CP violation in B decays to charm and charmonium at Belle

K. Vervink
Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland

We present the study of CP violation in charm and charmonium decays, using a data sample corresponding to 657×10^6 $B\overline{B}$ events collected with the Belle detector at the $\Upsilon(4S)$ resonance at the KEKB asymmetric-energy e^+e^- collider. We report measurements of the polarization fraction and time-dependent CP-violation parameters of the decay $B^0 \to D^{*+}D^{*-}$ and of the branching fraction and charge asymmetry in the decay of the Cabibbo- and color-suppressed process $B^\pm \to \psi(2S)\pi^\pm$.

1. INTRODUCTION

The study of exclusive B meson decays to charm and charmonium has played an important role in exploring CP violation [1–3]. Amongst them the Cabibbo-suppressed decays have an increased sensitivity to New Physics effects and can be studied at the B factories which, due to their high integrated luminosities, overcome the suppression factor. The $B^0 \to D^{*+}D^{*-}$ and $B^- \to \psi(2S)\pi^-$ decay proceed primarily via a $b \to c\bar{c}d$ tree diagram while penguin contributions are expected to be small in the Standard Model (SM). A large deviation of the measured CP parameters from the SM prediction can be a hint of New Physics.

2. DATASET AND EVENT RECONSTRUCTION

Both analyses are based on a data sample containing 657 million $B\overline{B}$ pairs, collected with the Belle detector [4] at the KEKB asymmetric-energy e^+e^- collider [5] operating at the $\Upsilon(4S)$ resonance. The $\Upsilon(4S)$ meson is produced with a Lorentz boost $\beta\gamma = 0.425$ along the z axis, opposite to the positron beam direction, and decays mainly into a $B^0\overline{B}^0$ or a B^+B^- pair.

The reconstructed B candidates are discriminated from background using the energy difference $\Delta E \equiv E_B^{\rm CM} - E_{\rm beam}^{\rm CM}$ and the beam-constrained mass $M_{\rm bc} \equiv \sqrt{(E_{\rm beam}^{\rm CM})^2 - (p_B^{\rm CM})^2}$, where $E_{\rm beam}^{\rm CM}$ is the beam energy in the center-of-mass (CM) system and $E_B^{\rm CM}$ and $p_B^{\rm CM}$ are the CM energy and momentum of the B candidate.

3. $B^- \to \psi(2S)\pi^-$

3.1. Theoretical Motivation

The main $B^- \to \psi(2S)\pi^-$ diagram is not only Cabbibo-suppressed but also color-suppressed. A measurement of its branching fraction, unknown so far, is shown in this paper. Assuming tree dominance and factorization, the branching fraction $\mathcal{B}(B^- \to \psi(2S)\pi^-)$ is expected to be about 5% of that of the Cabibbo-favored mode $B^- \to \psi(2S)K^-$ [6]. Furthermore under these assumptions, CP violation should be negligibly small. However if penguin contributions or new physics effects are present, a non-zero charge asymmetry can occur.

3.2. Results

The $\psi(2S)$ meson is reconstructed through the $\ell^+\ell^-$ and $J/\psi\pi^+\pi^-$ decay channels, where the J/ψ decays to $\ell^+\ell^-$ ($\ell = e\,{\rm or}\,\mu$). Inclusion of charge-conjugate modes is implied throughout the paper. Contamination from the $B^- \to \psi(2S)K^-$ decays, where a kaon is misinterpreted as a pion, results in a peak at $\Delta E \approx -0.07\,{\rm GeV}$, which is

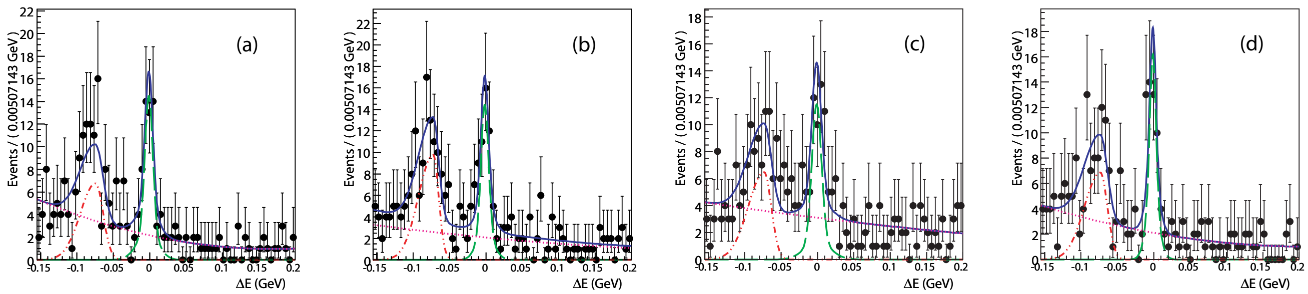

Figure 1: ΔE distributions of the $B^- \to \psi(2S)\pi^-$ candidates, reconstructed in (a) $\psi(2S) \to J/\psi(e^+e^-)\pi^+\pi^-$, (b) $\psi(2S) \to J/\psi(\mu^+\mu^-)\pi^+\pi^-$, (c) $\psi(2S) \to e^+e^-$ and (d) $\psi(2S) \to \mu^+\mu^-$. The curves show the signal (dashed) and background components (dot-dashed and dotted) as well as the overall fit (solid).

modeled using a Monte Carlo (MC) sample. A fit performed simultaneously to all the considered $\psi(2S)$ decay modes (Fig. 1) provides the branching fraction:

$$\mathcal{B}(B^- \to \psi(2S)\pi^-) = 2.44 \pm 0.22\,(\text{stat}) \pm 0.20\,(\text{syst}). \tag{1}$$

Branching fractions for the B^+ and B^- decays are extracted to measure the charge asymmetry $\mathcal{A}$. Signal yields of 89 ± 11 and 93 ± 11 events for B^+ and B^-, respectively, result in a charge asymmetry of

$$\mathcal{A} = \frac{\mathcal{B}(B^- \to \psi(2S)\pi^-) - \mathcal{B}(B^+ \to \psi(2S)\pi^+)}{\mathcal{B}(B^- \to \psi(2S)\pi^-) + \mathcal{B}(B^+ \to \psi(2S)\pi^+)} = 0.022 \pm 0.085\,(\text{stat}) \pm 0.016\,(\text{syst}), \tag{2}$$

which is consistent with no direct CP violation. Finally we measure

$$\frac{\mathcal{B}(B^- \to \psi(2S)\pi^-)}{\mathcal{B}(B^- \to \psi(2S)K^-)} = (3.99 \pm 0.36\,(\text{stat}) \pm 0.17\,(\text{syst}))\%, \tag{3}$$

which is consistent with the theoretical prediction of the factorization hypothesis.

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

4.1. Theoretical Motivation

The time-dependent decay rate of a neutral B meson to a CP eigenstate, such as $D^{*+}D^{*-}$, is given by:

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\Big\{1 + q\Big[\mathcal{S}\sin(\Delta m_d \Delta t) + \mathcal{A}\cos(\Delta m_d \Delta t)\Big]\Big\}, \tag{4}$$

where $q = +1(-1)$ when the other B meson in the event decays as a B^0 ($\overline{B}^0$) and $\Delta t = t_{CP} - t_{\text{tag}}$ is the proper time difference between the two B decays in the event, τ_{B^0} is the neutral B lifetime, Δm_d the mass difference between the two B^0 mass eigenstates. The CP-violating parameters are defined as

$$\mathcal{S} = \frac{2\Im(\lambda)}{|\lambda|^2 + 1}, \quad \mathcal{A} = \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1}, \tag{5}$$

where λ is a complex observable depending on the B^0 and $\overline{B}^0$ decay amplitudes to the final state and the relation between the B meson mass eigenstates and its flavor eigenstates. When ignoring penguin corrections, the SM predictions for the CP parameters are $\mathcal{A}_{D^{*+}D^{*-}} = 0$ and $\mathcal{S}_{D^{*+}D^{*-}} = -\eta_{D^{*+}D^{*-}} \sin 2\phi_1$, where $\phi_1 = \arg[-V_{cd}V_{cb}^*]/[V_{td}V_{tb}^*]$ and $\eta_{D^{*+}D^{*-}}$ is the CP eigenvalue of $D^{*+}D^{*-}$, which is $+1$ when the decay proceeds through the S or D wave, or -1 for the P wave. A significant shift of the CP parameters from the SM predictions can be a sign for New Physics.

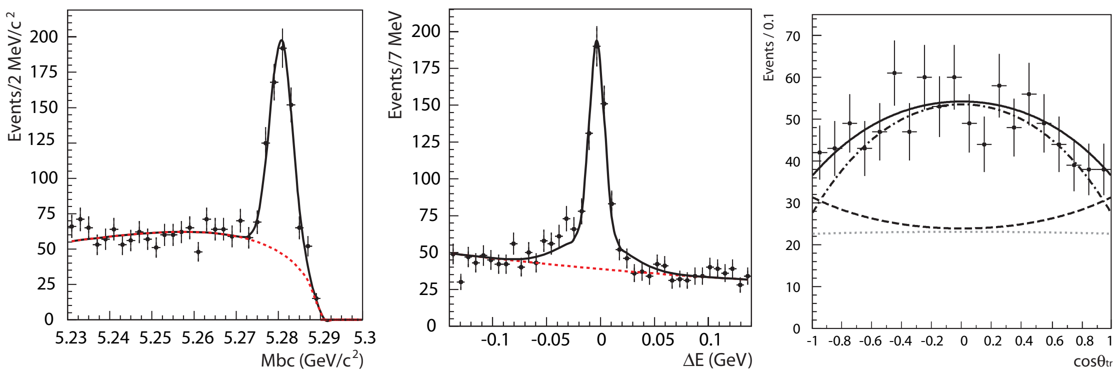

Figure 2: (Left) $M_{\rm bc}$ distribution in the ΔE signal region. (Middle) ΔE distribution in the $M_{\rm bc}$ signal region. (Right) $\cos\theta_{\rm tr}$ distribution in the signal region. The solid line represents the total fitted function and the dotted line shows the background contribution. In the right plot, the CP-even and CP-odd contributions are indicated above the background with the dashed and dot-dashed lines respectively.

4.2. Yield and angular analysis

The $D^{*\pm}$ mesons are reconstructed in the $D^0\pi^+$ and $D^+\pi^0$ modes. The signal is extracted from a two-dimensional unbinned maximum likelihood fit in the $M_{\rm bc}$ vs. ΔE plane. We obtain 553 ± 30 signal events with a signal purity of 55%. The first two plots in Fig. 2 show the projections of the fitted $M_{\rm bc}$ and ΔE distributions in the signal region.

To obtain the CP-odd fraction we perform a time-integrated angular analysis in the transversity basis [7]. The differential decay rate as a function of the transversity angle $\theta_{\rm tr}$ reads

$$\frac{1}{\Gamma}\frac{d\Gamma_{B\to D^{*+}D^{*-}}}{d\cos\theta_{\rm tr}} = \frac{3}{4}R_0\sin^2\theta_{\rm tr} + \frac{3}{2}R_\perp\cos^2\theta_{\rm tr} + \frac{3}{4}R_\parallel\sin^2\theta_{\rm tr} \qquad (6)$$

where $R_{0,\parallel}$ and $R_\perp$ are the CP-even and CP-odd fractions of the three transversity components respectively. A one-dimensional fit of the $\cos\theta_{\rm tr}$ distribution allows the extraction of the CP-odd fraction. Its distortion due to the angular resolution and the slow pion reconstruction efficiency is modeled using signal MC samples. The fraction $R_0/(R_0 + R_\parallel)$ is taken from the previous Belle analysis [3]. The signal-to-background ratio is determined on an event-by-event basis using the $M_{\rm bc} - \Delta E$ distribution. The result (shown in the right plot of Fig. 2) is

$$R_\perp = 0.125 \pm 0.043({\rm stat}) \pm 0.023({\rm syst}). \qquad (7)$$

4.3. Time-dependent CP violation measurement

Because the B^0 and $\overline{B}^0$ are approximately at rest in the $\Upsilon(4S)$ CM frame, the Δt value can be determined from the separation in z of the two decay vertices, $\Delta t \simeq \Delta z/(\beta\gamma c)$, where c is the speed of light. To obtain the Δt distribution, we reconstruct the tag-side B vertex and its flavor inclusively from properties of particles that are not associated with the reconstructed $B^0 \to D^{*+}D^{*-}$ decay [8]. The tagging information is represented by two parameters, the flavor of the tagging B^0, q, and the tagging quality given by seven r intervals from $r = 0$ meaning no flavor discrimination to $r = 1$ for unambiguous flavor assignment. Equation 4 is modified to incorporate the effect of incorrect flavor assignment, the CP-odd dilution, and the description of background events. The signal-to-background fraction is obtained on an event-by-event basis, using the previous fits of the $M_{\rm bc}$, ΔE and $\cos\theta_{\rm tr}$ distributions. The free parameters in the fit are $\mathcal{A}_{D^{*+}D^{*-}}$ and $\mathcal{S}'_{D^{*+}D^{*-}} = \mathcal{S}_{D^{*+}D^{*-}}/\eta_{D^{*+}D^{*-}}$; these are determined by maximizing an unbinned likelihood function for all events in the fit region. The result is

$$\begin{aligned}\mathcal{A}_{D^{*+}D^{*-}} &= 0.15 \pm 0.13({\rm stat}) \pm 0.04({\rm syst}),\\ \mathcal{S}'_{D^{*+}D^{*-}} &= -0.96 \pm 0.25({\rm stat})\,^{+0.12}_{-0.16}({\rm syst}),\end{aligned} \qquad (8)$$

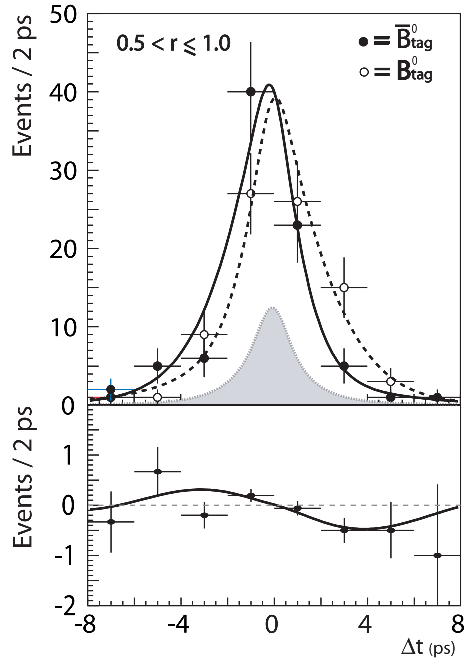

Figure 3: Top: Δt distribution of well-tagged $B^0 \to D^{*+}D^{*-}$ candidates ($r > 0.5$) for $q = +1$ and $q = -1$. The gray area is the background contribution while the solid and dashed curves are the superposition of the total PDFs for well-tagged $q = -1$ (solid line) and $q = +1$ (dotted line) events respectively. Bottom: fitted raw asymmetry of the two top distributions.

with a statistical correlation of 10.7%. The total significance of non-zero values of $\mathcal{S}'$ and $\mathcal{A}$ is $3.1\,\sigma$. We define the raw asymmetry in each Δt bin as $(N_+ - N_-)/(N_+ + N_-)$, where $N_+(N_-)$ is the number of observed candidates with $q = +1(-1)$. Figure 3 shows the Δt distribution and the raw asymmetry for events with a good-quality tag ($r > 0.5$). Our measurement of $\mathcal{S}'$ and $\mathcal{A}$ is consistent with the SM expectation for a tree-dominated $b \to c\bar{c}d$ transition.

5. Conclusion

We reported a measurement of the CP-violating parameters in $B^- \to \psi(2S)\pi^-$ and $B^0 \to D^{*+}D^{*-}$ decay using 657 million $B\overline{B}$ pairs recorded with the Belle detector. Both measurements are compatible with the SM predictions in absence of penguins. The branching fraction of $B^- \to \psi(2S)\pi^-$ is extracted as well as its ratio with respect to $B^- \to \psi(2S)K^-$. The result supports the factorization hypothesis. In the $B^0 \to D^{*+}D^{*-}$ analysis the CP-odd fraction is obtained to allow for an undiluted measurement of $\sin 2\phi_1$.

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