

## 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  $CP$ -violating asymmetries in fully reconstructed  $B^0 \rightarrow D^{(*)\pm} \pi^\mp$  decays in approximately 88 million  $\Upsilon(4S) \rightarrow B\bar{B}$  decays collected with the BABAR detector at the PEP-II asymmetric-energy  $B$  factory at SLAC. From a time-dependent maximum likelihood fit we obtain for the  $CP$ -violating parameters:  $a = -0.022 \pm 0.038$  (stat.)  $\pm 0.020$  (syst.),  $a^* = -0.068 \pm 0.038$  (stat.)  $\pm 0.020$  (syst.),  $c_{\text{lep}} = +0.025 \pm 0.068$  (stat.)  $\pm 0.033$  (syst.), and  $c_{\text{lep}}^* = +0.031 \pm 0.070$  (stat.)  $\pm 0.033$  (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 [1]. While it is sufficient to measure one of its angles  $\alpha$ ,  $\beta$ , or  $\gamma$  to be different from 0 or  $180^\circ$  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 [2, 3], but there are no such measurements of  $\alpha$  and  $\gamma$ . This letter reports the measurement of  $CP$ -violating asymmetries in  $B^0 \rightarrow D^{(*)\pm} \pi^\mp$  decays [4] in  $\Upsilon(4S) \rightarrow B\bar{B}$  decays and its interpretation in terms of constraints on  $|\sin(2\beta + \gamma)|$  [5, 6].

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

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

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

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

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

where  $\lambda_\pm = r^{\pm 1} e^{-i(2\beta + \gamma \mp \delta)}$ . 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  $B^0 \rightarrow D^{*\pm} \pi^\mp$  decays, with  $r$  and  $\delta$  replaced by the parameters  $r^*$  and  $\delta^*$ , respectively [7].

The analysis strategy is similar to that of the time-dependent mixing measurement performed at *BABAR* [8]. To identify the flavor of  $B_{\text{tag}}$ , 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  $(28.1 \pm 0.7)\%$  [2]. The time difference  $\Delta t$  is calculated from the separation along the beam collision axis,  $\Delta z$ , between the  $B_{\text{rec}}$  and  $B_{\text{tag}}$  decay vertices. We determine the  $B_{\text{rec}}$  vertex from its charged tracks. The  $B_{\text{tag}}$  decay vertex is obtained by fitting tracks that do not belong to  $B_{\text{rec}}$ , imposing constraints from the  $B_{\text{rec}}$  momentum and the beam-spot location. The  $\Delta t$  resolution is approximately 1.1 ps.

The expected  $CP$  asymmetry in these decays is small ( $r^{(*)} \approx |V_{ub}^* V_{cd} / V_{ud}^* V_{cb}| \approx 0.02$ ), and therefore this measurement is sensitive to the interference between the  $b \rightarrow u$  and  $b \rightarrow c$  amplitudes in the decay of  $B_{\text{tag}}$ . To account for this effect we use a parametrization different from Eq. 2, which is described in Ref. [9] 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  $r^{(*)2}$  and  $r_i'^2$ , for each tagging category the  $\Delta t$  distribution becomes

$$f_i^{\pm(*)}(\eta, \Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \times [1 \mp (a^{(*)} \mp \eta b_i - \eta c_i^{(*)}) \sin(\Delta m_d \Delta t) \mp \eta \cos(\Delta m_d \Delta t)], \quad (3)$$

where, in the Standard Model,

$$\begin{aligned} a^{(*)} &= 2r^{(*)} \sin(2\beta + \gamma) \cos \delta^{(*)}, \\ b_i &= 2r'_i \sin(2\beta + \gamma) \cos \delta'_i, \\ c_i^{(*)} &= 2 \cos(2\beta + \gamma) (r^{(*)} \sin \delta^{(*)} - r'_i \sin \delta'_i). \end{aligned} \quad (4)$$

Semileptonic  $B$  decays do not have a doubly-CKM-suppressed amplitude contribution, and hence  $r'_{\text{lep}} = 0$ . 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  $a^{(*)}$  and  $c_{\text{lep}}^{(*)}$ , 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  $\Upsilon(4S) \rightarrow B\bar{B}$  decays, corresponding to an integrated luminosity of  $82 \text{ fb}^{-1}$ , collected with the *BABAR* detector [10] at the PEP-II asymmetric-energy  $B$  factory at SLAC. We use a Monte Carlo simulation of the *BABAR* detector based on GEANT4 [11] to validate the analysis procedure and to estimate some of the backgrounds.

The event selection and the reconstruction of  $B^0 \rightarrow D^{(*)\pm} \pi^\mp$  candidates are detailed in Ref. [8]. Signal

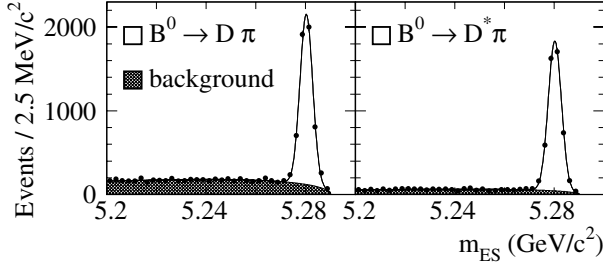


FIG. 1: Distributions of  $m_{ES}$  in the  $\Delta E$  signal region for events with tagging information in the  $B^0 \rightarrow D^\pm \pi^\mp$  (left plot) and the  $B^0 \rightarrow D^{*\pm} \pi^\mp$  sample (right plot).

and background are discriminated by two kinematic variables: the beam-energy substituted mass,  $m_{ES} \equiv \sqrt{(\sqrt{s}/2)^2 - p_B^{*2}}$ , and the difference between the  $B$  candidate's measured energy and the beam energy,  $\Delta E \equiv E_B^* - (\sqrt{s}/2)$ , where  $E_B^*$  ( $p_B^*$ ) 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 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  $5207 \pm 87$  and  $4746 \pm 78$  events for the  $B^0 \rightarrow D^\pm \pi^\mp$  and  $B^0 \rightarrow D^{*\pm} \pi^\mp$  sample respectively, with corresponding purities of  $(84.9 \pm 0.5)\%$  and  $(94.4 \pm 0.4)\%$  in a  $\pm 3\sigma$  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  $(0.21 \pm 0.06)\%$  and  $(0.13 \pm 0.05)\%$  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  $(0.93 \pm 0.23)\%$  and  $(0.93 \pm 0.10)\%$ .

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  $a^{(*)}$ ,  $c_i^{(*)}$ , and the coefficient of  $\cos(\Delta m_d \Delta t)$  by a factor  $D_i = 1 - 2w_i$  [2, 9], where  $w_i$  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  $B^\pm$  mesons is modeled with an exponential decay with the  $B^\pm$  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

$$\begin{aligned} a &= -0.022 \pm 0.038 \text{ (stat.)} \pm 0.020 \text{ (syst.)}, \\ a^* &= -0.068 \pm 0.038 \text{ (stat.)} \pm 0.020 \text{ (syst.)}, \\ c_{lep} &= +0.025 \pm 0.068 \text{ (stat.)} \pm 0.033 \text{ (syst.)}, \\ c_{lep}^* &= +0.031 \pm 0.070 \text{ (stat.)} \pm 0.033 \text{ (syst.)}. \end{aligned} \quad (5)$$

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. 5 has 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  $z$  scale, the internal 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 on the  $B^0$  lifetime and  $\Delta m_d$  [13], and the impact of neglecting higher order terms in  $r^{(*)}$  or  $r_i'$  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 background ( $\sigma_a = 0.001$ ,  $\sigma_c = 0.003$ ) 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  $|V_{ub}^* V_{cd} / V_{ud}^* V_{cb}| \approx 0.02$ , are known. Such small amplitude ratios cannot be determined from  $B^0 \rightarrow D^{(*)\pm} \pi^\mp$  events directly, because the current data sample is too small. We estimate  $r^{(*)}$  using the  $SU(3)$  symmetry re-

lation  $r^{(*)} = \tan \theta_C \sqrt{\frac{\mathcal{B}(B^0 \rightarrow D_s^{(*)+} \pi^-)}{\mathcal{B}(B^0 \rightarrow D^{(*)-} \pi^+)}} \frac{f_{D^{(*)}}}{f_{D_s^{(*)}}}$  [5]. From the measurements of the Cabibbo angle  $\tan \theta_C = 0.2250 \pm 0.0027$  [13], the branching fractions  $\mathcal{B}(B^0 \rightarrow D^- \pi^+) = (0.30 \pm 0.04)\%$  [13],  $\mathcal{B}(B^0 \rightarrow D^{*-} \pi^+) = (0.276 \pm$

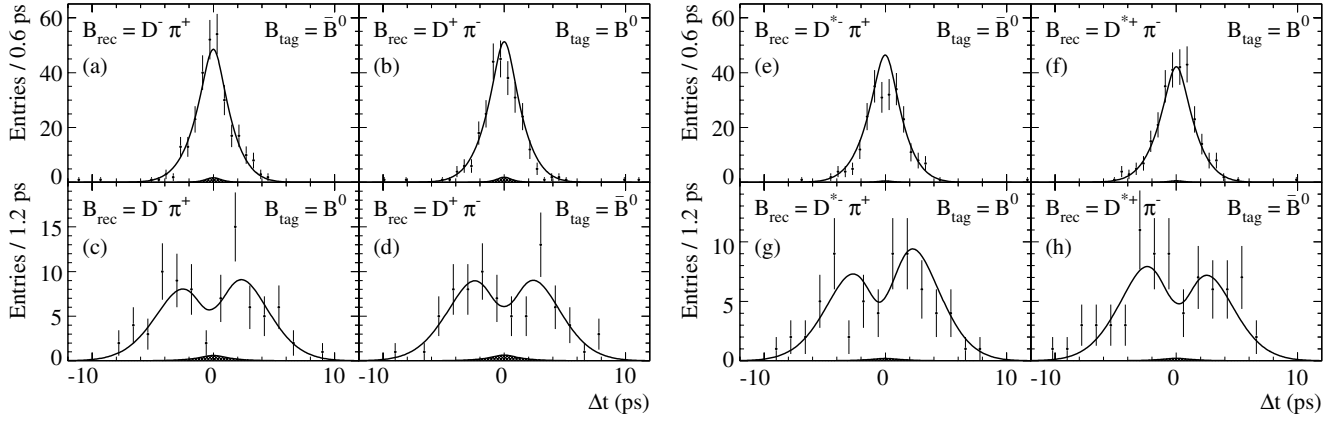


FIG. 2: Distributions of  $\Delta t$  for the  $B^0 \rightarrow D^\pm \pi^\mp$  (a-d) and  $B^0 \rightarrow D^{*\pm} \pi^\mp$  (e-h) candidates tagged with leptons, split by  $B$  tagging flavor and reconstructed final state. The lines are fit projections and hatched regions represent background.

$0.021\%$  [13],  $\mathcal{B}(B^0 \rightarrow D_s^+ \pi^-) = (2.7_{-0.6}^{+0.7} \pm 0.8) \times 10^{-5}$  [14],  $\mathcal{B}(B^0 \rightarrow D_s^{*+} \pi^-) = (1.9_{-1.3}^{+1.2} \pm 0.5) \times 10^{-5}$  [14], and from calculations of the decay constant ratios  $f_{D_s}/f_D = 1.11 \pm 0.01$  and  $f_{D_s^*}/f_{D^*} = 1.10 \pm 0.02$  [15] we obtain

$$r = 0.019 \pm 0.004, \quad r^* = 0.017_{-0.007}^{+0.005}. \quad (6)$$

To obtain  $\sin(2\beta + \gamma)$ , we minimize the  $\chi^2$

$$\chi^2(2\beta + \gamma, \delta^{(*)}, r^{(*)}) = \sum_i \left( \frac{\tilde{x}_i - x_i}{\sigma_i} \right)^2 + \Delta(r^{(*)}), \quad (7)$$

where  $x_i = a, a^*, c_{lep}, c_{lep}^*$  are functions of the physics parameters (Eq. 4), and  $\tilde{x}_i$  are the corresponding measured values.  $\Delta(r^{(*)})$  is a continuous function that is set equal to 0 within 30% of the estimated  $r^{(*)}$  (Eq. 6), and is an offset quadratic outside this range, with the errors in Eq. 6. The additional 30% error attributed on  $r^{(*)}$  is due to the unknown theoretical uncertainty on the validity of the  $SU(3)$  symmetry assumption and to neglecting  $W$ -exchange contributions to  $A(B^0 \rightarrow D^{(*)+} \pi^-)$ . This error estimate is consistent with the spread in  $r^{(*)}$  obtained using a variety of theoretical models [16]. The  $\sigma_i$  are the quadratic sums of the statistical and systematic uncertainties in Eq. 5. Correlations between the  $\tilde{x}_i$ , at most 28%, have negligible influence on the results of this analysis. The simultaneous analysis of two  $B$  decay modes allows one to extract  $|\sin(2\beta + \gamma)|$ .

Figure 3 shows the minimum  $\chi^2$  for each value of  $|\sin(2\beta + \gamma)|$ . The absolute minimum occurs for  $|\sin(2\beta + \gamma)| = 0.98$ , where  $\chi_{\min}^2/\text{d.o.f.} = 0.44/1$ . The values of  $r^{(*)}$  that minimize the  $\chi^2$  are consistent with the input values within their statistical errors. Because of the large uncertainties on the fit parameters and their limited physical range, the  $\chi^2$  curve is non-parabolic. Thus to obtain a probabilistic interpretation to the results, we consider, for each of many values of  $\sin(2\beta + \gamma)$ , a large number of simulated experiments with the same characteristics as the data. We compute the consistency of the data

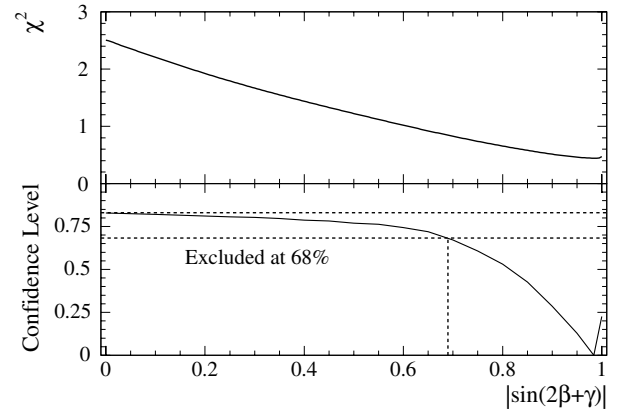


FIG. 3: Dependence of  $\chi^2$  on  $|\sin(2\beta + \gamma)|$  (top) and of the frequentist confidence level of the agreement of the data with expectations as a function of the hypothesis on  $|\sin(2\beta + \gamma)|$  (bottom). The assumptions on  $r$  and  $r^*$  are contained in the definition of  $\chi^2$  (Eq. 7). The dashed horizontal lines indicate the 68% and 83% confidence levels (defined in the text).

with a given value of  $\sin(2\beta + \gamma)$  by counting the fraction of simulated experiments for which  $\chi^2(\sin(2\beta + \gamma)) - \chi_{\min}^2$  is smaller than it is in the data. This fraction, the frequentist confidence level, is shown in the lower portion of Fig. 3, from which we read that  $|\sin(2\beta + \gamma)| > 0.69$  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  $B^0 \rightarrow D^{(*)\pm} \pi^\mp$  decays, and measured the  $CP$ -violating parameters listed in Eq. 5. 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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