Improved measurement of the branching fraction, polarization, and CP violation in $B^0 \to D^{*+}D^{*-}$ decays at the Belle experiment

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One of the main goals of the Belle experiment is the measurement of time-dependent CP violation in the decay of neutral B mesons. In this report, the measurement of the branching fraction, the polarization, and CP violation in $B^0 \to D^{*+}D^{*-}$ is presented. The analysis of this decay requires a measurement of its polarization, since it is the decay of a pseudo-scalar to two vector mesons. The measurement is performed using the final Belle data sample of 772 million $B\bar{B}$ pairs.

1 Introduction

The time-dependent CP violation in the decay of neutral B mesons to two charged D mesons is directly related to the angle ϕ_1 in the unitarity triangle of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix, which was precisely measured in $b \to (c\bar{c})s$ decays. These double charm decays have been analyzed in numerous final states both by the BaBar and the Belle collaboration [1,2,3,4], where Belle found unexpected evidence of large direct CP violation in $B^0 \to D^+D^-$ decays [1]. The analysis of $B^0 \to D^{*+}D^{*-}$ decays requires an additional measurement of the polarization, since it is the decay of a pseudo-scalar to two vector mesons and therefore the final state is not a pure CP-eigenstate but a mixture of CP-even and CP-odd final states, depending on the relative angular momentum of the D^* mesons.

The used data sample of 772 million $B\bar{B}$ pairs was collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider [5]. The last analysis of $B^0 \to D^{*+}D^{*-}$ decays of the Belle collaboration was performed using a data sample of 657 million $B\bar{B}$-pairs [2], which is only 15% less than the data used in this measurement. But new track finding algorithms and the reprocessing of a great fraction of the Belle data sample lead to a 79% higher reconstruction efficiency of $B^0 \to D^{*+}D^{*-}$ decays and therefore a more than doubled number of reconstructed signal events.

2 Event reconstruction

We fully reconstruct the signal decay mode $B^0 \to D^{*+}D^{*-}$, where D^{*+} mesons are reconstructed in the decay modes $D^{*+} \to D^0\pi^+$ and $D^{*+} \to D^+\pi^0$ [a]. Charged D mesons are reconstructed in the modes $K^-\pi^+\pi^+$, $K^0_S\pi^+$, $K^0_S\pi^+\pi^0$, and $K^+K^-\pi^+$ and neutral D mesons in $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$, $K^0_S\pi^+\pi^-$, and K^+K^-. Final states containing more than one D^{*+} decaying to $D^+\pi^0$ or two K^0_S mesons are discarded due to their high background level. This leads to 32 reconstructed decay channels in total. We select intermediate particle candidates based on

[a] Charge-conjugate decay modes are implied unless otherwise stated.

numerous properties, like their mass or the distance to the interaction region. Neutral B meson candidates are selected based on the beam-constrained-mass $M_{\rm bc} = \sqrt{\left(E^{\rm CMS}_{\rm beam}\right)^2 - \left(\vec{p}^{\,\rm CMS}_B\right)^2}$ and the energy difference $\Delta E = E^{\rm CMS}_B - E^{\rm CMS}_{\rm beam}$ with $E^{\rm CMS}_{\rm beam}$ being the beam energy in the center-of-mass system (CMS), $\vec{p}^{\,\rm CMS}_B$ the momentum, and $E^{\rm CMS}_B$ the energy of the fully reconstructed B meson. In case of multiple candidates, the best candidate is selected based on the masses of the D meson and the mass differences between the D^* and D meson candidates. The applied reconstruction and selection leads to an overall reconstruction efficiency, including the branching fraction of the intermediate particles, of 0.2%.

3 Branching fraction measurement

The number of reconstructed signal events is extracted with an extended, two-dimensional, unbinned maximum likelihood fit in $M_{\rm bc}$ and ΔE. The signal distribution is described in both dimensions by sums of Gausian distributions and empirically determined parameterized signal shape introduced by the Crystal Ball collaboration [6]. The fractions of the individual terms and the ratio of the widths are obtained using simulated signal events, while the mean and a scale factor of the width, which is introduced to absorb the possible difference between data and simulation, are floated in the fit. The background in ΔE is described by a second-order polynomial and in $M_{\rm bc}$ by an empirically determined parametrized background shape introduced by the ARGUS collaboration [7].

The so determined number of signal events is 1225 ± 59. The corresponding fit projections and data distributions are shown in Fig. 1. The reconstruction efficiencies of all individual decay channels are obtained using simulated signal events and the branching fractions of the intermediate decays are taken from Ref. [8]. This gives a branching fraction of $\mathcal{B}(B^0 \to D^{*+}D^{*-}) = (7.82 \pm 0.38 \pm 0.6) \times 10^{-4}$. The major contributions to the systematic error come from the uncertainty of the track reconstruction efficiencies of slow pions and neutral pions, the uncertainty of the efficiency of the selection performed for the separation of charged kaons and pions, and the uncertainty of the branching fractions of D and D^* mesons.

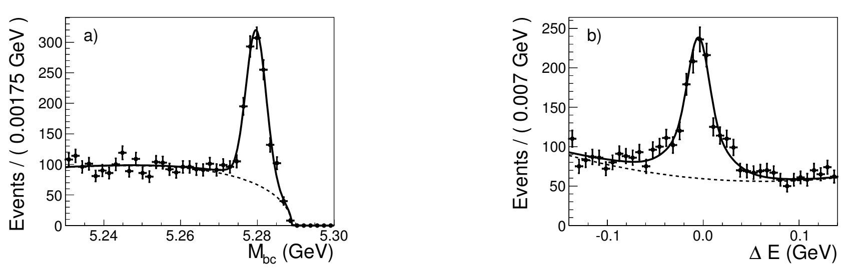

Figure 1: Fit projections and data points of $M_{\rm bc}$ (left) and ΔE (right). The solid lines show the total fitted distribution in the signal region of the other variable. The dashed lines show the fitted background distribution.

4 Measurement of the polarization and time-dependent CP violation

For the statistical separation of CP-even and CP-odd final states, we perform an angular analysis in the transversity basis, which is illustrated in Fig. 2, using two of the three possible angles: θ_{tr} and θ_1.

The signal distribution in these two angles is described by the sum of three polynomial distributions, where each of them represents one possible polarization. The fractions of the polarizations are defined to have a sum of one and are noted as $R_0, R_\perp$, and $R_\parallel$, where R_0 and $R_\parallel$ represent CP-even and $R_\perp$ CP-odd final states. The shapes of the individual polynomial

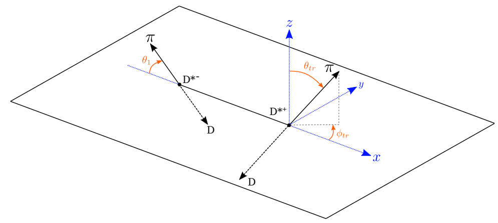

Figure 2: Illustration of the transversity base for the decay $B^0 \to D^{*+}D^{*-}$.

distributions are obtained using samples of simulated, polarized signal events and fixed in the fit. The background also is described by polynomial distributions, but all parameters are floated in the fit.

The angular analysis and the measurement of CP violation is performed simultaniously in a five-dimensional, unbinned, maximum-likelihood fit in $M_{\rm bc}$, ΔE, θ_{tr}, θ_1, and Δt, where Δt is the decay time difference of the fully reconstructed B meson, B_{CP}, and the accompanying B meson, referred to as tag B. It is calculated from the decay length difference $\Delta z = z_{CP} - z_{\rm tag}$ with $\Delta t \approx \Delta z\,(\beta\gamma)_{\Upsilon(4s)}\,c$. The decay vertex of the B_{CP} meson is obtained by a hirarchical system of kinematic fits, where some of the fits contain additional constraints like the known mass of the particle for neutral pions or the interaction region for the B_{CP} meson. The decay vertex of the tag B meson is obtained from the charged tracks which are not used for the reconstruction of the B_{CP} meson by constraining them with a kinematic fit to originate from a common vertex and discarding tracks which likely stem from secondary decays. The flavor of the tag B meson is obtained using the flavor tagging algorithm described in Ref. [9]. For each candidate it gives the flavor of the tag B meson q and a tagging quality variable r, which is divided in seven bins. The wrong tag fraction w and the wrong tag fraction difference between the tagging of B^0 and $\bar{B}^0$ mesons Δw were determined in each of the bins using high statistics control samples [10].

With S and A being the parameters of CP violation, where S is related to mixing-induced and A to direct CP violation, the signal component in Δt is described with

$$\mathcal{P}_{B^0}(\Delta t) = \frac{1}{4\tau_{B^0}} e^{-|\Delta t|/\tau_{B^0}} \{1 - q\Delta w + q(1-2w) \times [(1-2P_{\rm odd})S\sin(\Delta m\Delta t) + A\cos(\Delta m \Delta t)]\} \otimes R_{\rm sig}, \tag{1}$$

where τ_{B^0} is the lifetime of the neutral B meson, Δm the mass difference of the two mass-eigenstates of the neutral B system, $P_{\rm odd}$ the propability of an event to be CP-odd, obtained from the angular distributions, and $R_{\rm sig}$ a resolution term, describing the detector resolution and effects from secondary decays of the tag B. The resolution function and its parameters were obtained from high statistics control samples and are described in detail in Ref. [10]. The background in Δt is modeled with the sum of an exponential and a prompt component, convoluted with the sum of two Gaussian distributions, whose widths depend on the uncertainty of Δz. The signal fraction is determined in each bin of r independently, using the fit model in ΔE and $M_{\rm bc}$ which is the same as in the branching fraction measurement. In total, the PDF describing the signal and background in $M_{\rm bc}$, ΔE, $\cos\theta_{tr}$, $\cos\theta_1$, and Δt has 30 free parameters with four of them being S, A, R_0, and $R_\perp$. The result is

$$R_0 = 0.624 \pm 0.029 \pm 0.007 \qquad R_\perp = 0.138 \pm 0.024 \pm 0.005$$
$$S = -0.79 \pm 0.13 \pm 0.03 \qquad A = 0.15 \pm 0.08 \pm 0.04.$$

The major contributions to the systematic error come from the uncertainty of the parameters of the Δt signal resolution function and the influence of the interference of Cabibbo-favored $b \to c\bar{u}d$ and doubly Cabibbo-suppressed $\bar{b} \to \bar{u}c\bar{d}$ decays of the tag B meson.
Figure 3 shows the fit projections and the data points for the two angles, the Δt distribution of

well tagged events ($w < 0.25$) with $q = 1$ and $q = -1$, and the corresponding raw asymmetry $(N_+(\Delta t) - N_-(\Delta t))\,/\,(N_+(\Delta t) + N_-(\Delta t))$ with $N_i(\Delta t)$ being the number of events with the corresponding flavor tag in a bin of Δt.

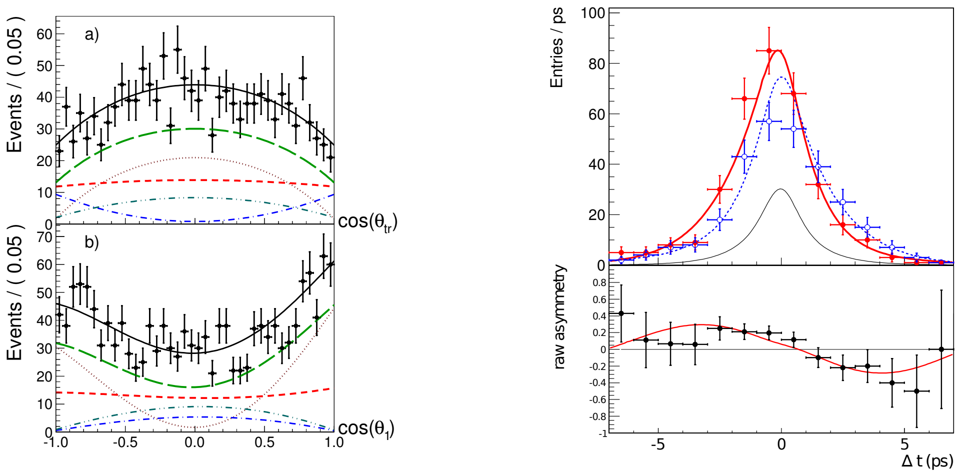

Figure 3: The left plot shows fit projections and data points of $\cos\theta_{tr}$ (top) and $\cos\theta_1$ (bottom) in the signal region of $M_{\rm bc}$ and ΔE. The black, solid line shows the total fitted function, the green, long dashed line the fitted signal, and the red, short dashed line the background. The brown dotted, the blue dash dotted, and the cyan dash double dotted lines show the contributions of the R_0, $R_\perp$, and $R_\parallel$ components, respectively. The right top plot shows events with $w < 0.25$ for $q = 1$ and $q = -1$ in the signal region of $M_{\rm bc}$ and ΔE. The red, solid (blue, dashed) line and markers show the data points and the according fit of events for $q = 1 (q = -1)$. The thin, black line shows the estimated background contribution. The right bottom plot shows the raw asymmetry of the two top curves.

5 Conclusion

We measure the branching fraction, the polarization, and the parameters of CP violation of $B^0 \to D^{*+}D^{*-}$ decays with $\mathcal{B}(B^0 \to D^{*+}D^{*-}) = [7.82 \pm 0.38(\text{stat.}) \pm 0.60(\text{syst.})] \times 10^{-4}$, $R_0 = 0.624 \pm 0.029(\text{stat.}) \pm 0.007(\text{syst.})$, $R_\perp = 0.138 \pm 0.024(\text{stat.}) \pm 0.005(\text{syst.})$, $S = -0.79 \pm 0.13(\text{stat.}) \pm 0.03(\text{syst.})$, and $A = 0.15 \pm 0.08(\text{stat.}) \pm 0.04(\text{syst.})$. This measurement is consistent with the previous measurements of the Belle collaboration [11,2] and supersedes them. It is also in agreement with the standard model expectation and is the first measurement in $B^0 \to D^{*+}D^{*-}$ decays, which excludes CP-conservation with more than $5\,\sigma$.

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