Improved Evidence for Direct CP Violation in $B^0 \to \pi^+\pi^-$ Decays and Model-Independent Constraints on ϕ_2

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We present a new measurement of the time-dependent CP-violating parameters in $B^0 \to \pi^+\pi^-$ decays with 275×10^6 $B\bar{B}$ pairs collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider operating at the $\Upsilon(4S)$ resonance. We find 666 ± 43 $B^0 \to \pi^+\pi^-$ events and measure the CP-violating parameters: $S_{\pi\pi} = -0.67 \pm 0.16(\mathrm{stat}) \pm 0.06(\mathrm{syst})$ and $\mathcal{A}_{\pi\pi} = +0.56 \pm 0.12(\mathrm{stat}) \pm 0.06(\mathrm{syst})$. We find evidence for large direct CP violation with a significance greater than 4 standard deviations for any $S_{\pi\pi}$ value. Using isospin relations, we obtain 95.4% confidence intervals for the Cabibbo-Kobayashi-Maskawa quark-mixing matrix angle ϕ_2 of $0° < \phi_2 < 19°$ and $71° < \phi_2 < 180°$.

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Kobayashi and Maskawa (KM) pointed out in 1973 that CP violation can be incorporated as an irreducible complex phase in the weak-interaction quark mixing matrix in the standard model framework [1]. The KM model predicts CP-violating asymmetries in the time-dependent rates of neutral B meson decays to the CP eigenstate $\pi^+\pi^-$ [2]. In the decay chain of $\Upsilon(4S) \to B^0\bar{B}^0 \to (\pi^+\pi^-)(f_{\mathrm{tag}})$, one of the neutral B mesons decays into $\pi^+\pi^-$ at time $t_{\pi\pi}$ and the other decays at time t_{tag} to a final state f_{tag} that distinguishes its flavor. The time-dependent decay rate is given by

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

where $\Delta t = t_{\pi\pi} - t_{\mathrm{tag}}$, τ_{B^0} is the B^0 lifetime, Δm_d is the mass difference between the two neutral B mass eigenstates, and $q = +1$ (-1) for $f_{\mathrm{tag}} = B^0(\bar{B}^0)$. We measure $S_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$, which are the mixing-induced and direct CP-violating parameters, respectively. In the case where only a $b \to u$ "tree" transition contributes to the decay $B^0 \to \pi^+\pi^-$ [3], we would have $S_{\pi\pi} = \sin 2\phi_2$ and $\mathcal{A}_{\pi\pi} = 0$. Because of possible contributions from $b \to d$ "penguin" transitions that have different weak and strong phases, $S_{\pi\pi}$ may deviate from $\sin 2\phi_2$, and direct CP violation, $\mathcal{A}_{\pi\pi} \neq 0$, may occur. Our previous measurement based on a 140 fb^{-1} data sample indicated large $S_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ values [4], while no significant CP asymmetry was observed by the *BABAR* Collaboration [5]. It is therefore important to measure the CP-violating parameters with larger statistics.

The measurement in this Letter is based on a 253 fb^{-1} data sample containing 275×10^6 $B\bar{B}$ pairs collected with the Belle detector at the KEKB e^+e^- asymmetric-energy (3.5 on 8 GeV) collider [6] operating at the $\Upsilon(4S)$ resonance. The $\Upsilon(4S)$ is produced with a Lorentz boost factor of $\beta\gamma = 0.425$ along the z axis, which is antiparallel to the positron beam direction. Since the two B mesons are produced nearly at rest in the $\Upsilon(4S)$ center-of-mass system (CMS), the decay time difference Δt is determined from the distance between the two B meson decay positions along the z direction (Δz): $\Delta t \cong \Delta z / c\beta\gamma$, where c is the velocity of light.

The Belle detector [7] is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector, a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters, and an electromagnetic calorimeter comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons. A sample containing 152×10^6 $B\bar{B}$ pairs (Set I) was collected with a 2.0 cm radius beampipe and a 3-layer silicon vertex detector, while a sample with 123×10^6 $B\bar{B}$ pairs (Set II) was collected with a 1.5 cm radius beampipe, a 4-layer silicon detector, and a small-cell inner drift chamber [8].

We employ the identical analysis procedure as the previous publication [4]. We reconstruct $B^0 \to \pi^+\pi^-$ candidates using oppositely charged track pairs that are positively identified as pions by combining information from the ACC and the CDC dE/dx measurements. The pion detection efficiency is 90%, and 11% of kaons are misidentified as pions. We select B meson candidates using the energy difference $\Delta E \equiv E_B^* - E_{\rm beam}^*$ and the beam-energy constrained mass $M_{\rm bc} \equiv \sqrt{(E_{\rm beam}^*)^2 - (p_B^*)^2}$, where $E_{\rm beam}^*$ is the CMS beam-energy, and E_B^* and p_B^* are the CMS energy and momentum of the B candidate. We define the signal region as $5.271\ {\rm GeV}/c^2 < M_{\rm bc} < 5.287\ {\rm GeV}/c^2$ and $|\Delta E| < 0.064$ GeV, which corresponds to ± 3 standard deviations (σ) from the central values.

We identify the flavor of the accompanying B meson from inclusive properties of particles that are not associated with the reconstructed $B^0 \to \pi^+\pi^-$ decay. We use q defined in Eq. (1) and r to represent the tagging information. The parameter r is an event-by-event, Monte Carlo (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 r intervals. The wrong tag fractions for the six r intervals, w_l ($l = 1, 6$), and the differences between B^0 and $\bar{B}^0$ decays, Δw_l, are determined from data [9,10].

To suppress the continuum background ($e^+e^- \to q\bar{q}$; $q = u, d, s, c$), we apply the technique used in Ref. [4]. We form a likelihood function $\mathcal{L}_{\rm S(B)}$ for the signal (background) based on event topology variables and impose requirements on a likelihood ratio ${\rm LR} = \mathcal{L}_{\rm S}/(\mathcal{L}_{\rm S} + \mathcal{L}_{\rm B})$ to suppress continuum events. The LR requirement is determined by optimizing the expected sensitivity using MC signal events and events in the sideband region in $5.20\ {\rm GeV}/c^2 < M_{\rm bc} < 5.26\ {\rm GeV}/c^2$ or $+0.1\ {\rm GeV} < \Delta E < +0.5$ GeV. We accept events having ${\rm LR} > 0.86$. In order to include additional events with ${\rm LR} < 0.86$, we optimize LR separately for each of the r bins, as the r also suppresses continuum events. We then determine the lower LR thresholds of 0.50, 0.45, 0.45, 0.45, 0.45, and 0.20 for the six r bins. There are thus 12 distinct bins of LR r for selected events.

We extract 2820 signal candidates by applying the above requirements and the vertex reconstruction algorithm used in Ref. [10] to the data sample. Figure 1 shows the ΔE distributions for the events with (a) ${\rm LR} > 0.86$ and (b) ${\rm LR} < 0.86$ in the $M_{\rm bc}$ signal region. The $B^0 \to \pi^+\pi^-$ signal yield is determined from an unbinned two-dimensional maximum likelihood fit to the ΔE-$M_{\rm bc}$ distribution in the range of $M_{\rm bc} > 5.20\ {\rm GeV}/c^2$ and $-0.3\ {\rm GeV} < \Delta E < +0.5$ GeV with signal events plus contributions from misidentified $B^0 \to K^+\pi^-$ events, the continuum background, and three-body B decays. We use a single Gaussian for the signal and $B^0 \to K^+\pi^-$ events in ΔE and $M_{\rm bc}$. The continuum background shapes in ΔE and $M_{\rm bc}$ are described by a first-order polynomial and an ARGUS function [11], respectively. For the three-body B decay background shape, we employ a smoothed two-dimensional histogram obtained from a large MC sample. The fit to the subset with ${\rm LR} > 0.86$ yields $415 \pm 27 \pi^+\pi^-$ events and $154 \pm 19 K^+\pi^-$ events in the signal region, where the errors are statistical only. The $K^+\pi^-$ contamination is consistent with the $K \to \pi$ misidentification probability, which is measured independently. Extrapolating from the size of the continuum background in this fit, we expect 315 ± 3 continuum events in the signal region. We use MC-determined fractions as in [4] to calculate the numbers of decays for ${\rm LR} < 0.86$, since the fit to the low LR events gives large statistical fluctuation because of the poor signal-to-noise ratio. We expect $251 \pm 16 \pi^+\pi^-$, $93 \pm 12 K^+\pi^-$, and 1592 ± 15 continuum events in the signal region. The contribution from three-body B decays is negligibly small in the signal region.

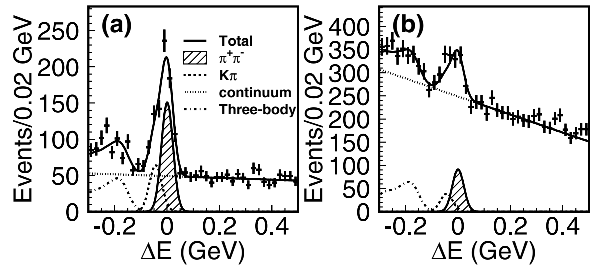

FIG. 1. ΔE distributions in the $M_{\rm bc}$ signal region for $B^0 \to \pi^+\pi^-$ candidates with (a) ${\rm LR} > 0.86$ and (b) ${\rm LR} < 0.86$.

We determine $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ by applying an unbinned maximum likelihood fit to the distribution of proper-time difference Δt. The probability density function (PDF) for the signal events is given in Eq. (1) modified to incorporate the effect of incorrect flavor assignment w_l and Δw_l. The distribution is convolved with the proper-time interval resolution function $R_{\rm sig}(\Delta t)$ in order to take into account the finite position resolution [10,12]. The PDF for $B^0 \to K^+\pi^-$ is $\mathcal{P}_{K\pi}^q(\Delta t, w_l, \Delta w_l) = (1/4\tau_{B^0})e^{-|\Delta t|/\tau_{B^0}}[1 - q\Delta w_l + q(1 - 2w_l)\mathcal{A}_{K\pi}^{\rm eff}\cos(\Delta m_d \Delta t)]$. We use $\mathcal{A}_{K\pi}^{\rm eff} = (\mathcal{A}_{K\pi} + \mathcal{A}_\varepsilon)/(1 + \mathcal{A}_{K\pi}\mathcal{A}_\varepsilon)$, where $\mathcal{A}_{K\pi} = -0.109 \pm 0.019$ is the measured direct CP-violating parameter in $B^0 \to K^+\pi^-$ decays [13], and $\mathcal{A}_\varepsilon$ is the difference in the product of the pion efficiency and kaon misidentification probability between $\pi^+(K^-)$ and $\pi^-(K^+)$ divided by their sum [14]. The inclusion of $\mathcal{A}_\varepsilon$ changes the $\mathcal{A}_{K\pi}$ value by 11%. We make use of the same resolution function $R_{\rm sig}(\Delta t)$ for the $B^0 \to K^+\pi^-$ events. The PDF for the continuum background events is $\mathcal{P}_{q\bar{q}}(\Delta t) = 1/2(1 + q\mathcal{A}_{q\bar{q}})[(f_\tau/2\tau_{q\bar{q}})e^{-|\Delta t|/\tau_{q\bar{q}}} + (1-f_\tau)\delta(\Delta t)]$, where f_τ is the fraction of the background with effective lifetime $\tau_{q\bar{q}}$, and δ is the Dirac delta function. We use $\mathcal{A}_{q\bar{q}} = 0$ as a default. A fit to the sideband events yields $\mathcal{A}_{q\bar{q}} = +0.01 \pm 0.01(-0.00 \pm 0.01)$ for the data in Set I (II). This uncertainty in the background asymmetry is included in the systematic error for the $S_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ measurement. The background PDF $\mathcal{P}_{q\bar{q}}$ is convolved with a background resolution function $R_{q\bar{q}}$. All parameters in $\mathcal{P}_{q\bar{q}}$ and $R_{q\bar{q}}$ are determined from sideband events.

We define a likelihood value for each (ith) event as a function of $S_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$:

$$P_i = (1-f_{\rm ol})\int_{-\infty}^{+\infty}[\{f^m_{\pi\pi}\mathcal{P}^q_{\pi\pi}(\Delta t', w_l, \Delta w_l; S_{\pi\pi}, \mathcal{A}_{\pi\pi}) + f^m_{K\pi}\mathcal{P}^q_{K\pi}(\Delta t', w_l, \Delta w_l)\}R_{\rm sig}(\Delta t_i - \Delta t') + f^m_{q\bar{q}}\mathcal{P}_{q\bar{q}}(\Delta t')R_{q\bar{q}}(\Delta t_i - \Delta t')]d\Delta t' + f_{\rm ol}\mathcal{P}_{\rm ol}(\Delta t_i). \quad (2)$$

Here, the probability functions $f^m_k(k = \pi\pi, K\pi,$ or $q\bar{q})$ are determined on an event-by-event basis as functions of ΔE and $M_{\rm bc}$ for each LR-r bin ($m = 1, 12$). A small number of signal and background events that have large values of Δt is accommodated by the outlier PDF, $\mathcal{P}_{\rm ol}$, with a fractional area $f_{\rm ol}$. In the fit, $S_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ are the only free parameters and are determined by maximizing the likelihood function $\mathcal{L} = \Pi_i P_i$, where the product is over all the $B^0 \to \pi^+\pi^-$ candidates.

The unbinned maximum likelihood fit to the 2820 $B^0 \to \pi^+\pi^-$ candidates containing $666 \pm 43\pi^+\pi^-$ signal events (1486 B^0 tags and 1334 $\bar{B}^0$ tags) yields $S_{\pi\pi} = -0.67 \pm 0.16(\text{stat}) \pm 0.06(\text{syst})$ and $\mathcal{A}_{\pi\pi} = +0.56 \pm 0.12(\text{stat}) \pm 0.06(\text{syst})$. The correlation between $S_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ is $+0.09$. In this Letter, we quote the usual fit errors from the likelihood functions, called the MINOS errors, as statistical uncertainties [15]. Figures 2(a) and 2(b) show the Δt distributions for the 470 B^0- and 414 $\bar{B}^0$-tagged events in the subset of data with LR > 0.86. We define the raw asymmetry $\mathcal{A}_{CP}$ in each Δt bin by $\mathcal{A}_{CP} = (N_+ - N_-)/(N_+ + N_-)$, where $N_{+(-)}$ is the number of observed candidates with $q = +1\ (-1)$. Figures 2(c) and 2(d) show the raw asymmetries for two regions of the flavor-tagging parameter r.

The main contributions to the systematic error are due to the uncertainties in the vertex reconstruction (± 0.04 for $S_{\pi\pi}$ and $^{+0.03}_{-0.01}$ for $\mathcal{A}_{\pi\pi}$) and event fraction (± 0.02 for $S_{\pi\pi}$ and ± 0.04 for $\mathcal{A}_{\pi\pi}$); the latter includes the uncertainties in $\mathcal{A}_{q\bar{q}}$ and final state radiation. We include the effect of tag side interference [16] on $S_{\pi\pi}(\pm 0.01)$ and $\mathcal{A}_{\pi\pi}(^{+0.02}_{-0.04})$. Other sources of systematic error are the uncertainties in

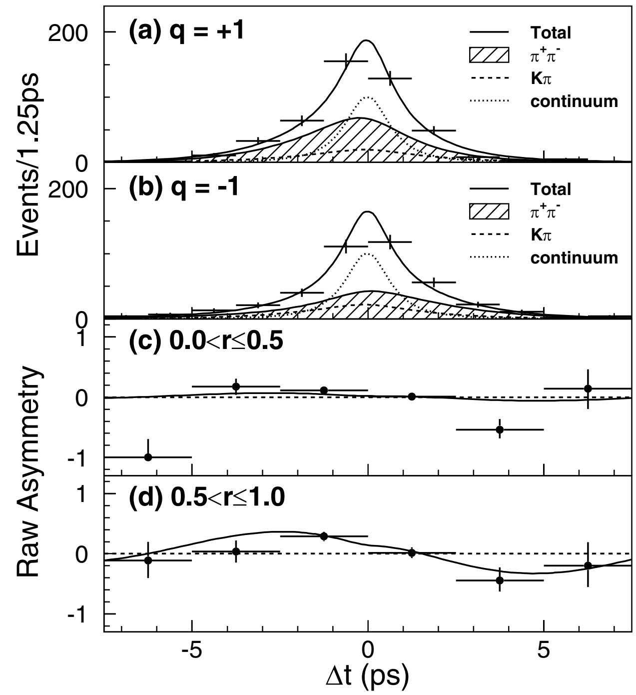

FIG. 2. Δt distributions for the 884 $B^0 \to \pi^+\pi^-$ candidates with LR > 0.86 in the signal region: (a) 470 candidates with $q = +1$, (b) 414 candidates with $q = -1$. Raw asymmetry, $\mathcal{A}_{CP}$, in each Δt bin with (c) $0 < r \le 0.5$ and (d) $0.5 < r \le 1.0$. The solid lines show the results of the unbinned maximum likelihood fit to the Δt distribution of the 2820 $B^0 \to \pi^+\pi^-$ candidates.

the wrong tag fraction (± 0.01 for $S_{\pi\pi}$ and ± 0.01 for $\mathcal{A}_{\pi\pi}$), physics parameters (τ_{B^0}, Δm_d, and $\mathcal{A}_{K\pi}$) (<0.01 for $S_{\pi\pi}$ and ± 0.01 for $\mathcal{A}_{\pi\pi}$), resolution function (± 0.04 for $S_{\pi\pi}$ and ± 0.01 for $\mathcal{A}_{\pi\pi}$), background Δt shape (<0.01 for $S_{\pi\pi}$ and <0.01 for $\mathcal{A}_{\pi\pi}$), and fit bias (± 0.01 for $S_{\pi\pi}$ and ± 0.01 for $\mathcal{A}_{\pi\pi}$). We add each contribution in quadrature to obtain the total systematic error.

We carry out a number of checks to validate our results. The B^0 lifetime is measured with $B^0 \to \pi^+\pi^-$ candidates. The result is $\tau_{B^0} = 1.50 \pm 0.07$ ps, consistent with the world average value [17]. The CP fit to the sideband events yields no significant asymmetry. We check the measurement of $\mathcal{A}_{\pi\pi}$ using a time-integrated fit and obtain $\mathcal{A}_{\pi\pi} = +0.52 \pm 0.14$, consistent with the time-dependent fit result. We also select $B^0 \to K^+\pi^-$ candidate events with charged tracks positively identified as kaons that have a topology similar to the $B^0 \to \pi^+\pi^-$ signal events. The CP fit to the 4293 $B^0 \to K^+\pi^-$ candidates (2207 signal events) yields $S_{K\pi} = +0.09 \pm 0.08$, consistent with zero, and $\mathcal{A}_{K\pi} = -0.06 \pm 0.06$, in agreement with the world average value [13]. With the $K^+\pi^-$ sample, we determine $\tau_{B^0} = 1.51 \pm 0.04$ ps and $\Delta m_d = 0.46 \pm 0.03\ \text{ps}^{-1}$, which are also in agreement with the world average values [17].

To determine the statistical significance of our measurement, we apply the frequentist procedure described in

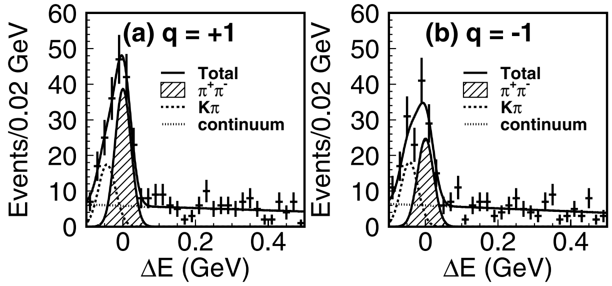

FIG. 3. ΔE distributions in the M_{bc} signal region for the $B^0 \to \pi^+\pi^-$ candidates with $LR > 0.86$ and $0.5 < r \leq 1.0$ for (a) $q = +1$ and (b) $q = -1$.

Ref. [4] that takes into account both statistical and systematic errors. The hypothesis of CP symmetry conservation, $S_{\pi\pi} = \mathcal{A}_{\pi\pi} = 0$, is ruled out at a confidence level (C.L.) of $1 - \text{C.L.} = 5.6 \times 10^{-8}$, equivalent to a 5.4σ significance for one-dimensional Gaussian errors. The case of no direct CP violation, $\mathcal{A}_{\pi\pi} = 0$, is also ruled out with a significance greater than 4.0σ for any $S_{\pi\pi}$ value.

Figure 3 shows the ΔE distributions for $B^0 \to \pi^+\pi^-$ candidates with $LR > 0.86$ and $0.5 < r \leq 1.0$ for (a) $q = +1$ and (b) $q = -1$ subsets in the M_{bc} signal region. An unbinned two-dimensional maximum likelihood fit to the $q = +1$ ($q = -1$) subset yields $107 \pm 13(69 \pm 11)\pi^+\pi^-$, $42 \pm 9(43 \pm 9)K^+\pi^-$, and $38 \pm 1(38 \pm 1)$ continuum events in the signal box. The $K^+\pi^-$ and continuum background yields are consistent between the two subsets as expected, while the $\pi^+\pi^-$ yields are appreciably different; direct CP violation in $B^0 \to \pi^+\pi^-$ decays is visible in the contrast of the two subsets. These results also support the expectation from $SU(3)$ symmetry that $\mathcal{A}_{\pi\pi} \sim -3\mathcal{A}_{K\pi}$ [18].

We constrain the ratio of the magnitude of the penguin to tree amplitudes $|P/T|$ and the strong phase difference $\delta \equiv \delta_P - \delta_T$ by adopting the notation of Ref. [19], where $\delta_{P(T)}$ is the strong phase of the penguin (tree) amplitude. By using $\phi_1 = 23.5° \pm 1.6°$ [13], we find 95.4% confidence intervals of $|P/T| > 0.17$ and $-180° < \delta < -4°$.

To constrain ϕ_2, we employ isospin relations [20] and the approach of Ref. [21] for the statistical treatment. We use the measured branching ratios of $B^0 \to \pi^+\pi^-$, $\pi^0\pi^0$, and $B^+ \to \pi^+\pi^0$, and the direct CP asymmetry for $B^0 \to \pi^0\pi^0$ [13] as well as our measured values of $S_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ taking into account their correlation. Figure 4 shows the obtained C.L. as a function of ϕ_2. We find an allowed range for ϕ_2 at 95.4% C.L. of $0° < \phi_2 < 19°$ and $71° < \phi_2 < 180°$.

In summary, we have performed a new measurement of the CP-violating parameters in $B^0 \to \pi^+\pi^-$ decays using a 253 fb^{-1} data sample. We obtain $S_{\pi\pi} = -0.67 \pm 0.16(\text{stat}) \pm 0.06(\text{syst})$ and $\mathcal{A}_{\pi\pi} = +0.56 \pm 0.12(\text{stat}) \pm 0.06(\text{syst})$. We rule out the CP-conserving case, $S_{\pi\pi} = \mathcal{A}_{\pi\pi} = 0$, at the 5.4σ level. We find compelling evidence for direct CP asymmetry with 4.0σ significance. The results confirm the previous Belle measurement of the CP-violating parameters as well as the earlier evidence for direct CP violation in $B^0 \to \pi^+\pi^-$ decays [4].

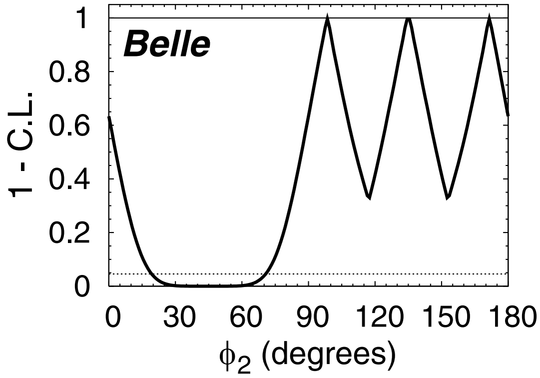

FIG. 4. Confidence level as a function of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix angle ϕ_2 obtained with an isospin analysis using Belle measurements of $S_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$. The dotted line indicates C.L. = 95.4%.

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