

## Measurements of Branching Fractions and $CP$ -Violating Asymmetries in $B^0 \rightarrow \rho^\pm h^\mp$ Decays

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We present measurements of branching fractions and  $CP$ -violating asymmetries in  $B^0 \rightarrow \rho^\pm \pi^\mp$  and  $B^0 \rightarrow \rho^- K^+$  decays. The results are obtained from a data sample of  $88.9 \times 10^6 T(4S) \rightarrow B\bar{B}$  decays collected with the BABAR detector at the PEP-II asymmetric-energy  $B$  Factory at SLAC. From a time-dependent maximum likelihood fit we measure the charge-averaged branching fractions  $\mathcal{B}(B^0 \rightarrow \rho^\pm \pi^\mp) = (22.6 \pm 1.8 \text{ (stat)} \pm 2.2 \text{ (syst)}) \times 10^{-6}$  and  $\mathcal{B}(B^0 \rightarrow \rho^- K^+) = (7.3^{+1.3}_{-1.2} \pm 1.3) \times 10^{-6}$ ;

and the  $CP$ -violating charge asymmetries  $A_{CP}^{\rho\pi} = -0.18 \pm 0.08 \pm 0.03$  and  $A_{CP}^{\rho K} = 0.28 \pm 0.17 \pm 0.08$ ; the direct  $CP$  violation parameter  $C_{\rho\pi} = 0.36 \pm 0.18 \pm 0.04$  and the mixing-induced  $CP$  violation parameter  $S_{\rho\pi} = 0.19 \pm 0.24 \pm 0.03$ ; and the dilution parameters  $\Delta C_{\rho\pi} = 0.28_{-0.19}^{+0.18} \pm 0.04$  and  $\Delta S_{\rho\pi} = 0.15 \pm 0.25 \pm 0.03$ .

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In the Standard Model,  $CP$ -violating effects arise from a single complex phase in the three-generation Cabibbo-Kobayashi-Maskawa quark-mixing matrix [1]. One of the central, unresolved questions is whether this mechanism is sufficient to explain the pattern of  $CP$  violation observed in nature. We present here a simultaneous measurement of branching fractions and  $CP$ -violating asymmetries in the decays  $B^0 \rightarrow \rho^\pm \pi^\mp$  and  $B^0 \rightarrow \rho^- K^+$  (and their charge conjugates). The BABAR and Belle experiments have performed searches for  $CP$ -violating asymmetries in  $B$  decays to  $\pi^+ \pi^-$  [3, 4], where the mixing-induced  $CP$  asymmetry is related to the angle  $\alpha \equiv \arg[-V_{td} V_{tb}^* / V_{ud} V_{ub}^*]$  of the Unitarity Triangle as it is for  $\rho^\pm \pi^\mp$ . However, unlike  $\pi^+ \pi^-$ ,  $\rho^\pm \pi^\mp$  is not a  $CP$  eigenstate, and four flavor-charge configurations ( $B^0(\bar{B}^0) \rightarrow \rho^\pm \pi^\mp$ ) must be considered. Although this leads to a more complicated analysis, it benefits from a branching fraction that is nearly five times larger [5, 6].

Following a quasi-two-body approach [7], we restrict the analysis to the two regions of the  $\pi^\mp \pi^0 h^\pm$  Dalitz plot ( $h = \pi$  or  $K$ ) that are dominated by either  $\rho^+ h^-$  or  $\rho^- h^+$ . With  $\Delta t \equiv t_{\rho h} - t_{\text{tag}}$  defined as the proper time interval between the decay of the reconstructed  $B_{\rho h}^0$  and that of the other meson  $B_{\text{tag}}^0$ , the time-dependent decay rates are given by

$$f_{Q_{\text{tag}}}^{\rho^\pm h^\mp}(\Delta t) = (1 \pm A_{CP}^{\rho h}) \frac{e^{-|\Delta t|/\tau}}{4\tau} \quad (1)$$

$$\times \left[ 1 + Q_{\text{tag}}(S_{\rho h} \pm \Delta S_{\rho h}) \sin(\Delta m_d \Delta t) - Q_{\text{tag}}(C_{\rho h} \pm \Delta C_{\rho h}) \cos(\Delta m_d \Delta t) \right],$$

where  $Q_{\text{tag}} = 1(-1)$  when the tagging meson  $B_{\text{tag}}^0$  is a  $B^0(\bar{B}^0)$ ,  $\tau$  is the mean  $B^0$  lifetime, and  $\Delta m_d$  is the  $B^0 \bar{B}^0$  oscillation frequency. The time- and flavor-integrated charge asymmetries  $A_{CP}^{\rho\pi}$  and  $A_{CP}^{\rho K}$  measure direct  $CP$  violation. For the  $\rho\pi$  mode, the quantities  $S_{\rho\pi}$  and  $C_{\rho\pi}$  parameterize mixing-induced  $CP$  violation related to the angle  $\alpha$ , and flavor-dependent direct  $CP$  violation, respectively. The parameters  $\Delta C_{\rho\pi}$  and  $\Delta S_{\rho\pi}$  are insensitive to  $CP$  violation.  $\Delta C_{\rho\pi}$  describes the asymmetry between the rates  $\Gamma(B^0 \rightarrow \rho^+ \pi^-) + \Gamma(\bar{B}^0 \rightarrow \rho^- \pi^+)$  and  $\Gamma(B^0 \rightarrow \rho^- \pi^+) + \Gamma(\bar{B}^0 \rightarrow \rho^+ \pi^-)$ , while  $\Delta S_{\rho\pi}$  is related to the strong phase difference between the amplitudes contributing to  $B^0 \rightarrow \rho\pi$  decays. More precisely, one finds the relations  $S_{\rho\pi} \pm \Delta S_{\rho\pi} = \sqrt{1 - (C_{\rho\pi} \pm \Delta C_{\rho\pi})^2} \sin(2\alpha_{\text{eff}}^\pm \pm \delta)$ , where  $2\alpha_{\text{eff}}^\pm = \arg[(q/p)(\bar{A}_{\rho\pi}^\pm / A_{\rho\pi}^\pm)]$ ,  $\delta = \arg[A_{\rho\pi}^- / A_{\rho\pi}^+]$ ,  $\arg[q/p]$

is the  $B^0 \bar{B}^0$  mixing phase, and  $A_{\rho\pi}^+(\bar{A}_{\rho\pi}^+)$  and  $A_{\rho\pi}^-(\bar{A}_{\rho\pi}^-)$  are the transition amplitudes of the processes  $B^0(\bar{B}^0) \rightarrow \rho^+ \pi^-$  and  $B^0(\bar{B}^0) \rightarrow \rho^- \pi^+$ , respectively. The angles  $\alpha_{\text{eff}}^\pm$  are equal to  $\alpha$  in the absence of contributions from penguin amplitudes. For the self-tagging  $\rho K$  mode, the values of the four time-dependent parameters are  $C_{\rho K} = 0$ ,  $\Delta C_{\rho K} = -1$ ,  $S_{\rho K} = 0$ , and  $\Delta S_{\rho K} = 0$ .

The data used in this analysis were accumulated with the BABAR detector [8], at the PEP-II asymmetric-energy  $e^+ e^-$  storage ring at SLAC. The sample consists of  $(88.9 \pm 1.0) \times 10^6$   $B\bar{B}$  pairs collected at the  $\Upsilon(4S)$  resonance (“on-resonance”), and an integrated luminosity of  $9.6 \text{ fb}^{-1}$  collected about 40 MeV below the  $\Upsilon(4S)$  (“off-resonance”). In Ref. [8] we describe the silicon vertex tracker and drift chamber used for track and vertex reconstruction, the Cherenkov detector (DIRC), the electromagnetic calorimeter (EMC), and their use in particle identification (PID).

We reconstruct  $B_{\rho h}^0$  candidates from combinations of two tracks and a  $\pi^0$  candidate. We require that the PID of both tracks be inconsistent with the electron hypothesis, and the PID of the track used to form the  $\rho$  be inconsistent with the kaon hypothesis. The  $\pi^0$  candidate mass must satisfy  $0.11 < m(\gamma\gamma) < 0.16 \text{ GeV}/c^2$ , where each photon is required to have an energy greater than 50 MeV in the laboratory frame and to exhibit a lateral profile of energy deposition in the EMC consistent with an electromagnetic shower. The mass of the  $\rho$  candidate must satisfy  $0.4 < m(\pi^\pm \pi^0) < 1.3 \text{ GeV}/c^2$ . To avoid the interference region, the  $B$  candidate is rejected if both the  $\pi^+ \pi^0$  and  $\pi^- \pi^0$  pairs satisfy this requirement. Taking advantage of the helicity structure of  $B \rightarrow \rho h$  decays ( $h$  is denoted *bachelor track* hereafter), we require  $|\cos\theta_\pi| > 0.25$ , where  $\theta_\pi$  is the angle between the  $\pi^0$  momentum and the negative  $B$  momentum in the  $\rho$  rest frame. The bachelor track from the  $\rho h$  decay must have a  $e^+ e^-$  center-of-mass (CM) momentum above  $2.4 \text{ GeV}/c$ .

For 86% of the  $B^0 \rightarrow \rho h$  decays that pass the event selection, the pion from the  $\rho$  has momentum below this value, and thus the charge of the  $\rho$  is determined unambiguously. For the remaining events, the charge of the  $\rho$  is taken to be that of the  $\pi^\pm \pi^0$  combination with mass closer to the  $\rho$  mass. With this procedure, 5% of the selected simulated signal events are assigned an incorrect charge.

To reject background from two-body  $B$  decays, the invariant masses of the  $\pi^\pm h^\mp$  and  $h^\pm \pi^0$  combinations must each be less than  $5.14 \text{ GeV}/c^2$ . Two kinematic variables allow the discrimination of signal- $B$  decays from fake- $B$

decays due to random combinations of tracks and  $\pi^0$  candidates. One variable is the difference,  $\Delta E$ , between the CM energy of the  $B$  candidate and  $\sqrt{s}/2$ , where  $\sqrt{s}$  is the total CM energy. The other variable is the beam-energy-substituted mass  $m_{ES} \equiv \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}$ , where the  $B$  momentum  $\mathbf{p}_B$  and the four-momentum of the initial state ( $E_i$ ,  $\mathbf{p}_i$ ) are defined in the laboratory frame. The  $\Delta E$  distribution for  $\rho\pi$  ( $\rho K$ ) signal peaks around 0 ( $-45$ ) MeV since the pion mass is always assigned to the bachelor track. We require  $5.23 < m_{ES} < 5.29$  GeV/ $c^2$  and  $-0.12 < \Delta E < 0.15$  GeV, where the asymmetric  $\Delta E$  window suppresses higher-multiplicity  $B$  background, which leads to mostly negative  $\Delta E$  values. Discrimination between  $\rho\pi$  and  $\rho K$  events is provided by the Cherenkov angle  $\theta_C$  and, to a lesser extent, by  $\Delta E$ .

Continuum  $e^+e^- \rightarrow q\bar{q}$  ( $q = u, d, s, c$ ) events are the dominant background. To enhance discrimination between signal and continuum, we use a neural network (NN) to combine four discriminating variables: the reconstructed  $\rho$  mass,  $\cos\theta_\pi$ , and the two event-shape variables that are used in the Fisher discriminant of Ref. [3]. The NN is trained in the signal region with off-resonance data and simulated signal events. The final sample of signal candidates is selected with a cut on the NN output that retains  $\sim 65\%$  (5%) of the signal (continuum).

Approximately 23% (20%) of simulated  $\rho\pi$  ( $\rho K$ ) events have more than one  $\rho h$  candidate passing the selection criteria. In these cases, we choose the candidate with the reconstructed  $\pi^0$  mass closest to the nominal  $\pi^0$  mass. A total of 20,497 events pass all selection criteria. The signal efficiency determined from Monte Carlo (MC) simulation is 20.7% (18.5%) for  $\rho\pi$  ( $\rho K$ ) events; 31% (30%) of the selected events are misreconstructed, mostly due to combinatorial- $\pi^0$  background.

We use MC-simulated events to study the cross-feed from other  $B$  decays. The charmless modes are grouped into eleven classes with similar kinematic and topological properties. Two additional classes account for the neutral and charged  $b \rightarrow c$  decays. For each of the background classes, a component is introduced into the likelihood, with a fixed number of events. In the selected  $\rho\pi$  ( $\rho K$ ) samples we expect  $6 \pm 1$  ( $20 \pm 2$ ) charmless two-body background events,  $93 \pm 23$  ( $87 \pm 22$ ) charmless three-body background events,  $118 \pm 65$  ( $36 \pm 18$ ) charmless four-body background events, and  $266 \pm 43$  ( $54 \pm 11$ )  $b \rightarrow c$  events. Backgrounds from two-, three-, and four-body decays to  $\rho\pi$  are dominated by  $B^+ \rightarrow \pi^+\pi^0$ ,  $B^+ \rightarrow \rho^0\pi^+$ , and longitudinally polarized  $B^0 \rightarrow \rho^+\rho^-$  decays. The  $\rho K$  sample receives its dominant two-body background from  $B^+ \rightarrow K^+\pi^0$ , and its dominant three- and four-body background from  $B \rightarrow K^*\pi$  and higher kaon resonances, estimated from inclusive  $B \rightarrow K\pi\pi$  measurements.

The time difference  $\Delta t$  is obtained from the measured distance between the  $z$  positions (along the beam direction) of the  $B_{\rho h}^0$  and  $B_{\text{tag}}^0$  decay vertices, and the boost  $\beta\gamma = 0.56$  of the  $e^+e^-$  system [3, 9]. To determine the

flavor of the  $B_{\text{tag}}^0$  we use the tagging algorithm of Ref. [9]. This produces four mutually exclusive tagging categories. We also retain untagged events in a fifth category to improve the efficiency of the signal selection and the sensitivity to charge asymmetries. Correlations between the  $B$  flavor tag and the charge of the reconstructed  $\rho h$  candidate are observed in various  $B$ -background channels and evaluated with MC simulation.

We use an unbinned extended maximum likelihood fit to extract the  $\rho\pi$  and  $\rho K$  event yields, the  $CP$  parameters and the other parameters defined in Eq. (1). The likelihood for the  $N_k$  candidates  $i$  tagged in category  $k$  is

$$\mathcal{L}_k = e^{-N'_k} \prod_{i=1}^{N_k} \sum_h^{\pi, K} \left\{ N^{\rho h} \epsilon_k \mathcal{P}_{i,k}^{\rho h} + N_k^{q\bar{q},h} \mathcal{P}_{i,k}^{q\bar{q},h} + \sum_{j=1}^{N_B} \mathcal{L}_{ij,k}^{B,h} \right\} \quad (2)$$

where  $N'_k$  is the sum of the signal and continuum yields (to be determined by the fit) and the fixed  $B$ -background yields,  $N^{\rho h}$  is the number of signal events of type  $\rho h$  in the entire sample,  $\epsilon_k$  is the fraction of signal events tagged in category  $k$ , and  $N_k^{q\bar{q},h}$  is the number of continuum background events with bachelor track of type  $h$  that are tagged in category  $k$ . The total likelihood  $\mathcal{L}$  is the product of likelihoods for each tagging category.

The probability density functions (PDFs)  $\mathcal{P}_k^{\rho h}$ ,  $\mathcal{P}_k^{q\bar{q},h}$  and the likelihood terms  $\mathcal{L}_{j,k}^{B,h}$  are the product of the PDFs of five discriminating variables. The signal PDF is thus given by  $\mathcal{P}_k^{\rho h} = \mathcal{P}_k^{\rho h}(m_{ES}) \cdot \mathcal{P}_k^{\rho h}(\Delta E) \cdot \mathcal{P}_k^{\rho h}(\text{NN}) \cdot \mathcal{P}_k^{\rho h}(\theta_C) \cdot \mathcal{P}_k^{\rho h}(\Delta t)$ , where  $\mathcal{P}_k^{\rho h}(\Delta t)$  contains the measured physics quantities defined in Eq. (1), diluted by the effects of mistagging and the  $\Delta t$  resolution. The PDF of the continuum contribution with bachelor track  $h$  is denoted  $\mathcal{P}_k^{q\bar{q},h}$ . The likelihood term  $\mathcal{L}_{j,k}^{B,h}$  corresponds to the  $B$ -background contribution  $j$  of the  $N_B$  categories.

The signal PDFs are decomposed into three parts with distinct distributions: signal events that are correctly reconstructed, misreconstructed signal events with right-sign  $\rho$  charge, and misreconstructed signal events with wrong-sign  $\rho$  charge. Their individual fractions are estimated by MC simulation. The  $m_{ES}$ ,  $\Delta E$ , and NN output PDFs for signal and  $B$  background are taken from the simulation except for the means of the signal Gaussian PDFs for  $m_{ES}$  and  $\Delta E$ , which are free to vary in the fit. The continuum PDFs are described by six free parameters. The  $\theta_C$  PDF is modeled as in Ref. [3]. The  $\Delta t$ -resolution function for signal and  $B$ -background events is a sum of three Gaussian distributions, with parameters determined from a fit to fully reconstructed  $B^0$  decays [9]. The continuum  $\Delta t$  distribution is parameterized as the sum of three Gaussian distributions with common mean, two relative fractions, and three distinct widths that scale the  $\Delta t$  event-by-event error, yielding six free parameters. For continuum, two charge asymmetries and the ten parameters  $N_k^{q\bar{q},h}$  are free. A total of 34 parameters, including signal yields and the parameters from

TABLE I: Summary of the systematic uncertainties.

Error source	$N^{\rho K}$	$N^{\rho\pi}$	$A_{CP}^{\rho K}$	$A_{CP}^{\rho\pi}$	$C_{\rho\pi}$	$\Delta C_{\rho\pi}$	$S_{\rho\pi}$	$\Delta S_{\rho\pi}$
	(events)		(in units of $10^{-2}$ )					
$\Delta m_d$ and $\tau$	0.1	0.1	0.0	0.0	0.4	0.4	0.2	0.1
$\Delta t$ PDF	1.2	1.9	0.4	0.2	1.4	0.8	1.5	1.2
Signal model	4.0	13.1	1.2	0.8	0.7	0.8	1.4	1.0
Particle ID	0.6	0.7	0.5	0.2	0.1	0.1	0.1	0.1
Fit procedure	8.0	15.7	0.4	0.2	0.4	0.4	0.4	0.3
DCS decays	0.0	0.3	0.0	0.1	2.2	2.2	0.8	0.7
$B$ background	16.0	14.2	7.9	2.8	3.0	3.5	2.1	1.8
Total	18.4	25.0	8.0	2.9	4.1	4.3	3.1	2.5

Eq. (1), are varied in the fit.

The contributions to the systematic error on the signal parameters are summarized in Table I. The uncertainties associated with  $\Delta m_d$  and  $\tau$  are estimated by varying these parameters within the uncertainty on the world average [10]. The uncertainties due to the signal model are obtained from a control sample of fully reconstructed  $B^0 \rightarrow D^- \rho^+$  decays. We perform fits on large MC samples with the measured proportions of  $\rho\pi/\rho K$  signal, and continuum and  $B$  backgrounds. Biases observed in these tests are due to imperfections in the PDF model; *e.g.*, unaccounted correlations between the discriminating variables of the signal and  $B$ -background PDFs. The biases are added in quadrature and assigned as a systematic uncertainty of the fit procedure. The systematic errors due to interference between the doubly-Cabibbo-suppressed (DCS)  $\bar{b} \rightarrow \bar{u}c\bar{d}$  amplitude with the Cabibbo-favored  $b \rightarrow \bar{c}u\bar{d}$  amplitude for tag-side  $B$  decays have been estimated from simulation by varying freely all relevant strong phases [11].

The main source of systematic uncertainty is the  $B$ -background model. The expected event yields from the background modes are varied according to the uncertainties in the measured or estimated branching fractions. Systematic errors due to possible nonresonant  $B^0 \rightarrow \pi^+ \pi^- \pi^0$  decays are derived from experimental limits [5]. Repeating the fit without using the  $\rho$ -candidate mass and helicity angle gives results that are compatible with those reported here. Since  $B$ -background modes may exhibit  $CP$  violation, the corresponding parameters are varied within their physical ranges.

The maximum likelihood fit results in the event yields  $N^{\rho\pi} = 428_{-33}^{+34}$  and  $N^{\rho K} = 120_{-20}^{+21}$ , where the errors are statistical. Correcting the yields by a small fit bias determined using the MC simulation (3% for  $\rho\pi$  and 0% for  $\rho K$ ), we find for the branching fractions

$$\begin{aligned} \mathcal{B}(B^0 \rightarrow \rho^\pm \pi^\mp) &= (22.6 \pm 1.8 \pm 2.2) \times 10^{-6}, \\ \mathcal{B}(B^0 \rightarrow \rho^- K^+) &= (7.3_{-1.2}^{+1.3} \pm 1.3) \times 10^{-6}, \end{aligned}$$

where the first errors are statistical and the second systematic. The systematic errors include an uncertainty of

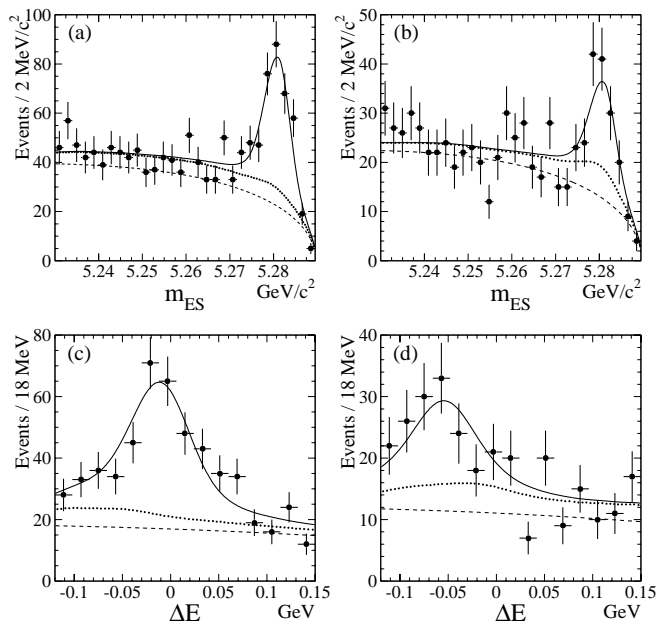


FIG. 1: Distributions of  $m_{ES}$  and  $\Delta E$  for samples enhanced in  $\rho\pi$  signal (a,c) and  $\rho K$  signal (b,d). The solid curve represents a projection of the maximum likelihood fit result. The dashed curve represents the contribution from continuum events, and the dotted line indicates the combined contributions from continuum events and  $B$ -related backgrounds.

7.7% for efficiency corrections, dominated by the uncertainty in the  $\pi^0$  reconstruction efficiency. Figure 1 shows distributions of  $m_{ES}$  and  $\Delta E$ , enhanced in signal content by cuts on the signal-to-continuum likelihood ratios of the other discriminating variables. For the  $CP$ -violating parameters, we obtain

$$\begin{aligned} A_{CP}^{\rho\pi} &= -0.18 \pm 0.08 \pm 0.03, & A_{CP}^{\rho K} &= 0.28 \pm 0.17 \pm 0.08, \\ C_{\rho\pi} &= 0.36 \pm 0.18 \pm 0.04, & S_{\rho\pi} &= 0.19 \pm 0.24 \pm 0.03. \end{aligned}$$

For the other parameters in the description of the  $B^0(\bar{B}^0) \rightarrow \rho\pi$  decay-time dependence, we find

$$\Delta C_{\rho\pi} = 0.28_{-0.19}^{+0.18} \pm 0.04, \quad \Delta S_{\rho\pi} = 0.15 \pm 0.25 \pm 0.03.$$

We find the linear correlation coefficients  $c_{C,\Delta C} = 0.18$  and  $c_{S,\Delta S} = 0.23$ , while all other correlations are smaller. As a validation of our treatment of the time dependence we allow  $\tau$  and  $\Delta m_d$  to vary in the fit. We find  $\tau = (1.64 \pm 0.13)$  ps and  $\Delta m_d = (0.52 \pm 0.12)$  ps<sup>-1</sup>; the remaining free parameters are consistent with the nominal fit. The raw time-dependent asymmetry  $A_{B^0/\bar{B}^0} = (N_{B^0} - N_{\bar{B}^0}) / (N_{B^0} + N_{\bar{B}^0})$  in the tagging categories dominated by kaons and leptons is represented in Fig. 2.

In summary, we have presented measurements of branching fractions and  $CP$ -violating asymmetries in  $B^0 \rightarrow \rho^\pm \pi^\mp$  and  $\rho^- K^+$  decays. We do not observe direct or mixing-induced  $CP$  violation in the time-dependent asymmetry of  $B^0 \rightarrow \rho^\pm \pi^\mp$  decays and there is no evidence for direct  $CP$  violation in  $B^0 \rightarrow \rho^- K^+$ .

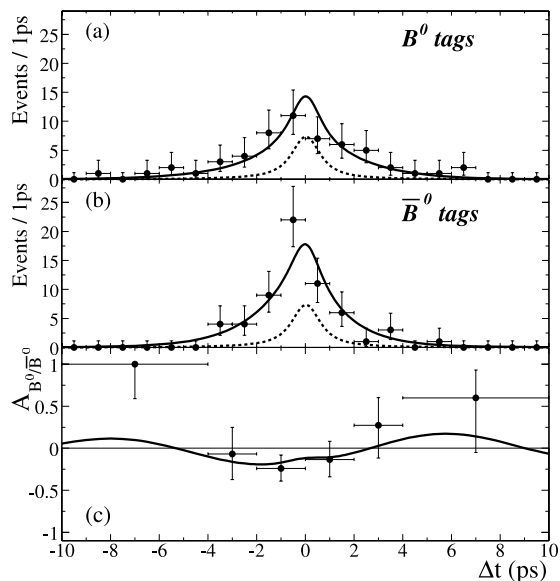


FIG. 2: Time distributions for events selected to enhance the  $\rho\pi$  signal tagged as (a)  $B_{\text{tag}}^0$  and (b)  $\bar{B}_{\text{tag}}^0$ , and (c) time-dependent asymmetry between  $B_{\text{tag}}^0$  and  $\bar{B}_{\text{tag}}^0$ . The solid curve is a likelihood projection of the fit result. The dashed line is the total  $B$ - and continuum-background contribution.

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