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Branching fraction measurement of $\overline{B}^0 \to D^{(*)+}\pi^-$ and $B^- \to D^{(*)0}\pi^-$ and isospin analysis of $\overline{B} \to D^{(*)}\pi$ decays

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Using 65 million $\Upsilon(4S) \to B\overline{B}$ events collected with the *BABAR* detector at the PEP-II e^+e^- storage ring at the Stanford Linear Accelerator Center, we measure the color-favored branching fractions $\mathcal{B}(\overline{B}^0 \to D^+\pi^-) = (2.55\pm0.05\pm0.16)\times10^{-3}$, $\mathcal{B}(\overline{B}^0 \to D^{*+}\pi^-) = (2.79\pm0.08\pm0.17)\times10^{-3}$, $\mathcal{B}(B^- \to D^0\pi^-) = (4.90 \pm 0.07 \pm 0.22) \times 10^{-3}$ and $\mathcal{B}(B^- \to D^{*0}\pi^-) = (5.52 \pm 0.17 \pm 0.42) \times 10^{-3}$, where the first error is statistical and the second is systematic. With these results and the current world average for the branching fraction for the color-suppressed decay $\overline{B}^0 \to D^{(*)0}\pi^0$, the cosines of the strong phase difference δ between the $I = 1/2$ and $I = 3/2$ isospin amplitudes are determined to be $\cos\delta = 0.872^{+0.008+0.031}_{-0.007-0.029}$ for the $\overline{B} \to D\pi$ process and $\cos\delta = 0.924^{+0.019+0.063}_{-0.017-0.054}$ for the $\overline{B} \to D^*\pi$ process. Under the isospin symmetry, the results for $\cos\delta$ suggest the presence of final-state interactions in the $D\pi$ system.

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The $\overline{B} \to D\pi$ and $\overline{B} \to D^*\pi$ processes provide very good opportunities to test the theories of hadronic B-meson decays due to their clean and dominant hadronic decay channels. With the development of heavy quark effective theory (HQET) [1, 2] and soft collinear effective theory (SCET) [3, 4], the theoretical description for these hadronic decays has improved considerably, and the factorization hypothesis in heavy quark hadronic decay has been put on a more solid basis. The three decay amplitudes $\mathcal{A}$ for $\overline{B} \to D\pi$ can be expressed in terms of two isospin amplitudes, $A_{1/2}$ and $A_{3/2}$, under the isospin symmetry of the strong interaction:

$$\mathcal{A}(\overline{B}^0 \to D^+\pi^-) = \sqrt{1/3}A_{3/2} + \sqrt{2/3}A_{1/2}, \quad (1)$$

$$\sqrt{2}\mathcal{A}(\overline{B}^0 \to D^0\pi^0) = \sqrt{4/3}A_{3/2} - \sqrt{2/3}A_{1/2}, \quad (2)$$

$$\mathcal{A}(B^- \to D^0\pi^-) = \sqrt{3}A_{3/2}, \quad (3)$$

where isospin amplitudes $A_{1/2}$ and $A_{3/2}$ correspond to the transitions into $D\pi$ final states with pure $I = 1/2$ and $I = 3/2$ isospin eigenstates [5, 6]. An identical decomposition holds for $\overline{B} \to D^*\pi$ decays. The isospin amplitudes are not necessarily the same in the $\overline{B} \to D\pi$ and $\overline{B} \to D^*\pi$ systems. In the context of QCD factorization [6], $A_{1/2}$ and $A_{3/2}$ for $\overline{B} \to D\pi$ (similarly for $\overline{B} \to D^*\pi$) are related by

$$\frac{A_{1/2}}{\sqrt{2}A_{3/2}} = 1 + O(\Lambda_{\rm QCD}/m_b), \quad (4)$$

where m_b is the b-quark mass and $\Lambda_{\rm QCD}$ is the QCD scale. The deviation of the ratio $A_{1/2}/(\sqrt{2}A_{3/2})$ from unity is a measure of the departure from the heavy-quark limit. The QCD factorization implies that the relative phase δ of $A_{1/2}$ and $A_{3/2}$ is $O(\Lambda_{\rm QCD}/m_b)$. Final-state interactions (FSI) in the $I = 3/2$ and $I = 1/2$ channels can lead to a non-zero δ. A large value of δ will substantially suppress the destructive interference for the color-suppressed decay $\overline{B}^0 \to D^{(*)0}\pi^0$, thereby increasing the associated branching fraction.

Recent experimental results on the color-suppressed decay $\overline{B}^0 \to D^{(*)0}\pi^0$ [7–9] provide evidence for a sizable relative strong interaction phase between color-favored and color-suppressed $\overline{B}^0 \to D^{(*)}\pi$ decay amplitudes. It has been suggested [5] that improved measurements of the color-favored hadronic two-body decay of the B meson will lead to a better understanding of these QCD effects. Further experimental results on the color-favored decay $\overline{B} \to D\pi$ suggest the presence of final-state interactions in the $\overline{B} \to D\pi$ process [10]. This paper presents new measurements of the branching fractions of $B^- \to D^{(*)0}\pi^-$ and $\overline{B}^0 \to D^{(*)+}\pi^-$ (charge conjugation is implied throughout this paper) and of the relative phase δ.

This analysis uses $(65.2\pm0.7)\times10^6$ $B\overline{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the *BABAR* detector [11] at the PEP-II asymmetric-energy storage ring during the 2001-2002 data taking period. Charged tracks are detected by a 5-layer silicon vertex tracker and a 40-layer drift chamber. Hadrons are identified by measuring the ionization energy loss $\mathrm{d}E/\mathrm{d}x$ in the tracking system and the opening angle of the Cherenkov radiation in a ring-imaging detector. Photons are identified by an electromagnetic calorimeter. These systems are mounted inside a 1.5-T solenoidal superconducting magnet.

Kaon and pion candidates are selected from charged-particle tracks using $\mathrm{d}E/\mathrm{d}x$ and the Cherenkov light signature. Each charged track, except the track used as the soft pion to reconstruct $D^{*+} \to D^0\pi^+$, is required to have at least 12 hits in the drift chamber and a transverse momentum greater than 100 MeV/c. D^0 and D^+ candidates are reconstructed in the $K^-\pi^+$ and $K^-\pi^+\pi^+$ channels, respectively. In each case, D meson candidates are required to have a mass within 3σ of the mean reconstructed mass value, where the mass resolution σ is approximately 7 MeV/c^2 for D^0 and 6 MeV/c^2 for D^+. A vertex fit is performed on D^0 (D^+) candidates with the mass constrained to the nominal value [12]. A D^0 candidate is combined with a low momentum π^+ or π^0 to form a D^{*+} or D^{*0} candidate, where the π^0 candidate is formed from two photon candidates and must have an invariant mass between 120 and 145 MeV/c^2. Combinations with an invariant mass difference $\Delta m = m_{D^0\pi} - m_{D^0}$ between 143 and 148 MeV/c^2 for D^{*+} and between 138 and 146 MeV/c^2 for D^{*0}, corresponding to $\pm 3\sigma$ about the Δm peak, are retained. Each B meson candidate is reconstructed using the selected D or D^* candidate and an additional charged track that is not consistent with the kaon hypothesis.

To reject jet-like continuum background events, the normalized second Fox-Wolfram moment R_2 [13], computed with charged tracks and neutral clusters, is required to be less than 0.5. We also require $|\cos\theta_T|$ to be less than 0.85, where θ_T is the angle between the thrust axis of the B candidate and the thrust axis of the rest of the event in the e^+e^- center-of-mass (CM) frame.

B candidates are identified using the beam-energy-substituted mass $m_{\rm ES} = \sqrt{(\sqrt{s}/2)^2 - p^{*2}}$ and energy difference $\Delta E = E^* - \sqrt{s}/2$, where E^* and p^* are the energy and momentum of the reconstructed B candidate and $\sqrt{s}$ is the total energy in the e^+e^- CM frame. B signal candidates have $m_{\rm ES} \sim m_B$, the B meson mass, and $\Delta E \simeq 0$, within their respective resolutions. The resolution in ΔE, $\sigma_{\Delta E}$, for various B modes ranges from 15.7 to 18.1 MeV. We require that $|\Delta E - \langle \Delta E\rangle| < 3\sigma_{\Delta E}$. For events with more than one B candidate, a χ^2 is defined with the D mass m_D, Δm and their resolutions as

$$\chi^2 = \left(\frac{m_D - \langle m_D\rangle}{\sigma_{m_D}}\right)^2 + \left(\frac{\Delta m - \langle \Delta m\rangle}{\sigma_{\Delta m}}\right)^2 \quad (5)$$

and the candidate with the smallest χ^2 is chosen.

The event yield n for each mode of $\overline{B} \to D^{(*)}\pi^-$ is extracted by fitting the $m_{\rm ES}$ distribution of the selected B candidates with an unbinned extended maximum likelihood fit. The $m_{\rm ES}$ distribution is fit to the sum of a signal component, modeled as a Gaussian, and a background shape. The background shape is parameterized as the sum of a Gaussian, representing the peaking background events that peak in $m_{\rm ES}$, and a phase space parameterization function [14] representing non-peaking combinatorial background and continuum events. The parameters describing the background shape, including the relative normalization of the peaking component, are determined by fitting Monte Carlo (MC) simulated samples, with the signal events removed. The total signal and background event yields, as well as the shape parameters describing signal events, are free parameters in the fit. The fitted $m_{\rm ES}$ distributions for each of the B meson decay modes are presented in Fig. 1. The peaking background yield $n_{\rm pb}$ is about (2–4)% of the observed B signal yield, as shown in Table I.

For each studied B decay mode of $\overline{B} \to D^{(*)}\pi$, the branching fraction is calculated as:

$$\mathcal{B}(\overline{B} \to D^{(*)}\pi) = \frac{n}{2fN_{B\overline{B}}\varepsilon\mathcal{B}(D^{(*)})}. \quad (6)$$

Here $N_{B\overline{B}}$ is the total number of $B\overline{B}$ pairs; ε is the efficiency determined from signal Monte Carlo events; f represents f_{+-} or f_{00}, the charged or neutral B meson production ratios at the $\Upsilon(4S)$, which we assume to be $f_{+-} = f_{00} = 0.5$; and $\mathcal{B}(D^{(*)})$ is the branching fraction of D or D^* decaying to its reconstructed final state [12]. The branching fractions we obtain are reported in Table I.

The final states $D^{(*)}\pi$ selected by this analysis are, in general, accompanied by some small amount of final state radiation (FSR). We model final state radiation in our experiment with PHOTOS [15], which predicts that 6-7% of our selected events, varying slightly with decay mode, are accompanied by an average FSR energy of about 17 MeV. Approximately two-thirds of this energy is produced in the initial B decay, while the remainder is generated in the $D^{(*)}$ decay.

We summarize systematic uncertainties on the measurements from various sources in Table II. $\Delta N_{B\overline{B}}$ is the uncertainty on the total number of $B\overline{B}$ pairs in data. The error on the efficicency, $\Delta\varepsilon$, is due to signal Monte Carlo sample statistics. The uncertainty from combinatoric background is estimated as the difference in the B yields obtained when fixing and floating the non-peaking background parameters in the $m_{\rm ES}$ fit. The uncertainty from peaking background is estimated as the B yield change by varying the peaking background parameters and the ratio of peaking background to non-peaking background within their errors in the $m_{\rm ES}$ fit. The uncertainties due to the differences in $D^{(*)}$ masses and ΔE between data and Monte Carlo samples are estimated by comparing the efficiencies using their resolutions and means from data and Monte Carlo samples in the event selection. The uncertainty due to D vertexing is estimated by comparing vertexing perfomance in data and Monte Carlo samples. The uncertainties in tracking, particle identification, and π^0 reconstruction efficiencies are due to potential residual inaccuracies in the Monte Carlo simulation, after correcting for known differences. The dominant uncertainty is from the $D^{(*)}$ branching fractions $\mathcal{B}(D^{(*)})$ and the tracking efficiency.

With the branching fractions of the four color-favored decay modes $\overline{B}^0 \to D^{(*)+}\pi^-$ and $B^- \to D^{(*)0}\pi^-$, as well as the two color-suppressed modes $\overline{B}^0 \to D^{(*)0}\pi^0$, one can calculate $\cos\delta$. Following Ref. [16] (equations have been modified to use the notation from Ref. [5]), $\cos\delta$ for $\overline{B} \to D\pi$ (similarly for $\overline{B} \to D^*\pi$) can be expressed as

$$\cos\delta = \frac{3\Gamma(D^+\pi^-) + \Gamma(D^0\pi^-) - 6\Gamma(D^0\pi^0)}{6\sqrt{2}|A_{1/2}A_{3/2}|}, \quad (7)$$

$$|A_{3/2}|^2 = \frac{1}{3}\Gamma(D^0\pi^-), \quad (8)$$

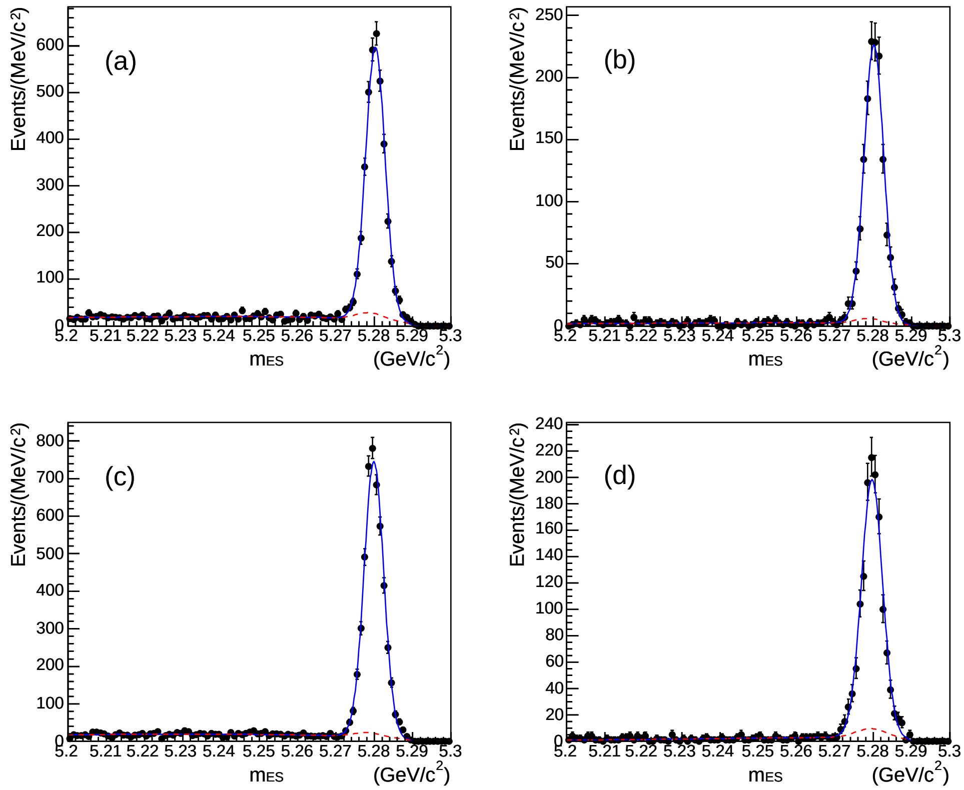

FIG. 1: Fit of $m_{\rm ES}$ distributions for the $B \to D^{(*)}\pi$ candidates in data: (a) $\overline{B}^0 \to D^+\pi^-$, (b) $\overline{B}^0 \to D^{*+}\pi^-$, (c) $B^- \to D^0\pi^-$, (d) $B^- \to D^{*0}\pi^-$. The fit is shown as a solid line and is described in the text. The background component (including peaking background) is shown as a dashed line.

TABLE I: Yield of signal (n) and peaking background ($n_{\rm pb}$), efficiency (ε), and branching fraction ($\mathcal{B}$) for each $\overline{B} \to D^{(*)}\pi$ decay mode.

Mode	n	$n_{\rm pb}$	ε (%)	$\mathcal{B}$ ($\times 10^{-3}$)
$\overline{B}^0 \to D^+\pi^-$	3593 ± 63	114 ± 14	22.8 ± 0.2	$2.55 \pm 0.05 \pm 0.16$
$\overline{B}^0 \to D^{*+}\pi^-$	1411 ± 39	28 ± 6	30.2 ± 0.2	$2.79 \pm 0.08 \pm 0.17$
$B^- \to D^0\pi^-$	4606 ± 70	89 ± 14	37.9 ± 0.2	$4.90 \pm 0.07 \pm 0.22$
$B^- \to D^{*0}\pi^-$	1297 ± 39	51 ± 8	15.5 ± 0.1	$5.52 \pm 0.17 \pm 0.42$

$$|A_{1/2}|^2 = \Gamma(D^+\pi^-) + \Gamma(D^0\pi^0) - \frac{1}{3}\Gamma(D^0\pi^-). \quad (9)$$

Using the measured branching fractions in this analysis, the ratio of the B lifetimes $\tau(B^-)/\tau(\overline{B}^0) = 1.071 \pm 0.009$ [12], and the branching fractions $\mathcal{B}(\overline{B}^0 \to D^0\pi^0) = (0.291 \pm 0.028) \times 10^{-4}$ and $\mathcal{B}(\overline{B}^0 \to D^{*0}\pi^0) = (0.27 \pm 0.05) \times 10^{-4}$ [12], we calculate $\cos\delta$ and $|A_{1/2}/(\sqrt{2}A_{3/2})|$ for $\overline{B} \to D\pi$ and $\overline{B} \to D^*\pi$ decays.

To estimate the systematic error on $\cos\delta$ for $\overline{B} \to D\pi$ (and, similarly, $\overline{B} \to D^*\pi$), we use a Monte Carlo technique [10]. We simulate 10^6 experiments, varying the measured branching fractions, the used color-suppressed decay branching fraction, and $\tau(B^-)/\tau(\overline{B}^0)$ about their central values according to Gaussian distributions where their errors are taken as the sigmas of the Gaussian distributions, to calculate the $\cos\delta$. The correlation of the systematic errors between the two color-favored decay modes in the $\cos\delta$ calculation is taken into account. We assume the errors are uncorrelated between the color-favored and color-suppressed modes. The statistical error on $\cos\delta$ is estimated in a similar fashion, with only the statistical errors on the branching fractions of color-favored modes are used in the procedure. The resulting normalized distribution of $\cos\delta$, ie., the estimated likelihood function of $\cos\delta$, is obtained. Figure 2 shows the likelihood function of $\cos\delta$ from the described experiments in which both the statistical and systematic errors are taken into account.

TABLE II: Relative systematic errors in the branching fractions of $\overline{B} \to D^{(*)}\pi$ decays from different sources.

Systematic error	$\overline{B}^0 \to D^+\pi^-$	$\overline{B}^0 \to D^{*+}\pi^-$	$B^- \to D^0\pi^-$	$B^- \to D^{*0}\pi^-$
$\Delta N_{B\overline{B}}$	1.1%	1.1%	1.1%	1.1%
$\mathcal{B}(D^{(*)})$	3.6%	2.0%	1.8%	5.0%
Δf	1.6%	1.6%	1.6%	1.6%
$\Delta\varepsilon$	1.0%	0.5%	0.5%	0.7%
Non-peaking background shape	2.8%	0.5%	1.9%	1.3%
Peaking background shape	0.4%	0.4%	0.3%	0.6%
Data/MC difference of m_D, Δm	0.2%	1.3%	0.4%	2.9%
Data/MC difference of ΔE	0.5%	0.2%	0.6%	0.7%
D^- and D^0 vertexing	0.2%	0.1%	0.1%	0.1%
Particle identification efficiency	2.0%	2.0%	1.5%	1.5%
Tracking efficiency	3.2%	4.9%	2.4%	2.4%
π^0 reconstruction efficiency	-	-	-	3.0%
Total	6.3%	6.2%	4.4%	7.6%

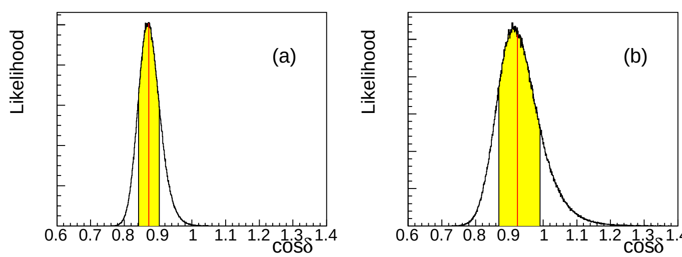

FIG. 2: Likelihood function (arbitrary unit in vertical axis) of $\cos\delta$ obtained from the ensemble of 10^6 Monte Carlo experiments described in the text for process (a) $\overline{B} \to D\pi$ and (b) $\overline{B} \to D^*\pi$. The shaded area in the plots is 68.27% of the total area.

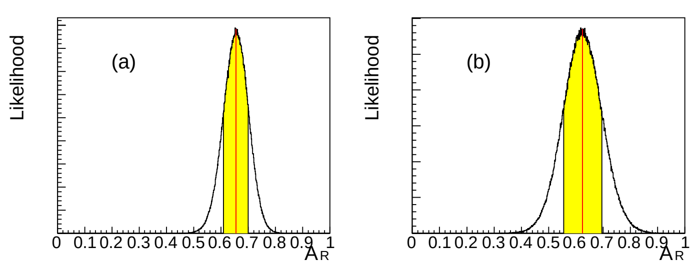

FIG. 3: Likelihood function (arbitrary unit in vertical axis) of $A_R \equiv |A_{1/2}/\sqrt{2}A_{3/2}|$ obtained from the ensemble of 10^6 Monte Carlo experiments described in the text for processes (a) $\overline{B} \to D\pi$ and (b) $\overline{B} \to D^*\pi$. The shaded area in the plots is 68.27% of the total area.

We define $\pm1\sigma$ confidence interval of $\cos\delta$ as the integral of its likelihood function over the region around the nominal value of $\cos\delta$, which is calculated from the central values of the branching fractions, to 68.27% (half below and half above the nominal value) of the total area.

The results are

$$\cos\delta = 0.872^{+0.008+0.031}_{-0.007-0.029} \tag{10}$$

for the $\overline{B} \to D\pi$ system and

$$\cos\delta = 0.924^{+0.019+0.063}_{-0.017-0.054} \tag{11}$$

for the $\overline{B} \to D^*\pi$ system, where the first error is statistical and the second is systematic. These results correspond to $|\delta| = 29.2^{\circ}{}^{+0.8^\circ+3.3^\circ}_{-0.9^\circ-3.8^\circ}$ and $|\delta| = 22.5^{\circ}{}^{+2.4^\circ+6.1^\circ}_{-3.1^\circ-9.9^\circ}$, for the $\overline{B} \to D\pi$ system and the $\overline{B} \to D^*\pi$ system, respectively. By comparing the likelihood function integral of $\cos\delta$ in region [0,1] with the full range integral, we exclude $\cos\delta \geq 1$ at a probability of 99.9% for the $\overline{B} \to D\pi$ system and 85.7% for the $\overline{B} \to D^*\pi$ system.

Similarly, we obtain

$$\left|\frac{A_{1/2}}{\sqrt{2}A_{3/2}}\right| = 0.655^{+0.015+0.042}_{-0.014-0.042} \tag{12}$$

and

$$\left|\frac{A_{1/2}}{\sqrt{2}A_{3/2}}\right| = 0.624^{+0.027+0.065}_{-0.026-0.063} \tag{13}$$

for the $\overline{B} \to D\pi$ and $\overline{B} \to D^*\pi$ system, respectively, where the first error is statistical and the second is systematic. The likelihood function from the simulated experiments, with both statistical and systematic errors are taken into account, is shown in Fig. 3.

In summary, we have measured the branching fractions for the color-favored $\overline{B}^0 \to D^{(*)+}\pi^-$ and $B^- \to D^{(*)0}\pi^-$ decays. Using these measurements together with the current world averages for $\mathcal{B}(\overline{B}^0 \to D^0\pi^0)$ and $\mathcal{B}(\overline{B}^0 \to D^{*0}\pi^0)$, we extract the cosines of the relative strong phase δ in the $D\pi$ and $D^*\pi$ systems, and the ratios of the $I = 3/2$ and $I = 1/2$ isospin amplitudes. Our results for the $\overline{B} \to D^{(*)}\pi$ branching fractions, except for $B^- \to D^{*0}\pi^-$, are consistent with the current world average values [12] but have a better precision. The branching fraction of $B^- \to D^{*0}\pi^-$ from this measurement is greater than the world average by about 2σ. Our results for $\cos\delta$ differ from unity by about 4.3σ for $\overline{B} \to D\pi$ decays and 1.1σ for $\overline{B} \to D^*\pi$ decays. The result of $\cos\delta$ for $\overline{B} \to D\pi$ decays is consistent with the result in Refs. [9, 10], and under the isospin symmetry it suggests the presence of final-state interactions in $\overline{B} \to D\pi$ decays.

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