# $\sin 2\phi_2 (= \alpha)$ from Belle

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## 1 Introduction

Recent measurements of the $CP$-violating parameter $\sin 2\phi_1$ by Belle [1] and BaBar [2] collaborations established $CP$ violation in the neutral $B$ meson system that is consistent with Kobayashi and Maskawa (KM) expectations [3]. Therefore, measurements of other $CP$-violating parameters such as $\phi_2$ and $\phi_3$ provide important tests of the KM model. In this note we describe a measurement of $CP$-violating asymmetries in the mode $B^0 \to \pi^+\pi^-$ which are sensitive to the parameter $\sin 2\phi_2$.

The KM model predicts $CP$-violating asymmetries in the time-dependent rates for $B^0$ and $\overline{B}^0$ decays to a common $CP$ eigenstates, $f_{CP}$ [4]. When the $\Upsilon(4S)$ decays into a $B^0\overline{B}^0$ meson pair, the two mesons remain in a coherent $p$-wave state until one of them decays. The decay of one of the $B$ mesons at time $t_{tag}$ to a final state, $f_{tag}$, which distinguishes between $B^0$ and $\overline{B}^0$, projects the accompanying $B$ meson onto the opposite $b$-flavor at $\tau_{tag}$; this meson decays to $\pi^+\pi^-$ at time $t_{CP}$. The decay rate has a time dependence given by [5]

$$P^q_{\pi\pi}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} [1 + q \cdot \{S_{\pi\pi} \sin(\Delta m_d \Delta t) + A_{\pi\pi} \cos(\Delta m_d \Delta t)\}] , \tag{1}$$

where $\tau_{B^0}$ is the $B^0$ lifetime, $\Delta m_d$ is the mass difference between the two $B^0$ mass eigenstates, $\Delta t = t_{CP} - t_{tag}$, and the $b$-flavor charge $q = +1$ (-1) when the tagging $B$ meson is a $B^0$ ($\overline{B}^0$). The $CP$-violating parameters $S_{\pi\pi}$ and $A_{\pi\pi}$ defined in Eq. (1) are expressed by

$$S_{\pi\pi} = \frac{2Im\lambda}{|\lambda|^2 + 1} \text{ and } A_{\pi\pi} = \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1} \tag{2}$$

where $\lambda$ is a complex parameter that depends on both $B^0\overline{B}^0$ mixing and on the amplitudes for $B^0$ and $\overline{B}^0$ decays to $\pi^+\pi^-$. In the Standard Model, to a good approximation, $|\lambda|$ is equal to the absolute value of the ratio of the $\overline{B}^0$ to $B^0$ decay amplitudes. Therefore $|\lambda| \neq 1$, or equivalently $A_{\pi\pi} \neq 0$, indicates direct $CP$ violation.

In the case of $B^0 \to (c\overline{c})K_s^0$ $CP$ eigenstate decays, the $CP$-violating parameters are rather precisely expressed as $S_{(c\overline{c})K_s^0} = \sin 2\phi_1$ and $A_{(c\overline{c})K_s^0} = 0$. This is due to the fact that the tree amplitude with $W$ emission dominates the $b \to s$ penguin amplitude with associated $c\overline{c}$ production, which is small and has the same weak phase. For the $B^0 \to \pi^+\pi^-$ decay, we would have $S_{\pi\pi} = \sin 2\phi_2$ and $A_{\pi\pi} = 0$ if the $b \to u$ tree amplitude were dominant. The situation is complicated by the possibility of significant contributions from gluonic $b \to d$ penguin amplitudes that have a different weak phase and additional strong phases [6]. As a result, $S_{\pi\pi}$ may not be equal to $\sin 2\phi_2$ and direct $CP$ violation, $A_{\pi\pi} \neq 0$, may occur. One can quantify the contributions from penguin amplitude as $\sin 2(\phi_2 + \theta)$ and determine $\theta$ using other decays. However, it requires measurements of branching fractions of $B^0 \to \pi^0\pi^0$ and $\overline{B}^0 \to \pi^0\pi^0$ separately, which is experimentally not within reach at this moment [7].

This measurement of $CP$-violating parameters in $B^0 \to \pi^+\pi^-$ is based on a 41.8 fb$^{-1}$ data sample, which contains 44.1 million $B\overline{B}$ pairs, collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ (3.5 on 8 GeV) collider operating at the $\Upsilon(4S)$ resonance.

## 2 Event Selection

We use oppositely charged pairs of well measured tracks that are positively identified as pions according to the combined information from the ACC and the CDC $dE/dx$ measurement. Candidate $B$ mesons are reconstructed using the energy difference $\Delta E \equiv E_B^{cms} - E_{beam}^{cms}$ and the beam energy constrained mass $M_{bc} \equiv \sqrt{(E_{beam}^{cms})^2 - (p_B^{cms})^2}$, where $E_{beam}^{cms}$ is the cms beam energy, and $E_B^{cms}$ and $p_B^{cms}$ are the cms energy and momentum of the $B$ candidate. The signal region is defined as 5.271 GeV/$c^2 < M_{bc} <$ 5.287 GeV/$c^2$ and $|\Delta E| < 0.067$ GeV, corresponding to $\pm\, 3\sigma$ from the central values. In order to suppress background from the $e^+e^- \to q\overline{q}$ continuum ($q = u, d, s, c$), we form signal and background likelihood functions, $\mathcal{L}_S$ and $\mathcal{L}_{BG}$, from two variables. One is a Fisher discriminant determined from six modified Fox-Wolfram moments [8] and the other is the $B$ flight direction in the cms, with respect to the $z$ axis ($\cos\theta_B$). We determine $\mathcal{L}_S$ from Monte Carlo (MC) and $\mathcal{L}_{BG}$ from data. The likelihood ratio $\mathcal{L}_S/\ (\mathcal{L}_S + \mathcal{L}_{BG})$ for candidate events is required to be greater than 0.825. Figure 1 shows the $\Delta E$ distribution for $\pi^+\pi^-$ candidates. The signal yield is extracted by fitting the $\Delta E$ distribution with a Gaussian $\pi^+\pi^-$ signal function, plus contributions from misidentified $B^0 \to K^+\pi^-$ events, three-body $B$-decays, and continuum background. From the fit, we obtain $73.5 \pm 13.8$ events, $28.4 \pm 12.5$ $K^+\pi^-$ events, and 98.7 $\pm$ 7.0 continuum background events in the signal region, where errors are statistical only. The $K^+\pi^-$ contamination level is consistent with the $K \to \pi$ misidentification probability measured independently, and the contribution from three-body $B$-decays is little in the signal region.

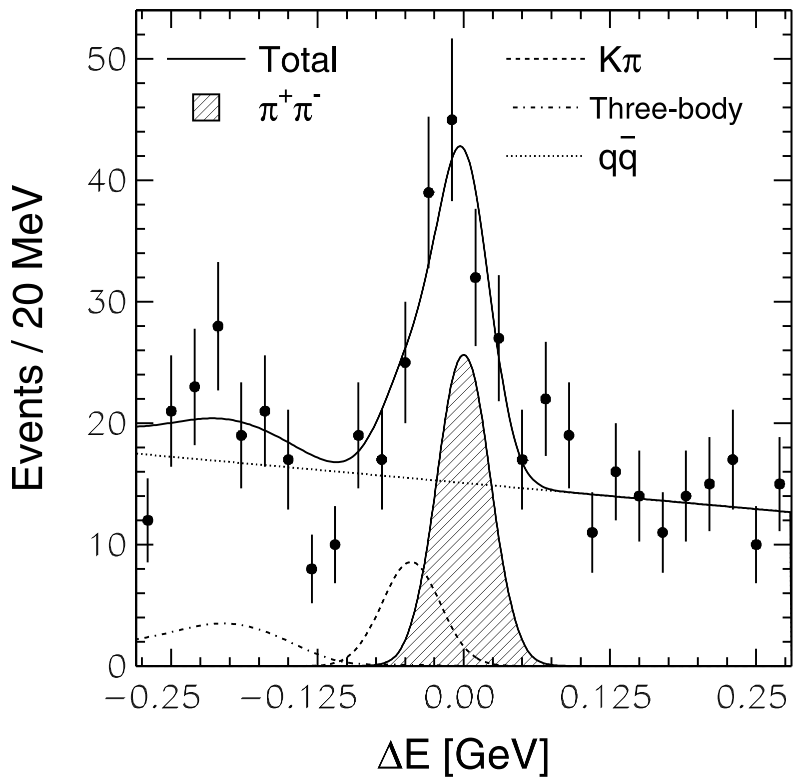


Figure 1: $\Delta E$ distribution for $\pi^+\pi^-$ event candidates that are in the $M_{bc}$ signal region. Closed circles with error bars are the data, and individual curves are results of fits using various components indicated in the figure.

Leptons, charged pions, and kaons that are not associated with the reconstructed $B^0 \to \pi^+\pi^-$ decay are used to identify the flavor of the accompanying $B$ meson. We apply the same method used for the $\sin 2\phi_1$ measurement [1]. We use two parameters, $q$ and $r$, to represent the tagging information. The first, $q$, corresponds to the sign of the $b$ quark charge where $q = +1$ for $\bar{b}$ and hence $B^0$, and $q = -1$ for $b$ and $\overline{B}^0$. The parameter $r$ is an event-by-event, MC-determined flavor-tagging dilution factor that ranges from $r = 0$ for no flavor discrimination to $r = 1$ for unambiguous flavor assignment. It is used only to sort data into six intervals of $r$, according to flavor purity.

The wrong tag fractions, $w_l$ ($l$=1,6), are determined directly from the data for the six $r$ intervals using exclusively reconstructed, self-tagged $B^0 \to D^{*-}l^+\nu$,$D^{(*)}\pi^+$, and $D^{*-}\rho^+$ decays. The $b$-flavor of the accompanying $B$ meson is assigned according to the flavor-tagging algorithm described above. The decay vertices are reconstructed using the same algorithm used for the accompanying $B$ mesons of $B^0 \to \pi^+\pi^-$ candidates. The values of $w_l$ are obtained from the time evolution of neutral $B$ meson pairs with opposite flavor (OF) or same flavor (SF), which is given by $P_{OF[SF]}(\Delta t) = e^{-|\Delta t|/\tau_{B^0}}/4\tau_{B^0}\ \{1+[-](1-2w_l)\cos(\Delta m_d \Delta t)\}$. For the fits, we fix $\Delta m_d$ at the world average value [9].

The vertex positions for the $\pi^+\pi^-$ and $f_{tag}$ decays are reconstructed using tracks that have at least one three-dimensional coordinate determined from associated $r-\phi$ and $z$ hits in the same SVD layer and one or more additional $z$ hits in the other layers. Each vertex position is required to be consistent with the interaction point profile smeared in the $r-\phi$ plane by the average transverse $B$ meson decay length. The $f_{tag}$ vertex is determined from all well reconstructed tracks, excluding the $B^0 \to \pi^+\pi^-$ candidate. Tracks that form a $K_s^0$ candidate are not used. The MC simulation indicates that the typical vertex-finding efficiency is 92% and 91% for $\pi^+\pi^-$ and $f_{tag}$, respectively, while the typical vertex rms resolution in the $z$ coordinate is 75 $\mu$m for $B^0 \to \pi^+\pi^-$ decays and 140 $\mu$m for $f_{tag}$ decays.

The proper-time interval resolution for the signal, $R_{sig}(\Delta t)$, is obtained by convolving a sum of two Gaussians with a function that takes into account the cms motion of the $B$ mesons. The fraction in the main Gaussian is determined to be 0.97 $\pm$ 0.02 from a study of $B^0 \to D^{*-}\pi^+$, $D^{*-}\rho^+$, $D^-\pi^+$, $J/\psi K^{*0}$, $J/\psi K_S^0$ and $B^+ \to \overline{D}^0\pi^+$, $J/\psi K^+$ events. The means ($\mu_{\rm main}$, $\mu_{\rm tail}$) and widths ($\sigma_{\rm main}$, $\sigma_{\rm tail}$) of the Gaussians are calculated event-by-event from the $f_{CP}$ and $f_{\rm tag}$ vertex fit error matrices and the $\chi^2$ values of the fit; typical values are $\mu_{\rm main} = -0.24$ ps, $\mu_{\rm tail} = 0.18$ ps and $\sigma_{\rm main} = 1.49$ ps, $\sigma_{\rm tail} = 3.85$ ps. The background resolution function $R_{q\bar{q}}(\Delta t)$, which is dominated by continuum background, has the same functional form but the parameters are obtained from a sideband region in $M_{bc}$ and $\Delta E$.

# 3 CP Fit Results

We determine $CP$ violation parameters by performing an unbinned maximum-likelihood fit of a $CP$-violating probability density function (pdf) to the observed $\Delta t$ distributions. We define the likelihood value for each event as a function of $S_{\pi\pi}$ and $A_{\pi\pi}$:

$$P_i = \int [\{f^l_{\pi\pi} P^q_{\pi\pi}(\Delta t', w_l; S_{\pi\pi}, A_{\pi\pi}) + f^l_{K\pi} P^q_{K\pi}(\Delta t', w_l)\} \cdot R_{sig}(\Delta t_i - \Delta t') + f^l_{q\bar{q}} P_{q\bar{q}}(\Delta t') \cdot R_{q\bar{q}}(\Delta t_i - \Delta t')] d\Delta t'. \quad (3)$$

Here $f^l_{\pi\pi}$, $f^l_{K\pi}$, and $f^l_{q\bar{q}}$ $(=1-f^l_{\pi\pi}-f^l_{K\pi})$ are the fractions of $\pi^+\pi^-$ signal, $K^+\pi^-$ background, and continuum background in flavor-tagging interval $l$, respectively. These fractions are determined on an event-by-event basis as a function of $\Delta E$ and $M_{\rm bc}$, properly normalized by the average signal and background fractions in the signal region. For higher $r$ values where we are more sensitive to the asymmetry, the fraction of continuum background decreases; the ratio of $\pi^+\pi^-$ signal events to background $K^+\pi^-$ events is the same for all $r$ bins. The pdfs for $\pi^+\pi^-$ $(P^q_{\pi\pi})$, $K^+\pi^-$ $(P^q_{K\pi})$, and continuum background $(P_{q\bar{q}})$, are convolved with their respective resolution functions. We use the same vertex resolution function for $\pi^+\pi^-$ and $K^+\pi^-$ candidates. For the $\pi^+\pi^-$ signal, the pdf is given by Eq. (1) with $q$ replaced by $q(1-2w_l)$, to account for the dilution due to wrong flavor tagging. The pdf for the $K^+\pi^-$ background is $P^q_{K\pi}(\Delta t, w_l) = e^{-|\Delta t|/\tau_{B^0}}/4\tau_{B^0}\{1+q\cdot(1-2w_l)A_{K\pi}\cos(\Delta m_d \Delta t)\}$, where $A_{K\pi}$ is the $\overline{B}^0 \to K^-\pi^+$ and $B^0 \to K^+\pi^-$ decay rate asymmetry. We fix $A_{K\pi}=0$ and $\tau_{B^0}$ and $\Delta m_d$ to their world average values [9]. Although the $K^+\pi^-$ background contamination is low, a possible deviation of $A_{K\pi}$ from zero is included in the systematic error. The pdf used for the $q\bar{q}$ background distribution is $P_{q\bar{q}}(\Delta t) = \{f_\tau\ e^{-|\Delta t|/\tau_{bkg}}/2\tau_{bkg} + (1-f_\tau)\delta(\Delta t)\ \}/2$, where $f_\tau$ is the background fraction with an effective lifetime $\tau_{bkg}$ and $\delta$ is the Dirac delta function. We determine $f_\tau = 0.011 \pm 0.004$ and $\tau_{bkg} = 2.7^{+1.0}_{-0.7}$ ps from the sideband data. In function $\mathcal{L} = \Pi P_i$, where the product is over all $B^0 \to \pi^+\pi^-$ candidates.

The result of the fit to the 162 candidates (92 $B^0$- and 70 $\overline{B}^0$-tags) that remain after flavor tagging and vertex reconstruction is:

$$\begin{aligned} S_{\pi\pi} &= -1.21\ ^{+0.38}_{-0.27}(\text{stat})\ ^{+0.16}_{-0.13}(\text{syst}); \\ A_{\pi\pi} &= +0.94\ ^{+0.25}_{-0.31}(\text{stat})\ \pm 0.09(\text{syst}). \end{aligned}$$

In Figs. 2(a) and (b), we show the $\Delta t$ distributions for $B^0$- and $\overline{B}^0$-tagged events together with the fit curves; the background-subtracted $\Delta t$ distributions are shown in Fig. 2(c). It appears that there are more $B^0$ tags than $\overline{B}^0$ tags. Figure 2(d) shows the background-subtracted $CP$ asymmetry between the $B^0$- and $\overline{B}^0$-tagged events as a function of $\Delta t$, with the result of the fit superimposed.

# 4 Systematic Uncertainties

The systematic error on $S_{\pi\pi}$ is primarily due to uncertainties in the background fractions ($\pm 0.09$) and from the fit bias near the physical boundary ($^{+0.11}_{-0.02}$). For $A_{\pi\pi}$, the background fractions ($\pm 0.06$) and the wrong-tag fractions ($\pm 0.06$) are the two leading components. Other sources of systematic error are uncertainties in the resolution function, physics parameters ($\Delta m_d$, $\tau_{B^0}$, and $A_{K\pi}$) and the background modeling. A value of $A_{K\pi} = -0.06 \pm 0.08$ is obtained from the self-tagged $B^0 \to K^+\pi^-$ sample. This introduces a systematic error of $< 0.01$ for $S_{\pi\pi}$ and $^{+0.02}_{-0.01}$ for $A_{\pi\pi}$.

We perform a number of cross checks. We examine the event yields and $\Delta t$ distributions for $B^0$- and $\overline{B}^0$-tagged events in the sideband region and find no significant difference between the two samples. Figure 2(e) shows the observed raw asymmetry in the side band region. We select $B^0 \to K^+\pi^-$ candidates, which have the same track topology as $B^0 \to \pi^+\pi^-$, by positively identifying charged kaons. A fit to 309 events yields $A_{K\pi} = 0.07 \pm 0.17$, consistent with the value mentioned above, and $S_{K\pi}$ $0.15 \pm 0.24$. We also select $B^0 \to D^-\pi^+$, $D^{*-}\pi^+$ and $D^-\rho^+$ candidates using the same event shape criteria. These are non-$CP$ eigenstate self-tagged modes, where neither mixing-induced nor direct $CP$-violating asymmetry is expected. We find no asymmetry in these modes. As an additional test of the consistency of the background treatment, we add events from the $B^0 \to \pi^+\pi^-$ sideband and adjust their $\Delta E$ and $M_{bc}$ values. A fit to this background-enriched control sample, which has a similar background fraction as the $B^0 \to \pi^+\pi^-$ sample, yields $S = 0.08 \pm 0.06$ and $A = 0.03 \pm 0.04$, both consistent with a null asymmetry. We measured $\tau_{B^0}$ from $B^0 \to \pi^+\pi-$ and $K^+\pi^-$ decays and obtained $1.49 \pm 0.21$ ps and $1.73 \pm 0.15$ ps, respectively (The world average value is $1.548 \pm 0.032$ ps [9]). We measured $\Delta m_d$ from $B^0 \to K^+\pi^-$ and found $\Delta m_d$ to be $0.57 \pm 0.08$ ps$^{-1}$, which is consistent with the current world average value ($0.472 \pm 0.017$ ps$^{-1}$ [9]).

Our central values of $S_{\pi\pi}$ and $A_{\pi\pi}$ are $1.2\sigma$ away from the physical boundary ($S^2_{\pi\pi} + A^2_{\pi\pi} < 1$). However, the components of the present analysis are the same as those used to measure $\sin 2\phi_1$, $\tau_B$, and $\Delta m_d$, which are all in good agreement with the world average values and we performed ensemble tests and found no indication of bias in the procedure and the likelihood fit errors are in reasonable agreement with expected from ensemble tests. Therefore, we attribute our central values of $S_{\pi\pi}$ and $A_{\pi\pi}$ being outside of the physical boundary as a statistical fluctuation.

## 5 Conclusions

In summary, we have measured the $CP$ violation parameters in $B^0 \to \pi^+\pi^-$ decay. Our results for $S_{\pi\pi}$ indicates that mixing-induced $CP$ violation is large. The large $A_{\pi\pi}$ term is an indication of direct $CP$ violation in $B$ meson decay, and suggests that there is a large hardronic phase and interference between the tree and penguin amplitudes. In this case, the precise determination of $\sin 2\phi_2$ from $S_{\pi\pi}$ requires additional measurements including the branching fractions for the decays $B^0 \to \pi^0\pi^0$ and $\overline{B}^0 \to \pi^0\pi^0$ [7], which will be performed in the near future at $B$ factories.

## References

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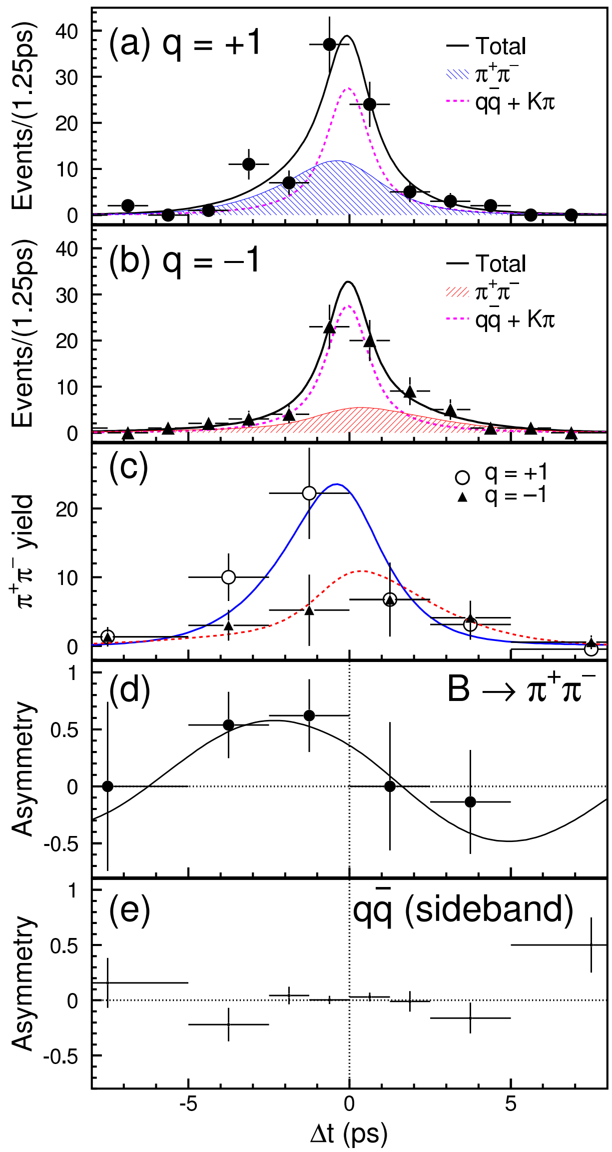


Figure 2: The $\Delta t$ distributions for the $B^0 \to \pi^+\pi^-$ candidates in the signal region: (a) candidates with $q = +1$, i.e. the tag side is identified as $B^0$; (b) candidates with $q = -1$; (c) $\pi^+\pi^-$ yields after background subtraction. The rightmost (leftmost) bin ranges from 5 to 10 ps ($-5$ to $-10$ ps); (d) the $CP$ asymmetry for $B^0 \to \pi^+\pi^-$ after background subtraction. The point in the rightmost bin has a large negative value that is outside of the range of the histogram; (e) the raw asymmetry for $B^0 \to \pi^+\pi^-$ sideband events. In Figs. (a) through (d), the curves show the results of the unbinned maximum likelihood fit.