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A possible explanation of the D0 like-sign dimuon charge asymmetry

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We reconsider the recent observation by the D0 experiment of a sizable like-sign dimuon charge asymmetry, highlighting that it could be affected by *CP*-violating new physics contributions not only in B_d- and B_s-meson mixings but also in semileptonic decays of b and c quarks producing muons. The D0 measurement could be reconciled with the standard model expectations for neutral-meson mixings, provided that the *CP* asymmetry in semileptonic b (c) decays reaches 0.3% (1%). Such effects, which lie within the available (rather loose) experimental bounds, would be clear indications of new physics and should be investigated experimentally.

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I. INTRODUCTION

The recent observation by the D0 experiment of a sizable like-sign dimuon charge asymmetry [1–3] has attracted tremendous theoretical interest. If interpreted as originating from mixing-induced *CP* violation in semileptonic b-quark decays, the observed value of Ref. [3],

$$A^b_{\rm sl} = (-0.787 \pm 0.172 \pm 0.093)\%, \qquad (1)$$

is significantly larger than expected within the standard model (SM) $A^{b\,\rm SM}_{\rm sl} = (-3.96^{+0.15}_{-0.04}) \times 10^{-4}$ [4] (see also Refs. [5]). On the other hand, recent measurements of *CP* violation in wrong-sign semileptonic B_s decays from the LHCb and D0 collaborations [6,7],

$$\begin{aligned} a^s_{\rm sl} &= (-1.08 \pm 0.72 \pm 0.17)\%[\text{D0}], \\ a^s_{\rm sl} &= (-0.24 \pm 0.54 \pm 0.33)\%[\text{LHCb}], \end{aligned} \qquad (2)$$

are in agreement with SM expectations. Furthermore, recent precise determinations of the *CP* asymmetry in the $B_s \to J/\psi\phi$ decay [8], which are consistent with SM predictions, already severely constrain a possible interpretation of the value in Eq. (1) in terms of nonstandard *CP*-violating contributions to B_s mixing [4]. While the large observed $A^b_{\rm sl}$ could still originate from new *CP*-violating effects in B_d mixing, this would, nonetheless, require sizable correlated nonstandard contributions also to the absorptive mixing amplitude [4] (see also Ref. [9]).

In view of this intriguing situation, it is important to revisit theoretical assumptions underlying the interpretation of the D0 measurement. Since the D0 result indicates a significant discrepancy with the SM concerning a tiny *CP* asymmetry, one should reconsider other possible new physics (NP) sources that could contribute the observed *CP* violation but are generally assumed to be negligible *within the SM*. Indeed, one can imagine other sources of *CP* violation contributing to the dimuon charge asymmetry. Given the sizable charm contributions in both the inclusive muon and same-sign dimuon data samples, an attractive possibility is represented by *CP* violation in D^0 mixing. However, the D^0 oscillation probability has been measured, and its smallness renders any such contribution negligible.

On the other hand, the D0 analysis also assumes that the semileptonic b- and c-quark decays conserve *CP*. In this paper, we explore the consequences of relaxing this assumption. Direct *CP* violation in semileptonic decays of b or c quarks is presently only poorly constrained experimentally. The related inclusive semileptonic *CP* asymmetries are expected to be tiny in the SM and so offer interesting venues for contributions of NP. This motivates us to investigate whether the observed dimuon asymmetry in Eq. (1) could originate from *CP* violation in semileptonic b- and c-quark decays.

Previously, a study of the potential impact of *CP* violation in semileptonic b decays has been performed in Ref. [10], finding that the impact on $A^b_{\rm sl}$ was very small in the SM, as well as in a large class of NP models in which the main effect comes from the interference between SM tree and NP loop contributions (leading to a generic bound of a few 10^{-6}). We consider the problem from a different angle, by studying the main ingredients and assumptions behind the D0 analysis carefully, including also possible *CP*-violating contributions from semileptonic c decays. We, furthermore, reestimate the size of possible SM effects as well as presently experimentally allowed NP contributions to *CP* asymmetries in semileptonic b and c decays.

The rest of the paper is structured as follows: in Sec. II, we recall the basic elements of the D0 analysis needed for the extraction of the *CP* asymmetries from their inclusive muon and same-sign dimuon data samples. Section III is devoted to the derivation of the relevant observables in the presence of *CP* violation in semileptonic b- and c-quark decays and the reinterpretation of the D0 measurement in terms of the related *CP* asymmetries. In Sec. IV, we discuss other existing bounds on *CP* violation in these decays, and we give their expectations within the SM in Sec. V. Finally, we conclude in Sec. VI.

II. ELEMENTS OF THE EXPERIMENTAL ANALYSIS

We recall the basic ingredients in the determination of A_{sl}^b from the measurement of the dimuon charge asymmetry according to Ref. [2] and applicable to the most recent update [3] (we will use the values quoted in the latter reference for our numerical analysis). Experimentally, both the like-sign dimuon charge asymmetry A and the inclusive muon charge asymmetry a are measured by counting

$$A = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}, \qquad a = \frac{n^+ - n^-}{n^+ + n^-}, \tag{3}$$

where $N^{++,--}$ ($n^{+,-}$) denote the number of events with two muons (one muon) with a given charge passing the kinematic selections.

There are various detector and material-related processes contributing to these asymmetries. The reconstructed muons are classified into two categories: "short" (or S), including muons from weak decays of b, c, τ and from electromagnetic decays of short-lived mesons (ϕ, ω, η, ρ^0), and "long" (or L), coming from decays of charged kaons and pions as well as from particle misidentification. One can separate the contribution from short muons a_S to the inclusive muon charge asymmetry

$$a = f_S(a_S + \delta) + f_K a_K + f_\pi a_\pi + f_p a_p, \tag{4}$$

where δ is the charged asymmetry related to muon detection and identification and to the background L processes. f_K (f_π, f_p) is the fraction of muons from charged kaon decays (charged pion decays, misidentifications), and a_K (a_π, a_p) the corresponding charge asymmetry. These quantities are directly measured from experiment.

One has also a similar expression for the dimuon charge asymmetry:

$$A = F_{SS}A_S + (F_{bkg} - 2F_{LL})a_S + (2 - F_{bkg})\Delta + F_K A_K + F_\pi A_\pi + F_p A_p, \tag{5}$$

where Δ is the detection asymmetry; $F_{K,\pi,p}$ and $A_{K,\pi,p}$ are the fractions and asymmetries related to the various background L processes.

Finally, D0 also considers the combination

$$A' = A - \alpha a = F_{SS}A_S + (F_{bkg} - 2F_{LL} - \alpha f_S)a_S + \cdots, \tag{6}$$

where $\alpha = 0.959$ [2] or $\alpha = 0.89$ [3] is tuned to reduce the background uncertainties (denoted by the ellipses), leading to a precise extraction of a linear combination of a_S and A_s.

Various processes ($T_i^\pm$) producing $\mu^\pm$ can contribute to the asymmetries a_S and A_S with relative weights (w_i) as determined from Monte Carlo simulations; see Table I. We start with the probabilities $P_{b(c)}^\pm$ for an initial $b(\bar{c})$ quark in

TABLE I. Processes contributing to the inclusive muon and like-sign dimuon samples, adapted from Refs. [2,3] to include CP violation in B_d, B_s mixings (A_{sl}^b) and in semileptonic decays (A_{dir}^b, A_{dir}^c). Numerical values of the weights (normalized to $w_1 = 1$) used in the analysis are $w_2 = 0.096 \pm 0.012$, $w_3 = 0.064 \pm 0.006$, $w_4 = w_{4a} + w_{4b} + w_{4c} = 0.021 \pm 0.001$, $w_5 = 0.013 \pm 0.002$, $w_6 = 0.675 \pm 0.101$ [3], and the mean $B_{d,s}$ mixing probability $\chi_0 = 0.147 \pm 0.011$ [2] or $\chi_0 = 0.1259 \pm 0.0042$ [3].

	Process T_i^- ($\to \mu^-$)	Weight
1a	$b \to \mu^- X$	$w_1(1-\chi_0)(1+A_{dir}^b)$
1b	$\bar{b} \to b \to \mu^- X$	$w_1\chi_0(1-A_{sl}^b+A_{dir}^b)$
2a	$\bar{b} \to \bar{c} \to \mu^- X$	$w_2(1-\chi_0)(1+A_{dir}^c)$
2b	$b \to \bar{b} \to \bar{c} \to \mu^- X$	$w_2\chi_0(1+A_{sl}^b+A_{dir}^c)$
3	$b \to c\bar{c}q$ or $\bar{b} \to c\bar{c}\,\bar{q}$ with $\bar{c} \to \mu^- X$	$w_3(1+A_{dir}^c)/2$
4a	$b\bar{b}$ with η, ω, ρ^0, ϕ, J/ψ, $\psi' \to (\mu^+)\mu^-$	$w_{4a}/2$
4b	$c\bar{c}$ with η, ω, ρ^0, ϕ, J/ψ, $\psi' \to (\mu^+)\mu^-$	$w_{4b}/2$
4c	η, ω, ρ^0, ϕ, J/ψ, $\psi' \to (\mu^+)\mu^-$	$w_{4c}/2$
5	$b\bar{b}c\bar{c}$ with $\bar{c} \to \mu^- X$	$w_5(1+A_{dir}^c)/2$
6	$c\bar{c}$ with $\bar{c} \to \mu^- X$	$w_6(1+A_{dir}^c)/2$
	Process T_i^+ ($\to \mu^+$)	Weight
1a	$\bar{b} \to \mu^+ X$	$w_1(1-\chi_0)(1-A_{dir}^b)$
1b	$b \to \bar{b} \to \mu^+ X$	$w_1\chi_0(1+A_{sl}^b-A_{dir}^b)$
2a	$b \to c \to \mu^+ X$	$w_2(1-\chi_0)(1-A_{dir}^c)$
2b	$\bar{b} \to b \to c \to \mu^+ X$	$w_2\chi_0(1-A_{sl}^b-A_{dir}^c)$
3	$b \to c\bar{c}q$ or $\bar{b} \to c\bar{c}\,\bar{q}$ with $c \to \mu^+ X$	$w_3(1-A_{dir}^c)/2$
4a	$b\bar{b}$ with η, ω, ρ^0, ϕ, J/ψ, $\psi' \to \mu^+(\mu^-)$	$w_{4a}/2$
4b	$c\bar{c}$ with η, ω, ρ^0, ϕ, J/ψ, $\psi' \to \mu^+(\mu^-)$	$w_{4b}/2$
4c	η, ω, ρ^0, ϕ, J/ψ, $\psi' \to \mu^+(\mu^-)$	$w_{4c}/2$
5	$b\bar{b}c\bar{c}$ with $c \to \mu^+ X$	$w_5(1-A_{dir}^c)/2$
6	$c\bar{c}$ with $c \to \mu^+ X$	$w_6(1-A_{dir}^c)/2$

$b\bar{b}$ production (prompt $c\bar{c}$ production, without b hadrons) to produce a $\mu^\pm$, respectively. In the same processes, $\bar{P}^\pm_{b(c)}$ are then the corresponding probabilities to also produce a $\mu^\pm$ from the accompanying $\bar{b}(c)$ quark. Finally, we have the probabilities $P^\pm_{\rm SLM} = \bar{P}^\pm_{\rm SLM}$ to produce $\mu^\pm$ from a short-lived meson (SLM, η, ω, ρ^0, ϕ, J/ψ, ψ') in events with no b or c hadrons (we assume these processes to conserve CP). We should mention that this table is adapted from Refs. [2,3] by distinguishing the CP-conjugate processes in order to include the CP-violating effects discussed in the present paper.

Assuming all the processes producing muons to be independent,[1] we can now construct both asymmetries as

$$a_S = \frac{\sum_{q=b,c,\rm SLM}[(P^+_q + \bar{P}^+_q) - (P^-_q + \bar{P}^-_q)]}{\sum_{q=b,c,\rm SLM}[(P^+_q + \bar{P}^+_q) + (P^-_q + \bar{P}^-_q)]}, \tag{7}$$

and

$$A_S = \frac{\sum_{q=b,c,\rm SLM}[(P^+_q \cdot \bar{P}^+_q) - (P^-_q \cdot \bar{P}^-_q)]}{\sum_{q=b,c,\rm SLM}[(P^+_q \cdot \bar{P}^+_q) + (P^-_q \cdot \bar{P}^-_q)]}. \tag{8}$$

Let us finally mention that another observable is introduced in Ref. [3] by considering A'_S restricted to a sample of dimuons with a large-enough muon impact parameter. We refrain from studying in detail this observable because of our lack of knowledge concerning the experimental inputs and correlations required, but we highlight that it could be analyzed along the same lines as what we present here for A'_S.

III. THE ROLE OF THE SEMILEPTONIC *CP* ASYMMETRIES

In the absence of CP violation in semileptonic b- and c-quark decays, a_S and A_S can be directly expressed in terms of $A^b_{\rm sl}$, a linear combination of the wrong-sign semileptonic flavor specific asymmetries of the $B_{d,s}$ mesons measuring CP violation in their respective mixings[2]:

$$A^b_{\rm sl} = f_d a^d_{\rm sl} + f_s a^s_{\rm sl},$$
$$a^q_{\rm sl} = \frac{\Gamma(\bar{B}_q \to \mu^+ X) - \Gamma(B_q \to \mu^- X)}{\Gamma(\bar{B}_q \to \mu^+ X) + \Gamma(B_q \to \mu^- X)}, \tag{9}$$

with f_d and f_s the fractions of B_d and B_s mesons contributing to the asymmetry, which depend on the experimental setting. The values used by the D0 collaboration are either taken from averages at the Tevatron [2] or at the LEP machines [3].

In the presence of CP violation in inclusive semileptonic b or c decays, one must define two additional asymmetries $A^b_{\rm dir}$ and $A^c_{\rm dir}$:

$$A^b_{\rm dir} = \frac{\Gamma(b \to \mu^- X) - \Gamma(\bar{b} \to \mu^+ X)}{\Gamma(b \to \mu^- X) + \Gamma(\bar{b} \to \mu^+ X)},$$
$$A^c_{\rm dir} = \frac{\Gamma(\bar{c} \to \mu^- X) - \Gamma(c \to \mu^+ X)}{\Gamma(\bar{c} \to \mu^- X) + \Gamma(c \to \mu^+ X)}. \tag{10}$$

Then the most general expressions for the probabilities $P^\pm_q$, $\bar{P}^\pm_q$ read

$$P^+_b \propto w_{1b}(1 + A^b_{\rm sl} - A^b_{\rm dir}) + w_{2a}(1 - A^c_{\rm dir}) + (w_3 + w_5)(1 - A^c_{\rm dir})/2 + w_{4a}/2, \tag{11a}$$
$$P^-_b \propto w_{1a}(1 + A^b_{\rm dir}) + w_{2b}(1 + A^b_{\rm sl} + A^c_{\rm dir}) + (w_3 + w_5)(1 + A^c_{\rm dir})/2 + w_{4a}/2, \tag{11b}$$
$$\bar{P}^+_b \propto w_{1a}(1 - A^b_{\rm dir}) + w_{2b}(1 - A^b_{\rm sl} - A^c_{\rm dir}) + (w_3 + w_5)(1 - A^c_{\rm dir})/2 + w_{4a}/2, \tag{11c}$$
$$\bar{P}^-_b \propto w_{1b}(1 - A^b_{\rm sl} + A^b_{\rm dir}) + w_{2a}(1 + A^c_{\rm dir}) + (w_3 + w_5)(1 + A^c_{\rm dir})/2 + w_{4a}/2, \tag{11d}$$
$$P^+_c \propto w_6(1 - A^c_{\rm dir}) + w_{4b}/2, \tag{11e}$$
$$\bar{P}^-_c \propto w_6(1 + A^c_{\rm dir}) + w_{4b}/2. \tag{11f}$$

Furthermore, since semileptonic charm decay contributions to wrong-sign muons P^-_c and $\bar{P}^+_c$ are suppressed by the small D^0 mixing probability, we have simply

$$P^-_c = \bar{P}^+_c \propto w_{4b}/2, \tag{12}$$

whereas the short-lived meson decays provide

$$P^\pm_{\rm SLM} = \bar{P}^\pm_{\rm SLM} \propto w_{4c}/2. \tag{13}$$

We can then use Eqs. (7) and (8) to express the three observables related to S muon production,

$$a_S(A^b_{\rm sl}, A^c_{\rm dir}, A^b_{\rm dir}), \quad A_S(A^b_{\rm sl}, A^c_{\rm dir}, A^b_{\rm dir}), \quad A'_S(A^b_{\rm sl}, A^c_{\rm dir}, A^b_{\rm dir}) = F_{SS}A_S + (F_{\rm bkg} - 2F_{LL} - \alpha f_s)a_S, \tag{14}$$

in terms of the three asymmetries of interest.

Let us emphasize that, in principle, one needs to distinguish the weights corresponding to the three different contributions from short-lived mesons $T_{4a,4b,4c}$. Unfortunately, D0 does not provide the three probabilities separately. By varying them in the intervals $w_{4c} \in [0, w_4]$, $w_{4b} \in [0, w_4 - w_{4c}]$, and $w_{4a} \in [0, w_4 - w_{4c} - w_{4b}]$, we have checked, however, that the associated additional uncertainty in relating $A^b_{\rm sl}$, $A^b_{\rm dir}$, and $A^c_{\rm dir}$ to a_S and A_S is negligible (for definiteness, we present the results corresponding to $w_{4b} = w_{4c} = 0$ in the following). In the limiting case in which $A^b_{\rm dir} = A^c_{\rm dir} = 0$ and $w_{4b} = w_{4c} = 0$, the resulting expressions coincide with the corresponding expressions in Ref. [3].

Unfortunately, lacking complete information on the correlations among the various inputs entering the D0 measurement, we cannot extract the values of $A^b_{\rm dir}$ and/or

[1]The correctness of this approximation was verified numerically using Monte-Carlo-generated data samples in Ref. [2] for the case of CP violation in $B_{d,s}$ mixing.

[2]As mentioned in the introduction, possible contributions due to CP violation in D^0 mixing are extremely suppressed by the small mixing probability of D^0 mesons as measured experimentally.

TABLE II. *CP* asymmetries (in %) needed in meson mixing (first row) or semileptonic decays (second and third rows) in order to obtain the measured values of a, A, A' from Ref. [3].

CP asymmetry (%)	a	A	A'
$A^b_{\rm sl}(A^c_{\rm dir}=0, A^b_{\rm dir}=0)$ [3]	$-1.04 \pm 1.30 \pm 2.31$	$-0.808 \pm 0.202 \pm 0.222$	$-0.787 \pm 0.172 \pm 0.093$
$A^b_{\rm dir}(A^b_{\rm sl}=A^{b\,\rm SM}_{\rm sl}, A^c_{\rm dir}=0)$	$0.11 \pm 0.15 \pm 0.28$	$0.26 \pm 0.07 \pm 0.07$	$0.28 \pm 0.06 \pm 0.04$
$A^c_{\rm dir}(A^b_{\rm sl}=A^{b\,\rm SM}_{\rm sl}, A^b_{\rm dir}=0)$	$0.13 \pm 0.17 \pm 0.31$	$0.69 \pm 0.18 \pm 0.21$	$0.93 \pm 0.21 \pm 0.20$

$A^c_{\rm dir}$ from the measurements of a, A (and A') in a trustable way. However, using a_S, A_S, and A'_S, we are in the position to at least estimate the values of $A^c_{\rm dir}$ or $A^b_{\rm dir}$ assuming $A^b_{\rm sl}$ as predicted in the SM.[3] We do this by looking for solutions of the following equations:

$$a_S(A^{b\,\rm SM}_{\rm sl}, A^c_{\rm dir}, 0) = a_S(A^b_{{\rm sl},a}, 0, 0), \tag{15a}$$

$$A_S(A^{b\,\rm SM}_{\rm sl}, A^c_{\rm dir}, 0) = A_S(A^b_{{\rm sl},A}, 0, 0), \tag{15b}$$

$$A'_S(A^{b\,\rm SM}_{\rm sl}, A^c_{\rm dir}, 0) = A_S(A^b_{{\rm sl},A'}, 0, 0), \tag{15c}$$

and similarly for the case of nonzero $A^b_{\rm dir}$ instead of $A^c_{\rm dir}$. Here, $A^b_{{\rm sl},a}$, $A^b_{{\rm sl},A}$, $A^b_{{\rm sl},A'}$ are values of $A^b_{\rm sl}$ as extracted from a, A, or A' in Ref. [3]. The results are collected in Table II. The uncertainties quoted are dominated by those coming from $A^b_{{\rm sl},a}$, $A^b_{{\rm sl},A}$, $A^b_{{\rm sl},A'}$. These implicitly include the uncertainties (and correlations) from the other parameters entering the D0 analysis. We, furthermore, include explicit contributions from additional input parameters entering Eqs. (15a)–(15c) to the systematical uncertainties (without the proper knowledge of their correlations with $A^b_{{\rm sl},a}$, $A^b_{{\rm sl},A}$, $A^b_{{\rm sl},A'}$, this can only be considered a very rough estimate of the potential size of their effects). We note that these additional contributions only significantly affect the extraction of $A^c_{\rm dir}$ from A', for which they almost double the systematic error budget. On the other hand, the uncertainties coming from the SM prediction for $A^b_{\rm sl}$ are completely subleading and, thus, not quoted. Finally, we have checked that consistent results (but with slightly larger errors) are obtained when using inputs and asymmetry measurements from the previous D0 analysis [1,2].

One notices that *CP* asymmetries in inclusive semileptonic b (c) decays below the 0.3% (1%) level are required to explain the D0 measurement. We also note that the values of $A^b_{\rm dir}$ as extracted from a and A are well consistent at the 0.4σ level (assuming Gaussian uncertainties and in the absence of correlations), while there is a slight 1.2σ difference between the values of $A^c_{\rm dir}$ extracted the same way. Although the values extracted from A' are even bigger, they are expected to be highly correlated with the ones from the other two observables, and we do not attempt to assign a statistical meaning to these differences.

[3]We consider the SM result from Ref. [4], which is larger in size than the SM result quoted in Refs. [2,3], and, thus, our results can be considered more conservative concerning the required size of *CP* violation in semileptonic b or c decays.

One can imagine that both $A^b_{\rm dir}$ and $A^c_{\rm dir}$ may differ from zero. It is then useful to compute the dependence of a_S, A_S, and A'_S on the three *CP* asymmetries (to first order), yielding

$$a_S = A^b_{\rm sl}(0.061 \pm 0.004) + A^b_{\rm dir}(-0.535 \pm 0.028) + A^c_{\rm dir}(-0.454 \pm 0.028), \tag{16a}$$

$$A_S = A^b_{\rm sl}(0.474 \pm 0.023) + A^b_{\rm dir}(-1.421 \pm 0.024) + A^c_{\rm dir}(-0.527 \pm 0.025), \tag{16b}$$

$$A'_S = A^b_{\rm sl}(0.312 \pm 0.023) + A^b_{\rm dir}(-0.849 \pm 0.061) + A^c_{\rm dir}(-0.250 \pm 0.038), \tag{16c}$$

where the relevant systematical and statistical uncertainties have been combined in quadrature. We see that the observables a_S, A_S, A'_S exhibit similar sensitivities to the three types of *CP* violation. This clearly indicates that the interpretation of these quantities in terms of neutral-meson mixing requires a further check of the absence of *CP* violation in decays at a similar level to the uncertainties quoted for $A^b_{\rm sl}$.

Assuming the SM value of $A^b_{\rm sl}$, the experimental values of a_S and A_S set constraints in the $(A^b_{\rm dir}, A^c_{\rm dir})$ plane, as illustrated in Fig. 1. One can see that the sensitivity of the

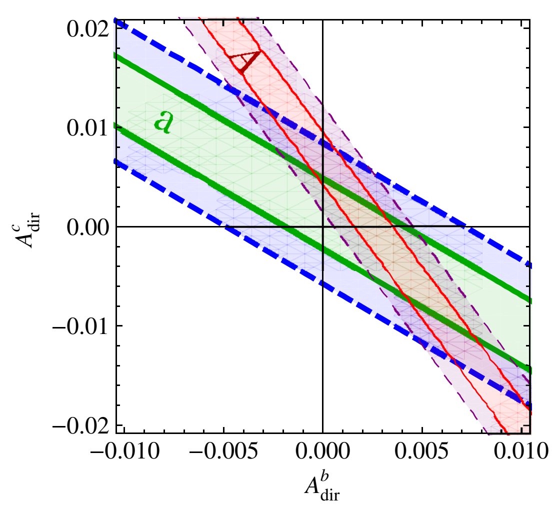

FIG. 1 (color online). The $A^c_{\rm dir}$ and $A^b_{\rm dir}$ semileptonic decay asymmetries needed in order to reproduce the measured values of inclusive semileptonic and same-sign dimuon asymmetries a (in thick contours) and A (in thin contours) (results for A' closely resemble those for A) using the SM predicted value for the inclusive wrong-sign semileptonic asymmetry $A^b_{\rm sl}$ (the weights and parameters of Ref. [3] have been used). The 1σ (2σ) bands are marked with full (dashed) contours.

observables to $A^b_{\rm dir}$ is larger than that to $A^c_{\rm dir}$, explaining that a larger asymmetry in charm is required to reproduce the D0 value for the dimuon asymmetry. Since our analysis does not include all the relevant correlations, we do not attempt to combine the two constraints statistically, even though this could be done easily by the D0 Collaboration.

IV. OTHER EXPERIMENTAL CONSTRAINTS ON DIRECT *CP* VIOLATION IN SEMILEPTONIC *b* AND *c* DECAYS

At present and to the best of our knowledge, there exists no direct experimental bound on the *CP* violation in semileptonic decays of either b or c quarks [11,12]. We can, nonetheless, form a poor man's estimate of the current constraints by considering the uncertainties on the *CP*-averaged (semi)leptonic branching fractions (estimating in this way the amount of *CP* violation in semileptonic decays that could be hidden by the systematics of the measurement). In particular, among the various measured semileptonic D^+, D^0, and D_s decays, the *CP*-averaged branching fraction of $D^+ \to \bar{K}^0 \mu^+ \nu_\mu$ (which accounts for more than half the inclusive semileptonic D^+ branching fraction) is currently most precisely known with 6.5% relative uncertainty [13]. Based on this and considering also the experimental bound on the *CP* asymmetries in leptonic $D^\pm \to \mu^\pm \nu$ decays [14], we observe that at the current level of uncertainty, *CP* violation in semileptonic D decays at or below 6% is still viable.

Concerning leptonic and semileptonic decays of B mesons, we find that the current level of uncertainty of the *CP* averaged inclusive $B \to X_c \ell \nu$ branching fractions [11], in principle, still allows for *CP* violation in semileptonic B decays at the level of around 3%. However, in this case, additional constraints can be derived using the measured flavor specific semileptonic charge asymmetries defined in Eq. (9) [12], which yields for the B_d meson

$$a^d_{\rm sl} = (-0.05 \pm 0.56)\%, \tag{17}$$

whereas the situation for $a^s_{\rm sl}$ is recalled in Eq. (2). These measurements are generally based on specific charmed decay modes associated with muons, so that they can be affected by *CP* violation in semileptonic b decays, but not in c decays, contrary to the D0 measurement.

In reinterpreting these results in terms of *CP*-violating asymmetries in inclusive semileptonic b decays at D0, we first identify $|a^d_{\rm sl}| \gtrsim |A^{B_d}_{\rm dir}|$ and $|a^s_{\rm sl}| \gtrsim |A^{B_s}_{\rm dir}|$, for which the semileptonic asymmetries $A^{B_q}_{\rm dir}$ are defined as in Eq. (10), but now refer to the relevant decaying $\bar{B}_q$ mesons. Next, we need to sum over the relative production fractions of the various b hadrons contributing to the semileptonic event samples:

$$A^b_{\rm dir} = f(B_u)A^{B_u}_{\rm dir} + f(B_d)A^{B_d}_{\rm dir} + f(B_s)A^{B_s}_{\rm dir} + \cdots, \tag{18}$$

where the ellipses denote neglected smaller b hadronic state contributions. As a first approximation for $f(B_q)$, we neglect different lifetime effects and use the measured unbiased b-hadron fractions as measured by various experiments at high energies $f(B_d) = f(B_u) = 0.401 \pm 0.007$ and $f(B_s) = 0.107 \pm 0.005$ [12]. Neglecting possible correlations between the various inputs and combining all uncertainties in quadrature, we obtain a bound of $|A^b_{\rm dir}| \lesssim 1.2\%$, which is safely above what is required for explaining the D0 result.

V. SM EXPECTATIONS FOR $A^b_{\rm dir}$ AND $A^c_{\rm dir}$

Finally, let us briefly comment on the expected size of $A^b_{\rm dir}$ and $A^c_{\rm dir}$ within the SM. Direct *CP* violation in decays requires the presence of (at least) two interfering decay amplitudes [we will denote them as $\mathcal{A}_T \equiv |\mathcal{A}_T| \exp i(\phi_T + \delta_T)$ and $\mathcal{A}_L \equiv |\mathcal{A}_L| \exp i(\phi_L + \delta_L)$] with different weak ($\phi_{T,L}$) and strong ($\delta_{T,L}$) phases. Denoting $\mathcal{R} \equiv |\mathcal{A}_L/\mathcal{A}_T|$, $\Delta\phi = \phi_L - \phi_T$, and $\Delta\delta = \delta_L - \delta_T$, the related *CP* asymmetry can then be written as

$$A_{\rm dir} = \frac{2\mathcal{R} \sin\Delta\delta \sin\Delta\phi}{1 + 2\mathcal{R}\cos\Delta\delta\cos\Delta\phi + \mathcal{R}^2}. \tag{19}$$

The dominant tree-level SM contributions to semileptonic transitions (below the W scale) are described by the relevant effective weak Hamiltonian

$$\mathcal{H}^{\rm sl}_{\rm eff} = \frac{4G_F}{\sqrt{2}} \sum_{U=u,c} \sum_{D=d,s,b} V^*_{UD}[\bar{U}\gamma_\mu(1-\gamma_5)D] \times [\bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell] + {\rm H.c.}, \tag{20}$$

leading to a very simple amplitude $\mathcal{A}_T$. The required additional amplitudes $\mathcal{A}_L$ can be generated at one loop via time ordered correlators of $\mathcal{H}^{\rm sl}_{\rm eff}$ with the effective weak Hamiltonian $\mathcal{H}^{nl}_{\rm eff}$ describing nonleptonic $b \to c\bar{u}d$ and $b \to c\bar{u}s$ decays $\int d^4x T\{\mathcal{H}^{nl}_{\rm eff}(0), \mathcal{H}^{\rm sl}_{\rm eff}(x)\}$. The presence of light quarks in the loop provides a source for the strong phase difference, while the weak phase difference is encoded in the relevant Cabibbo-Kobayashi-Maskawa matrix elements. However, being of higher order in $G_F \sim 1/v^2_{EW}$, these effects are expected to be severely suppressed leading to $\mathcal{R} \ll 1$. Expanding Eq. (19) to linear order in $\mathcal{R}$, assuming $\sin\Delta\delta = O(1)$ and using a naive dimensional analysis, we can estimate the resulting SM contributions to $A^b_{\rm dir}$ and $A^c_{\rm dir}$ coming from the interference between tree level and one loop as

$$A^{b\,{\rm SM}}_{\rm dir} \sim 2\frac{1}{4\pi}\left(\frac{m_b}{v_{EW}}\right)^2 {\rm Im}\left(\frac{V_{ub}V^*_{ud}V_{cd}}{V_{cb}}\right) \sim 10^{-6}, \tag{21a}$$

$$A^{c\,{\rm SM}}_{\rm dir} \sim 2\frac{1}{4\pi}\left(\frac{m_c}{v_{EW}}\right)^2 {\rm Im}\left(\frac{V_{cb}V^*_{ub}V_{us}}{V_{cs}}\right) \sim 10^{-10}. \tag{21b}$$

We observe that the sizes of $A^b_{\rm dir}$ or $A^c_{\rm dir}$ required to accommodate the D0 result are orders of magnitude larger than the above SM expectations for these quantities, and their confirmation would, thus, constitute a clear indication of NP.

A more elaborate discussion of the size of $A^{b\,{\rm SM}}_{\rm dir}$ was performed in Ref. [10], focusing on another intermediate state ($c\bar{s}$) with a contribution suppressed by three orders of magnitude compared to the naive estimate (21a) due to the consideration of another intermediate state (a $c\bar{s}$ pair) and the selection of penguin operators in $\mathcal{H}_{\rm eff}^{nl}$. It is not difficult to adapt the discussion presented in this reference to estimate the dominant SM effect coming from a $u\bar{d}$ intermediate state coupled through tree operators more precisely. One finds

$$A_{\rm dir}^{b\ {\rm SM}} = (c_1 N_c + c_2)\,{\rm Im}\left(\frac{V_{ub}V_{ud}^* V_{cd}}{V_{cb}}\right)\frac{G_F}{\sqrt{2}}\frac{m_b^2}{6\pi}R, \qquad (22)$$

where c_2 is the Wilson coefficient associated to the operator of corresponding to a tree-level W exchange in $\mathcal{H}_{\rm eff}^{nl}$ and c_1, its color-suppressed counterpart. R is the (strong part of the) interference ${\rm Im}(\mathcal{A}_T\mathcal{A}_L^\dagger)$ normalized to the (strong part of the) dominant amplitude $|M_0|^2$, each being integrated over the $b \to c\ell\nu$ phase space. The estimation of R in Ref. [10] must be adapted to take into account that the intermediate state consists of massless quarks, whereas the integration over phase space is unchanged:

$$R_{u\bar{d}} = \frac{\int_{r_c}^{(1-\sqrt{r_c})^2} dz F(z, r_c) G(z, 0)}{\int_0^{(1-\sqrt{r_c})^2} dz F(z, r_c)}, \qquad r_c = \frac{m_c^2}{m_b^2}, \qquad z = \frac{q^2}{m_b^2}, \qquad (23)$$

where the absorptive part of the $\mathcal{A}_L$ amplitude reads $G(z, m_q = 0) = 2z$ and the expression of the phase space $F(z, r_c)$ can be found in Eq. (32) of Ref. [10]. Varying m_c around 1.3 GeV and m_b around 4.8 GeV yields values of $A_{\rm dir}^{b\ {\rm SM}} \sim 2 \times 10^{-8}$, 1 order of magnitude larger than the estimate in Ref. [10]. This enhancement in our case is due to larger Wilson coefficients and a larger strong-interaction factor R for massless intermediate states.

In the same reference, a generic bound for NP contributions was presented for a large class of NP models in which the main effect comes from the interference between SM tree and NP loop contributions (leading to a generic bound of a few 10^{-6}), and the potential contribution to $A_{\rm dir}^b$ arising in the framework of a left-right symmetric model was studied. The experimental constraints on the right-handed charged currents led to values for the asymmetry of a similar size to the naive estimate in Eq. (21a) (around 10^{-7}), suggesting that $A_{\rm dir}^b \sim \mathcal{O}(10^{-3})$ would be difficult to accommodate with simple NP models.

While an explicit NP model construction reproducing the required effects is clearly beyond the scope of the present study, we briefly mention two possibilities of circumventing the generic bound of Ref. [10] by selecting cases in which its underlying assumptions (NP enters only via charged current loops) are not fulfilled. The first example involves introducing a light neutral Z' coupling only to quarks (with strength $g_{Z'}^{q,q'}$ naturally carrying a CP-odd phase) and charged under a non-Abelian family symmetry so that dangerous tree-level $\Delta F = 2$ flavor-changing neutral currents are forbidden. Such neutral vector bosons are also only weakly constrained by direct searches and electroweak precision tests (cf. Ref. [15]). At the same time, an effective $\bar{c}b\bar{d}u$ interaction can be generated, suppressed by a mass scale $(m_{Z'}/\sqrt{|g_{Z'}^{bd}g_{Z'}^{uc*}|})$ comparable or even below the SM weak scale. The resulting $A_{\rm dir}^b$ can be correspondingly enhanced compared to the SM estimate by a factor $(v_{EW}/m_{Z'})^2{\rm Im}(g_{Z'}^{bd}g_{Z'}^{uc*}/V_{ub}V_{cd})$, thus, in principle, circumventing the bound in Ref. [10].

The second possibility exists through final states involving light invisible particles mimicking the missing energy signature of the SM neutrinos in semileptonic decays (see Ref. [16] for recent work along these lines). For example, one can consider lepton-number (and CP) violating interactions of the form $\bar{c}b\bar{\ell}\chi_i$, where χ_i ($i = 1, 2$) are new light neutral fermions. If these fermions are very short lived (such that their decay widths are comparable to their masses) and decay to a common (invisible) final state, sizeable CP asymmetries can be generated from interferences of amplitudes with intermediate χ_1 and χ_2 (see Ref. [17] for previous discussions of this mechanism). Such incoherent effects, with new intermediate states and interactions, could, thus, in principle, provide another way to circumvent the generic bound of Ref. [10].

VI. CONCLUSIONS

We have reconsidered the recent measurement made by the D0 Collaboration of a like-sign dimuon asymmetry [1–3]. Since this measurement disagrees significantly with the SM prediction for CP violation in B_d- and B_s-meson mixing, we have reassessed some of the underlying assumptions of the analysis, allowing for NP effects violating CP not only in mixing but also in decays.

We have shown that the D0 result can be made compatible with the SM expectations for CP violation in $B_{d,s}$ mixing, provided that non-SM contributions are introduced either in

(i) CP violation in b semileptonic decays ($A_{\rm dir}^b \simeq 0.3\%$), which is currently allowed experimentally, though close to the uncertainties quoted for the individual semileptonic B_d and B_s asymmetries and difficult to accommodate with simple NP models.

(ii) CP violation in c semileptonic decays ($A_{\rm dir}^c \simeq 1\%$), which is currently allowed experimentally.

As indicated in Fig. 1, one could also consider the presence of both effects. We discussed briefly the size of these effects in the SM and showed that they are much smaller than what is required to explain the D0 result.

In particular, a CP-violating contribution to charm semileptonic decays would allow the D0 measurement of the like-sign dimuon asymmetry to differ from the SM value, but it would not affect the measurements of $a_{\rm sl}^q$ based on specific decay channels like $B_s \to D_s\mu X$.

Our analysis is obviously very naive as far as experimental uncertainties and correlations are concerned.

The numbers provided in this short paper are only indicative, but we firmly hope that they will incite experimentalists to revisit the D0 analysis and related studies to include and constrain *CP* violation in semileptonic b and c decays. Such cross-checks would be particularly useful to improve our understanding of neutral-meson mixing and its potential for NP searches.

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[1] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **105**, 081801 (2010).
[2] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. D **82**, 032001 (2010).
[3] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. D **84**, 052007 (2011).
[4] A. Lenz, U. Nierste, J. Charles, S. Descotes-Genon, A. Jantsch, C. Kaufhold, H. Lacker, S. Monteil, V. Niess, and S. T'Jampens, Phys. Rev. D **83**, 036004 (2011); A. Lenz, U. Nierste, J. Charles, S. Descotes-Genon, H. Lacker, S. Monteil, V. Niess, and S. T'Jampens, Phys. Rev. D **86**, 033008 (2012).
[5] S. Laplace, Z. Ligeti, Y. Nir, and G. Perez, Phys. Rev. D **65**, 094040 (2002); M. Beneke, G. Buchalla, A. Lenz, and U. Nierste, Phys. Lett. B **576**, 173 (2003); M. Ciuchini, E. Franco, V. Lubicz, F. Mescia, and C. Tarantino, J. High Energy Phys. 08 (2003) 031; A. Lenz and U. Nierste, J. High Energy Phys. 06 (2007) 072.
[6] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **110**, 011801 (2013).
[7] LHCb Collaboration, LHCb-CONF-2012-022.
[8] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. D **85**, 032006 (2012); T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D **85**, 072002 (2012); LHCb Collaboration, Phys. Rev. Lett. **108**, 101803 (2012); LHCb-CONF-2012-002; LHCb Collaboration, Phys. Lett. B **707**, 497 (2012).
[9] M. Freytsis, Z. Ligeti, and S. Turczyk, Phys. Rev. D **86**, 116004 (2012).
[10] S. Bar-Shalom, G. Eilam, M. Gronau, and J. L. Rosner, Phys. Lett. B **694**, 374 (2011).
[11] K. Nakamura *et al.* (Particle Data Group Collaboration), J. Phys. G **37**, 075021 (2010).
[12] D. Asner *et al.* (Heavy Flavor Averaging Group Collaboration), arXiv:1010.1589.
[13] M. Ablikim *et al.* (BES Collaboration), Phys. Lett. B **644**, 20 (2007).
[14] B. I. Eisenstein *et al.* (CLEO Collaboration), Phys. Rev. D **78**, 052003 (2008).
[15] B. Grinstein, A. L. Kagan, J. Zupan, and M. Trott, J. High Energy Phys. 10 (2011) 072.
[16] J. F. Kamenik and C. Smith, J. High Energy Phys. 03 (2012) 090; S. Fajfer, J. F. Kamenik, I. Nisandzic, and J. Zupan, Phys. Rev. Lett. **109**, 161801 (2012).
[17] G. Eilam, J. L. Hewett, and A. Soni, Phys. Rev. Lett. **67**, 1979 (1991); D. Atwood, G. Eilam, M. Gronau, and A. Soni, Phys. Lett. B **341**, 372 (1995).