Branching Fractions in $B \rightarrow \phi h$ and
Search for Direct $CP$ Violation in $B^\pm \rightarrow \phi K^\pm$

The \textit{BABar} Collaboration

March 20, 2003

Abstract

We present preliminary measurements of branching fractions of the $b \rightarrow s\bar{s}s$ penguin-dominated
decays $B^\pm \rightarrow \phi K^\pm$ and $B^0 \rightarrow \phi K^0$ in a sample of approximately 89 million $B\bar{B}$ pairs collected by
the \textit{BABar} detector at the PEP-II asymmetric-energy $B$-meson Factory at SLAC. We determine
$B(B^\pm \rightarrow \phi K^\pm) = (10.0^{+0.9}_{-0.8} \text{ (stat.)} \pm 0.5 \text{ (syst.)}) \times 10^{-6}$ and $B(B^0 \rightarrow \phi K^0) = (7.6^{+1.3}_{-1.2} \text{ (stat.)} \pm 0.5 \text{ (syst.)}) \times 10^{-6}$. Additionally, we measure the charge asymmetry $A_{CP}(B^\pm \rightarrow \phi K^\pm) = 0.039 \pm 0.086 \text{ (stat.)} \pm 0.011 \text{ (syst.)}$ and set an upper limit on the CKM– and color-suppressed decay $B^\pm \rightarrow \phi \pi^\pm$, $B(B^\pm \rightarrow \phi \pi^\pm) < 0.41 \times 10^{-6}$ (90% CL).

Presented at the XXXVIII$^{th}$ Rencontres de Moriond on
Electroweak Interactions and Unified Theories,
3/15–3/22/2003, Les Arcs, Savoie, France

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Work supported in part by Department of Energy contract DE–AC03–76SF00515.
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1 Introduction

$B$-meson decays with a $\phi$ in the final state present a special interest because they are dominated by the $b \to s(d)\bar{s}s$ gluonic penguins, possibly with a significant contribution from electroweak penguins (Figs. 1a, 1b), while other Standard Model (SM) contributions are strongly suppressed \[1\]. Since contributions of diagrams with a $c$ or a $u$ quark in the loop are small, all dominant SM decay amplitudes have the same weak phase, leading to a very small ($\sim 1\%$) predicted value of direct CP asymmetry $A_{CP}$ in $B^\pm \to \phi K^\pm$. However, many models of new physics introduce new heavy particles, with new couplings, that would contribute to these decays, potentially making $A_{CP}$ quite large \[2\]. The amounts of CP and flavor violation observed in these decays can therefore be used to constrain the parameters of models of new physics.

Recent preliminary results from BABAR and Belle on the time-dependent CP asymmetry in the decay $B^0 \to \phi K^0_s$ \[3, 4\] have raised questions about the rescattering contribution to the $B^0 \to \phi K^0$ decay amplitude (Fig. 1c). While this cannot be computed a priori, simply from the weak couplings it will be larger in $B \to \phi \pi$ than in $B \to \phi K$ by a factor of roughly $\cot(\theta_C) \approx 4.4$, where $\theta_C$ is the Cabibbo angle \[5\]. By searching for $B^\pm \to \phi \pi^\pm$, our analysis can constrain the magnitude of the rescattering contribution to $B^0 \to \phi K^0$.

Additional reasons to be interested in a detailed study of the $b \to s(d)\bar{s}s$ processes include their sensitivity to QCD dynamics \[6, 7\] and to the poorly measured Cabibbo–Kobayashi–Maskawa matrix element $V_{ts}$.

The decays $B^\pm \to \phi K^\pm$ and $B^0 \to \phi K^0$ have previously been observed by CLEO \[8\], BABAR \[9\], and Belle \[10\]. The significantly increased size of the BABAR data set and an improved analysis technique allow us to achieve a substantial reduction of both the statistical and the systematic errors on the branching fractions of the two decays. The analysis is based on a multivariate maximum-likelihood fit; the yields for the decay modes $B^\pm \to \phi K^\pm$ and $B^\pm \to \phi \pi^\pm$ are obtained simultaneously. A blind analysis technique is used to avoid the potential for an experimenter-induced bias: the signal region is hidden until all significant details of the analysis are finalized. The determination of systematic errors is completed subsequently.

2 The BABAR Detector and Data Set

The data were collected with the BABAR detector \[11\] in 1999–2002 at the PEP-II asymmetric-energy $e^+e^-$ collider \[12\] located at the Stanford Linear Accelerator Center. An integrated lu-
minosity of about 82 fb\(^{-1}\) was recorded at the peak of the \(\Upsilon(4S)\) resonance, corresponding to 88.9 \(\pm\) 1.0 million \(B\bar{B}\) pairs.

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 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 \((dE/dx)\) in the two tracking devices and by the novel internally reflecting ring-imaging Cherenkov detector (DIRC) covering the central region. A \(\pi/K\) separation of better than 4\(\sigma\) is achieved for tracks with momenta below 3 GeV/c, decreasing to 2.5\(\sigma\) for the highest momenta arising from \(B\)-meson decays. Electrons are identified with the use of the tracking system and the EMC.

### 3 Event Selection

Hadronic events are selected on the basis of track multiplicity and event topology. \(B\)-meson candidates are fully reconstructed from their charged decay products: \(\phi \rightarrow K^+K^-\) and \(K^0 \rightarrow K_s^0 \rightarrow \pi^+\pi^-\). Charged tracks that are \(B\) or \(\phi\) daughters are required to originate from the interaction point (within 10 cm along the beam direction and 1.5 cm in the transverse plane), have at least 12 DCH hits and a minimum transverse momentum of 0.1 GeV/c. Looser criteria are applied to tracks used to reconstruct \(K_s^0 \rightarrow \pi^+\pi^-\) candidates in order to allow for displaced \(K_s^0\) decay vertices. We suppress \(e^+e^- \rightarrow \tau^+\tau^-\) and \(e^+e^- \rightarrow e^+e^-\gamma\gamma\) backgrounds by rejecting events with fewer than 5 tracks.

Pairs of oppositely-charged tracks that are required to originate from a common vertex are combined to form the \(\phi\) and \(K_s^0\) candidates. A clean sample of \(K_s^0\) candidates is obtained with requirements on the two-pion invariant mass \(|M_{\pi^+\pi^-} - m_{K_s^0}| < 12\text{ MeV}/c^2\), the angle \(\alpha\) between the reconstructed flight and momentum directions \((\cos\alpha > 0.995)\) and the flight-length significance \((\ell/\sigma_\ell > 3)\). For \(\phi \rightarrow K^+K^-\), the invariant mass of the \(K^+K^-\) pair is required to lie within the [0.99, 1.05] GeV/c\(^2\) range (Fig. 2).

Tracks used to reconstruct the \(\phi \rightarrow K^+K^-\) decay are distinguished from pion and proton tracks via a relatively loose requirement on a likelihood ratio that includes, for momenta below 0.7 GeV/c, \(dE/dx\) information from the SVT and DCH and, for higher momenta, the Cherenkov angle and the number of photons as measured by the DIRC. In addition, these tracks are required to pass electron and proton vetoes. Determination of the flavor of the high-momentum \(h^\pm\) track in \(B^\pm \rightarrow \phi h^\pm\) decays is provided mostly by Cherenkov-angle residuals, normalized to their uncertainties, which are computed for the pion and the kaon hypotheses and are used in the maximum-likelihood fit. During event selection, \(h^\pm\) candidates are required to have Cherenkov angles consistent within \(\pm 4\sigma\) with either of the two hypotheses; they are also required to pass an electron veto.

We identify \(B\)-meson candidates kinematically using two nearly independent variables [11]: the beam-energy–substituted mass \(m_{\text{ES}} = \sqrt{((\frac{s}{2} + p_T \cdot \bar{p}_B)^2 + E_T^2 - \bar{p}_B^2)}\), which is computed in the laboratory frame and is independent of the mass hypotheses assigned to the \(B\)-candidate daughters, and the Lorentz-invariant missing energy \(\Delta E = (q_T \cdot q_B/\sqrt{s}) - \sqrt{s}\). Here \(q_T\) and \(q_B\) are four-momenta.
Figure 2: (a) $m_{KK}$ invariant mass distribution in the $B^\pm \to \phi h^\pm$ on-resonance sideband; (b) definition of the on-resonance sideband in $m_{ES}$ and $\Delta E$.

of the $\Upsilon(4S)$ and the $B$ candidate, $s \equiv (q_T)^2$ is the square of the center-of-mass energy, $\vec{p}_T$ and $\vec{p}_B$ are the three-momenta of the $\Upsilon(4S)$ and the $B$ in the laboratory frame, and $E_T \equiv q_T^0$ is the energy of the $\Upsilon(4S)$ in the laboratory frame. For signal events, $\Delta E$ peaks at zero and $m_{ES}$ peaks at the $B$ mass. Our selection requires $|\Delta E| < 0.2$ GeV and $m_{ES} > 5.2$ GeV/$c^2$. Being dependent on the mass hypotheses assigned to the $B$ decay products, $\Delta E$ provides additional momentum-dependent $\pi/K$ separation in the maximum-likelihood fit for $B^\pm \to \phi h^\pm$ branching fractions.

Detailed Monte Carlo studies demonstrate that backgrounds from other $B$ decays are negligible. Backgrounds are dominated by random combinations of tracks produced in the quark-antiquark ($q\bar{q}$) continuum. This background is distinguished by its jet-like structure—as opposed to the nearly spherical decay of the $\Upsilon(4S)$. We have considered a variety of CM event-shape variables that exploit this difference.

One such variable is $|\cos \theta_T|$, where $\theta_T$ is the angle between the thrust axis of the $B$ candidate and the thrust axis of the rest of the event, where the thrust axis $\vec{A}$ is defined as the unit vector that maximizes the thrust $T = \max \left( \sum_{i=1}^{N} |\vec{A} \cdot \vec{p}_i|/\sum_{i=1}^{N} \sqrt{\sum \vec{p}_i^2} \right)$. Since $B$’s are non-relativistic in the $\Upsilon(4S)$ rest frame ($\beta \approx 0.06$), the $|\cos \theta_T|$ distribution for true $B$ candidates is very well described by a nearly flat first-degree polynomial; on the other hand, the $|\cos \theta_T|$ distribution for $B$ candidates found in the $e^+e^- \to q\bar{q}$ continuum is sharply peaked at +1. We apply the cut $|\cos \theta_T| < 0.9$ throughout our analysis.

Other quantities that characterize the event shape are the $B$ polar angle $\theta_B$ and the angle $\theta_{q\bar{q}}$ of the $B$-candidate thrust axis, both defined with respect to the beam axis, as well as the zeroth and the second Legendre moments of the rest of the tracks and neutrals, $L_n = \sum p_i \times L_n(\theta_i)$, $n = 0, 2$, computed relative to the $B$-candidate thrust axis. For $\Upsilon(4S)$ decays into two pseudoscalar $B$ mesons, the $\theta_B$ distribution has a $\sin^2 \theta_B$ dependence, whereas the jets from continuum events lead to a uniform distribution in $\cos \theta_B$. In $\theta_{q\bar{q}}$, the continuum jets give rise to a $(1 + \cos^2 \theta_{q\bar{q}})$ distribution, while the thrust direction of true $B$ decays is random. We further suppress the background by forming an optimized linear combination (Fisher discriminant [13]) of the four variables: $|\cos \theta_B|$, $|\cos \theta_{q\bar{q}}|$, $L_0$ and $L_2$. 
4 Maximum Likelihood Fit

We use an unbinned extended maximum-likelihood (ML) fit to extract signal yields and charge asymmetries simultaneously. The extended likelihood for a sample of $N$ events is

$$\mathcal{L} = \exp \left( -\sum_{i,k}^{N} n_{i,k} \right) \prod_{j=1}^{N} \sum_{i,k}^{N} \mathcal{P}_{ik}(\tilde{x}_j; \tilde{\alpha}) ,$$

where $\mathcal{P}_{ik}(\tilde{x}_j; \tilde{\alpha})$ is the probability density function (PDF) for measured variables $\tilde{x}_j$ of an event $j$ in category $i$ and flavor state $k$, and $n_{i,k}$ are the yields extracted from the fit. The fixed parameters $\tilde{\alpha}$ describe the expected distributions of measured variables in each category and flavor state. The PDFs are non-zero only for the correct final state flavor ($k = 1$ for $B \to f$ and $k = 2$ for $B \to \bar{f}$).

In the simplest case, there are two categories, signal and background ($i = 1, 2$). The decays with a charged primary daughter $B^{\pm} \to \phi h^{\pm}$ ($h = \pi$ or $K$) 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 ($i = 3, 4$) categories.

We define the event yields $n_{i,k}$ in each category in terms of the asymmetry $A_i$ and the total event yield $n_i$: $n_{1,1} = n_i \times (1+A_i)/2$ and $n_{1,2} = n_i \times (1-A_i)/2$. The event yields $n_i$ and asymmetries $A_i$ in each category are obtained by maximizing $\mathcal{L}$. Statistical errors correspond to unit changes in the quantity $\chi^2 = -2 \ln (\mathcal{L}/\mathcal{L}_{\text{max}})$. The significance of a signal is measured by the square root of the change in $\chi^2$ when the number of signal events is constrained to zero in the likelihood fit; it describes the probability for the background to fluctuate to the observed event yield.

The probability $\mathcal{P}_i(\tilde{x}_j; \tilde{\alpha})$ for a given event $j$ is the product of independent PDFs in each of the fit input variables $\tilde{x}_j$. These variables are $\Delta E$, $m_{ES}$, $m_{KK}$, the Fisher discriminant $F$, and the cosine of the $\phi$ helicity angle (defined as the angle between the $K^+$ and $B$ momenta in the $\phi$ rest frame) $\cos \theta_H$. In addition, in the simultaneous fit for the modes $B^{\pm} \to \phi K^{\pm}$ and $B^{\pm} \to \phi \pi^{\pm}$ we include normalized residuals derived from the difference between the measured and expected DIRC Cherenkov angles for the charged primary daughter. Additional separation between the two final states is provided by $\Delta E$. The $\Delta E$ separation depends on the momentum of the charged primary daughter in the laboratory frame and is about 45 MeV on average, varying from about 30 MeV for the highest-momentum to about 80 MeV for the lowest-momentum primary daughters available in our final states. If a given event has multiple combinations satisfying the selection requirements (which occurs in fewer than 0.2% of the events), the “best” combination is selected using a $\chi^2$ quantity computed using all input variables with the exception, in the $B^{\pm} \to \phi h^{\pm}$ case, of the normalized Cherenkov-angle residuals and $\Delta E$, which are used for $\phi \pi^{\pm}/\phi K^{\pm}$ separation.

The fixed parameters $\tilde{\alpha}$ defining the PDFs are extracted for signal from Monte Carlo simulation and for background distributions from the on-resonance sidebands in $m_{ES}$ and $\Delta E$ (Fig. 2b). The MC resolutions and means are adjusted, when necessary, by comparing data and simulation in abundant calibration channels with kinematics and topologies similar to signal, $B^+ \to \pi^+ D^0, (D^0 \to K^+ \pi^-)$, and $B^0 \to \pi^+ D^-, (D^- \to K^0 \pi^-)$. The PDFs for the Cherenkov-angle residuals are determined from samples of $D^0 \to K^- \pi^+$ originating from $D^*$ decays.

We employ a double Gaussian to parametrize the signal $\Delta E$ and $m_{ES}$ PDFs. For the background, a first-degree polynomial is used for $\Delta E$ and an empirical phase-space function [14] is used for $m_{ES}$. The Fisher discriminant distributions both in signal and in background are parametrized by a Gaussian with different widths above and below the mean. The $\phi$-resonance shape in signal and the real-$\phi$ component of the continuum background are parametrized by the relativistic
Table 1: Summary of results. Equal production rates of $B^0\bar{B}^0$ and $B^+B^-$ are assumed. The total efficiency values include daughter branching fractions. Central values are followed by statistical and systematic errors; the upper limit on $\mathcal{B}(B^{\pm} \to \phi\pi^{\pm})$ incorporates the associated systematic error. The statistical significance of the $B^{\pm} \to \phi\pi^{\pm}$ signal is 0.5σ. The 90% confidence interval for $A_{CP}(B^{\pm} \to \phi K^{\pm})$ is $[-0.104; +0.181]$

|                | $B^\pm \to \phi K^\pm$ | $B^\pm \to \phi\pi^\pm$ | $B^0 \to \phi K^0$ |
|----------------|--------------------------|--------------------------|-------------------|
| Events to fit  | 14371                    | 2043                     | 50±9             |
| Signal yield   | 173 ± 15                 | 0.9±2.8−0.9 (< 6.7 at 90% CL) | 43.5             |
| Reconstruction eff. (%) | 39.8                   | 41.4                     | 7.4               |
| Total efficiency (%) | 19.6                   | 20.4                     | 4.0               |
| $B^{10^{-6}}$  | 10.0±0.9−0.8 ± 0.5       | < 0.41 (90% CL)          | 7.6±1.3−1.2 ± 0.5 |
| $A_{CP}$       | 0.039 ± 0.086 ± 0.011    | —                        | —                |
Figure 3: Projection plots for $B^\pm \to \phi K^\pm$ (left column) and $B^0 \to \phi K^0$ (right column), made with a probability-ratio cut to emphasize the signal, for the variables (a,b) $m_{ES}$, (c,d) $\Delta E$, (e,f) $m_{KK}$, (g,h) $\cos \theta_H$. The solid (dashed) lines show the signal+background (background only) PDF projections.
integrating the normalized likelihood distribution from zero. The limit incorporates changes by one standard deviation from uncertainties in PDFs and the reconstruction efficiency.

6 Summary

We have determined the branching fractions of the rare charmless penguin-dominated $B$-meson decays $B^\pm \to \phi K^\pm$ and $B^0 \to \phi K^0$, and have set a limit on the direct $CP$ asymmetry $A_{CP}(B^\pm \to \phi K^\pm)$, with substantially reduced statistical and systematic errors compared to previously published results. The results contained in this paper are preliminary.

The stringent upper limit on the CKM– and color-suppressed decay $B^\pm \to \phi \pi^\pm$ provides evidence against the presence of large non-penguin or non–Standard Model contributions to the $b \to s(d)\bar{c}c$ decay amplitudes.

7 Acknowledgements

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 the A. P. Sloan Foundation, the Research Corporation, and the Alexander von Humboldt Foundation.

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