

Fourth Generation CP Violation Effects on $B \rightarrow K\pi$, ϕK , and ρK in Next-to-Leading-Order Perturbative QCD

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We study the effect from a sequential fourth generation quark on penguin-dominated two-body nonleptonic B meson decays in the next-to-leading order perturbative QCD formalism. With an enhancement of the color-suppressed tree amplitude and possibility of a new CP phase in the electroweak penguin amplitude, we can account better for $A_{CP}(B^0 \rightarrow K^+ \pi^-) - A_{CP}(B^+ \rightarrow K^+ \pi^0)$. Taking $|V_{t's} V_{t'b}| \sim 0.02$ with a phase just below 90° , which is consistent with the $b \rightarrow s \ell^+ \ell^-$ rate and the B_s mixing parameter Δm_{B_s} , we find a downward shift in the mixing-induced CP asymmetries of $B^0 \rightarrow K_S \pi^0$ and ϕK_S . The predicted behavior for $B^0 \rightarrow \rho^0 K_S$ is opposite.

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CP violation (CPV) in $b \rightarrow s$ transitions is at the forefront of our quest to understand flavor and the origins of CPV, offering one of the best probes for new physics (NP) beyond the standard model (SM). Several hints for NP have emerged in the past few years. For example, a large difference is seen in direct CP asymmetries in $B \rightarrow K\pi$ decays [1],

$$\begin{aligned} \mathcal{A}_{K\pi} &\equiv A_{CP}(B^0 \rightarrow K^+ \pi^-) = -0.093 \pm 0.015, \\ \mathcal{A}_{K\pi^0} &\equiv A_{CP}(B^+ \rightarrow K^+ \pi^0) = +0.047 \pm 0.026, \end{aligned} \quad (1)$$

or $\Delta \mathcal{A}_{K\pi} \equiv \mathcal{A}_{K\pi^0} - \mathcal{A}_{K\pi} = (14 \pm 3)\%$ [2]. As it was not predicted when first measured in 2004, it has stimulated discussion on the potential mechanisms that may have been missed in the SM calculations [3–5].

Better known is the mixing-induced CP asymmetry \mathcal{S}_f measured in a multitude of CP eigenstates f . For penguin-dominated $b \rightarrow s q \bar{q}$ modes, within SM, $\mathcal{S}_{sq\bar{q}}$ should be close to that extracted from $b \rightarrow c \bar{c} s$ modes. The latter is now measured rather precisely: $\mathcal{S}_{c\bar{c}s} = \sin 2\phi_1 = 0.674 \pm 0.026$ [6], where ϕ_1 is the weak phase in V_{td} . However, for the past few years, data seem to indicate, at 2.6σ significance,

$$\Delta \mathcal{S} \equiv \mathcal{S}_{sq\bar{q}} - \mathcal{S}_{c\bar{c}s} \lesssim 0, \quad (2)$$

which has stimulated even more discussions.

Since the two modes in Eq. (1) differ by the subleading color-suppressed tree amplitude C' and electroweak penguin amplitude P'_{EW} , it is natural to conjecture that C' , P'_{EW} , or maybe both have been underestimated (see [7] and references therein). In this Letter we study the fourth generation effect on the $B \rightarrow K\pi$, ϕK , and ρK decays in the perturbative QCD (PQCD) approach, which exploits both C' and P'_{EW} to account for Eq. (1), and gives the right tendency towards explaining Eq. (2).

At leading order (LO), PQCD predicted [4] the sign and strength of $\mathcal{A}_{K\pi}$, but $\mathcal{A}_{K\pi^0}$ was also negative and not too different from $\mathcal{A}_{K\pi}$. Going to next-to-leading order (NLO) [8], it was shown that inclusion of the vertex corrections increases C' by a factor of 3; without affecting much the branching ratios, $\mathcal{A}_{K\pi^0}$ becomes much closer to zero, although still negative. However, like many other studies in the literature [9–11], NLO PQCD also predicts $\Delta \mathcal{S}_{K_S \pi^0} \equiv \mathcal{S}_{K_S \pi^0} - \mathcal{S}_{c\bar{c}s} > 0$ within SM, opposite to what is indicated by Eq. (2). Thus, if $\Delta \mathcal{S}$ stands the scrutiny of time, one would still need to go beyond SM.

The other path to account for Eq. (1), to have an effect coming from P'_{EW} , in fact requires NP CPV. Among the available models, the sequential fourth generation is found to modify only P'_{EW} significantly [12], but not other amplitudes such as the QCD penguin amplitude P' . With reasonable parameters, e.g., with $m_{t'}$ \simeq 300 GeV, the product of quark mixing matrix elements $|V_{t's} V_{t'b}| = 0.01 \sim 0.03$ with phase close to 90° , it was found in PQCD at LO that $\mathcal{A}_{K\pi^0}$ could also be rendered vanishing. Remarkably, the constraints of the $b \rightarrow s \ell^+ \ell^-$ rate and the B_s mixing parameter Δm_{B_s} are also satisfied. It was shown [13] in QCD factorization (QCDF) at NLO (and PQCD at LO for $B \rightarrow K\pi$) that the same parameter choice produces a downward shift for $\mathcal{S}_{K_S \pi^0}$ and $\mathcal{S}_{\phi K_S}$. The prediction is far from reliable, however, due to uncontrollable hadronic uncertainties in QCDF.

It is worthwhile, then, to reanalyze the fourth generation effect using the NLO PQCD formalism, in part to find whether the preferred parameter space [12] is affected, and also to investigate the efficacy of combining the C' and P'_{EW} approaches on CPV in penguin-dominated $b \rightarrow s q \bar{q}$ modes. It should be emphasized that both the strength and phase of $V_{t's}^* V_{t'b}$ would be effectively pinned down by the recent precise measurement of Δm_{B_s} [14], which will

then lead to rather definite predictions for CPV in B_s mixing, $\sin 2\Phi_{B_s}$, as well as D^0 mixing [15]. We show that, using the same fourth generation parameters as before, we can explain the trend of the observed ΔS in $B \rightarrow K\pi$ and ϕK decays simultaneously, while understanding of $\Delta \mathcal{A}_{K\pi}$ is also improved. We point out that the fourth generation effect is opposite in $B \rightarrow \rho K$, which increases $S_{\rho^0 K_S}$ from a low value in SM [10,16].

It is instructive to elucidate the underpinnings of the two proposals to resolve the $B \rightarrow K\pi$ puzzle, i.e., enhanced C' by vertex corrections in SM, versus fourth generation with a new CPV phase.

The NLO PQCD calculation within SM shows [8] that P' is in the second quadrant, and the color-allowed tree amplitude T' is roughly real and positive. Enhanced by the vertex corrections, C' turns almost imaginary, and $T' + C'$ is in the fourth quadrant and almost opposite in direction as $P' + P'_{EW}$. As $\mathcal{A}_{K\pi^0}$ is proportional to the sine of the angle between $T' + C'$ and $P' + P'_{EW}$, its value drops in NLO PQCD within SM. In the four generation model at LO in PQCD [12], the amplitude P'_{EW} acquires a large CPV phase from $V_{t's}^* V_{t'b}$, which effectively cancels the weak phase $\phi_3 \equiv \arg V_{ub}^*$ in $T' + C'$, making $\mathcal{A}_{K\pi^0}$ almost vanish. The $B^0 \rightarrow K^+ \pi^-$ decay, however, is less affected, as the P'_{EW} contribution is color suppressed. Since only subleading amplitudes are modified, in both proposals the $B \rightarrow K\pi$ branching ratios are not much affected. This is contrary to the proposals based on either inelastic [17] or elastic [18] final state rescattering, in which leading P' amplitudes are enhanced. This is the reason why the $B \rightarrow K\pi$ puzzle cannot be resolved in such approaches.

For mixing-induced CP asymmetries, there is clearly a major difference between the above proposals. The time-dependent CP asymmetry of the $B^0 \rightarrow K_S \pi^0$ mode is defined as

$$\begin{aligned} A_{CP}(B^0(t) \rightarrow K_S \pi^0) & \\ & \equiv \frac{\mathcal{B}(\bar{B}^0(t) \rightarrow K_S \pi^0) - \mathcal{B}(B^0(t) \rightarrow K_S \pi^0)}{\mathcal{B}(\bar{B}^0(t) \rightarrow K_S \pi^0) + \mathcal{B}(B^0(t) \rightarrow K_S \pi^0)} \\ & = \mathcal{A}_{K_S \pi^0} \cos \Delta m_{B_d} t + \mathcal{S}_{K_S \pi^0} \sin \Delta m_{B_d} t, \end{aligned} \quad (3)$$

where Δm_{B_d} is the mass difference of the two B -meson mass eigenstates, and

$$\mathcal{A}_{K_S \pi^0} = \frac{|\lambda_{K_S \pi^0}|^2 - 1}{1 + |\lambda_{K_S \pi^0}|^2}, \quad \mathcal{S}_{K_S \pi^0} = \frac{2\text{Im}\lambda_{K_S \pi^0}}{1 + |\lambda_{K_S \pi^0}|^2} \quad (4)$$

are the direct- and mixing-induced asymmetries, respectively. The $B^0 \rightarrow K_S \pi^0$ decay has a CP-odd final state, and the associated factor,

$$\lambda_{K_S \pi^0} = -e^{-2i\phi_1} \frac{\mathcal{M}(\bar{B}^0 \rightarrow K_S \pi^0)}{\mathcal{M}(B^0 \rightarrow K_S \pi^0)}, \quad (5)$$

with $\mathcal{M}(\bar{B}^0 \rightarrow K_S \pi^0) = P' - P'_{EW} - C' e^{-i\phi_3}$, where we have isolated the weak phase in SM [19].

Although C' can be enhanced by a few times from the vertex corrections in NLO PQCD, within SM $\mathcal{S}_{K_S \pi^0}$ is not much affected, which stays close to $\mathcal{S}_{c\bar{c}s}$. According to Eq. (5), the leading deviation caused by C' is proportional to the cosine of the relative strong phase between C' and $P' - P'_{EW}$. Because the vertex corrections also rotate C' , it becomes more orthogonal to P' , and the cosine diminishes. However, in the fourth generation model, a NP phase is introduced through P'_{EW} , so that $\Delta \mathcal{S}_{K_S \pi^0}$ could be sizable. As we will show, the simultaneous accommodation of $\Delta \mathcal{A}_{K\pi}$ and $\Delta \mathcal{S}_{K_S \pi^0}$ is nontrivial, with all experimental constraints suitably satisfied.

The NLO PQCD formalism for the $B \rightarrow PP, PV$ decays, in which the contributions from the NLO evolution of Wilson coefficients, the vertex corrections, the quark loops, and the magnetic penguin are taken into account, can be found in Refs. [8,16]. The main assumption involved is that we have neglected NLO corrections to B meson transition form factors, which is not essential for studies of CP asymmetries. The procedure to incorporate the fourth generation effect can be found in Ref. [12]. In Figs. 1(a)–1(c) we plot the predictions for $\mathcal{A}_{K\pi}$, $\mathcal{A}_{K\pi^0}$, and $\mathcal{S}_{K_S \pi^0}$ versus $\phi_{sb} \equiv \arg V_{t's}^* V_{t'b}$, for three values of $r_{sb} \equiv |V_{t's}^* V_{t'b}| = 0.01, 0.02,$ and 0.03 . We have taken $\phi_1 = 21.6^\circ$, $\phi_3 = 70^\circ$, and $m_{t'} = 300$ GeV. Theoretical uncertainties from the above Cabibbo-Kobayashi-Maskawa (CKM) matrix elements and from hadronic parameters, such as Gegenbauer coefficients in meson distribution amplitudes, can be included straightforwardly as in Ref. [8]. Considering these uncertainties, the predicted ranges of \mathcal{A} and \mathcal{S} will be enlarged by about 50% and a few percent, respectively. A variation in $m_{t'}$ just changes the range of r_{sb} (i.e., the CKM product $|V_{t's}^* V_{t'b}|$). Indeed, $\mathcal{A}_{K\pi^0}$ becomes more positive for $\phi_{sb} \approx 90^\circ$, while $\mathcal{S}_{K_S \pi^0}$ dips down-

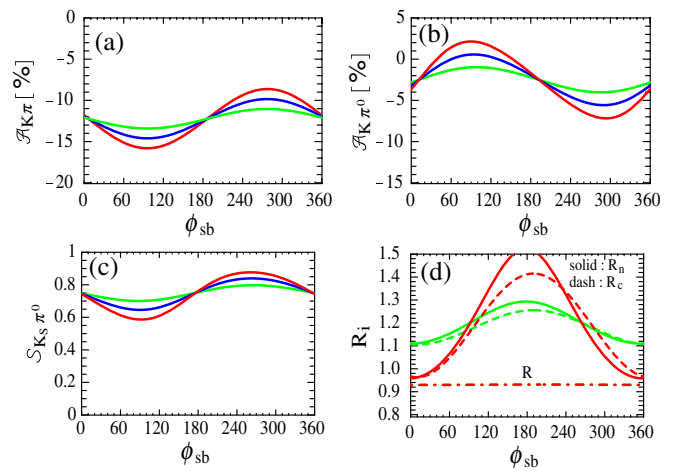


FIG. 1 (color online). (a) $\mathcal{A}_{K\pi}$, (b) $\mathcal{A}_{K\pi^0}$, (c) $\mathcal{S}_{K_S \pi^0}$, and (d) R_i ($i = \text{null}, c, n$) vs ϕ_{sb} for $m_{t'} = 300$ GeV with all of the NLO corrections. The curves are for $r_{sb} = 0.01, 0.02$ [not shown in (d)], 0.03 , with $r_{sb} = 0.03$ giving the strongest effect.

TABLE I. Branching ratios (in units of 10^{-6}) and direct CP asymmetries (in units of 10^{-2}) for $B \rightarrow K\pi$ decays, with $m_{t'} = 300$ GeV, $r_{sb} = 0.025$, and $\phi_{sb} = 65^\circ$ [20]. The labels +WC, +VC, +QL, +MP, and +NLO mean the LO results with the NLO Wilson coefficients, the inclusions of the vertex corrections, of the quark loops, of the magnetic penguin, and of all the above NLO corrections, respectively. The NLO predictions from SM are presented in the parentheses for comparison.

Quantity	+WC	+VC	+QL	+MP	+NLO (SM)
$\mathcal{B}(K^0\pi^\pm)$	23.6	22.8	25.2	17.7	18.3 (18.1)
$\mathcal{B}(K^\pm\pi^0)$	12.6	12.2	13.4	9.6	9.9 (10.7)
$\mathcal{B}(K^\pm\pi^\mp)$	20.3	19.8	21.6	15.2	15.8 (15.7)
$\mathcal{B}(K^0\pi^0)$	9.3	9.1	10.0	6.8	7.2 (6.5)
$\mathcal{A}_{K^0\pi}$	0	1	0	0	2 (0)
$\mathcal{A}_{K\pi^0}$	-5	1	-4	-7	1 (-2)
$\mathcal{A}_{K\pi}$	-11	-13	-9	-14	-15 (-12)
$\mathcal{A}_{K^0\pi^0}$	-5	-12	-4	-7	-14 (-8)

wards, showing that the nearly vanishing $\mathcal{A}_{K\pi^0}$ and the smaller $\mathcal{S}_{K_S\pi^0}$ occur at the same NP phase. Compared with Ref. [12] in LO PQCD, we observe that the strength of the parameter r_{sb} has shrunk: $\mathcal{A}_{K\pi^0}$ flips sign for $m_{t'} = 300$ GeV and $r_{sb} = 0.03$ in [12], but now for $r_{sb} = 0.02$. This implies that the larger color-suppressed tree amplitude in NLO PQCD has softened the need for larger NP parameters. The decrease of $R_n \approx 1.1$ for $\phi_{sb} \approx 90^\circ$ shown in Fig. 1(d) is now consistent with the observed value.

The rates and \mathcal{A}_{CPS} of all four $B \rightarrow K\pi$ modes are listed in Table I, which elucidates the effects from the NLO Wilson evolution, vertex corrections, quark loops, and the magnetic penguin, separately. The tendency is basically the same as in Ref. [8]. The main change from the incorporation of the fourth generation appears in the direct CP asymmetries: $\mathcal{A}_{K\pi^0}$ moves positive (flips sign) but remains small, and $\mathcal{A}_{K^0\pi^0}$, which also depends on P'_{EW} , becomes roughly equal to $\mathcal{A}_{K\pi}$. Note that $\mathcal{A}_{K\pi}$ and $\mathcal{A}_{K\pi^0}$ are not in perfect match with Eq. (1), but varying hadronic parameters such as meson distribution amplitudes, the rates, $\mathcal{A}_{K\pi}$, and $\mathcal{A}_{K\pi^0}$ could approach data. We do not attempt any such tuning at present, but took the input parameters from earlier NLO PQCD analyses that did not involve the fourth generation.

The predictions for the mixing-induced CP asymmetries are relatively insensitive to the hadronic parameters. The results for $\mathcal{S}_{\phi K_S}$ and $\mathcal{S}_{\rho^0 K_S}$ are displayed in Fig. 2. The effect for $\mathcal{S}_{\phi K_S}$ is similar to $\mathcal{S}_{K_S\pi^0}$, going down from $\mathcal{S}_{\phi K_S} \approx \sin 2\phi_1$ in SM. However, $\mathcal{S}_{\rho^0 K_S}$ behaves in an opposite way: it gets enhanced from 0.5 in SM [16], with Eq. (2) barely obeyed. The rates and \mathcal{A}_{CPS} of the $B \rightarrow \phi K$ and ρK decays are collected in Table II. Compared to the NLO results from SM, the branching ratios are not affected much by the fourth generation as stated before. The change mainly appears in the direct CP asymmetries: $\mathcal{A}_{\phi K}$ and

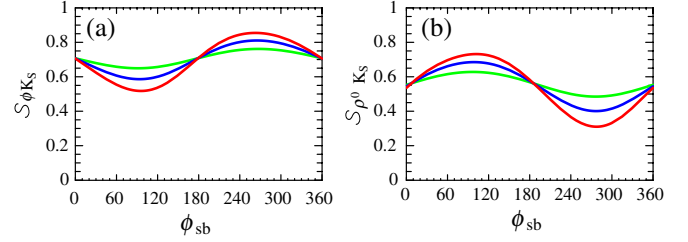


FIG. 2 (color online). (a) $\mathcal{S}_{\phi K_S}$ and (b) $\mathcal{S}_{\rho^0 K_S}$ vs ϕ_{sb} with all of the NLO corrections. Notation is the same as Fig. 1.

$\mathcal{A}_{\phi K^0}$, though small, turn negative; $\mathcal{A}_{\rho^0 K}$ decreases like $\mathcal{A}_{K\pi^0}$, but is still sizable; $\mathcal{A}_{\rho^0 K^0}$ increases like $\mathcal{A}_{K^0\pi^0}$, and becomes comparable with $\mathcal{A}_{\rho^0 K}$ and $\mathcal{A}_{\rho K}$.

We give a general explanation on the above findings, assuming that NP at high energy modifies the Wilson coefficients relevant to the electroweak penguin in the low-energy effective theory (SM). Both the four generation model and the Z' model [21] provide such examples. The NP effect on the direct CP asymmetries and mixing-induced CP asymmetries is written, up to corrections of $O(r_{EW}^2)$, as

$$\begin{aligned} \Delta \mathcal{A}_{K\pi^0} &= 2r_{EW} \sin \delta_{EW} \sin \phi_{EW}, \\ \Delta \mathcal{S}_{K_S\pi^0} &= -2r_{EW} \cos 2\phi_1 \cos \delta_{EW} \sin \phi_{EW}, \end{aligned} \quad (6)$$

where r_{EW} is the ratio of the magnitude of the NP contribution to the electroweak penguin over the full penguin amplitude, δ_{EW} the relative strong phase between the electroweak penguin amplitude and full penguin amplitude in the SM, and ϕ_{EW} the NP phase. Since P'_{EW} is antiparallel to $T' + C'$ from isospin symmetry [22], δ_{EW} is expected to be less than 90° . Hence, the NP phase $\phi_{EW} < 90^\circ$ leads to a decrease of the magnitude of both $\mathcal{A}_{K\pi^0}$ (if $\mathcal{A}_{K\pi^0} < 0$ in SM, such as in the PQCD ap-

TABLE II. Branching ratios (in units of 10^{-6}) and direct CP asymmetries (in units of 10^{-2}) for $B \rightarrow \phi K$ and ρK decays with $m_{t'} = 300$ GeV, $r_{sb} = 0.025$, and $\phi_{sb} = 65^\circ$. The notation is the same as Table I.

Quantity	+WC	+VC	+QL	+MP	+NLO (SM)
$\mathcal{B}(\phi K^\pm)$	31.0	12.9	33.0	21.7	8.1 (7.2)
$\mathcal{B}(\phi K^0)$	28.8	12.0	30.7	20.2	7.5 (6.8)
$\mathcal{B}(\rho^\pm K^0)$	5.4	7.3	5.3	6.0	7.7 (7.7)
$\mathcal{B}(\rho^0 K^\pm)$	2.9	3.7	2.9	2.9	3.7 (3.9)
$\mathcal{B}(\rho^\mp K^\pm)$	6.0	7.1	5.9	7.0	7.8 (7.6)
$\mathcal{B}(\rho^0 K^0)$	3.0	3.7	2.9	3.7	4.2 (4.5)
$\mathcal{A}_{\phi K}$	-3	-1	-2	-5	-3 (0)
$\mathcal{A}_{\phi K^0}$	-3	0	-2	-4	-2 (2)
$\mathcal{A}_{\rho K^0}$	4	3	4	5	4 (1)
$\mathcal{A}_{\rho^0 K}$	54	45	54	55	44 (67)
$\mathcal{A}_{\rho K}$	65	62	67	56	58 (57)
$\mathcal{A}_{\rho^0 K^0}$	19	27	0	16	27 (6)

proach) and $\mathcal{S}_{K_S\pi^0}$. That is, the current data of $\mathcal{S}_{K_S\pi^0}$ favor the presence of NP in the electroweak penguin amplitude. Adopting the same parameters, NP increases $\mathcal{S}_{\rho^0 K_S}$ as shown in Fig. 2, since the NLO PQCD analysis has indicated $\delta_{EW} > 90^\circ$ in the $B \rightarrow \rho K$ decays [16], which is attributed to the change of the penguin amplitude with destructive combination of the Wilson coefficients a_4 and a_6 . If the pattern of the direct CP asymmetries $\mathcal{A}_{\rho K} \approx \mathcal{A}_{\rho^0 K}$ [16], related to the orientation of the penguin amplitude, is confirmed, the increase of $\mathcal{S}_{\rho^0 K_S}$ will become solid. Note that implementing NP into other theoretical approaches may not resolve the $\Delta\mathcal{A}_{K\pi}$ and $\Delta\mathcal{S}_{K_S\pi^0}$ puzzles, and may not lead to the increase of $\mathcal{S}_{\rho^0 K_S}$. The recent first measurement of $\mathcal{S}_{\rho^0 K_S}$ [1,6] gives a low value, but with rather large errors.

In this Letter we have studied the effect of a fourth generation in the NLO PQCD framework. Combining the enhancement of the color-suppressed tree with CPV in the electroweak penguin amplitude renders the predictions for $\Delta\mathcal{A}_{K\pi}$ and $\Delta\mathcal{S}_{K_S\pi^0}$ more consistent with data, which is a nontrivial result. We predict several other mixing dependent and direct CPV effects. Future precise measurements at the B factories, the Tevatron, the LHC, and (hopefully) Super B factories, will determine whether NP is called for [23] by $\Delta S < 0$, and in turn constrain the NP parameters.

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