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Observation of B Meson Decays to $\omega\pi^+$, ωK^+, and ωK^0

The *BABAR* Collaboration

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Abstract

We present preliminary measurements of B meson decays to $B^+ \to \omega\pi^+$, $B^+ \to \omega K^+$, and $B^0 \to \omega K^0$. The data were recorded with the *BABAR* detector and correspond to 88.9×10^6 $B\overline{B}$ pairs produced in e^+e^- annihilation at the $\Upsilon(4S)$ resonance. We find statistically significant signals for all three channels: $\mathcal{B}(B^+ \to \omega\pi^+) = (5.4 \pm 1.0 \pm 0.5) \times 10^{-6}$, $\mathcal{B}(B^+ \to \omega K^+) = (5.0 \pm 1.0 \pm 0.4) \times 10^{-6}$, and $\mathcal{B}(B^0 \to \omega K^0) = (5.3^{+1.4}_{-1.2} \pm 0.5) \times 10^{-6}$. We also measure time-integrated charge asymmetries $\mathcal{A}_{ch}(B^+ \to \omega\pi^+) = 0.04 \pm 0.17 \pm 0.01$ and $\mathcal{A}_{ch}(B^+ \to \omega K^+) = -0.05 \pm 0.16 \pm 0.01$.

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1 Introduction

We report the results of searches for B decays to the charmless final states $\omega\pi^+$, ωK^+, and ωK^0. We reconstruct the ω mesons via the dominant decay mode $\omega \to \pi^+\pi^-\pi^0$, and K^0 via $K^0 \to K^0_S \to \pi^+\pi^-$. For the charged modes we also measure the direct *CP*-violating time-integrated charge asymmetry $\mathcal{A}_{ch} = (\Gamma^- - \Gamma^+)/(\Gamma^- + \Gamma^+)$, where $\Gamma^\pm \equiv \Gamma(B^\pm \to \omega h^\pm)$.

Table 1 summarizes the current knowledge of these decays, coming from measurements by CLEO [1], *BABAR* [2, 3] and Belle [4]. CLEO and *BABAR* find significant signals for the $B^+ \to \omega\pi^+$ channel. The $B^+ \to \omega K^+$ decay has an interesting history. It was originally seen by CLEO but a re-analysis with the full CLEO dataset could not confirm the earlier large branching fraction measurement. *BABAR* confirmed the smaller result of the CLEO re-analysis (see Table 1) but Belle has now published a significant observation with a relatively large branching fraction. A more precise measurement would help settle the situation. *BABAR* reported a significant signal for the $B^0 \to \omega K^0$ decay at conferences in summer 2002.

The early indications from CLEO and now Belle of a branching fraction for $B^+ \to \omega K^+$ of $\gtrsim 10 \times 10^{-6}$ were hard to accommodate theoretically. The $B^+ \to \omega K^+$ decay is an interesting penguin-dominated decay with cancellations between primary Wilson coefficients. The $B^+ \to \omega\pi^+$ decay is expected to be dominated by the external and color-supressed tree diagrams. Typical calculations found branching fractions for both ω decays of a few times 10^{-6} [5, 6, 7], although parameter tuning was able to accommodate $\gtrsim 10 \times 10^{-6}$ with difficulty. The decay $B^0 \to \omega K^0$ is expected to have a comparable branching fraction to that of $B^+ \to \omega K^+$. However the presence of a (suppressed) tree diagram in the charged decay would reduce the rate than for the neutral decay if there is substantial destructive tree-penguin interference for $B^+ \to \omega K^+$. The theoretical situation has changed little recently. There are few calculations for these modes from the QCD factorization or perturbative QCD groups. One recent calculation of pseudoscalar-vector modes with QCD factorization [8] finds predicted branching fractions of $\lesssim 5 \times 10^{-6}$ for all three decays.

2 Detector and Data

The results presented in this paper are based on data collected in 1999–2002 with the *BABAR* detector [9] at the PEP-II asymmetric-energy e^+e^- collider [10] located at the Stanford Linear Accelerator Center. An integrated luminosity of 81.9 fb^{-1}, corresponding to 88.9 million $B\overline{B}$ pairs, was recorded at the $\Upsilon(4S)$ resonance ("on-resonance", center-of-mass energy $\sqrt{s} = 10.58$ GeV). An additional 9.6 fb^{-1} were taken about 40 MeV below this energy ("off-resonance") for the study of continuum backgrounds in which a light or charm quark pair is produced instead of an $\Upsilon(4S)$.

The asymmetric beam configuration in the laboratory frame provides a boost of $\langle\beta\gamma\rangle = 0.56$ to the $\Upsilon(4S)$. Charged particles are detected and their momenta measured by a combination of a silicon vertex tracker (SVT), consisting of five layers of double-sided detectors, and a 40-layer central drift chamber, both operating in the 1.5 T magnetic field of a solenoid. Photons and electrons are detected by a CsI(Tl) electromagnetic calorimeter (EMC).

Charged particle identification (PID) is provided primarily by an internally reflecting ring-imaging Cherenkov detector (DIRC) covering the central region, though the average energy loss (dE/dx) in the tracking devices is also used for the pion daughters from the ω decay. From the Cherenkov angle, a K–π separation greater than 4 standard deviations (σ) is achieved for tracks with momenta below 3 GeV/c, decreasing to $2.5\,\sigma$ at the highest momenta in the final states considered here [11].

Table 1: Summary of branching fraction results for B decays to ω mesons from CLEO [1], previous *BABAR* measurements [2, 3], Belle [4], and the present analysis. The results for all fits are given as well as a 90% confidence level upper limit if the measured yield is not judged to be significant. The signal yields and efficiencies (ϵ) are also given.

Expt.	# $B\overline{B}$ ($\times 10^6$)	Fit $\mathcal{B}(\times 10^{-6})$	UL $\mathcal{B}(\times 10^{-6})$	Signif. (σ)	Signal yield	ϵ (%)
$B^+ \to \omega K^+$						
CLEO	10	$3.2^{+2.4}_{-1.9} \pm 0.8$	7.9	2.1	$7.9^{+6.0}_{-4.7}$	26
BABAR	23	$1.4^{+1.3}_{-1.0} \pm 0.3$	3.3	1.6	$6.4^{+5.6}_{-4.4}$	19
Belle	32	$9.2^{+2.6}_{-2.3} \pm 1.0$	-	6.0	$18.9^{+5.4}_{-4.7}$	6.0
This result	89	$5.0 \pm 1.0 \pm 0.4$	-	8.9	87 ± 15	18
$B^+ \to \omega \pi^+$						
CLEO	10	$11.3^{+3.3}_{-2.9} \pm 0.8$	-	6.2	$28.5^{+8.2}_{-7.3}$	26
BABAR	23	$6.6^{+2.1}_{-1.8} \pm 0.7$	-	5.1	28^{+9}_{-8}	19
Belle	32	$4.2^{+2.0}_{-1.8} \pm 0.5$	8.1	3.3	$10.4^{+4.7}_{-4.3}$	7.7
This result	89	$5.4 \pm 1.0 \pm 0.5$	-	8.4	101 ± 18	19
$B^0 \to \omega K^0$						
CLEO	10	$10.0^{+5.4}_{-4.2} \pm 1.4$	21	3.9	$7.0^{+3.0}_{-2.9}$	7.4
BABAR	62	$5.9^{+1.7}_{-1.5} \pm 0.9$	-	6.6	27^{+8}_{-7}	7.4
This result	89	$5.3^{+1.4}_{-1.2} \pm 0.5$	-	7.5	33^{+9}_{-8}	7.0

3 Event Selection

Monte Carlo (MC) simulations [12] of the target decay modes and of continuum and $B\overline{B}$ backgrounds are used to establish the event selection criteria. The selection is designed to achieve high efficiency and retain sidebands sufficient to characterize the background for subsequent fitting.

From photons with energy $E_\gamma > 50$ MeV, we select π^0 candidates by requiring the invariant mass to satisfy $120 < m_{\gamma\gamma} < 150$ MeV. Candidate ω mesons must satisfy $735 < m_{\pi\pi\pi} < 825$ MeV. For K^0_S candidates we require $488 < m_{\pi\pi} < 508$ MeV, the three-dimensional flight distance from the event primary vertex > 2 mm, and the two-dimensional angle between flight and momentum vectors < 40 mrad.

We make several particle identification requirements to ensure the identity of the signal pions and kaons. Daughter tracks of ω candidates must have DIRC, dE/dx, and EMC responses consistent with pions. For the $B^+ \to \omega K^+$ decay, the prompt charged track must have an associated DIRC Cherenkov angle between $-5\,\sigma$ and $+2\,\sigma$ of the value expected for a kaon. For $B^+ \to \omega\pi^+$, the DIRC Cherenkov angle must be between $-2\,\sigma$ and $+5\,\sigma$ of the value expected for a pion.

A B meson candidate is characterized kinematically by the energy-substituted mass $m_{ES} = \sqrt{(\frac{1}{2}s + \mathbf{p}_0 \cdot \mathbf{p}_B)^2/E_0^2 - \mathbf{p}_B^2}$ and energy difference $\Delta E = E_B^* - \frac{1}{2}\sqrt{s}$, where the subscripts 0 and B refer to the initial $\Upsilon(4S)$ and the B candidate, respectively, and the asterisk denotes the $\Upsilon(4S)$ frame. We require $|\Delta E| \leq 0.2$ GeV and $5.2 \leq m_{ES} \leq 5.29$ GeV. The resolutions on these quantities are about 30 MeV and 3.0 MeV, respectively.

3.1 Tau, QED, and continuum background

To discriminate against tau-pair and two-photon background, we require that the event contain at least five (four) charged tracks for neutral (charged) B pairs. To reject continuum background, we define an angle θ_T between the thrust axes of the B candidate and of the rest of the tracks and neutral clusters in the event, calculated in the center-of-mass frame. The distribution of $|\cos\theta_{\rm T}|$ is sharply peaked near 1.0 for combinations drawn from jet-like $q\bar{q}$ pairs, and nearly uniform for the isotropic B meson decays; we require $|\cos\theta_{\rm T}| < 0.8$ for the charged modes and $|\cos\theta_{\rm T}| < 0.8$ for the lower-background $B^0 \to \omega K^0$ decay. A second B candidate satisfying the selection criteria is found in about 10–20% of the events. In this case the "best" combination is chosen as the one closest to the nominal ω mass.

3.2 $B\overline{B}$ background

We use MC simulations of $B^0\overline{B}^0$ and B^+B^- pair production and decay to look for possible $B\overline{B}$ backgrounds. From these studies we find that $B\overline{B}$ background is small for all three decay channels. The uncertainty is limited by the statistical errors of these studies and is included in the systematic errors (see §6).

4 Maximum Likelihood Fit

We use an unbinned, multivariate maximum-likelihood fit to extract signal yields for our modes. With the cuts in §3, candidates are selected to match the kinematic structure of the desired decay chain.

4.1 Likelihood Function

We incorporate several uncorrelated variables for the kinematics of the B decay chain and a Fisher discriminant $\mathcal{F}$ for the B production and energy flow. Thus the input observables are ΔE, m_{ES}, $m_{\pi\pi\pi}$, $\mathcal{H} \equiv |\cos\theta_H|$, and a Fisher discriminant $\mathcal{F}$. The helicity angle θ_H is defined as the angle, measured in the ω rest frame, between the normal to the ω decay plane and the flight direction of the ω. The Fisher discriminant [13] combines four variables: the angles with respect to the beam axis, in the $\Upsilon(4S)$ frame, of the B momentum and B thrust axis, and the zeroth and second angular moments $L_{0,2}$ of the energy flow about the B thrust axis. The moments are defined by

$$L_j = \sum_i p_i \times |\cos\theta_i|^j \,, \tag{1}$$

where θ_i is the angle with respect to the B thrust axis of track or neutral cluster i, p_i is its momentum, and the sum excludes the B candidate.

Since we measure the correlations among the observables in the data to be small, we take the probability density function (PDF) for each event to be a product of the PDFs for the separate observables. We define two hypotheses j, where j represents signal or continuum background. The product PDF (to be evaluated with the observable set for event i) is then given by

$$\mathcal{P}^i_j = \mathcal{P}_j(m_{ES}) \cdot \mathcal{P}_j(\Delta E) \cdot \mathcal{P}_j(\mathcal{F}) \cdot \mathcal{P}_j(m_{\pi\pi\pi}) \cdot \mathcal{P}_j(\mathcal{H}) \;. \tag{2}$$

The likelihood function for each decay chain is

$$\mathcal{L} = \frac{\exp\left(-\sum_j Y_j\right)}{N!} \prod_i^N \sum_j Y_j \mathcal{P}_j^i \,, \tag{3}$$

where Y_j is the yield of events of hypothesis j found by maximizing $\mathcal{L}$ and N is the number of events in the sample. The first factor takes into account the Poisson fluctuations in the total number of events.

4.2 Fit Parameters

The determination of PDF parameters for the likelihood fit is accomplished with use of Monte Carlo (MC) simulation for the signal and on-peak data from a m_{ES}-ΔE sideband for the continuum background. Several of the principle background parameters are allowed to float in the final fit.

Peaking distributions (signal masses, ΔE, and $\mathcal{F}$) are parameterized with Gaussian functions, with a second or third Gaussian or asymmetric width as required for good fits to these samples. Because these are pseudoscalar–vector decays of the B, the signal helicity-angle distribution is proportional to $\mathcal{H}^2$. Slowly varying distributions (mass, energy or helicity-angle distributions for combinatoric background) have low order polynomial shapes, with the peaking and combinatoric ω mass components each having their own $\mathcal{H}$ shape. The combinatoric background in m_{ES} is described by a phase-space-motivated empirical function [14]. The background Fisher PDF contains a second Gaussian component wide enough to ensure the PDF is not excessively small anywhere in its domain.

Control samples of B decays to charm final states of similar topology are used to test the quality of the MC simulation for variables describing B decay kinematics. Where the control data samples reveal differences from MC in mass or energy resolution, we scale the resolution used in the likelihood fits.

The efficiency bias of the likelihood fit is determined from simulated data samples. The $q\overline{q}$ background in these samples is generated from the continuum PDF shapes. A small number of signal events from the detailed MC simulation are added to create a sample with the same size as the data. The bias in the fit efficiency is determined from the mean of the fit yield for 500 such simulated samples.

5 Fit Results

By generating and fitting samples with both signal and continuum background events generated from the PDFs, we verify that our fitting procedure is functioning properly. We find that the minimum $-\ln\mathcal{L}$ value in the on-resonance sample lies well within the $-\ln\mathcal{L}$ distribution from these simulated samples.

In Table 2 we show the results of the fits for off-peak and on-peak data. Shown for each decay mode are the number of events that were fit, the signal yield, the fully corrected efficiency and product branching fraction (for the ω and K_S^0 decays), the measured branching fraction, and the statistical significance of the result. We also give the branching fraction after correction for a crossfeed between the two charged channels. The K/π misidentification rate of $9 \pm 2\%$ is found in studies with kaon and pion samples tagged kinematically from the decay $D^{*+} \rightarrow \pi^+ D^0$ with $D^0 \rightarrow K^-\pi^+$. The statistical error on the number of events is taken as the change in the central value when the quantity $-2\ln\mathcal{L}$ changes by one unit. The statistical significance is taken as the

Table 2: Fit values for ωK^+, $\omega\pi^+$, and ωK^0. The corrected $\mathcal{B}$ for the charged modes is the branching fraction after correcting for crossfeed from one charged mode into the other.

Fit quantity	ωK^+	$\omega\pi^+$	ωK^0
Fit sample size			
On-resonance	16729	30563	9563
Off-resonance	1900	3490	972
Signal yield			
On-res data	87 ± 15	101 ± 18	33^{+9}_{-8}
Off-res data	$0.0^{+2.7}_{-0.0}$	$0.0^{+3.6}_{-0.0}$	$0.0^{+0.9}_{-0.0}$
Combinations/event	1.13	1.15	1.15
Selection ϵ (%)	20.0	21.9	23.1
$\prod \mathcal{B}_i$ (%)	88.8	88.8	30.5
Corr. $\epsilon \times \prod \mathcal{B}_i$ (%)	17.8	19.4	7.0
Stat. significance (σ)	8.9	8.4	7.5
$\mathcal{B}(\times 10^{-6})$	$5.5 \pm 1.0 \pm 0.4$	$5.9 \pm 1.0 \pm 0.5$	$5.3^{+1.4}_{-1.2} \pm 0.5$
Corrected $\mathcal{B}(\times 10^{-6})$	$5.0 \pm 1.0 \pm 0.4$	$5.4 \pm 1.0 \pm 0.5$	
Signal $\mathcal{A}_{ch}$	$-0.05 \pm 0.16 \pm 0.01$	$0.04 \pm 0.17 \pm 0.01$	—
Background $\mathcal{A}_{ch}$	-0.005 ± 0.008	-0.012 ± 0.006	—

square root of the difference between the value of $-2\ln\mathcal{L}$ for zero signal and the value at its minimum. We also give the charge asymmetry $\mathcal{A}_{ch}$ for the charged modes for both signal and $q\overline{q}$ background.

In Fig. 1 we show projections of m_{ES} and ΔE made by selecting events with signal likelihood (computed without the variable shown in the figure) exceeding a mode-dependent threshold that optimizes the expected sensitivity.

6 Systematic Uncertainties

Most of the systematic errors on yields that arise from uncertainties in the values of the PDF parameters have already been incorporated into the overall statistical error, because their background parameters are free in the fit. We determine the sensitivity to parameters of the signal PDF components by varying these within their uncertainties. The results are shown in the first row of Table 3. This is the only additive systematic error.

The uncertainty in our knowledge of the efficiency is found from auxiliary studies to be $0.8N_t$%, $2.5N_\gamma$%, and 3% for a K^0_S decay, where N_t and N_γ are the number of signal tracks and photons, respectively. We estimate the uncertainty in the number of produced $B\overline{B}$ pairs to be 1.1%. The systematic bias from the fitter itself (1–2%) is estimated from fits of simulated samples with varying background populations. Published world averages [15] provide the B daughter branching fraction uncertainties. We account for systematic effects in $\cos\theta_{\rm T}$ (1%) and in the PID requirements (0.5%). Values for each of these contributions are given in Table 3.

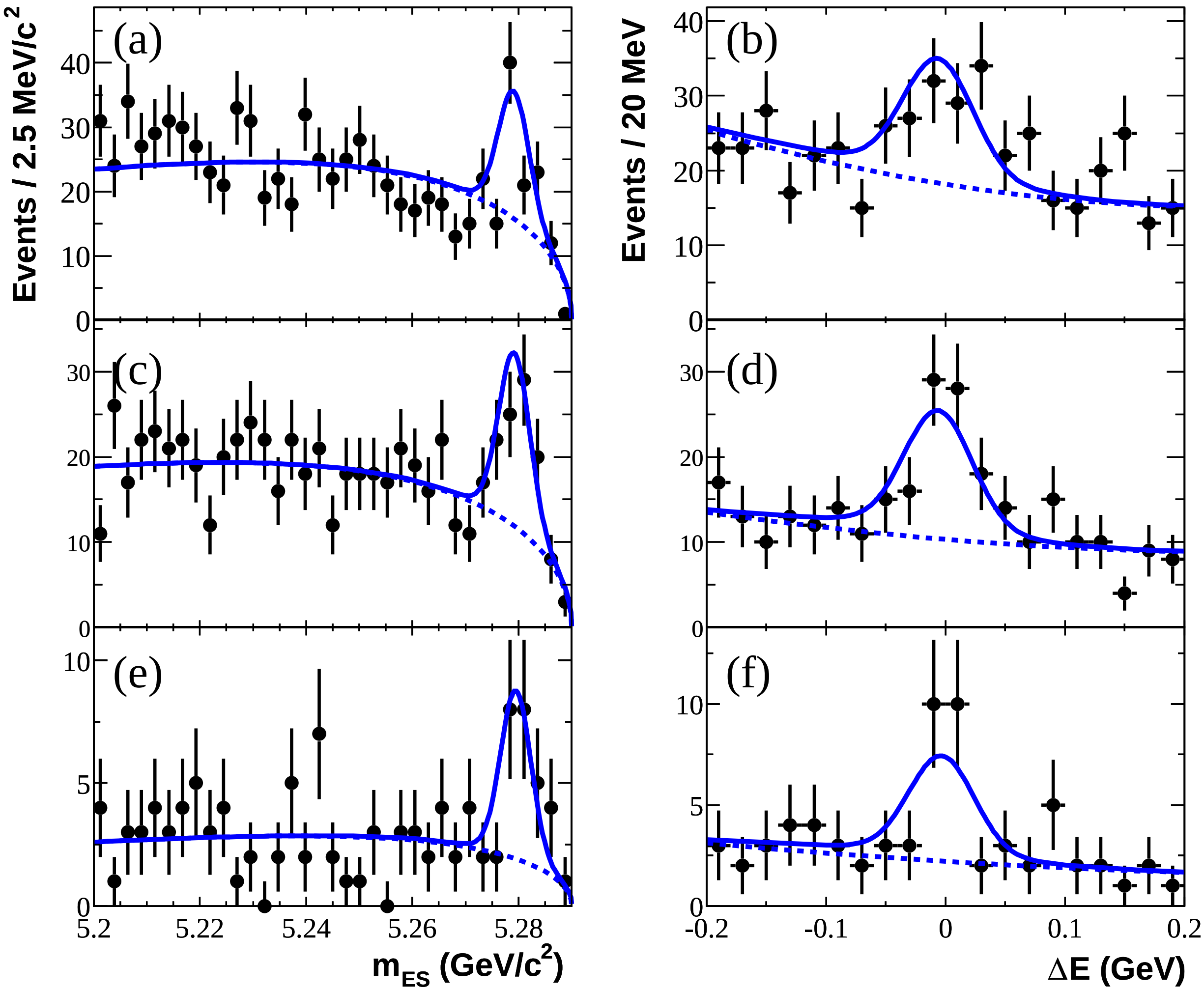

Figure 1: The B candidate m_{ES} and ΔE for $B^+ \to \omega\pi^+$ (a, b), $B^+ \to \omega K^+$ (c, d), and $B^0 \to \omega K^0$ (e, f). Points with errors represent data passing a cut on a likelihood ratio calculated without the quantity that is shown in the plots. The solid curves show the projected fit functions and dashed curves the background functions.

A study of the charge asymmetry as a function of momentum for all tracks in hadronic events bounds the tracking efficiency component of a charge-asymmetry bias to be below 1%. D^*-tagged $D \to K\pi$ and B samples provide additional crosschecks that the bias is negligible. We assign a systematic uncertainty for $\mathcal{A}_{ch}$ of 1.1% based on the tracking study and a small PID contribution determined from the D^* studies.

7 Conclusion

We report preliminary measurements of branching fractions for the decays $B^+ \to \omega\pi^+$, $B^+ \to \omega K^+$, and $B^0 \to \omega K^0$. We find statistically significant signals for all three decays and measure the

Table 3: Estimates of systematic errors (in percent) for the ωK^+, $\omega\pi^+$and ωK^0 branching fractions.

Quantity	ωK^+	$\omega\pi^+$	ωK^0
Fit yield	2.7	3.1	3.2
Fit efficiency/bias	2.7	3.9	2.1
Track multiplicity	1.0	1.0	1.0
Tracking eff/qual	2.4	2.4	3.7
π^0/ γ eff	5.0	5.0	5.0
K_s^0 efficiency	—	—	2.9
Number $B\overline{B}$	1.1	1.1	1.1
Branching fractions	1.0	1.0	1.0
MC statistics	1.0	1.0	1.0
$\cos\theta_{\rm T}$	1.0	1.0	1.0
PID	1.4	1.4	1.0
$B\overline{B}$ Background	1.1	1.0	3.0
Total	7.3	8.0	8.8

following branching fractions:

$$\begin{aligned}
\mathcal{B}(B^+ \to \omega\pi^+) &= (5.4 \pm 1.0 \pm 0.5) \times 10^{-6}, \\
\mathcal{B}(B^+ \to \omega K^+) &= (5.0 \pm 1.0 \pm 0.4) \times 10^{-6}, \\
\mathcal{B}(B^0 \to \omega K^0) &= (5.3^{+1.4}_{-1.2} \pm 0.5) \times 10^{-6}.
\end{aligned}$$

These results supersede the previous *BABAR* measurements [2, 3]. The result for $\mathcal{B}(B^+ \to \omega K^+)$ is larger than the previous measurement with one quarter the luminosity. From studies of the old and new measurements, we conclude that the difference is a statistical fluctuation.

These results are much more precise than previous results and in good agreement with theoretical expectations. A branching fraction for $B^+ \to \omega K^+$ near 10×10^{-6}, as reported first by CLEO and more recently by Belle, is now definitively ruled out. In addition, we measure the charge asymmetries $\mathcal{A}_{ch}(B^+ \to \omega\pi^+) = 0.04 \pm 0.17 \pm 0.01$ and $\mathcal{A}_{ch}(B^+ \to \omega K^+) = -0.05 \pm 0.16 \pm 0.01$. These values are consistent with being small as generally expected for these decays [16] though both experimental and theoretical uncertainties are still large.

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