

## ***B* meson decays to charmless meson pairs containing $\eta$ or $\eta'$ mesons**

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We present updated measurements of the branching fractions for  $B^0$  meson decays to  $\eta K^0$ ,  $\eta\eta$ ,  $\eta\phi$ ,  $\eta\omega$ ,  $\eta'K^0$ ,  $\eta'\eta'$ ,  $\eta'\phi$ , and  $\eta'\omega$ , and branching fractions and  $CP$ -violating charge asymmetries for  $B^+$  decays to  $\eta\pi^+$ ,  $\eta K^+$ ,  $\eta'\pi^+$ , and  $\eta'K^+$ . The data represent the full dataset of  $467 \times 10^6$   $B\bar{B}$  pairs collected with the BABAR detector at the PEP-II asymmetric-energy  $e^+e^-$  collider at the SLAC National Accelerator Laboratory. Besides large signals for the four charged  $B$  decay modes and for  $B^0 \rightarrow \eta'K^0$ , we find evidence for three  $B^0$  decay modes at greater than  $3.0\sigma$  significance. We find  $\mathcal{B}(B^0 \rightarrow \eta K^0) = (1.15_{-0.38}^{+0.43} \pm 0.09) \times 10^{-6}$ ,  $\mathcal{B}(B^0 \rightarrow \eta\omega) = (0.94_{-0.30}^{+0.35} \pm 0.09) \times 10^{-6}$ , and  $\mathcal{B}(B^0 \rightarrow \eta'\omega) = (1.01_{-0.38}^{+0.46} \pm 0.09) \times 10^{-6}$ , where the first (second) uncertainty is statistical (systematic). For the  $B^+ \rightarrow \eta K^+$  decay mode, we measure the charge asymmetry  $\mathcal{A}_{ch}(B^+ \rightarrow \eta K^+) = -0.36 \pm 0.11 \pm 0.03$ .

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Experimental measurements of branching fractions and  $CP$ -violating charge asymmetries in rare  $B$  decays play an important role in testing the theoretical predictions of the standard model and its extensions. We report the results of branching fraction measurements for  $B^0$  meson decays to  $\eta K^0$ ,  $\eta\eta$ ,  $\eta\phi$ ,  $\eta\omega$ ,  $\eta'K^0$ ,  $\eta'\eta'$ ,  $\eta'\phi$ ,

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and  $\eta'\omega$  final states and of branching fraction and charge asymmetry measurements for  $B^+$  decays to  $\eta\pi^+$ ,  $\eta K^+$ ,  $\eta'\pi^+$ , and  $\eta'K^+$  [1]. We search for charge asymmetry by measuring

$$\mathcal{A}_{ch} \equiv \frac{\Gamma^- - \Gamma^+}{\Gamma^- + \Gamma^+} \quad (1)$$

where  $\Gamma^\pm = \Gamma(B^\pm \rightarrow f^\pm)$  is the decay width for a given charged final state  $f^\pm$ . These branching fraction and charge asymmetry measurements represent an improvement over previous results published by *BABAR* [2] and Belle [3].

The branching fractions and charge asymmetries of the charmless hadronic  $B$  decays are predicted using approaches based on QCD factorization [4–7] and flavor SU(3) symmetry [8–10]. These  $B$  decays proceed through loop (penguin) and suppressed tree diagram amplitudes, as shown in Fig. 1. The branching fraction and charge

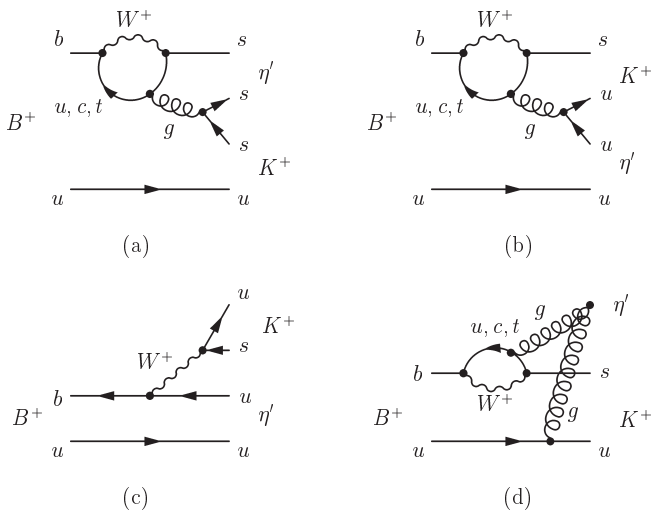


FIG. 1: Examples of Feynman diagrams involved in decays studied in this paper: (a,b) penguin diagrams, (c) Cabibbo-suppressed tree diagram, (d) gluonic penguin diagram.

asymmetry measurements may provide sensitivity to the presence of heavy non-standard model particles in the loop diagrams [11]. The measured  $\eta'K$  branching fraction is found to be much larger than the  $\eta K$  one [2, 3]. Many suggestions have been proposed to explain such a difference, including flavor singlet enhancement [12], intrinsic charm [13], and constructively interfering internal penguin diagrams [14, 15]. This last approach is supported by next-to-leading order QCD factorization calculations [6].

The  $CP$ -violating parameters  $S_{\eta'K}$  and  $S_{\phi K}$ , measured in the time-dependent analysis of  $\eta'K^0$  and  $\phi K^0$  decays [16], are expected to equal  $S_{c\bar{c}s} \approx \sin 2\beta$ , where  $S_{c\bar{c}s}$  is measured in the Cabibbo-Kobayashi-Maskawa (CKM) favored  $b \rightarrow c\bar{c}s$  decays, if penguin  $b \rightarrow s$  transitions are dominant. However, CKM-suppressed amplitudes

and color-suppressed tree diagrams can introduce additional weak phases whose contributions may not be negligible [6, 17, 18]. As a consequence, deviations from  $\sin 2\beta$  may occur even within the standard model. Rates of the decay modes to  $\eta\eta$ ,  $\eta\phi$ ,  $\eta'\eta'$ , and  $\eta'\phi$  are used in flavor SU(3)-based calculations of the  $|S_{c\bar{c}s} - S_f|$  (with  $f = \eta'K, \phi K$ ) [17] bound. This bound may be improved by more precise measurements of the branching fractions of these modes.

The charge asymmetry is expected to be sizable in  $\eta K^+$  and suppressed in  $\eta'K^+$  decays [6, 9, 19]. However, different approaches predict the two asymmetries to have the same [9] or opposite [6] signs; precise measurement of such asymmetries can discriminate between these models. Furthermore, the charge asymmetries in  $\eta'\pi^+$  and  $\eta\pi^+$  decays are expected to be sizable [6, 9], with model-dependent predictions for their magnitudes.

The results presented here are based on the full dataset collected with the *BABAR* detector [20] at the PEP-II asymmetric-energy  $e^+e^-$  collider located at the SLAC National Accelerator Laboratory. An integrated luminosity of  $426 \text{ fb}^{-1}$ , corresponding to  $N_{B\bar{B}} = 467 \times 10^6$   $B\bar{B}$  pairs, was recorded at the  $\Upsilon(4S)$  resonance (center-of-mass energy  $\sqrt{s} = 10.58 \text{ GeV}$ ). A further  $44 \text{ fb}^{-1}$  was collected approximately 40 MeV below the resonance (off-peak) for the study of the  $e^+e^- \rightarrow q\bar{q}$  background, where  $q$  is a  $u, d, s,$  or  $c$  quark.

Charged particles are detected, and their momenta measured, by a combination of a vertex tracker, consisting of five layers of double-sided silicon microstrip detectors, and 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 ( $dE/dx$ ) measurements in the tracking devices and by the information provided by an internally reflecting Cherenkov detector (DIRC) covering the central region.

We select  $\eta, \eta', \phi, \rho^0, K_s^0, \omega,$  and  $\pi^0$  candidates through the decays  $\eta \rightarrow \gamma\gamma$  ( $\eta_{\gamma\gamma}$ ),  $\eta \rightarrow \pi^+\pi^-\pi^0$  ( $\eta_{3\pi}$ ),  $\eta' \rightarrow \eta\pi^+\pi^-$  with  $\eta \rightarrow \gamma\gamma$  ( $\eta'_{\eta\pi\pi}$ ),  $\eta' \rightarrow \rho^0\gamma$  ( $\eta'_{\rho\gamma}$ ),  $\phi \rightarrow K^+K^-$ ,  $\rho^0 \rightarrow \pi^+\pi^-$ ,  $K_s^0 \rightarrow \pi^+\pi^-$ ,  $\omega \rightarrow \pi^+\pi^-\pi^0$ , and  $\pi^0 \rightarrow \gamma\gamma$ . We do not study the decay  $B^0 \rightarrow \eta'\eta'$  with both  $\eta'$  mesons decaying to  $\rho\gamma$ , because it suffers large backgrounds. Requirements applied to the photon energy  $E_\gamma$  and to the invariant mass of the  $B$  daughters are listed in Table I. The requirements on the  $\eta$  and  $\eta'$  invariant masses depend on the decay mode. Branching fractions of charged  $B$  decays with  $\eta'$  in the final state and of  $B^0 \rightarrow \eta'K_s^0$  are higher than those of the other neutral  $B$  modes. In neutral decay modes we apply a tighter requirement on  $\eta_{3\pi}$  invariant mass in order to prevent possible contamination from  $B\bar{B}$  background. The different requirements on the  $\eta'$  mass increase the purity of the charged  $B$  and  $\eta'K_s^0$  modes and enhance the selection efficiency for the other neutral  $B$  decay modes. The energy (momentum) of the  $\pi^0$  ( $\eta$ ) candidates is required

TABLE I: Selection requirements on the invariant masses of the signal resonances and on the laboratory energies of the photons coming from their decays.

State	Invariant mass (MeV/c <sup>2</sup> )	$E_\gamma$ (MeV)
$\pi^0$	$120 < m_{\gamma\gamma} < 150$	$> 30$
Prompt $\eta_{\gamma\gamma}$	$505 < m_{\gamma\gamma} < 585$	$> 100$
Secondary $\eta_{\gamma\gamma}$	$490 < m_{\gamma\gamma} < 600$	$> 50^\dagger$
$\eta_{3\pi}$ in $B^+$ decays	$534 < m_{\pi\pi\pi} < 561$	–
$\eta_{3\pi}$ in $B^0$ decays	$535 < m_{\pi\pi\pi} < 555$	–
$\eta'_{\pi\pi}$ in $B^+$ and $B^0 \rightarrow \eta' K_S^0$ decays	$945 < m_{\eta\pi\pi} < 970$	–
$\eta'_{\eta\pi\pi}$ in other $B^0$ decays	$930 < m_{\eta\pi\pi} < 990$	–
$\eta'_{\rho\gamma}$ in $B^+$ decays	$930 < m_{\rho\gamma} < 980$	$> 200$
$\eta'_{\rho\gamma}$ in $B^0 \rightarrow \eta'_{\rho\gamma} K_S^0$	$930 < m_{\rho\gamma} < 980$	$> 100$
$\eta'_{\rho\gamma}$ in other $B^0$ decays	$910 < m_{\rho\gamma} < 990$	$> 200$
$\rho^0$	$470 < m_{\pi\pi} < 990$	–
$\omega$	$735 < m_{\pi\pi\pi} < 825$	–
$\phi$	$1012 < m_{K^+K^-} < 1026$	–
$K_S^0$	$486 < m_{\pi\pi} < 510$	–

$^\dagger E_\gamma > 100$  MeV in the  $B^+ \rightarrow \eta'_{\eta\pi\pi} K^+$  and  $B^+ \rightarrow \eta'_{\eta\pi\pi} \pi^+$  decay modes.

to exceed 200 MeV (200 MeV/c) in the laboratory frame. The prompt charged tracks in  $B^+ \rightarrow \eta' \pi^+$  and secondary charged tracks in  $\eta$ ,  $\eta'$ , and  $\omega$  candidates are required to have DIRC, dE/dx, and EMC signatures consistent with the pion hypothesis. After selection, we constrain the  $\eta$ ,  $\eta'$ , and  $\pi^0$  masses to their world average values [21]. The prompt charged track in  $B^+ \rightarrow \eta' K^+$  is required to be consistent with the kaon hypothesis. The signatures for the charged kaons from  $\phi$  decays are required to be inconsistent with hypotheses for electrons, pions and protons. For the prompt charged track in  $B^+$  decays to  $\eta K^+$  and  $\eta \pi^+$ , we define the variables  $\mathcal{C}_K$  and  $\mathcal{C}_\pi$  as

$$\mathcal{C}_{K,\pi} = \frac{\theta_{K,\pi}^{meas} - \theta_{K,\pi}^{exp}}{\sigma_{K,\pi}^{meas}}, \quad (2)$$

where  $\theta_{K,\pi}^{meas}$  ( $\theta_{K,\pi}^{exp}$ ) is the measured (expected) DIRC Cherenkov angle and  $\sigma_{K,\pi}^{meas}$  is its uncertainty, for the kaon and pion hypothesis, respectively. We require  $-3 < \mathcal{C}_K < 13$  and  $-13 < \mathcal{C}_\pi < 3$ . For  $K_S^0$  candidates we require a vertex  $\chi^2$  probability larger than 0.001 and a reconstructed decay length greater than three times its uncertainty.

We reconstruct the  $B$  meson candidate by combining the four-momenta of the final state particles and imposing a vertex constraint. A  $B$  meson candidate is kinematically characterized by the energy-substituted mass  $m_{ES} = \sqrt{s/4 - \mathbf{p}_B^2}$  and energy difference  $\Delta E = E_B - \frac{1}{2}\sqrt{s}$ , where  $(E_B, \mathbf{p}_B)$  is the  $B$ -meson four-momentum vector expressed in the  $\Upsilon(4S)$  rest frame. For signal events, the  $m_{ES}$  and  $\Delta E$  distributions peak around 5.28 GeV/c<sup>2</sup> and zero, respectively. We require  $5.25 < m_{ES} < 5.29$  GeV/c<sup>2</sup> and  $|\Delta E| < 0.2$  GeV for all decay

modes except  $B^0 \rightarrow \eta K_S^0$ , where we require  $-0.15 < \Delta E < 0.2$  GeV in order to suppress most of the background from radiative  $B$  decays.

Backgrounds arise primarily from random combinations of tracks and neutral clusters in  $e^+e^- \rightarrow q\bar{q}$  continuum events. We use large samples of Monte Carlo (MC) simulated [22] events and control samples to optimize criteria to suppress the background. We reject continuum events by using the angle  $\theta_T$  between the thrust axis of the  $B$  candidate in the  $\Upsilon(4S)$  frame and that of the rest of the event. The thrust axis of the  $B$  candidate is given by the thrust axis of the  $B$  decay products. The distribution of  $|\cos \theta_T|$  is sharply peaked near 1.0 for jet-like  $q\bar{q}$  pair events and is nearly uniform for  $\Upsilon(4S) \rightarrow B\bar{B}$  events. We require  $|\cos \theta_T| < 0.9$  (0.85 for  $\eta'_{\rho\gamma} \pi^+$ , 0.8 for  $\eta_{\gamma\gamma} \omega$  and  $\eta'_{\rho\gamma} \omega$ ). To discriminate against  $\tau$ -pair and two-photon backgrounds, and to better describe the event shape, we require the event to contain at least three charged tracks, or one track beyond the minimum required for the signal decay topology, whichever is larger.

In  $\eta \rightarrow \gamma\gamma$  ( $\phi$ ) decays, we define  $\mathcal{H}_\eta$  ( $\mathcal{H}_\phi$ ) as the cosine of the angle between the direction of a daughter  $\gamma$  ( $K$ ) and the flight direction of the parent of  $\eta$  ( $\phi$ ) in the  $\eta$  ( $\phi$ ) rest frame; for  $\eta'_{\rho\gamma}$ ,  $\mathcal{H}_\rho$  is the cosine of the angle between the direction of a daughter pion and the flight direction of the  $\eta'$  in the  $\rho$  rest frame. For  $B$  decays containing an  $\omega$  meson in the final state we define  $\mathcal{H}_\omega$  as the cosine of the angle between the  $B$  recoil direction and the normal to the plane defined by the  $\omega$  daughters in the  $\omega$  rest frame. We require  $|\mathcal{H}_\eta| < 0.95$  in  $B^0 \rightarrow \eta\eta$  decay modes. We reject candidate events if  $|\mathcal{H}_\rho| > 0.9$  ( $> 0.75$  in the  $B^+ \rightarrow \eta'_{\rho\gamma} \pi^+$  decay mode).

For the  $B^0 \rightarrow \eta_{\gamma\gamma} K_S^0$  ( $B^+ \rightarrow \eta_{\gamma\gamma} h^+$ ,  $h^+ = K^+, \pi^+$ ) decay, the main source of  $B\bar{B}$  background is the  $B^0 \rightarrow \pi^0 K_S^0$  ( $B^+ \rightarrow \pi^0 h^+$ ) decay. To suppress this background, we search for  $\pi^0$  candidates with a photon in common (overlapping) with the  $\eta$  candidate from the reconstructed signal  $B$  candidate. We require the  $\pi^0$  mass not to be in the range (0.117, 0.152) GeV/c<sup>2</sup> for the  $B^0 \rightarrow \eta_{\gamma\gamma} K_S^0$  decay mode, and (0.118, 0.150) GeV/c<sup>2</sup> for the  $B^+ \rightarrow \eta_{\gamma\gamma} h^+$  decay modes. Further suppression of this background is obtained with suitable requirements on  $|\mathcal{H}_\eta|$  and on the energy of the second (non-overlapping with  $\eta$ )  $\pi^0$  photon ( $E_\gamma^{2nd}$ ). We optimize these requirements by maximizing  $S/\sqrt{S+B}$ , where  $S$  ( $B$ ) is the number of signal (background) events surviving the selection. We find the optimal criteria to be  $|\mathcal{H}_\eta| < 0.966$  and  $E_\gamma^{2nd} < 0.207$  GeV for the  $B^0 \rightarrow \eta_{\gamma\gamma} K_S^0$  decay mode, and  $|\mathcal{H}_\eta| < 0.977$  and  $E_\gamma^{2nd} < 0.143$  GeV for the  $B^+ \rightarrow \eta_{\gamma\gamma} h^+$  decay modes.

We find a mean number of  $B$  candidates per event in the range 1.0–1.4, depending on the final state. Signal events are divided into two categories: correctly reconstructed (CR) signal where all candidate particles come from the correct signal  $B$ , and self cross-feed (SCF) signal where at least one candidate particle is exchanged with a particle coming from the rest of the event. Simula-

tions show that the fraction of SCF candidates is in the range (3–7)% in charged  $B$  decay modes and (2–20)% in neutral  $B$  decay modes. If an event has multiple  $B$  candidates, we select the candidate with the highest  $B$  vertex  $\chi^2$  probability, determined from a vertex fit that includes both charged and neutral particles [23]. This algorithm selects the correct candidate, if present, with an efficiency of (91–99)% and introduces negligible bias.

We obtain yields from unbinned extended maximum-likelihood (ML) fits. The main input observables are  $\Delta E$ ,  $m_{\text{ES}}$ , and a Fisher discriminant  $\mathcal{F}$  [24]. Where relevant, the invariant masses  $m_{\text{res}}$  of the intermediate resonances and angular variables  $\mathcal{H}$  are used. The Fisher discriminant  $\mathcal{F}$  combines five variables: the angles with respect to the beam axis of the  $B$  momentum and  $B$  thrust axis, the zeroth and second angular moments  $L_{0,2}$  of the energy flow about the  $B$  thrust axis, and the absolute value of the continuous output of a flavor-tagging algorithm. The first four variables are evaluated in the  $\Upsilon(4S)$  rest frame. The moments are defined by  $L_r = \sum_s p_s \times |\cos \theta_s|^r$ , where  $\theta_s$  is the angle with respect to the  $B$  thrust axis of track or neutral cluster  $s$  with momentum  $p_s$ , and the sum excludes the  $B$  candidate. Flavor tagging information is derived from an analysis of the decay products of the non-signal candidate  $B$  meson ( $B_{\text{tag}}$ ), using a neural network based technique [25]. The output value of the tagging algorithm reflects the different final states identified in  $B_{\text{tag}}$  decay. In particular, the presence of a lepton in the final state usually results in a large tagging output value, for both  $B^0\bar{B}^0$  and  $B^+B^-$  events. Since leptons are not generally present in continuum background events, the inclusion of the tagging algorithm output in  $\mathcal{F}$  improves its discriminating power between continuum background and  $B\bar{B}$  events. The coefficients of  $\mathcal{F}$  are chosen to maximize the separation between the signal and the continuum background. They are determined from studies of MC signal events and off-peak data.

The set of probability density functions (PDF) used in the ML fits, specific to each decay mode, is determined on the basis of studies with MC samples. We estimate  $B\bar{B}$  backgrounds using MC samples of  $B$  decays. Where needed, we add components to account for  $B\bar{B}$  background events with a  $m_{\text{ES}}$  or  $\Delta E$  distribution that peaks in the signal region and for background from  $B$  meson decays with charmed particles in the final state.

The extended likelihood function is

$$\mathcal{L} = \exp\left(-\sum_{j=1}^3 n_j\right) \prod_{i=1}^N \left[ \sum_{j=1}^3 n_j \mathcal{P}_j(\mathbf{x}_i) \right], \quad (3)$$

where  $N$  is the number of input events,  $n_j$  is the number of events for hypothesis  $j$  ( $j = 1$  for signal,  $j = 2$  for continuum background, and  $j = 3$  for  $B\bar{B}$  background), and  $\mathcal{P}_j(\mathbf{x}_i)$  is the corresponding PDF evaluated with the observables  $\mathbf{x}_i$  of the  $i^{\text{th}}$  event. In the  $B^0 \rightarrow \eta'\omega$ ,  $\eta'\phi$ , and  $\eta'_{\rho\gamma}\omega$  decay modes the signal includes both the CR and SCF signal components with the SCF fraction fixed to the value estimated from simulation. Due to the similar

kinematics and branching fractions of the  $\eta K^+$  and  $\eta\pi^+$  decay modes, we perform a combined fit to extract the two signal yields and charge asymmetries. In this fit we use the  $\mathcal{C}_K$  and  $\mathcal{C}_\pi$  variables to discriminate the mass hypothesis of the prompt track. Since the correlations among the observables in the data are small, we assume each  $\mathcal{P}_j$  to be the product of the PDFs for the separate variables. Correlations between the  $\eta K^+$  and  $\eta\pi^+$  signal yields (charge asymmetries) are below 5% (7%).

We determine the PDF functional form and parameters from MC simulation for the signal and  $B\bar{B}$  backgrounds, and from sideband data ( $5.25 < m_{\text{ES}} < 5.27$  GeV/ $c^2$ ;  $0.1 < |\Delta E| < 0.2$  GeV) for the continuum background. For  $B^+ \rightarrow \eta h^+$  decay modes, PDF functional form and parameters for the continuum background are determined using off-peak data. We parameterize each of the functions  $\mathcal{P}_1(m_{\text{ES}})$ ,  $\mathcal{P}_1(\Delta E)$ ,  $\mathcal{P}_j(\mathcal{F})$ , and the peaking components of  $\mathcal{P}_j(m_{\text{res}})$  with either a symmetric or a bifurcated Gaussian, the sum of two symmetric or bifurcated Gaussian shapes, a bifurcated Gaussian distribution with exponential tails [26] or a Crystal Ball function [27], as required to describe the distribution. Slowly varying distributions ( $m_{\text{res}}$  and  $\Delta E$  for the continuum background, and angular variables) are represented by linear or quadratic functions. For the continuum background, the  $m_{\text{ES}}$  distribution is described by the ARGUS function [28]. Large data control samples of  $B$  decays to charmed final states of similar topologies are used to verify the simulated resolutions in  $m_{\text{ES}}$  and  $\Delta E$ . Where the control samples reveal differences between data and MC samples in mass (energy) resolution, we correct the mean and scale the width of the mass (energy) distribution used in the likelihood fits.

The validity of the fit procedure and PDF parameterization, including the effects of unmodeled correlations among observables, is checked with simulated experiments. This is done by embedding a number of signal and peaking  $B\bar{B}$  background events from fully simulated MC samples and by drawing a number of  $q\bar{q}$  and charm  $B\bar{B}$  events from PDFs, according to the values found in the data. In each fit the free parameters are: the yields, the charge asymmetry for the signal and continuum background, and several parameters describing the  $\Delta E$ ,  $m_{\text{ES}}$ , and  $\mathcal{F}$  distributions of the continuum background. A systematic uncertainty due to fixing signal and background parameters in the fit is accounted. The charge asymmetry for  $B\bar{B}$  background is fixed to zero in the fit. A systematic is evaluated to account for this restriction.

Table II and Table III show, for  $B^0$  and  $B^+$  decays, respectively, the measured yields, fit biases, efficiencies, and products of daughter branching fractions for each decay mode. The efficiency is calculated as the ratio of the number of signal MC events after the event selection to the total generated, and is corrected for known differences between simulations and data. We compute the branching fractions from the fitted signal event yields, reconstruction efficiencies, daughter branching fractions, and the number of produced  $B$  mesons  $N_{B\bar{B}}$ , assum-



TABLE II: Fitted signal event yield and fit bias in events (ev), detection efficiency  $\epsilon$ , daughter branching fraction product  $\prod \mathcal{B}_i$ , significance  $\mathcal{S}$ , and measured branching fraction  $\mathcal{B}$  with statistical error for each  $B^0$  decay mode. For the combined measurements we give the significance (with systematic uncertainties included) and the branching fraction with the statistical and systematic uncertainties (in parentheses the 90% CL upper limit). Significances greater than 7 standard deviations ( $\sigma$ ) are omitted.

Mode	Yield (ev)	Fit bias (ev)	$\epsilon$ (%)	$\prod \mathcal{B}_i$ (%)	$\mathcal{S}$ ( $\sigma$ )	$\mathcal{B}(10^{-6})$
$\eta_{\gamma\gamma}K^0$	$21_{-9}^{+10}$	0	32.1	13.6	2.5	$1.03_{-0.44}^{+0.49}$
$\eta_{3\pi}K^0$	$12_{-6}^{+7}$	0	20.6	7.9	2.5	$1.56_{-0.79}^{+0.92}$
<b><math>\eta K^0</math></b>					<b>3.5</b>	<b><math>1.15_{-0.38}^{+0.43} \pm 0.09</math> (&lt; 1.8)</b>
$\eta_{\gamma\gamma}\eta_{\gamma\gamma}$	$13_{-9}^{+10}$	+1	23.9	15.5	1.4	$0.7_{-0.5}^{+0.6}$
$\eta_{\gamma\gamma}\eta_{3\pi}$	$9_{-5}^{+6}$	+1	18.0	17.9	1.5	$0.5_{-0.3}^{+0.4}$
$\eta_{3\pi}\eta_{3\pi}$	$0.2_{-1.7}^{+2.4}$	-0.1	11.1	5.2	0.1	$0.1_{-0.6}^{+0.9}$
<b><math>\eta\eta</math></b>					<b>1.9</b>	<b><math>0.5 \pm 0.3 \pm 0.1</math> (&lt; 1.0)</b>
$\eta_{\gamma\gamma}\phi$	$0_{-5}^{+6}$	0	29.3	19.4	0.1	$0.0 \pm 0.2$
$\eta_{3\pi}\phi$	$4_{-3}^{+4}$	0	18.3	11.2	1.9	$0.4_{-0.3}^{+0.4}$
<b><math>\eta\phi</math></b>					<b>1.4</b>	<b><math>0.2 \pm 0.2 \pm 0.1</math> (&lt; 0.5)</b>
$\eta_{\gamma\gamma}\omega$	$36_{-12}^{+13}$	+3	18.7	35.1	3.4	$1.08_{-0.39}^{+0.42}$
$\eta_{3\pi}\omega$	$8_{-5}^{+7}$	+1	13.1	20.2	1.8	$0.59_{-0.40}^{+0.57}$
<b><math>\eta\omega</math></b>					<b>3.7</b>	<b><math>0.94_{-0.30}^{+0.35} \pm 0.09</math> (&lt; 1.4)</b>
$\eta'_{\eta\pi\pi}K^0$	$490_{-24}^{+25}$	-2	26.6	6.1	-	$64.9_{-3.2}^{+3.3}$
$\eta'_{\rho\gamma}K^0$	$1003 \pm 41$	+27	28.3	10.2	-	$72.4 \pm 3.0$
<b><math>\eta'K^0</math></b>					-	<b><math>68.5 \pm 2.2 \pm 3.1</math></b>
$\eta'_{\eta\pi\pi}\eta'_{\eta\pi\pi}$	$1.6_{-1.1}^{+2.1}$	0	19.9	3.1	2.2	$0.6_{-0.3}^{+0.7}$
$\eta'_{\eta\pi\pi}\eta'_{\rho\gamma}$	$8_{-7}^{+9}$	+2	19.8	10.3	0.8	$0.6_{-0.7}^{+0.9}$
<b><math>\eta'\eta'</math></b>					<b>1.0</b>	<b><math>0.6_{-0.4}^{+0.5} \pm 0.4</math> (&lt; 1.7)</b>
$\eta'_{\eta\pi\pi}\phi$	$-2_{-1}^{+2}$	0	24.4	8.6	0.0	$-0.2_{-0.1}^{+0.2}$
$\eta'_{\rho\gamma}\phi$	$5_{-7}^{+8}$	0	23.9	14.5	0.7	$0.3_{-0.4}^{+0.5}$
<b><math>\eta'\phi</math></b>					<b>0.5</b>	<b><math>0.2 \pm 0.2 \pm 0.3</math> (&lt; 1.1)</b>
$\eta'_{\eta\pi\pi}\omega$	$14_{-6}^{+7}$	+1	17.9	15.6	3.4	$1.03_{-0.46}^{+0.54}$
$\eta'_{\rho\gamma}\omega$	$16_{-15}^{+17}$	-2	15.2	26.2	1.2	$0.94_{-0.81}^{+0.91}$
<b><math>\eta'\omega</math></b>					<b>3.6</b>	<b><math>1.01_{-0.38}^{+0.46} \pm 0.09</math> (&lt; 1.8)</b>

TABLE III: Fitted signal event yield and fit bias, detection efficiency  $\epsilon$ , daughter branching fraction product  $\prod \mathcal{B}_i$ , measured branching fraction  $\mathcal{B}$ , charge asymmetry  $\mathcal{A}_{ch}$  with statistical error, and significance  $\mathcal{S}_{\mathcal{A}}$  of the charge asymmetry for each charged decay mode. For the combined measurements we give the branching fraction, the charge asymmetry and the significance of the charge asymmetry with the statistical and systematic uncertainties.

Mode	Yield (ev)	Fit bias (ev)	$\epsilon$ (%)	$\prod \mathcal{B}_i$ (%)	$\mathcal{B}(10^{-6})$	$\mathcal{A}_{ch}$	$\mathcal{S}_{\mathcal{A}}(\sigma)$
$\eta_{\gamma\gamma}\pi^+$	$286_{-30}^{+31}$	+18	35.1	39.3	$4.16_{-0.47}^{+0.48}$	$-0.02_{-0.11}^{+0.10}$	0.4
$\eta_{3\pi}\pi^+$	$95_{-18}^{+19}$	+7	23.4	22.7	$3.53_{-0.73}^{+0.77}$	$+0.06 \pm 0.18$	0.4
<b><math>\eta\pi^+</math></b>					<b><math>4.00 \pm 0.40 \pm 0.24</math></b>	<b><math>-0.03 \pm 0.09 \pm 0.03</math></b>	<b>0.3</b>
$\eta_{\gamma\gamma}K^+$	$215_{-30}^{+31}$	+21	34.0	39.3	$3.11_{-0.48}^{+0.50}$	$-0.37 \pm 0.12$	3.1
$\eta_{3\pi}K^+$	$69_{-15}^{+16}$	+6	22.9	22.7	$2.60_{-0.62}^{+0.66}$	$-0.32 \pm 0.22$	1.5
<b><math>\eta K^+</math></b>					<b><math>2.94_{-0.34}^{+0.39} \pm 0.21</math></b>	<b><math>-0.36 \pm 0.11 \pm 0.03</math></b>	<b>3.3</b>
$\eta'_{\eta\pi\pi}\pi^+$	$96_{-19}^{+20}$	+1	29.4	17.5	$4.0 \pm 0.8$	$-0.25 \pm 0.19$	1.3
$\eta'_{\rho\gamma}\pi^+$	$111_{-29}^{+31}$	+7	25.9	29.4	$2.9_{-0.8}^{+0.9}$	$+0.56_{-0.27}^{+0.29}$	2.1
<b><math>\eta'\pi^+</math></b>					<b><math>3.5 \pm 0.6 \pm 0.2</math></b>	<b><math>+0.03 \pm 0.17 \pm 0.02</math></b>	<b>0.2</b>
$\eta'_{\eta\pi\pi}K^+$	$1601_{-43}^{+44}$	-5	28.7	17.5	$68.5_{-1.8}^{+1.9}$	$-0.004 \pm 0.027$	0.2
$\eta'_{\rho\gamma}K^+$	$2991_{-71}^{+72}$	-10	29.3	29.4	$74.6 \pm 1.8$	$+0.016 \pm 0.023$	0.7
<b><math>\eta'K^+</math></b>					<b><math>71.5 \pm 1.3 \pm 3.2</math></b>	<b><math>+0.008_{-0.018}^{+0.017} \pm 0.009</math></b>	<b>0.4</b>

ing equal production rates of charged and neutral  $B$  pairs from  $\Upsilon(4S)$  decays. We correct the yields for any bias measured with the simulations. We combine results from different sub-decays by adding the values of  $-2 \ln(\mathcal{L}/\mathcal{L}_{max})$  (parameterized in terms of the branching fraction or charge asymmetry), where  $\mathcal{L}_{max}$  is the

value of  $\mathcal{L}$  at its maximum, taking into account the correlated and uncorrelated systematic errors. We report the branching fractions for the individual decay channels and their significances  $\mathcal{S}$  in units of standard deviations ( $\sigma$ ). For  $B^0 \rightarrow \eta'K_s^0$  and all charged decay modes, where the significance of the branching fraction is always

greater than  $7\sigma$ , the value of  $\mathcal{S}$  is omitted. For the combined measurements we also report the 90% confidence level (CL) upper limits of the branching fraction for the  $B^0$  modes where the significance is less than  $5\sigma$ . For charged  $B$  decays we give the combined result for the charge asymmetry  $\mathcal{A}_{ch}$  and its significance  $\mathcal{S}_{\mathcal{A}}$  in units of  $\sigma$ .

The statistical uncertainty on the signal yield and charge asymmetry is calculated as the change in the central value when the quantity  $-2\ln\mathcal{L}$  increases by one from its minimum. The significance is calculated as the square root of  $-2\ln(\mathcal{L}_0/\mathcal{L}_{max})$ , with systematic uncertainties included, where  $\mathcal{L}_0$  is the value of  $\mathcal{L}$  for zero signal events or zero value for the charge asymmetry. We determine a Bayesian 90% CL upper limit on the branching fraction, assuming a uniform prior probability distribution, by finding the branching fraction below which lies 90% of the total of the likelihood integral in the positive branching fraction region.

Figures 2 and 3 show the projections onto the  $m_{ES}$  and  $\Delta E$  variables for the four neutral decay modes that have a branching fraction significance greater than  $3\sigma$ , and for the four charged decay modes, respectively. For each decay mode we optimize a requirement on the probability ratio  $\mathcal{P}_1/(\mathcal{P}_1+\mathcal{P}_2+\mathcal{P}_3)$  in order to enhance the visibility of the signal. The probabilities  $\mathcal{P}_j$  are evaluated with-

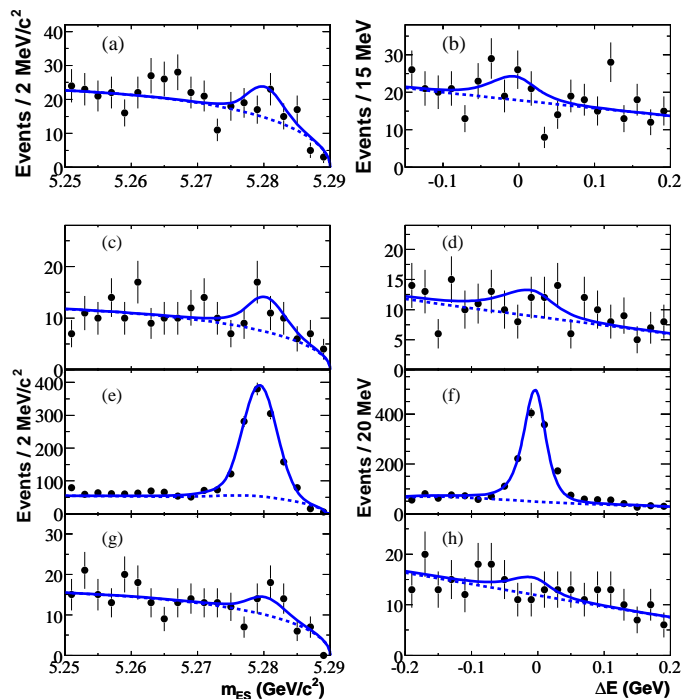


FIG. 2: The  $B^0$  candidate  $m_{ES}$  and  $\Delta E$  projections for  $\eta K_S^0$  (a, b),  $\eta\omega$  (c, d),  $\eta'K_S^0$  (e, f), and  $\eta'\omega$  (g, h) decays, with sub-decays combined. Points with errors represent the data, solid curves the full fit functions, and dashed curves the background functions.

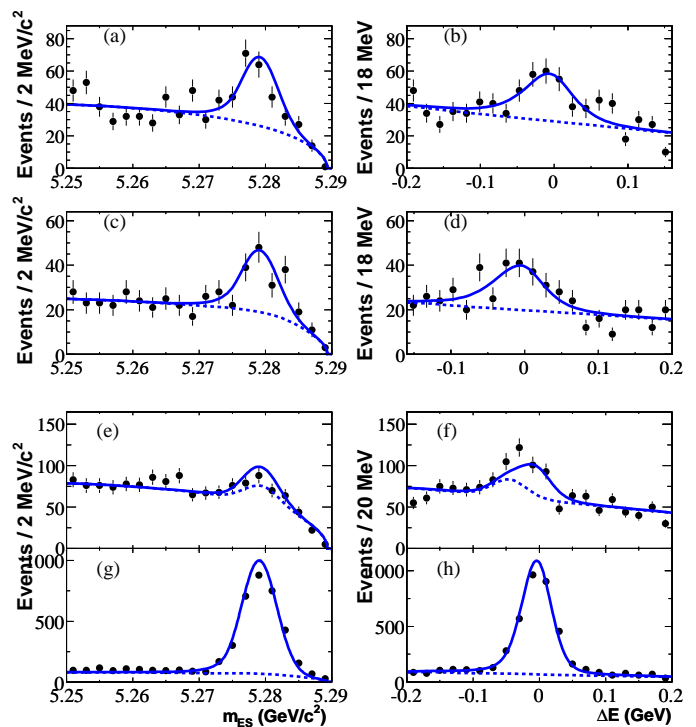


FIG. 3: The  $B^+$  candidate  $m_{ES}$  and  $\Delta E$  projections for  $\eta\pi^+$  (a, b),  $\eta K^+$  (c, d),  $\eta'\pi^+$  (e, f), and  $\eta'K^+$  (g, h) decays, with sub-decays combined. Points with errors represent the data, solid curves the full fit functions, and dashed curves the background functions.

out using the variable shown. The points show the data that satisfy such a requirement, while the solid curves show the total rescaled fit functions. In  $\eta'\omega$  decays, a fit performed on  $\omega$  mass sidebands  $m_{\pi\pi\pi} < 735 \text{ MeV}/c^2$  or  $m_{\pi\pi\pi} > 825 \text{ MeV}/c^2$  shows that contamination from possible  $B^0 \rightarrow \eta'\pi^+\pi^-\pi^0$  background is negligible.

The main sources of systematic error include ML fit bias (0–14 events) and uncertainties in the PDF parameterization (0–12 events). The ML fit bias systematic error is taken to be half of the bias, summed in quadrature with its statistical uncertainty. The uncertainties related to the PDF parameterization are obtained by varying the PDF parameters within their errors. Published world averages [21] provide the uncertainties of the  $B$ -daughter branching fractions (0–4)%. These uncertainties are the main contribution to the systematic errors of the  $B \rightarrow \eta'K$  decay modes. The uncertainty on  $N_{B\bar{B}}$  is 1.1%. Other sources of systematic uncertainty are track (1%) and neutral particle (3–6%) reconstruction efficiencies; selection efficiency uncertainties are 1% each for the  $\cos\theta_T$  and PID requirements. Using large inclusive kaon and  $B$  decay samples we estimate a systematic uncertainty for  $\mathcal{A}_{ch}$  of 0.005 due to the dependence of the reconstruction efficiency on the charge of the high momentum  $K^\pm$ . Other sources of systematic uncertainties for  $\mathcal{A}_{ch}$  are the fit bias (0–0.02) and the presence of a fit

bias in the signal yield (0.02–0.03). The systematic uncertainty due to fixing the value of the charge asymmetry in  $B\bar{B}$  background components is taken to be the largest deviation observed when varying this value of  $\pm 10\%$ , and is in range (0–0.02).

In summary we present updated measurements of branching fractions for eight  $B^0$  and four  $B^+$  decays to charmless meson pairs. The results shown in Table II and Table III are consistent with, but generally more precise than, previous measurements [2, 3] and supersede our previous ones [2]. The branching fraction results are in agreement with predictions within the theoretical uncertainties that limit discrimination between different models [4–10]. We find evidence for three  $B^0$  decay modes:  $\eta K^0$  ( $3.5\sigma$ ),  $\eta\omega$  ( $3.7\sigma$ ) and  $\eta'\omega$  ( $3.6\sigma$ ). In the decay mode  $B^+ \rightarrow \eta K^+$  we find evidence at  $3.3\sigma$  for non-zero charge asymmetry, in agreement with theoretical predictions [6, 9, 19]. Discrimination between QCD factorization [6] and flavor SU(3) [9] symmetry models, based on the relative sign of the charge asymmetry in  $B^+ \rightarrow \eta K^+$  and  $B^+ \rightarrow \eta' K^+$  decays, is limited by the accuracy of the latter measurement. The measurement of  $\mathcal{A}_{ch}$  for  $\eta'\pi^+$  shows a slightly better agreement with the QCD factorization prediction [6] than with the flavor SU(3) symmetry based model [9], within large theoretical

and experimental uncertainties.

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