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CP violation studies in $B^0 \to D^{(*)+}\overline{D}^{(*)-}$ and $B^0 \to J/\psi\, K^*$

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Abstract. Recent experimental results on $B^0 \to D^{(*)+}\overline{D}^{(*)-}$ and $B \to J/\psi\, K^*$ decays at the B factories by the *BABAR* and BELLE collaborations are reviewed.

1 Introduction

In the Standard Model (SM) *CP* violation is made possible by an irreducible complex phase in the CKM quark-mixing matrix [1]. In this framework, measurements of *CP* asymmetries in the proper-time distribution of neutral B decays to *CP* final states can be related to the parameter sin2β, β being one of the angles of the unitarity triangle of the CKM matrix. The theoretically cleanest environment to measure sin2β are the $b \to c\bar{c}s$ (charmonium) decays, such as $B^0 \to J/\psi K^0_S$. A precise measurement of sin2β in the charmonium modes has been reported in the last years by the *BABAR* and BELLE collaborations [2].

In addition to the charmonium modes, *CP* violation measurement can be performed in many other *CP* decays. Cabibbo suppressed modes $b \to c\bar{c}d$ and vector-vector decays are excellent candidates to broaden *CP* violation studies.

The *CP* violating asymmetry in the Cabibbo suppressed modes $b \to c\bar{c}d$ such as $B^0 \to D^{*+}D^{*-}$ and $B^0 \to D^{*\pm}D^{\mp}$ is related to sin2β when corrections due to theoretically uncertain penguin diagram contributions are neglected [3,4]. Penguin-induced corrections are predicted to be small in models based on the factorization approximation and heavy-quark symmetry; an effect of about 2% is predicted by [5]. A comparison of measurements of sin2β from $b \to c\bar{c}s$ modes with that obtained in $B^0 \to D^{(*)+}\overline{D}^{(*)-}$ is an important test of these models and the SM.

In vector-vector decays such as $B^0 \to D^{*+}D^{*-}$ and $B^0 \to J/\psi\, K^{*0}(\to K^0_S\pi^0)$ different partial waves contribute with different *CP* parities to the *CP* asymmetry, leading to a dilution in the observed asymmetry. An angular analysis allows to separate out the two different *CP* contributions to the asymmetry [6]. For $B^0 \to J/\psi\, K^{*0}(\to K^0_S\pi^0)$ a $\cos 2\beta$ factor appears in the interference between the *CP*-odd and *CP*-even amplitudes. Moreover time integrated angular analyses allow to extract the decay amplitudes, providing a test for the models based on factorization hypothesis and heavy-quark symmetry.

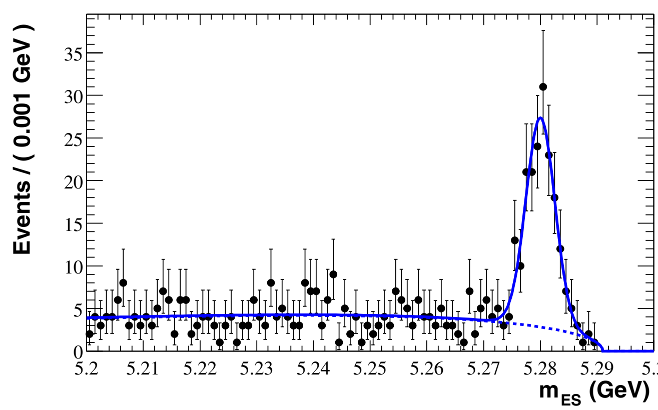

Fig. 1. Energy-substituted mass for the *BABAR* selected $B^0 \to D^{*+}D^{*-}$ candidates in the region $-39 < \Delta E < 31$ MeV. The *solid line* is a fit result using a Gaussian and an Argus function

2 $B^0 \to D^{*+}D^{*-}$

B^0 mesons decaying in $D^{*+}D^{*-}$ are exclusively reconstructed by combining two charged D^* candidates reconstructed in the modes $D^{*+} \to D^0\pi^+$ and $D^{*+} \to D^+\pi^0$. The primary variables used to distinguish signal from background are the difference of the B candidate energy and the beam energy, $\Delta E \equiv E_B - E_{\rm Beam}$, and the energy-substituted mass, $m_{\rm ES} \equiv \sqrt{E^2_{\rm Beam} - p^2_B}$, where all variables are evaluated in the $\Upsilon(4S)$ center-of-mass frame.

Both *BABAR* [7] and BELLE [8] have measured the branching fraction $Br(B^0 \to D^{*+}D^{*-})$:

$$Br(BABAR) = (8.3 \pm 1.6({\rm stat}) \pm 1.2({\rm syst})) \times 10^{-4}$$
$$Br(BELLE) = (7.6 \pm 0.9({\rm stat}) \pm 1.4({\rm syst})) \times 10^{-4}$$

with data corresponding to an integrated luminosity of $21 fb^{-1}$ and $78 fb^{-1}$ respectively and systematic uncertainties dominated by tracking efficiencies and acceptance effects.

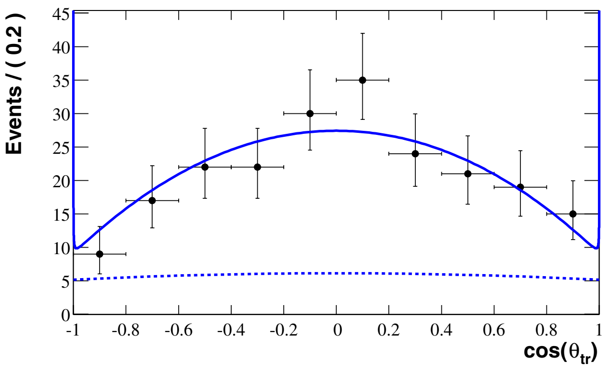

Fig. 2. Measured distribution of $\cos\theta_{\rm tr}$ by *BABAR* in $B^0 \to D^{*+}D^{*-}$ events. The *data points* are from the region $m_{\rm ES} > 5.27$ GeV/c^2 and the *solid line* is the fit result; the *dotted line* represents the background component

2.1 *CP* odd fraction in $B^0 \to D^{*+}D^{*-}$

The $B^0 \to D^{*+}D^{*-}$ mode is a pseudo-scalar decay to a vector-vector final state, with contributions from three partial waves with different *CP* parities: even for the *S*- and *D*-waves, odd for the *P*-wave. The *CP*-odd contribution is predicted to be about 6% in [9,10].

BABAR has performed a one-dimensional time integrated angular analysis to determine the fraction, $R_\perp$, of the *P*-wave, *CP*-odd component of the $B^0 \to D^{*+}D^{*-}$ decay, with data corresponding to an integrated luminosity of $81 fb^{-1}$ and a signal yield of 156 ± 14(stat) events [11].

Only the polar angle $\theta_{\rm tr}$ between the normal to the D^{*-} decay plane and the direction of flight of the slow pion from the D^{*+} in the D^{*+} rest frame is used. The expected one-dimensional differential decay rate is:

$$\frac{1}{\Gamma}\,\frac{{\rm d}\Gamma}{{\rm d}\cos\theta_{\rm tr}} = \frac{3}{4}(1-R_\perp)\sin^2\theta_{\rm tr} + \frac{3}{2}R_\perp\cos^2\theta_{\rm tr}. \quad (1)$$

The dependence of the detector efficiency on the decay angles can introduce a bias in the measured value of $R_\perp$. Including the efficiency explicitly in the decay rate, leads to a modified expression for the (1), in terms of the three efficiency moments which can be determined by using simulated events [11].

The measurement of $R_\perp$ is based on a combined unbinned maximum likelihood fit of the $\cos\theta_{\rm tr}$ and $m_{\rm ES}$ distributions. The experimental resolution of $\theta_{\rm tr}$ is not negligible and is accounted for by convolving the signal pdf with a double Gaussian. The fit to the dataset (Fig. 2) yields a value of

$$R_\perp = 0.063 \pm 0.055({\rm stat}) \pm 0.009({\rm syst}).$$

The largest systematic uncertainties arise from the parameterization of the angular resolution (0.005) and the determination of the efficiency moments (0.005).

2.2 Time dependent angular analysis in $B^0 \to D^{*+}D^{*-}$

In addition to the time-integrated measurement of the *CP*-odd fraction, *BABAR* has performed a combined analysis of the $\cos\theta_{\rm tr}$ distribution, the time dependence and the information from the other B meson in the event to tag its flavor as either a B^0 or $\overline{B}^0$, in order to determine the time-dependent *CP* asymmetry [11].

Although factorization models predict a small penguin contamination in the weak phase difference in ${\rm Im}(\lambda_f) = -\sin 2\beta$ [5], a sizable penguin contribution cannot *a priori* be excluded. Thus, the value of $\lambda_f = \eta_{CP}\frac{q}{p}\frac{\bar{A}(f)}{A(f)}$ [12] can be different for the three transversity amplitudes ($f = \perp, 0, \|$) because of possible different penguin-to-tree ratios. This possibility is explicitly included in the parameterization of the decay rates $F_+(F_-)$ for a neutral B meson tagged as a $B^0(\overline{B}^0)$:

$$F_\pm(\Delta t, \cos\theta_{\rm tr}) = \frac{{\rm e}^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} G \mp$$
$$\left.[S\sin(\Delta m_d \Delta t) + C\cos(\Delta m_d\Delta t)]\right\},$$

where $\Delta t = t_{\rm rec} - t_{\rm tag}$ is the difference between the proper decay time of the reconstructed B meson ($B_{\rm rec}$) and of the tagging B meson ($B_{\rm tag}$), τ_{B^0} is the B^0 lifetime, and Δm_d is the mass difference determined from the B^0-$\overline{B}^0$ oscillation frequency. The G, C and S coefficients are defined as

$$G = \tfrac{3}{4}[(1-R_\perp)\sin^2\theta_{\rm tr} + 2R_\perp\cos^2\theta_{\rm tr}],$$
$$C = \tfrac{3}{4}[(1-R_\perp)\tfrac{1-|\lambda_+|^2}{1+|\lambda_+|^2}\sin^2\theta_{\rm tr} + 2R_\perp\tfrac{1-|\lambda_\perp|^2}{1+|\lambda_\perp|^2}\cos^2\theta_{\rm tr}],$$
$$S = -\tfrac{3}{4}[(1-R_\perp)\tfrac{2{\rm Im}(\lambda_+)}{1+|\lambda_+|^2}\sin^2\theta_{\rm tr} - 2R_\perp\tfrac{2{\rm Im}(\lambda_\perp)}{1+|\lambda_\perp|^2}\cos^2\theta_{\rm tr}].$$

Because the two *CP*-even transversity amplitudes produce the same distribution in $\cos\theta_{\rm tr}$, the only sensitivity is on λ_+, the appropriate average of $\lambda_\|$ and λ_0 [11].

The parameters ${\rm Im}(\lambda_+)$ and $|\lambda_+|$ are determined with a simultaneous unbinned maximum likelihood fit to the Δt distributions of the $B_{\rm rec}$ and $B_{\rm flav}$ tagged samples (Fig. 3). Since the *CP*-odd fraction is small, there is little sensitivity to the parameters $|\lambda_\perp|$ and ${\rm Im}(\lambda_\perp)$. Therefore they are fixed to 1.0 and -0.741 [2] respectively. These are the values expected if direct *CP* violation and contributions from penguin diagrams are neglected. The results obtained from the fit (Fig. 3) are

$${\rm Im}(\lambda_+) = 0.05 \pm 0.29({\rm stat}) \pm 0.10({\rm syst})$$
$$|\lambda_+| = 0.75 \pm 0.19({\rm stat}) \pm 0.02({\rm syst}).$$

The dominant sources of systematic uncertainty come from the variation of the value of $\lambda_\perp$ (0.056 and 0.008, respectively, for ${\rm Im}(\lambda_+)$ and $|\lambda_+|$), and the level, composition, and *CP* asymmetry of the background (0.078 and 0.005). If the $B \to D^{*+}D^{*-}$ transition proceeds only through the $b \to c\bar{c}d$ tree amplitude, one expects that ${\rm Im}(\lambda_+) = -\sin 2\beta$ and $|\lambda_+| = 1$. To test this hypothesis, ${\rm Im}(\lambda_+)$ and $|\lambda_+| = 1$ are fixed to -0.741 and 1 respectively [2] and the fit is repeated. The observed change in the likelihood corresponds to 2.5 standard deviations (statistical uncertainty only).

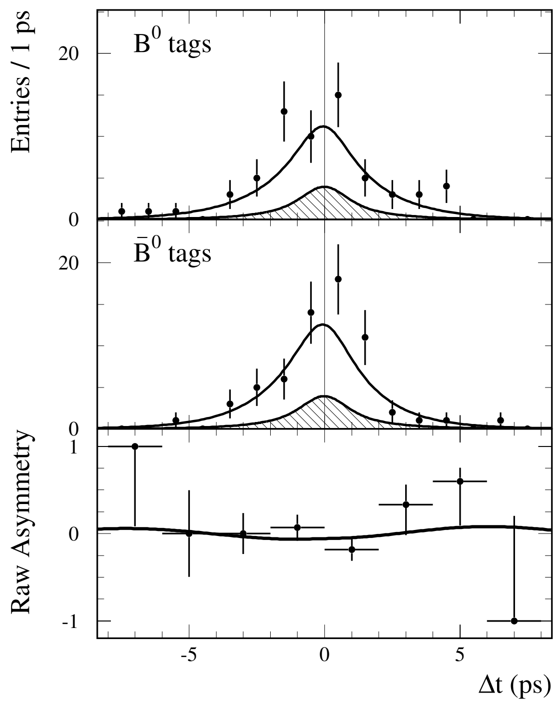

Fig. 3. From *top* to *bottom*: Number N_{B^0} ($N_{\overline{B}^0}$) of candidate events in the region $m_{\rm ES} > 5.27$ GeV/c^2 with a B^0 ($\overline{B}^0$) tag, and the raw asymmetry $(N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$, as functions of Δt in *BABAR* $B^0 \to D^{*+}D^{*-}$ events. The *solid curves* represent the result of the combined fit to the full sample. The *shaded regions* represent the background contributions

3 $B^0 \to D^{*\pm}D^{\mp}$

Both BELLE [13] and *BABAR* [14] have measured the branching fraction $Br(B^0 \to D^{*\pm}D^{\mp})$:

$$Br(BELLE) = (11.7 \pm 2.6(\text{stat}) \pm 2.3(\text{syst})) \times 10^{-4}$$
$$Br(BABAR) = (8.8 \pm 1.0(\text{stat}) \pm 1.3(\text{syst})) \times 10^{-4}$$

with data corresponding to an integrated luminosity of $29 fb^{-1}$ and $81 fb^{-1}$ respectively.

On the same data corresponding to a signal yield of 113 ± 13(stat) events *BABAR* has also performed *CP* violation studies [14].

First of all *BABAR* has determined the time-integrated *CP* violating asymmetry between the rates to $D^{*-}D^+$ and $D^{*+}D^-$ to be $\mathcal{A} = -0.03 \pm 0.11(\text{stat}) \pm 0.05(\text{syst})$.

The decay rate distributions $f^{\pm}$, where the superscript $+(-)$ refers to whether the flavor tag was B^0 ($\overline{B}^0$), are given by

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

The states $D^{*-}D^+$ and $D^{*+}D^-$ are not *CP* eigenstates. The formalism of time evolution for non-*CP* eigenstate vector-pseudo-scalar decays is given in [15]. Separate S and C parameters are fitted for the two decays $D^{*-}D^+$ and $D^{*+}D^-$, resulting in the four fitted *CP* violation parameters $\{S_{-+}, C_{-+}, S_{+-}, C_{+-}\}$. The time-dependent fit to the $B \to D^{*\pm}D^{\mp}$ and $B_{\rm flav}$ samples yields

$$S_{-+} = -0.24 \pm 0.69(\text{stat}) \pm 0.12(\text{syst}),$$
$$C_{-+} = -0.22 \pm 0.37(\text{stat}) \pm 0.10(\text{syst}),$$
$$S_{+-} = -0.82 \pm 0.75(\text{stat}) \pm 0.14(\text{syst}),$$
$$C_{+-} = -0.47 \pm 0.40(\text{stat}) \pm 0.12(\text{syst}).$$

In the case of equal amplitudes for $B \to D^{*-}D^+$ and $B \to D^{*+}D^-$, one expects that at tree level $C_{-+} = C_{+-} = 0$ and $S_{-+} = S_{+-} = -\sin 2\beta$.

4 $B \to J/\psi K^*$

For $B \to J/\psi K^*$ new results were not available for this conference, but time integrated and time dependent full angular analyses were already published by both *BABAR* [16] and BELLE [17].

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