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Search for Charmless Hadronic Decays of B Mesons to Final States Including ω or ϕ Mesons

CLEO Collaboration

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Abstract

A search for charmless hadronic B-meson decays to exclusive final states including ω or ϕ mesons was performed using data collected with the CLEO II detector at the CESR e^+e^- storage ring. Signals are observed in the $B^+ \to \omega K^+$ and $B^+ \to \omega\pi^+$ decay channels, with branching fractions of $(1.5^{+0.7}_{-0.6} \pm 0.3) \times 10^{-5}$ and $(1.1^{+0.6}_{-0.5} \pm 0.2) \times 10^{-5}$ and statistical significance of 4.3σ and 2.9σ, respectively. A signal is also observed for $B \to \phi K^*$ with a statistical significance of 3.5σ, and a measured branching fraction of $(1.3^{+0.7}_{-0.6} \pm 0.2) \times 10^{-5}$. Upper limits are given for a number of other modes, some of which are comparable to theoretical predictions.

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I. INTRODUCTION

In the past year, the CLEO II collaboration has reported several measurements of charmless hadronic B decays. Last summer [1], we reported an observation of the decay modes $B^+ \to \omega K^+$ and $B^+ \to \omega \pi^+$ [1], with unexpectedly large branching fractions; a more refined analysis was presented in March [2]. In January [3], we reported the observation of the decay $B^+ \to \eta' K^+$, also with a surprisingly large branching fraction, and in March [2], we reported clear evidence for the decay $B^0 \to K^+ \pi^-$. There is a great deal of interest in these measurements since they provide information on the relative importance of spectator and "penguin" decay amplitudes. This led to a significant amount of theoretical activity, much of it focusing on final states with two pseudoscalar particles. Further results for decay modes involving η' and η particles are reported in another contribution to this conference [4].

This paper describes searches for B-meson decays to exclusive final states that include an ω or ϕ particle. Theoretical predictions for ω modes vary from 3×10^{-7} to 1.1×10^{-5} [5–8]. More recently, Ali and Greub [9] used a Standard Model effective Hamiltonian and a factorization ansatz for hadronic matrix elements to predict the $B^+ \to \omega K^+$ and $B^+ \to \omega \pi^+$ branching fractions. For ϕ modes, the theoretical predictions are in the range (0.8 - 3.1)$\times 10^{-5}$ [5,7,8,10–13]. These are of particular interest because they proceed only through penguin or annihilation amplitudes, with no contribution from spectator amplitudes. Since in principle the ϕ is a pure $s\bar{s}$ state, these decays can be used to isolate the $b \to s$ penguin contribution to the total decay rate of other exclusive non-leptonic B decay modes.

II. DATA SAMPLE AND INITIAL EVENT SELECTION

The results presented in this paper are based on data collected with the CLEO II detector [14] at the Cornell Electron Storage Ring (CESR). The data sample corresponds to an integrated luminosity of 3.11 fb^{-1} taken on the Υ(4S) resonance and 1.61 fb^{-1} taken slightly below. The on-resonance data sample contains 3.3×10^6 $B\overline{B}$ pairs. The detector elements most important to the analyses presented here are the tracking system, which is used to measure the momentum and energy loss rate (dE/dx) of charged particles, and the CsI crystal calorimeter which is used to measure the energy and position of photons.

Most of the results are obtained with a maximum likelihood analysis technique. A few others are the result of event-counting analyses, in which events that satisfy a series of cuts are taken as signal for the decay mode investigated. Some preliminary cuts are applied for both these techniques. The total number of charged tracks in each event is required to be at least two (three) greater than the number from the candidate B^+ (B^0) meson. All reconstructed charged tracks are required to pass quality cuts based on their track fit residual and impact parameter, and to have a momentum greater than 100 MeV/c. For event-counting analyses, the latter requirement is increased to 175 MeV/c.

The measured dE/dx of charged pions and kaons is required to be within 3σ of the expected value. To ensure the quality of the dE/dx information we require that tracks have

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[1] Charge conjugate modes are implied throughout the paper.

at least four associated pulse height measurements and satisfy $|\cos\theta| < 0.9$, where θ is the angle of the track with respect to the beam axis. Since the identity of the high momentum track is crucial in the assignment of events for the pairs of decay modes $B^+ \to \omega K^+/\pi^+$ and $B^+ \to \phi K^+/\pi^+$, we require at least 11 pulse height measurements and $|\cos\theta| < 0.85$. Electrons are rejected based on dE/dx and the ratio of the measured track momentum and the associated shower energy in the calorimeter. Muons are rejected by requiring that the track penetrate the magnet steel return yoke by less than five interaction lengths. Pairs of charged tracks used to reconstruct K_S's are required to have a common vertex displaced from the primary interaction point by at least 3 mm, and an invariant mass within 10 MeV/c^2 of the nominal K_S mass [16]. For event-counting analyses, the cut positions for charged track quality cuts are the same as the ones used in Ref. [15]. These cut positions were re-optimized and are less stringent for the maximum likelihood analyses reported here.

Photons are defined as isolated showers, not matched to any charged tracks, that have a measured energy of at least 30 MeV in the central region of the calorimeter ($\cos\theta < 0.71$), and at least 50 MeV elsewhere. These showers are also required to have a lateral shape consistent with that of photons. Pairs of photons used to reconstruct π^0's are required to have an invariant mass within two standard deviations of the nominal π^0 mass. The π^0 momentum is obtained with a kinematic fit of the photon momenta with the π^0 mass constrained to its nominal value; to reduce combinatoric background, the π^0 momentum is required to be greater than 175 MeV/c. We also require that the angle θ^* between the direction of the π^0 and the direction of the photons in the rest frame of the π^0 satisfy $|\cos\theta^*| < 0.97$.

The large background from continuum quark–anti-quark ($q\bar{q}$) production can be reduced with the use of event shape cuts. These rely on the fact that at the Υ(4S) B mesons are produced almost at rest. The decay products of the $B\bar{B}$ pair tend to be spherically distributed, while particles from $q\bar{q}$ production have a more jet-like distribution. One such cut used in all analyses is based on the angle θ_T between the thrust axis of the charged particles and photons forming the candidate B and the thrust axis of the remainder of the event. For $|\cos\theta_T|$, continuum background is strongly peaked near 1.0 and signal is approximately flat. We require $|\cos\theta_T| < 0.9$.

We reconstruct the final states using the following decay modes: $\omega \to \pi^+\pi^-\pi^0$, $\rho^0 \to \pi^+\pi^-$, $\phi \to K^+K^-$, K^0 via $K_S \to \pi^+\pi^-$, $K^{*+} \to K^+\pi^0$, and $K^{*0} \to K^+\pi^-$. For decay modes involving a ϕ and a K^*, we also use $K^{*+} \to K^0\pi^+$ and $K^{*0} \to K^0\pi^0$.

III. MAXIMUM LIKELIHOOD ANALYSES

A. METHOD

The results described in this section are obtained with unbinned multi-variable maximum likelihood fits. For N input events, the likelihood is defined as

$$\mathcal{L} = e^{-(N_S+N_B)} \prod_{i=1}^{N} \{N_S \mathcal{P}_S(f_1, ..., f_m; x_i) + N_B \mathcal{P}_B(f_1, ..., f_m; x_i)\}, \tag{1}$$

where $\mathcal{P}_S$ and $\mathcal{P}_B$ are the probabilities for event i with input quantities x_i and parameters f_j to be signal and continuum background, respectively. N_S and N_B, the free parameters of the fit, are the number of signal and continuum background events in the fitted data sample, respectively. The exponential factor preceding the product ensures that $N_S + N_B$ is equal to the total number of input events. For the pairs of charged decay modes $B^+ \to \omega K^+/\pi^+$ and $B^+ \to \phi K^+/\pi^+$ the final states are identical except for the identity of the high momentum charged kaon or pion. In these cases, a simultaneous fit is performed, and the likelihood is defined as

$$\mathcal{L} = e^{-(N_S^\pi + N_S^K + N_B)} \prod_{i=1}^{N} \{N_S^\pi \mathcal{P}_S^\pi + N_S^K \mathcal{P}_S^K + N_B[f_B^K \mathcal{P}_B^K + (1 - f_B^K)\mathcal{P}_B^\pi]\}, \tag{2}$$

where the π and K superscripts refer to the hypothesis made for the ambiguous charged track and f_B^K is the fraction of continuum background events for which the ambiguous charged track is a kaon. The latter is also a free parameter of the maximum likelihood fit.

Three quantities are used as input for all decay modes: ΔE, M_B, and $\mathcal{F}$. ΔE is defined as $\Delta E \equiv E_1 + E_2 - E_b$, where E_1 and E_2 are the energy of the two daughter particles of the B and E_b is the beam energy. ΔE should peak at zero for B mesons, and have a linearly falling distribution for continuum background. The beam-constrained mass of the candidate is defined as $M_B \equiv \sqrt{E_b^2 - p_B^2}$, where p_B is the measured momentum of the candidate. Using the beam energy instead of the measured energy of the B candidate improves the mass resolution by about one order of magnitude. The Fisher discriminant ($\mathcal{F}$) is an event shape variable formed with 11 quantities: the momentum scalar sum of charged particles and photons in nine cones of increasing polar angle around the thrust axis of the candidate; the angle between the thrust axis of the candidate and the beam axis; and the angle between the candidate B direction and the beam axis. This discriminant is described in detail in Ref. [15]. For this variable, signal peaks around 0.4 and background around 0.7. In each case, the low side of the distribution has a σ of ~ 0.13 and the high side ~ 0.17.

We also use as appropriate M_ω, M_ϕ, $M_{K^{*+}}$, and $M_{K^{*0}}$, the reconstructed invariant masses of ω, ϕ, K^{*+}, and K^{*0} particles. For simultaneous fits of two decay modes, to resolve the ambiguity in the identity of the high-momentum charged track we use the fact that ΔE is computed assuming that the charged track is a kaon. If the track is a pion, the mean of the distribution is shifted by approximately 44 MeV. For these modes we also include the dE/dx information for the ambiguous track as input to the fit. The quantity used is

$$S_K = \frac{(dE/dx)_{\text{measured}} - (dE/dx)_{\text{K hypothesis}}}{\sigma}, \tag{3}$$

where σ is the expected resolution. As for ΔE, this variable will have a distribution centered on zero for kaons and will be shifted for pions. Finally, for decay modes involving a vector and a pseudoscalar meson in the final state, we use the fact that the vector meson is in a defined helicity state. For ϕ mesons, the input quantity to the maximum likelihood fit is the cosine of the angle between the direction of one of the decay kaons and the direction of the ϕ, calculated in the ϕ rest frame. For ω mesons, the angle is between the normal to the ω decay plane and the direction of the ω, calculated in the ω rest frame. In both cases, we expect signal to have a distribution proportional to $\cos^2\theta_h$, where θ_h is the angle of interest, while for background $\cos\theta_h$ will be nearly flat.

The probability distribution functions for each of the input variables are determined by separate fits to signal Monte Carlo and background data for $\mathcal{P}_\mathcal{S}$ and $\mathcal{P}_\mathcal{B}$, respectively.

Background data is selected in a "grand sideband" region defined by $|\Delta E| < 0.2$ GeV and $5.2 < M_B < 5.27$ GeV/c^2. For M_B signal we use a Gaussian function; for ΔE and M_ω signal we use double Gaussians; for M_ϕ, $M_{K^{*0}}$, and $M_{K^{*+}}$ signal we use Breit-Wigner functions; and for $\mathcal{F}$ and S_K signal and background we use bifurcated Gaussians. For backgrounds under resonance masses we use the sum of a second-degree polynomial and the signal shape to describe the pure combinatoric background and the component of real particles in the background. Finally, for ΔE the background is described by a first-degree polynomial and for M_B we use the empirical shape

$$f(M_B) \propto M_B\sqrt{1-x^2}\exp\left(-\xi(1-x^2)\right), \tag{4}$$

where $x \equiv M_B/E_b$ and ξ is a parameter to be fit.

Before performing the likelihood fit, a number of preliminary cuts are applied. We require $|\Delta E| < 0.2$ GeV, $5.2 < M_B < 5.3$ GeV/c^2, and as required $0.73 < M_\omega < 0.83$ GeV/c^2, $0.9 < M_\phi < 1.1$ GeV/c^2, $0.75 < M_{K^{*0}} < 1.05$ GeV/c^2, and $0.75 < M_{K^{*+}} < 1.05$ GeV/c^2. For events in which multiple combinations of tracks and showers satisfy these preliminary requirements, a single one is chosen based on a χ^2 test that uses M_B, $\mathcal{F}$, and reconstructed invariant masses. For analyses in which a single decay mode is fit, we also use ΔE in the χ^2 test.

B. RESULTS

Table I gives the results of the maximum likelihood analyses. Shown in the table are the signal yields (N_S), the efficiency for signal Monte Carlo events (ϵ), which does not include the branching fractions of particles in the final state, the total efficiency (ϵ_{tot}) and its associated systematic error, and the calculated branching fraction ($\mathcal{B}$). For branching fractions reported as upper limits, the 90% confidence level upper limit on the yield is determined by finding the point at which the integral of the likelihood curve is at 90% of its total. To take systematic errors on the fit yield into account, we increase the calculated upper limit by 15%. We also reduce the efficiency by one standard deviation in the calculation of the upper limit, to take that component of the systematic error into account. The first error on the quoted branching fractions is statistical and the second systematic. The systematic error includes a contribution from the efficiency and a contribution from changes in fit yield that depend on variations in the parameters of the probability distribution functions.

In Table I, the entry for $B^+ \to \omega h^+$ refers to the sum of $B^+ \to \omega K^+$ and $B^+ \to \omega\pi^+$. Fig. 1 shows the maximum likelihood fit contours in 1σ increments for $B^+ \to \omega K^+$ and $B^+ \to \omega\pi^+$. The statistical significances of the observed signals are 4.3σ and 2.9σ for $B^+ \to \omega K^+$ and $B^+ \to \omega\pi^+$, respectively. Figs. 2, 3, and 4 show projections of M_B, ΔE, and M_ω for these two decay modes. Note that for the data histogram, cuts are applied to the likelihood fit input quantities other than the one plotted. The likelihood fit curves overlayed on the data are not a fit to the data shown but rather show the overall fit, scaled to take the effect of the additional cuts into account.

For ϕK^* modes, individual channels have a statistical significance of 2.6σ or less. We combine channels together by taking the product of the likelihood functions, and obtain a statistical significance for $B^+ \to \phi K^{*+}$ and $B^0 \to \phi K^{*0}$ of 3.1σ and 2.1σ, respectively.

Assuming that the decay rates for these two modes are equal, as would be expected if annihilation diagrams are negligible, we combine the results for both modes and obtain a statistical significance of 3.5σ. Figure 5 shows the value of $-2\ln\mathcal{L}$ as a function of the branching fraction for $B \to \phi K^*$. The minimum of the curve corresponds to a branching fraction of $(1.3^{+0.7}_{-0.6} \pm 0.2) \times 10^{-5}$. Fig. 6 shows projections of M_B, ΔE, M_ϕ, and M_{K^*} for the combined $B \to \phi K^*$ modes.

TABLE I. Results from maximum likelihood analyses. Branching fraction upper limits are at the 90% confidence level. The significance is quoted in units of standard deviation.

Mode	$\epsilon(\%)$	$\epsilon_{tot}(\%)$	N_S	Signif.	$\mathcal{B}(\times 10^{-5})$
$B^+ \to \phi K^+$	50	25 ± 2	0.0	0.0	< 0.53
$B^+ \to \phi\pi^+$	52	26 ± 2	0.0	0.0	< 0.56
$B^0 \to \phi K^0$	34	5.7 ± 0.5	2.2	2.8	< 4.2
$B^0 \to \phi\pi^0$	33	16 ± 1	0.0	0.0	< 0.65
$B \to \phi K^*$ combined				3.5	$1.3^{+0.7}_{-0.6} \pm 0.2$
$B^+ \to \phi K^{*+}$				3.1	< 4.1
$(K^{*+} \to K^+\pi^0)$	27	4.4 ± 0.4	3.4	1.5	< 8.0
$(K^{*+} \to K^0\pi^+)$	30	3.4 ± 0.4	2.4	2.6	< 7.4
$B^0 \to \phi K^{*0}$				2.1	< 2.2
$(K^{*0} \to K^+\pi^-)$	39	13 ± 1	3.4	2.0	< 2.9
$(K^{*0} \to K^0\pi^0)$	19	1.0 ± 0.1	0.0	0.0	< 16
$B^+ \to \omega K^+$	26	23 ± 4	12	4.3	$1.5^{+0.7}_{-0.6} \pm 0.3$
$B^+ \to \omega\pi^+$	27	24 ± 4	8.8	2.9	$1.1^{+0.6}_{-0.5} \pm 0.2$
$B^+ \to \omega h^+$				6.8	$2.6^{+0.8}_{-0.7} \pm 0.4$

IV. EVENT-COUNTING ANALYSES

A. FINAL EVENT SELECTION

Event-counting analyses are used to search for the decay modes $B^+ \to \omega K^{*+}$, $B^0 \to \omega K^{*0}$ and $B^0 \to \omega\rho^0$. The final cuts for these analyses are designed to reduce the large background from continuum $q\bar{q}$ production while maintaining high efficiency for signal. The cut positions are chosen to optimize the expected branching fraction upper limit. The largest background rejection comes from event shape cuts. As mentioned above, we require $|\cos\theta_T| < 0.9$; we also require $\mathcal{F} < 0.4$ for $B^+ \to \omega K^{*+}$ and $B^0 \to \omega\rho^0$ analyses, and $\mathcal{F} < 0.45$ for $B^0 \to \omega K^{*0}$. Cuts on the reconstructed invariant masses of particles in the final state are: $|M_\omega - 781.9| <$ 20 MeV/c^2, $|M_{K^{*+}} - 896| < 75$ MeV/c^2, $|M_{K^{*0}} - 896| < 75$ MeV/c^2, and $|M_\rho - 768.5| < 160$ MeV/c^2. The square of the decay amplitude of the ω, normalized to be distributed between 0 and 1, has to be greater than 0.15. This cut selects the central region of the Dalitz plot where ω decays are enhanced, and minimizes any isotropic background.

Final candidate selection is based on the energy and mass of the candidate B. The quantities used, ΔE and M_B, are described above. The measured resolutions for signal Monte

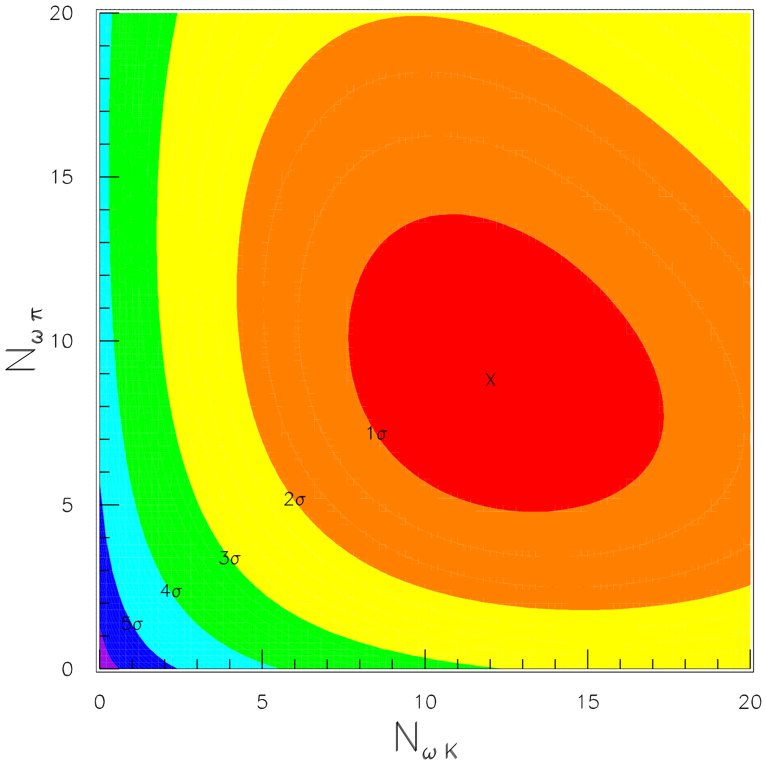


FIG. 1. Maximum likelihood fit contours in 1σ increments (statistical error only) for $B^+ \to \omega K^+$ and $B^+ \to \omega\pi^+$.

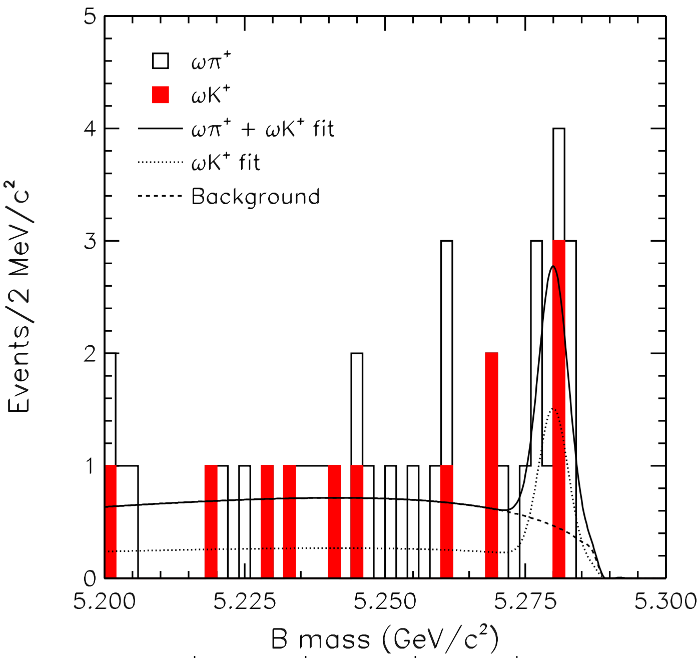


FIG. 2. Projection of M_B for $B^+ \to \omega K^+$ and $B^+ \to \omega\pi^+$. Cuts on all other input quantities to the fit have been applied before making the projection.

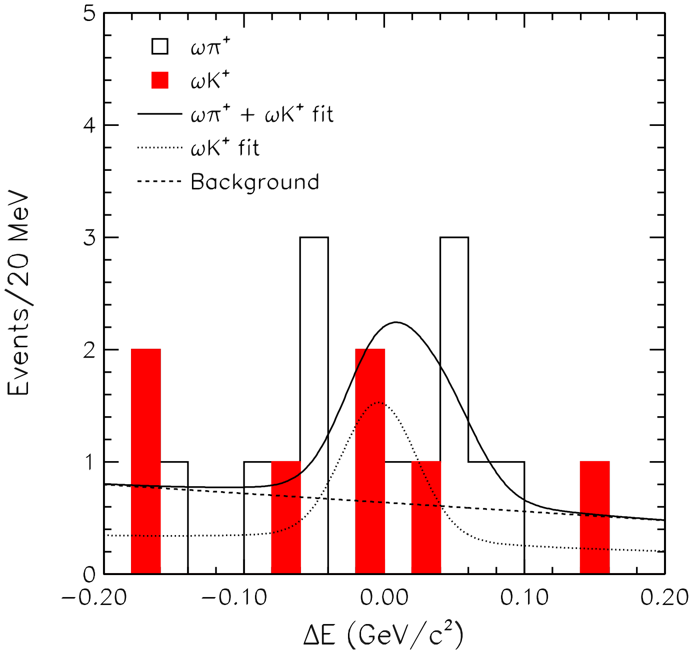


FIG. 3. Projection of ΔE for $B^+ \to \omega K^+$ and $B^+ \to \omega\pi^+$.

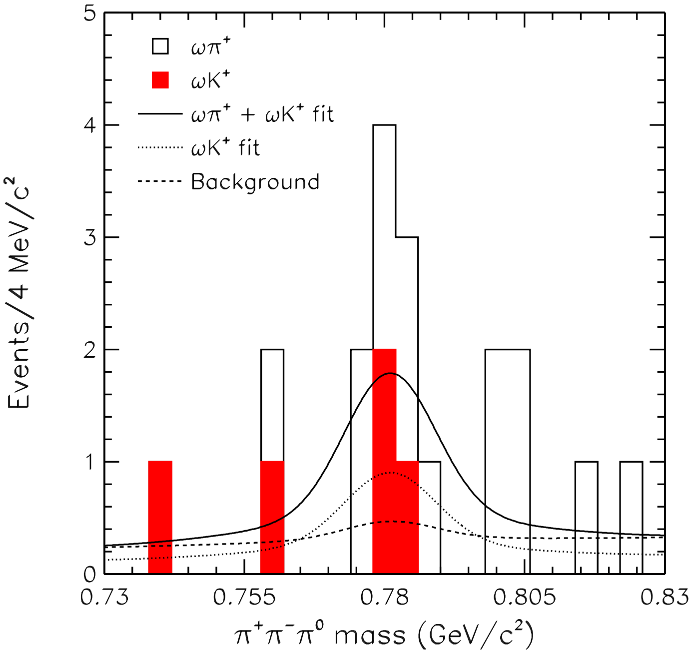


FIG. 4. Projection of M_ω for $B^+ \to \omega K^+$ and $B^+ \to \omega\pi^+$.

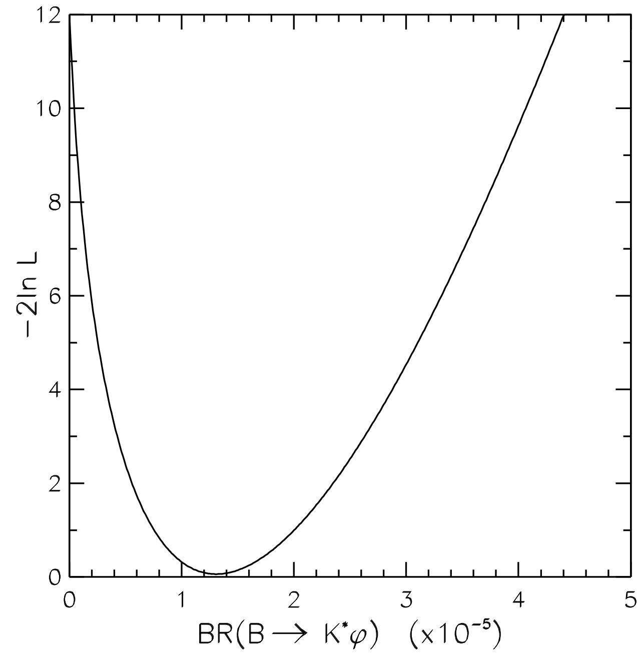


FIG. 5. $-2\ln\mathcal{L}$ as a function of the branching fraction for $B \to \phi K^*$.

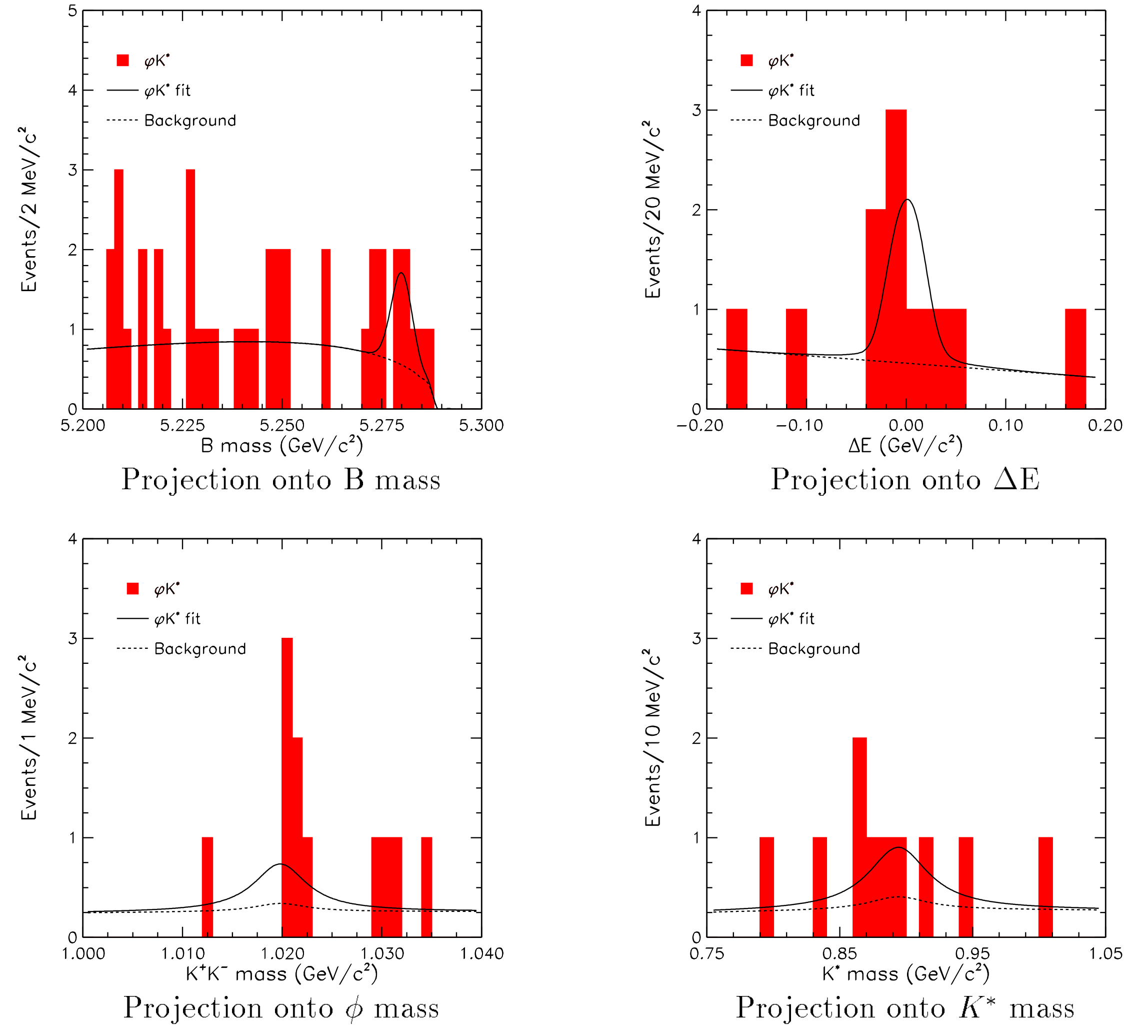
Carlo are approximately 30 MeV and 3 MeV/c^2 for ΔE and M_B, respectively. Candidates are selected in the region $|M_B - 5280| < 6$ MeV/c^2 and $|\Delta E| < 60$ MeV.

B. BACKGROUND ESTIMATE AND RESULTS

The expected number of background events after all cuts is based on an estimate of the ratio $\mathcal{A}$ defined as the number of events in the ΔE—M_B signal region divided by the number of events in the grand sideband region ($|\Delta E| < 0.2$ GeV and $5.2 < M_B < 5.27$ GeV/c^2). The ratio is determined from a sample of Monte Carlo simulated continuum events about twice as large as the on-resonance data sample. To further increase the statistical accuracy of the measurement, cuts not affecting the ratio are released. The measured value of $\mathcal{A}$ is 0.036 ± 0.007. The background estimate for each decay mode studied is obtained by multiplying the measured ratio $\mathcal{A}$ by the number of events observed in the grand sideband for the on-resonance data sample after all other cuts are applied. Background from $b \to c$ decays is studied with a Monte Carlo generated sample approximately four times as large as the data sample. The contribution from this source is found to be negligible.

Table II gives the results for each mode. Included in the table are the number of observed events, the estimated number of background events (N_B) with its combined statistical and systematic uncertainty, the efficiency for signal Monte Carlo events, the total efficiency with its associated systematic error, and the branching fraction upper limit at the 90% confidence level. The upper limits on the number of signal events are determined with the standard calculation for Poisson upper limits in the presence of background [16]. In the calculation of

FIG. 6. Projection plots for $K^*\phi$ combined analysis. The overlayed curves are the result of the full likelihood fit, scaled by the efficiency of the cuts used to make the projection.



the upper limit, we reduced both the background estimate and the efficiency by one standard deviation of their error to take the systematic uncertainty into account.

TABLE II. Final results for event-counting analyses. Branching fraction upper limits are at the 90% confidence level.

Mode	N_S	N_B	$\epsilon(\%)$	$\epsilon_{tot}(\%)$	$\mathcal{B}(\times 10^{-5})$
$\omega\rho^0$	0	1.2 ± 0.3	2.6	2.3 ± 0.3	< 3.4
ωK^{*0}	1	1.7 ± 0.4	4.7	2.8 ± 0.3	< 3.8
ωK^{*+}	0	0.9 ± 0.3	2.5	0.7 ± 0.1	< 11

V. CONCLUSION

We have searched for exclusive hadronic decays of B mesons to final states that include ω or ϕ mesons. Signals are observed for the modes $B^+ \to \omega K^+$ and $B^+ \to \omega\pi^+$, with statistical significance of 4.3σ and 2.9σ, respectively. The corresponding branching fractions are $\mathcal{B}(B^+ \to \omega K^+) = (1.5^{+0.7}_{-0.6} \pm 0.3) \times 10^{-5}$ and $\mathcal{B}(B^+ \to \omega\pi^+) = (1.1^{+0.6}_{-0.5} \pm 0.2) \times 10^{-5}$, both in excess of theoretical predictions. We also observe a signal of 3.5σ statistical significance for the sum of the decay modes $B^+ \to \phi K^{*+}$ and $B^0 \to \phi K^{*0}$, that corresponds to a branching fraction of $\mathcal{B}(B \to \phi K^*) = (1.3^{+0.7}_{-0.6} \pm 0.2) \times 10^{-5}$. Finally, we set upper limits for other related decay modes, several of which now approach the theoretical predictions. In particular, we set $\mathcal{B}(B^+ \to \phi K^+) < 0.53 \times 10^{-5}$, implying a ratio for $\mathcal{B}(B^+ \to \omega K^+)/\mathcal{B}(B^+ \to \phi K^+)$ greater than one. Accounting for this ratio may turn out to be a theoretical challenge.

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