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CP violation in charm decays at Belle

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Using the full data sample collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider, we present CP violation in charm decays. The $D^0-\bar{D}^0$ mixing parameter y_{CP} and indirect CP violation parameter A_Γ in $D^0 \to h^+h^-$ decays are reported, where h denotes K and π. The preliminary results are $y_{CP} = (1.11 \pm 0.22 \pm 0.11)\%$ and $A_\Gamma = (-0.03 \pm 0.20 \pm 0.08)\%$. We also report searches for CP violation in $D^0 \to h^+h^-$ and $D^+ \to K^0_S K^+$ decays. No evidence for CP violation in $D^0 \to h^+h^-$ is observed with $A^{KK}_{CP} = (-0.32 \pm 0.21 \pm 0.09)\%$ and $A^{\pi\pi}_{CP} = (+0.55 \pm 0.36 \pm 0.09)\%$. The CP asymmetry difference between $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays is measured with $\Delta A^{hh}_{CP} = (-0.87 \pm 0.41 \pm 0.06)\%$. The CP asymmetry in $D^+ \to K^0_S K^+$ decay is measured to be $(-0.25 \pm 0.28 \pm 0.14)\%$. After subtracting CP violation due to $K^0-\bar{K}^0$ mixing, the CP asymmetry in $D^+ \to \bar{K}^0 K^+$ decay is found to be $(+0.08 \pm 0.28 \pm 0.14)\%$.

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1. Introduction

Violation of the combined Charge-conjugation and Parity symmetries (*CP*) in the standard model (SM) is produced by a non-vanishing phase in the Cabibbo-Kobayashi-Maskawa flavor-mixing matrix [1] and that in charm decays is expected to be very small in the SM [2, 3], thus it provides a unique probe to search for beyond the SM.

2. y_{CP} and A_Γ measurements with $D^0 \to h^+h^-$ and $D^0 \to K^-\pi^+$ decays

The neutral charmed meson mixing and indirect *CP* violation (*CPV*) parameters, y_{CP} and A_Γ are defined as

$$y_{CP} = \frac{\hat{\Gamma}(D^0 \to h^+h^-) + \hat{\Gamma}(\bar{D}^0 \to h^+h^-)}{2\Gamma} - 1, \tag{2.1}$$

$$A_\Gamma = \frac{\hat{\Gamma}(D^0 \to h^+h^-) - \hat{\Gamma}(\bar{D}^0 \to h^+h^-)}{2\Gamma}, \tag{2.2}$$

where Γ is the average decay width of the two mass eigenstates of the neutral charmed mesons and $\hat{\Gamma}$ is the effective decay width of $D^0 \to h^+h^-$ that can be described with a single exponential form [4]. Under *CP* conservation, y_{CP} is y that is $\Delta\Gamma/2\Gamma$ and characterizes the charm mixing where $\Delta\Gamma$ is the decay width difference between the two mass eigenstates of the neutral charmed mesons. Therefore, any large deviation between y_{CP} and y strongly indicates *CPV* in charm decays.

The experimental observable for y_{CP} is the lifetime difference between $D^0 \to h^+h^-$ and $D^0 \to K^-\pi^+$ states, where the former is *CP*-even and the latter is an equal mixture of *CP*-even and *CP*-odd under *CP* conservation. The *CPV* parameter A_Γ can be measured from lifetime difference between the two *CP* conjugate decays. From Eq. (2.1) the lifetime of $D^0 \to h^+h^-$ can be expressed as $\tau(D^0 \to h^+h^-) = \tau/(1+y_{CP})$ and from (2.2) that of $D^0 \to h^+h^-$ and $\bar{D}^0 \to h^+h^-$ can be described with $\tau(D^0 \to h^+h^-) = \tau(1-A_\Gamma)$ and $\tau(\bar{D}^0 \to h^+h^-) = \tau(1+A_\Gamma)$, respectively, where τ is the lifetime of $D^0 \to K^-\pi^+$. Therefore, the lifetimes of $D^0 \to h^+h^-$ and $\bar{D}^0 \to h^+h^-$ can be parameterized in terms of y_{CP}, A_Γ, and τ as shown in Eq. (2.3).

$$\begin{aligned} \tau(D^0 \to h^+h^-) &= \tau(1-A_\Gamma)/(1+y_{CP}), \\ \tau(\bar{D}^0 \to h^+h^-) &= \tau(1+A_\Gamma)/(1+y_{CP}). \end{aligned} \tag{2.3}$$

In order to extract y_{CP}, A_Γ, and τ, we perform simultaneous fit to the five proper decay time distributions from $D^0 \to K^+K^-$, $\bar{D}^0 \to K^+K^-$, $D^0 \to K^-\pi^+$ + c.c., $D^0 \to \pi^+\pi^-$, and $\bar{D}^0 \to \pi^+\pi^-$.

Since the experimental data were taken with two different silicon vertex detector configurations [5], we treat them separately with the two different proper decay time resolution functions. Figure 1 shows the simultaneous fits to the five proper decay time distributions. To reduce systematic effects due to the resolution function dependence on $\cos\theta^*$, where θ^* is the polar angle of the D^0 momentum at the center-of-mass system (c.m.s.), the simultaneous fits are actually performed in bins of $\cos\theta^*$ to extract y_{CP}, A_Γ and τ. Figure 2 shows the results of the simultaneous fits, y_{CP}, A_Γ, and τ as a function of the $\cos\theta^*$. The averages of the fit results shown in Fig. 2 are $y_{CP} = (1.11 \pm 0.22 \pm 0.11)\%$, $A_\Gamma = (-0.03 \pm 0.20 \pm 0.08)\%$, and $\tau = (408.56 \pm 0.54)$ fs, where the last is consistent with world average [6].

To conclude, we observe y_{CP} with 4.5σ significance and find no indirect *CPV* in $D^0 \to h^+h^-$ decays.

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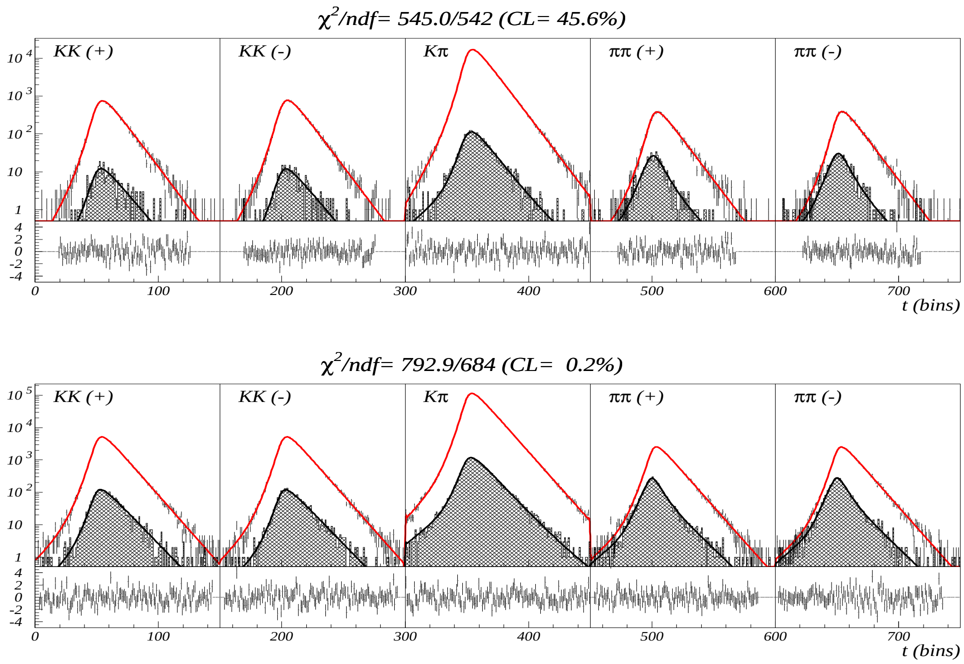

Figure 1: Simultaneous fits to the proper decay time distributions that are integrated over the $\cos\theta^*$. Top (bottom) plots are obtained with 3-layer (4-layer) silicon vertex detector. The distributions of signal and sideband regions are shown as error bars and the hatched, respectively. The "(+)" and "(-)" denote the charge of the tagging soft pion.

3. Direct *CPV* measurements in $D^0 \to h^+h^-$ and $D^+ \to K_S^0 K^+$ decays

The direct *CP* asymmetry of $D \to f$ decays is defined as

$$A_{CP}^{D\to f} = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}, \tag{3.1}$$

where Γ is the partial decay width. Experimental determination of $A_{CP}^{D\to f}$ can be done with the asymmetry in the signal yield

$$A_{\rm rec}^{D\to f} = \frac{N_{\rm rec}^{D\to f} - N_{\rm rec}^{\bar{D}\to\bar{f}}}{N_{\rm rec}^{D\to f} + N_{\rm rec}^{\bar{D}\to\bar{f}}} = A_{CP}^{D\to f} + A_{\rm others}, \tag{3.2}$$

where $N_{\rm rec}$ is the number of reconstructed decays and $A_{\rm others}$ are asymmetries other than $A_{CP}^{D\to f}$, production and particle detection asymmetries. The methods developed in Refs. [7] and [8] are used to correct for charged kaon and soft pion detection asymmetries, respectively. To correct for asymmetry caused by neutral kaons, we rely on the method in Ref. [9]. Once we correct for asymmetries due to particle detection, then we extract $A_{CP}^{D\to f}$ using the antisymmetry of the production asymmetry which is the forward-backward asymmetry at Belle.

The $D^0 \to h^+h^-$ final states are singly Cabibbo-suppressed (SCS) decays in which both direct and indirect *CPV* are expected in the SM [2, 3], while the *CP* asymmetry difference between the

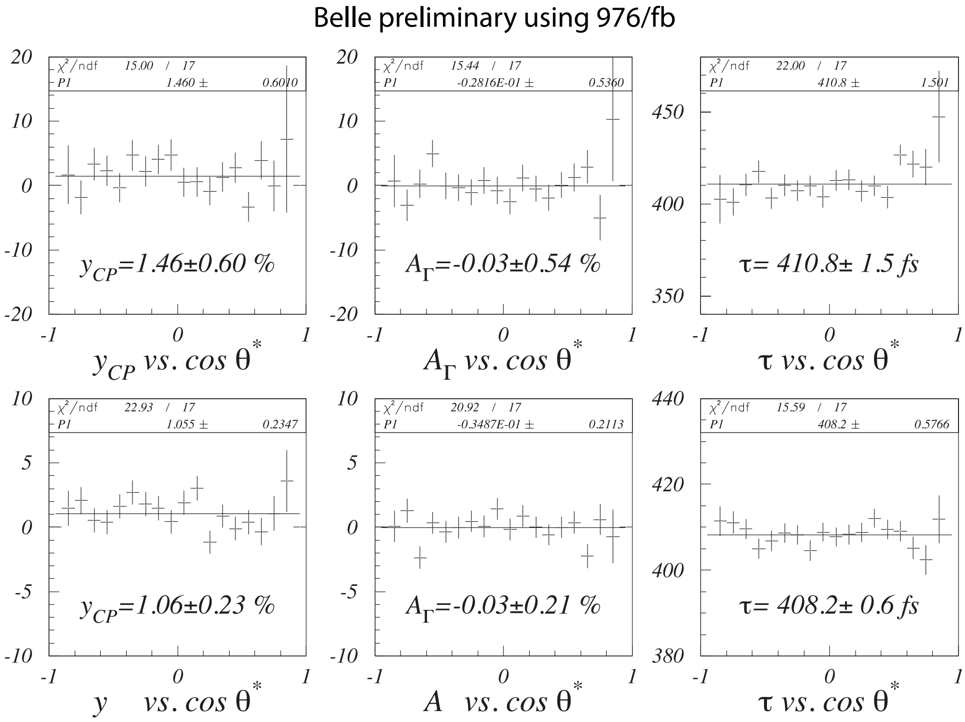

Figure 2: y_{CP}, A_Γ, and τ as a function of the $\cos\theta^*$. Top (bottom) three plots are obtained with 3-layer (4-layer) silicon vertex detector.

two decays, $\Delta A_{CP}^{hh} = A_{CP}^{KK} - A_{CP}^{\pi\pi}$ reveals approximately direct *CPV* with the universality of indirect *CPV* in charm decays [3]. Figure 3 shows reconstructed signal distributions showing 14.7M $D^0 \to K^-\pi^+$, 3.1M D^{*+} tagged $D^0 \to K^-\pi^+$, 282k D^{*+} tagged $D^0 \to K^+K^-$, and 123k D^{*+} tagged $D^0 \to \pi^+\pi^-$, respectively, and the measured A_{CP} in bins of $|\cos\theta^*_{D^{*+}}|$. From the bottom plots in Fig. 3, we obtain $A_{CP}^{KK} = (-0.32 \pm 0.21 \pm 0.09)\%$ and $A_{CP}^{\pi\pi} = (+0.55 \pm 0.36 \pm 0.09)\%$ where the former shows the best sensitivity to date. From the two measurements, we obtain $\Delta A_{CP}^{hh} = (-0.87 \pm 0.41 \pm 0.06)\%$.

The D^+ decaying to the final state $K_S^0K^+$ proceeds from $D^+ \to \bar{K}^0K^+$ decay which is SCS, where direct *CPV* is predicted to occur [2, 3]. With a K_S^0 in the final state, $D^+ \to K_S^0K^+$ decay is also expected to generate *CPV* due to $K^0 - \bar{K}^0$ mixing, referred to as $A_{CP}^{\bar{K}^0}$. The decay $D^+ \to \bar{K}^0K^+$ shares the same decay diagrams with $D^0 \to K^+K^-$ by exchanging the spectator quarks, $d \leftrightarrow u$. Therefore, neglecting the helicity and color suppressed contributions in $D^+ \to \bar{K}^0K^+$ and $D^0 \to K^+K^-$ decays, the direct *CPV* in the two decays is expected to be effectively the same. Thus, as a complementary test of the ΔA_{CP}^{hh} measurement[1], the precise measurement of A_{CP} in $D^+ \to \bar{K}^0K^+$ helps to pin down the origin of ΔA_{CP}^{hh} [12]. Figure 4 shows invariant masses of $D^\pm \to K_S^0K^\pm$ together with the fits that result in ~277k reconstructed decays and the measured A_{CP} in bins of $|\cos\theta^{\text{c.m.s.}}_{D^+}|$. From the right plot in Fig. 4, we obtain $A_{CP}^{D^+\to K_S^0K^+} = (-0.25 \pm 0.28 \pm 0.14)\%$. After

[1] Now the tension is rather released [10], but was strong [11].

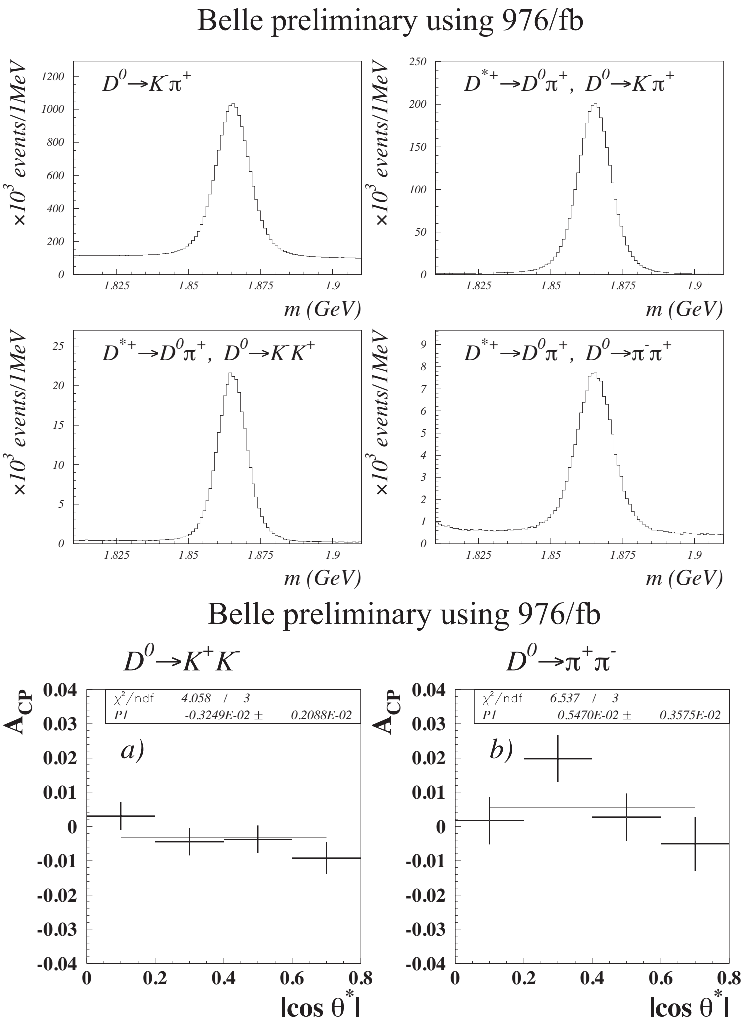

Figure 3: Top four plots show reconstructed signal distributions described in the text and bottom two plots show preliminary results of A_{CP} as a function of the polar angle of D^{*+} momentum at the c.m.s.

subtracting experiment dependent $A_{CP}^{\bar{K}^0}$ [13], the *CPV* in charm decay, $A_{CP}^{D^+\to\bar{K}^0K^+}$, is measured to be $(+0.08 \pm 0.28 \pm 0.14)\%$ [14].

4. Summary

In summary, using the full data sample collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider, we report the charm mixing parameter y_{CP} and indirect *CPV* parameter A_Γ using $D^0 \to h^+h^-$ and $D^0 \to K^-\pi^+$ decays. The preliminary results are:

$$y_{CP} = (1.11 \pm 0.22 \pm 0.11)\%,$$
$$A_\Gamma = (-0.03 \pm 0.20 \pm 0.08)\%.$$

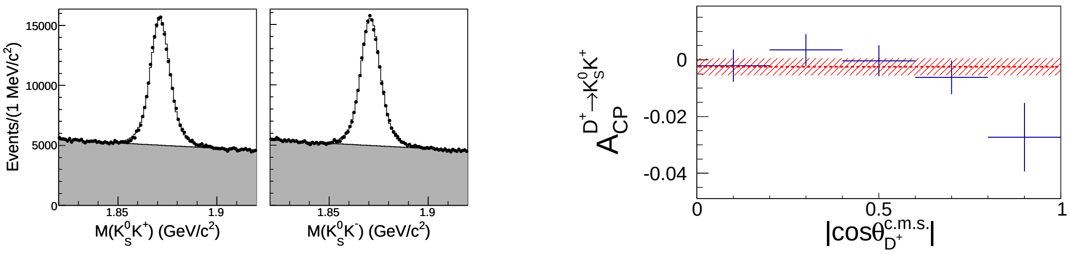

Figure 4: Left two plots show $M(K_S^0K^+)$ and $M(K_S^0K^-)$ distributions, respectively, and right plot shows A_{CP} in the decay as a function of the polar angle of D^+ momentum at the c.m.s.

We also report searches for CP violation in $D^0 \to h^+h^-$ and $D^+ \to K_S^0K^+$ decays. The preliminary results of A_{CP} in $D^0 \to h^+h^-$ decays and the difference between the two A_{CP} results are:

$$\begin{aligned} A_{CP}^{KK} &= (-0.32 \pm 0.21 \pm 0.09)\%, \\ A_{CP}^{\pi\pi} &= (+0.55 \pm 0.36 \pm 0.09)\%, \\ \Delta A_{CP}^{hh} &= (-0.87 \pm 0.41 \pm 0.06)\%, \end{aligned}$$

and the results of A_{CP} in $D^+ \to K_S^0K^+$ decays are:

$$\begin{aligned} A_{CP}^{D^+\to K_S^0K^+} &= (-0.25 \pm 0.28 \pm 0.14)\%, \\ A_{CP}^{D^+\to \bar{K}^0K^+} &= (+0.08 \pm 0.28 \pm 0.14)\%. \end{aligned}$$

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