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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 penguins (Fig. 1), possibly with smaller contributions from electroweak penguins, while other Standard Model (SM) amplitudes are strongly suppressed [1]. In this 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], 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. The $B \to \phi K$ and $B \to \phi\pi$ decay rates are also sensitive to new physics. The branching fractions of $B^{0} \to \phi K^{0}$ and $B^{+} \to \phi K^{+}$ have been studied by CLEO [5], BABAR [6, 7], and Belle [8]; $\mathcal{A}_{CP}(B^{+} \to \phi K^{+})$ has been studied by BABAR [7].

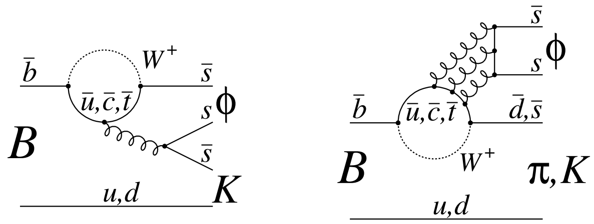

FIG. 1: Examples of quark-level diagrams for $B \to \phi K$ and $B \to \phi\pi$. Left: internal penguin, right: flavor-singlet penguin.

This analysis is based on about 89 million $B\overline{B}$ pairs collected at SLAC with the BABAR detector [9] at the PEP-II asymmetric-energy $e^{+}e^{-}$ storage ring operating on the $\Upsilon(4S)$ resonance. An additional sample with an integrated luminosity of 9.6 fb^{-1} was collected 40 MeV below the $\Upsilon(4S)$ resonance (off-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 ± 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 the average energy loss ($\mathrm{d}E/\mathrm{d}x$) 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 2.5σ for the highest momenta arising from B-meson decays. Electrons are identified with the use of the tracking system and the EMC.

We fully reconstruct B-meson candidates in the decay modes ϕK^{0}_{S} and ϕh^{+}, 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. 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 [10]), 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 pions and protons using $\mathrm{d}E/\mathrm{d}x$ information from the DCH in conjunction with $\mathrm{d}E/\mathrm{d}x$ information from the SVT for $p_T < 0.7$ GeV/c, or with the measured Cherenkov angle and number of photons recorded by the DIRC when $p_T > 0.7$ GeV/c.

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 $m_{\mathrm{ES}} = [(s/2 + \vec{p}_{\Upsilon} \cdot \vec{p}_B)^2/E_{\Upsilon}^2 - \vec{p}_B^{\,2}]^{1/2}$ [9]. 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_{ES} peaks at the nominal B mass. The signal PDFs of both variables are adequately described by sums of two Gaussian distributions. The background shape in ΔE is parametrized by a linear function and in m_{ES} by a threshold function [11]. 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}, which is described by a relativistic Breit–Wigner function convolved with a Gaussian ($\sigma = 1.0\,\mathrm{MeV}/c^2$) 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 [9]. 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 $\mathcal{F}$ [13]. Contamination from other B decays, as well as $\tau^+\tau^-$ and $e^+e^-\gamma\gamma$ production, is negligible, as demonstrated in Monte Carlo (MC) simulation studies. Possible K^+K^- S-wave contributions, such as the $f_0(980)$, are not expected to contribute under the ϕ mass peak [12] and are distinguished by their uniform distribution in $\cos\theta_H$.

The likelihood for candidate j in the B-flavor category c is obtained by summing the product of event yield $N_{i,c}$ and probability $\mathcal{P}_{i,c}$ over signal and background hypotheses i. The total likelihood $\mathcal{L}$ is given by

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

with N being the total number of events entering the fit. The probabilities $\mathcal{P}_{i,c}$ 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 Monte Carlo, data control channels, and on-resonance sidebands. 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 ϕh^+ and ϕK^0_S. In the fit for $B^+ \to \phi h^+$ decays, we determine

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)	—

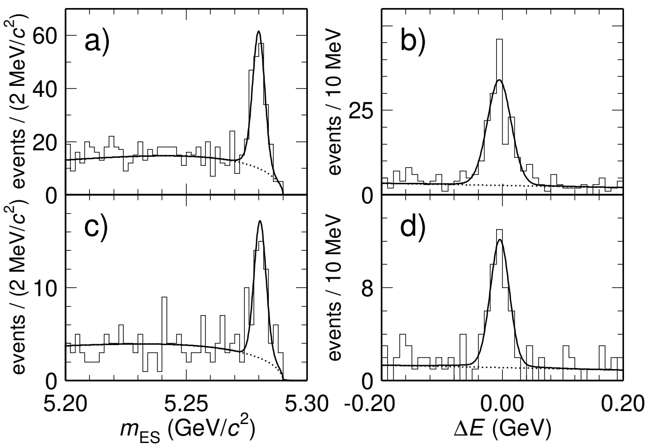

FIG. 2: Projection plots of the variables m_{ES} (a, c) and ΔE (b, d) in the fit for the ϕK^+ (top) and $\phi K^0_S(\pi^+\pi^-)$ (bottom) branching fractions. The data is shown by the histogram, while the curve is the result of the fit. The signal-to-background ratio is enhanced with a requirement on the event probability.

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 yields for the decay modes $B^+ \to \phi K^+$ and $B^+ \to \phi\pi^+$ are obtained simultaneously.

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. Fig. 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.

In the $\mathcal{B}$ and $\mathcal{A}_{CP}$ measurements, we estimate systematic errors due to PDF parameter uncertainties (0.005 for $\mathcal{A}_{CP}$, 2.0% for $\mathcal{B}(\phi K^+)$, 2.8% for $\mathcal{B}(\phi K^0)$, and 10.9% for the upper limit on $\mathcal{B}(\phi\pi^+)$), tracking efficiency (2.4% for $\mathcal{B}(\phi K^+)$ and 4.2% for $\mathcal{B}(\phi K^0_S)$), particle 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. We do not observe a significant charge asymmetry in the mode $B^\pm \to \phi K^\pm$ 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 [6, 7]. They are also consistent with existing SM predictions.

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