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Measurements of branching fractions in $B \to \phi K$ and $B \to \phi \pi$ and search for direct CP violation in $B^{\pm} \to \phi K^{\pm}$

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We present measurements of branching fractions in the $b \to s\bar{s}s$ penguin-dominated decays $B^+ \to \phi K^+$ and $B^0 \to \phi K^0$ in a sample of approximately 89 million $B\overline{B}$ pairs collected by the BABAR detector at the PEP-II asymmetric-energy B-meson factory at SLAC. We determine $\mathcal{B}(B^+ \to \phi K^+) = (10.0^{+0.9}_{-0.8} \pm 0.5) \times 10^{-6}$ and $\mathcal{B}(B^0 \to \phi K^0) = (8.4^{+1.5}_{-1.3} \pm 0.5) \times 10^{-6}$. Additionally, we measure the CP-violating charge asymmetry $\mathcal{A}_{CP}(B^\pm \to \phi K^\pm) = 0.04 \pm 0.09 \pm 0.01$, with a 90% confidence-level interval of $[-0.10, 0.18]$, and set an upper limit on the CKM– and color-suppressed decay $B^+ \to \phi\pi^+$, $\mathcal{B}(B^+ \to \phi\pi^+) < 0.41 \times 10^{-6}$ (at the 90% confidence level).

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Decays of B mesons into charmless hadronic final states with a ϕ meson are dominated by $b \to s\bar{s}s$ gluonic penguin diagrams (Fig. 1), possibly with smaller contributions from electroweak penguin diagrams, while other Standard Model (SM) amplitudes are strongly suppressed [1]. In the Standard Model, *CP* violation arises from a single complex phase in the Cabibbo–Kobayashi–Maskawa (CKM) quark-mixing matrix [2]. Since many scenarios of physics beyond the SM introduce additional diagrams with heavy particles in the penguin loops and new *CP*-violating phases [3], a comparison of *CP*-violating observables with SM expectations is a sensitive probe for new physics. In the SM, neglecting CKM-suppressed contributions, the direct *CP* violation in $B^+ \to \phi K^+$ [4], detected as an asymmetry $\mathcal{A}_{CP} = (\Gamma_{\phi K^-} - \Gamma_{\phi K^+})/(\Gamma_{\phi K^-} + \Gamma_{\phi K^+})$ in the decay rates $\Gamma_{\phi K^\pm} = \Gamma(B^\pm \to \phi K^\pm)$, 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 [5]. The $B \to \phi K$ and $B \to \phi\pi$ decay rates are also sensitive to new physics; the latter is strongly suppressed in the SM, and a measurement of $\mathcal{B}(B \to \phi\pi) \gtrsim 10^{-7}$ would serve as evidence for new physics [6]. The branching fractions of $B^+ \to \phi K^+$ and $B^0 \to \phi K^0$ have been studied by CLEO [7], *BABAR* [8, 9], and Belle [10]; $\mathcal{A}_{CP}(B^+ \to \phi K^+)$ has been studied by *BABAR* [9].

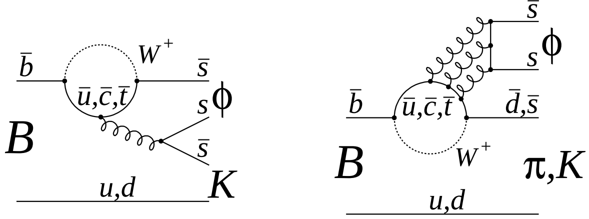

FIG. 1: Examples of quark-level diagrams for $B \to \phi K$ and $B \to \phi\pi$. Left: internal penguin diagram, right: flavor-singlet penguin diagram.

This analysis is based on an integrated luminosity of about 82 fb^{-1}, corresponding to approximately 89 million $B\overline{B}$ pairs, collected at SLAC with the *BABAR* detector [11] at the PEP-II asymmetric-energy e^+e^- storage ring operating on the $\Upsilon(4S)$ resonance.

The asymmetric beam configuration provides a boost to the $\Upsilon(4S)$ in the laboratory frame ($\beta\gamma \approx 0.56$), increasing the maximum momentum of the B-meson decay products to 4.4 GeV/c. Charged particles are detected and their momenta measured by a combination of a silicon vertex tracker (SVT), consisting of five double-sided layers, and a 40-layer central drift chamber (DCH), both operating in a 1.5 T solenoidal magnetic field. The tracking system covers 92% of the solid angle in the center-of-mass (CM) frame. The track-finding efficiency is, on average, $(98 \pm 1)\%$ for momenta above 0.2 GeV/c and polar angles greater than 0.5 rad. Photons are detected by a CsI(Tl) electromagnetic calorimeter (EMC), which provides excellent angular and energy resolution with high efficiency for energies above 20 MeV.

Charged-particle identification is provided by measuring the average energy loss (dE/dx) in the two tracking devices and by the novel internally reflecting ring-imaging Cherenkov detector (DIRC) covering the central region. A π/K separation of better than 4σ is achieved for tracks with momenta below 3 GeV/c, decreasing to 2.4σ for the highest momenta arising from $B^+ \to \phi h^+$ decays. Electrons are identified with the use of the tracking system and the EMC.

We fully reconstruct B-meson candidates in the decay modes ϕh^+ and ϕK^0_S, with $\phi \to K^+K^-$ and $K^0_S \to \pi^+\pi^-$. For the h^+ track and the charged-track daughters of the ϕ we require at least 12 measured DCH hits and a minimal transverse momentum p_T of 0.1 GeV/c. The tracks must originate from the interaction point (within 10 cm along the beam direction and 1.5 cm in the transverse plane). Looser criteria are applied to tracks belonging to $K^0_S \to \pi^+\pi^-$. We combine pairs of oppositely charged tracks originating from a common vertex to form K^0_S and ϕ candidates. A $K^0_S \to \pi^+\pi^-$ candidate is accepted on the basis of requirements on the two-pion invariant mass (within 12 MeV/c^2 of the nominal K^0_S mass [12]), the flight-length (ℓ) significance ($\ell/\sigma_\ell > 3$), and the angle between the line connecting the B and K^0_S decay vertices and the K^0_S momentum (< 0.1 rad). Kaon tracks used to reconstruct the ϕ meson are distinguished from pion and proton tracks using dE/dx information from the DCH in conjunction with dE/dx information from the SVT for track momenta below 0.7 GeV/c, and, for momenta above 0.7 GeV/c, with the measured Cherenkov angle and number of photons recorded by the DIRC.

For an extended unbinned maximum-likelihood (ML) fit we parameterize the distributions of kinematic and topological variables for signal and background events in terms of probability density functions (PDFs). Each B candidate is characterized by the energy difference $\Delta E = (q_\Upsilon \cdot q_B/\sqrt{s}) - \sqrt{s}/2$ and the beam-energy–substituted mass $m_{\rm ES} = [(s/2 + \vec{p}_\Upsilon \cdot \vec{p}_B)^2/E^2_\Upsilon - \vec{p}^{\,2}_B]^{1/2}$ [11]. Here q_Υ and q_B are four-momenta of the $\Upsilon(4S)$ and the B candidate, $s \equiv (q_\Upsilon)^2$ is the square of the center-of-mass energy, $\vec{p}_\Upsilon$ and $\vec{p}_B$ are the three-momenta of the $\Upsilon(4S)$ and the B in the laboratory frame, and $E_\Upsilon \equiv q^0_\Upsilon$ is the energy of the $\Upsilon(4S)$ in the laboratory frame. For signal events, ΔE peaks at zero and $m_{\rm ES}$ peaks at the nominal B mass. The signal PDFs of both variables are adequately described by sums of two Gaussian distributions (whose means are not required to be the same). The background shape in ΔE is parametrized by a linear func-

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tion and in m_{ES} by a threshold function [13]. Candidates for our analysis are required to satisfy $|\Delta E| < 0.2\,\mathrm{GeV}$ and $m_{\mathrm{ES}} > 5.2\,\mathrm{GeV}/c^2$. The variable ΔE provides additional momentum-dependent π/K separation in the ML fit for the $B^+ \to \phi h^+$ branching fractions. The likelihood also incorporates the invariant mass of the $\phi \to K^+K^-$ candidate m_{KK} in the $[0.99, 1.05]$ GeV/c^2 range, which is described by a relativistic Breit–Wigner function convolved with a Gaussian, $\sigma = 1.0\,\mathrm{MeV}/c^2$, determined in Monte Carlo (MC) simulation studies, to account for resolution effects, and the ϕ helicity angle θ_H, which is defined as the angle between the directions of the K^+ and the parent B in the ϕ rest frame. The $\cos\theta_H$ distribution is a quadratic function for pseudoscalar-vector B decay modes and is nearly uniform for the combinatorial background.

Backgrounds in the candidate sample arise primarily from random combinations of tracks produced in the quark-antiquark continuum. In such events, particles appear bundled into jets, which can be identified with several variables computed in the CM frame. We use the angle θ_T between the thrust axis of the B candidate and the thrust axis of the other charged and neutral particles [11]. We require the angle θ_T to satisfy $|\cos\theta_T| < 0.9$. Other quantities that characterize the event topology are the CM angle θ_B between the B momentum and the beam axis and the sum of the momenta p_i of the other charged and neutral particles in the event weighted with Legendre polynomials $L_n(\theta_i), n = 0, 2$, where θ_i is the angle between the momentum of particle i and the thrust axis of the B candidate. We combine these variables into a Fisher discriminant $\mathcal{F}$ [15]. Contamination from other B decays, as well as $\tau^+\tau^-$ and $e^+e^-\gamma\gamma$ production, is negligible, as demonstrated in MC simulation studies. Possible K^+K^- S-wave contributions, such as the $f_0(980)$ and the $a_0(980)$, are not expected to contribute under the ϕ mass peak [14] and are distinguished by their uniform distribution in $\cos\theta_H$; this systematic effect is small compared with current statistical and systematic uncertainties.

We use an unbinned extended ML fit to extract signal yields and charge asymmetries simultaneously. The likelihood for candidate j in the flavor category c is obtained by summing the product of event yield N_{ic} and probability $\mathcal{P}_{ic}$ over signal and background hypotheses i. The total extended likelihood $\mathcal{L}$ for a sample of N events is given by

$$\mathcal{L} = \frac{1}{N!} \exp\left(-\sum_{i,c} N_{ic}\right) \prod_{j=1}^{N} \left[\sum_{i,c} N_{ic} \mathcal{P}_{ic}(\vec{x}_j; \vec{\alpha}_i)\right]. \quad (1)$$

The probabilities $\mathcal{P}_{ic}$ are products of PDFs for each of the independent variables $\vec{x}_j = \{m_{\mathrm{ES}}, \Delta E, \mathcal{F}, m_{KK}, \cos\theta_H\}$. The $\vec{\alpha}_i$ are the parameters of the distributions in $\vec{x}_j$, which are fixed to values derived from signal MC, on-resonance sidebands in (m_{ES}, ΔE), and high-statistics data control channels $B^+ \to \pi^+\overline{D}^0$ ($\overline{D}^0 \to K^+\pi^-$) and $B^0 \to \pi^+D^-$ ($D^- \to K^0_S\pi^-$). The control channels have event topologies similar to those in $B^+ \to \phi K^+$ and $B^0 \to \phi K^0_S$, and are used to compare central values and resolutions of the variables m_{ES}, ΔE, and $\mathcal{F}$ in data and MC simulation. By minimizing the quantity $-\ln\mathcal{L}$ in two separate fits, we determine the branching fractions, $\mathcal{B}$, and the charge asymmetry, $\mathcal{A}_{CP}$, for $\phi h^\pm$ and ϕK^0_S. In the ϕK^0_S case, there are two hypotheses, signal and background ($i = 1, 2$), and a single flavor category. In the fit for $B^\pm \to \phi h^\pm$ decays, we determine the flavor of the high-momentum track by comparing the measured Cherenkov angle with that expected for a pion or a kaon. In this way, the $\phi h^\pm$ ($h = \pi, K$) decays are fitted simultaneously with two signal ($i = 1$ for $B^\pm \to \phi K^\pm$ and $i = 2$ for $B^\pm \to \phi\pi^\pm$) and two corresponding background ($i = 3, 4$) hypotheses. We define the event yields n_{ic} in each of the two flavor categories ($c = 1$ for $B^+ \to \phi h^+$ and $c = 2$ for $B^- \to \phi h^-$) in terms of the charge asymmetry $\mathcal{A}_i$ and the total event yield n_i: $n_{i1} = n_i \times (1 + \mathcal{A}_i)/2$ and $n_{i2} = n_i \times (1 - \mathcal{A}_i)/2$.

TABLE I: Summary of branching fraction ($\mathcal{B}$) and direct CP-asymmetry ($\mathcal{A}_{CP}$) results. N_{sig} and ε are the signal yield and the total efficiency in the branching fraction fit. The 90% confidence-level interval for $\mathcal{A}_{CP}$ is $[-0.10, 0.18]$.

Mode	ε (%)	N_{sig}	$\mathcal{B}$ (10^{-6})	$\mathcal{A}_{CP}$
ϕK^0	6.7	50^{+9}_{-8}	$8.4^{+1.5}_{-1.3} \pm 0.5$	—
ϕK^+	19.6	173 ± 15	$10.0^{+0.9}_{-0.8} \pm 0.5$	$0.04 \pm 0.09 \pm 0.01$
$\phi\pi^+$	20.4	$0.9^{+2.4}_{-0.9}$	< 0.41 (90% CL)	—

For charged tracks originating from the interaction point, we determine the ratio of track-finding efficiencies in data and MC simulation by conducting a study of a large sample of unambiguous charged-track candidates that have at least 10 measured hits in the SVT; the method relies on the fact that for both the SVT and the DCH the differences between the track-finding efficiencies in data and MC simulation are small, and so the two detectors can be used to calibrate each other. The ratio of $K^0_S \to \pi^+\pi^-$ reconstruction efficiencies in data and MC simulation as a function of the K^0_S momentum and decay point is determined from a study of a large inclusive sample of $K^0_S \to \pi^+\pi^-$ decays; this method employs the results of the tracking-efficiency study that covers K^0_S decays occuring in the immediate vicinity of the interaction point. The charged-kaon–identification efficiencies in data and MC simulation are compared in a study of fully reconstructed $D^{*+} \to D^0\pi^+ (D^0 \to K^-\pi^+)$ decays.

Results of the branching-fraction and CP-asymmetry fits are given in Table I. Equal production rates of $B^0\overline{B}^0$ and B^+B^- are assumed. Figure 2 shows the m_{ES} and ΔE distributions of $\phi K^0_S(\pi^+\pi^-)$ and ϕK^+ events together with the likelihood projections from the $\mathcal{B}$ fits. Goodness-of-fit tests have been performed to confirm that the values of likelihood $\mathcal{L}$ obtained in the fits are consistent with MC-based expectations.

Systematic uncertainties in the ML fit originate from assumptions about the signal and background distribu-

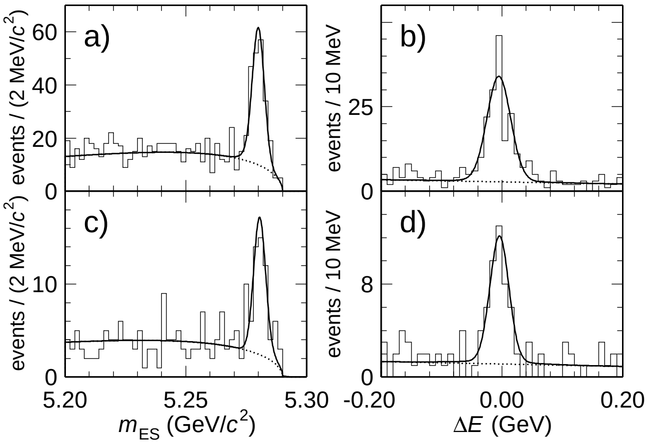

FIG. 2: Projection plots of the variables $m_{\rm ES}$ [(a) and (c)] and ΔE [(b) and (d)] in the fit for the ϕK^+ (top) and $\phi K^0_S(\pi^+\pi^-)$ (bottom) branching fractions. The data are shown by the histogram, while the curve is the result of the fit. The signal-to-background ratio is enhanced with a requirement on the signal probability $\mathcal{P}_{\rm sig}/(\mathcal{P}_{\rm sig}+\mathcal{P}_{\rm bkg})$ with the PDF for the variable being plotted excluded.

tions and are dominated by the limited sideband and control-channel statistics. We simultaneously vary all PDF parameters within their uncertainties, and derive the associated systematic errors: 0.005 for $\mathcal{A}_{CP}$, 2.0% for $\mathcal{B}(\phi K^+)$, and 2.8% for $\mathcal{B}(\phi K^0)$. To account for the systematic uncertainty on the upper limit on $\mathcal{B}(\phi\pi^+)$, we increase the upper limit by one standard deviation due to PDF variations (10.9%) and due to uncertainty in the reconstruction efficiency (4.2%). The dominant systematic errors in the efficiency come from track finding (2.4% for $\mathcal{B}(\phi h^+)$ and 4.2% for $\mathcal{B}(\phi K^0_S)$), charged-kaon identification (2% per ϕ), and K^0_S reconstruction efficiency (2%). Other systematic errors from event-selection criteria, daughter branching fractions, MC statistics, $B\overline{B}$ backgrounds and B-meson counting sum in quadrature to 3.0%. The systematic uncertainty on $\mathcal{A}_{CP}$ due to charge asymmetries in tracking and the DIRC is less than 0.01.

In summary, we have studied branching fractions and charge asymmetries in the B-meson final states ϕh^+ and ϕK^0_S; the results are listed in Table I. We do not observe a significant charge asymmetry in the mode $B^+ \to \phi K^+$ and do not see evidence for $B^+ \to \phi\pi^+$. Our branching fraction and charge asymmetry measurements are consistent with, and supersede, our previous results reported in [8, 9]. They are also consistent with existing SM predictions.

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