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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.

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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 β 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 τ is the mean B^0 lifetime, Δm_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 $\lambda_\pm = \frac{q}{p}A(\overline{B}^0 \to D^\mp\pi^\pm)/A(B^0 \to D^\mp\pi^\pm) = |\lambda|^{\pm 1}e^{-i(2\beta+\gamma\mp\delta)}$, q/p is a function of the elements of the mixing matrix and δ 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 δ replaced by different values $|\lambda^*|$ and δ^*.

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 Δt 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]

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

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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 δ_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 $K_S^0\pi^+\pi^-$. The D^+ is reconstructed in $K^-\pi^+\pi^+$ or $K_S^0\pi^+$. 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 $\Upsilon(4S)$ resonnance, the signal yield is 5207 ± 87 events with a 85% purity for $B^0 \to D^+\pi^-$ and 4746 ± 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 Δt 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 $\sin(2\beta+\gamma)$, δ and δ^* by minimizing the χ^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 χ^2, is non-parabolic due to the limited physical range and to the large errors. A minimum of the χ^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 σ_{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 (σ_{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 ± 129 events with a lepton tag and 25157 ± 323 events with a kaon tag for 76.4 fb^{-1} on the $\Upsilon(4S)$ resonance.

In order to compute the time difference Δt 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 Δt 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 χ^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.

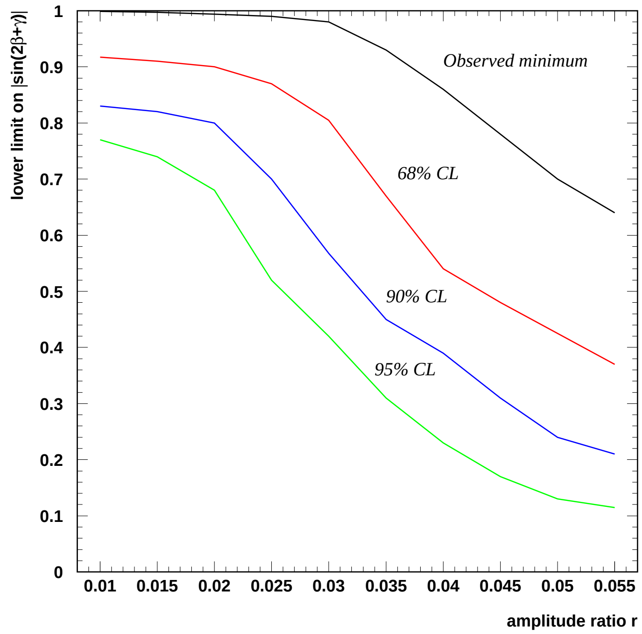

Fig. 1. *BABAR* lower limit on $|\sin(2\beta+\gamma)|$ as a function of $r = |\lambda| = |\lambda^*|$ for various values of the C.L. The $|\sin(2\beta+\gamma)|$ value corresponding to the minimum χ^2 is also shown.

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 fb^{-1} of data and including background effect, the expected statistical uncertainty on $2|\lambda|\sin(2\beta+\gamma)$ is equal to ± 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 ± 0.028.

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