Standard Model expectations on $\sin 2\beta(\phi_1)$ from $b \to s$ penguins

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Recent results of the standard model expectations on $\sin 2\beta_{\rm eff}$ from penguin-dominated $b \to s$ decays are briefly reviewed.

1. Introduction

Although the Standard Model is very successful, New Physics is called for in various places, such as neutrino-oscillation, dark matter (energy) and baryon-asymmetry. Possible New Physics beyond the Standard Model is being intensively searched via the measurements of time-dependent CP asymmetries in neutral B meson decays into final CP eigenstates defined by

$$\frac{\Gamma(\overline{B}(t) \to f) - \Gamma(B(t) \to f)}{\Gamma(\overline{B}(t) \to f) + \Gamma(B(t) \to f)} = \mathcal{S}_f \sin(\Delta m t) + \mathcal{A}_f \cos(\Delta m t), \qquad (1)$$

where Δm is the mass difference of the two neutral B eigenstates, S_f monitors mixing-induced CP asymmetry and $\mathcal{A}_f$ measures direct CP violation. The CP-violating parameters $\mathcal{A}_f$ and $\mathcal{S}_f$ can be expressed as

$$\mathcal{A}_f = -\frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}, \qquad \mathcal{S}_f = \frac{2\,{\rm Im}\lambda_f}{1 + |\lambda_f|^2}, \qquad (2)$$

where

$$\lambda_f = \frac{q_B}{p_B}\,\frac{A(\overline{B}^0 \to f)}{A(B^0 \to f)}. \qquad (3)$$

In the standard model $\lambda_f \approx \eta_f e^{-2i\beta}$ for $b \to s$ penguin-dominated or pure penguin modes with $\eta_f = 1$ (-1) for final CP-even (odd) states. Therefore, it is expected in the Standard Model that $-\eta_f S_f \approx \sin 2\beta$ and $\mathcal{A}_f \approx 0$ with β being one of the angles of the unitarity triangle.

The mixing-induced CP violation in B decays has been already observed in the golden mode $B^0 \to J/\psi K_S$ for several years. The current world average the mixing-induced asymmetry from tree $b \to c\bar{c}s$ transition is [1]

$$\sin 2\beta = 0.687 \pm 0.032\,. \qquad (4)$$

However, the time-dependent CP-asymmetries in the $b \to sq\bar{q}$ induced two-body decays such as $B^0 \to (\phi, \omega, \pi^0, \eta', f_0)K_S$ are found to show some indications of deviations from the expectation of the Standard Model (SM) [1] (see Fig. 1). In the SM, CP asymmetry in all above-mentioned modes should be equal to $\mathcal{S}_{J/\psi K}$ with a small deviation *at most* $\mathcal{O}(0.1)$ [2]. As discussed in [2], this may originate from the $\mathcal{O}(\lambda^2)$ truncation and from the subdominant (color-suppressed) tree contribution to these processes. Since the penguin loop contributions are sensitive to high virtuality, New Physics beyond the SM may contribute to $\mathcal{S}_f$ through the heavy particles in the loops. In order to detect the signal of New Physics unambiguously in the penguin $b \to s$ modes, it is of great importance to examine how much of the deviation of S_f from $\mathcal{S}_{J/\psi K}$,

$$\Delta\mathcal{S}_f \equiv -\eta_f \mathcal{S}_f - \mathcal{S}_{J/\psi K_S}, \qquad (5)$$

is allowed in the SM [2–15].

The decay amplitude for the pure penguin or penguin-dominated charmless B decay in general has the form

$$M(\overline{B}^0 \to f) = V_{ub}V_{us}^* F^u + V_{cb}V_{cs}^* F^c + V_{tb}V_{ts}^* F^t. \qquad (6)$$

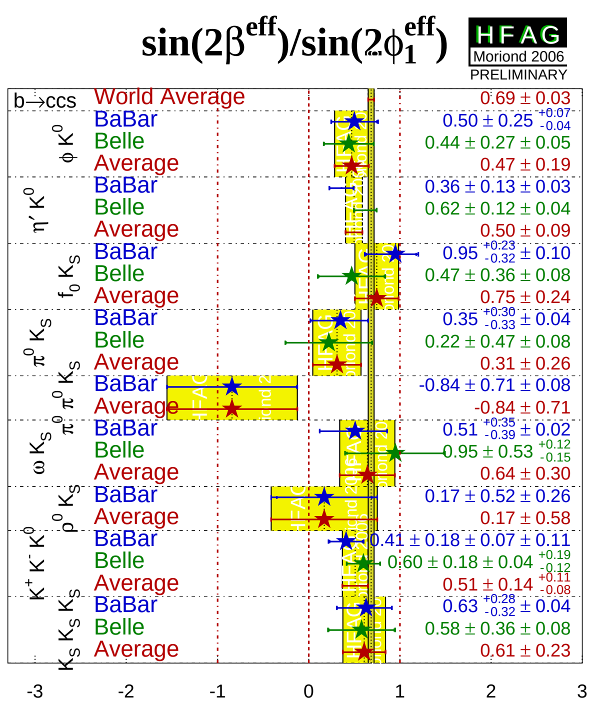

Figure 1: Experimental results for $\sin 2\beta_{\rm eff}$ from $b \to s$ penguin decays [1].

Unitarity of the CKM matrix elements leads to

$$M(\overline{B}^0 \to f) = V_{ub}V_{us}^* A_f^u + V_{cb}V_{cs}^* A_f^c \approx A\lambda^4 R_b e^{-i\gamma} A_f^u + A\lambda^2 A_f^c, \quad (7)$$

where $A_f^u = F^u - F^t$, $A_f^c = F^c - F^t$, $R_b \equiv |V_{ud}V_{ub}/(V_{cd}V_{cb})| = \sqrt{\bar\rho^2+\bar\eta^2}$. The first term is suppressed by a factor of λ^2 relative to the second term. For a pure penguin decay such as $B^0 \to \phi K^0$, it is naively expected that A_f^u is in general comparable to A_f^c in magnitude. Therefore, to a good approximation $-\eta_f S_f \approx \sin 2\beta \approx S_{J/\psi K}$. For penguin-dominated modes such as $\omega K_S, \rho^0 K_S, \pi^0 K_S$, A_f^u also receives tree contributions from the $b \to u\bar u s$ tree operators. Since the Wilson coefficient for the penguin operator is smaller than the one for the tree operator, A_f^u could be significantly larger than A_f^c. As the first term carries a weak phase γ, it is possible that S_f is subject to a significant "tree pollution". To quantify the deviation, it is known that to the first order in $r_f \equiv (\lambda_u A_f^u)/(\lambda_c A_f^c)$ [5, 16]

$$\Delta\mathcal{S}_f = 2|r_f|\cos 2\beta \sin\gamma \cos\delta_f,\ \mathcal{A}_f = 2|r_f|\sin\gamma\sin\delta_f,$$

with $\delta_f = \arg(A_f^u/A_f^c)$. Hence, the magnitude of the CP asymmetry difference $\Delta\mathcal{S}_f$ and direct CP violation are both governed by the size of A_f^u/A_f^c. However, for the aforementioned penguin-dominated modes, the tree contribution is color suppressed and hence in practice the deviation of $\mathcal{S}_f$ is expected to be small [2]. It is useful to note that $\Delta\mathcal{S}_f$ is proportional to the real part of A_f^u/A_f^c as shown in the above equation.

Below I will review the results of the SM expectations on $\Delta\mathcal{S}_f$ from short-distance and long-distance calculations. Recent reviews of results obtained from the SU(3) approach can be found in [17].

2. $\Delta\mathcal{S}_f$ from short-distance calculations

There are several QCD-based approaches in calculating hadronic B decays [18–20]. $\Delta\mathcal{S}_f$ from calculations of QCDF [9, 10], pQCD [11], SCET [12] are shown in Table 1. The QCDF calculations on PP, VP modes are from [9] [1], while those in SP modes are from [10]. It is interesting to note that (i) $\Delta\mathcal{S}_f$ are small and positive in most cases, while experimental central values for $\Delta\mathcal{S}_f$ are all negative, except the one from $f_0 K_S$; (ii) QCDF and pQCD results agree with each other, since the main difference of these two approach is the (penguin) annihilation contribution, which hardly affects S_f; (iii) The SCET results involve some non-perturbative contributions fitted from data. These contributions affect ΔS_f and give results in the $\eta' K_S$ mode different from the QCDF ones.

Table I $\Delta\mathcal{S}_f$ from various short-distance calculations.

$\Delta\mathcal{S}_f$	QCDF	pQCD	SCET	Expt
ϕK_S	0.02 ± 0.01	$0.020^{+0.005}_{-0.008}$		-0.22 ± 0.19
ωK_S	0.13 ± 0.08			-0.06 ± 0.30
$\rho^0 K_S$	$-0.08^{+0.08}_{-0.12}$			-0.52 ± 0.58
$\eta' K_S$	0.01 ± 0.01		-0.02 ± 0.01 -0.01 ± 0.01	-0.19 ± 0.09
ηK_S	$0.10^{+0.11}_{-0.07}$		-0.03 ± 0.17 $+0.07\pm0.14$	
$\pi^0 K_S$	$0.07^{+0.05}_{-0.04}$	$0.06^{+0.02}_{-0.03}$	0.08 ± 0.03	-0.38 ± 0.26
$f_0 K_S$	0.02 ± 0.00			$+0.06\pm0.24$
$a_0 K_S$	0.02 ± 0.01			
$\bar K_0^{*0}\pi^0$	$0.00^{+0.03}_{-0.05}$ $0.02^{+0.00}_{-0.02}$			

It is instructive to understand the size and sign of $\Delta\mathcal{S}_f$ in the QCDF approach [9], for example. Recall that $\Delta\mathcal{S}_f$ is proportional to the real part of A_f^u/A_f^c. We follow [9] to denote a complex number x by $[x]$ if $\mathrm{Re}(x) > 0$. In QCDF the dominant contributions to A_f^u/A_f^c are basically given by [9, 21]

$$\begin{aligned}
\frac{A^u_{\phi K_S}}{A^c_{\phi K_S}} &\sim \frac{[-(a_4^u + r_\chi^\phi a_6^u)]}{[-(a_4^c + r_\chi^\phi a_6^c)]} \sim \frac{[-P^u]}{[-P^c]},\\
\frac{A^u_{\omega K_S}}{A^c_{\omega K_S}} &\sim \frac{+[a_4^u - r_\chi^\phi a_6^u] + [a_2^u R]}{+[a_4^c - r_\chi^\phi a_6^c]} \sim \frac{+[P^u]+[C]}{+[P^c]},\\
\frac{A^u_{\rho K_S}}{A^c_{\rho K_S}} &\sim \frac{-[a_4^u - r_\chi^\phi a_6^u] + [a_2^u R]}{-[a_4^c - r_\chi^\phi a_6^c]} \sim \frac{-[P^u]+[C]}{-[P^c]}, \quad (8)\\
\frac{A^u_{\pi^0 K_S}}{A^c_{\pi^0 K_S}} &\sim \frac{[-(a_4^u + r_K^\phi a_6^u)] + [a_2^u R']}{[-(a_4^c + r_K^\phi a_6^c)]} \sim \frac{[-P^u]+[C]}{[-P^c]},\\
\frac{A^u_{\eta' K_S}}{A^c_{\eta' K_S}} &\sim \frac{-[-(a_4^u + r_K^\phi a_6^u)] + [a_2^u R'']}{-[-(a_4^c + r_K^\phi a_6^c)]} \sim \frac{[-P^u]-[C]}{[-P^c]},
\end{aligned}$$

where a_i^p are effective Wilson coefficients [2], $r_\chi = O(1)$ are the chiral factors and $R^{(\prime,\prime\prime)}$ are (real and positive) ratios of form factors and decay constants.

From Eq.(8), it is clear that $\Delta\mathcal{S}_f > 0$ for ϕK_S, ωK_S, $\pi^0 K_S$, since their $\mathrm{Re}(A_f^u/A_f^c)$ can only be positive. Furthermore, due to the cancellation between a_4 and $r_\chi a_6$ in the ωK_S amplitude, the corresponding penguin contribution is suppressed. This leads to a large and positive $\Delta\mathcal{S}_{\omega K_S}$ as shown in Table I. For the cases of $\rho^0 K_S$ and $\eta' K_S$, there are chances for $\Delta\mathcal{S}_f$ to be positive or negative. The different signs

[1] Results obtained agree with those in [13].

[2] In general, we have $\mathrm{Re}(a_2) > 0$, $\mathrm{Re}(a_6) <\mathrm{Re}(a_4) < 0$.

Table II Direct CP asymmetry parameter $\mathcal{A}_f$ and the mixing-induced CP parameter $\Delta\mathcal{S}_f^{SD+LD}$ for various modes. The first and second theoretical errors correspond to the SD and LD ones, respectively [13].

Final State	$\Delta\mathcal{S}_f$			$\mathcal{A}_f(\%)$		
	SD	SD+LD	Expt	SD	SD+LD	Expt
ϕK_S	$0.02^{+0.01}_{-0.02}$	$0.04^{+0.01+0.01}_{-0.02-0.02}$	-0.22 ± 0.19	$0.8^{+0.5}_{-0.2}$	$-2.3^{+0.9+2.2}_{-1.0-5.1}$	9 ± 14
ωK_S	$0.12^{+0.06}_{-0.05}$	$0.02^{+0.03+0.03}_{-0.04-0.02}$	-0.06 ± 0.30	$-6.8^{+2.4}_{-4.0}$	$-13.5^{+3.5+2.4}_{-5.7-1.5}$	44 ± 23
$\rho^0 K_S$	$-0.08^{+0.03}_{-0.10}$	$-0.04^{+0.07+0.10}_{-0.10-0.12}$	-0.52 ± 0.58	$7.8^{+4.5}_{-2.0}$	$48.9^{+15.8+5.8}_{-13.7-12.5}$	-64 ± 48
$\eta' K_S$	$0.01^{+0.01}_{-0.02}$	$0.00^{+0.01+0.00}_{-0.02-0.00}$	-0.19 ± 0.09	$1.7^{+0.4}_{-0.3}$	$2.1^{+0.2+0.1}_{-0.5-0.4}$	7 ± 7
ηK_S	$0.07^{+0.03}_{-0.03}$	$0.07^{+0.03+0.00}_{-0.03-0.01}$	–	$-5.7^{+2.0}_{-5.5}$	$-3.9^{+1.8+2.5}_{-5.0-1.6}$	–
$\pi^0 K_S$	$0.06^{+0.03}_{-0.03}$	$0.04^{+0.01+0.02}_{-0.02-0.02}$	-0.38 ± 0.26	$-3.2^{+1.1}_{-2.3}$	$3.7^{+1.9+1.7}_{-1.6-1.7}$	2 ± 13

in front of $[P]$ in $\rho^0 K_S$ and ωK_S are originated from the second term of the wave functions $(u\bar u \pm d\bar d)/\sqrt{2}$ of ω and ρ^0 in the $\overline{B}^0 \to \omega$ and $\overline{B}^0 \to \rho^0$ transitions, respectively. The $[P]$ in $\rho^0 K_S$ is also suppressed as the one in ωK_S, resulting a negative $\Delta\mathcal{S}_{\rho^0 K_S}$. On the other hand, $[-P]$ in $\eta' K_S$ is not only unsuppressed (no cancellation in the a_4 and a_6 terms), but, in fact, is further enhanced due to the constructive interference of various penguin amplitudes [22]. This enhancement is responsible for the large $\eta' K_S$ rate [22] and also for the small $\Delta\mathcal{S}_{\eta' K_S}$ [9, 13].

3. FSI contributions to $\Delta\mathcal{S}_f$

Evidence of direct CP violation in the decay $\overline{B}^0 \to K^-\pi^+$ is now established, while the combined BaBar and Belle measurements of $\overline{B}^0 \to \rho^\pm\pi^\mp$ imply a sizable direct CP asymmetry in the $\rho^+\pi^-$ mode [1]. In fact, direct CP asymmetries in these channels are much bigger than expectations (of many people) and may be indicative of appreciable LD rescattering effects, in general, in B decays [23]. The possibility of final-state interactions in bringing in the possible tree pollution sources to $\mathcal{S}_f$ are considered in [13]. Both A_f^u and A_f^c will receive long-distance tree and penguin contributions from rescattering of some intermediate states. In particular there may be some dynamical enhancement of light u-quark loop. If tree contributions to A_f^u are sizable, then final-state rescattering will have the potential of pushing S_f away from the naive expectation. Take the penguin-dominated decay $\overline{B}^0 \to \omega\overline{K}^0$ as an illustration. It can proceed through the weak decay $\overline{B}^0 \to K^{*-}\pi^+$ followed by the rescattering $K^{*-}\pi^+ \to \omega\overline{K}^0$. The tree contribution to $\overline{B}^0 \to K^{*-}\pi^+$, which is color allowed, turns out to be comparable to the penguin one because of the absence of the chiral enhancement characterized by the a_6 penguin term. Consequently, even within the framework of the SM, final-state rescattering may provide a mechanism of tree pollution to $\mathcal{S}_f$. By the same token, we note that although $\overline{B}^0 \to \phi\overline{K}^0$ is a pure penguin process at short distances, it does receive tree contributions via long-distance rescattering. Note that in addition to these charmless final states contributions, there are also contributions from charmful $D_s^{(*)}D^{(*)}$ final states, see Fig. 2. These final-state rescatterings provide the long-distance u- and c-penguin contributions.

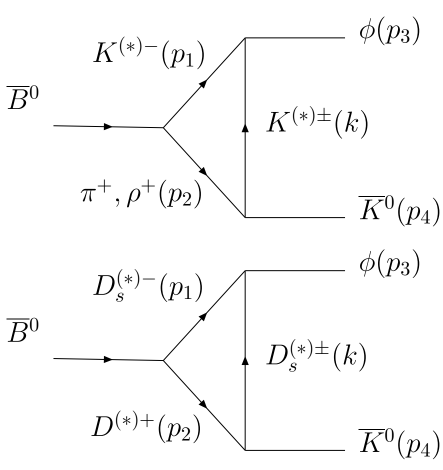

Figure 2: Final-state rescattering contributions to the $\overline{B}^0 \to \phi\overline{K}^0$ decay.

An updated version of results in [13] are shown in Table II. Several comments are in order. (i) ϕK_S and $\eta' K_S$ are the theoretical and experimental cleanest modes for measuring $\sin 2\beta_{\rm eff}$ in these penguin modes. The constructive interference behavior of penguins in the $\eta' K_S$ mode is still hold in the LD case, resulting a tiny $\Delta\mathcal{S}_{\eta' K_S}$. (ii) Tree pollutions in ωK_S and $\rho^0 K_S$ are diluted due to the LD c-penguin contributions.

It is found that LD tree contributions are in general not large enough in producing sizable $\Delta\mathcal{S}_f$, since their constributions are overwhelmed by LD c-penguin contributions from $D_s^{(*)}D^{(*)}$ rescatterings. On the other hand, while it may be possible to have a large $\Delta\mathcal{S}_f$ from rescattering models that enhance the contributions from charmless states, a sizable direct CP violation will also be generated. Since direct CP violations are sensitive to strong phases generated from FSI, these approaches will also give a sizable direct CP violation at the same time when a large $\Delta\mathcal{S}_f$ is produced. The present data on the ϕK_S and $\eta' K_S$ modes do not support large direct CP violations in these modes. Consequently, it is unlikely that FSI will enlarge their $\Delta\mathcal{S}_f$. In order to constrain or to refine these calculations, it will be very useful to have more and better data on direct CP violations.

4. $\Delta\mathcal{S}_f$ in KKK modes

$\overline{B}^0 \to K^+K^-K_{S,L}$ and $\overline{B}^0 \to K_SK_SK_S$ are penguin-dominated and pure penguin decays, respectively. They are also used to extracted $\sin 2\beta_{\rm eff}$ with results shown in Fig. 1. Three-body modes are in general more complicated than two-body modes. For example, while the $K_SK_SK_S$ mode remains as a CP-even mode, the $K^+K^-K_{S(L)}$ mode is not a CP-eigen state [3]. Furthermore, the mass spectra of these modes are in general complicated and non-trivial.

A factorization approach is used to study these KKK modes [14]. In the factorization approach, the $\overline{B}^0 \to K^+K^-K_S$ amplitude, for example, basically consists of two factorized terms: $\langle \overline{B}^0 \to K_S\rangle \times \langle 0 \to K^+K^-\rangle$ and $\langle \overline{B}^0 \to K^+K_S\rangle \times \langle 0 \to K^-\rangle$, where $\langle A \to B\rangle$ denotes a $A \to B$ transition matrix element. The dominant contribution is from the $\langle \overline{B}^0 \to K_S\rangle \times \langle 0 \to K^+K^-\rangle$ term, which is a penguin induced term, while the sub-leading $\langle \overline{B}^0 \to K^+K_S\rangle \times \langle 0 \to K^-\rangle$ term contains both tree and penguin contributions. In fact, $\overline{B}^0 \to K^+K_S$ transition is a $b \to u$ transition, which has a color allowed tree contribution.

Results of CP asymmetries for these modes are given in Table III. The first uncertainty is from hadronic parameter in $\overline{B}^0 \to K^+K_{S,L}$ transition in $K^+K^-K_{S,L}$ mode (and a similar term in $K_SK_SK_S$ mode), the second uncertainty is from other hadronic parameters, while the last uncertainty is from the uncertainty in γ.

To study $\Delta\mathcal{S}_f$ and $\mathcal{A}_f$, it is crucial to know the size of the $b \to u$ transition term (A^u_f). For the pure-penguin $K_SK_SK_S$ mode, the smallness of $\Delta\mathcal{S}_{K_SK_SK_S}$ and $\mathcal{A}_{K_SK_SK_S}$ can be easily understood. For the $K^+K^-K_S$ mode, there is a $b \to u$ transition in the $\langle \overline{B}^0 \to K^+K_S\rangle \otimes \langle 0 \to K^-\rangle$ term. It has the potential of giving large tree pollution in $\Delta\mathcal{S}_{K^+K^-K_S}$. It requires more efforts to study the size and the impact of this term.

It is important to note that the $b \to u$ transition term in the $K^+K^-K_S$ mode is not a CP self-conjugated term, since under a CP conjugation, this term will be turned into a $\langle \overline{B}^0 \to K^-K_S\rangle \times \langle 0 \to K^+\rangle$ term, which is, however, missing in the original amplitude. Hence, this term contributes to both CP-even and CP-odd configurations with similar strength. Therefore, information in the CP-odd part can be used to constrain its size and its impact on $\Delta\mathcal{S}_f$ and $\mathcal{A}_f$. Indeed, it is found recently [24] that the CP-odd part is highly dominated by ϕK_S, where other contributions (at $m_{K^+K^-} \neq m_\phi$) are highly suppressed. Since the $\langle \overline{B}^0 \to K^+K_S\rangle \times \langle 0 \to K^-\rangle$ term favors a large $m_{K^+K^-}$ region, which is clearly separated from the ϕ-resonance region, the result of the CP-odd configuration strongly constrains the contribution from this $b \to u$ transition term. Consequently, the tree pollution is constrained and the $\Delta\mathcal{S}_{K^+K^-K_S}$ should not be large. Note that results shown in Table III were obtained without fully incorporating these information. The first uncertainty in Table III will be reduced, if the CP-odd result is taken into account. To further refine the results it will be very useful to perform a detail Dalitz-plot analysis.

Table III Mixing-induced and direct CP asymmetries $\Delta\mathcal{S}_f$ (top) and $\mathcal{A}_f$ (in %, bottom), respectively, in $B^0 \to K^+K^-K_S$ and $K_SK_SK_S$ decays. Results for $(K^+K^-K_L)_{CP\pm}$ are identical to those for $(K^+K^-K_S)_{CP\mp}$.

Final State	$\Delta\mathcal{S}_f$	Expt.
$(K^+K^-K_S)_{\phi K_S \text{ excluded}}$	$0.03^{+0.08+0.02+0.00}_{-0.01-0.01-0.02}$	$-0.12^{+0.18}_{-0.17}$
$(K^+K^-K_S)_{CP+}$	$0.05^{+0.11+0.04+0.00}_{-0.03-0.02-0.01}$	
$(K^+K^-K_L)_{\phi K_L \text{ excluded}}$	$0.03^{+0.08+0.02+0.00}_{-0.01-0.01-0.02}$	-0.60 ± 0.34
$K_SK_SK_S$	$0.02^{+0.00+0.00+0.01}_{-0.00-0.00-0.02}$	0.19 ± 0.23
$K_SK_SK_L$	$0.02^{+0.00+0.00+0.01}_{-0.00-0.00-0.02}$	
	$\mathcal{A}_f(\%)$	Expt.
$(K^+K^-K_S)_{\phi K_S \text{ excluded}}$	$0.2^{+1.0+0.3+0.0}_{-0.1-0.3-0.0}$	-8 ± 10
$(K^+K^-K_S)_{CP+}$	$-0.1^{+0.7+0.2+0.0}_{-0.0-0.3-0.0}$	
$(K^+K^-K_L)_{\phi K_L \text{ excluded}}$	$0.2^{+1.0+0.3+0.0}_{-0.1-0.3-0.0}$	-54 ± 24
$K_SK_SK_S$	$0.7^{+0.0+0.0+0.1}_{-0.1-0.0-0.1}$	31 ± 17
$K_SK_SK_L$	$0.8^{+0.1+0.1+0.1}_{-0.3-0.1-0.1}$	

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[3] However, it is found that $K^+K^-K_S$ is dominated by the CP-even part and hence it is still useful in extracting $\sin 2\beta_{\rm eff}$.

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