

**Observation of  $B$  meson decays to  $\omega K^*$  and improved measurements for  $\omega\rho$  and  $\omega f_0$** 

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We present measurements of  $B$  meson decays to the final states  $\omega K^*$ ,  $\omega\rho$ , and  $\omega f_0$ , where  $K^*$  indicates a spin 0, 1, or 2 strange meson. The data sample corresponds to  $465 \times 10^6$   $B\bar{B}$  pairs collected with the *BABAR* detector at the PEP-II  $e^+e^-$  collider at SLAC.  $B$  meson decays involving vector-scalar, vector-vector, and vector-tensor final states are analyzed; the latter two shed new light on the polarization of these final states. We measure the branching fractions for nine of these decays; five are observed for the first time. For most decays we also measure the charge asymmetry and, where relevant, the longitudinal polarization  $f_L$ .

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Studies of vector-vector ( $VV$ ) final states in  $B$  decays resulted in the surprising observation that the longitudinal polarization fraction  $f_L$  in  $B \rightarrow \phi K^*$  decays is  $\sim 0.5$ , not  $\sim 1$  [1]. The latter value is expected from simple helicity arguments and has been confirmed in the tree-dominated [2]  $B \rightarrow \rho\rho$  decays [3] and  $B^+ \rightarrow \omega\rho^+$  decays [4]. It appears that the  $f_L \sim 1$  expectation is correct for tree-dominated decays but is not generally true for decays where  $b \rightarrow s$  loop (penguin) amplitudes are dominant.

There have been numerous attempts to understand the polarization puzzle (small  $f_L$ ) within the standard model (SM) [5], and many papers have suggested non-SM explanations [6]. The SM picture improved recently with the calculation of  $f_L$  for most charmless  $VV$  decays [2] with inclusion of nonfactorizable effects and penguin annihilation amplitudes. Improved understanding of these effects can come from branching fraction and  $f_L$  measurements in decays such as  $B \rightarrow \omega K^*$ , which is related to  $B \rightarrow \phi K^*$  via  $SU(3)$  symmetry [7]. Among these decays, there is evidence for only  $B^0 \rightarrow \omega K^{*0}$  [4,8]. Information on these and related charmless  $B$  decays can be used to provide constraints on the Cabibbo-Kobayashi-Maskawa angles  $\alpha$ ,  $\beta$ , and  $\gamma$  [9].

Further information on the polarization puzzle can come from measurements that include the tensor meson  $K_2^*(1430)$ . A measurement of the vector-tensor ( $VT$ ) decay  $B \rightarrow \phi K_2^*(1430)$  [10] finds a value of  $f_L$  inconsistent with 0.5 (but consistent with 1), so a measurement of the related decay  $B \rightarrow \omega K_2^*(1430)$  would be interesting. The only theoretical predictions for these modes are from generalized factorization calculations [11]; the branching fraction predictions for the  $B \rightarrow \omega K_2^*(1430)$  decays are  $\sim (1-2) \times 10^{-6}$ , but there are no predictions for  $f_L$ . There have been a variety of measurements for similar  $B$  decays that include the scalar meson  $K_0^*(1430)$  [10,12]. For the scalar-vector ( $SV$ ) decays  $B \rightarrow \omega K_0^*(1430)$ , there are recent QCD factorization calculations [13] that predict branching fractions of about  $10^{-6}$ .

We report measurements of  $B$  decays to the final states  $\omega K^*$ ,  $\omega\rho$ , and  $\omega f_0(980)$ , where  $K^*$  includes the spin 0, 1, and 2 states,  $K_0^*(1430)$ ,  $K^*(892)$ , and  $K_2^*(1430)$ , respectively. While a complete angular analysis of the  $VV$  and  $VT$  decays would determine helicity amplitudes fully, because of the small signal samples we measure only  $f_L$ . Given our uniform azimuthal acceptance, we obtain, after integration, the angular distributions  $d^2\Gamma/(d\cos\theta_1 d\cos\theta_2)$ :

$$f_T \sin^2\theta_1 \sin^2\theta_2 + 4f_L \cos^2\theta_1 \cos^2\theta_2, \quad (1)$$

$$f_T \sin^2\theta_1 \sin^2\theta_2 \cos^2\theta_2 + \frac{f_L}{3} \cos^2\theta_1 (3\cos^2\theta_2 - 1)^2 \quad (2)$$

for the  $VV$  and  $VT$  [14] decays, respectively, where  $f_T = 1 - f_L$  and  $\theta_1$  and  $\theta_2$  are the helicity angles in the  $V$  or  $T$  rest frame with respect to the boost axis from the  $B$  rest frame. For decays with significant signals, we also measure the direct  $CP$ -violating, time-integrated charge asymmetry  $\mathcal{A}_{\text{ch}} \equiv (\Gamma^- - \Gamma^+)/(\Gamma^- + \Gamma^+)$ , where the superscript on the  $\Gamma$  corresponds to the charge of the  $B^\pm$  meson or the charge of the kaon for  $B^0$  decays.

The results presented here are obtained from data collected with the *BABAR* detector [15] at the PEP-II asymmetric-energy  $e^+e^-$  collider located at SLAC. An integrated luminosity of  $424 \text{ fb}^{-1}$ , corresponding to  $465 \times 10^6$   $B\bar{B}$  pairs, was recorded at the  $Y(4S)$  resonance, with  $e^+e^-$  center-of-mass (CM) energy  $\sqrt{s} = 10.58 \text{ GeV}$ .

Charged particles from the  $e^+e^-$  interactions are detected, and their momenta measured, by five layers of double-sided silicon microstrip detectors surrounded by a 40-layer drift chamber, both operating in the 1.5-T magnetic field of a superconducting solenoid. We identify photons and electrons using a CsI(Tl) electromagnetic calorimeter (EMC). Further charged particle identification (PID) is provided by the average energy loss ( $dE/dx$ ) in the tracking devices and by an internally reflecting ring-

imaging Cherenkov detector (DIRC) covering the central region.

We reconstruct  $B$ -daughter candidates through their decays  $\rho^0 \rightarrow \pi^+ \pi^-$ ,  $f_0(980) \rightarrow \pi^+ \pi^-$ ,  $\rho^+ \rightarrow \pi^+ \pi^0$ ,  $K^{*0} \rightarrow K^+ \pi^-$ ,  $K^{*+} \rightarrow K^+ \pi^0(K_{K^+ \pi^0}^{*+})$ ,  $K^{*+} \rightarrow K_S^0 \pi^+(K_{K_S^0 \pi^+}^{*+})$ ,  $\omega \rightarrow \pi^+ \pi^- \pi^0$ ,  $\pi^0 \rightarrow \gamma \gamma$ , and  $K_S^0 \rightarrow \pi^+ \pi^-$ . Charge-conjugate decay modes are implied unless specifically stated. Table I lists the requirements on the invariant masses of these final states. For the  $\rho$ ,  $K^*$ , and  $\omega$  selections, these mass requirements include sidebands, as the mass values are treated as observables in the maximum-likelihood fit described below. For  $K_S^0$  candidates we further require the three-dimensional flight distance from the primary vertex to be greater than 3 times its uncertainty. Daughters of  $\rho$ ,  $K^*$ , and  $\omega$  candidates are rejected if their DIRC,  $dE/dx$ , and EMC PID signatures are highly consistent with protons or electrons; kaons must have a kaon signature while the pions must not.

Table I also gives the restrictions on the  $K^*$  and  $\rho$  helicity angle  $\theta$  imposed to avoid regions of large combinatorial background from low-momentum particles. To calculate  $\theta$  we take the angle relative to a specified axis: for  $\omega$ , the normal to the decay plane; for  $\rho$ , the positively charged daughter momentum; and for  $K^*$ , the daughter kaon momentum.

A  $B$ -meson candidate is characterized kinematically by the energy-substituted mass  $m_{\text{ES}} \equiv \sqrt{(\frac{1}{2}s + \mathbf{p}_0 \cdot \mathbf{p}_B)^2 / E_0^{*2} - \mathbf{p}_B^2}$  and the energy difference  $\Delta E \equiv E_B^* - \frac{1}{2}\sqrt{s}$ , where  $(E_0, \mathbf{p}_0)$  and  $(E_B, \mathbf{p}_B)$  are four-momenta of the  $e^+e^-$  CM and the  $B$  candidate, respectively,  $s$  is the square of the CM energy, and the asterisk denotes the  $e^+e^-$  CM frame. Signal events peak at zero for  $\Delta E$ , and at the  $B$  mass [16] for  $m_{\text{ES}}$ , with a resolution for  $\Delta E(m_{\text{ES}})$  of 30–45 MeV (3.0 MeV). We require  $|\Delta E| \leq 0.2$  GeV and  $5.25 \leq m_{\text{ES}} < 5.29$  GeV.

The angle  $\theta_T$  between the thrust axis of the  $B$  candidate in the  $e^+e^-$  CM frame and that of the charged tracks and neutral clusters in the rest of the event is used to reject the dominant continuum  $e^+e^- \rightarrow q\bar{q}$  ( $q = u, d, s, c$ ) background events. The distribution of  $|\cos\theta_T|$  is sharply

peaked near 1.0 for combinations drawn from jetlike  $q\bar{q}$  pairs, and is nearly uniform for the almost isotropic  $B$ -meson decays. We reduce the sample sizes to 30 000–65 000 events by requiring  $|\cos\theta_T| < 0.7$  for the  $\omega\rho/f_0$  modes and  $|\cos\theta_T| < 0.8$  for the  $\omega K^*$  modes. Further discrimination from continuum is obtained with a Fisher discriminant  $\mathcal{F}$  that combines four variables: the polar angles, with respect to the beam axis in the  $e^+e^-$  CM frame, of the  $B$  candidate momentum and of the  $B$  thrust axis; and the zeroth and second angular moments  $L_{0,2}$  of the energy flow, excluding the  $B$  candidate, about the  $B$  thrust axis. The mean of  $\mathcal{F}$  is adjusted so that it is independent of the  $B$ -flavor tagging category [17]. The moments are defined by  $L_j = \sum_i p_i \times |\cos\theta_i|^j$ , where  $\theta_i$  is the angle with respect to the  $B$  thrust axis of track or neutral cluster  $i$  and  $p_i$  is its momentum. The average number of  $B$  candidates found per selected event in data is in the range 1.1–1.3, depending on the final state. We choose the candidate with the highest value of the probability for the  $B$  vertex fit.

We obtain yields and values of  $f_L$  and  $\mathcal{A}_{\text{ch}}$  from extended unbinned maximum-likelihood (ML) fits with input observables  $\Delta E$ ,  $m_{\text{ES}}$ ,  $\mathcal{F}$ , and, for the scalar, vector or tensor meson, the invariant mass and  $\mathcal{H} = \cos\theta$ . For each event  $i$  and hypothesis  $j$  (signal,  $q\bar{q}$  background,  $B\bar{B}$  background), we define the probability density function (PDF) with resulting likelihood  $\mathcal{L}$ :

$$\mathcal{P}_j^i = \mathcal{P}_j(m_{\text{ES}}^i) \mathcal{P}_j(\Delta E^i) \mathcal{P}_j(\mathcal{F}^i) \mathcal{P}_j(m_1^i, m_2^i, \mathcal{H}_1^i, \mathcal{H}_2^i), \quad (3)$$

$$\mathcal{L} = \frac{e^{-(\sum_j Y_j)}}{N!} \prod_{i=1}^N \sum_j Y_j \mathcal{P}_j^i, \quad (4)$$

where  $Y_j$  is the yield of events of hypothesis  $j$ ,  $N$  is the number of events in the sample, and the subscript 1 (2) represents  $3\pi$  ( $K\pi$  or  $\pi\pi$ ). There are as many as three signal categories and the PDFs for each are split into two components: correctly reconstructed events and those where candidate particles are exchanged with a particle from the rest of the event. The latter component is called self cross feed (SXF) and its fractions are fixed to the values found in Monte Carlo (MC) simulations, (15–35)%. We find correlations among the observables to be small for  $q\bar{q}$  background.

From MC simulation [18] we form a sample of the most relevant charmless  $B\bar{B}$  backgrounds (20–35 modes for each signal final state). We include a fixed yield (70–200 events, derived from MC simulations with known or estimated branching fractions) for these in the fit described below. For  $B^+ \rightarrow \omega\rho^+$  we also introduce a component for nonresonant  $\omega\pi^+\pi^0$  background; for the other decays nonresonant backgrounds are smaller and are included in the charmless  $B\bar{B}$  sample. The magnitude of the nonresonant component is fixed in each fit as determined from fits

TABLE I. Selection requirements on the invariant masses and helicity angles of  $B$ -daughter resonances. The helicity angle is unrestricted unless indicated otherwise.

State	Inv. mass (MeV)	Helicity angle
$K_{K^+ \pi^-}^{*0}, K_{K_S^0 \pi^+}^{*+}$	$750 < m_{K\pi} < 1550$	$-0.85 < \cos\theta < 1.0$
$K_{K^+ \pi^0}^{*+}$	$750 < m_{K\pi} < 1550$	$-0.80 < \cos\theta < 1.0$
$\rho^0/f_0$	$470 < m_{\pi\pi} < 1070$	$-0.80 < \cos\theta < 0.80$
$\rho^+$	$470 < m_{\pi\pi} < 1070$	$-0.70 < \cos\theta < 0.80$
$\omega$	$735 < m_{\pi\pi\pi} < 825$	
$\pi^0$	$120 < m_{\gamma\gamma} < 150$	
$K_S^0$	$488 < m_{\pi\pi} < 508$	

to regions of higher  $\pi\pi$  or  $K\pi$  mass. For the  $\omega\rho$  modes, we also include a sample of  $b \rightarrow c$  backgrounds; for the other modes, this component is not used since it is not clearly distinguishable from  $q\bar{q}$  background.

Signal is also simulated with MC calculations; for the  $(K\pi)_0^*$  line shape, we use a LASS model [19,20] which consists of the  $K_0^*(1430)$  resonance together with an effective-range nonresonant component. For the  $f_0(980)$ , we use a Breit-Wigner shape with parameters taken from Ref. [21].

The PDF for resonances in the signal takes the form  $\mathcal{P}_{1,\text{sig}}(m_1^i)\mathcal{P}_{2,\text{sig}}(m_2^i)\mathcal{Q}(\mathcal{H}_1^i, \mathcal{H}_2^i)$ , with  $\mathcal{Q}$  given by Eq. (1) or (2), modified to account for detector acceptance. For  $q\bar{q}$  background we use for each resonance independently  $\mathcal{P}_{q\bar{q}}(m_k^i, \mathcal{H}_k^i) = \mathcal{P}_{q\bar{q}}(m_k^i)\mathcal{P}_{q\bar{q}}(\mathcal{H}_k^i)$ , where  $\mathcal{P}_{q\bar{q}}(m_k^i)$  is a sum of true resonance and combinatorial mass terms. The PDFs for  $B\bar{B}$  background have a similar form.

For the signal,  $B\bar{B}$  background, and nonresonant background components we determine the PDF parameters from simulation. We study large data control samples of  $B^+ \rightarrow \bar{D}^0\pi^+$  and  $B^+ \rightarrow \bar{D}^0\rho^+$  decays with  $\bar{D}^0 \rightarrow K^+\pi^-\pi^0$  to check the simulated resolutions in  $\Delta E$  and  $m_{\text{ES}}$ , and adjust the PDF parameters to account for small differences. For the continuum background we use  $(m_{\text{ES}}, \Delta E)$  sideband data to obtain initial values of the parameters, and leave them free to vary in the ML fit.

The parameters that are allowed to vary in the fit include the signal and  $q\bar{q}$  background yields,  $f_L$  (for all  $VV$  and  $VT$  modes except  $B^0 \rightarrow \omega\rho^0$ ), continuum background PDF parameters, and, for  $\omega\rho$ , the  $b \rightarrow c$  background yield. Since there is not a significant yield for  $B^0 \rightarrow \omega\rho^0$ , we

fix  $f_L$  to a value that is consistent with *a priori* expectations [2] (see Table II). For all modes except  $B^0 \rightarrow \omega\rho^0$  the signal and background charge asymmetries are free parameters in the fit.

To describe the PDFs, we use simple functions such as the sum of two Gaussian distributions for many signal components and the peaking parts of backgrounds, low-order polynomials to describe most background shapes, an asymmetric Gaussian for  $\mathcal{F}$ , and the function  $x\sqrt{1-x^2}\exp[-\xi(1-x^2)]$  (with  $x \equiv m_{\text{ES}}/E_B^*$ ) for the  $m_{\text{ES}}$  background distributions. These are illustrated for  $B^+ \rightarrow \omega\rho^+$  with projection plots of each fit variable in Figs. 1, 2(d), and 3(d). The parameters that determine the main features of the background PDF shapes are allowed to vary in the fit.

We evaluate biases from our neglect of correlations among discriminating variables by fitting ensembles of simulated experiments. Each such experiment has the same number of events as the data for both background and signal;  $q\bar{q}$  background events are generated from their PDFs while signal and  $B\bar{B}$  background events are taken from fully simulated MC samples. Since events from the  $B\bar{B}$  background samples are included in the ensembles, the bias includes the effect of these backgrounds.

We compute the branching fraction  $\mathcal{B}$  for each decay by subtracting the yield bias  $Y_0$  from the measured yield, and dividing the result by the efficiency and the number of produced  $B\bar{B}$  pairs. We assume that the branching fractions of the  $Y(4S)$  to  $B^+B^-$  and  $B^0\bar{B}^0$  are each equal to 50%. In Table II we show for each decay mode the measured  $\mathcal{B}$ ,  $f_L$ , and  $\mathcal{A}_{\text{ch}}$  together with the quantities entering into these

TABLE II. Signal yield  $Y$  and its statistical uncertainty, bias  $Y_0$ , detection efficiency  $\epsilon$ , daughter branching fraction product  $\prod \mathcal{B}_i$ , significance  $S$  (with systematic uncertainties included), measured branching fraction  $\mathcal{B}$  with statistical and systematic errors, 90% C.L. upper limit (U.L.), measured or assumed  $f_L$ , and  $\mathcal{A}_{\text{ch}}$ . In the case of  $\omega f_0$ , the quoted branching fraction is a product with  $\mathcal{B}(f_0 \rightarrow \pi\pi)$ , which is not well known.  $(K\pi)_0^*$  refers to the  $S$ -wave  $K\pi$  system.

Mode	$Y$ (events)	$Y_0$ (events)	$\epsilon$ (%)	$\prod \mathcal{B}_i$ (%)	$S$ ( $\sigma$ )	$\mathcal{B}$ ( $10^{-6}$ )	$\mathcal{B}$ U.L. ( $10^{-6}$ )	$f_L$	$\mathcal{A}_{\text{ch}}$
$\omega K^{*0}$	$101 \pm 25$	$8 \pm 4$	15.2	59.5	4.1	$2.2 \pm 0.6 \pm 0.2$	...	$0.72 \pm 0.14 \pm 0.02$	$0.45 \pm 0.25 \pm 0.02$
$\omega K^{*+}$					2.5	$2.4 \pm 1.0 \pm 0.2$	7.4	$0.41 \pm 0.18 \pm 0.05$	$0.29 \pm 0.35 \pm 0.02$
$\omega K_{K^+\pi^0}^{*+}$	$72 \pm 24$	$3 \pm 2$	10.4	29.7	3.7	$4.8 \pm 1.7$		$0.37 \pm 0.18$	$0.22 \pm 0.33$
$\omega K_{K_S^0\pi^+}^{*+}$	$8 \pm 16$	$0 \pm 1$	13.6	20.6	0.5	$0.6 \pm 1.2$		0.5 fixed	...
$\omega(K\pi)_0^{*0}$	$540 \pm 47$	$49 \pm 25$	9.7	59.5	9.8	$18.4 \pm 1.8 \pm 1.7$	...	...	$-0.07 \pm 0.09 \pm 0.02$
$\omega(K\pi)_0^{*+}$					9.2	$27.5 \pm 3.0 \pm 2.6$	...	...	$-0.10 \pm 0.09 \pm 0.02$
$\omega(K^+\pi^0)_0^{*+}$	$191 \pm 36$	$18 \pm 9$	6.4	29.7	5.9	$19.6 \pm 4.1$	...	...	$-0.38 \pm 0.19$
$\omega(K_S^0\pi^+)_0^{*+}$	$357 \pm 39$	$34 \pm 17$	9.1	20.6	10.6	$37.1 \pm 4.5$	...	...	$-0.01 \pm 0.10$
$\omega K_2^*(1430)^0$	$185 \pm 32$	$19 \pm 10$	11.9	29.7	5.0	$10.1 \pm 2.0 \pm 1.1$	...	$0.45 \pm 0.12 \pm 0.02$	$-0.37 \pm 0.17 \pm 0.02$
$\omega K_2^*(1430)^+$					6.1	$21.5 \pm 3.6 \pm 2.4$	...	$0.56 \pm 0.10 \pm 0.04$	$0.14 \pm 0.15 \pm 0.02$
$\omega K_2^*(1430)_{K^+\pi^0}^+$	$182 \pm 30$	$6 \pm 3$	8.2	14.9	7.2	$31.0 \pm 5.2$		$0.52 \pm 0.10$	$0.17 \pm 0.16$
$\omega K_2^*(1430)_{K_S^0\pi^+}^+$	$64 \pm 25$	$10 \pm 5$	10.1	10.3	2.4	$11.2 \pm 4.9$		$0.76 \pm 0.26$	$-0.04 \pm 0.35$
$\omega\rho^0$	$30_{-18}^{+21}$	$-3 \pm 2$	9.5	89.2	1.9	$0.8 \pm 0.5 \pm 0.2$	1.6	0.8 fixed	...
$\omega f_0$	$37_{-12}^{+14}$	$1 \pm 1$	14.4	59.5	4.5	$1.0 \pm 0.3 \pm 0.1$	1.5	...	...
$\omega\rho^+$	$411 \pm 43$	$27 \pm 14$	5.8	89.2	9.8	$15.9 \pm 1.6 \pm 1.4$	...	$0.90 \pm 0.05 \pm 0.03$	$-0.20 \pm 0.09 \pm 0.02$

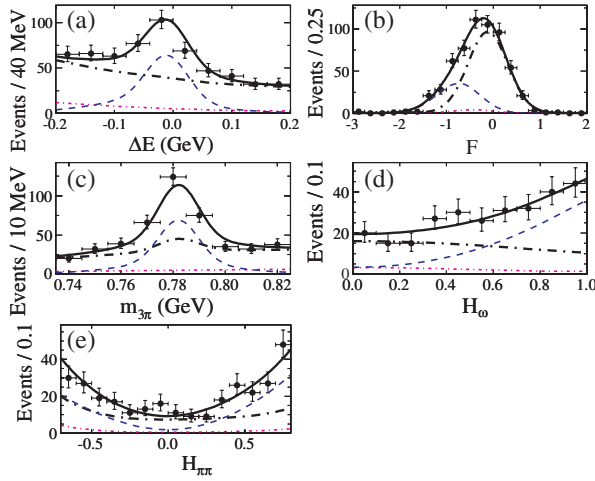


FIG. 1 (color online). Projections for  $B^+ \rightarrow \omega\rho^+$ : (a)  $\Delta E$ , (b)  $\mathcal{F}$ , (c)  $m_{3\pi}$ , (d)  $\mathcal{H}_\omega$ , and (e)  $\mathcal{H}_{\pi\pi}$ . Points with errors represent data and solid curves represent the full fit functions. Also shown are signal (blue dashed line),  $b \rightarrow c$  background (magenta dotted-dashed line), and total background (black long-dashed-dotted line). Charmless background and nonresonant background are too small to be seen. To suppress background, the plots are made with requirements on  $\ln\mathcal{L}$  that have an efficiency for signal of (40–60)% depending on the plot.

computations. For decays with  $K^{*+}$  we combine the results from the two  $K^*$  decay channels, by adding their values of  $-2\ln\mathcal{L}$ . For the significance  $S$  we use the difference between the value of  $-2\ln\mathcal{L}$  for zero signal and the value

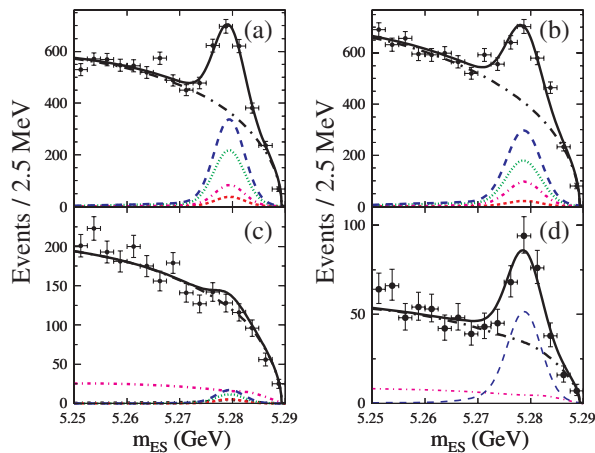


FIG. 2 (color online).  $B$ -candidate  $m_{ES}$  projections for (a)  $\omega K^{*0}$ , (b)  $\omega K^{*+}$ , (c)  $\omega\rho^0/\omega f_0$ , and (d)  $\omega\rho^+$ . The solid curve is the fit function, the black long-dashed-dotted curve is the total background, and the blue dashed curve is the total signal contribution. For (a),(b) we also show the signal components:  $K^*(892)$  (red dashed line),  $(K\pi)^*_0$  (green dotted line), and  $K_2^*(1430)$  (magenta dotted-dashed line). We show for (c),(d) the  $b \rightarrow c$  background (magenta dotted-dashed line), and for (c) the  $B^0 \rightarrow \omega\rho^0$  (red dashed line) and  $B^0 \rightarrow \omega f_0$  (green dotted line) components. The plots are made with a requirement on  $\ln\mathcal{L}$  that has an efficiency of (40–60)% depending on the plot.

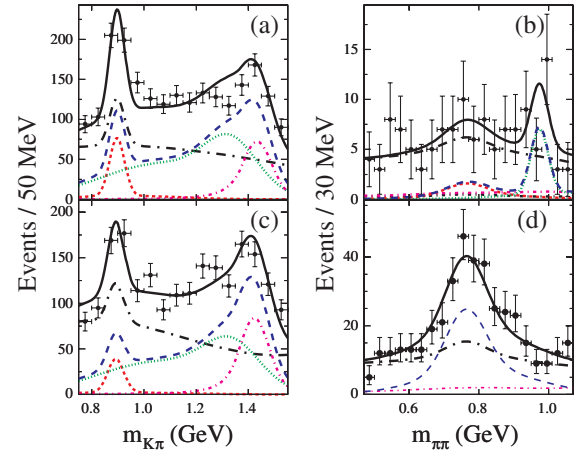


FIG. 3 (color online).  $B$ -candidate  $K\pi$  mass projections for (a)  $\omega K^{*0}$  and (c)  $\omega K^{*+}$ , and  $\pi\pi$  mass projections for (b)  $\omega\rho^0/\omega f_0$  and (d)  $\omega\rho^+$ . The efficiency range and description of the curves are the same as for Fig. 2.

at its minimum; the corresponding probability is interpreted with the number of degrees of freedom equal to two for modes with a measured  $f_L$  and one for the others. For modes without a significant signal, we quote a 90% confidence level (C.L.) upper limit, taken to be the branching fraction below which lies 90% of the total of the likelihood integral in the region of positive branching fraction. In all of these calculations  $\mathcal{L}(\mathcal{B})$  is a convolution of the function obtained from the fitter with a Gaussian function representing the correlated and uncorrelated systematic errors detailed below.

We show in Fig. 2 the data and PDFs projected onto  $m_{ES}$ . Figure 3 shows similar projections for the  $K\pi$  and  $\pi\pi$  masses. Figure 4 gives projections onto  $\mathcal{H}$  for the  $\omega K^*$  modes.

The systematic uncertainties on the branching fractions arising from lack of knowledge of the signal PDF parameters are estimated by varying these parameters within uncertainties obtained from the consistency of fits to MC and data control samples. The uncertainty in the yield bias correction is taken to be the quadratic sum of two terms: half the bias correction and the statistical uncertainty on the bias itself. We estimate the uncertainty from the mod-

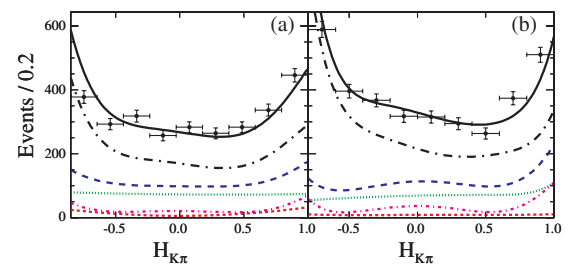


FIG. 4 (color online).  $B$ -candidate  $K\pi$  helicity projections for (a)  $\omega K^{*0}$  and (b)  $\omega K^{*+}$ . The efficiency range and key for the curves are the same as for Figs. 2(a) and 2(b).

eling of the nonresonant and  $B\bar{B}$  backgrounds by varying the background yields by their estimated uncertainties (from Ref. [16] and studies of our data). We vary the SXF fraction by its uncertainty; we find this to be 10% of its value, determined from studies of the control samples. For the  $K_0^*(1430)$  modes, we vary the LASS parameters within their measured uncertainties [19]. For  $B^0 \rightarrow \omega\rho^0$  where  $f_L$  is fixed, the uncertainty due to the assumed value of  $f_L$  is evaluated as the change in branching fraction when  $f_L$  is varied by  $^{+0.2}_{-0.3}$ . These additive systematic errors are dominant for all modes and are typically similar in size except for the error due to  $B\bar{B}$  background, which is usually smaller than the others.

Uncertainties in reconstruction efficiency, found from studies of data control samples, are 0.4%/track, 3.0%/ $\pi^0$ , and 1.4%/ $K_S^0$  decay. We estimate the uncertainty in the number of  $B$  mesons to be 1.1%. Published data [16] provide the uncertainties in the  $B$ -daughter branching fractions ( $\leq 2\%$ ). The uncertainty in the efficiency of the  $\cos\theta_T$  requirement is (1.0–1.5)%. Since we do not account for interference among the  $K^*$  components, we assign systematic uncertainties based on separate calculations where we vary the phases between the three components over their full range.

The systematic uncertainty on  $f_L$  includes the effects of fit bias, PDF-parameter variation, and  $B\bar{B}$  and nonresonant backgrounds, all estimated with the same method as used for the yield uncertainties described above. From large inclusive kaon and  $B$ -decay samples, we estimate the  $\mathcal{A}_{\text{ch}}$  bias to be negligible for pions and  $-0.01$  for kaons, due primarily to material interactions. Thus we correct the measured  $\mathcal{A}_{\text{ch}}$  for the  $K^*$  modes by  $+0.01$ . The systematic uncertainty for  $\mathcal{A}_{\text{ch}}$  is estimated to be 0.02 due mainly to the uncertainty in this bias correction. This estimate is

supported by the fact that the corrected background  $\mathcal{A}_{\text{ch}}$  is smaller than 0.015.

In summary, we have searched for nine charmless hadronic  $B$ -meson decays as shown in Table II, and have observed most of them (for the first time in all cases except  $B^+ \rightarrow \omega\rho^+$ ). We calculate the branching fractions for  $\omega K_0^*(1430)$  using the composition of  $(K\pi)_0^*$  from Ref. [20]. We find  $\mathcal{B}(B^0 \rightarrow \omega K_0^*(1430)^0) = (16.0 \pm 1.6 \pm 1.5 \pm 2.6) \times 10^{-6}$  and  $\mathcal{B}(B^+ \rightarrow \omega K_0^*(1430)^+) = (24.0 \pm 2.6 \pm 2.2 \pm 3.8) \times 10^{-6}$ , where the third errors arise from uncertainties in the branching fraction  $K_0^*(1430) \rightarrow K\pi$  [16] and the resonant fraction of  $(K\pi)_0^*$ . For most decays we measure  $\mathcal{A}_{\text{ch}}$  and find it to be consistent with zero. For  $VV$  and  $VT$  decays we also measure  $f_L$ . For  $B^+ \rightarrow \omega\rho^+$ ,  $f_L$  is near 1.0, as it is for  $B \rightarrow \rho\rho$  [3]. For the  $VT$   $B \rightarrow \omega K_2^*(1430)$  decays  $f_L$  is about  $4\sigma$  from 1.0 for both charge states; it is similar to the value of  $\sim 0.5$  found in  $B \rightarrow \phi K^*$  decays. Branching fraction results are in agreement with theoretical estimates [2] except for the  $SV$  and  $VT$  decays where the estimates are more uncertain [11,13].

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