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Measurements of Branching Fractions and *CP*-Violating Asymmetries in $B^0 \to \rho^{\pm} h^{\mp}$ Decays

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We present measurements of branching fractions and CP-violating asymmetries in $B^0 \to \rho^\pm\pi^\mp$ and $B^0 \to \rho^- K^+$ decays. The results are obtained from a data sample of 88.9×10^6 $\Upsilon(4S) \to B\overline{B}$ decays collected between 1999 and 2002 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 $\mathcal{B}(B^0 \to \rho^\pm\pi^\mp) = (22.6 \pm 1.8\,(\text{stat}) \pm 2.2\,(\text{syst})) \times 10^{-6}$ and $\mathcal{B}(B^0 \to$

$\rho^- K^+) = (7.3\,^{+1.3}_{-1.2} \pm 1.3) \times 10^{-6}$; 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 $S_{\rho\pi} = 0.19 \pm 0.24 \pm 0.03$; the dilution parameters $\Delta C_{\rho\pi} = 0.28\,^{+0.18}_{-0.19} \pm 0.04$ 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. The *BABAR* and Belle experiments have performed searches for *CP*-violating asymmetries in B decays to $\pi^+\pi^-$ [2, 3], 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.

We present herein a simultaneous measurement of branching fractions and *CP*-violating asymmetries in the decays $B^0 \to \rho^\pm\pi^\mp$ and $B^0 \to \rho^- K^+$ (and their charge conjugate). The $\rho^\pm\pi^\mp$ mode provides a probe of both mixing-induced and direct *CP* violation [4], whereas the self-tagging $\rho^- K^+$ can only exhibit direct *CP* violation. As in the case of $\pi^+\pi^-$, the mixing-induced *CP* violation is related to the angle α. However, unlike $\pi^+\pi^-$, $\rho^\pm\pi^\mp$ is not a *CP* eigenstate, and four flavor-charge configurations ($B^0(\overline{B}^0) \to \rho^\pm\pi^\mp$) 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 $\Delta t \equiv t_{\rho h} - t_{\rm tag}$ defined as the proper time interval between the decay of the reconstructed $B^0_{\rho h}$ and that of the other meson $B^0_{\rm tag}$, the time-dependent decay rates are given by

$$f_{Q_{\rm tag}}^{\rho^\pm h^\mp}(\Delta t) = (1 \pm A_{CP}^{\rho h})\frac{e^{-|\Delta t|/\tau}}{4\tau} \times \Big[1 + Q_{\rm tag}(S_{\rho h} \pm \Delta S_{\rho h})\sin(\Delta m_d \Delta t) - Q_{\rm tag}(C_{\rho h} \pm \Delta C_{\rho h})\cos(\Delta m_d \Delta t)\Big] , \quad (1)$$

where $Q_{\rm tag} = 1(-1)$ when the tagging meson $B^0_{\rm tag}$ is a $B^0(\overline{B}^0)$, τ is the mean B^0 lifetime, and Δm_d the mixing frequency due to the eigenstate mass difference. The time-integrated and flavor-integrated charge asymmetries $A_{CP}^{\rho\pi}$ and $A_{CP}^{\rho K}$ measure direct *CP* violation. The time dependence is described by four additional parameters. For the $\rho\pi$ mode, the quantities $S_{\rho\pi}$ and $C_{\rho\pi}$ parameterize mixing-induced *CP* violation related to the angle α, 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 $\Gamma(B^0 \to \rho^+\pi^-) + \Gamma(\overline{B}^0 \to \rho^-\pi^+)$ and $\Gamma(B^0 \to \rho^-\pi^+) + \Gamma(\overline{B}^0 \to \rho^+\pi^-)$, while $\Delta S_{\rho\pi}$ is related to the strong phase difference between the amplitudes contributing to $B^0 \to \rho\pi$ decays. More precisely, one finds the relations $S_{\rho\pi} \pm \Delta S_{\rho\pi} = \sqrt{1-(C_{\rho\pi} \pm \Delta C_{\rho\pi})^2}\,\sin(2\alpha_{\rm eff}^\pm \pm \delta)$, where $2\alpha_{\rm eff}^\pm = \arg[q\,p^*\overline{A}_{\rho\pi}^\pm A_{\rho\pi}^{\mp *}]$, $\delta = \arg[A_{\rho\pi}^- A_{\rho\pi}^{+*}]$, $\arg[q\,p^*]$ is the $B^0\overline{B}^0$ mixing phase, and $A_{\rho\pi}^+(\overline{A}_{\rho\pi}^+)$ and $A_{\rho\pi}^-(\overline{A}_{\rho\pi}^-)$ are the transition amplitudes of the processes $B^0(\overline{B}^0) \to \rho^+\pi^-$ and $B^0(\overline{B}^0) \to \rho^-\pi^+$, respectively. The angles $\alpha_{\rm eff}^\pm$ are equal to α in the absence of contributions from penguin amplitudes. For the ρK 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 between 1999 and 2002 with the *BABAR* detector [8], at the PEP-II asymmetric-energy e^+e^- storage ring at SLAC. The sample consists of $(88.9 \pm 1.0) \times 10^6$ $B\overline{B}$ pairs collected at the $\Upsilon(4S)$ resonance ("on-resonance"), and an integrated luminosity of 9.6 fb^{-1} collected about 40 MeV below the $\Upsilon(4S)$ ("off-resonance"). In Ref. [8] we describe the two-stage vertexing and tracking system, the Cherenkov detector (DIRC), the electromagnetic calorimeter (EMC), and their use for the implementation of particle identification (PID).

We reconstruct $B^0_{\rho h}$ candidates from combinations of two tracks and a π^0 candidate. We require that the PID of both tracks be inconsistent with electron, and of the track used to form the ρ candidate be inconsistent with kaon. The π^0 candidate mass must satisfy $0.11 < m(\gamma\gamma) < 0.16$ 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 ρ candidate must satisfy $0.4 < m(\pi^\pm\pi^0) < 1.3$ 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 $B \to \rho h$ decays (h is denoted *bachelor track* hereafter), we require $|\cos\theta_\pi| > 0.25$, where θ_π is the angle between the π^0 momentum and the negative B momentum in the ρ rest frame. The bachelor track from the ρh decay must have a CM momentum above 2.4 GeV/c. For 86% of the $B^0 \to \rho h$ decays that pass the event selection, the pion from the ρ has a momentum below this value, and thus the charge of the ρ is determined unambiguously. For the remaining events, the charge of the ρ is taken to be that of the $\pi^\pm\pi^0$ combination with mass closer to the ρ mass [10]. With this

procedure, 5% of the selected simulated signal events are assigned an incorrect charge.

To reject two-body B background, the invariant masses of the $\pi^{\pm}h^{\mp}$ and $h^{\pm}\pi^0$ combinations must each be less than 5.14 GeV/c^2. Two kinematic variables allow the discrimination of signal B from fake B candidates due to random combinations of tracks and π^0 candidates. One variable is the difference, ΔE, between the center-of-mass (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 ΔE distribution for $\rho\pi$ (ρK) 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 ΔE window suppresses the high multiplicity B-background which leads to mostly negative ΔE values. Discrimination between $\rho\pi$ and ρK events is provided by the DIRC.

Continuum $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) events are the dominant background to charmless B decays. To enhance discrimination between signal and continuum, we use a neural network (NN) to combine four discriminating variables: the reconstructed ρ mass, $\cos\theta_\pi$, and the two event-shape variables that are used in the Fisher discriminant of Ref. [2]. 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 which retains $\sim 65\%$ (5%) of the signal (continuum).

Approximately 23% (20%) of the $\rho\pi$ (ρK) events have more than one candidate passing the selection criteria. In these cases, we choose the candidate with the reconstructed π^0 mass closest to the nominal π^0 mass [10]. A total of 20,497 events pass all selection criteria and enter a likelihood fit. The signal efficiency determined from Monte Carlo (MC) simulation is 20.7% (18.5%) for $\rho\pi$ (ρK) events; 31% (30%) of the selected events are misreconstructed, mostly due to combinatorial photon background to the π^0.

We use MC-simulated events to study the cross-feed from other B decays. The branching fractions of unmeasured decay channels are estimated within conservative error ranges. We group the charmless modes into eleven classes with similar kinematic and topological properties. Two additional classes account for the neutral and charged $b \to c$ decays. For each of the background classes, a component is introduced into the likelihood, with a fixed number of events. In the selected $\rho\pi$ (ρK) samples, we expect 6 ± 1 (20 ± 2) B decays into two bodies, 93 ± 23 (87 ± 22) three-body events, 118 ± 65 (36 ± 18) four-body events and 266 ± 43 (54 ± 11) $b \to c$ events. Backgrounds from two-, three-, and four-body decays to $\rho\pi$ are dominated by $B^+ \to \pi^+\pi^0$, $B^+ \to \rho^0\pi^+$, and longitudinally polarized $B^0 \to \rho^+\rho^-$ decays, respectively. The ρK sample receives dominant two-body background from $B^+ \to K^+\pi^0$ and three and four-body background from $B \to K^*\pi$ and higher kaonic resonances, estimated from inclusive $B \to K\pi\pi$ measurements. The time difference Δt is obtained from the measured distance between the z positions (along the beam direction) of the $B^0_{\rho h}$ and $B^0_{\rm tag}$ decay vertices, and the boost $\beta\gamma = 0.56$ of the e^+e^- system [2, 9]. To determine the flavor of the $B^0_{\rm tag}$ 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 sensitivity to charge asymmetries. Correlations between the B flavor tag and the charge of the reconstructed ρh candidate are observed in various B-background channels and evaluated with MC simulation. For neutral B background modes we assume as central values $A^h_{CP} = S_h = \Delta S_h = C_h = 0$, and vary them for systematic studies.

The $\rho\pi$ and ρK event yields, the CP parameters and the other parameters defined in Eq. 1 are determined by minimizing the quantity $-2\ln\mathcal{L}$, where

$$\mathcal{L} = \prod_{k=1}^{5} e^{-N'_k} \prod_{i=1}^{N_k} \sum_{h}^{\pi,K} \left\{ N^{\rho h}\epsilon_k \mathcal{P}^{\rho h}_{i,\,k} + N^{q\rho h}_k \mathcal{P}^{q\rho h}_{i,\,k} + \sum_{j=1}^{N_B} \mathcal{L}^{B,h}_{ij,\,k} \right\} \tag{2}$$

is the total extended likelihood over all tagging categories k with events i per tagging category, N'_k (N_k) is the expected (observed) number of events in category k, $N^{\rho h}$ is the number of signal events of type ρh in the entire sample, ϵ_k is the fraction of signal events that are tagged in category k, and $N^{q\rho h}_k$ is the number of continuum background events with bachelor track of type h that are tagged in category k. The probability density functions (PDFs) $\mathcal{P}^{\rho h}_k$, $\mathcal{P}^{q\rho h}_k$ and the likelihood terms $\mathcal{L}^{B,h}_{j,\,k}$ are the product of the PDFs of five discriminating variables. The signal PDF is thus given by $\mathcal{P}^{\rho h}_k = \mathcal{P}^{\rho h}(m_{ES}) \cdot \mathcal{P}^{\rho h}(\Delta E) \cdot \mathcal{P}^{\rho h}(\mathrm{NN}) \cdot \mathcal{P}^{\rho h}(\theta_C) \cdot \mathcal{P}^{\rho h}_k(\Delta t)$, where $\mathcal{P}^{\rho h}_k(\Delta t)$ contains the measured physics quantities defined in Eq. 1, diluted by the effects of mistagging and the Δt resolution. The PDF of the continuum contribution with bachelor track h is denoted $\mathcal{P}^{q\rho h}_k$. The likelihood term $\mathcal{L}^{B,h}_{j,\,k}$ corresponds to the B-background contribution j of the N_B B-background categories. Due to imperfect π^0 reconstruction, the signal PDFs are decomposed into three parts with distinct distributions: signal events that are correctly reconstructed, misreconstructed signal events with right-sign ρ charge, and misreconstructed signal events with wrong-sign ρ charge. Their individual fractions are estimated by MC simulation. The variables m_{ES}, ΔE, Δt, and the NN output discriminate signal from background, while the Cherenkov angle θ_C and, to a lesser extent, ΔE are sensitive to the relative amount of $\rho\pi$ and ρK. The variable Δt allows the determination of the time-dependent parameters defined

TABLE I: Summary of the systematic uncertainties.

Source	$N^{\rho K}$	$N^{\rho\pi}$	$A_{CP}^{\rho K}$	$A_{CP}^{\rho\pi}$	$C_{\rho\pi}$	$\Delta C_{\rho\pi}$	$S_{\rho\pi}$	$\Delta S_{\rho\pi}$
	(in units of 10^{-2})							
Δm_d and τ	0.1	0.1	0.0	0.0	0.4	0.4	0.2	0.1
Δt parameterization	1.2	1.9	0.4	0.2	1.4	0.8	1.5	1.2
Signal modeling	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
Fitting 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-backgrounds	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

in Eq. 1. The m_{ES}, ΔE, and the 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 ΔE, which are free to vary in the fit. The continuum PDFs are described by six free parameters. The Cherenkov angle PDF is modeled as in Ref. [2]. The Δt resolution function for signal and B background events is a sum of three Gaussian distributions, with parameters determined from a fit to fully reconstructed neutral B decays; identical with the scheme described in Ref. [9]. The continuum Δt distribution is parameterized as the sum of three Gaussian distributions with common mean, two relative fractions, and three distinct widths that scale the Δt event-by-event error, yielding six free parameters. For continuum, two charge asymmetries and the ten parameters $N_k^{q\rho h}$ are free. A total of 34 parameters including signal yields and the parameters from Eq. 1 are varied in the fit.

The various sources contributing to the systematic error on the signal yields, the CP and the other time-dependent observables are summarized in Table I. The systematic uncertainties associated with Δm_d and the B lifetime are estimated by varying these parameters within one standard deviation of their world average values [10]. The uncertainties due to the modeling of the signal and the estimated fraction of misreconstructed events are obtained from a control sample of fully-reconstructed $B^0 \to D^-\rho^+$ decays. We perform fits on large MC samples with the measured proportions of $\rho\pi/\rho K$ signal, continuum, and B background. Biases observed in these tests are due to imperfections in the PDF modeling, *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 fitting procedure. The systematic errors due to possible interference between the doubly-Cabibbo-suppressed (DCS) $\bar{b} \to \bar{u}c\bar{d}$ amplitude with the Cabibbo-favored $b \to c\bar{u}d$ amplitude for tag-side B decays have been estimated from simulation by varying freely all relevant strong phases [11]. The main source of systematic uncertainties arises from the uncertainty

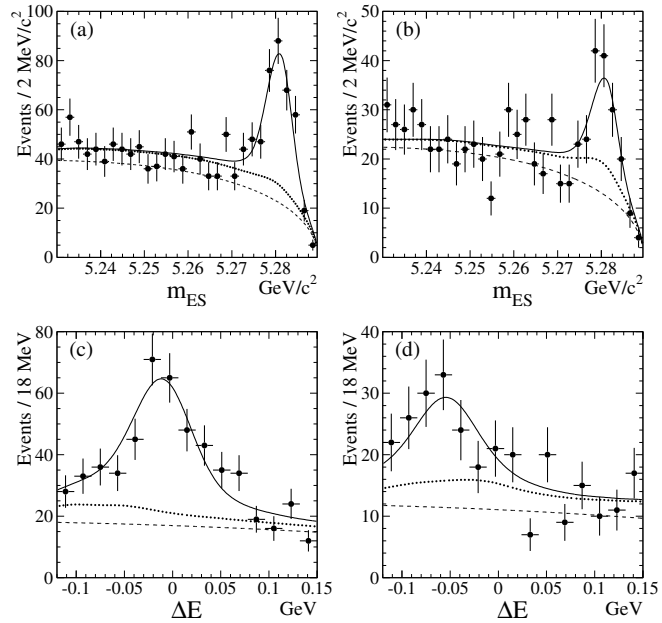

FIG. 1: Distributions of m_{ES} and ΔE for samples enhanced in $\rho\pi$ signal (a,c) and ρK signal (b,d). The solid curve represents a time-dependent projection of the maximum likelihood fit result. The dashed curve represents the contribution from continuum events, and the dotted line indicates the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

on the B-background model. The expected event yields from the various background modes are varied according to the uncertainties of the measured or estimated branching fractions. Systematics due to possible non-resonant $B^0 \to \pi^+\pi^-\pi^0$ decays are derived from experimental limits [5], assuming no interference. Repeating the fit without using the ρ candidate mass and helicity angle gives results that are compatible with the ones reported here. The flavor-charge correlation parameters estimated with MC are varied within conservative ranges. Finally, since B-background modes may exhibit direct CP violation, and a few of them mixing-induced CP violation, the corresponding parameters are varied in ranges, taking into account their dilution due to the incomplete reconstruction of the background events.

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

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

where the first errors are statistical and the second systematic. The systematic errors include an uncertainty of 7.7% for efficiency corrections, dominated by the uncertainty in the π^0 reconstruction efficiency. Figure 1

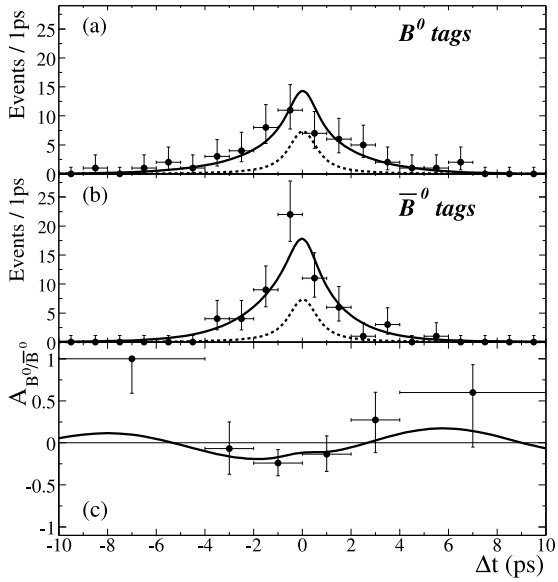

FIG. 2: Time distributions for events enhanced in signal $\rho\pi$ tagged as (a) $B^0_{\rm tag}$ and (b) $\overline{B}^0_{\rm tag}$, and (c) time asymmetry between $B^0_{\rm tag}$ and $\overline{B}^0_{\rm tag}$. The solid curve is a likelihood projection of the result of the full fit. The dashed line is the total B and continuum background contribution.

shows distributions of m_{ES} and ΔE, enhanced for signal content by application of cuts to the signal-to-continuum likelihood ratios of the other discriminating variables.

For the CP-violating parameters we obtain

$$A^{\rho\pi}_{CP} = -0.18 \pm 0.08 \pm 0.03\,, \quad A^{\rho K}_{CP} = 0.28 \pm 0.17 \pm 0.08\,,$$
$$C_{\rho\pi} = \quad 0.36 \pm 0.18 \pm 0.04\,, \quad S_{\rho\pi} = 0.19 \pm 0.24 \pm 0.03\,.$$

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

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

We find the linear correlation coefficients $c(A^{\rho\pi}_{CP}, C) = -0.08$, $c(A^{\rho\pi}_{CP}, \Delta C) = -0.06$, $c(C, \Delta C) = 0.18$, $c(C, S) = -0.10$, $c(C, \Delta S) = -0.09$, $c(\Delta C, S) = -0.09$, $c(\Delta C, \Delta S) = -0.10$ and $c(S, \Delta S) = 0.23$, while all other correlations are smaller. As a validation of the Δt parameterization in data, we allow τ and Δm_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^{-1}; the remaining free parameters are consistent with the nominal fit with fixed $\tau = 1.542$ ps and $\Delta m_d = 0.489$ ps^{-1} [10]. The raw time asymmetry $A_{B^0/\overline{B}^0} = (N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$ in the tagging categories dominated by kaons and leptons is represented in Figure 2.

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

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