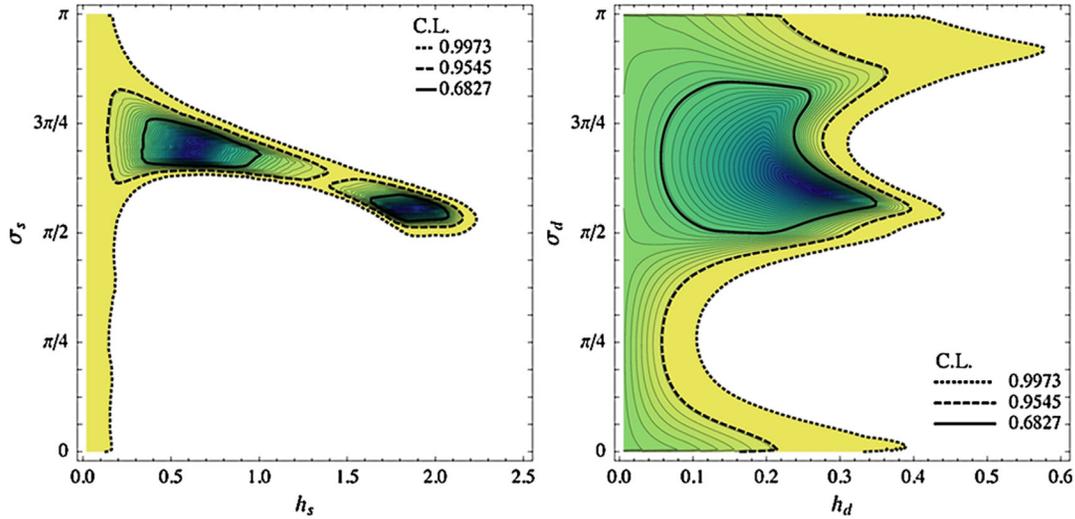


FIG. 2 (color online). The allowed ranges of  $h_s$ ,  $\sigma_s$  (left) and  $h_d$ ,  $\sigma_d$  (right) from the combined fit to all four NP parameters.

We now move to interpreting the above results, assuming that the dimuon asymmetry is indeed providing evidence for deviation from the SM. Interestingly, without restricting our discussion to a specific model, we can still make the following general statements.

(i) The present data support the hypothesis that new sources of  $CP$  violation are present and that they contribute mainly to  $\Delta F = 2$  processes via the mixing amplitude. As is well known, these processes are highly suppressed in the SM.

(ii) The SM extensions with  $SU(2)_q$  universality, where the new contributions to  $B_d$  and  $B_s$  transition are similar in size (relative to the SM), can accommodate the data but are not the most preferred scenarios experimentally. Universality is expected in a large class of well motivated models with approximate  $SU(2)_q$  invariance, for instance when flavor transitions are mediated by the third

generation sector [20]. The case where the NP contributions are  $SU(2)_q$  universal [see Eq. (7) and Fig. 3] is also quite generically obtained in the minimal flavor violation (MFV) framework [21] where new diagonal  $CP$  violating phases are present [22,23]. In an effective theory approach such a contribution may arise from the four-quark operators  $O_1^{bq} = \bar{b}_L^\alpha \gamma_\mu q_L^\alpha \bar{b}_L^\beta \gamma_\mu q_L^\beta$ ,  $O_2^{bq} = \bar{b}_R^\alpha q_L^\alpha \bar{b}_R^\beta q_L^\beta$ ,  $O_3^{bq} = \bar{b}_R^\alpha q_L^\beta \bar{b}_R^\beta q_L^\alpha$ , suppressed by scales  $\Lambda_{\text{MFV};1,2,3}$ , respectively. We find that the data require

$$\Lambda_{\text{MFV};1,2,3} \gtrsim \{8.8, 13y_b, 6.8y_b\} \sqrt{0.2/h_b} \text{ TeV}. \quad (8)$$

If the central value of the measurement in Eq. (1) is confirmed, this inequality would become an equality. Note that the dependence on the bottom Yukawa,  $y_b$ , is not shown for  $\Lambda_{\text{MFV};1}$ , since sizable  $CP$  violation in this case requires resummation of large effective bottom Yukawa coupling [23,24]. In general the presence of flavor diagonal phases could contribute to the neutron electric dipole moment [25]. However, this effect arises from a different class of operators and requires a separate investigation. Another interesting aspect of these flavor diagonal phases is that there are examples where these can contribute to the generation of matter-antimatter asymmetry, another issue which deserves further investigation.

(iii) While case (ii) is not excluded by the data, Fig. 1 shows that most of the allowed parameter space prefers  $h_s > h_d$ . This raises the following question: What kind of new physics can generate a large breaking of the approximate  $SU(2)_q$  symmetry without being excluded by  $CP$  violation in the  $K$  or  $D$  systems? Remarkably, even this case can be accounted for by the general MFV framework [23]. Consider models where operators with  $O_4$ -type chiral and color structure (defined in [26]) are the dominant ones. This may be possible because their contributions are renormalization group evolution enhanced. An example of such an operator is (similar  $O_5$ -type operators are typically suppressed compared to the  $O_4$ -type ones)

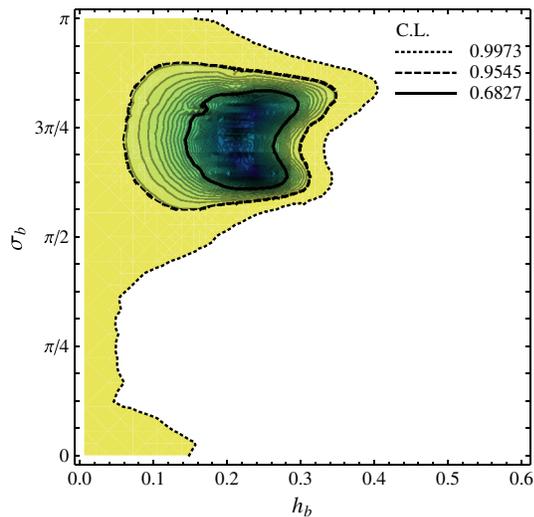


FIG. 3 (color online). The allowed  $h_b$ ,  $\sigma_b$  range assuming  $SU(2)$  universality.

$$O_4^{\text{NL}} = \frac{c}{\Lambda_{\text{MFV};4}^2} [\bar{Q}_3(A_d^m A_u^n Y_d)_{3i} d_i] [\bar{d}_3(Y_d^\dagger A_d^{l\dagger} A_u^{p\dagger})_{3i} Q_i]. \quad (9)$$

Here  $A_{u,d} \equiv Y_{u,d} Y_{u,d}^\dagger$  and  $n, m, l, p$  are integer powers and  $c$  is an  $\mathcal{O}(1)$  complex number. We focus on the nonlinear MFV regime, where the contributions of higher powers of the Yukawa couplings are equally important, so a resummation of the third generation eigenvalues is required (both for the up and down Yukawas), due to large logarithms or large anomalous dimensions. In Eq. (9) we adopt a linear formulation where the resummation of the third generation is not manifest; see [23,24] for a more rigorous treatment. Such operators can carry a new  $CP$  violating phase and may contribute dominantly to  $b \rightarrow s$  and *not* to  $b \rightarrow d$  transition, because of the chiral suppression induced by  $Y_d$ . We find that the data require

$$\Lambda_{\text{MFV};4} \gtrsim 13 y_b \sqrt{\frac{m_s}{m_b} \frac{0.5}{h_s}} \text{ TeV} \approx 2 y_b \sqrt{\frac{0.5}{h_s}} \text{ TeV}. \quad (10)$$

Thus, remarkably,  $h_s \gg h_d$  can arise in MFV models with flavor diagonal  $CP$  violating phases, where large chirality flipping sources exist at the TeV scale. Such models have not been studied in great detail, but possible interesting examples are supersymmetric extensions of the SM at large  $\tan\beta$  [27] or warped extra dimension models with MFV structure in the bulk [28]. We finally note that the operator  $O_4^{\text{NL}}$  predicts contributions to the  $B_d$  system suppressed by  $m_d/m_s \sim 5\%$ , which may be accessible in the near future and provide a direct test for the above scenario.

(iv) The fact that the data can be accounted for within the MFV framework makes it clear that it can be accommodated in models with even more general flavor structure [29,30]. Several conditions need to be met, though. For instance, the operators  $O_{2,3,4}$  require large chirality violating sources in addition to the  $CP$  violating phases, which are generically strongly constrained by neutron electric dipole moment and  $b \rightarrow s\gamma$ . Contributions to the  $O_1$  operator from  $SU(2)_w$  invariant new physics, on the other hand, are constrained by  $CP$  violation in  $D - \bar{D}$  mixing. They may also induce observable  $\Delta t = 1$  and  $\Delta t = 2$  top flavor violation at the LHC [31,32].

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*Note added.*—During the completion of this work, Ref. [33] appeared with partial overlaps with our ideas.

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