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# CP Violation Studies in $B^0 \to D^{(*)\pm}\pi^\mp$ in BABAR and Belle

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**Abstract.** We present a preliminary measurement of the time-dependent *CP* asymmetries in decays of $B^0$ mesons to the final states $D^{(*)}\pi$ using data collected by the *BABAR* experiment at the PEP-II storage rings. $B$ mesons decaying to $D\pi$ are fully reconstructed, while events containing $B \to D^*\pi$ are selected using a full or a partial reconstruction technique. These results can be interpreted in terms of a constraint on the angles of the unitarity triangle to set a lower bound on $|\sin(2\beta+\gamma)|$. The Belle experiment at the KEK-B collider is performing the same kind of studies and a preliminary estimation of the achievable error is presented.

## 1 Introduction

The main physics goal of the *BABAR* and Belle experiments running on B-factories is the measurement of the *CP*-violating phase of the quark-mixing (CKM) matrix [1] and to over-constrain the unitarity triangle in order to check whether the CKM mechanism is the correct explanation of the *CP* violation phenomenon. The *CP* violation in the B sector has been established by measuring the $\beta$ angle of the unitarity triangle [2], [3]. We present here an analysis to constrain $|\sin(2\beta+\gamma)|$ from the study of the time evolution for $B^0 \to D^{(*)\pm}\pi^\mp$ decays [4] [5].

## 2 Principle of the measurement

### 2.1 Time-dependent decay rates

The decays $B^0 \to D^{(*)\pm}\pi^\mp$ may proceed via a favored $b \to c\overline{u}d$ or a doubly-CKM-suppressed $b \to u\overline{c}d$ amplitude. Interference between these amplitudes through $B^0$ - $\overline{B}^0$ mixing provides a time-dependent *CP*-violation signal. The time-dependent decay rate for $B^0 \to D^\pm\pi^\mp$ decays is:

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

where $\tau$ is the mean $B^0$ lifetime, $\Delta m_d$ is the $B^0$- $\overline{B}^0$ mixing frequency, and $\Delta t = t_{rec} - t_{tag}$ is the time elapsed between the $B^0 \to D^\pm\pi^\mp$ decay ($B_{rec}$) and the decay of the other $B$ ($B_{tag}$). The superscript $+(-)$ refers to whether the flavor of ($B_{tag}$) was $B^0$ ($\overline{B}^0$), while $\eta = +1(-1)$ for $D^-\pi^+$ ($D^+\pi^-$) final states. The S and C parameters can be expressed as:

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

where we define $|\lambda| = |\lambda_+| = 1/|\lambda_-|$, and $\lambda_\pm = \frac{q}{p}A(\overline{B}^0 \to D^\mp\pi^\pm)/A(B^0 \to D^\mp\pi^\pm) = |\lambda|^{\pm1}e^{-i(2\beta+\gamma\mp\delta)}$, $q/p$ is a function of the elements of the mixing matrix and $\delta$ is the relative strong phase between the two contributing amplitudes. The same equations apply for $B^0 \to D^{*\pm}\pi^\mp$ decays with $|\lambda|$ and $\delta$ replaced by different values $|\lambda^*|$ and $\delta^*$.

The analysis strategy is similar to other *BABAR* and Belle time dependent CP asymmetry measurements [2], [3]. The $B^0$ meson decaying to the $D^{(*)}\pi$ final state ($B_{rec}$) is reconstructed using a partial or a full reconstruction method. The flavor of the other $B^0$ meson ($B_{tag}$) is determined using the charge correlation with a lepton or a kaon. Each event is assigned to one of four hierarchical, mutually exclusive tagging categories. The decay time difference $\Delta t$ is computed from the distance separating the $B_{tag}$ and $B_{rec}$ vertices.

### 2.2 Estimation of $|\lambda^{(*)}|$

In principle the ratio $|\lambda^{(*)}|$ of the magnitudes of the suppressed and favored amplitudes can be estimated from a global time-dependent fit of equation 1. In practice, this is not possible with the current *BABAR* statistics. As suggested in [5] [6], the value of $|\lambda^{(*)}|$ is estimated from the ratio of branching fractions $\mathcal{B}(B^0 \to D_s^{(*)+}\pi^-)/\mathcal{B}(B^0 \to D^{(*)-}\pi^+)$. Using the *BABAR* measurement [6]

$$|\lambda|(D\pi) = 0.021^{+0.004}_{-0.005}, \quad |\lambda^*|(D^*\pi) = 0.017^{+0.005}_{-0.007} \quad (3)$$

As this estimation is based on the approximate SU(3) symmetry and is not taking into account annhilation contributions to $B^0 \to D^{(*)+}\pi^-$, there is an unknown, potentialy large, theoretical uncertainty on $|\lambda^{(*)}|$.

### 2.3 CP violation on the tag side

In the same way that the interference between the $b \to u$ and $b \to c$ amplitudes is present in the reco side and is used to measure the CP asymmetry, the same interference exists on the tag side and induces a time-dependent effect which cannot be neglected [7]. This effect depends on the $B_{tag}$ decay modes. For each tagging category (i), this interference is parametrized in terms of the effective parameters $|\lambda'_i|$ and $\delta'_i$. The time-dependent decay rate becomes:

$$f_i^{\pm(*)}(\eta, \Delta t) \propto 1 \mp \left(a^{(*)} \mp \eta b_i - \eta c_i^{(*)}\right)\sin(\Delta m_d \Delta t) \mp \eta\cos(\Delta m_d \Delta t) \quad (4)$$

where

$$\begin{aligned} a^{(*)} &= 2|\lambda^{(*)}|\sin(2\beta+\gamma)\cos\delta^{(*)}, \\ b_i &= 2|\lambda'_i|\sin(2\beta+\gamma)\cos\delta'_i, \\ c_i^{(*)} &= 2\cos(2\beta+\gamma)\left(|\lambda^{(*)}|\sin\delta^{(*)} - |\lambda'_i|\sin\delta'_i\right). \end{aligned} \quad (5)$$

The $b$ and $c$ parameters absorb the tag side interference effects while $a$ is independent of them. The lepton tag category does not have doubly-CKM-suppressed amplitude contribution, therefore $|\lambda'_{lep}| = 0$.

## 3 $B^0 \to D^{(*)\pm}\pi^\mp$ full reconstruction method

In the full reconstruction method [8], the final state $B^0 \to D^{(*)\pm}\pi^\mp$ is completly reconstructed. The $D^{*+}$ is reconstructed in its decay to $D^0\pi^+$, where the $D^0$ subsequently decays to $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$ or $K^0_S\pi^+\pi^-$. The $D^+$ is reconstructed in $K^-\pi^+\pi^+$ or $K^0_S\pi^+$. After selection, signal and background are discriminated by two kinematic variables: the beam energy substituted mass, $m_{\rm ES} \equiv \sqrt{\left(\sqrt(s)/2\right)^2 - {p^*_B}^2}$ and the difference between the $B$ candidate's measured energy and the beam energy, $\Delta E \equiv E^*_B - \left(\sqrt(s)/2\right)$. $E^*_B$ ($P^*_B$) 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. This method provides a very clean signal selection, with a small background coming mainly from combinatorics. The remaining peaking is of the order of 1%. Based on an integrated luminosity of $81.9\,\mathrm{fb}^{-1}$ on the $\Upsilon(4S)$ resonance, the signal yield is $5207 \pm 87$ events with a 85% purity for $B^0 \to D^+\pi^-$ and $4746 \pm 78$ events with a 94% purity for $B^0 \to D^{*+}\pi^-$.

An unbinned maximum likelihood fit is performed on the selected candidates using the $\Delta t$ distribution in Eq. 4 convoluted with a three-Gaussian resolution function and taking into account the probabilities of incorrect tagging. The results from the fit to the data including the systematic uncertainties summarized in Table 1 are:

$$\begin{aligned} a &= -0.022 \pm 0.038(stat) \pm 0.021(syst), \\ a^* &= -0.068 \pm 0.038(stat) \pm 0.021(syst), \\ c_{lep} &= 0.025 \pm 0.068(stat) \pm 0.035(syst), \\ c^*_{lep} &= 0.031 \pm 0.070(stat) \pm 0.035(syst). \end{aligned} \quad (6)$$

These results can be interpreted in terms of $\sin(2\beta+\gamma)$, $\delta$ and $\delta^*$ by minimizing the $\chi^2$

$$\chi^2 = \sum_i \left(\frac{\tilde{x}_i - x_i}{\sigma_i}\right)^2 + \chi^2(|\lambda|) + \chi^2(|\lambda^*|), \quad (7)$$
$$x_i = a, a^*, c_{lep}, c^*_{lep},$$

where the $\tilde{x}_i$ refers to the measured values for $a^{(*)}$ and $c^{(*)}_{lep}$. The terms $\chi^2(|\lambda|)$ and $\chi^2(|\lambda^*|)$ are taking into account a 30% non-gaussian uncertainty on $|\lambda^{(*)}|$. The $\chi^2$, is non-parabolic due to the limited physical range and to the large errors. A minimum of the $\chi^2$ is found for $|\sin(2\beta+\gamma)| = 0.98$. In order to give a frequentistic interpretation to this result, a large number of simulated experiments are performed with the same characteristics as the data and with different true values of $\sin(2\beta+\gamma)$. The consistency of the data with a given value of $\sin(2\beta+\gamma)$ is computed by counting the fraction of simulated experiments in which $\chi^2(\sin(2\beta+\gamma)) - \chi^2_{min}$ is larger than in the data. The limit computed in this way is: $|\sin(2\beta+\gamma)| > 0.69$ at 68% C.L. and the value: $|\sin(2\beta+\gamma)| = 0$ is excluded at 83% C.L.

**Table 1.** Systematic uncertainties on $a^{(*)}$ and $c^{(*)}$ and the total uncertainty $\sigma_{tot}$

| Source | $\sigma_a = \sigma^*_a$ | $\sigma_c = \sigma^*_c$ |
|---|---|---|
| Vertexing | 0.015 | 0.026 |
| Tagging | 0.004 | 0.003 |
| Background | 0.001 | 0.003 |
| Fit | 0.014 | 0.023 |
| Total ($\sigma_{tot}$) | 0.021 | 0.035 |

## 4 $B^0 \to D^{*\pm}\pi^\mp$ partial reconstruction method

In the partial reconstruction method [9], only the $B^0 \to D^{*\pm}\pi^\mp$ decay channel is considered. Only the hard pion track from the $B^0$ decay and the soft pion track from the decay $D^* \to D^0\pi$ are reconstructed. Using the two pions and kinematic constraints, a missing mass variable is computed. In this variable, signal events peak at the nominal $D^0$ mass with a spread of about 3 MeV/$c^2$, while the distribution of the combinatoric background is significantly broader. The background is coming mainly from combinatorics and from $B^0 \to D^*\rho$. The statistics is larger than for the full reconstruction method: $6409 \pm 129$ events with a lepton tag and $25157 \pm 323$ events with a kaon tag for 76.4 fb$^{-1}$ on the $\Upsilon(4S)$ resonance.

In order to compute the time difference $\Delta t$ the $B^0 \to D^{*\pm}\pi^\mp$ decay position along the beam axis is estimated by fitting the hard pion track with a beam spot constraint in the plane perpendicular to the beams. The typical $\Delta t$ resolution is $\simeq 1$ ps.

The analysis is carried out with a series of unbinned maximum likelihood fits performed simultaneously on the on- and off-resonance data samples and independently for the lepton-tagged and kaon-tagged events. The parameters $S_+$ and $S_-$ from Eq. 1 are extracted from the lepton tags while $a$, $b$ and $c$ of Eq. 4 are determined from kaon tags. Combining both tagging categories:

$$a = -0.063 \pm 0.024(stat) \pm 0.017(syst)$$
$$c_{lep} = -0.004 \pm 0.037(stat) \pm 0.020(syst). \quad (8)$$

The systematic uncertainties are summarized in Table 2 A $\chi^2$ similar to Eq. 8 is minimized and a probabilistic interpretation of the result identical to the one exposed in section 3 allows to give the following limits on $|\sin(2\beta+\gamma)|$, assuming a 30% non-gaussian error on $|\lambda|$: $|\sin(2\beta+\gamma)| > 0.88$ at 68% C.L. $|\sin(2\beta+\gamma)| > 0.75$ at 90% C.L. $|\sin(2\beta+\gamma)| > 0.62$ at 95% C.L. and the value $|\sin(2\beta+\gamma)| = 0$ is excluded at 98.3% C.L.

**Table 2.** Systematic uncertainties on $S_-$, $S_+$, $a$, $b$ and $c^{(*)}$ and the total uncertainty

| Source | Error ($\times 10^{-3}$) in | | | | |
|---|---|---|---|---|---|
| | $S_-$ | $S_+$ | $a$ | $b$ | $c$ |
| Background | 3.0 | 8.0 | 5.0 | 4.0 | 6.0 |
| Bkg *CP* content | 10.0 | 10.0 | 13.0 | 7.0 | 13.0 |
| Fit | 5.0 | 7.0 | 5.0 | 2.0 | 1.0 |
| Detector | 10.0 | 10.0 | 10.0 | 6.0 | 10.0 |
| MC stat | 13.0 | 13.0 | 8.0 | 4.0 | 9.0 |
| Total | 20.0 | 21.0 | 19.0 | 11.0 | 10.0 |

## 5 Combined results

The results from the full reconstruction and the partial reconstruction method are combined and give the following limits: $|\sin(2\beta+\gamma)| > 0.89$ at 68% C.L. $|\sin(2\beta+\gamma)| > 0.76$ at 90% C.L. and $|\sin(2\beta+\gamma)| = 0$ is excluded at 99.5% C.L.

As there is a large theoretical uncertainty on the value of $|\lambda^{(*)}|$, the lower limit on $|\sin(2\beta+\gamma)|$ is plotted in Fig. 1 as a function of $r = |\lambda|$ for various values of the confidence level. In this case $r = |\lambda|$ and $|\lambda^*|$ are assumed to be equal.

## 6 Status of $B^0 \to D^{(*)\pm}\pi^\mp$ in Belle

The Belle experiment is performing similar studies on $B^0 \to D^{(*)}\pi$. For the partial reconstruction technique, with 78 $\text{fb}^{-1}$ of data and including background effect, the expected statistical uncertainty on $2|\lambda|\sin(2\beta+\gamma)$ is equal to $\pm 0.029$. For the full reconstruction method, with the complete data sample available this summer, estimated from a Monte-Carlo simulation study and not taking into account background effect, the statistical uncertainty on $2|\lambda|\sin(2\beta+\gamma)$ is equal to $\pm 0.028$.

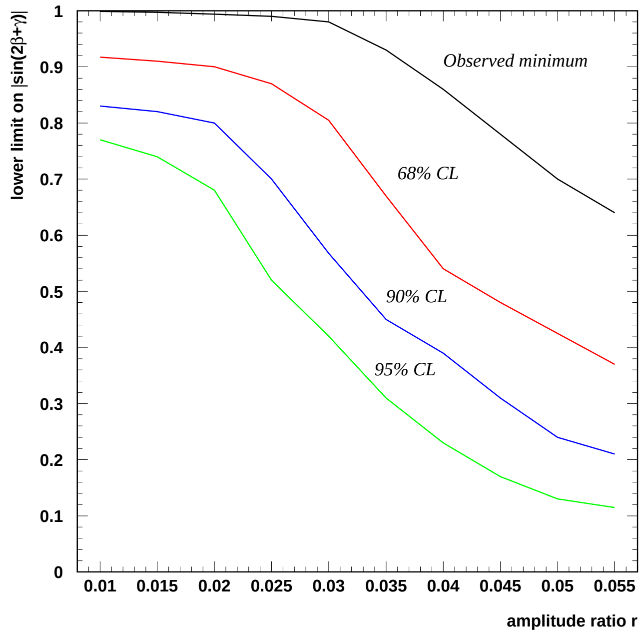


**Fig. 1.** *BABAR* lower limit on $|\sin(2\beta+\gamma)|$ as a function of $r = |\lambda| = |\lambda^*|$ for various values of the C.L. The $|\sin(2\beta+\gamma)|$ value corresponding to the minimum $\chi^2$ is also shown.

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