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

The BABAR Collaboration

March 20, 2003

Abstract

We present preliminary measurements of branching fractions of the $b \to s\bar{s}s$ penguin-dominated decays $B^{\pm} \to \phi K^{\pm}$ 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 $\mathcal{B}(B^{\pm} \to \phi K^{\pm}) = (10.0^{+0.9}_{-0.8}\,(\text{stat.}) \pm 0.5\,(\text{syst.})) \times 10^{-6}$ and $\mathcal{B}(B^0 \to \phi K^0) = (7.6^{+1.3}_{-1.2}\,(\text{stat.}) \pm 0.5\,(\text{syst.})) \times 10^{-6}$. Additionally, we measure the charge asymmetry $\mathcal{A}_{CP}(B^{\pm} \to \phi K^{\pm}) = 0.039 \pm 0.086\,(\text{stat.}) \pm 0.011\,(\text{syst.})$ and set an upper limit on the CKM– and color-suppressed decay $B^{\pm} \to \phi\pi^{\pm}$, $\mathcal{B}(B^{\pm} \to \phi\pi^{\pm}) < 0.41 \times 10^{-6}$ (90% CL).

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1 Introduction

B-meson decays with a ϕ 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 $\mathcal{A}_{CP}$ 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 $\mathcal{A}_{CP}$ 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.

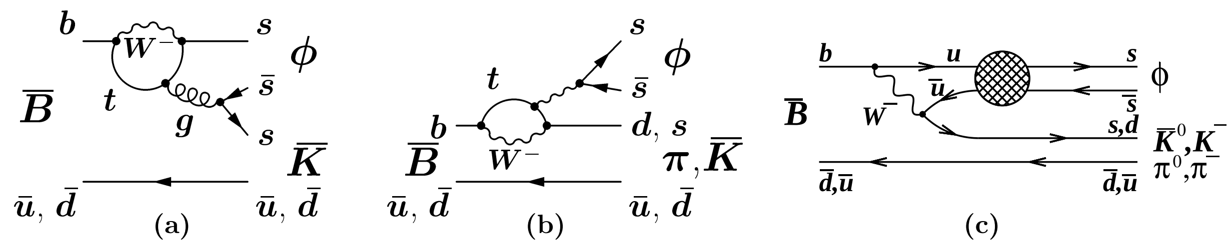

Figure 1: Examples of penguin diagrams for *(a)* $B \to \phi K$, *(b)* $B \to \phi K$ and $B \to \phi\pi$; *(c)* the rescattering diagram for $B \to \phi K$ and $B \to \phi\pi$. The unlabled spin-1 propagator in diagram (b) should be interpreted either as a hard gluon (with two or more additional soft gluons that are not shown), or as a γ or a Z. The tree part of diagram (c) could lead directly to a $B \to \phi h$ final state via the small, poorly understood $u\bar{u}$ component of the ϕ resonance

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 $\cot(\theta_{\rm C}) \approx 4.4$, where $\theta_{\rm C}$ 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 luminosity of about 82 fb^{-1} was recorded at the peak of the $\Upsilon(4S)$ resonance, corresponding to 88.9 ± 1.0 million $B\overline{B}$ 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 $4.4\,\text{GeV}/c$. 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 $0.2\,\text{GeV}/c$ 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 ($\mathrm{d}E/\mathrm{d}x$) 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 $3\,\text{GeV}/c$, 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.

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: $\phi \to K^+K^-$ and $K^0 \to K^0_S \to \pi^+\pi^-$. Charged tracks that are B or ϕ 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 $0.1\,\text{GeV}/c$. Looser criteria are applied to tracks used to reconstruct $K^0_S \to \pi^+\pi^-$ candidates in order to allow for displaced K^0_S decay vertices. We suppress $e^+e^- \to \tau^+\tau^-$ and $e^+e^- \to e^+e^-\gamma\gamma$ 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 ϕ and K^0_S candidates. A clean sample of K^0_S candidates is obtained with requirements on the two-pion invariant mass ($|M_{\pi^+\pi^-} - m_{K^0}| < 12\,\text{MeV}/c^2$), the angle α between the reconstructed flight and momentum directions ($\cos\alpha > 0.995$) and the flight-length significance ($\ell/\sigma_\ell > 3$). For $\phi \to K^+K^-$, the invariant mass of the K^+K^- pair is required to lie within the $[0.99, 1.05]\,\text{GeV}/c^2$ range (Fig. 2).

Tracks used to reconstruct the $\phi \to K^+K^-$ decay are distinguished from pion and proton tracks via a relatively loose requirement on a likelihood ratio that includes, for momenta below $0.7\,\text{GeV}/c$, $\mathrm{d}E/\mathrm{d}x$ 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 $B^\pm \to \phi h^\pm$ 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 $m_{\text{ES}} = \sqrt{((\frac{s}{2} + \vec{p}_\Upsilon \cdot \vec{p}_B)^2)/(E^2_\Upsilon) - \vec{p}^{\,2}_B}$, 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 $\Delta E = (q_\Upsilon \cdot q_B/\sqrt{s}) - \sqrt{s}$. Here q_Υ and q_B are four-momenta

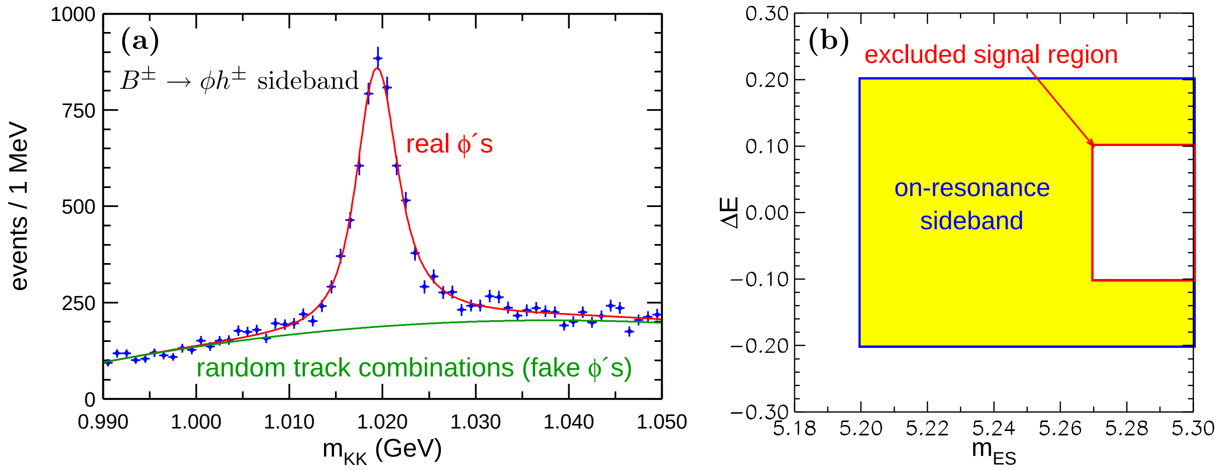

Figure 2: *(a)* m_{KK} invariant mass distribution in the $B^{\pm} \to \phi h^{\pm}$ on-resonance sideband; *(b)* definition of the on-resonance sideband in $m_{\rm ES}$ and ΔE

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 B mass. Our selection requires $|\Delta E| < 0.2\,{\rm GeV}$ and $m_{\rm ES} > 5.2\,{\rm GeV}/c^2$. Being dependent on the mass hypotheses assigned to the B decay products, ΔE provides additional momentum-dependent π/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 $(q\overline{q})$ 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 θ_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 $T = \max\left(\sum_{i=1}^{N}|\vec{A}\cdot\vec{p_i}|/\sum_{i=1}^{N}\sqrt{|\vec{p_i}|^2}\right)$. 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 $e^+e^- \to q\overline{q}$ 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 θ_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, $\mathcal{L}_n = \sum p_i \times L_n(\theta_i)$, $n = 0$, 2, computed relative to the B-candidate thrust axis. For $\Upsilon(4S)$ decays into two pseudoscalar B mesons, the θ_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: $|\cos\theta_B|$, $|\cos\theta_{q\bar{q}}|$, $\mathcal{L}_0$ and $\mathcal{L}_2$.

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

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

where $\mathcal{P}_{ik}(\vec{x}_j;\vec{\alpha})$ is the probability density function (PDF) for measured variables $\vec{x}_j$ of an event j in category i and flavor state k, and n_{ik} are the yields extracted from the fit. The fixed parameters $\vec{\alpha}$ 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 $\overline{B} \to \bar{f}$ and $k = 2$ for $B \to f$). 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_{ik} in each category in terms of the asymmetry $\mathcal{A}_i$ and the total event yield n_i: $n_{i1} = n_i \times (1+\mathcal{A}_i)/2$ and $n_{i2} = n_i \times (1-\mathcal{A}_i)/2$. The event yields n_i and asymmetries $\mathcal{A}_i$ in each category are obtained by maximizing $\mathcal{L}$. Statistical errors correspond to unit changes in the quantity $\chi^2 = -2\ln(\mathcal{L}/\mathcal{L}_{\rm max})$. The significance of a signal is measured by the square root of the change in χ^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 $\mathcal{P}_i(\vec{x}_j;\vec{\alpha})$ for a given event j is the product of independent PDFs in each of the fit input variables $\vec{x}_j$. These variables are ΔE, $m_{\rm ES}$, m_{KK}, the Fisher discriminant $\mathcal{F}$, and the cosine of the ϕ helicity angle (defined as the angle between the K^+ and B momenta in the ϕ 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 ΔE. The ΔE 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 χ^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 ΔE, which are used for $\phi\pi^{\pm}/\phi K^{\pm}$ separation.

The fixed parameters $\vec{\alpha}$ defining the PDFs are extracted for signal from Monte Carlo simulation and for background distributions from the on-resonance sidebands in $m_{\rm ES}$ and ΔE (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, $B^+ \to \pi^+\overline{D}^0$ ($\overline{D}^0 \to K^+\pi^-$) 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 ΔE and $m_{\rm ES}$ PDFs. For the background, a first-degree polynomial is used for ΔE and an empirical phase-space function [14] is used for $m_{\rm ES}$. The Fisher discriminant distributions both in signal and in background are parametrized by a Gaussian with different widths above and below the mean. The ϕ-resonance shape in signal and the real-ϕ component of the continuum background are parametrized by the relativistic

Table 1: Summary of results. Equal production rates of $B^0\overline{B}^0$ 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 $\mathcal{A}_{CP}$ ($B^\pm \to \phi K^\pm$) 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
Signal yield	173 ± 15	$0.9^{+2.8}_{-0.9}$ (< 6.7 at 90% CL)	50^{+9}_{-8}
Reconstruction eff. (%)	39.8	41.4	43.5
Total efficiency (%)	19.6	20.4	7.4
$\mathcal{B}$ (10^{-6})	$10.0^{+0.9}_{-0.8} \pm 0.5$	< 0.41 (90% CL)	$7.6^{+1.3}_{-1.2} \pm 0.5$
$\mathcal{A}_{CP}$	$0.039 \pm 0.086 \pm 0.011$	—	—

spin-1 Breit–Wigner function [15] with the Blatt–Weisskopf damping factor correction [16] convoluted with a Gaussian resolution function ($\sigma = 1.0\,\mathrm{MeV}/c^2$); the combinatorial component of the m_{KK} distribution in the continuum background is parametrized with a second-degree polynomial (Fig. 2a). Since $B \to \phi K$ and $B \to \phi\pi$ are decays of a pseudoscalar particle into a vector and a pseudoscalar, the helicity-angle distribution for the signal is $\cos^2\theta_H$; the background shape is again separated into contributions from combinatorial sources and from real ϕ mesons, both of which are parametrized by second-degree polynomials with no linear terms. The Cherenkov-angle–residual PDFs are unit Gaussians for both the pion and kaon distributions.

For all modes, we test the fitting procedure with background samples generated according to the PDFs and signal from Monte Carlo simulation, with numbers of signal and background events close to the expected. Signal yields are found to be unbiased. Correlations among the input variables in data are less than 5%.

5 Physics Results and Systematic Uncertainties

The results of our ML fit analyses are summarized in Table 1. For the branching fractions, equal production rates of $B^0\overline{B}^0$ and B^+B^- are assumed. The projections of the fit results are shown in Fig. 3, where we plot only a subsample of events, enhancing the signal with a requirement on the ratio of probabilities for each event to belong either to the signal or to the background categories.

Systematic uncertainties in the ML fit originate from assumptions about the signal and background distributions. We simultaneously vary all PDF parameters within their uncertainties and derive the associated systematic errors, which are found to be 2.0% for $\mathcal{B}(B^\pm \to \phi K^\pm)$, 10.9% for the 90% upper limit on $\mathcal{B}(B^\pm \to \phi\pi^\pm)$, 2.8% for $\mathcal{B}(B^0 \to \phi K^0)$, and 0.5% for $\mathcal{A}_{CP}(B^\pm \to \phi K^\pm)$.

The dominant systematic errors in the efficiency come from track finding (0.8% per high-momentum or $\phi \to K^+K^-$ track), particle identification (1% per $\phi \to K^+K^-$ track), and K^0_S reconstruction efficiency (4.0%). Other minor systematic effects from event-selection criteria, daughter branching fractions, MC statistics, $B\overline{B}$ backgrounds and B-meson counting sum to 3.0%. Efficiency uncertainties affect the values of the branching fractions, but not their significances. The systematic uncertainty on $\mathcal{A}_{CP}$ due to charge asymmetries in tracking and the DIRC is less than 1.0%.

Given the low significance of $\mathcal{B}(B^\pm \to \phi\pi^\pm)$, we quote a 90% CL upper limit obtained by

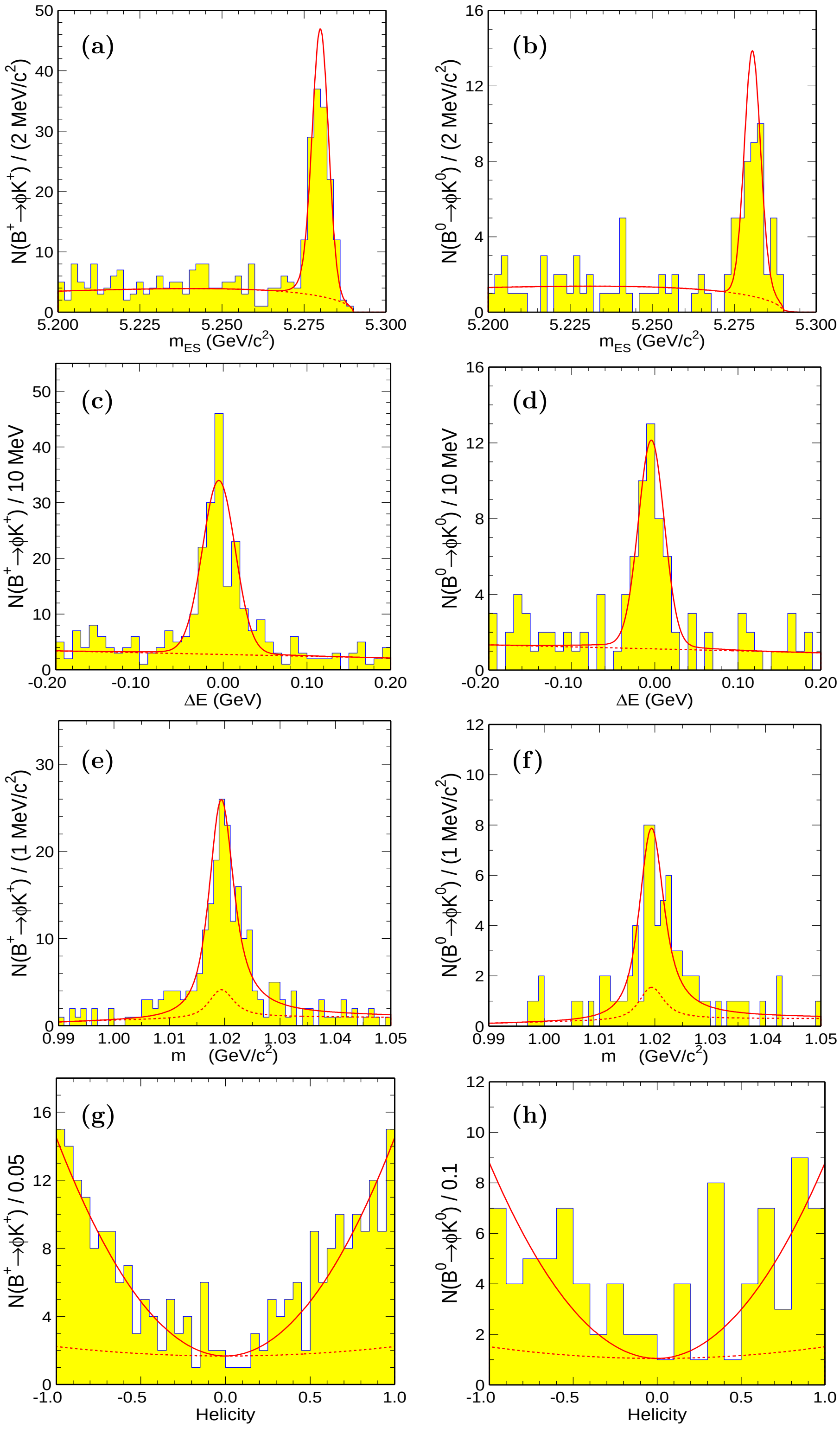

Figure 3: Projection plots for $B^{\pm} \to \phi K^{\pm}$ (left column) and $B^0 \to \phi K^0$ (right column), made with a probability-ratio cut to emphasize the signal, for the variables *(a,b)* $m_{\rm ES}$, *(c,d)* ΔE, *(e,f)* m_{KK}, *(g,h)* $\cos\theta_H$. The solid (dashed) lines show the signal+background (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 $\mathcal{A}_{CP}(B^{\pm} \to \phi K^{\pm})$, 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 $b \to s(d)\overline{s}s$ decay amplitudes.

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References

[1] N.G. Deshpande and J. Trampetic, Phys. Rev. D **41**, 895 (1990); N.G. Deshpande and X.-G. He, Phys. Lett. B **336**, 471 (1994); R. Fleischer, Z. Phys. C **62**, 81 (1994).

[2] I. Hinchliffe and N. Kersting, Phys. Rev. D **63**, 015003 (2001).

[3] B. Aubert *et al.* [BABAR Collaboration], arXiv:hep-ex/0207070.

[4] K. Abe *et al.* [Belle Collaboration], arXiv:hep-ex/0207098.

[5] Y. Grossman, G. Isidori and M. P. Worah, Phys. Rev. D **58**, 057504 (1998).

[6] H. Y. Cheng and K. C. Yang, Phys. Rev. D **64**, 074004 (2001).

[7] C. H. Chen, Y. Y. Keum and H. n. Li, Phys. Rev. D **64**, 112002 (2001).

[8] R. A. Briere *et al.* [CLEO Collaboration], Phys. Rev. Lett. **86**, 3718 (2001).

[9] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **87**, 151801 (2001).

[10] A. Bozek [Belle Collaboration], arXiv:hep-ex/0104041.

[11] B. Aubert *et al.* [BABAR Collaboration], Nucl. Instrum. Meth. A **479**, 1–116 (2002).

[12] PEP-II Conceptual Design Report, SLAC-R-418 (1993).

[13] R. A. Fisher, Annals Eugen. **7**, 179 (1936).

[14] H. Albrecht *et al.* [ARGUS Collaboration], Phys. Lett. B **241**, 278 (1990).

[15] J. D. Jackson, Nuovo Cim. **34**, 1644 (1964).

[16] F. Von Hippel and C. Quigg, Phys. Rev. D **5**, 624 (1972).