Measurement of time-dependent $CP$ asymmetries in $B^0 \rightarrow D^{(*)\pm} \pi^\mp$ decays and constraints on $\sin(2\beta + \gamma)$

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We present a measurement of $\text{CP}$-violating asymmetries in fully reconstructed $B^0 \rightarrow D^{(*)\pm} \pi^\mp$ decays in approximately 88 million $T(4S) \rightarrow B\bar{B}$ decays collected with the $\text{B}\bar{\text{A}}\text{B}\bar{\text{A}}$ detector at the PEP-II asymmetric-energy $B$ factory at SLAC. From a time-dependent maximum likelihood fit we obtain for the $\text{CP}$-violating parameters: $a = -0.022 \pm 0.038 \text{ (stat.)} \pm 0.020 \text{ (syst.)} , a^* = -0.068 \pm 0.038 \text{ (stat.)} \pm 0.020 \text{ (syst.)} , c_{\text{lep}} = +0.025 \pm 0.068 \text{ (stat.)} \pm 0.033 \text{ (syst.)} , \text{ and } c_{\text{lep}} = +0.031 \pm 0.070 \text{ (stat.)} \pm 0.033 \text{ (syst.)}$. Using other measurements and theoretical assumptions we interpret
the results in terms of the angles of the Cabibbo-Kobayashi-Maskawa unitarity triangle, and find $|\sin(2\beta + \gamma)| > 0.69$ at 68% confidence level. We exclude the hypothesis of no CP violation ($\sin(2\beta + \gamma) = 0$) at 83% confidence level.

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In the Standard Model, CP violation in the weak interactions between quarks manifests itself as a non-zero area of the Cabibbo-Kobayashi-Maskawa (CKM) unitarity triangle. While it is sufficient to measure one of its angles $\alpha$, $\beta$, or $\gamma$ to be different from 0 or 180° to demonstrate the existence of CP violation, the unitarity triangle needs to be overconstrained with different measurements to test the CKM mechanism. Measurements of $\beta$ free from theoretical uncertainties exist, but there are no such measurements of $\alpha$ and $\gamma$. This letter reports the measurement of CP-violating asymmetries in $B^0 \to D^{(*)\pm} \pi^\mp$ decays in $\Upsilon(4S) \to BB$ decays and its interpretation in terms of constraints on $|\sin(2\beta + \gamma)|$.

The time evolution of $B^0 \to D^{(*)\pm} \pi^\mp$ decays is sensitive to $\gamma$ because of the interference between the CKM-favored decay $B^0 \to D^{(*)\pm} \pi^\mp$, whose amplitude is proportional to the CKM matrix elements $V_{ub} V_{cd}$, and the doubly-CKM-suppressed decay $B^0 \to D^{(*)}\mp \pi^\pm$, whose amplitude is proportional to $V_{cd}^* V_{ub}$. The relative weak phase between the two amplitudes is $\gamma$, which, when combined with $B^0$ mixing, yields a weak phase difference of $2\beta + \gamma$ between the interfering amplitudes.

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

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

where $\tau$ is the $B^0$ lifetime, neglecting the decay width difference, $\Delta m_d$ is the $B^0$-$B^0$ mixing frequency, and $\Delta t = t_{rec} - t_{tag}$ 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 $B^0$ ($\bar{B}^0$), while $\eta = +1$ (-1) and $\zeta = +1$ (-1) for the final state $D^- \pi^+$ ($D^+ \pi^-$). In the Standard Model, the $S$ and $C$ parameters can be expressed as

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

where $\lambda_{\pm} = r \pm i e^{-i(2\beta + \gamma + \delta)}$. Here $\delta$ is the relative strong phase and $r$ is the magnitude of the ratio of the suppressed and the favored amplitudes. The same equations apply for $B^0 \to D^{(*)\pm} \pi^\mp$ decays, with $r$ and $\delta$ replaced by the parameters $r'$ and $\delta'$, respectively.

The analysis strategy is similar to that of the time-dependent mixing measurement performed at BABAR. 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 charges of identified leptons and kaons, and a fourth category for remaining events. The effective tagging efficiency is $(28.1 \pm 0.7)\%$. The time difference $\Delta t$ is calculated from the separation along the beam collision axis, $\Delta z$, between the $B_{rec}$ and $B_{tag}$ decay vertices. 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 $\Delta t$ resolution is approximately 1.1 ps.

The expected CP asymmetry in these decays is small $(r^{(*)} \approx |V_{ub}^* V_{cd}/V_{cd}^* V_{ub}| \approx 0.02)$, and therefore this measurement is sensitive to the interference between the $b \to u$ and $b \to c$ amplitudes in the decay of $B_{tag}$. To account for this effect we use a parametrization different from Eq. 2, which is described in Ref. 3 and summarized here. For each tagging category ($i$) the interference is parametrized in terms of the effective parameters $r_i'$ and $\delta_i'$. Neglecting terms of order $r_i'^2$ and $r_i''$, for each tagging category the $\Delta t$ distribution becomes

$$f_i^{A,B}(\eta, \Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \times [1 \mp (a_i^{(*)} \mp \eta b_i - \eta c_i^{(*)}) \sin(\Delta m_d \Delta t) \mp \eta \cos(\Delta m_d \Delta t)],$$

where, in the Standard Model,

$$a_i^{(*)} = 2r_i^{(*)} \sin(2\beta + \gamma) \cos \delta_i^{(*)}, \quad b_i = 2r_i^{(*)} \sin(2\beta + \gamma) \cos \delta_i', \quad c_i^{(*)} = 2\cos(2\beta + \gamma)(r_i^{(*)} \sin \delta_i^{(*)} - r_i' \sin \delta_i').$$

Semileptonic $B$ decays do not have a doubly-CKM-suppressed amplitude contribution, and hence $r_i'^{lep} = 0$. Given that we have two $B$ decay modes and four tagging categories, we use two $a$ parameters (one for each final state), three $b$ parameters (one for each non-lepton tagging category), and eight $c$ parameters (one for each combination of tagging category and final state). Results are quoted only for the four parameters $a_i^{(*)}$ and $c_i^{(*)}$, which are independent of the unknowns $r_i'$ and $\delta_i'$. The other parameters are allowed to float in the fit, but, as they depend on $r_i'$ and $\delta_i'$, they do not contribute to the interpretation of the result in terms of $\sin(2\beta + \gamma)$.

This measurement is based on 88 million $\Upsilon(4S) \to BB$ decays, corresponding to an integrated luminosity of 82 fb$^{-1}$, collected with the BABAR detector at the PEP-II asymmetric-energy $B$ factory at SLAC. We use a Monte Carlo simulation of the BABAR detector based on GEANT4 to validate the analysis procedure and to estimate some of the backgrounds.

The event selection and the reconstruction of $B^0 \to D^{(*)\pm} \pi^\mp$ candidates are detailed in Ref. 3. Signal
and background are discriminated by two kinematic variables: the beam-energy substituted mass, 
\[ m_{ES} \equiv \sqrt{(\sqrt{s}/2)^2 - p_T^2}, \]
and the difference between the \( B \) candidate’s measured energy and the beam energy, \( \Delta E \equiv E_B - (\sqrt{s}/2), \) where \( E_B \) (\( p_T \)) 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 as \( |\Delta E| < 3\sigma \), where the resolution \( \sigma \) is mode-dependent and approximately 20 MeV, as determined from data. Figure 1 shows the \( m_{ES} \) distribution for candidates in the \( \Delta E \) signal region. The \( m_{ES} \) distribution is fit with the sum of a threshold function \( 12 \), which accounts for the background from random combinations of tracks, and a Gaussian distribution with a fitted width of about 2.5 MeV/c\(^2\) describing the signal. After tagging, the Gaussian yield is 5207 ± 87 and 4746 ± 78 events for the \( B^0 \rightarrow D^{\pm}\pi^\mp \) and \( B^0 \rightarrow D^{\pm}\pi^\mp \) sample respectively, with corresponding purities of (84.9 ± 0.5)% and (94.4 ± 0.4)% in a ±3\( \sigma \) region around the nominal \( B \) mass. Backgrounds from \( B^0 \) decays that peak in the \( m_{ES} \) signal region were estimated with Monte Carlo simulation to constitute (0.21 ± 0.06)% and (0.13 ± 0.05)% of the \( B^0 \rightarrow D^{\pm}\pi^\mp \) and \( B^0 \rightarrow D^{\pm}\pi^\mp \) yields, respectively. For backgrounds from \( B^+ \) decays, the corresponding figures are (0.93 ± 0.23)% and (0.93 ± 0.10)%.

An unbinned maximum-likelihood fit is performed on the selected \( B \) candidates using the \( \Delta t \) distribution in Eq. 3, convolved with a resolution function composed of three Gaussian distributions. Incorrect tagging dilutes the parameters \( a^{(*)} \), \( c^{(*)} \), and the coefficient of \( \cos(\Delta m_d\Delta t) \) by a factor \( D_t = 1 - 2w_t \) \( 2 \), \( 4 \), where \( w_t \) is the mistag fraction. The resolution function and the parameters associated with flavor tagging are determined from the data and are consistent with previous \( BABAR \) analyses \( 2 \). 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 component and the \( \Delta t \) resolution parameters are left free in the fit to the data. The background coming from \( B^- \) mesons is modeled with an exponential decay with the \( B^- \) lifetime, and its size is fixed to the value predicted by simulation. The background from \( B^0 \) mesons is neglected in the nominal fit, but is considered in evaluating the systematic uncertainties.

The results from the fit to the data are

\[
\begin{align*}
   a &= -0.022 \pm 0.038 \text{ (stat.)} \pm 0.020 \text{ (syst.)}, \\
   a^{*} &= -0.068 \pm 0.038 \text{ (stat.)} \pm 0.020 \text{ (syst.)}, \\
   c_{lep} &= +0.025 \pm 0.068 \text{ (stat.)} \pm 0.033 \text{ (syst.)}, \\
   c_{lep}^{*} &= +0.031 \pm 0.070 \text{ (stat.)} \pm 0.033 \text{ (syst.)}.
\end{align*}
\]  

All other fitted \( b \) and \( c \) parameters are consistent with zero. Figure 2 shows the fitted \( \Delta t \) distributions for events from the lepton tagging category, which has the lowest level of background and mistag probability.

The systematic uncertainties on the parameters in Eq. 3 have been calculated in a manner similar to that used in Ref. 8. A small bias in the \( \Delta t \) measurement could result in a bias on the \( c \) parameters in Eq. 3. For instance, a realistic \( \Delta t \) bias of 0.024 ps results in a shift in \( c_{lep} \) of 0.002. We are immune from this effect because we fit for tagging category dependent biases in the resolution function directly on data. Nonetheless, the impact of a possible mismeasurement of \( \Delta t \) has been estimated by varying the assumptions on the resolution function, the position of the beam-spot, the absolute alignment of the vertex detector, and quality criteria on the reconstructed vertex. The corresponding error on \( a^{(*)} \) is \( \sigma_a = 0.015 \), while that on \( c^{(*)} \) is \( \sigma_c = 0.026 \). The systematic uncertainties on the fit technique (\( \sigma_a = 0.013 \), \( \sigma_c = 0.020 \)) include the upper limit on the fit bias estimated from samples of fully simulated events, the uncertainty in the \( B^0 \) lifetime and \( \Delta m_d \), and the impact of neglecting higher order terms in \( r^{(*)} \) or \( r'_t \) in Eq. 3. As a cross-check, we performed the same fits on samples of 18233 \( B^- \rightarrow D^{(*)0}\pi^- \) and 1740 \( \bar{B}^0 \rightarrow J/\psi K^{*0} \) candidates, where we find no significant \( CP \) asymmetries, as expected. The systematic uncertainties in tagging (\( \sigma_a = 0.004 \), \( \sigma_c = 0.003 \)) are estimated allowing for different tagging efficiencies between \( B^0 \) and \( \bar{B}^0 \) and for different \( \Delta t \) resolutions for correctly and incorrectly tagged events. We also account for uncertainties on the backgrounds (\( \sigma_a = 0.001 \), \( \sigma_c = 0.003 \)) by varying the effective lifetimes, dilutions, \( m_{ES} \) shape parameters and signal fractions, and background \( CP \) asymmetry up to five times the expected \( CP \) asymmetry for signal.

The results can be interpreted in terms of \( \sin(2\beta + \gamma) \) (Eq. 4) if the decay amplitude ratios \( r^{(*)} \), expected to be \( |V_{ub}/V_{cd}/V_{ts}V_{cb}| \approx 0.02 \), are known. Such small amplitude ratios cannot be determined from \( B^0 \rightarrow D^{(*)0}\pi^- \) events directly, because the current data sample is too small. We estimate \( r^{(*)} \) using the \( SU(3) \) symmetry relation

\[
\begin{align*}
   r^{(*)} &= \tan \theta_C \sqrt{\frac{|B(B^0 \rightarrow D^{(*)0}\pi^-) f_{D^{(*)0}}|}{|B(D^+ \rightarrow D^{(*)0}\pi^-) f_{D^+}|}} \text{[13]}. \end{align*}
\]  

From the measurements of the Cabibbo angle \( \tan \theta_C = 0.2250 \pm 0.0027 \) \[12\], the branching fractions \( B(B^0 \rightarrow D^-\pi^-) = (0.30 \pm 0.04)% \) \[12\], \( B(B^0 \rightarrow D^{*-}\pi^-) = (0.276 \pm 0.038\% \) \[12\].
where $B(r)$ to 0 within 30% of the estimated physical range, the put values within their statistical errors. Because of the $\gamma - 28\%$, have negligible influence on the results of this analysis.

Excluded at 68% C.L. we exclude the hypothesis of no CP violation $\sin(2\beta + \gamma) = 0$ at 83% confidence level. In order to study the impact of the assumed theoretical error on $r^{(*)}$, we doubled it to 60% and we found that the lower limit on $|\sin(2\beta + \gamma)|$ at 68% C.L. drops from 0.69 to 0.60.

In conclusion, we studied the time-dependent CP-violating asymmetries in fully reconstructed $B^0\rightarrow D^{(*)+}\pi^+$ decays, and measured the CP-violating parameters listed in Eq. 13. With some theoretical assumptions, we interpret the result in terms of $\sin(2\beta + \gamma)$ and we find that $|\sin(2\beta + \gamma)| > 0.69$ at 68% C.L. and that $\sin(2\beta + \gamma) = 0$ is excluded at 83% C.L.
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