PROCEEDINGS OF SCIENCE

phi2 and phi3 measurements at Belle

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We present a summary of the measurements of the CKM angles ϕ_2 and ϕ_3, performed by the Belle experiment which collects $B\bar{B}$ pairs at the $\Upsilon(4S)$ resonance produced in asymmetric-energy e^+e^- collisions. We discuss the most precise measurements of the ADS observables $\mathscr{R}_{DK}$ and $\mathscr{A}_{DK}$ as well as the first model-independent determination of ϕ_3 in the GGSZ method. We also speculate on the precision that can be achieved with the final Belle data set on the ϕ_2 related channels $B^0 \to \pi^+\pi^-$, $\rho^0\rho^0$, and $a_1^\pm\pi^\mp$.

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1. Introduction

The main goal of the Belle experiment at KEK is to constrain the unitarity triangle for B decays. This allows us to test the Cabibbo-Kobayashi-Maskawa (CKM) mechanism for violation of the combined charge-parity (CP) symmetry [1, 2], as well as search for new physics effects beyond the Standard Model (SM). These proceedings give a summary of the experimental status of measurements of the CKM phases ϕ_2 and ϕ_3, defined from CKM matrix elements as $\phi_2 \equiv \arg(-V_{td}V_{tb}^*)/(V_{ud}V_{ub}^*)$ and $\phi_3 \equiv \arg(-V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*)$.

First-order weak processes (tree) proceeding by $b \to u\bar{u}d$ quark transitions such as $B^0 \to \pi\pi$, $\rho\pi$, $\rho\rho$ and $a_1^{\pm}\pi$, are directly sensitive to ϕ_2. In the quasi-two-body approach, CKM angles can be determined by measuring the time-dependent asymmetry between B^0 and $\bar{B}^0$ decays [3]. For the decay sequence $\Upsilon(4S) \to B_{CP}B_{\rm Tag} \to f_{CP}f_{\rm Tag}$, where one of the B mesons decays at time t_{CP}, to a CP eigenstate f_{CP}, and the other decays at time $t_{\rm Tag}$, to a flavour specific final state $f_{\rm Tag}$, with $q = +1(-1)$ for $B_{\rm Tag} = B^0(\bar{B}^0)$, the decay rate has a time-dependence given by

$$P(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 + q(\mathscr{A}_{CP}\cos\Delta m_d\Delta t + \mathscr{S}_{CP}\sin\Delta m_d\Delta t)\right], \tag{1.1}$$

where $\Delta t \equiv t_{CP} - t_{\rm Tag}$ and Δm_d is the mass difference between the B_H and B_L mass eigenstates. The parameters, $\mathscr{A}_{CP}$ and $\mathscr{S}_{CP}$, describe direct and mixing-induced CP violation, respectively.

If a single first-order weak amplitude dominates the decay, then we expect $\mathscr{A}_{CP} = 0$ and $\mathscr{S}_{CP} = \sin 2\phi_2$. On the other hand, if second-order loop processes (penguins) are present, then direct CP violation is possible, $\mathscr{A}_{CP} \neq 0$. Additionally, as these loop processes are not directly proportional to V_{ub}, our measurement of $\mathscr{S}_{CP}$ does not directly determine ϕ_2, rather $\mathscr{S}_{CP} = \sqrt{1-\mathscr{A}_{CP}^2}\sin(2\phi_2 - 2\Delta\phi_2)$, where $\Delta\phi_2$ is the shift caused by the second order contributions.

A theoretically clean way of accessing ϕ_3 is through $B^- \to DK^-$ decays where D represents an admixture of D^0 and $\bar{D}^0$ states. This is possible through an interference if the D decays to a common final state $|D\rangle = |D^0\rangle + r_B e^{i\theta}|\bar{D}^0\rangle$, where $\theta \equiv \delta_B \pm \phi_3$ is the relative phase difference between the two processes for B^+ and B^- in which δ_B is the relative strong phase difference in B decays. The quantity r_B, is the amplitude ratio $A(B^- \to \bar{D}^0K^-)/A(B^- \to D^0K^-)$, and should be around the order of colour suppression as the two processes are of similar strength in the Cabibbo angle λ.

2. $B^- \to DK^-$, $D \to K^+\pi^-$

In the so-called ADS method [4], $B^- \to DK^-$ with $D \to K^+\pi^-$ and the charge conjugate decays are used. Here, the favoured B decay ($b \to c$) followed by the doubly CKM-suppressed D decay interferes with the suppressed B decay ($b \to u$) followed by the CKM-favoured D decay. The relative similarity of the combined decay amplitudes enhances the possible CP asymmetry.

The ADS variables are defined as,

$$\mathscr{R}_{DK} \equiv \frac{\mathscr{B}([K^+\pi^-]K^-) + \mathscr{B}([K^-\pi^+]K^+)}{\mathscr{B}([K^-\pi^+]K^-) + \mathscr{B}([K^+\pi^-]K^+)},$$
$$\mathscr{A}_{DK} \equiv \frac{\mathscr{B}([K^+\pi^-]K^-) - \mathscr{B}([K^-\pi^+]K^+)}{\mathscr{B}([K^+\pi^-]K^-) + \mathscr{B}([K^-\pi^+]K^+)}, \tag{2.1}$$

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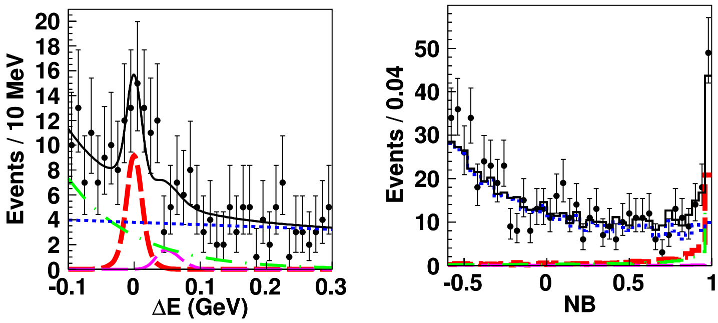

Figure 1: $\Delta E (NB > 0.9)$ and NB ($|\Delta E| < 0.03$ GeV) distributions for the suppressed $B^- \to D_{\rm Sup}[K^+\pi^-]K^-$. The red curve shows the signal, the magenta curve the $D\pi$ component, the green curve the $B\bar{B}$ background and the blue curve the continuum.

which are related to ϕ_3 as

$$\mathscr{R}_{DK} = r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D)\cos\phi_3,$$
$$\mathscr{A}_{DK} = \frac{2 r_B r_D \sin(\delta_B + \delta_D)\sin\phi_3}{\mathscr{R}_{DK}}, \tag{2.2}$$

where the amplitude ratio $r_D = A(D^0 \to K^+\pi^-)/A(\bar{D}^0 \to K^+\pi^-)$, and δ_D is the strong phase difference between the two D amplitudes.

This analysis has been performed with the final Belle data set containing 772 million $B\bar{B}$ pairs. The main difficulty is in separating the small signal from the dominant continuum background and is achieved by a fit to the kinematic variable ΔE, and a neural network output NB, based on the event shape. First evidence for the suppressed $B^- \to D_{\rm Sup}[K^+\pi^-]K^-$ was found at a 4.1σ significance as shown in Fig. 1. From this measurement, the ADS observables were found to be

$$\mathscr{R}_{DK} = [1.63^{+0.44}_{-0.41}\,({\rm stat})^{+0.07}_{-0.13}\,({\rm syst})] \times 10^{-2},$$
$$\mathscr{A}_{DK} = -0.39^{+0.26}_{-0.28}\,({\rm stat})^{+0.04}_{-0.03}\,({\rm syst}). \tag{2.3}$$

which was the most precise measurement at the time of publication [5].

3. $B^- \to DK^-, D \to K^0_S\pi^+\pi^-$

In the so-called GGSZ method [6], $B^- \to D^{(*)}K^-$ decays where the D decays to the CP eigenstate $D \to K^0_S\pi^+\pi^-$, are used. One can fit the $D \to K^0_S\pi^+\pi^-$ Dalitz plot with the matrix element $|\mathscr{M}_\pm(m_+^2, m_-^2)|^2 = |f_D(m_+^2, m_-^2) + r_B e^{i(\delta_B \pm \phi_3)} f_D(m_-^2, m_+^2)|^2$, thereby determining ϕ_3 directly in the fit. The amplitude f_D, which depends on the invariant squared masses $m_\pm(K^0_S\pi^\pm)$ is typically parametrised as the coherent sum of 2-body decays via intermediate resonances and also measured in the fit.

This measurement has been performed previously at Belle using 657 million $B\bar{B}$ pairs [7]. By combining the results of $B^- \to DK^-$ and D^*K^-, where $D^* \to D\pi^0$ and $D\gamma$, $\phi_3 = (78^{+11}_{-12}\,({\rm stat}) \pm 4\,({\rm syst}) \pm 9\,({\rm model}))^\circ$ was obtained. Note that the dominant systematic uncertainty arises from model dependence in the parametrisation of f_D which would eventually dominate the total uncertainty at LHCb and the next generation B factories.

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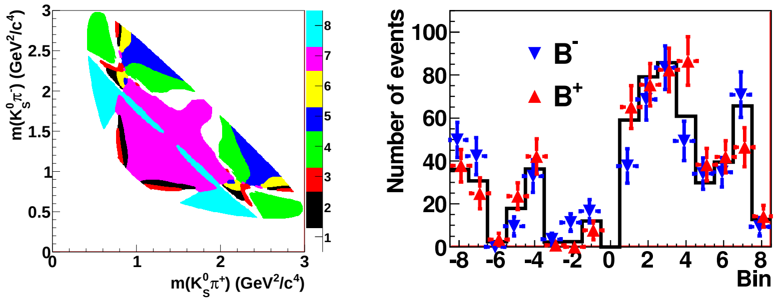

Figure 2: The left figure shows the optimised binning where the colours represent different bins. The right figure shows the fitted $B^- \to DK^-$ yields determined in each Dalitz plot bin as the data points, while the solid curve shows the expected yield in each bin.

A new method removing the model uncertainty has recently been developed [8] which involves binning the Dalitz plot and working with the measured number of signal events in each bin instead. This can be compared in a χ^2 fit with the expected number of events in each bin i,

$$N_i^{\pm} = h_B[K_i + r_B^2 K_{-i} + 2\sqrt{K_i K_{-i}}(x_{\pm} c_i + y_{\pm} s_i)], \tag{3.1}$$

where $x_{\pm} = r_B \cos(\delta_B \pm \phi_3)$ and $y_{\pm} = r_B \sin(\delta_B \pm \phi_3)$ are free parameters in the fit, constraining the phase ϕ_3, and h_B is a normalisation constant. Here, K_i is the number of events in bin i determined from a flavour-tagged sample $D^{*\pm} \to D\pi^{\pm}$, while $c_i = \langle \cos\Delta\delta_D \rangle_i$ and $s_i = \langle \sin\Delta\delta_D \rangle_i$ are related to average strong phase difference in bin i and are measured by CLEO [9], but can also be measured at BES-III in the future.

Compared to measuring $|f_D|^2$, a binned analysis reduces the statistical precision of ϕ_3, but this can be optimised. The advantage of this method is that the optimal binning depends on the model, however ϕ_3 does not. Studies show that the precision depends strongly on the amplitude behaviour across the bins. Better precision can be achieved when the phase difference between the D^0 and $\bar{D}^0$ amplitudes varies as little as possible. The optimised binning was found using the amplitude measured by BaBar [10] and is shown in Fig. 2.

This analysis has been performed with the final Belle data set of 772 million $B\bar{B}$ pairs which obtained a total signal yield of 1176 ± 43 events. Following this, the signal yield in the optimised Dalitz plot bins is determined then compared in a χ^2 fit with the expected signal yield given in Eq. 3.1. A significant *CP* asymmetry can be seen in Fig. 2 which has a 0.4% probability of being a statistical fluctuation.

The parameters $x_{\pm}$ and $y_{\pm}$ are determined in the fit, constraining ϕ_3, r_B and δ_B,

$$\begin{aligned} \phi_3 &= (77.3^{+15.1}_{-14.9} \pm 4.2 \pm 4.3)^\circ, \\ r_B &= 0.145 \pm 0.030 \pm 0.011 \pm 0.011, \\ \delta_B &= (129.9 \pm 15.0 \pm 3.9 \pm 4.7)^\circ, \end{aligned} \tag{3.2}$$

where the first error is statistical, the second systematic and the third is the precision on c_i and s_i from CLEO. This is a promising proof of concept as the precision on ϕ_3 is comparable to the previous measurement with $B^- \to DK^-$ only.

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4. $B^0 \to \pi^+\pi^-$, $\rho^0\rho^0$, $a_1^\pm\pi^\mp$

These analyses are ongoing at Belle and will be based on the final data set. Improvements have been made to the tracking algorithm and fitting methods to improve the detection efficiency. We expect our final results for $B^0 \to \pi^+\pi^-$ and $a_1^\pm\pi^\mp$ to be the most precise measurements when they are released and at least an improved upper limit is expected on $B^0 \to \rho^0\rho^0$ which will have an impact on ϕ_2.

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