Measurement of CP-violating parameters in fully reconstructed $B \to D^{(*)}\pi$ and $B \to D\rho$ decays.

The *BABAR* Collaboration

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Abstract

We present a preliminary measurement of *CP*-violating asymmetries in fully reconstructed $B^0 \to D^{(*)\pm}\pi^\mp$ and $B^0 \to D^{\pm}\rho^\mp$ decays in approximately 110 million $\Upsilon(4S) \to B\overline{B}$ decays collected with the *BABAR* detector at the PEP-II asymmetric-energy B factory at SLAC. From a maximum likelihood fit to the time-dependent decay distributions we obtain for the *CP*-violating parameters: $a^{D\pi} = -0.032 \pm 0.031\,(\text{stat.}) \pm 0.020\,(\text{syst.}), c_{\text{lep}}^{D\pi} = -0.059 \pm 0.055\,(\text{stat.}) \pm 0.033\,(\text{syst.})$ on the $B^0 \to D^{\pm}\pi^\mp$ sample, $a^{D^*\pi} = -0.049 \pm 0.031\,(\text{stat.}) \pm 0.020\,(\text{syst.}), c_{\text{lep}}^{D^*\pi} = +0.044 \pm 0.054\,(\text{stat.}) \pm 0.033\,(\text{syst.})$ on the $B^0 \to D^{*\pm}\pi^\mp$ sample, and $a^{D\rho} = -0.005 \pm 0.044\,(\text{stat.}) \pm 0.021\,(\text{syst.}), c_{\text{lep}}^{D\rho} = -0.147 \pm 0.074\,(\text{stat.}) \pm 0.035\,(\text{syst.})$ on the $B^0 \to D^{\pm}\rho^\mp$ sample.

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1 INTRODUCTION

While the measurement of $\sin 2\beta$ is now a precision measurement [1, 2], the constraints on the other two angles of the Unitarity Triangle [3], α and γ, are still limited by statistics and/or by theoretical uncertainties. This conference paper reports on the measurement of CP-violating asymmetries in $B^0 \to D^{(*)\pm}\pi^\mp$ and $B^0 \to D^\pm\rho^\mp$ decays [4] in $\Upsilon(4S) \to B\overline{B}$ decays, asymmetries which are related to $|\sin(2\beta + \gamma)|$ [5, 6]. This analysis updates the results already published in [8] by including a new decay mode ($B^0 \to D^\pm\rho^\mp$) and a larger data sample (110 instead of 88 million $\Upsilon(4S) \to B\overline{B}$ decays).

The time evolution of $B^0 \to D^{(*)\pm}h^\mp$ decays, where h is a meson made of a u and a d quarks, is sensitive to γ because the CKM-favored decay $\overline{B}^0 \to D^{(*)+}h^-$, which amplitude is proportional to the CKM matrix elements $V_{cb}V_{ud}^*$, and the doubly-CKM-suppressed decay $B^0 \to D^{(*)+}h^-$, which amplitude is proportional to $V_{cd}V_{ub}^*$ interfere due to the B^0-$\overline{B}^0$ mixing. The relative weak phase between the two amplitudes is γ, and, when combined with $B^0\overline{B}^0$ mixing, yields a weak phase difference of $2\beta + \gamma$ between the interfering amplitudes.

The decay rate distribution for $B^0 \to D^\pm h^\mp$ decays is

$$ f^\pm(\eta, \Delta t) \;\; = \;\; \frac{e^{-|\Delta t|/\tau}}{4\tau} \times \left[1 \mp S_\zeta \sin(\Delta m_d \Delta t) \mp \eta C \cos(\Delta m_d \Delta t) \right], \tag{1} $$

where τ is the B^0 lifetime, neglecting the decay width difference, Δm_d is the $B^0\overline{B}^0$ mixing frequency, and $\Delta t = t_{\text{rec}} - t_{\text{tag}}$ is the time of the $B^0 \to D^\pm\pi^\mp$ decay (B_{rec}) relative to the decay of the other B (B_{tag}). In this equation the upper (lower) sign refers to the flavor of B_{tag} as B^0 ($\overline{B}^0$), while $\eta = +1 \; (-1)$ and $\zeta = + \; (-)$ for the final state D^-h^+ (D^+h^-). In the Standard Model, the S and C parameters can be expressed as

$$ S_\pm = -\frac{2\text{Im}(\lambda_\pm)}{1 + |\lambda_\pm|^2}, \quad \text{and} \quad C = \frac{1 - r^2}{1 + r^2}, \tag{2} $$

where $r \equiv |\lambda_+| = 1/|\lambda_-|$ and

$$ \lambda_\pm = \frac{q}{p} A(\overline{B}^0 \to D^\mp\pi^\pm)/A(B^0 \to D^\mp\pi^\pm) = r^{\pm 1} e^{-i(2\beta + \gamma \mp \delta)}. \tag{3} $$

Here $\frac{q}{p}$ is a function of the elements of the mixing matrix [7], and δ is the relative strong phase between the two contributing amplitudes. In these equations the parameters r and δ depend on the choice of the final state and will be indicated as $r^{D\pi}$, $\delta^{D\pi}$, in the $B^0 \to D^\pm\pi^\mp$ case, $r^{D^*\pi}$, $\delta^{D^*\pi}$, in the $B^0 \to D^{*\pm}\pi^\mp$ case [6], and $r^{D\rho}$, $\delta^{D\rho}$, in the $B^0 \to D^\pm\rho^\mp$ case.

Interpreting the S and C parameters in terms of the angles of the Unitarity Triangle requires the measurement of the r parameters as detailed in Sec. 2. Since the amplitude in the numerator of Eq. 3 is suppressed with respect to the one in the denominator, the r parameters are expected to be small (~ 0.02) and they cannot therefore be extracted from the measurement of C with the current statistics. They can be determined, assuming $SU(3)$ symmetry and neglecting contributions from annihilation diagrams, from the ratios of branching fractions $\mathcal{B}(B^0 \to D_s^{(*)+}\pi^-)/\mathcal{B}(B^0 \to D^{(*)-}\pi^+)$ and $\mathcal{B}(B^0 \to D_s^{(*)+}\rho^-)/\mathcal{B}(B^0 \to D^{(*)-}\rho^+)$ [5, 8, 9]. Since there is no evidence yet of $B^0 \to D_s^{(*)+}\rho^-$ decays, we will report here the result of the measurement of CP-violating parameters defined in Eq. 4, but will not be able to include the interpretation in terms of $\sin(2\beta + \gamma)$. Nonetheless, the

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[6]According to Ref. [6] the strong phase is actually $\delta^{D^*\pi} + \pi$, but this does not affect this measurement.
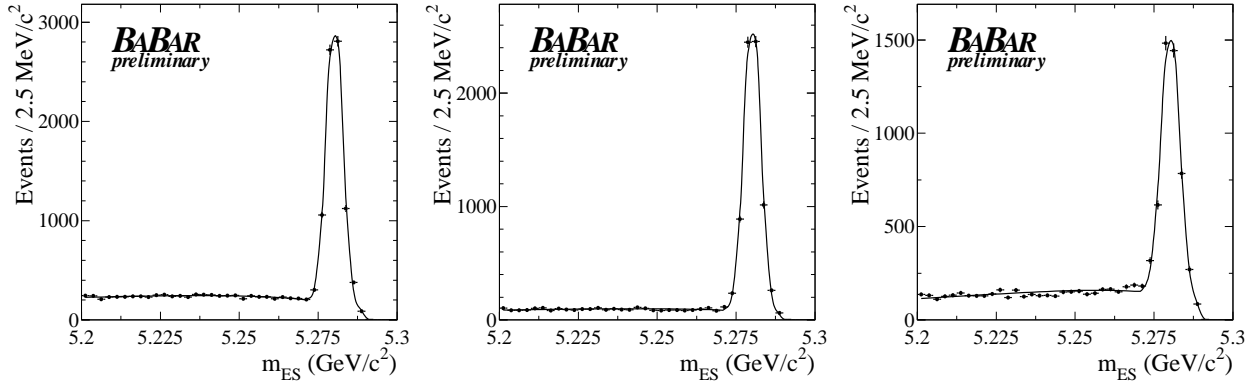
Figure 1: m_{ES} distributions in the ΔE signal region for, from left to right, the $B^0 \to D^{\pm}\pi^{\mp}$, $B^0 \to D^{*\pm}\pi^{\mp}$ and $B^0 \to D^{\pm}\rho^{\mp}$ sample for events with tagging information. A fit to a Gaussian plus a threshold is overlaid.

addition of the $B^0 \to D^{\pm}\rho^{\mp}$ mode to the analysis is of interest because on one side unexpectedly large values for the CP-violating parameters would signal new physics and on the other side when the statistics will be sufficient it will allow one more measurement of $\sin(2\beta + \gamma)$, redundant with respect to the one made with the other modes.

2   ANALYSIS OVERVIEW

This measurement is based on 110 million $\Upsilon(4S) \to B\overline{B}$ decays collected with the *BABAR* detector [10] at the PEP-II asymmetric-energy B factory at SLAC. We use Monte Carlo simulation of the *BABAR* detector based on GEANT4 [11] to validate the analysis procedure and to estimate some of the backgrounds. The analysis strategy is identical to our previous publication on this topic [8].

Candidate $B^0 \to D^{(*)\pm}\pi^{\mp}$ and $B^0 \to D^{\pm}\rho^{\mp}$ decays are reconstructed with the D^{*+} decaying to $D^0\pi^+$, where the D^0 subsequently decays to one of the four modes $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$, or $K^0_S\pi^+\pi^-$, the D^+ decaying into $K^-\pi^+\pi^+$ and $K^0_S\pi^+$, and the ρ^+ decaying into $\pi^+\pi^0$. The $D^{(*)}$ candidates are then combined with either a single track or a track and a π^0 candidate with invariant mass in the ρ window, $620 < m_{\pi\pi} < 920\,\mathrm{MeV}/c^2$. Finally, exploiting the spin properties of the decay of a pseudo-scalar meson into another pseudo-scalar and a vector, we require the cosine of the angle θ_l between the charged pion and the ρ candidate in the ρ rest frame to satisfy $|\cos\theta_h| > 0.4$.

Signal and background are discriminated by two kinematic variables: the beam-energy substituted mass, $m_{\mathrm{ES}} \equiv \sqrt{(\sqrt{s}/2)^2 - p_B^{*\,2}}$, and the difference between the B candidate's measured energy and the beam energy, $\Delta E \equiv E_B^* - (\sqrt{s}/2)$. E_B^* (p_B^*) is the energy (momentum) of the B candidate in the e^+e^- center-of-mass frame, and $\sqrt{s}$ is the total center-of-mass energy. The signal region is defined to be $|\Delta E| < 3\sigma$, where the resolution σ is mode-dependent and is approximately $20\,\mathrm{MeV}$ as determined from data. Figure 1 shows the m_{ES} distribution for candidates in the signal region.

To identify the flavor of B_{tag}, each event is assigned by a neural network to one of four hierarchical, mutually exclusive tagging categories: one lepton and two kaon categories based on the

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charges of identified leptons and kaons, and a fourth category for remaining events [1]. The effective tagging efficiency is $(28.1 \pm 0.7)\%$. The time difference Δt is calculated from the measured separation along the beam collision axis, Δz, between the reconstructed (B_{rec}) and tagged (B_{tag}) decay vertexes. We determine the B_{rec} vertex from its charged tracks. The B_{tag} decay vertex is obtained by fitting tracks that do not belong to B_{rec}, imposing constraints from the B_{rec} momentum and the beam-spot location. The Δt resolution is approximately 1.1 ps.

An unbinned likelihood fit is performed to the time distribution of events in this sample. The likelihood accounts for possible CP violation on the tag side [12]: for each tagging category i and for each decay mode $\mu = D^{\mp}\pi^{\pm}, D^{*\mp}\pi^{\pm}, D^{\mp}\rho^{\pm}$

$$
\begin{aligned}
f_i^{\pm\mu}(\eta, \Delta t) \quad = \quad & \frac{e^{-|\Delta t|/\tau}}{4\tau} \times [1 \mp (a^{\mu} \mp \eta b_i - \eta c_i^{\mu}) \\
& \sin(\Delta m_d \Delta t) \mp \eta \cos(\Delta m_d \Delta t)] ,
\end{aligned}
\tag{4}
$$

where in the Standard Model

$$
\begin{aligned}
a^{\mu} &= 2r^{\mu}\sin(2\beta + \gamma)\cos\delta^{\mu} , \\
b_i &= 2r_i'\sin(2\beta + \gamma)\cos\delta_i' , \\
c_i^{\mu} &= 2\cos(2\beta + \gamma)(r^{\mu}\sin\delta^{\mu} - r_i'\sin\delta_i') .
\end{aligned}
\tag{5}
$$

Here r_i' (δ_i') is, for each tagging category, the effective amplitude (phase) used to parameterize the tag side interference. Terms of order $r^{\mu\,2}$ and $r_i'^2$ have been neglected. Results are quoted only for the six a^{μ} and c_{lep}^{μ} parameters, which are independent of the unknowns r_i' and δ_i' (semileptonic B decays have no doubly CKM- suppressed contributions and therefore $r_{lep}'=0$). The other parameters are constrained by the fit, but, as they depend on r_i' and δ_i', they do not contribute to the interpretation of the result in terms of $\sin(2\beta + \gamma)$.

3   SAMPLE COMPOSITION

The background can be separated in two categories, one of which is due to random combinations of particles in the event (*combinatorial* background) and the other is due to B decays into similar final states, which therefore has the m_{ES} distribution similar to the signal (*peaking* background). To separate the combinatorial background, the m_{ES} distribution is fit with the sum of a threshold function [13] and a Gaussian, with a width of about $2.5\,\text{MeV}/c^2$, to describe the signal.

Table 1: Yields, fraction of combinatorial background f_{comb} and of peaking backgrounds f_{peak} of the selected samples.

Decay mode	yields	$f_{comb}(\%)$	$f_{peak}(\%)$ B^0	$B^{\pm}$
$B^0 \rightarrow D^{\pm}\pi^{\mp}$	7611 ± 97	8.6	0.21 ± 0.06	0.93 ± 0.23
$B^0 \rightarrow D^{*\pm}\pi^{\mp}$	7068 ± 89	4.2	0.13 ± 0.06	0.93 ± 0.10
$B^0 \rightarrow D^{\pm}\rho^{\mp}$	4400 ± 79	12.7	-0.01 ± 0.07	0.31 ± 0.13

We considered all possible sources of background peaking in the m_{ES} signal region, those coming from decays into open-charm final states similar to that of the signal (e.g., $B^- \rightarrow D^{*0}\pi^-, \rho^-$ or

$\overline{B}^0 \to D^{*+}\pi^-, \rho^-$), and those arising from charmless decays into the same final state as the signal. We estimated their contributions on MC simulation, varying the branching fractions within errors when observed and within the existing upper limits otherwise. The Gaussian yields and the amount of peaking background are summarized in Table 1, identified by the source, either neutral or charged B mesons.

In the case of the $B^0 \to D^{*\pm}\rho^{\mp}$ decays, an additional source of background must be considered, which has the same final state, $B^0 \to D^{\pm}\pi^{\mp}\pi^0$, where the $\pi^{\mp}\pi^0$ system is not produced by a ρ meson. This background component can be studied by looking at the distribution of $m_{\pi\pi}$ and $\cos\theta_h$. When the $\pi^{\mp}$ and π^0 come from a ρ meson, $m_{\pi\pi}$ follows the ρ lineshape, while $\cos\theta_h$ is distributed as $(\cos\theta_h)^2$. In order to satisfy the Bose-Einstein statistics, $\pi^{\mp}$ and π^0 must come from a resonance with odd spins ($J = 1, 3, ...$), and therefore, to first approximation, we only consider excited states of the ρ meson. In the mass range of interest, $\rho(1450)$ is the only possible candidate. For $B^0 \to D^{\pm}\rho(1450)$ decays, the $m_{\pi\pi}$ distribution would be peaked at higher masses (the $\rho(1450)$ pole mass is $(1465 \pm 25)\,\mathrm{MeV}/c^2$, its width is (400 ± 60) [7]), but would have the same $(\cos\theta_h)^2$ distribution. In order to have a $\cos\theta_h$ distribution different from the signal, the background would have to come from non-resonant $B^0 \to D^{\pm}\pi^{\mp}\pi^0$ decays. We therefore consider the possibility of having three components: the signal, $B^0 \to D^{\pm}\rho^{\mp}$, $B^0 \to D^{\pm}\rho(1450)$, and an S-wave non-resonant component, $B^0 \to D^{\pm}(\pi^{\mp}\pi^0)_{nr}$.

The presence of these two additional components would imply that the value of $A(\overline{B}^0 \to D^{\mp}\pi^{\pm}\pi^0)/A(B^0 \to D^{\mp}\pi^{\pm}\pi^0)$ (and thus $\lambda^{D\rho}$, see Eq. 3) is not constant with $m_{\pi\pi}$:

$$A(\overline{B}^0 \to D^{\mp}\pi^{\pm}\pi^0)/A(B^0 \to D^{\mp}\pi^{\pm}\pi^0) = \tag{6}$$

$$\frac{A(\bar{B}^0 \to D^-\rho+)A_\rho(m_{\pi\pi}) + A(\bar{B}^0 \to D^-\rho(1450)^+)A_{\rho(1450)}(m_{\pi\pi}) + A(\bar{B}^0 \to D^-\pi^+\pi^0)A_{nr}(m_{\pi\pi})}{A(B^0 \to D^-\rho^+)A_\rho(m_{\pi\pi}) + A(B^0 \to D^-\rho(1450)^+)A_{\rho(1450)}(m_{\pi\pi}) + A(B^0 \to D^-\pi^+\pi^0)A_{nr}(m_{\pi\pi})}.$$

Here $A_\rho(m_{\pi\pi})$, $A_{\rho(1450)}(m_{\pi\pi})$, and $A_{nr}(m_{\pi\pi})$ are the amplitudes of the three components and depend on $m_{\pi\pi}$[7].

Figure 2 shows the comparison of the $m_{\pi\pi}$ and $\cos\theta_h$ distributions between data and a simulation of pure $B^0 \to D^{\pm}\rho^{\mp}$ decays. The good agreement suggests that the contribution of higher resonances is negligible. To quantify this statement, we perform a fit to the $m_{\pi\pi}$ distribution including the lineshapes of the three components, and extract the relative amplitudes and phases. Given this set of amplitudes and phases, we generate the $m_{\pi\pi}$ distribution and, for each value of $m_{\pi\pi}$, the appropriate Δt distribution. We then fit these samples with the likelihood described in Eq.(4), which ignores the dependence of $\lambda^{D\rho}$ on $m_{\pi\pi}$. We repeat this procedure for several sets of amplitudes and phases according to the measured covariance matrix and find the bias induced to the a (c) parameters to be at most 0.0018 (0.0047). This maximum bias will be included as a systematic error.

An unbinned maximum likelihood fit is performed on the selected B candidates using the signal Δt distribution in Eq.(4), convoluted with a three-Gaussian resolution function. The probabilities of incorrect tagging (w_i) are accounted for by multiplying the a^μ, c_i^μ parameters and the $\cos(\Delta m_d \Delta t)$ term by the dilutions $D_i = 1 - 2w_i$. The resolution function and the tagging parameters are consistent within errors with previous *BABAR* analyses [1].

The combinatorial background is parametrized as the sum of a component with zero lifetime and one with an effective lifetime fixed to the value obtained from simulation. The fraction of each background component is determined from the events in the m_{ES} sidebands, $5.2 < m_{\mathrm{ES}} < 5.27\,\mathrm{GeV}/c^2$,

---

[7]In a Dalitz analysis they would depend also on the $D\pi$ invariant mass, but here we integrate over it to study a single variable at a time.
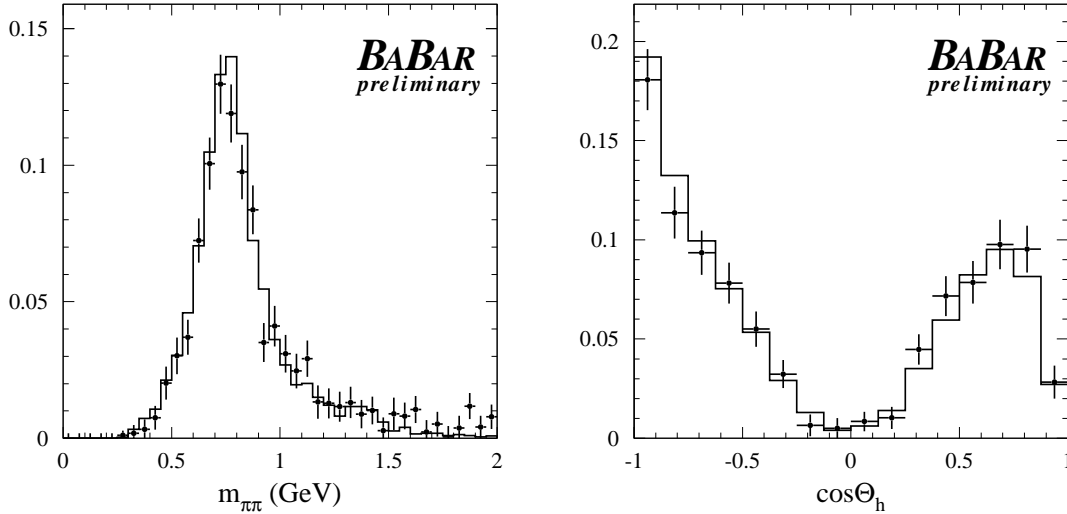
Figure 2: Sideband-subtracted $m_{\pi\pi}$ and $\cos\theta_h$ distributions on data (dots) and $B^0 \to D^\pm \rho^\mp$ simulation (open histogram).

while the Δt resolution is a double-Gaussian fitted on the same data as the CP-violating parameters. The charmed background coming from $B^\pm$ mesons is modeled by an exponential with the $B^\pm$ lifetime, and its amount is fixed to the value predicted by simulation. The charmed and charmless backgrounds from B^0 mesons are neglected in the nominal fit, but are considered in evaluating the systematic uncertainties.

4   RESULTS

From the unbinned maximum likelihood fit we obtain:

$$
\begin{aligned}
a^{D\pi} &= -0.032 \pm 0.031 \text{ (stat.)} &, & \quad c_{lep}^{D\pi} &= -0.059 \pm 0.055 \text{ (stat.)} \\
a^{D^*\pi} &= -0.049 \pm 0.031 \text{ (stat.)} &, & \quad c_{lep}^{D^*\pi} &= 0.044 \pm 0.054 \text{ (stat.)} \\
a^{D\rho} &= -0.005 \pm 0.044 \text{ (stat.)} &, & \quad c_{lep}^{D\rho} &= -0.147 \pm 0.074 \text{ (stat.)}
\end{aligned}
$$

Table 2 shows the contributions to the systematic uncertainty. Errors are found to be independent of the B_{rec} reconstruction mode because the systematic effects are dominated by uncertainties in the B_{tag} reconstruction. In the table we compare the results obtained with $B^0 \to D^{(*)\pm}\pi^\mp$ decays and $B^0 \to D^\pm \rho^\mp$.

The impact of a possible mismeasurement of Δt ($\sigma_{\Delta t}$) has been estimated by comparing the different parameterizations of the resolution function, varying the position of the beam spot, and the absolute z scale within their uncertainties, and loosening and tightening the quality criteria on the reconstructed vertex. We also estimate the impact of the uncertainties on the alignment of the silicon detector (SVT) by repeating the measurement on simulated events, intentionally misaligning the SVT in the simulation. As systematic uncertainty of the fit (σ_{fit}), we quote the upper limit on the bias on the a^μ and c^μ, as estimated from samples of fully simulated events. The model

Table 2: Systematic uncertainties on the a and c parameters.

Source	$B^0 \to D^{(*)\pm}\pi^\mp$		$B^0 \to D^\pm \rho^\mp$	
	σ_a	σ_c	σ_a	σ_c
Vertexing ($\sigma_{\Delta t}$)	0.015	0.026	0.017	0.031
Fit (σ_{fit})	0.011	0.019	0.009	0.016
Model (σ_{mod})	0.006	0.007	0.0007	0.0015
Tagging (σ_{tag})	0.004	0.0034	0.0028	0.0033
Background (σ_{bkg})	0.0012	0.0027	0.006	0.0031
Dependence from $m_{\pi\pi^0}$ ($\sigma_{\lambda\text{dep}}$)			0.0018	0.0047
Total (σ_{tot})	0.020	0.033	0.021	0.035

error (σ_{mod}) contains the uncertainty on the B^0 lifetime and Δm_d, varied by the uncertainties on the world averages [7], and the impact of neglecting higher order terms in r or r'_i in Eq.(4). The tagging error (σ_{tag}) is estimated considering possible differences in tagging efficiency between B^0 and $\overline{B}^0$ and allowing for different Δt resolutions for correctly and incorrectly tagged events. We also account for uncertainties on the background (σ_{bkg}) by varying the effective lifetimes, dilutions, m_{ES} shape parameters, signal fractions, and background CP asymmetry up to five times the expected CP asymmetry for signal. For the $B \to D\rho$ decay we also include the maximum bias of the a and c_{lep} parameters due to the possible dependence of λ on the $\pi\pi^0$ invariant mass ($\sigma_{\lambda\text{dep}}$), as discussed in section 3.

5 CONCLUSIONS

We studied the time evolution of fully reconstructed $B^0 \to D^{(*)\pm}\pi^\mp$ and $B^0 \to D^\pm\rho^\mp$ decays in a data sample of 110 million $\Upsilon(4S) \to B\overline{B}$ decays. CP-violation arising from the interference of the CKM-suppressed and the CKM-favored amplitudes is expected to be small but sensitive to $\sin(2\beta + \gamma)$.

The CP-violating parameters defined in Eq. 5 are measured to be

$$
\begin{aligned}
a^{D\pi} &= -0.032 \pm 0.031 \text{ (stat.)} \pm 0.020 \text{ (syst.)} &,& \quad c^{D\pi}_{lep} &= -0.059 \pm 0.055 \text{ (stat.)} \pm 0.033 \text{ (syst.)} \\
a^{D^*\pi} &= -0.049 \pm 0.031 \text{ (stat.)} \pm 0.020 \text{ (syst.)} &,& \quad c^{D^*\pi}_{lep} &= +0.044 \pm 0.054 \text{ (stat.)} \pm 0.033 \text{ (syst.)} \\
a^{D\rho} &= -0.005 \pm 0.044 \text{ (stat.)} \pm 0.021 \text{ (syst.)} &,& \quad c^{D\rho}_{lep} &= -0.147 \pm 0.074 \text{ (stat.)} \pm 0.035 \text{ (syst.)}.
\end{aligned}
$$

No significant CP asymmetry is observed thus far.

6 ACKNOWLEDGMENTS

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