Measurements of $CP$ Asymmetries in the Decay $B \to \phi K$

The $BABAR$ Collaboration

March 25, 2022

Abstract

We present a preliminary measurement of the time-dependent $CP$ asymmetry for the neutral $B$-meson decay $B^0 \to \phi K^0$. We use a sample of approximately 227 million $B$-meson pairs recorded at the $\Upsilon(4S)$ resonance with the $BABAR$ detector at the PEP-II $B$-meson Factory at SLAC. We reconstruct the $CP$ eigenstates $\phi K_S^0$ and $\phi K_L^0$ where $\phi \to K^+K^-$, $K_S^0 \to \pi^+\pi^-$, and $K_L^0$ is observed via its hadronic interactions. The other $B$ meson in the event is tagged as either a $B^0$ or $\bar{B}^0$ from its decay products. The values of the $CP$-violation parameters derived from the combined $\phi K^0$ dataset are $S_{\phi K} = +0.50 \pm 0.25 \text{ (stat)}^{+0.05}_{-0.04} \text{ (syst)}$ and $C_{\phi K} = 0.00 \pm 0.23 \text{ (stat)} \pm 0.05 \text{ (syst)}$. In addition, we measure the $CP$-violating charge asymmetry $A_{CP}(B^+ \to \phi K^+) = 0.054 \pm 0.056 \text{ (stat)} \pm 0.012 \text{ (syst)}$. All results are preliminary.

Submitted to the 32$^{\text{nd}}$ International Conference on High-Energy Physics, ICHEP 04, 16 August—22 August 2004, Beijing, China

Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

Work supported in part by Department of Energy contract DE-AC03-76SF00515.
The **BABAR** Collaboration,

B. Aubert, R. Barate, D. Boutigny, F. Couderc, J.-M. Gaillard, A. Hicheur, Y. Karyotakis, J. P. Lees, V. Tisserand, A. Zghiche

*Laboratoire de Physique des Particules, F-74941 Annecy-le-Vieux, France*

A. Palano, A. Pompili

*Università di Bari, Dipartimento di Fisica and INFN, I-70126 Bari, Italy*

J. C. Chen, N. D. Qi, G. Rong, P. Wang, Y. S. Zhu

*Institute of High Energy Physics, Beijing 100039, China*

G. Eigen, I. Ofte, B. Stugu

*University of Bergen, Inst. of Physics, N-5007 Bergen, Norway*

G. S. Abrams, A. W. Borgland, A. B. Breon, D. N. Brown, J. Button-Shafer, R. N. Cahn, E. Charles, C. T. Day, M. S. Gill, A. V. Gritsan, Y. Groysman, R. G. Jacobsen, R. W. Kadel, J. Kadyk, L. T. Kerth, Yu. G. Kolomensky, G. Kukartsev, G. Lynch, L. M. Mir, P. J. Oddone, T. J. Orimoto, M. Pripstein, N. A. Roe, M. T. Ronan, V. G. Shelkov, W. A. Wenzel

*Lawrence Berkeley National Laboratory and University of California, Berkeley, CA 94720, USA*

M. Barrett, K. E. Ford, T. J. Harrison, A. J. Hart, C. M. Hawkes, S. E. Morgan, A. T. Watson

*University of Birmingham, Birmingham, B15 2TT, United Kingdom*

M. Fritsch, K. Goetzen, T. Held, H. Koch, B. Lewandowski, M. Pelizaues, M. Steinke

*Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany*

J. T. Boyd, N. Chevalier, W. N. Cottingham, M. P. Kelly, T. E. Latham, F. F. Wilson

*University of Bristol, Bristol BS8 1TL, United Kingdom*

T. Cuhadar-Donszelmann, C. Hearty, N. S. Knecht, T. S. Mattison, J. A. McKenna, D. Thiessen

*University of British Columbia, Vancouver, BC, Canada V6T 1Z1*

A. Khan, P. Kyberd, L. Teodorescu

*Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom*

A. E. Blinov, V. E. Blinov, V. P. Druzhinin, V. B. Golubev, V. N. Ivanchenko, E. A. Kravchenko, A. P. Onuchin, S. I. Serednyakov, Yu. I. Skovpen, E. P. Solodov, A. N. Yushkov

*Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia*

D. Best, M. Bruinsma, M. Chao, I. Eschrich, D. Kirkby, A. J. Lankford, M. Mandelkern, R. K. Mommsen, W. Roethel, D. P. Stoker

*University of California at Irvine, Irvine, CA 92697, USA*

C. Buchanan, B. L. Hartfiel

*University of California at Los Angeles, Los Angeles, CA 90024, USA*

S. D. Foulkes, J. W. Gary, B. C. Shen, K. Wang

*University of California at Riverside, Riverside, CA 92521, USA*
D. del Re, H. K. Hadavand, E. J. Hill, D. B. MacFarlane, H. P. Paar, Sh. Rahatlou, V. Sharma

University of California at San Diego, La Jolla, CA 92093, USA

J. W. Berryhill, C. Campagnari, B. Dahmes, O. Long, A. Lu, M. A. Mazur, J. D. Richman, W. Verkerke

University of California at Santa Barbara, Santa Barbara, CA 93106, USA

T. W. Beck, A. M. Eisner, C. A. Heusch, J. Kroseberg, W. S. Lockman, G. Nesom, T. Schalk, B. A. Schumm, A. Seiden, P. Spradlin, D. C. Williams, M. G. Wilson

University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, CA 95064, USA

J. Albert, E. Chen, G. P. Dubois-Felsmann, A. Dvoretskii, D. G. Hitlin, I. Narsky, T. Piatenko, F. C. Porter, A. Ryd, A. Samuel, S. Yang

California Institute of Technology, Pasadena, CA 91125, USA

S. Jayatilleke, G. Mancinelli, B. T. Meadows, M. D. Sokoloff

University of Cincinnati, Cincinnati, OH 45221, USA

T. Abe, F. Blanc, P. Bloom, S. Chen, W. T. Ford, U. Nauenberg, A. Olivas, P. Rankin, J. G. Smith, J. Zhang, L. Zhang

University of Colorado, Boulder, CO 80309, USA

A. Chen, J. L. Harton, A. Soffer, W. H. Toki, R. J. Wilson, Q. L. Zeng

Colorado State University, Fort Collins, CO 80523, USA

D. Altenburg, T. Brandt, J. Brosé, M. Dickopp, E. Feltresi, A. Hauke, H. M. Lackner, R. Müller-Pfefferkorn, R. Nogowski, S. Otto, A. Petzold, J. Schubert, K. R. Schubert, R. Schwierz, B. Spaan, J. E. Sundermann

Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany

D. Bernard, G. R. Bonneau, F. Brochard, P. Grenier, S. Schrenk, Ch. Thieaux, G. Vasileiadis, M. Verderi

Ecole Polytechnique, LLR, F-91128 Palaiseau, France

D. J. Bard, P. J. Clark, D. Lavin, F. Muheim, S. Playfer, Y. Xie

University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom

M. Andreotti, V. Azzolini, D. Bettoni, C. Bozzi, R. Calabrese, G. Cibinetto, E. Luppi, M. Negrini, L. Piemontese, A. Sarti

Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy

E. Treadwell

Florida A&M University, Tallahassee, FL 32307, USA

F. Anulli, R. Baldini-Ferroli, A. Calcaterra, R. de Sangro, G. Finocchiaro, P. Patteri, I. M. Peruzzi, M. Piccolo, A. Zallo

Laboratori Nazionali di Frascati dell’INFN, I-00044 Frascati, Italy

A. Buzzo, R. Capra, R. Contri, G. Crosetti, M. Lo Vetere, M. Macri, M. R. Monge, S. Passaggio, C. Patrignani, E. Robutti, A. Santroni, S. Tosi

Università di Genova, Dipartimento di Fisica and INFN, I-16146 Genova, Italy

S. Bailey, G. Brandenburg, K. S. Chaisanguanthum, M. Mori, E. Won

Harvard University, Cambridge, MA 02138, USA
R. Cowan, G. Sciolla, S. J. Sekula, F. Taylor, R. K. Yamamoto

Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, MA 02139, USA

D. J. J. Mangeol, P. M. Patel, S. H. Robertson

McGill University, Montréal, QC, Canada H3A 2T8

A. Lazzaro, V. Lombardo, F. Palombo

Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy

J. M. Bauer, L. Cremaldi, V. Eschenburg, R. Godang, R. Kroeger, J. Reidy, D. A. Sanders, D. J. Summers, H. W. Zhao

University of Mississippi, University, MS 38677, USA

S. Brunet, D. Côté, P. Taras

Université de Montréal, Laboratoire René J. A. Lévesque, Montréal, QC, Canada H3C 3J7

H. Nicholson

Mount Holyoke College, South Hadley, MA 01075, USA

N. Cavallo, F. Fabozzi, ²C. Gatto, L. Lista, D. Monorchio, P. Paolucci, D. Piccolo, C. Sciacca

Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy

M. Baak, H. Bulten, G. Raven, H. L. Snoek, L. Wilden

NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands

C. P. Jessop, J. M. LoSecco

University of Notre Dame, Notre Dame, IN 46556, USA

T. Allmendinger, K. K. Gan, K. Honscheid, D. Hufnagel, H. Kagan, R. Kass, T. Pulliam, A. M. Rahimi, R. Ter-Antonyan, Q. K. Wong

Ohio State University, Columbus, OH 43210, USA

J. Brau, R. Frey, O. Igonkina, C. T. Potter, N. B. Sinev, D. Strom, E. Torrence

University of Oregon, Eugene, OR 97403, USA

F. Colecchia, A. Dorigo, F. Galeazzi, M. Margoni, M. Morandin, M. Posocco, M. Rotondo, F. Simonetto, R. Stroili, G. Tiozzo, C. Voci

Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy

M. Benayoun, H. Briand, J. Chauveau, P. David, Ch. de la Vaissière, L. Del Buono, O. Hamon, M. J. J. John, Ph. Leruste, J. Malcles, J. Ocariz, M. Pivk, L. Roos, S. T’Jampens, G. Therin

Universités Paris VI et VII, Laboratoire de Physique Nucléaire et de Hautes Energies, F-75252 Paris, France

P. F. Manfredi, V. Re

Università di Pavia, Dipartimento di Elettronica and INFN, I-27100 Pavia, Italy

²Also with Università della Basilicata, Potenza, Italy
W. Bugg, M. Krishnamurthy, S. M. Spanier
University of Tennessee, Knoxville, TN 37996, USA

R. Eckmann, H. Kim, J. L. Ritchie, A. Satpathy, R. F. Schwitters
University of Texas at Austin, Austin, TX 78712, USA

J. M. Izen, I. Kitayama, X. C. Lou, S. Ye
University of Texas at Dallas, Richardson, TX 75083, USA

F. Bianchi, M. Bona, F. Gallo, D. Gamba
Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy

L. Bosisio, C. Cartaro, F. Cossutti, G. Della Ricca, S. Dittongo, S. Grancagnolo, L. Lanceri, P. Poropat,\textsuperscript{5}
L. Vitale, G. Vuagnin
Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy

R. S. Panvini
Vanderbilt University, Nashville, TN 37235, USA

Sw. Banerjee, C. M. Brown, D. Fortin, P. D. Jackson, R. Kowalewski, J. M. Roney, R. J. Sobie
University of Victoria, Victoria, BC, Canada V8W 3P6

H. R. Band, B. Cheng, S. Dasu, M. Datta, A. M. Eichenbaum, M. Graham, J. J. Hollar, J. R. Johnson,
P. E. Kutter, H. Li, R. Liu, A. Mihalyi, A. K. Mohapatra, Y. Pan, R. Prepost, P. Tan, J. H. von
Wimmersperg-Toeller, J. Wu, S. L. Wu, Z. Yu
University of Wisconsin, Madison, WI 53706, USA

M. G. Greene, H. Neal
Yale University, New Haven, CT 06511, USA

\textsuperscript{5}Deceased
1 INTRODUCTION

Decays of $B$ mesons into charmless hadronic final states with a $\phi$ meson are dominated by $b \to s\bar{s}s$ gluonic penguin amplitudes, possibly with smaller contributions from electroweak penguins, while other Standard Model (SM) amplitudes are strongly suppressed \[1\]. In the SM, $CP$ violation arises from a single complex phase in the Cabibbo–Kobayashi–Maskawa (CKM) quark-mixing matrix \[2\]. Neglecting CKM-suppressed contributions, the time-dependent $CP$-violating asymmetries in the decays $B^0 \to \phi K^0$ and $B^0 \to J/\psi K^0$ are proportional to the same parameter $\sin2\beta$ \[3\], where the latter decay is dominated by tree diagrams. Since many scenarios of physics beyond the SM introduce additional diagrams with heavy particles in the penguin loops and new $CP$-violating phases, comparison of $CP$-violating observables with SM expectations is a sensitive probe for new physics. Measurements of $\sin2\beta$ in $B$ decays to charmonium such as $B^0 \to J/\psi K^0$ have been reported by the BABAR \[4\] and Belle \[5\] collaborations, and the world average for $\sin2\beta$ is $0.731 \pm 0.056$ \[6\]. In the decay $B^0 \to \phi K^0$, the Belle collaboration measures $\sin2\beta = -0.96 \pm 0.50^{+0.09}_{-0.11}$ \[7\], while the BABAR collaboration (with a sample of approximately 114 million $BB$ pairs) measures $\sin2\beta = 0.47 \pm 0.34$(stat)$^{+0.08}_{-0.06}$(syst) \[8\] in the decays $B^0 \to \phi K^0$ and $B^0 \to \phi K^0$.

In the SM, neglecting CKM-suppressed contributions, the direct $CP$ violation in $B^+ \to \phi K^+$ \[9\], detected as an asymmetry $A_{CP} = (\Gamma_{\phi K^0} - \Gamma_{\phi K^+})/\Gamma_{\phi K^0}$ in the decay rates $\Gamma_{\phi K^\pm} = \Gamma(B^\pm \to \phi K^\mp)$, is expected to be zero; in the presence of large new-physics contributions to the $b \to s\bar{s}s$ transition, it could be of order 1 \[10\]. The BABAR collaboration measures (with a sample of approximately 89 million $B\bar{B}$ pairs) $A_{CP}(B^0 \to \phi K^+) = 0.04 \pm 0.09 \pm 0.01$ \[11\].

In this paper we report preliminary measurements of the time-dependent $CP$ asymmetry in the decay $B^0 \to \phi K^0$ and the charge asymmetry in the decay $B^+ \to \phi K^+$ based on a sample of approximately 227 million $BB$ pairs collected at the $\Upsilon(4S)$ resonance with the BABAR detector \[12\] at the PEP-II asymmetric-energy $e^+e^-$ storage ring \[13\] located at the Stanford Linear Accelerator Center.

2 THE BABAR DETECTOR

The BABAR detector is described elsewhere \[12\]. The primary components used in the analysis are a charged-particle tracking system consisting of a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) surrounded by a 1.5-T solenoidal magnet with an instrumented flux return (IFR), an electromagnetic calorimeter (EMC) comprised of 6580 CsI(Tl) crystals, and a detector of internally reflected Cherenkov light (DIRC) providing excellent charged $K$ and $\pi$ identification \[14\] in the momentum range relevant for this analysis.

3 ANALYSIS METHOD

From a $B^0\bar{B}^0$ meson pair we fully reconstruct one meson, $B_{CP}$, in the final state $\phi K^0$, and partially reconstruct the recoil $B$ meson, $B_{tag}$. We examine $B_{tag}$ for evidence that it decayed either as $B^0$ or $\bar{B}^0$ (flavor tag). The asymmetric beam configuration in the laboratory frame provides a nominal boost of $\beta\gamma = 0.56$ to the $\Upsilon(4S)$, which allows the determination of the proper decay-time difference $\Delta t = t_{CP} - t_{tag}$ using the vertex separation of the two neutral $B$ mesons along the beam ($z$) axis. The decay rate $f_+(f_-)$ when the tagging meson is a $B^0(\bar{B}^0)$ is given by

$$f_+(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} [1 \mp \eta_f S_{\phi K} \sin (\Delta m_d \Delta t) \mp C_{\phi K} \cos (\Delta m_d \Delta t)], \quad (1)$$

$$f_-(-\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} [1 \mp \eta_f S_{\phi K} \sin (\Delta m_d \Delta t) \mp C_{\phi K} \cos (\Delta m_d \Delta t)], \quad (1)$$

where $\eta_f$ is the branching fraction of the $B$ meson with flavor $f$, $\tau_{B^0}$ is the $B^0$ lifetime, $S_{\phi K}$ is the form factor for the $\phi K$ transition, $C_{\phi K}$ is another form factor, and $\Delta m_d$ is the mass difference between the $D_s$ and $D_s^*$ states.
where $\tau_{B^{0}}$ is the neutral $B$ meson mean lifetime, $\Delta m_{d}$ is the $B^{0}\rightarrow \overline{B}^{0}$ oscillation frequency, and the 
$CP$ eigenvalue is $\eta_{f} = -1 \ (+1)$ for $\phi K_{S}^{0}$ ($\phi K_{L}^{0}$). The time-dependent $CP$-violating asymmetry is 
defined as $A_{CP} \equiv (f_{+} - f_{-})/(f_{+} + f_{-})$. In the SM, decays that proceed purely via the $b \rightarrow s\bar{s}s$ penguin transitions have $CP$ parameters $S_{\phi K} = \sin 2\beta$ and $C_{\phi K} = 0$, where $\beta \equiv \arg [-V_{cd}V_{cb}^{*}/V_{td}V_{tb}]$. Here $V_{ik}$ is the CKM matrix element for quarks $i$ and $k$.

4 EVENT RECONSTRUCTION

The $B_{CP}$ candidate is reconstructed in the decay mode $\phi K^{0}$ with $\phi \rightarrow K^{+}K^{-}$; the $K^{0}$ is either a 
$K_{L}^{0}$ or a $K_{S}^{0}$ decaying into $\pi^{+}\pi^{-}$. We combine pairs of oppositely charged tracks extrapolated to a 
common vertex to form $\phi$ and $K_{S}^{0}$ candidates. For the charged tracks from the $\phi$ decay we require 
at least 12 measured drift-chamber coordinates and a minimal transverse momentum of 0.1 GeV/c.

The tracks must also originate from within 1.5 cm of the nominal beam spot in the plane transverse 
to the beam axis and ±10 cm along the $z$-axis. Tracks with momentum less than 0.7 GeV/c that 
are used to reconstruct the $\phi$ meson are distinguished from pions and protons via a requirement 
on the likelihood that combines $dE/dx$ information from the SVT and the DCH. For tracks with 
higher momentum, $dE/dx$ in the DCH and the Cherenkov angle and the number of photons as 
measured by the DIRC are used in the likelihood. The two-kaon invariant mass must be within 
15 MeV/$c^{2}$ of the known $\phi$ mass [6].

For tracks corresponding to $K_{S}^{0}$ and $B_{tag}$ daughters our requirements are less restrictive. A 
$K_{S}^{0} \rightarrow \pi^{+}\pi^{-}$ candidate is accepted if its two-pion invariant mass is within 15 MeV/$c^{2}$ of the known 
$K^{0}$ mass [6], its reconstructed decay vertex is separated from the $\phi$ decay vertex by at least 3 
standard deviations, and the projected angle between the line connecting the $\phi$ and $K_{S}^{0}$ decay 
vertices and the $K_{S}^{0}$ momentum direction, in the plane perpendicular to the beam axis, is less than 
45 mrad.

We identify a $K_{L}^{0}$ candidate like in our $B^{0} \rightarrow J/\psi K_{S}^{0}$ analysis [15] either as a cluster of energy 
deposited in the electromagnetic calorimeter or as a cluster of hits in two or more layers of the 
instrumented flux return that cannot be associated with any charged track in the event. The $K_{L}^{0}$ 
energy is not well measured. Therefore, we determine the $K_{L}^{0}$ laboratory momentum from its flight 
direction as measured from the EMC or IFR cluster, and the constraint that the invariant $\phi K_{L}^{0}$ mass 
agrees with the known $B^{0}$ mass. In those cases where the $K_{L}^{0}$ is detected in both the IFR and EMC 
we use the angular information from the EMC, because it has higher precision. In order to reduce 
background from $\pi^{0}$ decays, we reject an EMC $K_{L}^{0}$ candidate cluster if it forms an invariant mass 
between 100 and 150 MeV/$c^{2}$ with any other cluster in the event under the $\gamma\gamma$ hypothesis, or if it 
has energy greater than 1 GeV and contains two shower maxima consistent with two photons from a 
$\pi^{0}$ decay. The remaining background of $K_{L}^{0}$ candidates due to photons and overlapping showers is 
further reduced with the use of a neural network constructed from cluster shape variables, trained 
on Monte Carlo (MC) simulated $B^{0} \rightarrow \phi K_{L}^{0}$ and measured radiative Bhabha events, and tested on 
measured $e^{+}e^{-} \rightarrow \phi(\rightarrow K_{S}^{0}K_{L}^{0})\gamma$ and $B^{0} \rightarrow J/\psi K_{L}^{0}$ events.

5 EVENT VARIABLES

The results are extracted from an extended unbinned maximum likelihood fit for which we parameterize 
distributions of several kinematic and topological variables for signal and background 
events in terms of probability density functions (PDFs) [16]. The selection keeps loose requirements 
in those variables to include ranges dominated by background, too. The background $B$ candidates
come primarily from random combinations of tracks produced in events of the type $e^+e^- \to q\bar{q}$, where $q = u,d,s,c$ (continuum). Background from other $B$ decay final states with and without charm is estimated with MC simulations. Opposite-$CP$ contributions from the $K^+K^-K^0$ final state ($K^+K^-S$-wave) are estimated with data using a moment analysis method to be less than 6.6% at a 95% confidence level and are treated as a systematic error. The shapes of event variable distributions are obtained from signal and background MC samples and high statistics data control samples. In many cases parameters describing these distributions are varied in the likelihood fit.

Each $B_{CP}$ candidate is characterized by the energy difference $\Delta E = E_B^* - \frac{1}{2}\sqrt{s}$ and, except for $B^0 \to \phi K^0_L$, the beam-energy–substituted mass $m_{ES} = \sqrt{\frac{1}{2}s + \vec{p}_0 \cdot \vec{p}_B)}^2/E_0^2 - p^2_B$. The subscripts 0 and B refer to the initial $\Upsilon(4S)$ and the $B_{CP}$ candidate, respectively, and the asterisk denotes the $\Upsilon(4S)$ rest frame. For signal events, $\Delta E$ is expected to peak at zero and $m_{ES}$ at the known $B$ mass. We require $\Delta E < 0.08$ GeV for $B^0 \to \phi K^0_L$, and $|\Delta E| < 0.1$ GeV and $m_{ES} > 5.21$ GeV/$c^2$ for $B^0 \to \phi K^0_S$. The $\phi$-meson signal in the $KK$ invariant mass, $m_{KK}$, is described with a relativistic $P$-wave Breit-Wigner function with parameters obtained from data. In the fit we also use the helicity angle $\theta_H$, which is defined as the angle between the directions of the $K^+$ and the parent $B_{CP}$ in the $K^+K^-$ rest frame. The $\cos\theta_H$ distribution for pseudoscalar-vector $B$ decay modes is $\cos^2\theta_H$, and for the combinatorial background it is nearly uniform.

In continuum events, particles appear mostly in two jets. This topology can be characterized with several variables computed in the $\Upsilon(4S)$ frame. One such quantity is the angle $\theta_T$ between the thrust axis of the $B_{CP}$ candidate and the thrust axis formed from the other charged and neutral particles in the event. We also use the angle $\theta_B$ between the $B_{CP}$ momentum and the beam axis, and the sum of the momenta $p_i$ of the other charged and neutral particles in the event weighted by the Legendre polynomials $L_0(\theta_i)$ and $L_2(\theta_i)$ where $\theta_i$ is the angle between the momentum of particle $i$ and the thrust axis of the $B_{CP}$ candidate. For $B^0 \to \phi K^0$ candidates, we combine these variables into a Fisher discriminant $F$. In this mode, background from other $B$ decays is negligible, as demonstrated in MC simulation studies.

More stringent criteria must be applied to suppress backgrounds in the case of $B^0 \to \phi K^0$ candidates, and we require $|\cos\theta_T| < 0.8$ and $|\cos\theta_B| < 0.85$. We define the missing momentum $p_{miss}$, calculated in the laboratory frame from the sum of beam momenta and all tracks and EMC clusters, excluding the $K^0_L$ candidate. We require the polar angle $\theta_{miss}$ of the missing momentum with respect to the beam direction to be greater than 0.3 rad. The cosine of the angle between $p_{miss}$ and the $K^0_L$ direction, $\theta_K$, must satisfy $\cos\theta_K > 0.6$. In the plane transverse to the beam direction, the difference between the missing momentum projected along the $K^0_L$ direction and the calculated $K^0_L$ momentum must be greater than $-0.75$ GeV/$c$. In the Fisher discriminant we replace $|\cos\theta_B|$ by the cosine of the angle between the missing momentum and the $K^+$ from the $\phi$ decay.

The dominant $CP$ contamination is the mode $B \to \phi K^{*0}$, where the $K^{*0}$ decays to $K^0_L\pi^0$. In the likelihood fit we explicitly parameterize backgrounds from both charm and charmless $B$ decays, differently for neutral and charged $B$ mesons, as derived from MC simulations.

All the other tracks and clusters that are not associated with the reconstructed $B^0 \to \phi K^0$ decay are used to form the $B_{tag}$, and its flavor is determined with a multivariate tagging algorithm. The tagging efficiency $\epsilon_i$ and mistag probability $w_i$ in six hierarchical and mutually exclusive categories are measured from fully reconstructed $B^0$ decays into the $D^{(*)}X^+(X^+ = \pi^+,\rho^+,a_1^+)$ and $J/\psi K^{*0}(K^{*0} \to K^+\pi^-)$ flavor eigenstates ($B_{flav}$ sample). The analyzing power $\sum_{i=1}^{6} \epsilon_i(1 - 2w_i)^2$ is $(30.5 \pm 0.4)\%$.

A detailed description of the $\Delta t$ reconstruction algorithm is given in Ref. The $B_{CP}$ vertex
resolution is determined by the $\phi$ vertex. The average $\Delta z$ resolution is 190 $\mu$m and is dominated by the tagging vertex in the event. Thus, we can characterize the resolution with the much larger $B_{\text{ flav}}$ sample, which we fit simultaneously with the $CP$ samples. The amplitudes for the $B_{\text{CP}}$ asymmetries and for the $B_{\text{ flav}}$ flavor oscillations are reduced by the same factor due to wrong-flavor tags. Both distributions are convoluted with a common $\Delta t$ resolution function. Backgrounds are accounted for by adding terms to the likelihood, incorporated with different assumptions about their $\Delta t$ evolution and resolution function.

6 MAXIMUM LIKELIHOOD FIT

Since we measure the correlations among the observables to be small in the data samples entering the fit (the largest one is 13% between $m_{ES}$ and $\Delta E$ for the signal, all others are below 7%), we take the probability density function $P_{i,c}^{j}$ for each event $j$ to be a product of the PDFs for the separate observables. For each event hypothesis $i$ (signal, backgrounds) and tagging category $c$, for the $\phi K_{S}^{0}$ mode we define $P_{i,c}^{j} = P_{i}(m_{ES}) \cdot P_{i}(\Delta E) \cdot P_{i}(F) \cdot P_{i}(m_{KK}) \cdot P_{i}(\cos \theta_{H}) \cdot P_{i}(\Delta t; \sigma_{\Delta t}, c)$, for the $\phi K_{L}^{0}$ mode $P_{i,c}^{j} = P_{i}(\Delta E) \cdot P_{i}(F) \cdot P_{i}(m_{KK}) \cdot P_{i}(\cos \theta_{H}) \cdot P_{i}(\Delta t; \sigma_{\Delta t}, c)$, and for the flavor sample $P_{i,c}^{j} = P_{i}(m_{ES}) \cdot P_{i}(\Delta t; \sigma_{\Delta t}, c)$. The $\sigma_{\Delta t}$ is the error on $\Delta t$ for a given event. The likelihood function for each decay is then

$$L = \prod_{c} \exp \left( -\sum_{i} N_{i,c} \right) \prod_{j} \left[ \sum_{i} N_{i,c} P_{i,c}^{j} \right],$$

where $N_{i,c}$ is the yield of events of hypothesis $i$ determined by the fit in category $c$, and $N_{c}$ is the number of category $c$ events in the sample. The total sample consists of 135,315 $B_{\text{ flav}}$, 4300 $\phi K_{S}^{0}$ and 8238 $\phi K_{L}^{0}$ candidates. The reconstruction efficiency for the $\phi K_{S}^{0}$ mode is about 40% and and for the $\phi K_{L}^{0}$ mode about 20%. From the fit we find $114 \pm 12$ $\phi K_{S}^{0}$ and $98 \pm 18$ $\phi K_{L}^{0}$ signal events. The signal yields in both the $\phi K^{0}$ channels agree well with our determination of the branching fraction for $B^{0} \rightarrow \phi K^{0}$ \cite{11}. Figure 4 shows the $m_{ES}$ ($\Delta E$) distribution for $\phi K_{S}^{0}$ ($\phi K_{L}^{0}$) events together with the result from the fit after applying a requirement on the ratio of signal likelihood to the signal-plus-background likelihood (computed without the variable plotted) to reduce the background.

We determine the $CP$ parameters $S_{\phi K}$ and $C_{\phi K}$ along with 83 other unconstrained parameters: event yields in signal and background (18 parameters), distributions of kinematic and topological variables for signal and background (12), the signal efficiency per tagging category (6), the average mistag fraction and the difference between $B^{0}$ and $\bar{B}^{0}$ mistags for each tagging category in the signal (12), and the signal $\Delta t$ resolution (17). The $\Delta t$ parameters for the charmless $B$ background are the same as for the $\phi K^{0}$ signal. For the $B$ decays into charm final states we parameterize the $\Delta t$ resolution (3) and the mistag fractions (12). Their parameters are shared with the $B_{\text{ flav}}$ sample. The $\Delta t$ resolution for the continuum background (3) is kept unconstrained in the $\phi K^{0}$ datasets. We fix $\tau_{B^{0}}$ and $\Delta m_{d}$ to the world averages \cite{11}. The determination of the mistag fractions and $\Delta t$-resolution parameters is dominated by the large $B_{\text{ flav}}$ sample. The fit was tested with both a parameterized simulation of a large number of data-sized experiments and a full detector simulation. The likelihood of our data fit agrees with the likelihoods from fits to the simulated data. The fit was also verified with our $J/\psi K_{S}^{0}$ and $J/\psi K_{L}^{0}$ data samples.

As a cross check the analysis was also performed using different selection criteria which we describe in turn. The invariant $K^{+} K^{-}$ mass is required to be within 10 MeV/c$^{2}$ of the known mass.
Figure 1: Distribution of the event variable (a) $m_{ES}$ for the $\phi K^0_S$ final state and (b) $\Delta E$ for the $\phi K^0_L$ final state after reconstruction and a requirement on the ratio of signal likelihood to the signal-plus-background likelihood, calculated without the plotted variable. The signal efficiency for the selection and likelihood requirements is 32% for (a) and 9% for (b). The solid line represents the fit result for the total event yield and the dotted line for the total background. The dash-dotted (lower) line in (b) represents the continuum background only.

of the $\phi$ meson and is not used in the likelihood fit. The $K^0$ flight requirements are tightened. The same four-category multivariate tagging algorithm as was used for the earlier published analysis [4] is used. Instead of the Fisher discriminant a multivariate algorithm [20] for continuum background suppression is used, which in the $\phi K^0_S$ final state combines the same four variables. In the case of $\phi K^0_L$ the ingredients are $L_0$, $L_2$, $p_{\text{miss}}$, $\cos \theta_B$, and $\cos \theta_T$. The algorithm is trained in the same way as the Fisher discriminant and tested on data control samples. The central values of $S_{\phi K}$ and $C_{\phi K}$ for both the cross-check analysis and the primary analysis were hidden until the analyses were complete. We measure values for $S_{\phi K}$ and $C_{\phi K}$ in very close agreement for the $\phi K^0_S$ and the $\phi K^0_L$ sample, separately, and for the combined samples.

In the measurement of the CP-violating charge asymmetry in the decay $B^+ \rightarrow \phi K^+$ the selection of the $\phi$ meson candidate is identical. For the $K^+$ candidate from the $B^+$ decay the track requirements are the same as for the $\phi$ daughters but we apply a more restrictive kaon identification criterion. We use the same set of event variables as for the $\phi K^0_S$ channel. The likelihood is the same as in Eq. 2 with $c$ corresponding to the two charge categories in signal and continuum background. The total sample consists of 6654 $\phi K^+$ candidates and from the fit we find $400 \pm 23$ signal candidates. Figure 2 shows the distribution of $m_{ES}$ and $m_{KK}$ with the result of the likelihood fit superimposed. We do not observe a significant asymmetry in Monte Carlo or in the continuum background data.
7 SYSTEMATIC STUDIES

We consider systematic uncertainties in the $CP$ coefficients $S_{\phi K}$ and $C_{\phi K}$ due to contributions from $B^0$ final states with opposite $CP$ ($+0.06$ for $S_{\phi K}$, $\pm 0.02$ for $C_{\phi K}$), the parameterization of PDFs for the event yield in signal and background ($\pm 0.01$, $\pm 0.01$), $CP$ asymmetry of the background ($\pm 0.02$, $\pm 0.01$), the assumed parameterization of the $\Delta t$ resolution function ($\pm 0.02$, $\pm 0.01$), a possible difference in the efficiency for $B^0$ and $\overline{B}^0$ ($\pm 0.01$, $\pm 0.02$), the fixed values for $\Delta m_d$ and $\tau_B$ ($\pm 0.00$, $\pm 0.01$), the beam-spot position ($\pm 0.01$, $\pm 0.01$), and uncertainties in the SVT alignment ($\pm 0.01$, $\pm 0.01$). The bias in the coefficients due to the fit procedure is included as uncertainty ($\pm 0.01$, $\pm 0.01$) without making corrections to the final results. We estimate errors due to the effect of doubly CKM-suppressed decays [21] to be ($\pm 0.01$, $\pm 0.03$). We add these contributions in quadrature to obtain the total systematic uncertainty.

For the measurement of the charge asymmetry $A_{CP}$ we estimate the uncertainty due to charge asymmetries in tracking and particle identification to be 0.011. We also consider the systematic error due to uncertainties in the parameterization of the signal Fisher PDF (0.005) and $B$ background content (0.002). We add these contributions in quadrature to obtain the total systematic uncertainty.

8 RESULTS

The simultaneous fit to the $\phi K^0$ and flavor decay modes yields the preliminary result

\begin{align*}
S_{\phi K} &= +0.50 \pm 0.25 \text{ (stat)}^{+0.07}_{-0.04} \text{ (syst)}, \\
C_{\phi K} &= 0.00 \pm 0.23 \text{ (stat)} \pm 0.05 \text{ (syst)}.
\end{align*}
The preliminary results in the channel $B^0 \to \phi K^0_S$ alone are $S_{\phi K} = 0.29 \pm 0.31$ and $C_{\phi K} = -0.07 \pm 0.27$, and in the channel $B^0 \to \phi K^0_L$, $S_{\phi K} = 1.05 \pm 0.51$ and $C_{\phi K} = 0.31 \pm 0.49$, with statistical errors only. Figure 3 shows the $\Delta t$ distributions of the $B^0$ and the $B^0$-tagged subsets together with the raw asymmetry, for $\phi K^0_S$ and $\phi K^0_L$ events separately, with the result of the combined time-dependent $CP$-asymmetry fit superimposed.

The preliminary value of the charge asymmetry in $B^+ \to \phi K^+$ is

$$A_{CP} = 0.054 \pm 0.056 \text{ (stat)} \pm 0.012 \text{ (syst)}.$$ 

9 CONCLUSION

In the decay $B^0 \to \phi K^0$ we measure preliminary values for $S_{\phi K}$ and $C_{\phi K}$ in the time-dependent $CP$ asymmetry that are in close agreement with our previously published values [8]. Our value of $S_{\phi K}$ agrees within one standard deviation with the value of $\sin^2 \beta$ in the $B^0 \to (\bar{c}c)K^0$ decays [19]. We do not observe a significant charge asymmetry in the mode $B^+ \to \phi K^+$.  

10 ACKNOWLEDGMENTS

We are grateful for the extraordinary contributions of our PEP-II colleagues in achieving the excellent luminosity and machine conditions that have made this work possible. The success of this project also relies critically on the expertise and dedication of the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its support and the kind hospitality extended to them. This work is supported by the US Department of Energy and National Science Foundation, the Natural Sciences and Engineering Research Council (Canada), Institute of High Energy Physics (China), the Commissariat à l’Energie Atomique and Institut National de Physique Nucléaire et de Physique des Particules (France), the Bundesministerium für Bildung und Forschung and Deutsche Forschungsgemeinschaft (Germany), the Istituto Nazionale di Fisica Nucleare (Italy), the Foundation for Fundamental Research on Matter (The Netherlands), the Research Council of Norway, the Ministry of Science and Technology of the Russian Federation, and the Particle Physics and Astronomy Research Council (United Kingdom). Individuals have received support from CONACyT (Mexico), the A. P. Sloan Foundation, the Research Corporation, and the Alexander von Humboldt Foundation.

References

[1] N. G. Deshpande and J. Trampetic, Phys. Rev. D 41, 895 (1990); N. G. Deshpande and G. He, Phys. Lett. B 336, 471 (1994); R. Fleischer, Z. Phys. C 62, 81 (1994); Y. Grossman et al., Phys. Rev. D 68, 015004 (2003).

[2] N. Cabibbo, Phys. Rev. Lett. 10, 531 (1963); M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49, 652 (1973).

[3] A. B. Carter and A. I. Sanda, Phys. Rev. D 23, 1567 (1981); I. I. Bigi and A. I. Sanda, Nucl. Phys. B 193, 85 (1981); Y. Grossman and M. P. Worah, Phys. Lett. B 395, 241 (1997); R. Fleischer, Int. J. Mod. Phys. A 12, 2459 (1997); D. London and A. Soni, Phys. Lett. B 407, 61 (1997).
Figure 3: Plots a) and b) show the $\Delta t$ distributions of $B^0$- and $B^0$-tagged $\phi K^0_S$ candidates. The solid lines refer to the fit for all events; the dashed lines correspond to the background. Plot c) shows the asymmetry. Plots d), e), and f) are the corresponding plots for $\phi K^0_L$ candidates. For each final state, a requirement is applied on the event likelihood to suppress background.
[4] BABAR Collaboration, B. Aubert et al., Phys. Rev. Lett. 89, 201802 (2002).
[5] Belle Collaboration, K. Abe et al., Phys. Rev. D 66, 071102 (2002).
[6] Particle Data Group, S. Eidelman et al., Phys. Lett. B 592, 1 (2004).
[7] Belle Collaboration, K. Abe et al., Phys. Rev. Lett. 91, 261602 (2003).
[8] BABAR Collaboration, B. Aubert et al., Phys. Rev. Lett. 93, 071801 (2004).
[9] Charge-conjugate states are included unless explicitly stated otherwise.
[10] M. Ciuchini and L. Silvestrini, Phys. Rev. Lett. 89, 231802 (2002).
[11] BABAR Collaboration, B. Aubert et al., Phys. Rev. D 69, 011102 (2004).
[12] BABAR Collaboration, B. Aubert et al., Nucl. Instr. Meth. A 479, 1 (2002).
[13] PEP-II Conceptual Design Report, SLAC-R-418 (1993).
[14] BABAR Collaboration, B. Aubert et al., [hep-ex/0407057], submitted to Phys. Rev. Lett.
[15] BABAR Collaboration, B. Aubert et al., Phys. Rev. D 66, 032003 (2002).
[16] BABAR Collaboration, B. Aubert et al., Phys. Rev. Lett. 87, 151801 (2001).
[17] S.U. Chung, Phys. Rev. D 56, 7299 (1997).
[18] R. A. Fisher, Annals Eugen. 7, 179 (1936).
[19] BABAR Collaboration, B. Aubert et al., ‘Improved Measurement of Time-Dependent CP Violation in $B^0 \rightarrow (\bar{c}c)K^0$ Decays’, BABAR-PUB-04/38, Contribution to the 32nd International Conference on High-Energy Physics, ICHEP 04.
[20] K.S. Cranmer, ALEPH 99-144 (1999), [hep-ex/0011057]
[21] O. Long, M. Baak, R. N. Cahn and D. Kirkby, Phys. Rev. D 68, 034010 (2003).