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Direct CP violation in charm 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 have searched for CP violation of charmed mesons in $D^+ \to K_S^0\pi^+$ and $D^0 \to h^+h^-$ decays, where h denotes K and π. We observe evidence for CP violation in $D^+ \to K_S^0\pi^+$ decay with 3.2 standard deviations away from zero, $(-0.363\pm0.094\pm0.067)$%, while the asymmetry is consistent with the expected CP violation due to the neutral kaon in the final state. No evidence for CP violation in $D^0 \to h^+h^-$ is observed with $A_{CP}^{KK} = (-0.32\pm0.21\pm0.09)$% and $A_{CP}^{\pi\pi} = (+0.55\pm0.36\pm0.09)$%. The CP asymmetry difference between $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays is also measured with $\Delta A_{CP}^{hh} = (-0.87\pm0.41\pm0.06)$%, which is 2.1 standard deviations away from zero and supports recent LHCb and CDF measurements.

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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], where the violation may be observed as a non-zero CP asymmetry defined as

$$A_{CP}^{D\to f} = \frac{\Gamma(D\to f)-\Gamma(\bar{D}\to \bar{f})}{\Gamma(D\to f)+\Gamma(\bar{D}\to \bar{f})} \tag{1}$$

where Γ is the partial decay width, D denotes a charmed meson, and f is a final state.

In this presentation, we report CP asymmetries of charmed mesons in the decays $D^+\to K_S^0\pi^+$, $D^0\to K^+K^-$, $D^0\to \pi^+\pi^-$ [2], and the CP asymmetry difference between $D^0\to K^+K^-$ and $D^0\to \pi^+\pi^-$, which is an update of our previous publications [3, 4] using the full data sample collected with the Belle detector [5] at the KEKB [6] asymmetric-energy e^+e^- collider. The $D^+\to K_S^0\pi^+$ final state is a coherent sum of Cabibbo-favored and doubly Cabibbo-suppressed decays where no SM CP violation in charm decay is expected, while $(-0.332\pm0.006)\%$ [7] CP violation due to $K^0-\bar{K}^0$ mixing (denoted by $A_{CP}^{\bar{K}^0}$) is expected with a neutral kaon in the final state. The $D^0\to h^+h^-$ final states where h denotes K and π are singly Cabibbo-suppressed decays in which both direct ($a_{CP}^{\rm dir}$) and indirect CP violations ($a_{CP}^{\rm ind}$) are expected in the SM, while the CP asymmetry difference between the two decays, $\Delta A_{CP}^{hh} = A_{CP}^{KK} - A_{CP}^{\pi\pi}$, reveals approximately direct CP violation with the universality of indirect CP violation in charm decays [8]. The data were recorded at the $\Upsilon(nS)$ resonances ($n=1,2,3,4,5$) or near the $\Upsilon(4S)$ resonance and the integrated luminosity is $\sim$1 ab^{-1}.

We determine the quantity $A_{CP}^{D\to f}$ defined in Eq. (1) by measuring the asymmetry in the signal yield

$$A_{\rm rec}^{D\to f} \;=\; \frac{N_{\rm rec}^{D\to f}-N_{\rm rec}^{\bar{D}\to \bar{f}}}{N_{\rm rec}^{D\to f}+N_{\rm rec}^{\bar{D}\to \bar{f}}} \;=\; A_{CP}^{D\to f} \;+\; A_{FB} + A_{\varepsilon}^{f}, \tag{2}$$

where $N_{\rm rec}$ is the number of reconstructed decays. The A_{FB} is forward-backward asymmetry in $e^+e^-\to c\bar{c}$ process and the A_{ε}^{f} is final state particle detection asymmetry where the latter depends on the final state particles while the former does not. For a slow pion detection asymmetry which is involved in $D^0\to h^+h^-$ reconstruction via D^{*+}, we correct for the asymmetry using the method described in our previous publication [4]. A fast pion detection asymmetry which is involved in $D^+\to K_S^0\pi^+$ reconstruction is corrected for using the method described in Ref. [9]. With assumption the A_{FB} is the same for all charmed mesons, Refs. [4, 9] use CP violation free large statistics of resonance data samples to correct for the A_{ε}^{f}. For the final state with a neutral kaon, we have to take into account additional corrections which are asymmetry due to different interactions between K^0 and $\bar{K}^0$ with detector [10] and experiment dependent $A_{CP}^{\bar{K}^0}$ with K_S^0 decay time dependency on it [11]. Once we correct for A_{ε}^{f}, then $A_{CP}^{D\to f}$ is obtained in bins of the polar angle of charmed meson momentum at the center-of-mass system (c.m.s.) using antisymmetry of A_{FB} in the polar angle of charmed meson momentum at the c.m.s.

Figure 1 shows invariant masses of $D^\pm\to K_S^0\pi^\pm$ together with the fits that result in $\sim$1.74M reconstructed decays and the measured A_{CP} in bins of the polar angle of D^+ momentum at the c.m.s. From the right plot in Fig. 1, we obtain $A_{CP}^{D^+\to K_S^0\pi^+} = (-0.363\pm0.094\pm0.067)\%$ which shows 3.2σ deviations from zero. This is the first evidence for CP violation in charm decays from a single decay mode while the measured asymmetry is consistent with the $A_{CP}^{\bar{K}^0}$. After subtracting experiment dependent $A_{CP}^{\bar{K}^0}$ [11], the CP violation due to change in charm, $A_{CP}^{\Delta C}$, is measured to be $(-0.024\pm0.094\pm0.067)\%$ [9].

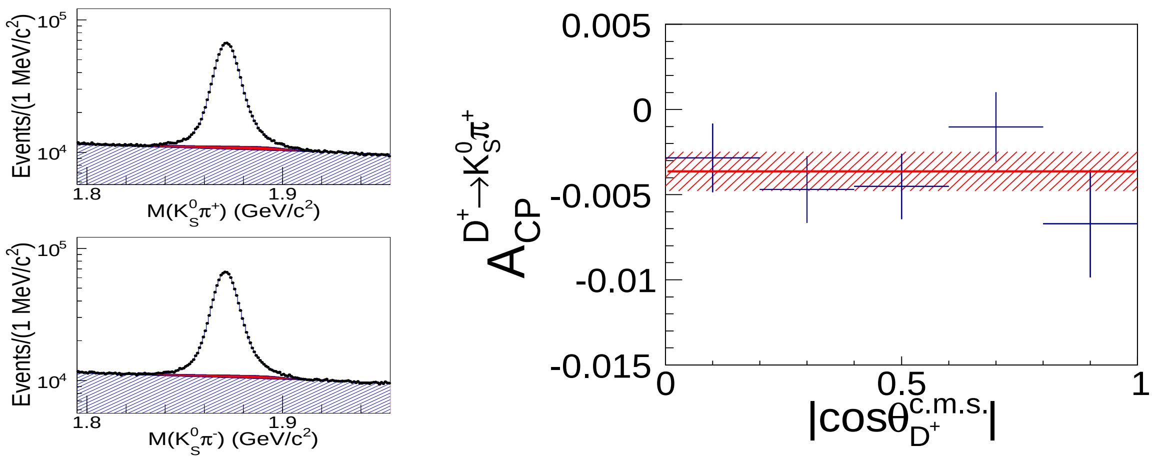

Figure 1: $M(K_S^0\pi^+)$ (left top) and $M(K_S^0\pi^-)$ (left bottom) distributions where the shaded and hatched are $D_s^+ \to K_S^0 K^+$ due to particle misidentification and combinatorial backgrounds. Right plot is A_{CP} as a function of $\cos\theta_{D^+}^{\text{c.m.s.}}$ where the thick line is the mean value of A_{CP} while the hatched band is the $\pm 1\sigma_{\text{total}}$ interval, where σ_{total} is the total uncertainty.

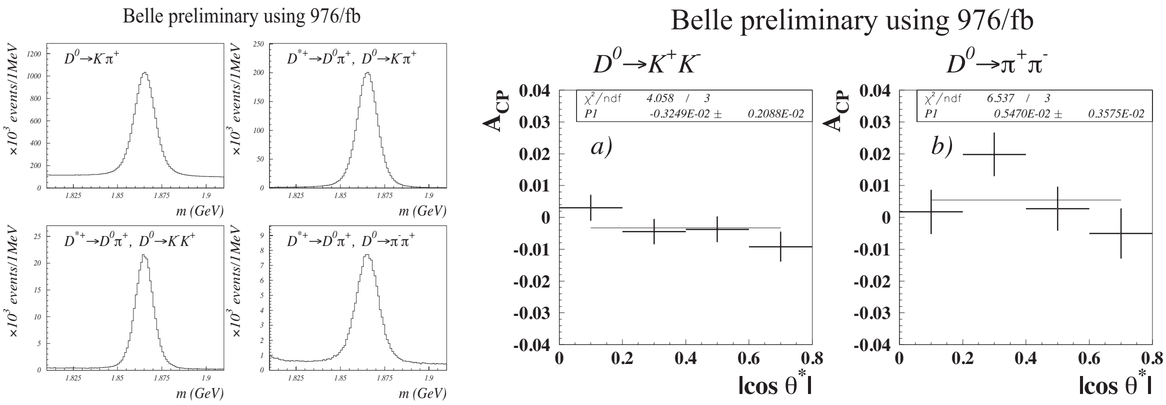

Figure 2: Left four plots show reconstructed signal distributions described in the text and right two plots show preliminary results of A_{CP} as a function of the polar angle of D^{*+} momentum at the c.m.s.

Figure 2 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 $D^0 \to \pi^+\pi^-$ on top of the high signal purities, respectively, and the measured A_{CP} in bins of the polar angle of D^{*+} momentum at the c.m.s. From the right plot in Fig. 2, 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 $\Delta A_{CP}^{hh} = (-0.87 \pm 0.41 \pm 0.06)\%$ which shows 2.1σ deviations from zero and supports recent LHCb and CDF measurements [12, 13]. By combining LHCb, CDF, and Belle results, the average of ΔA_{CP}^{hh} becomes $(-0.74 \pm 0.15)\%$.

With a help from Marco Gersabeck from Heavy Flavor Averaging Group (HFAG), Fig. 3 shows ΔA_{CP} and A_Γ fit reflecting the new Belle results reported in this presentation and results in $\Delta a_{CP}^{\text{dir}} = (-0.678 \pm 0.147)\%$ and $a_{CP}^{\text{ind}} = (+0.027 \pm 0.163)\%$ [14].

In summary, we observe evidence for CP violation in the decay $D^+ \to K_S^0\pi^+$ where the ev-

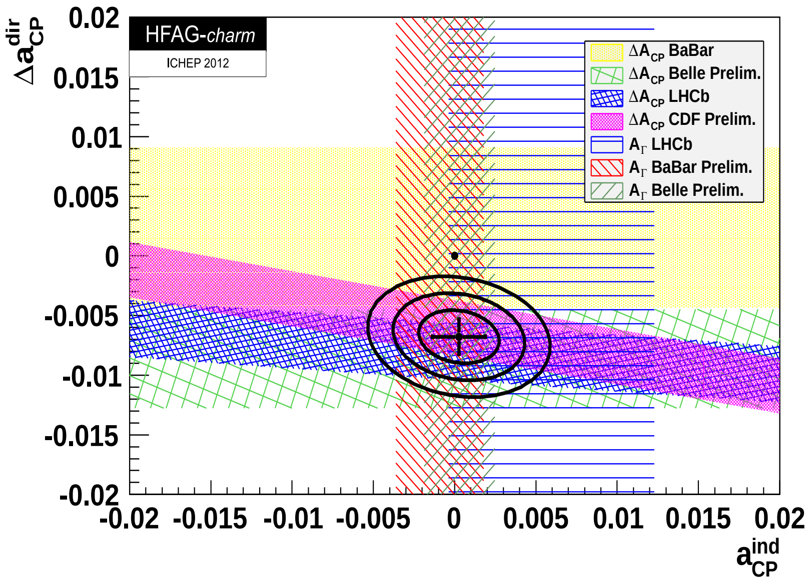

Figure 3: ΔA_{CP} and A_Γ fit from HFAG.

idence is consistent with the expected CP violation due to $K^0 - \bar{K}^0$ mixing. No evidence for CP violation in $D^0 \to h^+h^-$ is observed and the ΔA^{hh}_{CP} is measured to be $(-0.87 \pm 0.41 \pm 0.06)\%$.

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