CP Asymmetries in Charm Decays into Neutral Kaons

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We find a new CP-violation effect in charm decays into neutral kaons, which results from the interference between two tree (Cabibbo-favored and doubly Cabibbo-suppressed) amplitudes with the mixing of final-state mesons. This effect, estimated to be of an order of 10^{-3}, is much larger than the direct CP asymmetries in these decays, but missed in the literature. It can be revealed by measuring the difference of the time-dependent CP asymmetries in the $D^+ \to \pi^+ K_S^0$ and $D_s^+ \to K^+ K_S^0$ modes, which are accessible at the LHCb and Belle II experiments. If confirmed, the new effect has to be taken into account, as the above direct CP asymmetries are used to search for new physics.

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CP violation plays an important role in interpreting the matter-antimatter asymmetry in the Universe and in searching for new physics beyond the standard model (SM). It has been well established in the kaon and B meson systems, but not yet in the charm sector. Many theoretical and experimental efforts have been devoted to the study of CP violation in the singly Cabibbo-suppressed (SCS) D meson decays, with the interests in flavor-changing-neutral currents from penguin amplitudes. The most precise individual measurements up to now are obtained for the time-integrated CP asymmetry by the LHCb Collaboration [1],

$$\Delta A_{CP} \equiv A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-) = (-1.0 \pm 0.8 \pm 0.3) \times 10^{-3}, \quad (1)$$

which is dominated by the direct CP violation $\Delta a_{CP}^{\rm dir}$, and for the asymmetry in effective decay widths through time-dependent rates [2], $A_\Gamma(D^0 \to K^+K^-) = (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3}$, which is sensitive to the indirect CP violation in the D^0-$\bar{D}^0$ mixing. With the precision lower than 10^{-3}, there is still no evidence of CP violation in the charm system.

CP violation can also occur via the interference between the Cabibbo-favored (CF) and doubly Cabibbo-suppressed (DCS) channels of $D \to f K_S^0$, with f being a final-state particle. These decays, with large branching factions from the CF amplitudes, are more experimentally accessible. However, the CP asymmetries, such as

$$A_{CP}(D^+ \to \pi^+ K_S^0) = (-3.63 \pm 0.94 \pm 0.67) \times 10^{-3}, \quad (2)$$

with 3.2σ from zero observed by the Belle Collaboration [3], are mainly attributed to the K^0-$\bar{K}^0$ mixing. It has been claimed [3–7] that deviation from the kaon-mixing effect in a precise measurement of the above mode can be identified as the direct CP violation. Because of its smallness in the SM, the direct CP violation in these decays has been regarded as a promising observable for searching for new physics [6–9].

In this Letter, we will point out a new CP-violation effect in charm decays into neutral kaons, which results from the interference between the CF and DCS amplitudes with the mixing of final-state mesons. This new effect, estimated to be of the order of 10^{-3}, turns out to be much larger than the direct CP asymmetry, but has been, to our surprise, missed in the literature [3–6]. We propose to measure the difference of the CP asymmetries in the decay chains $D^+ \to \pi^+ K(t)(\to \pi^+\pi^-)$ and $D_s^+ \to K^+ K(t)(\to \pi^+\pi^-)$, where $K(t)$ represents a time-evolved neutral kaon $K^0(t)$ or $\bar{K}^0(t)$ with t being the time difference between the charm decays and the neutral kaon decays in the kaon rest frame. It will be shown that the contributions to the above difference from the pure kaon mixing cancel, and the new effect can be clearly revealed. Only when this new effect has been well determined can the direct CP asymmetries in charm decays into neutral kaons be extracted correctly and used to search for new physics.

A K_S^0 state is reconstructed via its decay into two charged pions at a time close to its lifetime τ_S in measurements of the $D \to f K_S^0$ processes. Hence, not only K_S^0, but also K_L^0 serve as the intermediate states in the $D \to f K(t)(\to \pi^+\pi^-)$ chain decays through the K_S^0-K_L^0 oscillation, and to their CP asymmetries [4]. The K_S^0 and K_L^0 states are linear combinations of the flavor eigenstates

$$|K_{S,L}^0\rangle = p|K^0\rangle \mp q|\bar{K}^0\rangle, \quad (3)$$

where $q/p = (1-\epsilon)/(1+\epsilon)$, and ϵ is a small complex parameter characterizing the indirect CP violation in the kaon mixing with the magnitude $|\epsilon| = (2.228 \pm 0.011) \times 10^{-3}$ and the phase $\phi_\epsilon = 43.52 \pm 0.05°$ [10]. Let $m_{S,L}$, $\Gamma_{S,L}$, and $\tau_{S,L}$ denote the masses, widths, and lifetimes of

$|K^0_{S,L}\rangle$, respectively. The average of widths is then given by $\Gamma = (\Gamma_S + \Gamma_L)/2$, and the differences of widths and masses are $\Delta\Gamma \equiv \Gamma_S - \Gamma_L$ and $\Delta m \equiv m_L - m_S$, respectively. We write the ratio between the DCS and CF amplitudes as

$$\mathcal{A}(D \to fK^0)/\mathcal{A}(D \to f\bar{K}^0) = r_f e^{i(\phi+\delta_f)}, \tag{4}$$

with the magnitude $r_f \propto |V^*_{cd}V_{us}/V^*_{cs}V_{ud}| \sim \mathcal{O}(10^{-2})$, the relative strong phase δ_f that depends on final states, and the weak phase $\phi \equiv Arg[-V^*_{cd}V_{us}/V^*_{cs}V_{ud}] = (-6.2 \pm 0.4) \times 10^{-4}$ in the SM.

We consider the time-dependent CP asymmetry

$$A_{CP}(t) \equiv \frac{\Gamma_{\pi\pi}(t) - \bar{\Gamma}_{\pi\pi}(t)}{\Gamma_{\pi\pi}(t) + \bar{\Gamma}_{\pi\pi}(t)}, \tag{5}$$

where

$$\Gamma_{\pi\pi}(t) \equiv \Gamma(D \to fK(t)(\to \pi^+\pi^-)),$$
$$\bar{\Gamma}_{\pi\pi}(t) \equiv \Gamma(\bar{D} \to \bar{f}K(t)(\to \pi^+\pi^-)). \tag{6}$$

Neglecting the tiny direct CP asymmetry in the $K \to \pi\pi$ decays, namely, assuming the equality of the amplitudes $\mathcal{A}(\bar{K}^0 \to \pi^+\pi^-) = -\mathcal{A}(K^0 \to \pi^+\pi^-)$, we derive from Eq. (5)

$$A_{CP}(t) \simeq [A^{\bar{K}^0}_{CP}(t) + A^{\rm dir}_{CP}(t) + A^{\rm int}_{CP}(t)]/D(t), \tag{7}$$

with the denominator $D(t) = e^{-\Gamma_S t}(1 - 2r_f \cos\delta_f \cos\phi) + e^{-\Gamma_L t}|\epsilon|^2$. The first term corresponds to the known CP violation in the kaon mixing [4],

$$A^{\bar{K}^0}_{CP}(t) = 2e^{-\Gamma_S t}\mathcal{R}e(\epsilon) - 2e^{-\Gamma t}[\mathcal{R}e(\epsilon)\cos(\Delta m t) + \mathcal{I}m(\epsilon)\sin(\Delta m t)], \tag{8}$$

which is independent of r_f, i.e., of the DCS amplitude. The second term is the direct CP asymmetry originating from the interference between the CF and DCS amplitudes,

$$A^{\rm dir}_{CP}(t) = e^{-\Gamma_S t} 2r_f \sin\delta_f \sin\phi. \tag{9}$$

The third term in Eq. (7) represents the new CP-violation effect,

$$A^{\rm int}_{CP}(t) = -4r_f \cos\phi \sin\delta_f [e^{-\Gamma_S t}\mathcal{I}m(\epsilon) - e^{-\Gamma t}(\mathcal{I}m(\epsilon)\cos(\Delta m t) - \mathcal{R}e(\epsilon)\sin(\Delta m t))], \tag{10}$$

which is induced by the interference between the CF and DCS amplitudes of the decays $D \to f\bar{K}^0(t)(\to \pi^+\pi^-)$ and $D \to fK^0(t)(\to \pi^+\pi^-)$ with the kaon mixing. The mechanism responsible for Eq. (10) is more complicated than for

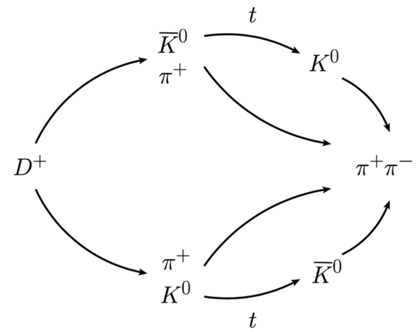

FIG. 1. Schematic description of the chain decay $D^+ \to \pi^+ K(t)(\to \pi^+\pi^-)$.

the ordinary mixing-induced CP asymmetry in, for example, the $B^0(t) \to \pi^+\pi^-$ mode: both the oscillation and decay take place in the mother particle in the latter, while $A^{\rm int}_{CP}$ arises from the mother decay and the daughter mixing as depicted in Fig. 1. $A^{\rm int}_{CP}$ is not a direct CP asymmetry in charm decays, since it does not vanish as $\phi = 0$.

Compared to the SCS case, both the CF and DCS amplitudes, being of the tree level, can be extracted from data of branching fractions [11–14]. A global fit to the newest data in the factorization-assisted topological-amplitude (FAT) approach [11] gives the parameters r_{π^+,K^+} and δ_{π^+,K^+} for the $D^+ \to \pi^+ K^0_S$ and $D^+_s \to K^+ K^0_S$ decays [15]

$$r_{\pi^+} = -0.073 \pm 0.004, \qquad \delta_{\pi^+} = -1.39 \pm 0.05,$$
$$r_{K^+} = -0.055 \pm 0.002, \qquad \delta_{K^+} = +1.45 \pm 0.05. \tag{11}$$

The solution with opposite signs of δ_{π^+,K^+} contributes equivalently to branching fractions, which depend only on the cosine of strong phases. The one presented above is preferred by the central value of the CP-asymmetry data in Eq. (2) in the global fit, to which the sign of strong phases is relevant.

The time-dependent CP asymmetries in the $D^+ \to \pi^+ K(t)(\to \pi^+\pi^-)$ decay as a function of t/τ_S are displayed in Fig. 2. It is found that the total CP asymmetry is dominated by $A^{\bar{K}^0}_{CP}$, and the new effect $A^{\rm int}_{CP}$, reaching an order of 10^{-3} or even 10^{-2} in the range $2\tau_S \lesssim t \lesssim 5\tau_S$, are experimentally accessible. The direct CP asymmetry is too small to be seen in the plots. Hence, deviation of the total CP asymmetry in $D \to fK^0_S$ decays from $A^{\bar{K}^0}_{CP}$ should be attributed to $A^{\rm int}_{CP}$, instead of to the direct CP asymmetry. Figure 2 also indicates that the total CP asymmetry approaches to zero at $t = 0$, because both $A^{\bar{K}^0}_{CP}$ and $A^{\rm int}_{CP}$ diminish at $t = 0$, and $A^{\rm dir}_{CP}$ is tiny. With the inputs in Eq. (11), the direct CP asymmetries are predicted to be

$$A^{\rm dir}_{CP}(D^+ \to \pi^+ K^0_S) = (-8.6 \pm 0.4) \times 10^{-5},$$
$$A^{\rm dir}_{CP}(D^+_s \to K^+ K^0_S) = (6.6 \pm 0.3) \times 10^{-5}. \tag{12}$$

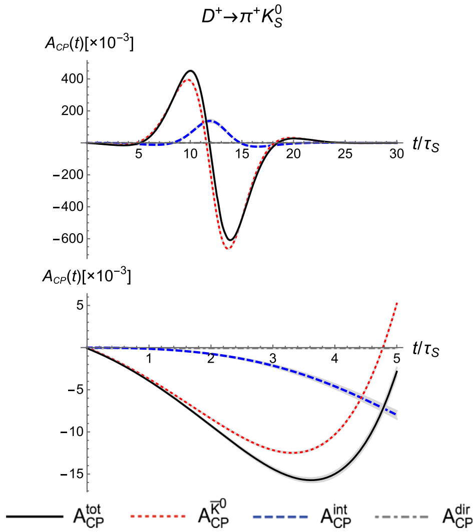

FIG. 2. Time-dependent CP asymmetries in the $D^+ \to \pi^+ K(t)(\to \pi^+\pi^-)$ decay as a function of t/τ_S, with the zoomed-in plot for the small t region in the lower plot. The gray bands represent the theoretical uncertainties.

Both the forthcoming experiments, Belle II and LHCb upgrade, cannot attain such a precision at an order of 10^{-5}. However, a large weak phase difference between the CF and DCS amplitudes could exist in new physics models [6–9,16], resulting in a larger $A_{CP}^{\rm dir}$. Therefore, an observation with nonvanishing $A_{CP}(t=0)$ at the Belle II and LHCb upgrade would be a signature of new physics.

Searching for new physics through the direct CP asymmetries in Eq. (12) might be more promising than through those in the SCS processes. For the latter, it is difficult to predict the CP asymmetries precisely due to the ambiguity in estimating the penguin contributions: the QCD-inspired approaches do not work at the charm scale, and the penguin topologies cannot be extracted from data of branching fractions. This is the reason why predictions for $\Delta a_{CP}^{\rm dir}$ in the SM vary from $\mathcal{O}(10^{-4})$ to $\mathcal{O}(1\%)$ [11,17–29], and cannot be used to discriminate new physics.

The denominator $D(t)$ in Eq. (7) can be related to the K_S^0-K_L^0 asymmetry,

$$R \equiv \frac{\Gamma(D\to fK_S^0) - \Gamma(D\to fK_L^0)}{\Gamma(D\to fK_S^0) + \Gamma(D\to fK_L^0)} = -2r_f\cos(\phi+\delta_f) \approx -2r_f\cos\phi\cos\delta_f, \quad (13)$$

in the limit $\phi \to 0$. The K_S^0-K_L^0 asymmetry in $D^+ \to \pi^+ K_{S,L}^0$ has been measured by the CLEO Collaboration with a value 0.022 ± 0.024 [30]. The FAT approach leads to $R(D^+ \to \pi^+ K_{S,L}^0) = 0.025 \pm 0.008$, consistent with the data, and $R(D_s^+ \to K^+ K_{S,L}^0) = 0.012 \pm 0.006$ [15]. The above small results, in agreement with those derived in the literature [13,31–33], are due to $\delta_{\pi^+,K^+} \sim \pm\pi/2$ in Eq. (11). That is, the term $2r_f\cos\phi\cos\delta_f$ causes an effect at least 1 order of magnitude lower than $A_{CP}^{\rm int}$.

Measurements of CP asymmetries depend on time intervals selected in experiments. To obtain a time-integrated CP asymmetry defined by

$$A_{CP} = \frac{\int_0^\infty F(t)[\Gamma_{\pi\pi}(t) - \bar{\Gamma}_{\pi\pi}(t)]dt}{\int_0^\infty F(t)[\Gamma_{\pi\pi}(t) + \bar{\Gamma}_{\pi\pi}(t)]dt}, \quad (14)$$

a function of time, $F(t)$, is introduced to take into account relevant experimental effects, such as detecting efficiencies and kaon energies. We adopt the approximation with $F(t) = 1$ in the interval $[t_1, t_2]$ and $F(t) = 0$ elsewhere [4]. Equation (14) then yields

$$A_{CP}(t_1,t_2) = \frac{\int_{t_1}^{t_2}[A_{CP}^{\bar{K}^0}(t) + A_{CP}^{\rm dir}(t) + A_{CP}^{\rm int}(t)]dt}{\int_{t_1}^{t_2} D(t)dt}$$
$$= \frac{2\mathcal{R}e(\epsilon) - 4\mathcal{I}m(\epsilon)r_f\cos\phi\sin\delta_f}{1-2r_f\cos\delta_f\cos\phi}\left(1 - \frac{[c(t_1)-c(t_2)] + \frac{\mathcal{I}m(\epsilon)+2\mathcal{R}e(\epsilon)r_f\cos\phi\sin\delta_f}{\mathcal{R}e(\epsilon)-2\mathcal{I}m(\epsilon)r_f\cos\phi\sin\delta_f}[s(t_1)-s(t_2)]}{\tau_S\Gamma(1+x^2)(e^{-\Gamma_S t_1} - e^{-\Gamma_S t_2})}\right)$$
$$+ 2r_f\sin\delta_f\sin\phi, \quad (15)$$

where $x \equiv \Delta m/\Gamma$, $c(t) = e^{-t\Gamma}[\cos(\Delta m t) - x\sin(\Delta m t)]$, and $s(t) = e^{-t\Gamma}[x\cos(\Delta m t) + \sin(\Delta m t)]$. In the second line, the terms proportional to r_f stand for the new effect $A_{CP}^{\rm int}$, and those without r_f for the CP violation in the neutral kaon system. The last term, being independent of $t_{1,2}$, corresponds to the direct CP asymmetry. The time-integrated CP asymmetries in the $D^+ \to \pi^+ K_S^0$ decays are exhibited in Fig. 3 with the upper plot for the total CP asymmetry and the lower one for the new effect. Both quantities are relatively large in some ranges of t_1 and t_2, suggesting the favorable time intervals for experimental investigations of these CP asymmetries.

With the same approximation as in [34] for the limit of $t_1 \ll \tau_S \ll t_2 \ll \tau_L$, we get

$$A_{CP}(t_1 \ll \tau_S \ll t_2 \ll \tau_L) \simeq \frac{-2\mathcal{R}e(\epsilon) + 2r_f\sin\phi\sin\delta_f - 4\mathcal{I}m(\epsilon)r_f\cos\phi\sin\delta_f}{1-2r_f\cos\phi\cos\delta_f}. \quad (16)$$

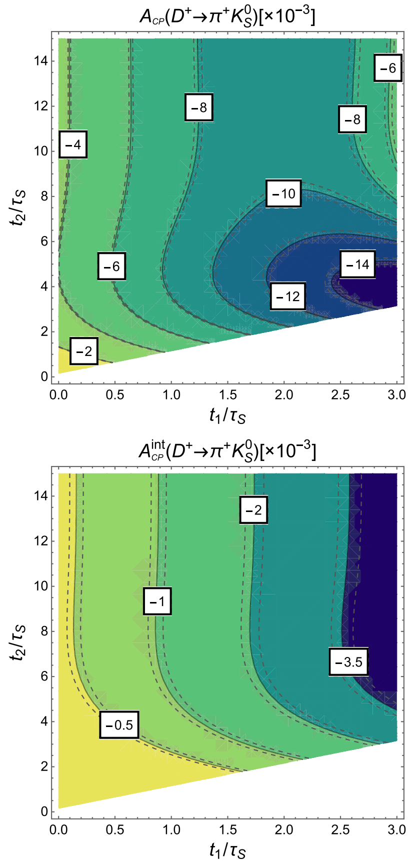

FIG. 3. Time-integrated CP asymmetries as a function of t_1 and t_2 ($t_1 < t_2$) in the $D^+ \to \pi^+ K_S^0$ decay with the upper plot for the total CP asymmetry and the lower one for the new CP-violation effect. The dashed lines indicate the theoretical uncertainties of our predictions.

In the absence of the DCS contributions, i.e., $r_f = 0$, the above formula reduces to $-2\mathcal{R}e(\epsilon)$ derived in [3–6,8,9]. The effect of $A_{CP}^{\rm int}$, namely, the third term in the numerator of Eq. (16) was missed in the study of the CP asymmetry in $D^+ \to \pi^+ K_S^0$ by the Belle Collaboration [3]. The direct CP violation has to be extracted by subtracting the kaon-mixing and new effects from the total CP asymmetry. The sum of the latter two effects in Eq. (16) is predicted to be $(-3.57 \pm 0.05) \times 10^{-3}$. The direct CP violation $(-0.06 \pm 1.15) \times 10^{-3}$ is then obtained from the Belle data in Eq. (2), consistent with our prediction in Eq. (12). The $D^+ \to \pi^+ K_S^0$ and $D_s^+ \to K^+ K_S^0$ decays have been employed to cancel the systematic asymmetries from the production and detection at the LHCb for the measurements of CP violation in the SCS processes [35–38]. The working assumption is that there is no sizable CP violation other than the one from the kaon mixing in the $D^+ \to \pi^+ K_S^0$ and $D_s^+ \to K^+ K_S^0$ decays. However, $A_{CP}^{\rm int}$ observed here is of the same order as the direct CP asymmetries in the SCS processes, which are expected to be $\mathcal{O}(10^{-3})$ or $\mathcal{O}(10^{-4})$. That is, the effect of $A_{CP}^{\rm int}$ has to be considered in these measurements as well.

To verify the new CP-violation effect, we propose an observable, the difference of the time-integrated CP asymmetries in the $D^+ \to \pi^+ K_S^0$ and $D_s^+ \to K^+ K_S^0$ modes,

$$\begin{aligned}\Delta A_{CP}^{\pi^+,K^+} &\equiv A_{CP}^{D^+\to\pi^+K_S^0}(t_1,t_2) - A_{CP}^{D_s^+\to K^+K_S^0}(t_1,t_2)\\ &\simeq A_{CP}^{{\rm int},D^+\to\pi^+K_S^0}(t_1,t_2) - A_{CP}^{{\rm int},D_s^+\to K^+K_S^0}(t_1,t_2).\end{aligned} \tag{17}$$

Our global-fit analysis indicates that the new effect is the most significant in this observable. The CP violation in the kaon mixing, being mode-independent as implied by Eq. (8), is canceled in the above difference, and the direct CP violation is negligible. The new effect survives in $\Delta A_{CP}^{\pi^+,K^+}$ according to the following model-independent argument. The topological diagrams of the CF and DCS amplitudes in these two decays are exchanged to each other under the flavor $SU(3)$ symmetry, $\mathcal{A}(D^+ \to \pi^+ K^0)/V_{us}V_{cd}^* = \mathcal{A}(D_s^+ \to K^+ \bar{K}^0)/V_{ud}V_{cs}^* = C + A$ and $\mathcal{A}(D^+ \to \pi^+ \bar{K}^0)/V_{ud}V_{cs}^* = \mathcal{A}(D_s^+ \to K^+ K^0)/V_{us}V_{cd}^* = T + C$, with the color-favored tree-emission diagram T, the color-suppressed tree-emission diagram C, and the W-annihilation diagram A [39–41]. The relative strong phases δ_f in these two modes are, thus, opposite in sign, as shown in Eq. (11), so that the new effects are constructive in $\Delta A_{CP}^{\pi^+,K^+}$. The dependencies of $\Delta A_{CP}^{\pi^+,K^+}$ on t_1 and t_2 are displayed in Fig. 4. It is seen that this observable is of the order of 10^{-3} in most of the time intervals, and increases with t_1.

The effect of $A_{CP}^{\rm int}$ are measurable in the forthcoming experiments. The precision of Belle II measurements on the CP asymmetry in $D^+ \to \pi^+ K_S^0$ can attain 3×10^{-4} at 50 ab^{-1} [42]. In the LHCb upgrade, the error bar of ΔA_{CP} defined in Eq. (1) would be reduced to 1.2×10^{-4} at 50 fb^{-1} [43]. The signal yields of $D^+ \to \pi^+ K_S^0$ and $D_s^+ \to K^+ K_S^0$ are of the same order as of $D^0 \to K^+ K^-$ and

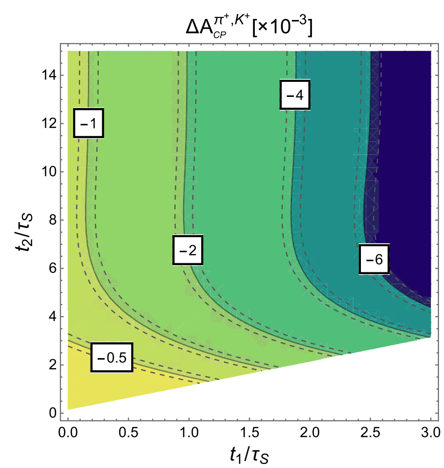

FIG. 4. Same as FIG. 3 but for $\Delta A_{CP}^{\pi^+,K^+}$.

$\pi^+\pi^-$ [1,37]. It is then expected that the precision of $\Delta A_{CP}^{\pi^+,K^+}$ can also reach $\mathcal{O}(10^{-4})$ at the LHCb upgrade, and that $\Delta A_{CP}^{\pi^+,K^+} \sim \mathcal{O}(10^{-3})$ is accessible at both the Belle II and LHCb upgrade.

In this Letter, we have studied the time-dependent and time-integrated CP asymmetries in the $D \to f K_S^0(\to \pi^+\pi^-)$ chain decays. A new CP-violation effect was identified in these processes, which is induced by the interference between the CF and the DCS amplitudes with the K^0-$\bar{K}^0$ mixing. Compared to the SCS processes, both the CF and DCS amplitudes, occurring at the tree level, can be extracted from the data of branching fractions. Therefore, their CP asymmetries can be estimated more accurately, and have been shown to be as large as 10^{-3} in the $D^+ \to \pi^+ K_S^0$ and $D_s^+ \to K^+ K_S^0$ modes. Nevertheless, its effect has been missed in the literature. To reveal this new CP-violation effect, we have proposed an observable, the difference of the CP asymmetries in the $D^+ \to \pi^+ K_S^0$ and $D_s^+ \to K^+ K_S^0$ decays accessible at Belle II and LHCb. In addition, the direct CP asymmetries used to search for new physics can be determined either by subtracting the kaon-mixing and DCS interference effects from total CP asymmetries, or by the time-dependent measurements of CP violation in these processes.

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