Physics Letters B 670 (2008) 190–195

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Search for a CP asymmetry in Cabibbo-suppressed D^0 decays

Belle Collaboration

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0370-2693/$ – see front matter
doi:10.1016/j.physletb.2008.10.052

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ARTICLE INFO

Article history:
Received 1 July 2008
Received in revised form 30 September 2008
Accepted 28 October 2008
Available online 31 October 2008
Editor: M. Doser

PACS:
11.30.Er
13.25.Ft
14.40.Lb

Keywords:
Charm mesons
CP violation
Cabibbo suppressed decays

ABSTRACT

We measure the CP-violating asymmetries in decays to the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ CP eigenstates using 540 fb^{-1} of data collected with the Belle detector at or near the $\Upsilon(4S)$ resonance. Cabibbo-favored $D^0 \to K^-\pi^+$ decays are used to correct for systematic detector effects. The results, $A_{CP}^{KK} = (-0.43 \pm 0.30 \pm 0.11)\%$ and $A_{CP}^{\pi\pi} = (+0.43 \pm 0.52 \pm 0.12)\%$, are consistent with no CP violation.

1. Introduction

Decays of neutral D mesons are a promising area in which to search for physics beyond the Standard Model (SM). Recently, evidence for D^0–$\bar{D}^0$ mixing has been reported [1–3]. However, whether the observed mixing is due to the Cabibbo–Kobayashi–Maskawa (CKM) theory or due to new physics (NP) has yet to be determined and will require further measurements to resolve. One possible measurement sensitive to NP is that of a CP asymmetry in D^0 decays to Cabibbo-suppressed (CS) final states [4]. Within the SM such an asymmetry is predicted to be very small ($\lesssim$0.1%), but within NP scenarios it can reach the 1% level [4,5].

In this Letter we present a high statistics search for a CP asymmetry in the CS modes $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$. These final states are accessible to both D^0 and $\bar{D}^0$ mesons. The time-integrated CP asymmetry for decays into a CP eigenstate f is defined as

$$A_{CP}^f = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} = a_d^f + a_{\text{ind}}. \quad (1)$$

This quantity receives contributions from both direct (a_d^f) and indirect (a_{ind}) CP violation (CPV) [4]. While the direct contribution is, in general, distinct for different final states, the indirect contribution has the same magnitude for all final CP eigenstates. The indirect CPV contribution is constrained by our recent measurement of the lifetime difference using $D^0(\bar{D}^0) \to K^+K^-, \pi^+\pi^-$ decays [1]: $A_\Gamma \equiv -a_{\text{ind}} = (0.01 \pm 0.30 \pm 0.15)\%$. CP asymmetries in $D^0 \to K^+K^-, \pi^+\pi^-$ decays have previously been searched for [6]; currently the most precise results are limits reported by the BaBar Collaboration [7]. CP asymmetries in CS decays have also been searched for in $D^0 \to \pi^+\pi^-\pi^0$ and $D^0 \to K^+K^-\pi^0$ decays [8].

2. Method

The flavour of neutral D mesons at production is tagged by reconstructing $D^{*+} \to D^0\pi_s^+$ decays[1] in which the charge of the low momentum pion, π_s, determines the flavour of the D^0 meson. The measured asymmetry,

$$A_{\text{rec}}^f = \frac{N(D^0 \to f) - N(\bar{D}^0 \to f)}{N(D^0 \to f) + N(\bar{D}^0 \to f)}, \quad (2)$$

with $f = K^+K^-, \pi^+\pi^-$ and N denoting the number of reconstructed decays, can be written as a sum of several contributions, that are assumed to be small:

$$A_{\text{rec}}^f = A_{\text{FB}} + A_{CP}^f + A_\epsilon^\pi. \quad (3)$$

In addition to the intrinsic asymmetry, A_{CP}^f, there is a contribution due to an asymmetry in the reconstruction efficiencies of oppositely charged π_s mesons (A_ϵ^π). Since the final state f is self-conjugate, its reconstruction efficiency does not affect A_{rec}^f. Furthermore, there is a forward–backward asymmetry (A_{FB}) in the production of D^{*+} mesons in $e^+e^- \to c\bar{c}$ arising from γ–Z^0 interference and higher order QED effects [9]. This term is an odd function of the cosine of the D^{*+} production polar angle in the center-of-mass (CM) system[2] ($\cos\theta^*$). Since our detector acceptance is not symmetric with respect to $\cos\theta^*$, the measurement

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[1] Unless explicitly noted, charge conjugated processes are implied throughout the Letter.
[2] Symbols with an asterix denote quantities in the CM frame, while those without an asterix denote quantities in the laboratory frame.

is performed in bins of $\cos\theta^*$. This allows us to correct for acceptance and extract both $A_{\rm FB}$ and $A^f_{\rm CP}$ as described below.

To reliably determine A^π_ϵ we adopt the method of Ref. [7] with some appropriate modifications. In addition to the $D^0 \to h^+h^-$ modes mentioned above, we also reconstruct two $D^0 \to K^-\pi^+$ samples: one consisting of D mesons with tagged initial flavour, and another consisting of untagged candidates. The measured asymmetries for these modes can be written as

$$A^{\rm tag}_{\rm rec} = A_{\rm FB} + A^{K\pi}_{\rm CP} + A^{K\pi}_\epsilon + A^\pi_\epsilon,$$
$$A^{\rm untag}_{\rm rec} = A_{\rm FB} + A^{K\pi}_{\rm CP} + A^{K\pi}_\epsilon. \qquad (4)$$

A notable difference with (3) is that this final state is not self-conjugate and thus an additional term $A^{K\pi}_\epsilon$ appears as a consequence of a possible asymmetry in the $K\pi$ reconstruction efficiency. We first use the two measurements in (4) to determine A^π_ϵ; we then insert the result into (3) and use the fact that $A_{\rm FB}$ is antisymmetric with respect to $\cos\theta^*$ and $A^f_{\rm CP}$ is constant.

However, reconstruction efficiencies and their asymmetries A^i_ϵ are functions of the momenta of particle $i = \pi_s$, $K\pi$ in the laboratory frame. For a D^0 meson with a given momentum $\vec{p}_{D^0}$, the efficiency for reconstructing the final state $K^-\pi^+$ is $\epsilon_{K\pi}(\vec{p}_{D^0}) = \int \epsilon_K(\vec{p}_K)\epsilon_\pi(\vec{p}_\pi) w_{\vec{p}_{D^0}}(\vec{p}_K, \vec{p}_\pi)\, d\vec{p}_K\, d\vec{p}_\pi$, where $w_{\vec{p}_{D^0}}(\vec{p}_K, \vec{p}_\pi)$ denotes the six-dimensional distribution of final state particles. For a given $\vec{p}_{D^0}$, this distribution is independent of whether the D meson candidate is flavour-tagged or not. Using the same selection criteria for the K and π candidates in the tagged and untagged sample implies the selection efficiencies $\epsilon_{K(\pi)}(\vec{p}_{K(\pi)})$ are equal for the two samples. Hence the asymmetry $A^{K\pi}_\epsilon(\vec{p}_{D^0})$ is identical for tagged and untagged D mesons of a given momentum $\vec{p}_{D^0}$, as implied by (4). Since the distribution of D^0 mesons is uniform in the azimuthal angle, the dimension of the problem can be reduced. It is sufficient to obtain $A^{K\pi}_\epsilon$ as a function of the magnitude and polar angle of the laboratory momentum, p_{D^0} and $\cos\theta_{D^0}$.

The slow pion asymmetry A^π_ϵ depends on the momentum $\vec{p}_{\pi_s}$ and is independent of the D^0 final state. Since the π_s azimuthal angle distribution is also found to be uniform, A^π_ϵ is examined as a function of $(p_{\pi_s}, \cos\theta_{\pi_s})$.

3. Measurement

The measurement is based on 540 fb^{-1} of data recorded by the Belle detector [10] at the KEKB asymmetric-energy e^+e^- collider [11], running at the CM energy of the $\Upsilon(4S)$ resonance and 60 MeV below. The Belle detector is described in detail elsewhere [10]: in particular, it includes a silicon vertex detector (SVD), a central drift chamber, an array of aerogel Cherenkov counters, and time-of-flight scintillation counters. Two different SVD configurations were used: a 3-layer configuration for the first 153 fb^{-1} of data, and a 4-layer configuration [12] for the remaining data.

We reconstruct $D^{*+} \to D^0\pi_s^+$, $D^0 \to K^+K^-$, $K^-\pi^+$, $\pi^+\pi^-$ decay chains, as well as the decay $D^0 \to K^-\pi^+$ without requiring an accompanying D^{*+} decay. Each final state charged particle is required to have at least two associated SVD hits in each of the two measured coordinates. To select pion and kaon candidates, we impose standard particle identification criteria [13]. The identification efficiency and the misidentification probability are about 85% and 9%, respectively, for the D^0 daughter particles, and about 99% and 2%, respectively, for the π_s. D^0 daughter particles are refitted to a common vertex. The D^0 production vertex is found by constraining the D^0 (and π_s for the tagged decays) to originate from the e^+e^- interaction region. Confidence levels exceeding 10^{-3} are required for both fits. The D^{*+} (D^0 for untagged decays) momentum must satisfy $p^*_D > 2.5$ GeV/c^2 in order to reject D-mesons produced in B-meson decays and to suppress combinatorial background.

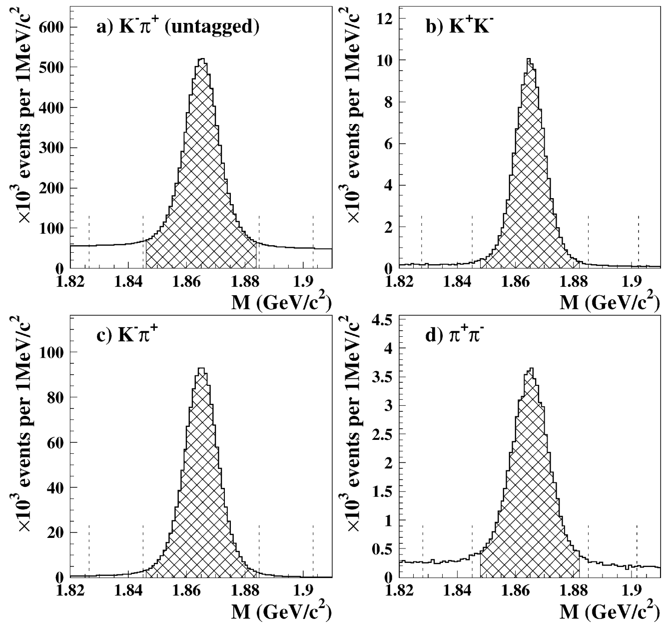

Fig. 1. Invariant mass spectra of selected events. For the tagged data samples (b, c, d) events with $|\Delta q| < 1$ MeV are selected. The cross-hatched area represents the signal region; the sideband positions are indicated by vertical lines.

We accept candidates with a D^0 invariant mass M in the range 1.81 GeV/$c^2 < M <$ 1.91 GeV/c^2. For final states with a π_s, we require that the energy released in the D^{*+} decay, $q = (M_{D^{*+}} - M - m_\pi)c^2$, be less than 20 MeV. In this expression, $M_{D^{*+}}$ is the invariant mass of the $D^0\pi_s^+$ combination and m_π is the charged pion mass. For the small fraction of events with multiple candidates (0.1% for the tagged samples, 2.9% for the untagged sample), we select only one candidate: that in which the sum of the production and decay vertex χ^2's is smallest. We also require[3] $|\cos\theta_{D^0}| < 0.9$ to remove events in which large slow pion asymmetry corrections and consequently large systematic uncertainties are expected. The resulting invariant mass spectra are shown in Fig. 1.

We measure the signal yield by performing a mass-sideband subtraction, as this method is robust and reduces sensitivity to the signal shape. The possibility of a non-linear background shape is considered as a systematic uncertainty. The sizes of signal windows in M and q are chosen to minimize the expected statistical error on the $A_{\rm CP}$ measurement. Using a Monte Carlo (MC) simulation, which has been tuned to reproduce the signal shapes and the signal-to-background ratios of the data, the optimal signal windows are found to be $|\Delta M| < 17.3$ (18.6, 16.8) MeV/c^2 and $|\Delta q| <$ 1.00 (1.85, 0.90) MeV for the KK ($K\pi$, $\pi\pi$) final states. The quantities ΔM and Δq measure the difference of the corresponding observable and the nominal D^0 mass and the nominal energy release in the D^{*+} decay, respectively. Sidebands of the same size as the signal window are chosen, starting at ± 20 MeV/c^2 from the nominal D^0 mass. Within the optimal signal window we find 6.3×10^6 untagged $K^-\pi^+$ signal events with a purity of 80%; the number of tagged signal events is $120 \times 10^3 K^+K^-$, $1.3 \times 10^6 K^-\pi^+$ and $51 \times 10^3 \pi^+\pi^-$, with purities of 97%, 99% and 91%, respectively.

The asymmetries $A^{\rm untag}_{\rm rec}$ and A^π_ϵ are measured separately for the 3-layer and 4-layer SVD configurations. We first determine the

[3] This cut limits the range of measurement to $|\cos\theta^*| < 0.8$.

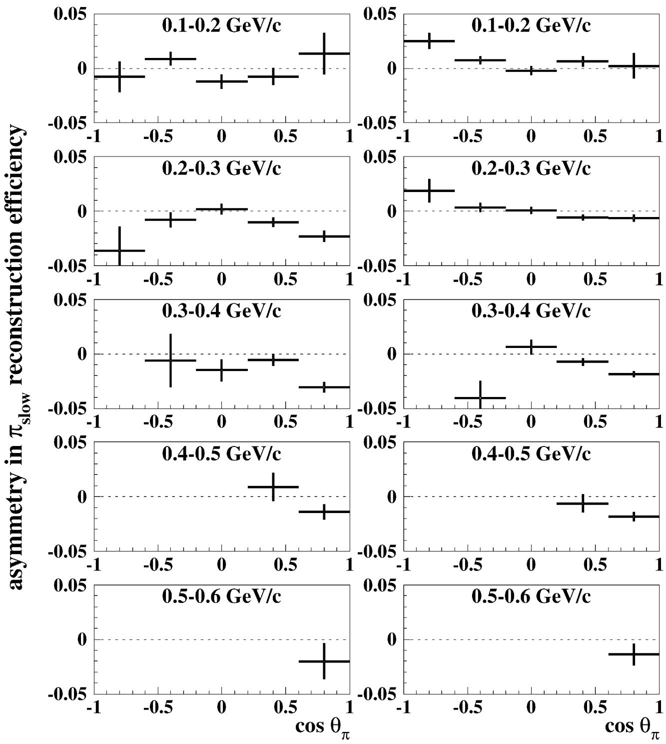

Fig. 2. Asymmetry of the slow pion efficiency, A^π_ϵ, in momentum slices for the 3-layer (left) and the 4-layer (right) SVD configurations.

asymmetry $A^{\rm untag}_{\rm rec}$ of the untagged $K\pi$ sample in 20×20 bins of the two-dimensional phase space $(p_{D^0}, \cos\theta_{D^0})$ using,

$$A^{\rm untag}_{{\rm rec},ij} = \frac{N_{ij}-\bar N_{ij}}{N_{ij}+\bar N_{ij}}, \tag{5}$$

where N_{ij} and $\bar N_{ij}$ are the numbers of reconstructed D^0 and $\bar D^0$ decays, respectively, in bin ij. In order to avoid large statistical fluctuations near the phase space boundaries, we calculate the asymmetry only for those bins with $N_{ij}+\bar N_{ij} > 1000$. The asymmetry is used to correct the tagged $K\pi$ events by weighting each D^0 ($\bar D^0$) candidate falling into a valid bin with a weight,

$$u_{D^0} = 1 - A^{\rm untag}_{\rm rec}(p_{D^0}, \cos\theta_{D^0}),$$
$$u_{\bar D^0} = 1 + A^{\rm untag}_{\rm rec}(p_{\bar D^0}, \cos\theta_{\bar D^0}). \tag{6}$$

Other tagged $K\pi$ candidates are discarded. The weighting applied to the tagged $K\pi$ decays results in a measured $A^{\rm tag}_{\rm rec}$ free of all contributions in (4) except for A^π_ϵ.

The slow pion asymmetry in bin kl of the phase space $(p_{\pi_s}, \cos\theta_{\pi_s})$ is thus determined with,

$$A^\pi_{\epsilon,kl} = \frac{n_{kl}-\bar n_{kl}}{n_{kl}+\bar n_{kl}}, \tag{7}$$

where n_{kl} ($\bar n_{kl}$) are the sums of weights of the D^0 ($\bar D^0$) candidates falling in that bin. Again, we consider only bins with $n_{kl}+\bar n_{kl} > 1000$. The resulting asymmetry $A^\pi_\epsilon(p_{\pi_s}, \cos\theta_{\pi_s})$ determined in 5×5 bins for the two SVD configurations is shown in Fig. 2. Averaging over the phase space the correction due to the slow pion efficiency is found to be $(+0.76\pm 0.09)\%$.

The slow pion asymmetry is used to correct the KK and $\pi\pi$ events. The $D^0/\bar D^0$ candidates are weighted according to,

$$w_{D^0} = 1 - A^\pi_\epsilon(p_{\pi_s}, \cos\theta_{\pi_s}),$$
$$w_{\bar D^0} = 1 + A^\pi_\epsilon(p_{\pi_s}, \cos\theta_{\pi_s}), \tag{8}$$

and only candidates in bins with valid A^π_ϵ measurements are taken into account. This procedure results in a corrected asymmetry $A^f_{\rm rec}$ of (3), $A^{f,{\rm corr}}_{\rm rec}$, which is free of the contribution due to the slow pion efficiency asymmetry. It is calculated as,

$$A^{f,{\rm corr}}_{\rm rec}(\cos\theta^*) = \frac{m^f(\cos\theta^*) - \bar m^f(\cos\theta^*)}{m^f(\cos\theta^*) + \bar m^f(\cos\theta^*)}, \tag{9}$$

where m^f ($\bar m^f$) represent the sum of weights of the D^0 ($\bar D^0$) candidates in each bin of $\cos\theta^*$.

Finally, taking into account their specific dependence on $\cos\theta^*$, the asymmetries $A_{\rm CP}$ and $A_{\rm FB}$ are extracted by adding or subtracting bins at $\pm\cos\theta^*$:

$$A^f_{\rm CP} = \frac{A^{f,{\rm corr}}_{\rm rec}(\cos\theta^*) + A^{f,{\rm corr}}_{\rm rec}(-\cos\theta^*)}{2},$$
$$A^f_{\rm FB} = \frac{A^{f,{\rm corr}}_{\rm rec}(\cos\theta^*) - A^{f,{\rm corr}}_{\rm rec}(-\cos\theta^*)}{2}. \tag{10}$$

The results are presented in Fig. 3. By fitting a constant to the $A^f_{\rm CP}$ data points we obtain results consistent with no CP violation:

$$A^{KK}_{\rm CP} = \big(-0.43\pm 0.30({\rm stat})\big)\%,$$
$$A^{\pi\pi}_{\rm CP} = \big(+0.43\pm 0.52({\rm stat})\big)\%. \tag{11}$$

The errors are statistical only; however, the statistical uncertainties of the slow pion corrections are not included. The forward–backward asymmetry $A_{\rm FB}$ decreases with $\cos\theta^*$ and has a value $\approx -3\%$ at $\cos\theta^* = 0.8$; results from the two samples are consistent. At leading order, the asymmetry at this energy is expected to be $A^{c\bar c}_{\rm FB}(\cos\theta^*) = a^{c\bar c}\cos\theta^*/(1+\cos^2\theta^*)$, with $a^{c\bar c} = -2.9\%$ [14]. A simultaneous fit to the two samples yields $\chi^2/n_{\rm dof} = 4.5/7$ and $a^{c\bar c} = (-4.9\pm 0.8)\%$, where the error is statistical (see Fig. 3).

4. Systematics

The experimental procedure was checked using the generic continuum MC simulation. Events were generated with non-zero $A_{\rm FB}$ and zero $A_{\rm CP}$. The resulting $A_{\rm CP}$ and $A_{\rm FB}$ were found to be in a good agreement with the generated values. We also tested for possible bias in the result by reweighting MC samples with several non-zero $A_{\rm CP}$ values; no significant bias was found.

We consider three sources of systematic uncertainty to be significant (Table 1). The first source is the mass-sideband subtraction procedure used for signal counting. Possible systematic uncertainties arise due to the difference in signal shapes of D^0 and $\bar D^0$ candidates and due to the possible difference in the background between the signal window and sideband. The former source can introduce an additional asymmetry if the signal window is not sufficiently wide. We observe small but significant differences in the q signal shape of the tagged samples. By studying the normalized q distributions of the tagged $D^0(\bar D^0)\to K\pi$ samples we estimate the systematic uncertainty of this source to be 0.02% (0.04%) for the KK ($\pi\pi$) sample. We use normalized distributions to assess the effect of the shape difference. To account for a possible nonlinearity of the smooth (non-peaking) background, we vary the position of the sideband. We find 0.01% (KK) and 0.03% ($\pi\pi$) variations in the result. The small peaking background due to a correctly reconstructed D^0 candidate combined with a random slow pion is not removed by the M sideband subtraction. Its fraction (0.6%) is estimated from the tuned MC simulation. The possible asymmetry induced by this type of background is estimated from the q sideband to be less than 0.03%.

The second source of systematic error is the slow pion reconstruction efficiency correction. The statistical errors on $A^\pi_\epsilon(p_{\pi_s}, \cos\theta_{\pi_s})$ contribute an uncertainty of 0.09%. The impact of binning

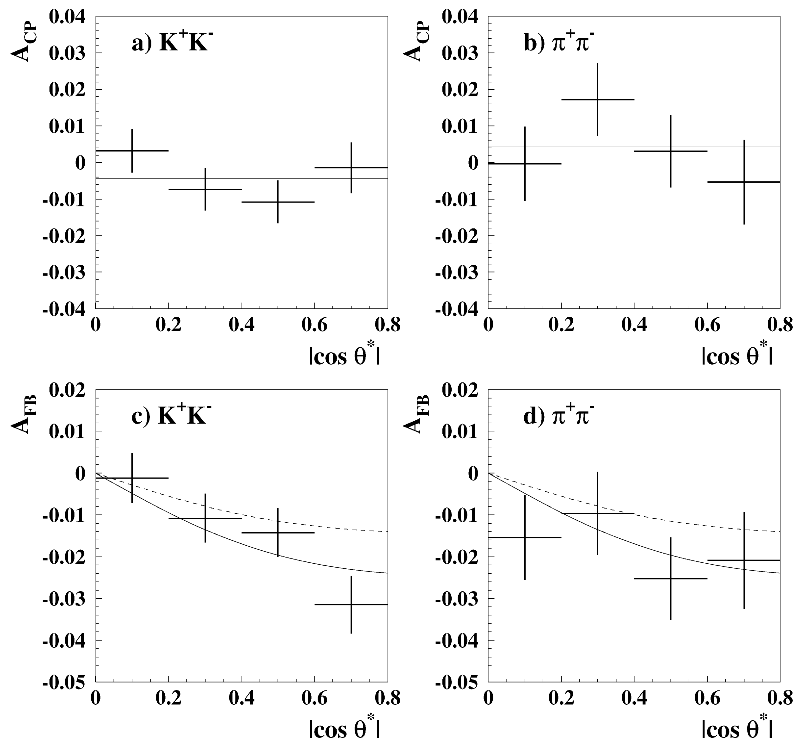

Fig. 3. CP-violating asymmetries in (a) KK and (b) $\pi\pi$ final states, and forward–backward asymmetries in (c) KK and (d) $\pi\pi$ final states. The solid curves represent the central values obtained from the least square minimizations; the dashed curves in (c) and (d) show the leading order expectation.

Table 1
Summary of systematic uncertainties in $A_{\rm CP}$.

Source	$D^0 \to K^+K^-$	$D^0 \to \pi^+\pi^-$
Signal counting	0.04%	0.06%
Slow pion corrections	0.10%	0.10%
$A_{\rm CP}$ extraction	0.03%	0.04%
Sum in quadrature	0.11%	0.12%

of the slow pion asymmetry is studied by producing maps with three different choices of bin sizes ($10 \times 10, 20 \times 20, 50 \times 50$ for $A_{\rm rec}^{\rm untag}$, and $5 \times 5, 10 \times 10, 20 \times 20$ for A_ϵ^π) and repeating the procedure for extracting $A_{\rm CP}$. We find 0.03% (KK) and 0.02% ($\pi\pi$) variations in the result. The minimum required number of events per bin is varied from 100 to 10000, and the resulting variation in $A_{\rm CP}$ is 0.04% (0.03%) for the KK ($\pi\pi$) sample.

The third source of systematic uncertainty is the $A_{\rm CP}$ extraction procedure. By varying the binning in $|\cos\theta^*|$ we obtain a 0.03% variation in the result. We change the treatment of the running periods with 3- and 4-layer SVD configurations; we find an 0.01% (0.02%) change in the result for the KK ($\pi\pi$) sample.

Finally, we add the individual contributions in quadrature to obtain the total systematic uncertainty. The result is 0.11% (0.12%) for the KK ($\pi\pi$) sample. The dominant source is the statistical uncertainty on A_ϵ^π, and thus the majority of the systematic error will decrease when a larger $K\pi$ data sample is available.

5. Conclusions

We measure time-integrated CP-violating asymmetries in the CP eigenstate decays $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ using 540 fb^{-1} of data. The detector-induced asymmetries are corrected by using tagged and untagged $D^0 \to K^-\pi^+$ decays. We obtain:

$$A_{\rm CP}^{KK} = (-0.43 \pm 0.30 \pm 0.11)\%,$$
$$A_{\rm CP}^{\pi\pi} = (+0.43 \pm 0.52 \pm 0.12)\%,$$
$$A_{\rm CP}^{KK} - A_{\rm CP}^{\pi\pi} = (-0.86 \pm 0.60 \pm 0.07)\%. \qquad (12)$$

We also measure the forward–backward asymmetry in the production of D^{*+} that arises from the underlying asymmetry in the $e^+e^- \to c\bar{c}$ process. The asymmetry agrees with the form $A_{\rm FB}^{c\bar{c}}(\cos\theta^*) = a^{c\bar{c}}\cos\theta^*/(1+\cos^2\theta^*)$ expected at leading order, but we find $a^{c\bar{c}} = (-4.9 \pm 0.8(\text{stat}))\%$, larger than the leading-order value of -2.9%. The uncertainty in the result is statistical only. Radiative and other (hadronic) corrections are expected to cause the effective $a^{c\bar{c}}$ to deviate from its leading-order value. A similar forward–backward asymmetry is apparent in the BaBar data [7].

The results (12) show no evidence for CP violation and agree with SM predictions. In (12) we also give the difference $A_{\rm CP}^{KK} - A_{\rm CP}^{\pi\pi}$, which is calculated by treating the systematic errors arising from the slow pion corrections and $A_{\rm CP}$ extraction as fully correlated between the two modes. A significant difference between the measured asymmetries in the KK and $\pi\pi$ modes would be a sign of direct CPV (Eq. (1)).

To determine the direct CPV asymmetries a_d^f of (1), the results in (12) can be compared to the result for the indirect CPV asymmetry in Ref. [1]. While the selected data samples of $D^0 \to K^+K^-, \pi^+\pi^-$ decays in the two measurements are almost identical, the methods of extracting the CP-violating asymmetries depend on different observables and hence the statistical uncertainties are uncorrelated. The same also holds for the systematic errors. The direct CPV asymmetries following from the sum of $A_{\rm CP}^f$ and A_Γ are:

$$a_d^{KK} = (-0.42 \pm 0.42 \pm 0.19)\%,$$
$$a_d^{\pi\pi} = (+0.44 \pm 0.60 \pm 0.19)\%. \qquad (13)$$

Again, the results (13) show no evidence for direct CP violation. While the measurement uncertainties are larger than the expected asymmetry in the SM, the results (13) can provide new constraints on some NP models [4].

Acknowledgements

We thank the KEKB group for excellent operation of the accelerator, the KEK cryogenics group for efficient solenoid operations, and the KEK computer group and the NII for valuable computing and SINET3 network support. We acknowledge support from MEXT and JSPS (Japan); ARC and DEST (Australia); NSFC (China); DST (India); MOEHRD, KOSEF and KRF (Korea); KBN (Poland); MES and RFAAE (Russia); ARRS (Slovenia); SNSF (Switzerland); NSC and MOE (Taiwan); and DOE (USA).

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