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# New physics effects in tree-level decays and the precision in the determination of the quark mixing angle $\gamma$

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We critically review the assumption that no new physics is acting in tree-level $B$-meson decays and study the consequences for the ultimate precision in the direct determination of the Cabibbo-Kobayashi-Maskawa (CKM) angle $\gamma$. In our exploratory study we find that sizeable universal new physics contributions, $\Delta C_{1,2}$, to the tree-level Wilson coefficients $C_{1,2}$ of the effective Hamiltonian describing weak decays of the $b$ quark are currently not excluded by experimental data. In particular, we find that $\mathrm{Im}\Delta C_1$ and $\mathrm{Im}\Delta C_2$ can easily be of order $\pm 10\%$ without violating any constraints from data. Such a size of new physics effects in $C_1$ and $C_2$ corresponds to an intrinsic uncertainty in the CKM angle $\gamma$ of the order of $|\delta\gamma| \approx 4°$, which is slightly below the current experimental precision. The accuracy in the determination of $\gamma$ can be improved by putting stronger constraints on the tree-level Wilson coefficients, in particular $C_1$. To this end we suggest a more refined theoretical study as well as more precise measurements of the observables that currently provide the strongest bounds on hypothetical new weak phases in $C_1$ and $C_2$. We note that the semileptonic $CP$ asymmetries seem to have the best prospect for improving the bound on the weak phase in $C_1$.

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## I. INTRODUCTION

The standard model of particle physics (SM) seems to be more successful than previously expected. With the detection of the Higgs particle in 2012 its particle content is finally complete. Up to now we have neither directly detected new particles nor did we find significant new physics effects in indirect searches. Nevertheless, many of the motivations for new physics searches, like the origin of the baryon asymmetry in the universe or the nature of dark matter, remain unanswered within the SM. In addition, there are several hints for experimental deviations from SM predictions, e.g., in the quark flavor sector. (See for example [1,2].) In order to draw any definite conclusions from these arising hints for new physics, a higher precision is mandatory both in experiment and theory.

An important example for such a necessary improvement in precision is the determination of the Cabibbo-Kobayashi-Maskawa (CKM) angle $\gamma$ from $B \to DK$ decays. The current experimental uncertainty from LHCb is 10°, while the expected experimental accuracy at Belle II and LHCb (after the next LHC run) is 1° [3,4]. In the SM this angle can be determined essentially without any hadronic uncertainties [5]. The remaining relative theoretical uncertainty is of the order of $10^{-7}$ [6].

A crucial assumption in this analysis is the absence of weak phases other than the CKM angle $\gamma$ in $B \to DK$ decays. This assumption is correct within the SM but could be spoiled by the existence of new physics. In view of the expected experimental accuracy on $\gamma$ one should wonder to what extent this assumption is backed up by experimental data. While many different corrections to this assumption have been studied in the literature (see the discussion in Sec. III), the absence of new-physics contributions to the tree-level Wilson coefficients of the SM current-current operators has, to our knowledge, hitherto not been questioned in this context. In this article we investigate the experimental bounds on new physics contributions to these Wilson coefficient by extending the set of observables considered in [7,8]. Assuming that the new-physics effects are flavor universal we find that, from a purely phenomenological viewpoint, we cannot exclude shifts in $\gamma$ of the order of $\pm 4°$. Such shifts are clearly not negligible in view of the expected sensitivity. Hence, the statement that the extraction of $\gamma$ from tree-level decays corresponds to a pure SM value should be taken with care.

This article is organized as follows. First we collect all bounds on the Wilson coefficients of the current-current operators in Sec. II, and then investigate the implication for the extraction of $\gamma$ in Sec. III. Finally, in Sec. IV we summarize our findings and point out some strategies on how to improve the bounds on new physics effects in tree-level decays.

 

## II. NEW PHYSICS IN TREE-LEVEL DECAYS

We are interested in the following effective Hamiltonian for nonleptonic $b$-quark decays, of the form $b \to u_1 \bar{u}_2 d_1$, where $u_{1,2}$ are up-type quarks and $d_1$ is a down-type quark:

$$\mathcal{H}_{\rm eff}^{\bar{u}_1 u_2 d_1} = \frac{G_F}{\sqrt{2}} V_{u_1 b} V^*_{u_2 d_1} [C_1 Q_1^{\bar{u}_1 u_2 d_1} + C_2 Q_2^{\bar{u}_1 u_2 d_1}] + \cdots. \tag{1}$$

Here, $Q_1^{\bar{u}_1 u_2 d_1}$ and $Q_2^{\bar{u}_1 u_2 d_1}$ are the tree-level operators which are already present in the SM,

$$\begin{aligned} Q_1^{\bar{u}_1 u_2 d_1} &= (\bar{u}_1^\alpha b^\beta)_{V-A} (\bar{d}_1^\beta u_2^\alpha)_{V-A}, \\ Q_2^{\bar{u}_1 u_2 d_1} &= (\bar{u}_1^\alpha b^\alpha)_{V-A} (\bar{d}_1^\beta u_2^\beta)_{V-A}, \end{aligned} \tag{2}$$

and the ellipses denote the penguin operators that we do not consider. We decompose the Wilson coefficients as

$$C_{1,2} = C_{1,2}^{\rm SM} + \Delta C_{1,2}, \tag{3}$$

where $C_{1,2}^{\rm SM}$ denote the SM values of the Wilson coefficients $C_1$ and $C_2$. The shifts induced by integrating out possible new particles with weak-scale masses are denoted by $\Delta C_{1,2}$. We assume that these shifts are flavor independent (i.e., they are the same for each choice of $u_1$, $u_2$, $d_1$).

Let us motivate this particular ansatz for new physics. The conventional line of reasoning is that loop-induced operators (e.g., those that induce flavor-changing neutral current transitions) are more sensitive to new physics than tree-level operators. As a result, most "model-independent" studies focus on new-physics contributions to the loop-induced operators and neglect new physics contributions to the tree-level operators. However, there is no physical principle that forbids new physics to affect the tree-level operators. For instance, the effect of new right-handed charged currents on the measurement of $V_{ub}$ has already been studied (see, e.g., Ref. [9,10]).

In this work, we are mainly interested in the effect of new-physics contributions on the extraction of the CKM angle $\gamma$ from tree-level decays. Therefore, we look at modifications of the SM tree-level Wilson coefficients whilst leaving the loop-induced coefficients unaltered. A truly model-independent analysis would have to allow for new physics in all operators (e.g., those contributing to $D$-meson mixing). This would result in more than 100 complex free parameters and is beyond the scope of this paper. However, note that in a frequentist analysis the allowed range of any given parameter (determined from the profile likelihood) can only *increase* when more free parameters are included in the analysis. In particular, the possible variation in $\Delta\gamma$ would only get bigger.

New physics contributions to the Wilson coefficients $C_1$ and $C_2$ will not only modify tree-level dominated $B$-meson decays, but will, via operator mixing when running from $\mu \sim M_W$ to $\mu \sim m_b$, contribute to FCNC processes. Both effects allow us to obtain constraints on $\Delta C_{1,2}$.

The modification of the decay rate difference of the neutral $B_d$ meson system, $\Delta\Gamma_d$, has already been investigated in [7] (without the assumption of flavor universality). Here we extend this analysis by including more $b$-decay channels and thus more observables. In [8] new physics contributions to the tree-level part of the $b \to u\bar{u}s$ decay were considered as solution to the "$\Delta\mathcal{A}_{\rm CP}$ puzzle" in $B \to K\pi$ decays. We will not consider the observables from [8], because they are very sensitive to penguin contributions, and we concentrate on tree-dominated decays in this paper. Moreover, our final conclusion would not change with the inclusion of the $B \to K\pi$ observables.

The following observables are taken over directly from [7]:

(i) The $b \to c\bar{u}d$-transition is constrained by $B \to D\pi$ and $B \to D^{(*)0}h^0$ decays. For the corresponding theory expressions QCD factorization [11] is used.

(ii) The rare decay $b \to d\gamma$ gives the strongest bound on the $b \to c\bar{c}d$-transition, where we use the theoretical formulas from [12] and [13]. This decay gets also restrictions [7] from the direct measurement of the CKM angle $\beta$ in the decay $B \to J/\psi K_S$ and the semileptonic asymmetry $a_{sl}^d$ described in more detail below.

(iii) QCD factorization [14] is used again to constrain the $b \to u\bar{u}d$-channel with $B \to \pi\pi, \rho\pi, \rho\rho$-decays. As in [7] for the $B \to \pi\pi$ transition two observables are considered: the indirect $CP$ asymmetry $S_{\pi\pi}$ and the ratio of hadronic and differential semileptonic decay rate $R_{\pi^-\pi^0}$.

For these observables we use the same formalism and the same experimental data as described in [7] and we refer the interested reader to this paper for details. Next we extend some of the formulas used already in [7].

(i) The total lifetime of $b$-hadrons can be compared with the experimental measurements. We use the following expression that shows the explicit dependence on the Wilson coefficients, see, e.g., [15]:

$$\frac{\Gamma_{\rm tot}}{\Gamma_{\rm tot}^{\rm SM}} = \frac{3|C_1|^2 + 3|C_2|^2 + 2{\rm Re}[C_1^* C_2]}{3|C_1^{\rm SM}|^2 + 3|C_2^{\rm SM}|^2 + 2{\rm Re}[C_1^{*\rm SM} C_2^{\rm SM}]}. \tag{4}$$

For $\Gamma_{\rm tot}^{\rm SM}$ we take the result from [16] that includes $\alpha_s$-corrections and terms that are subleading in the heavy-quark expansion; the experimental value is taken from [17]: $\Gamma_{\rm tot}^{\rm SM} = (3.6 \pm 0.8) \cdot 10^{-13}$ GeV and $\Gamma_{\rm tot} = (4.20 \pm 0.02) \cdot 10^{-13}$ GeV.

(ii) For the channel $b \to c\bar{c}s$ we take constraints from the branching ratio $\mathcal{B}(B \to X_s\gamma)$ into account. The bounds for this observable were calculated using the NLO expressions given in [18] as well as the NNLO SM value quoted in [19], the experimental result considered was obtained from [17].

Additional bounds on $C_1$ and $C_2$ can be obtained from the decay rate difference of the neutral $B_s$-mesons, $\Delta\Gamma_s$, and the semileptonic $CP$ asymmetries, $a_{sl}^s$. These observables have not been considered in [7]; they can be extracted for both neutral $B$-meson systems from the theory expression for $\Gamma_{12}^q/M_{12}^q$:

$$a_{sl}^q = \mathrm{Im}\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right), \qquad \frac{\Delta\Gamma_q}{\Delta M_q} = -\mathrm{Re}\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right). \tag{5}$$

Using the results from [20–22] we find for the explicit dependence on the NP contributions $\Delta C_1$ and $\Delta C_2$ at the scale $m_b$:

$$\frac{\Gamma_{12}^d/M_{12}^d}{\Gamma_{12}^{d,\mathrm{SM}}/M_{12}^{d,\mathrm{SM}}} = 1 - (0.23 - 0.047i)\cdot\Delta C_1 + (0.76 + 0.25i)\cdot\Delta C_1^2 + (1.91 - 0.0029i)\cdot\Delta C_2 + (0.084 + 0.14i)\cdot\Delta C_1\cdot\Delta C_2 + (0.93 + 0.0072i)\cdot\Delta C_2^2, \tag{6}$$

$$\frac{\Gamma_{12}^s/M_{12}^s}{\Gamma_{12}^{s,\mathrm{SM}}/M_{12}^{s,\mathrm{SM}}} = 1 - (0.24 + 0.0022i)\cdot\Delta C_1 + (0.68 - 0.012i)\cdot\Delta C_1^2 + (1.90 + 0.00013i)\cdot\Delta C_2 + (0.043 - 0.0068i)\cdot\Delta C_1\cdot\Delta C_2 + (0.93 - 0.00035i)\cdot\Delta C_2^2. \tag{7}$$

We now express the semileptonic asymmetry and the decay rate difference in terms of these ratios as

$$a_{sl}^q = \mathrm{Im}\left(\frac{\Gamma_{12}^q/M_{12}^q}{\Gamma_{12}^{q,\mathrm{SM}}/M_{12}^{q,\mathrm{SM}}}\cdot\frac{\Gamma_{12}^{q,\mathrm{SM}}}{M_{12}^{q,\mathrm{SM}}}\right), \tag{8}$$

$$\Delta\Gamma_q = -\mathrm{Re}\left(\frac{\Gamma_{12}^q/M_{12}^q}{\Gamma_{12}^{q,\mathrm{SM}}/M_{12}^{q,\mathrm{SM}}}\cdot\frac{\Gamma_{12}^{q,\mathrm{SM}}}{M_{12}^{q,\mathrm{SM}}}\right)\cdot\Delta M_q^{\mathrm{Exp}}. \tag{9}$$

The SM prediction for $\Gamma_{12}^q/M_{12}^q$ is given in [23] and reads

$$\frac{\Gamma_{12}^{d,\mathrm{SM}}}{M_{12}^{d,\mathrm{SM}}} = -0.0050 - 0.00045i, \qquad \frac{\Gamma_{12}^{s,\mathrm{SM}}}{M_{12}^{s,\mathrm{SM}}} = -0.0050 + 0.000021i. \tag{10}$$

The experimental value for $\Delta\Gamma_s$ is taken from [24], for the semileptonic asymmetries we take the naive average of the values in [25–30], and for the mass difference we use the Heavy Flavor Averaging Group average [17]. We find

$$a_{sl}^d = (+2.2 \pm 2.2)\cdot 10^{-3}, \quad \Delta\Gamma_s = 0.0805 \pm 0.0091 \pm 0.0032\ \mathrm{ps}^{-1}, \quad a_{sl}^s = (-4.8 \pm 4.8)\cdot 10^{-3}, \quad \Delta M_s = 17.761 \pm 0.022\ \mathrm{ps}^{-1}. \tag{11}$$

We do not use $\Delta\Gamma_d$ since there are currently only loose experimental bounds available. To obtain the constraints on new-physics contributions to $C_1$ and $C_2$ we perform a parameter scan for all the observables described above, combining all errors in quadrature. In Fig. 1 and Fig. 2 we show the regions allowed by each observable at 90% CL; for clarity we restrict ourselves to the observables that lead to the strongest bounds. Moreover, we did not consider possible cancellations among the new contributions to $C_1$

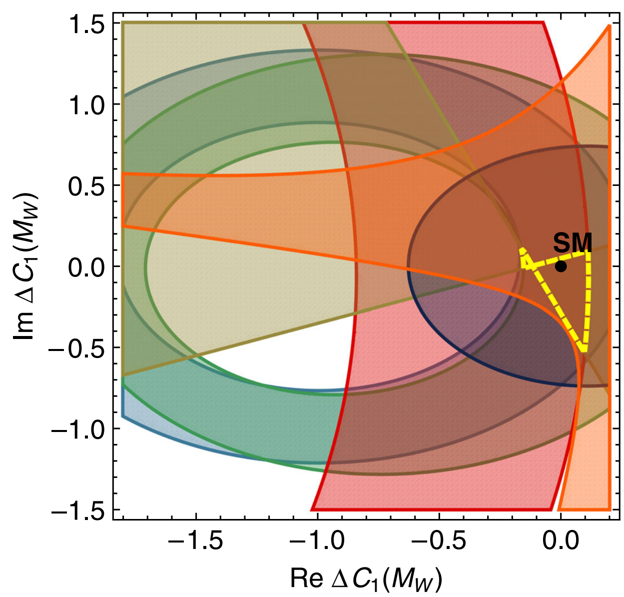


FIG. 1 (color online). Constraints on $\Delta C_1$, the new-physics contribution to the tree-level Wilson coefficient $C_1$, at the scale $\mu_W = M_W$. The red region is associated with constraints from the $B\to D\pi$ decay channel, the green and blue rings with the transitions $B\to\rho\rho$ and the observable $R_{\pi^-\pi^0}$ calculated from the decay $B\to\pi\pi$, respectively. The brown sections are related to the decays $B^0\to D^{(*)0}h^0$ and the blue circle to the total lifetime of $b$-hadrons. Finally, the region allowed by the semileptonic asymmetry $a_{sl}^d$ is contained within the orange boundaries.

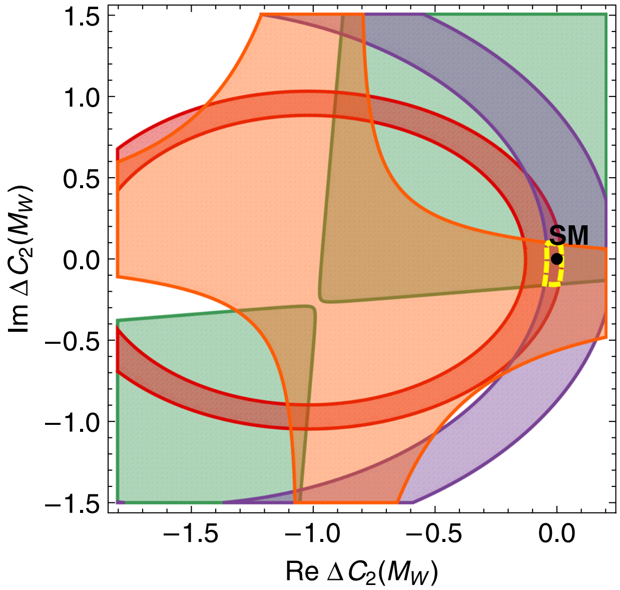


FIG. 2 (color online). Constraints on $\Delta C_2$, the new-physics contribution to the tree-level Wilson coefficient $C_2$, at the scale $\mu_W = M_W$. The red and purple rings enclose the bounds from the decays $B \to D\pi$ and $B \to X_s\gamma$, respectively. The orange star-shaped region is related to the semileptonic asymmetry $a^d_{sl}$. The constraint from $B \to \pi\pi$ comes from the observable $S_{\pi\pi}$ and is visualized by the green sections.

and $C_2$, i.e., when investigating the bounds on $\Delta C_1(M_W)$, we set $\Delta C_2(M_W) = 0$ and vice versa.

We read from the plot the following ranges as rough estimates for possible new-physics contributions to the current-current operators:

$$\mathrm{Im}\Delta C_1 \in [-0.56; +0.13], \\ \mathrm{Im}\Delta C_2 \in [-0.17; +0.10], \quad (12)$$

$$\mathrm{Re}\Delta C_1 \in [-0.17; +0.12], \\ \mathrm{Re}\Delta C_2 \in [-0.06; +0.02]. \quad (13)$$

More quantitative statements will be obtained in [31]. Note that the bounds obtained in [8] from $B \to K^{(*)}\pi/\rho$ observables would slightly shrink the regions given in Eq. (12) and Eq. (13), but this does not change our main conclusion: that new physics effects in $\mathrm{Im}C_1$, $\mathrm{Re}C_1$, and $\mathrm{Im}C_2$ can easily be of order 10%.

## III. PRECISION IN $\gamma$

We will now study the implications of our findings for the expected precision of the extraction of the CKM angle $\gamma$ from tree-level decays. It is defined by $\gamma \equiv \arg(-V_{ud}V^*_{ub}/V_{cd}V^*_{cb})$ and can be determined from $B^\pm \to DK^\pm$ decays that receive contributions only from tree-level operators [5]. The fact that all relevant hadronic matrix elements can be obtained from data and the absence of penguin contributions leads to the exceptional theoretical cleanness of this determination. The sensitivity to the angle $\gamma$ arises via the interference between the $b \to c\bar{u}s$ and the $b \to u\bar{c}s$ decay amplitudes. Denoting the $B^- \to DK^-$-amplitude by $A_1 e^{i\delta_1}$ and the $B^- \to \bar{D}K^-$-amplitude by $A_2 e^{i(\delta_2-\gamma)}$, where we have made the dependence on the CKM angle $\gamma$ explicit, we get

$$\mathcal{A}(B^- \to f_D K^-) = A_1 e^{i\delta_1}[1 + r_B e^{i(\delta_B-\gamma)}], \quad (14)$$

$$\mathcal{A}(B^+ \to f_D K^+) = A_1 e^{i\delta_1}[1 + r_B e^{i(\delta_B+\gamma)}], \quad (15)$$

with $r_B = A_2/A_1$ and the difference of the strong phases $\delta_B = \delta_2 - \delta_1$. The interference of the two decay modes is achieved via common final states $f_D$ of the decaying $D^0$ and $\bar{D}^0$ mesons. Different methods to extract $\gamma$ have been devised, conventionally distinguished according to the different $D$ decay modes. In the Gronau-London-Wyler method [32,33] one uses $D$ decays into $CP$ eigenstates. In the Atwood-Dunietz-Soni method [34,35] a combination of Cabibbo-favored and doubly Cabibbo-suppressed $D$-decays is chosen such that interference effects are maximized. Finally, in the GGSZ method [36] three-body $D$ decays are studied with a Dalitz-plot analysis. Subsequently, further methods were studied, see, e.g., the review in [37]. The angle $\gamma$ has been measured by *BABAR* [38] and Belle [39,40]. Currently the best experimental precision is achieved by the LHCb collaboration which quotes $\gamma = (73^{+9}_{-10})^\circ$ [41] for their "robust" combination which includes only $B \to DK$ modes. However, the $B \to D\pi$ modes where the smaller interference term is compensated by larger branching ratios also start to play a role in the extraction of $\gamma$ [41].

Theoretical corrections to the extraction of $\gamma$ were investigated extensively in the literature. The effects of $D - \bar{D}$ mixing and of $CP$ violation in $D$ and also $K$ decays (for final states with neutral kaons) have been studied in [42–48]. These effects lead to shifts in $\gamma$ of at most a few degrees and can be taken into account exactly by a suitable modification of the expressions for the amplitudes. The shifts can be larger in the $B \to D\pi$ modes. The irreducible theoretical uncertainty is due to higher-order electroweak corrections and has been found to be negligible for the extraction of $\gamma$ using the $B \to DK$ modes [6]. It is expected to be tiny also in the $B \to D\pi$ case [49]. Given the expected sensitivity of order 1° at LHCb [4] and Belle II [3] we now address the following question: How large of a shift in $\gamma$ due to new-physics contributions in tree-level decays is still allowed by data? In order to compute the shift in $\gamma$ induced by $\Delta C_1$ and $\Delta C_2$ we start from the effective Hamiltonians for $b \to c\bar{u}s$ and $b \to u\bar{c}s$ decays. We will consider the two amplitudes

$$A(B^- \to D^0 K^-) = \langle D^0 K^- | \mathcal{H}^{\bar{c}us}_{\mathrm{eff}} | B^- \rangle, \\ A(B^- \to \bar{D}^0 K^-) = \langle \bar{D}^0 K^- | \mathcal{H}^{\bar{u}cs}_{\mathrm{eff}} | B^- \rangle. \quad (16)$$

The CKM angle $\gamma$ can be extracted from the ratio of these two amplitudes via

$$r_B e^{i(\delta_B-\gamma)} = \frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)}. \tag{17}$$

Inserting the expressions for the effective Hamiltonian (1) we get

$$r_B e^{i(\delta_B-\gamma)} = \frac{V_{ub}V_{cs}^*}{V_{cb}V_{us}^*} \frac{\langle \bar{D}^0 K^- | Q_2^{\bar{u}cs} | B^- \rangle}{\langle D^0 K^- | Q_2^{\bar{c}us} | B^- \rangle} \left[ \frac{C_2 + r_{A'} C_1}{C_2 + r_A C_1} \right], \tag{18}$$

where we defined the additional amplitude ratios

$$r_{A'} = \frac{\langle \bar{D}^0 K^- | Q_1^{\bar{u}cs} | B^- \rangle}{\langle \bar{D}^0 K^- | Q_2^{\bar{u}cs} | B^- \rangle}, \qquad r_A = \frac{\langle D^0 K^- | Q_1^{\bar{c}us} | B^- \rangle}{\langle D^0 K^- | Q_2^{\bar{c}us} | B^- \rangle}. \tag{19}$$

Note that here the Wilson coefficients should be evaluated at the scale $\mu_b \sim m_b$; we assume this convention throughout the current section. The estimates given in Eqs. (12) and (13) correspond to the following ranges at scale $\mu_b$, obtained using renormalization group running at leading order:

$$\begin{aligned} \mathrm{Im}\Delta C_1 &\in [-0.62; +0.14], \\ \mathrm{Im}\Delta C_2 &\in [-0.19; +0.11], \end{aligned} \tag{20}$$

$$\begin{aligned} \mathrm{Re}\Delta C_1 &\in [-0.19; +0.13], \\ \mathrm{Re}\Delta C_2 &\in [-0.066; +0.022]. \end{aligned} \tag{21}$$

New physics effects in $C_1$ and $C_2$ then modify the ratio $r_B e^{i(\delta_B-\gamma)}$ as

$$r_B e^{i(\delta_B-\gamma)} \to r_B e^{i(\delta_B-\gamma)} \cdot \left[ \frac{C_2 + \Delta C_2 + r_{A'}(C_1 + \Delta C_1)}{C_2 + r_{A'} C_1} \frac{C_2 + r_A C_1}{C_2 + \Delta C_2 + r_A (C_1 + \Delta C_1)} \right]. \tag{22}$$

Thus any new complex contribution to $C_1$ and/or $C_2$ will introduce a shift in $\gamma$. Using that $|C_1/C_2| \approx 0.22$ at the scale $m_b$ and that also $|\Delta C_1/C_2|$ and $|\Delta C_2/C_2|$ are small (see Sec. II) we can further simplify the above relation by expanding in these small ratios:

$$r_B e^{i(\delta_B-\gamma)} \to r_B e^{i(\delta_B-\gamma)} \cdot \left[ 1 + (r_{A'} - r_A) \frac{\Delta C_1}{C_2} \right], \tag{23}$$

which depends now only on the modification of the Wilson coefficient $\Delta C_1$. This modification leads then to a modified value of $\gamma$

$$\gamma \to \gamma + \delta\gamma = \gamma + (r_A - r_{A'}) \frac{\mathrm{Im}\Delta C_1}{C_2}. \tag{24}$$

Here the dominant dependence of the shift in $\gamma$ on $\mathrm{Im}\Delta C_1$ can be nicely seen; for numerical evaluations we recommend, however, to use the exact expression in Eq. (22). In order to relate the bounds in Eqs. (20) and (21) to the shift in $\gamma$ we need to estimate the ratios of matrix elements (19). Naive color counting and neglecting the annihilation topology in $r_{A'}$ gives $r_A \approx \mathcal{O}(1)$ and $r_{A'} \approx \mathcal{O}(N_c)$, where $N_c = 3$ is the number of colors. On the other hand, naive factorization yields

$$r_A \approx \frac{f_D F_0^{B\to K}(0)}{f_K F_0^{B\to D}(0)} \approx 0.4, \tag{25}$$

whereas including the annihilation topology would reduce $r_{A'}$. There are certainly large uncertainties on these estimates, but it seems very unlikely that the two ratios cancel accidentally. As a conservative estimate we will take $r_A - r_{A'} \approx -0.6$. Having $\mathrm{Im}\Delta C_1(m_b)$ of order $\pm 0.1$ we get $\delta\gamma$ of order $\mp 4°$, with large uncertainties due to the hadronic matrix elements.

## IV. CONCLUSION AND OUTLOOK

We have investigated constraints on flavor-universal new physics contributions to the tree-level Wilson coefficients $C_1$ and $C_2$, arising from a set of observables in the $B$-meson sector. We find that sizeable deviations from the SM are still possible. Specifically, we find that the allowed ranges of $\mathrm{Re}\Delta C_1$, $\mathrm{Im}\Delta C_1$, and $\mathrm{Im}\Delta C_2$ are of the order of 10%, whereas the allowed range for $\mathrm{Re}\Delta C_2$ is slightly smaller. A new-physics contribution to the imaginary parts of $C_1$ and $C_2$ plays a particularly important role in view of the precise determination of the CKM angle $\gamma$ from tree-level decays. The possible presence of a new weak phase in $C_1$ and $C_2$ introduces an uncertainty into the extraction of $\gamma$, the latter essentially being defined as the phase of the CKM element $V_{ub}^*$. The ranges given in Eqs. (12) and (13) induce an uncertainty of $|\delta\gamma| \approx 4°$ which is not negligible in view of the expected sensitivity of 1° at LHCb and Belle II. To reduce this uncertainty the bounds on $\Delta C_1$ and $\Delta C_2$ should be improved. For instance, the bound on $\Delta C_1$ depends sensitively on the semileptonic asymmetry $a_{\mathrm{sl}}^d$. For instance, assuming a decrease of the experimental error for $a_{\mathrm{sl}}^d$ by 20% would cut out most of the allowed region for the imaginary part of $\Delta C_1$ given in Fig. 1. Moreover, further improvements (both in experiment and theory) in the observables $R_{D\pi}$, $R_{\rho\rho}$, $R_{\pi\pi}$, and $S_{Dh}$, as well as an improvement in the theory expression for the total lifetime—e.g., NNLO QCD corrections to the inclusive nonleptonic decay rates—would also reduce the allowed parameter ranges for new physics effects in tree-level decays. We have also seen that the effect of new weak phases in $C_1$ and $C_2$ on the determination of $\gamma$ depends sensitively on two ratios of hadronic matrix elements which are hard to evaluate numerically, and it would be worthwhile to go beyond our very naive estimates. Note that, conversely, the $CP$ asymmetries in $B \to DK$ decays might yield the strongest bounds on new weak phases in the current-current sector, given an independent measurement of $\gamma$. In this article we have attempted only a rough estimate of the new physics contribution to the tree-level Wilson coefficients; our main conclusion is that sizable effect cannot be excluded from the viewpoint of data. Our analysis can be improved in many ways. First of all, the combination of the different observables was done at the level of a simple parameter scan, i.e., by computing the 90% CL region for each observable separately and intersecting these regions. Statistical and systematic errors for each observable were combined in quadrature. For a complete (frequentist) statistical analysis all observables have to be combined in a single likelihood function and systematic errors have to be treated within the Rfit scheme [50]. The combination into a single likelihood function necessarily reduces the allowed region, but the treatment of systematic errors in the Rfit scheme typically overcompensates this effect. In any case, these modifications do not change the result by orders of magnitude and will therefore have no impact on the main message of this paper that new-physics effects in $C_1$ and $C_2$ of the order of 10% are not in contradiction to data. We postpone a systematic fit to a future publication [31] where we will also investigate flavor specific bounds. More generally, an advanced study should also allow for new physics contributions to operators other than exclusively $Q_1$ and $Q_2$.

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