PROCEEDINGS OF SCIENCE

Studies Related to the CKM angles ϕ_2 and ϕ_3 at Belle

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We present a summary of recent measurements of the CKM angles ϕ_2 and ϕ_3, performed by the Belle experiment which collects $B\overline{B}$ pairs at the $\Upsilon(4S)$ resonance produced in asymmetric-energy e^+e^- collisions. This includes the first evidence of CP violation in $B^0 \to a_1^{\pm}\pi$. We also discuss measurements of GLW and ADS observables as well as the first model-independent determination of ϕ_3 in the GGSZ method.

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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

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

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. $B^0 \to a_1^{\pm}\pi^{\mp}$

Decays proceeding by first-order $b \to u\bar{u}d$ quark transitions such as $B^0 \to a_1^{\pm}\pi^{\mp}$, are sensitive to $\mathscr{S}_{CP} = \sin 2\phi_2$. On the other hand, if second-order loop processes are present, then direct CP violation is possible and the measurement of ϕ_2 is shifted by an amount $\Delta\phi_2$. Despite this, it is possible to recover ϕ_2 with an $SU(2)$ isospin analysis [4], though many of the branching fractions required to constrain ϕ_2 are at present unknown. A more practical method at this time is to use the $SU(3)$ related channels $B \to a_1K$ and $B \to K_{1A}\pi$, which are known, to constrain $|\Delta\phi_2|$ [5]. The decay $B^0 \to a_1^{\pm}\pi^{\mp}$, is a flavour non-specific final state, so 4 flavour-charge configurations (q, c)

need to be considered. The time-dependence is governed by,

$$\mathscr{P}(\Delta t, q, c) = (1 + c\mathscr{A}_{CP})\frac{e^{-|\Delta t|/\tau_{B^0}}}{8\tau_{B^0}}\left\{1 + q\left[(\mathscr{S}_{CP} + c\Delta\mathscr{S})\sin\Delta m_d \Delta t - (\mathscr{C}_{CP} + c\Delta\mathscr{C})\cos\Delta m_d \Delta t\right]\right\}, \tag{2.1}$$

where c is the a_1 charge. The parameter $\mathscr{S}_{CP}$ measures mixing-induced CP violation, and $\mathscr{C}_{CP}$ measures flavor-dependent direct CP violation. The quantity $\Delta\mathscr{C}$ measures the rate asymmetry between the flavor-charge configurations where the a_1 does not contain the spectator quark ($\Gamma[B^0 \to a_1^+\pi^-] + \Gamma[\bar{B}^0 \to a_1^-\pi^+]$), and where it does contain the spectator quark ($\Gamma[B^0 \to a_1^-\pi^+] + \Gamma[\bar{B}^0 \to a_1^+\pi^-]$), while $\Delta\mathscr{S}$ is related to the strong phase difference between these two processes.

Belle has recently released its final CP violation measurement in this channels with 772 million $B\bar{B}$ pairs [6], shown in Fig. 1. They obtain $\mathscr{S}_{CP} = -0.51 \pm 0.14\,(\text{stat}) \pm 0.08\,(\text{syst})$ which is first evidence of CP violation with a 3.1σ significance.

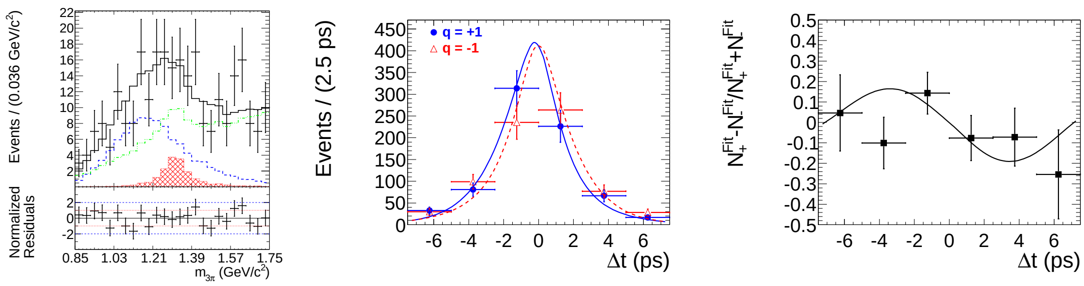

Figure 1: Fit results for $B^0 \to a_1^{\pm}\pi^{\mp}$. The left plot shows the 3-pion mass highlighting the a_1 (a_2) contribution in blue (red). The middle and right plots show the Δt distributions for each flavour tag and its asymmetry, respectively.

3. ϕ_3 with GLW

In the so-called GLW method [7], a theoretically clean measurement of the angle ϕ_3 can be obtained from the rate and asymmetry measurements of $B^- \to D_{CP}^{(*)}K^{(*)-}$ decays, where the $D^{(*)}$ meson decays to CP-even ($D_{CP+}^{(*)}$) and CP-odd ($D_{CP-}^{(*)}$) eigenstates. The method benefits from the interference between the dominant $b \to c\bar{u}s$ transitions with the corresponding doubly CKM-suppressed $b \to u\bar{c}s$ transition.

The GLW variables are defined as,

$$R_{CP\pm} = \frac{\mathscr{B}(B^- \to D_{CP\pm}K^-) + \mathscr{B}(B^+ \to D_{CP\pm}K^+)}{\mathscr{B}(B^- \to D^0K^-) + \mathscr{B}(B^+ \to \bar{D}^0K^+)},$$
$$A_{CP\pm} = \frac{\mathscr{B}(B^- \to D_{CP\pm}K^-) - \mathscr{B}(B^+ \to D_{CP\pm}K^+)}{\mathscr{B}(B^- \to D_{CP\pm}K^-) + \mathscr{B}(B^+ \to D_{CP\pm}K^+)}, \tag{3.1}$$

which are related to ϕ_3 as

CP-even D_{CP+} decays	CP-odd D_{CP-} decays
$R_{CP+} = 1 + r_B^2 + 2r_B\cos\delta_B\cos\phi_3,$	$R_{CP-} = 1 + r_B^2 - 2r_B\cos\delta_B\cos\phi_3,$
$A_{CP+} = \dfrac{+2r_B\sin\delta_B\sin\phi_3}{1 + r_B^2 + 2r_B\cos\delta_B\cos\phi_3},$	$A_{CP-} = \dfrac{-2r_B\sin\delta_B\sin\phi_3}{1 + r_B^2 - 2r_B\cos\delta_B\cos\phi_3}.$ (3.2)

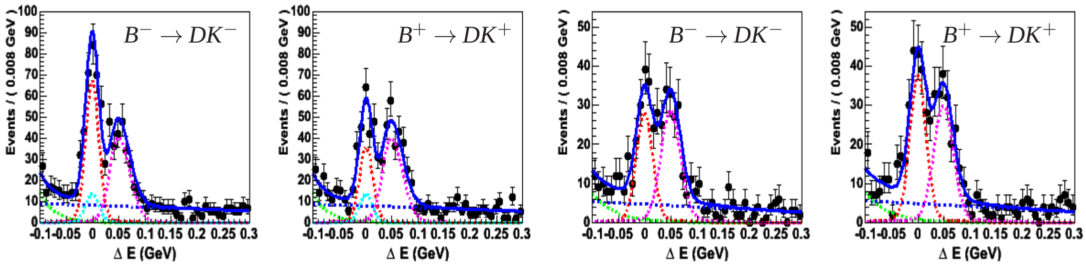

Figure 2: The two left-most plots show the fit results with the CP-even D_{CP} channels. The red curve shows $B \to DK$ signal, while the cyan curve shows the charmless $K^+K^-K^+$ background. The two right-most plots show the fit results with the CP-odd D_{CP} channels. The pink curve shows the $B \to D\pi$ background, the green curve shows the $B\bar{B}$ component and the blue curve shows the continuum contribution.

This analysis has been performed with the final Belle data set containing 772 million $B\bar{B}$ pairs using the CP-even channels $D_{CP+} \to \pi^+\pi^-$, K^+K^-, and the CP-odd channels $D_{CP-} \to K^0_S\pi^0$, $K^0_S\eta$, shown in Fig. 2. From this measurement, the GLW observables were found to be

$$R_{CP+} = (7.56 \pm 0.51)\%, \qquad R_{CP-} = (8.29 \pm 0.63)\%,$$
$$A_{CP+} = (+28.7 \pm 6.0)\%, \qquad A_{CP-} = (-12.4 \pm 6.4)\%. \tag{3.3}$$

4. ϕ_3 with ADS

In the so-called ADS method [8], $B^- \to DK^-$ 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,

$$\mathscr{R}_{DK} \equiv \frac{\mathscr{B}([K^+\pi^-]K^-) + \mathscr{B}([K^-\pi^+]K^+)}{\mathscr{B}([K^-\pi^+]K^-) + \mathscr{B}([K^+\pi^-]K^+)},$$
$$\mathscr{A}_{DK} \equiv \frac{\mathscr{B}([K^+\pi^-]K^-) - \mathscr{B}([K^-\pi^+]K^+)}{\mathscr{B}([K^+\pi^-]K^-) + \mathscr{B}([K^-\pi^+]K^+)}, \tag{4.1}$$

which are related to ϕ_3 as

$$\mathscr{R}_{DK} = r_B^2 + r_D^2 + 2r_Br_D\cos(\delta_B + \delta_D)\cos\phi_3,$$
$$\mathscr{A}_{DK} = \frac{2r_Br_D\sin(\delta_B + \delta_D)\sin\phi_3}{\mathscr{R}_{DK}}, \tag{4.2}$$

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 using the decays $D \to K^+\pi^-$ [9], $D^{*0} \to D[K^+\pi^-]\pi^0$, and $D^{*0} \to D[K^+\pi^-]\gamma$. From this

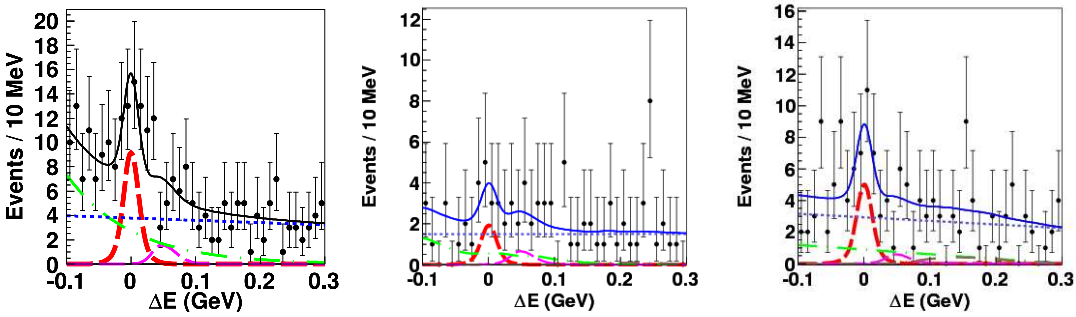

Figure 3: Fit results showing the suppressed $D_{\rm Sup} \to K^+\pi^-$ for $B^- \to DK^-$ (left), $B^- \to D^{*0}[D\pi^0]K^-$ (middle), and $B^- \to D^{*0}[D\gamma]K^-$ (right). The red curve shows the signal, the magenta curve the $D^{(*0)}\pi$ component, the green curve the $B\bar{B}$ background and the blue curve the continuum.

measurement, the ADS observables were found to be

$$\begin{aligned}
\mathscr{R}_{DK} &= (1.63^{+0.44+0.07}_{-0.41-0.13}) \times 10^{-2}, & \mathscr{R}_{D\pi^0} &= (1.0^{+0.8+0.1}_{-0.7-0.2}) \times 10^{-2}, & \mathscr{R}_{D\gamma} &= (3.6^{+1.4}_{-1.2} \pm 0.2) \times 10^{-2}, \\
\mathscr{A}_{DK} &= -0.39^{+0.26+0.04}_{-0.28-0.03} & \mathscr{A}_{D\pi^0} &= +0.4^{+1.1+0.2}_{-0.7-0.1}, & \mathscr{A}_{D\gamma} &= -0.51^{+0.33}_{-0.29} \pm 0.08.
\end{aligned} \tag{4.3}$$

where the first uncertainty is statistical and the second is systematic.

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

In the so-called GGSZ method [10], $B^- \to D^{(*)}K^-$ 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 [11]. By combining the results of $B^- \to DK^-$ and D^*K^-, where $D^* \to D\pi^0$ and $D\gamma$, $\phi_3 = (78^{+11}_{-12}\,(\text{stat}) \pm 4\,(\text{syst}) \pm 9\,(\text{model}))^\circ$ 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.

A new method removing the model uncertainty has recently been developed [12] 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,

$$N^\pm_i = h_B[K_i + r^2_B K_{-i} + 2\sqrt{K_i K_{-i}}(x_\pm c_i + y_\pm s_i)], \tag{5.1}$$

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 [13], but can also be measured at BES-III in the future.

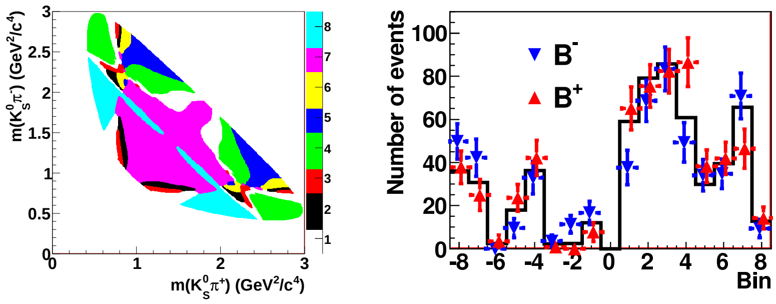

Figure 4: The left figure shows the optimised binning where the colours represent different bins. The right figure shows the fitted $B^- \to DK^-$ yields determined in each Dalitz plot bin as the data points, while the solid curve shows the expected yield in each bin.

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 [14] and is shown in Fig. 4.

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. 5.1. A significant *CP* asymmetry can be seen in Fig. 4 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,

$$\begin{aligned}
\phi_3 &= (77.3^{+15.1}_{-14.9} \pm 4.2 \pm 4.3)^\circ, \\
r_B &= 0.145 \pm 0.030 \pm 0.011 \pm 0.011, \\
\delta_B &= (129.9 \pm 15.0 \pm 3.9 \pm 4.7)^\circ, \qquad (5.2)
\end{aligned}$$

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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