

## Study of time-dependent $CP$ -violating asymmetries in $b \rightarrow s\bar{q}q$ decays

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(Received 25 December 2002; published 27 February 2003)

We present a measurement of  $CP$ -violation parameters in the  $b \rightarrow s\bar{q}q$  penguin transitions ( $q = s, u, d$ ) based on a  $78 \text{ fb}^{-1}$  data sample collected at the  $\Upsilon(4S)$  resonance with the Belle detector at the KEKB energy-asymmetric  $e^+e^-$  collider. One neutral  $B$  meson is reconstructed in the  $\phi K_S^0$ ,  $K^+K^-K_S^0$ , or  $\eta'K_S^0$  decay channel, and the flavor of the accompanying  $B$  meson is identified from its decay products.  $CP$  violation parameters for each of the three modes are obtained from the asymmetries in the distributions of the proper-time intervals between the two  $B$  decays.

DOI: 10.1103/PhysRevD.67.031102

PACS number(s): 11.30.Er, 12.15.Hh, 13.25.Hw

In the standard model (SM),  $CP$  violation arises in weak interactions from an irreducible complex phase in the Kobayashi-Maskawa (KM) quark-mixing matrix [1]. In particular, the SM predicts  $CP$ -violating asymmetries in the time-dependent rates for  $B^0$  and  $\bar{B}^0$  decays to a common  $CP$  eigenstate  $f_{CP}$  [2]. Recent measurements of the  $CP$ -violating parameter  $\sin 2\phi_1$  by the Belle [3,4] and BaBar [5] Collaborations established  $CP$  violation in neutral  $B$  meson decays mediated by the  $b \rightarrow c\bar{c}s$  tree transition [6] at a level consistent with KM expectations.

Despite this success, many tests remain before one can conclude that the KM model provides a complete description. For example, the charmless decays  $B^0 \rightarrow \phi K_S^0$ ,  $B^0 \rightarrow K^+K^-K_S^0$ , and  $B^0 \rightarrow \eta'K_S^0$ , which are mediated by the  $b \rightarrow s\bar{s}s$  transition ( $B^0 \rightarrow \eta'K_S^0$  also receives  $b \rightarrow s\bar{d}d$  and  $b \rightarrow s\bar{u}u$  penguin contributions) are potentially sensitive to new  $CP$ -violating phases from physics beyond the SM [7]. SM contributions from the  $b \rightarrow u\bar{u}s$  tree diagram are expected to be highly suppressed [8,9]. Thus, the SM predicts that  $CP$  violation measurements in these charmless modes should yield  $\sin 2\phi_1$  to a good approximation. Consequently,

a significant deviation in the time-dependent  $CP$  asymmetry in these modes from what is observed in  $b \rightarrow c\bar{c}s$  decays would be evidence of a  $CP$ -violating phase not expected in the KM model.

In the decay chain  $\Upsilon(4S) \rightarrow B^0\bar{B}^0 \rightarrow f_{CP}f_{\text{tag}}$ , where one of the  $B$  mesons decays at time  $t_{CP}$  to a final state  $f_{CP}$  and the other decays at time  $t_{\text{tag}}$  to a final state  $f_{\text{tag}}$  that distinguishes between  $B^0$  and  $\bar{B}^0$ , the decay rate has a time dependence given by [10]

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \{1 + q \cdot [S \sin(\Delta m_d \Delta t) + \mathcal{A} \cos(\Delta m_d \Delta t)]\}, \quad (1)$$

where  $\tau_{B^0}$  is the  $B^0$  lifetime,  $\Delta m_d$  is the mass difference between the two  $B^0$  mass eigenstates,  $\Delta t = t_{CP} - t_{\text{tag}}$ , and the  $b$ -flavor charge  $q = +1$  ( $-1$ ) when the tagging  $B$  meson is a  $B^0$  ( $\bar{B}^0$ ). The  $CP$ -violating parameters  $S$  and  $\mathcal{A}$  are given by

$$S \equiv \frac{2 \text{Im}(\lambda)}{|\lambda|^2 + 1}, \quad \mathcal{A} \equiv \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1}, \quad (2)$$

where  $\lambda$  is a complex parameter that depends on both the  $B^0$ - $\bar{B}^0$  mixing and the amplitudes for  $B^0$  and  $\bar{B}^0$  decay to  $f_{CP}$ . To a good approximation in the SM,  $|\lambda|$  is equal to the absolute value of the ratio of the  $\bar{B}^0 \rightarrow f_{CP}$  to  $B^0 \rightarrow f_{CP}$  decay

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amplitudes. The SM predicts  $S = -\xi_f \sin 2\phi_1$ , where  $\xi_f = +1$  ( $-1$ ) corresponds to  $CP$ -even ( $-$ odd) final states; and  $\mathcal{A} = 0$  (or equivalently  $|\lambda| = 1$ ) for both  $b \rightarrow c\bar{c}s$  and  $b \rightarrow s\bar{s}s$  transitions.

In this paper, we report the first measurement of  $CP$  asymmetries in  $B^0 \rightarrow \phi K_S^0$  and  $K^+ K^- K_S^0$  decays, and an improved measurement for  $B^0 \rightarrow \eta' K_S^0$  decay [11] based on a  $78 \text{ fb}^{-1}$  data sample, which contains  $85 \times 10^6 B\bar{B}$  pairs. Data are collected with the Belle detector at the KEKB energy-asymmetric  $e^+e^-$  (3.5 on 8 GeV) collider [12] operating at the  $Y(4S)$  resonance. At KEKB, the  $Y(4S)$  is produced with a Lorentz boost of  $\beta\gamma = 0.425$  nearly along the electron beamline ( $z$ ). Since the  $B^0$  and  $\bar{B}^0$  mesons are approximately at rest in the  $Y(4S)$  center-of-mass system (cms),  $\Delta t$  can be determined from the displacement in  $z$  between the  $f_{CP}$  and  $f_{\text{tag}}$  decay vertices:  $\Delta t \simeq (z_{CP} - z_{\text{tag}}) / \beta\gamma c \equiv \Delta z / \beta\gamma c$ .

The Belle detector [13] is a large-solid-angle spectrometer that includes a three-layer silicon vertex detector (SVD), a 50-layer central drift chamber, an array of aerogel threshold Cherenkov counters, time-of-flight scintillation counters, and an electromagnetic calorimeter comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect  $K_L^0$  mesons and to identify muons.

We reconstruct  $B^0$  decays to  $\phi K_S^0$  and  $\eta' K_S^0$  final states for  $\xi_f = -1$ , and  $B^0 \rightarrow K^+ K^- K_S^0$  decays that are a mixture of  $\xi_f = +1$  and  $-1$ .  $K^+ K^-$  pairs that are consistent with the  $\phi \rightarrow K^+ K^-$  decay are excluded from the  $B^0 \rightarrow K^+ K^- K_S^0$  sample. We find that the  $K^+ K^- K_S^0$  state is primarily  $\xi_f = +1$ ; the  $\xi_f = +1$  fraction is  $1.04 \pm 0.19$  (stat)  $\pm 0.06$  (syst) [9]. In the following determination of  $S$  and  $\mathcal{A}$ , we fix  $\xi_f = +1$ . The intermediate meson states are reconstructed from the following decay chains:  $\eta' \rightarrow \rho^0 (\rightarrow \pi^+ \pi^-) \gamma$  or  $\eta' \rightarrow \pi^+ \pi^- \eta (\rightarrow \gamma\gamma)$ ,  $K_S^0 \rightarrow \pi^+ \pi^-$ , and  $\phi \rightarrow K^+ K^-$ .

Candidate  $K_S^0 \rightarrow \pi^+ \pi^-$  decays are oppositely charged track pairs that have an invariant mass within 15 (12)  $\text{MeV}/c^2$  of the nominal  $K_S^0$  mass for the  $B^0 \rightarrow \phi K_S^0$  ( $B^0 \rightarrow K^+ K^- K_S^0$ ) mode. The displacement of the  $\pi^+ \pi^-$  vertex from the nominal interaction point (IP) in the plane transverse to the positron beam axis ( $r$ - $\phi$  plane) is required to be greater than 0.1 cm and less than 20 cm. The direction of the combined pion-pair momentum in the  $r$ - $\phi$  plane is required to be within 0.2 rad of the direction defined by the IP and the displaced vertex. We select candidate  $\phi \rightarrow K^+ K^-$  decays requiring that the  $K^+ K^-$  invariant mass is within 10  $\text{MeV}/c^2$  of the nominal  $\phi$  meson mass, the  $\phi$  meson momentum in the cms exceeds 2.0  $\text{GeV}/c$ , and the  $K^+ K^-$  vertex is consistent with the IP. Since the  $\phi$  meson selection is effective in reducing background events, we impose only minimal kaon-identification requirements. For selection of non-resonant  $K^+ K^- K_S^0$  candidates, more stringent kaon-identification requirements, which retain 86% of  $K^\pm$  at a 7% fake rate for  $\pi^\pm$ , are used. In this case, charged tracks that are positively identified as electrons or protons are excluded. In addition to the rejection of  $\phi$  meson candidates, we reject

$K^+ K^-$  pairs that are consistent with  $D^0 \rightarrow K^+ K^-$  or  $\chi_{c0} \rightarrow K^+ K^-$  decay.

For reconstructed  $B \rightarrow f_{CP}$  candidates, we identify  $B$  meson decays using the energy difference  $\Delta E \equiv E_B^{\text{cms}} - E_{\text{beam}}^{\text{cms}}$  and the beam-energy constrained mass  $M_{\text{bc}} \equiv \sqrt{(E_{\text{beam}}^{\text{cms}})^2 - (p_B^{\text{cms}})^2}$ , where  $E_{\text{beam}}^{\text{cms}}$  is the beam energy in the cms, and  $E_B^{\text{cms}}$  and  $p_B^{\text{cms}}$  are the cms energy and momentum of the reconstructed  $B$  candidate, respectively. The  $B$  meson signal region is defined as  $5.27 \text{ GeV}/c^2 < M_{\text{bc}} < 5.29 \text{ GeV}/c^2$  and  $|\Delta E| < 0.051 \text{ GeV}$  for  $B^0 \rightarrow \phi K_S^0$  or  $|\Delta E| < 0.040 \text{ GeV}$  for  $B^0 \rightarrow K^+ K^- K_S^0$ . In order to suppress the background from the  $e^+ e^- \rightarrow q\bar{q}$  ( $q = u, d, s$ ) and  $c\bar{c}$  continuum, we form signal and background likelihood functions,  $\mathcal{L}_S$  and  $\mathcal{L}_{\text{BG}}$ , from a set of variables that characterize the event topology [9,11]. We determine  $\mathcal{L}_S$  from Monte Carlo (MC) simulation and  $\mathcal{L}_{\text{BG}}$  from data, and impose mode-dependent thresholds on the likelihood ratio  $\mathcal{L}_S / (\mathcal{L}_S + \mathcal{L}_{\text{BG}})$ . The numbers of reconstructed candidates are 59 and 230 for  $B^0 \rightarrow \phi K_S^0$  and  $B^0 \rightarrow K^+ K^- K_S^0$ , respectively.

For  $B^0 \rightarrow \eta' K_S^0$  decay, we use the same selection criteria as those used in our previously published analysis [11] if both of the charged pions in the  $\eta' \rightarrow \pi^+ \pi^- \eta$  or the  $\eta' \rightarrow \rho^0 \gamma$  decay have associated SVD hits. We also reconstruct events where only one of the charged pions has associated SVD hits. In this case, the requirement on the impact parameter is relaxed for the track without SVD hits, while a higher threshold is imposed on the likelihood ratio. The number of reconstructed  $B^0 \rightarrow \eta' K_S^0$  candidates is 311.

Charged leptons, kaons, pions, and  $\Lambda$  baryons that are not associated with the reconstructed  $f_{CP}$  decay are used to identify the  $b$  flavor of the accompanying  $B$  meson, which decays into  $f_{\text{tag}}$ . Based on the measured properties of these tracks, two parameters,  $q$  and  $r$ , are assigned to each event. The first,  $q$ , has the discrete value  $+1$  ( $-1$ ) when the tag-side  $B$  meson is more likely to be a  $B^0$  ( $\bar{B}^0$ ). The parameter  $r$  is an event-by-event MC-determined flavor-tagging dilution factor that ranges from  $r = 0$  for no flavor discrimination to  $r = 1$  for an unambiguous flavor assignment. It is used only to sort data into six intervals of  $r$ , according to the estimated flavor purity. The wrong-tag probabilities for each of these intervals,  $w_l$  ( $l = 1, 6$ ), which are used in the final fit, are determined directly from the data. Samples of  $B^0$  decays to exclusively reconstructed self-tagging channels are utilized to obtain  $w_l$  using time-dependent  $B^0$ - $\bar{B}^0$  mixing:  $(N_{\text{OF}} - N_{\text{SF}}) / (N_{\text{OF}} + N_{\text{SF}}) = (1 - 2w_l) \cos(\Delta m_d \Delta t)$ , where  $N_{\text{OF}}$  and  $N_{\text{SF}}$  are the numbers of opposite ( $B^0 \bar{B}^0 \rightarrow B^0 \bar{B}^0$ ) and same ( $B^0 \bar{B}^0 \rightarrow B^0 B^0, \bar{B}^0 \bar{B}^0$ ) flavor events. The event fractions and wrong tag fractions for each  $r$  interval are described elsewhere [4].

The decay vertices of  $B^0$  mesons are reconstructed using tracks that have enough SVD hits: i.e. both  $z$  and  $r$ - $\phi$  hits in at least one SVD layer and at least one additional layer with a  $z$  hit, where the  $r$ - $\phi$  plane is perpendicular to the  $z$  axis. Each vertex position is required to be consistent with the IP profile, which is determined run-by-run and smeared in the  $r$ - $\phi$  plane by 21  $\mu\text{m}$  to account for the  $B$  meson decay length. With these requirements, we are able to determine a

TABLE I. The numbers of reconstructed  $B^0 \rightarrow f_{CP}$  candidates used for  $\mathcal{S}$  and  $\mathcal{A}$  determination,  $N_{ev}$ , and the estimated signal purity in the  $\Delta E$ - $M_{bc}$  signal region for each  $f_{CP}$  mode.

Mode	$\xi_f$	$N_{ev}$	Purity
$\phi K_S^0$	-1	53	$0.67^{+0.07}_{-0.05}$
$K^+ K^- K_S^0$	+1 (100%)	191	$0.50^{+0.04}_{-0.03}$
$\eta' K_S^0$	-1	299	$0.49 \pm 0.05$

vertex even with a single track. The vertex position for the  $f_{CP}$  decay is reconstructed using charged kaons for  $B^0 \rightarrow \phi K_S^0$  and  $B^0 \rightarrow K^+ K^- K_S^0$  decays and charged pions from  $\rho^0$  or  $\eta'$  decays for  $B^0 \rightarrow \eta' K_S^0$ . The algorithm for the  $f_{tag}$  vertex reconstruction is chosen to minimize the effect of long-lived particles, secondary vertices from charmed hadrons, and a small fraction of poorly reconstructed tracks [14]. From all the charged tracks with associated SVD hits except those used for  $f_{CP}$ , we select tracks with a position error in the  $z$  direction of less than  $500 \mu\text{m}$ , and with an impact parameter with respect to the  $f_{CP}$  vertex of less than  $500 \mu\text{m}$ . Track pairs with opposite charges are removed if they form a  $K_S^0$  candidate with an invariant mass within  $\pm 15 \text{ MeV}/c^2$  of the nominal  $K_S^0$  mass. If the reduced  $\chi^2$  associated with the  $f_{tag}$  vertex exceeds 20, the track making the largest  $\chi^2$  contribution is removed and the vertex is re-fitted. This procedure is repeated until an acceptable reduced  $\chi^2$  is obtained.

After flavor tagging and vertex reconstruction, we obtain the numbers of  $B^0 \rightarrow f_{CP}$  candidates,  $N_{ev}$ , listed in Table I.

Figure 1 shows the  $M_{bc}$  distributions for the reconstructed  $B$  candidates that have  $\Delta E$  values within the signal region.

To assign an event-by-event signal probability for use in the maximum-likelihood fit of the  $CP$ -violating parameters, we determine event distribution functions in the  $\Delta E$ - $M_{bc}$  plane for both signal and background. The signal distribution is modeled with a single two-dimensional Gaussian, where the widths are allowed to float in the fit to data. For the continuum background, we use a linear function for  $\Delta E$  and the ARGUS parameterization [15] for  $M_{bc}$ . We use events outside the signal region as well as a large MC sample to study the background components. The dominant back-

ground comes from continuum events. In addition, according to MC simulation, there is a non-negligible ( $\sim 8\%$ ) contamination from  $B\bar{B}$  background events in  $B^0 \rightarrow \eta' K_S^0$  ( $\eta' \rightarrow \rho^0 \gamma$ ). The contributions from  $B\bar{B}$  events are smaller for other decay modes. The contamination of  $K^+ K^- K_S^0$  events in the  $\phi K_S^0$  sample (and vice versa) is also small and is treated as a source of systematic uncertainty. Finally, backgrounds from  $B^0 \rightarrow f_0(980) K_S^0$  decay, which has the opposite  $CP$  eigenvalue to  $\phi K_S^0$ , are found to be negligible.

We determine  $\mathcal{S}$  and  $\mathcal{A}$  for each mode by performing an unbinned maximum-likelihood fit to the observed  $\Delta t$  distribution. The probability density function (PDF) expected for the signal distribution is given by Eq. (1) with  $q$  replaced by  $q(1-2w_l)$  to account for the effect of incorrect flavor assignment. The distribution is convolved with the proper-time interval resolution function  $R_{sig}(\Delta t)$ , which takes into account the finite vertex resolution. It is formed by convolving four components: the detector resolutions for  $z_{CP}$  and  $z_{tag}$ , the shift in the  $z_{tag}$  vertex position due to secondary tracks originating from charmed particle decays, and the kinematic approximation that the  $B$  mesons are at rest in the cms [14]. A small component of broad outliers in the  $\Delta z$  distribution, caused by mis-reconstruction, is represented by a Gaussian function  $P_{ol}(\Delta t)$ . We determine 12 resolution parameters and the neutral- and charged- $B$  lifetimes simultaneously from a fit to the  $\Delta t$  distributions of hadronic  $B$  decays and obtain an average  $\Delta t$  resolution of  $\sim 1.43 \text{ ps}$  (rms). We determine the following likelihood value for each event:

$$P_i(\Delta t_i; \mathcal{S}, \mathcal{A}) = (1 - f_{ol}) \int_{-\infty}^{\infty} [f_{sig} \mathcal{P}_{sig}(\Delta t', q, w_l) R_{sig}(\Delta t_i - \Delta t') + (1 - f_{sig}) \mathcal{P}_{bkg}(\Delta t') R_{bkg}(\Delta t_i - \Delta t')] d(\Delta t') + f_{ol} P_{ol}(\Delta t_i), \quad (3)$$

where  $f_{ol}$  is the outlier fraction and  $f_{sig}$  is the signal probability calculated as a function of  $\Delta E$  and  $M_{bc}$ .  $\mathcal{P}_{bkg}(\Delta t)$  is a PDF for background events, which dilutes the significance of  $CP$  violation in Eq. (1). It is modeled as a sum of exponential and prompt components, and is convolved with a sum of two Gaussians,  $R_{bkg}$ , which represents a resolution function for the background. All parameters in  $\mathcal{P}_{bkg}(\Delta t)$  and  $R_{bkg}$

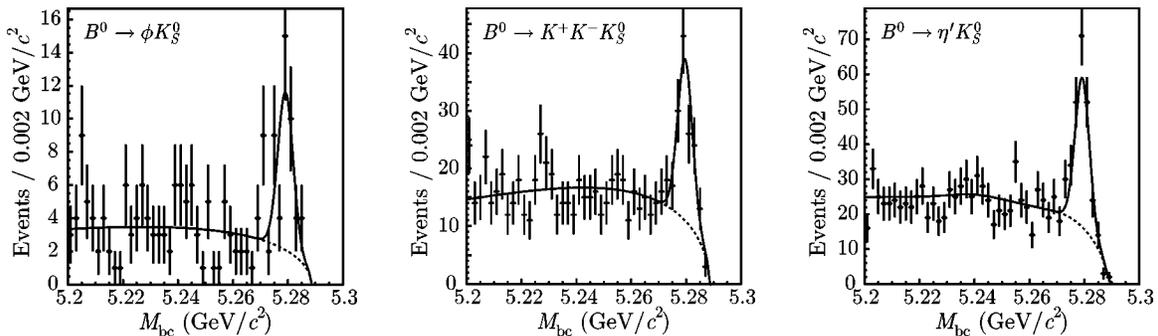


FIG. 1. The beam-energy constrained mass distributions for  $B^0 \rightarrow \phi K_S^0$  (left),  $B^0 \rightarrow K^+ K^- K_S^0$  (center), and  $B^0 \rightarrow \eta' K_S^0$  (right) within the  $\Delta E$  signal region. Solid curves show the fit to signal plus background distributions, and dotted curves show the background contributions. The background for  $B^0 \rightarrow \eta' K_S^0$  decay includes an MC-estimated  $B\bar{B}$  background component.

TABLE II. Results of the fits to the  $\Delta t$  distributions. The first errors are statistical and the second errors are systematic. The third error for the  $K^+K^-K_S^0$  mode arises from the uncertainty in the fraction of the  $CP$ -odd component.

Mode	$-\xi_f \mathcal{S} (= \sin 2\phi_1 \text{ in the SM})$	$\mathcal{A} (= 0 \text{ in the SM})$
$\phi K_S^0$	$-0.73 \pm 0.64 \pm 0.22$	$-0.56 \pm 0.41 \pm 0.16$
$K^+K^-K_S^0$	$+0.49 \pm 0.43 \pm 0.11^{+0.33}_{-0.00}$	$-0.40 \pm 0.33 \pm 0.10^{+0.00}_{-0.26}$
$\eta' K_S^0$	$+0.71 \pm 0.37^{+0.05}_{-0.06}$	$+0.26 \pm 0.22 \pm 0.03$

are determined by the fit to the  $\Delta t$  distribution of a background-enhanced control sample [16]; i.e. events away from the  $\Delta E$ - $M_{bc}$  signal region. We fix  $\tau_{B^0}$  and  $\Delta m_d$  at their world-average values [17]. The only free parameters in the final fit are  $\mathcal{S}$  and  $\mathcal{A}$ , which are determined by maximizing the likelihood function

$$L = \prod_i P_i(\Delta t_i; \mathcal{S}, \mathcal{A}), \quad (4)$$

where the product is over all events. Table II summarizes the results of the fit. The table shows the values of  $\mathcal{A}$  and of  $-\xi_f \mathcal{S}$ , which, in the SM, is equal to  $\sin 2\phi_1$ . The first errors are statistical and the second errors are systematic. The third error for the  $K^+K^-K_S^0$  mode arises from the uncertainty in the fraction of the  $CP$ -odd component [9].

Figure 2 shows the observed  $\Delta t$  distribution for  $q\xi_f = -1$  (upper figure) and  $q\xi_f = +1$  (lower figure) event samples for each  $f_{CP}$  mode. We test the goodness-of-fit using Fig. 2 from a  $\chi^2$  comparison of the results of the unbinned fit and the  $\Delta t$  projections for  $B^0 \rightarrow \phi K_S^0$ ,  $B^0 \rightarrow K^+K^-K_S^0$ , and  $B^0 \rightarrow \eta' K_S^0$  candidates [18]; we obtain 22.1, 15.8, and 16.5, respectively, where the number of bins for each decay mode is 16.

Figure 3 shows the raw asymmetry in each  $\Delta t$  bin without background subtraction, which is defined by

$$A \equiv \frac{N_{q\xi_f=-1} - N_{q\xi_f=+1}}{N_{q\xi_f=-1} + N_{q\xi_f=+1}}, \quad (5)$$

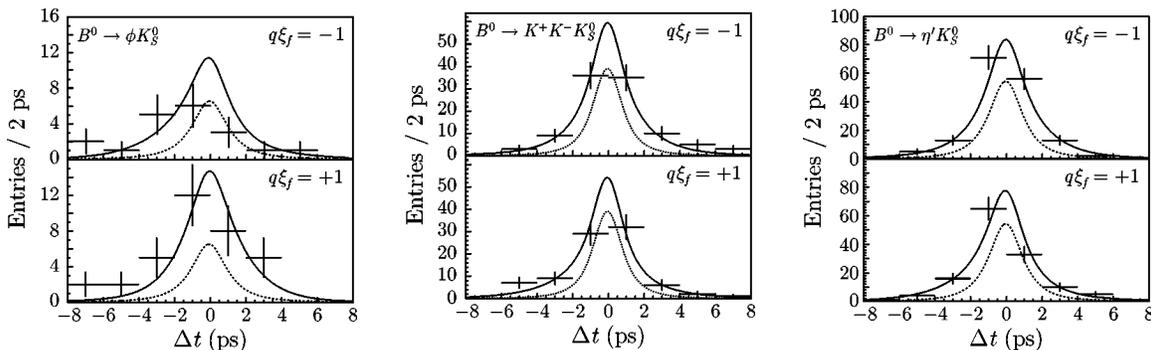


FIG. 2. The  $\Delta t$  distributions for  $B^0 \rightarrow \phi K_S^0$  (left),  $B^0 \rightarrow K^+K^-K_S^0$  (center), and  $B^0 \rightarrow \eta' K_S^0$  (right) decays. The upper and lower plots are for  $q\xi_f = -1$  and  $q\xi_f = +1$  candidates, respectively. The solid curves show the results of the global fits, and dashed curves show the background distributions.

where  $N_{q\xi_f=+1(-1)}$  is the number of observed candidates with  $q\xi_f = +1$  ( $-1$ ). The curves are obtained from an unbinned-maximum likelihood fit to the  $\Delta t$  distributions. These are the first measurements of the  $CP$  violation parameters for  $B^0 \rightarrow \phi K_S^0$  and  $B^0 \rightarrow K^+K^-K_S^0$  decays. The result for  $\eta' K_S^0$  supersedes the previous result [11]. We obtain values consistent with the present world average of  $\sin 2\phi_1 = +0.734 \pm 0.054$  [19] in  $B^0 \rightarrow K^+K^-K_S^0$  and  $\eta' K_S^0$  decays, while a  $2.1\sigma$  deviation is observed in  $B^0 \rightarrow \phi K_S^0$  decay.

Fits to the same samples with the direct  $CP$  violation parameter  $\mathcal{A}$  fixed at zero yield  $-\xi_f \mathcal{S} = -0.83 \pm 0.72$  (stat) for  $B^0 \rightarrow \phi K_S^0$ ,  $-\xi_f \mathcal{S} = +0.59 \pm 0.47$  (stat) for  $B^0 \rightarrow K^+K^-K_S^0$ , and  $-\xi_f \mathcal{S} = +0.77 \pm 0.38$  (stat) for  $B^0 \rightarrow \eta' K_S^0$ . As a consistency check for the  $\mathcal{S}$  term, we select the charged  $B$  meson decays  $B^+ \rightarrow \phi K^+$  and  $B^+ \rightarrow \eta' K^+$  and apply the same fit procedure. We obtain  $\mathcal{S} = +0.05 \pm 0.32$  (stat),  $\mathcal{A} = +0.29 \pm 0.24$  (stat) for  $B^+ \rightarrow \phi K^+$  decay and  $\mathcal{S} = -0.03 \pm 0.20$  (stat),  $\mathcal{A} = +0.05 \pm 0.13$  (stat) for  $B^+ \rightarrow \eta' K^+$  decay. Both results on the  $\mathcal{S}$  term are consistent with no  $CP$  asymmetry, as expected.

The largest source of systematic error for the  $B^0 \rightarrow \phi K_S^0$  mode is the uncertainty in the signal fraction and the background  $\Delta t$  shape ( $\pm 0.17$  for  $\mathcal{S}$  and  $\pm 0.14$  for  $\mathcal{A}$  in total) determined from the events in the sideband regions in the  $\Delta E$ - $M_{bc}$  plane. Other significant contributions come from uncertainties in the vertex reconstruction, the resolution function parameters, wrong tag fractions,  $\tau_{B^0}$ , and  $\Delta m_d$ . We add each contribution in quadrature to obtain the total systematic uncertainty. Systematic uncertainties from these sources are also examined for the other modes. We find that the largest uncertainties arise from the vertex reconstruction ( $\pm 0.09$  for  $\mathcal{S}$  and  $\pm 0.08$  for  $\mathcal{A}$ ) for the  $B^0 \rightarrow K^+K^-K_S^0$  mode, and from the resolution function parameters ( $^{+0.03}_{-0.04}$  for  $\mathcal{S}$ ) and the signal fraction ( $\pm 0.02$  for  $\mathcal{A}$ ) for the  $B^0 \rightarrow \eta' K_S^0$  mode.

In summary, we have performed the first measurement of  $CP$  violation parameters in the  $B^0 \rightarrow \phi K_S^0$  and  $K^+K^-K_S^0$  decays. We also provide an improved measurement for  $\eta' K_S^0$  decay. These modes are dominated by the  $b \rightarrow s\bar{s}s$  transition and are sensitive to possible new  $CP$ -violating phases. Our results for  $B^0 \rightarrow \eta' K_S^0$  and  $K^+K^-K_S^0$  are consistent with

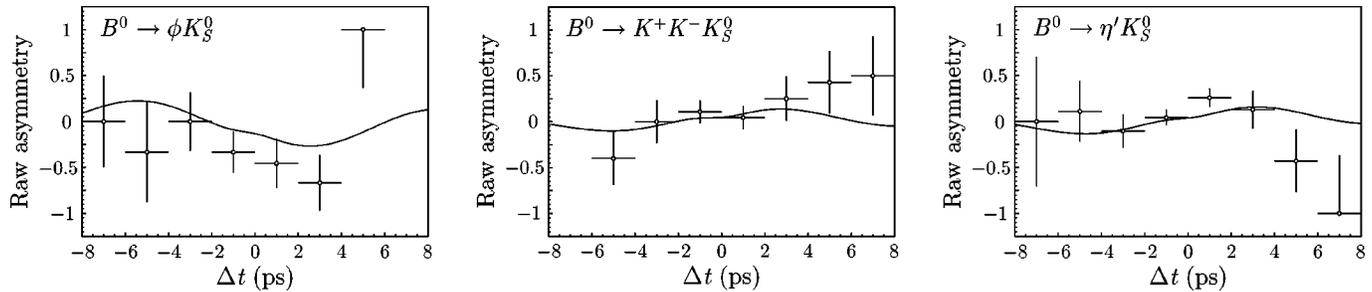


FIG. 3. The  $\Delta t$  asymmetry,  $A$ , in each bin for  $B^0 \rightarrow \phi K_S^0$  (left),  $B^0 \rightarrow K^+ K^- K_S^0$  (center), and  $B^0 \rightarrow \eta' K_S^0$  (right), respectively. The curves, which originate from time-dependent asymmetries given by  $-\xi_f \mathcal{S} \sin(\Delta m_d \Delta t) - \xi_f \mathcal{A} \cos(\Delta m_d \Delta t)$ , show the results of the unbinned-maximum likelihood fit.

those obtained for  $B^0 \rightarrow J/\psi K_S^0$  and other decays governed by the  $b \rightarrow c \bar{c} s$  transition. A  $2.1\sigma$  deviation is observed for  $B^0 \rightarrow \phi K_S^0$ .

We wish to thank the KEKB accelerator group for the excellent operation of the KEKB accelerator. We acknowledge support from the Ministry of Education, Culture, Sports, Science, and Technology of Japan and the Japan Society for the Promotion of Science; the Australian Research Council and the Australian Department of Industry, Science and Resources; the National Science Foundation of China

under contract No. 10175071; the Department of Science and Technology of India; the BK21 program of the Ministry of Education of Korea and the CHEP SRC program of the Korea Science and Engineering Foundation; the Polish State Committee for Scientific Research under contract No. 2P03B 17017; the Ministry of Science and Technology of the Russian Federation; the Ministry of Education, Science and Sport of the Republic of Slovenia; the National Science Council and the Ministry of Education of Taiwan; and the U.S. Department of Energy.

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