Measurements of branching fractions in $B \to \phi K$ and $B \to \phi \pi$
and search for direct CP violation in $B^\pm \to \phi K^\mp$
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 $B \bar{B}$ pairs collected by the BABAR detector at the PEP-II asymmetric-energy $B$-meson factory at SLAC. We determine $B(B^+ \to \phi K^+) = (10.0^{+2.9}_{-1.8} \pm 0.5) \times 10^{-6}$ and $B(B^0 \to \phi K^0) = (8.4^{+1.3}_{-1.1} \pm 0.5) \times 10^{-6}$. Additionally, we measure the CP-violating charge asymmetry $A_{CP}(B^\pm \to \phi K^\mp) = 0.04 \pm 0.09 \pm 0.01$, with a 90% confidence-level interval of $[-0.10, 0.18]$, and set an upper limit on the CKM- and color-suppressed decay $B^+ \to \phi \tau^+$, $B(B^+ \to \phi \tau^+) < 0.41 \times 10^{-6}$ (at the 90% confidence level).

PACS numbers: 13.25.Hw, 11.30.Er, 12.15.Hh
Decays of $B$ mesons into charmless hadronic final states with a $\phi$ 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 $B^+ \to \phi K^+$, detected as an asymmetry $A_{CP} = (\Gamma_{\phi K^+} - \Gamma_{\phi K^-})/(\Gamma_{\phi K^+} + \Gamma_{\phi K^-})$ 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 [3]. The $B \to \phi K$ and $B \to \phi\pi$ decay rates are also sensitive to new physics; the latter is strongly suppressed.

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 $\pi/K$ separation of between 4.6 and 2.4 is achieved for tracks with momenta below 3 GeV/c, decreasing to 2.4 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 $\phi h^+$ and $K^0_s$, with $\phi \to K^+ K^-$ and $K^0_s \to \pi^+ \pi^-$. For the $h^+$ track and the charged-track daughters of the $\phi$ we require at least 12 measured DCH hits and a minimal transverse momentum $p_T > 0.1$ 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 $\phi$ 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 ($\ell$) 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 $\phi$ 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 $\Delta E = (q_T \cdot q_B / \sqrt{s}) - \sqrt{s}/2$ and the beam-energy–substituted mass $m_{ES} = [s/2 + p_T \cdot \bar{p}_B] / E_T^{0} - p_T^{0}]^{1/2}$ [11]. Here $q_T$ and $q_B$ are four-momenta of the $T(4S)$ and the $B$ candidate, and $s \equiv (q_T)^2$ is the square of the center-of-mass energy, $\vec{p}_T$ and $\bar{p}_B$ are the three-momenta of the $T(4S)$ and the $B$ in the laboratory frame, and $E_T^{0} \equiv q_B^{0}$ is the energy of the $T(4S)$ in the laboratory frame. For signal events, $\Delta E$ 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 (whose means are not required to be the same). The background shape in $\Delta E$ is parametrized by a linear func-

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig1.png}
\caption{Examples of quark-level diagrams for $B \to \phi K$ and $B \to \phi\pi$. Left: internal penguin diagram, right: flavor-singlet penguin diagram.}
\end{figure}
tion and in $m_{ES}$ by a threshold function $\Delta E < 0.2$ GeV and $m_{ES} > 5.2$ GeV/$c^2$. The variable $\Delta E$ provides additional momentum-dependent $\pi/K$ 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, $\sigma = 1.0$ MeV/$c^2$, determined in Monte Carlo (MC) simulation studies, to account for resolution effects, and the $\phi$ helicity angle $\beta_{\phi}$, which is defined as the angle between the directions of the $K^+$ and the parent $B$ in the $\phi$ 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 $\theta_B$ between the thrust axis of the $B$ candidate and the thrust axis of the other charged and neutral particles. We require the angle $\theta_T$ to satisfy $|\cos \theta_T| < 0.9$. Other quantities that characterize the event topology are the CM angle $\beta_H$ 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 $L_n(\cos \theta_i), n = 0, 2$, where $\theta_i$ 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 $F$. 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 $\phi$ mass peak 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 $P_{ic}$ over signal and background hypotheses $i$. The total extended likelihood $\mathcal{L}$ for a sample of $N$ events is given by

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

The probabilities $P_{ic}$ are products of PDFs for each of the independent variables $\vec{x}$, which are fixed to values derived from signal MC, on-resonance sidebands in $(m_{ES}, \Delta E, F, m_{KK}, \cos \theta_H)$. The $\vec{\alpha}_i$ are the parameters of the distributions in $\vec{x}$, which are fixed to values derived from signal MC, on-resonance sidebands in $(m_{ES}, \Delta E, F, m_{KK}, \cos \theta_H)$.

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

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\varepsilon$ (%)</th>
<th>$N_{sig}$</th>
<th>$B$ ($10^{-6}$)</th>
<th>$A_{CP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi K^0$</td>
<td>6.7</td>
<td>50.2</td>
<td>8.4</td>
<td>0.4</td>
</tr>
<tr>
<td>$\phi K^+$</td>
<td>19.6</td>
<td>173.15</td>
<td>10.0</td>
<td>0.04</td>
</tr>
<tr>
<td>$\phi \pi^+$</td>
<td>20.4</td>
<td>0.9</td>
<td>&lt; 0.41 (90% CL)</td>
<td></td>
</tr>
</tbody>
</table>
increase the upper limit by one standard deviation due to
FIG. 2: Projection plots of the variables $m_{ES}$ [(a) and (c)] and
the associated systematic errors: 0.005 for
$\Delta E$ [(b) and (d)] in the fit for the $\phi K^+$ (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 $P_{sig}/(P_{sig} + P_{bkg})$ 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 $A_{CP}$, 2.0%
for $B(\phi K^+)$, and 2.8% for $B(\phi K^0_s)$. To account for the
systematic uncertainty on the upper limit on $B(\phi\pi^+)$, we
increase the upper limit by one standard deviation due to
PDF variations (10.9%) and due to uncertainty in the re-
construction efficiency (4.2%). The dominant systematic
errors in the efficiency come from track finding (2.4%
for $B(\phi h^+)$ and 4.2% for $B(\phi K^0_s)$), charged-kaon iden-
tification (2% per $\phi$), and $K^0_s$ reconstruction efficiency
(2%). Other systematic errors from event-selection cri-
tera, daughter branching fractions, MC statistics, B-$\bar{B}$
backgrounds and $B$-meson counting sum in quadrature to
3.0%. The systematic uncertainty on $A_{CP}$ 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 $\phi h^+$
and $\phi K^0_s$; 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 consist-
ent with, and supersede, our previous results reported in
[3, 4]. They are also consistent with existing SM pre-
dictions.

We are grateful for the excellent luminosity and ma-
chine conditions provided by our PEP-II colleagues, and
for the substantial dedicated effort from the computing
organizations that support BaBar. The collaborating
institutions wish to thank SLAC for its support and
kind hospitality. This work is supported by DOE and
NSF (USA), NSERC (Canada), IHEP (China), CEA and
CNRS-IN2P3 (France), BMBF and DFG (Germany),
INFN (Italy), FOM (The Netherlands), NFR (Norway),
MIST (Russia), and PPARC (United Kingdom). Indi-
viduals have received support from the A. P. Sloan Foun-
dation, Research Corporation, and Alexander von Hum-
boldt Foundation.


[14] See, for example, Note on Scalar Mesons in [12].