Eur Phys J C **33**, s01, s361–s363 (2004)
Digital Object Identifier (DOI) 10.1140/epjcd/s2004-03-1640-1

EPJ C direct
electronic only

Results on direct CP violation in PV and three body B decays in BABAR and Belle

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Received: 31 October 2003 / Accepted: 6 January 2004 /
Published Online: 6 February 2004 –

Abstract. This paper reviews recent searches for *CP* violating asymmetries in charmless pseudoscalar-vector and three body B decays, based on data collected between 1999 and 2003 by the *BABAR* and Belle experiments.

1 Introduction

The *BABAR* and Belle experiments have recently released precise measurements of sin2β using *CP* violating asymmetries in charmonium B decays modes [1,2] and the remarkable agreement with the value predicted in the standard model could be used to put stringent limits on new physics in the B^0 /$\overline{B}^0$ flavor mixing. However, a wide variety of effects in B decays is predicted by the standard model, and significant deviations due to a new physics contribution are not yet excluded in most cases. Direct *CP* violation in charmless B decays is one of them.

Given a final state f, direct *CP* violation occurs when the partial widths of the two *CP*-conjugate decay channels $B \to f$ and $\overline{B} \to \bar{f}$ (where B is B^+ or B^0) are different. We thus define the following direct *CP* violating asymmetry:

$$A_{CP}(f) = \frac{|A_{\overline{B}\to\bar{f}}|^2 - |A_{B\to f}|^2}{|A_{\overline{B}\to\bar{f}}|^2 + |A_{B\to f}|^2}, \quad (1)$$

where $A_{B\to f}$ and $A_{\overline{B}\to\bar{f}}$ are the decay amplitudes of the corresponding processes. If we assume that $A_{B\to f}$ may be written as the sum of various competing amplitudes A_i for which we can factorize the weak phases Φ_i (*CP*-odd) and the strong phases δ_i (*CP*-even):

$$A_{B\to f} = \sum_i |A_i| e^{i\Phi_i} e^{i\delta_i}, \quad (2)$$

then the *CP*-conjugate amplitude will be written:

$$A_{\overline{B}\to\bar{f}} = \sum_i |A_i| e^{-i\Phi_i} e^{i\delta_i}, \quad (3)$$

and the direct *CP* violating asymmetry will have the following dependence:

$$A_{CP} \propto \sum_{i,j} |A_i||A_j| \sin(\Phi_i - \Phi_j) \sin(\delta_i - \delta_j). \quad (4)$$

Table 1. Results on branching fractions ($\mathcal{B}$) in units of 10^{-6} and direct *CP* violating asymmetries (A_{CP}) for the modes $B \to hhh$ (upper limits are 90% CL)

	BABAR	Belle
$\mathcal{B}(\pi^+\pi^-\pi^+)$	$10.9 \pm 3.3 \pm 1.6$	–
$\mathcal{B}(K^+\pi^-\pi^+)$	$59.1 \pm 3.8 \pm 3.2$	$53.6 \pm 3.1 \pm 5.1$
$\mathcal{B}(K^+K^-\pi^+)$	< 6.3	$9.3 \pm 2.3 \pm 1.1$
$\mathcal{B}(K^+K^-K^+)$	$29.6 \pm 2.1 \pm 1.6$	$32.8 \pm 1.8 \pm 2.8$
$\mathcal{B}(K^-\pi^+\pi^+)$	< 1.8	< 4.5
$\mathcal{B}(K^+K^+\pi^-)$	< 1.3	< 2.4
$A_{CP}(\pi^+\pi^-\pi^+)$	$-0.39 \pm 0.33 \pm 0.12$	–
$A_{CP}(K^+\pi^-\pi^+)$	$0.01 \pm 0.07 \pm 0.03$	–
$A_{CP}(K^+K^-K^+)$	$0.02 \pm 0.07 \pm 0.03$	–

In other words, direct *CP* violation will arise if at least two competing amplitudes of the same order contribute to the decay, and both their weak phase and strong phase are different.

In the standard model, most charmless B decays are dominated by two amplitudes which are referred to as *tree* (T) and *penguin* (P), the weak phase difference between the two being equal to the angle γ of the unitarity triangle. If both amplitudes are allowed for a given decay mode, then direct *CP* violation may occur and may give some information on γ. However, A_{CP} will depend on the relative weight $|T|/|P|$ and the difference in strong phases of T and P, these parameters having a heavy dependence on long-distance contributions to strong interaction. On the opposite, if one of the two amplitudes T or P is suppressed for a given decay mode, then a relatively clean prediction may be derived from the standard model: $A_{CP} = 0$ and new physics in B decays could bias this prediction. In either case, the motivation for the experimental search for direct *CP* violation is obvious.

Table 2. Results on branching fractions ($\mathcal{B}$) in units of 10^{-6} and direct *CP* violating asymmetries (A_{CP}) for the modes $B \to \omega K, \omega\pi$ (upper limits are 90% CL)

	BABAR	Belle
$\mathcal{B}(\omega K^+)$	$5.0 \pm 1.0 \pm 0.4$	$6.7^{+1.3}_{-1.2} \pm 0.6$
$\mathcal{B}(\omega\pi^+)$	$5.4 \pm 1.0 \pm 0.5$	$5.7^{+1.4}_{-1.3} \pm 0.6$
$\mathcal{B}(\omega K^0)$	$5.3^{+1.4}_{-1.2} \pm 0.5$	$4.0^{+1.9}_{-1.6} \pm 0.5$
$\mathcal{B}(\omega\pi^0)$	–	< 1.9
$A_{CP}(\omega K^+)$	$-0.05 \pm 0.16 \pm 0.01$	$0.06^{+0.20}_{-0.18} \pm 0.01$
$A_{CP}(\omega\pi^+)$	$0.04 \pm 0.17 \pm 0.01$	$0.48^{+0.23}_{-0.20} \pm 0.02$

The data used in the analyses presented in this paper were collected at the PEP-II and KEKB asymmetric B factories with the *BABAR* and Belle detectors, described in detail elsewhere [3,4]. The data samples recorded between 1999 and 2003 correspond to approximately 124×10^6 (152×10^6) produced $B\overline{B}$ pairs at PEP-II (KEKB) respectively. Not all analyses use these full samples.

2 The decays $B \to hhh$ ($h = K^\pm, \pi^\pm$)

The study of three-body B decays may lead to important constraints on parameters of the unitarity triangle, such as γ [5] and α [6]. To understand the feasibility of such analyses, and also to look for some decays that are suppressed in the standard model such as $B^+ \to K^-\pi^+\pi^+$ and $B^+ \to K^+K^+\pi^-$, recent results have been released on branching fractions and direct *CP* violation in B decays to three-body final states of charged pions and kaons, with charm contributions subtracted.

BABAR [7] has used a sample of 89×10^6 $B\overline{B}$ pairs to give results on branching fractions for all the $B \to hhh$ modes. Significant signals were observed for the three modes $\pi^+\pi^-\pi^+$, $K^+\pi^-\pi^+$ and $K^+K^-K^+$ and A_{CP} asymmetries could thus be derived. Belle [8] has used a sample of 85×10^6 $B\overline{B}$ pairs to give results only on branching fractions. All the results are summarized in Table 1 and no disagreement is found between the two experiments. The significant signals found for best observed modes are encouraging results to carry out the full Dalitz analyses. Additionally, no signal is found for the standard model suppressed decays $B^+ \to K^-\pi^+\pi^+$ and $B^+ \to K^+K^+\pi^-$.

3 The decays $B \to \omega K, \omega\pi$

The various modes $B \to \omega K$ and $B \to \omega\pi$ involve similar *tree* and *penguin* amplitudes, each of them being either Cabibbo suppressed or favoured. Additionally, the tree amplitudes of $B^0 \to \omega K^0$ and $B^0 \to \omega\pi^0$ are colour-suppressed. This variety of situations could lead to interesting interferences between *tree* and *penguin*, thus making the search for direct *CP* violation in these modes appealing. Another interest of these modes is the confrontation with theoretical calculations [9].

Table 3. Results on branching fractions ($\mathcal{B}$) in units of 10^{-6} and direct *CP* violating asymmetries (A_{CP}) for the modes $B \to \phi K, \phi\pi$. (upper limits are 90% CL) The ϕK^0_S final state is excluded from the analysis for $A_{CP}(K^+K^-K^0_S)$

	BABAR	Belle
$\mathcal{B}(\phi K^0)$	$8.4^{+1.5}_{-1.3} \pm 0.5$	$9.0^{+2.2}_{-1.8} \pm 0.7$
$\mathcal{B}(K^+K^-K^0)$	$23.8 \pm 2.3 \pm 2.2$	$28.3 \pm 3.3 \pm 4.0$
$\mathcal{B}(\phi K^+)$	$10.0^{+0.9}_{-0.8} \pm 0.5$	$9.4 \pm 1.1 \pm 0.7$
$\mathcal{B}(\phi\pi^+)$	< 0.41	–
$A_{CP}(\phi K^0_S)$	$0.38 \pm 0.37 \pm 0.12$	$-0.15 \pm 0.29 \pm 0.07$
$A_{CP}(K^+K^-K^0_S)$	–	$-0.17 \pm 0.16 \pm 0.04$
$A_{CP}(\phi K^+)$	$0.04 \pm 0.09 \pm 0.01$	$0.01 \pm 0.12 \pm 0.05$

BABAR [10] and Belle [11] have analysed data samples corresponding to 89×10^6 and 85×10^6 $B\overline{B}$ pairs, respectively. Significant signals are found by both experiments for the three modes $B^0 \to \omega K^+$, $B^+ \to \omega\pi^+$ and $B^0 \to \omega K^0$, leading to the search for a direct *CP* violating asymmetry for the first two modes. The mode $B^0 \to \omega\pi^0$ was searched by Belle only and no signal could be found. All the results are summarized in Table 2. No significant direct *CP* violating asymmetry is observed, even though a little more than a 2σ effect is seen by Belle for $\omega\pi^+$.

4 The decays $B \to \phi K, \phi\pi$

In charmless B decays into final states with a ϕ meson, the *tree* amplitude is forbidden in the standard model, so that the *penguin* amplitude should dominate. In fact, other contributions from the standard model (*electroweak penguins*) may also contribute, but they are expected to be smaller. In this situation, no direct *CP* violation is expected to occur in these decays, in other words it is sensitive to new physics.

The measurement of direct *CP* violation in the neutral modes at a B factory is based on an analysis combining the flavor of the other B in the event and the decay time difference between the two B mesons (*time-dependent analysis*). The parameters of such an analysis have in general a specific notation ($\mathcal{A}, C$), which may be easily converted to that defined in (1): $A_{CP} = \mathcal{A} = -C$.

BABAR [12] and Belle [13] have updated their search for direct *CP* violation in $B^0 \to \phi K^0_S$ with 124×10^6 and 152×10^6 $B\overline{B}$ pairs, respectively. Belle has also an update for $A_{CP}(B^0 \to K^+K^-K^0_S)$ with that sample. All other measurements are performed using 89×10^6 and 86×10^6 $B\overline{B}$ pairs for *BABAR* and Belle, respectively. The results are summarized in Table 3. No direct *CP* violating asymmetry is found to deviate from 0.

5 The decays $B \to \rho\pi, \rho K$

The motivation for the study of the modes $B \to \rho\pi, \rho K$ is that their branching fractions are quite large and moreover

Table 4. Results on branching fractions ($\mathcal{B}$) in units of 10^{-6} and direct *CP* violating asymmetries (A_{CP}, $\mathcal{A}_{\rho\pi}$) for the modes $B \to \rho\pi$ (upper limits are 90% CL)

	BABAR	Belle
$\mathcal{B}(\rho^{\pm}\pi^{\mp})$	$22.6 \pm 1.8 \pm 2.2$	$29.1^{+5.0}_{-4.9} \pm 4.0$
$\mathcal{B}(\rho^0\pi^0)$	< 2.5	$6.0^{+2.9}_{-2.3} \pm 1.2$
$\mathcal{B}(\rho^0\pi^+)$	$9.3 \pm 1.0 \pm 0.8$	$8.0^{+2.3}_{-2.0} \pm 0.7$
$\mathcal{B}(\rho^+\pi^0)$	$11.0 \pm 1.9 \pm 1.9$	–
$\mathcal{B}(\rho^-K^+)$	$7.3^{+1.3}_{-1.2} \pm 1.3$	$15.1^{+3.4+1.4+2.0}_{-3.3-1.5-2.1}$
$\mathcal{B}(K^+\pi^-\pi^0)$	–	$36.6^{+4.2}_{-4.3} \pm 3.0$
$A_{CP}(\rho^+\pi^-)$	$-0.18 \pm 0.13 \pm 0.05$	–
$A_{CP}(\rho^-\pi^+)$	$-0.52^{+0.17}_{-0.19} \pm 0.07$	–
$\mathcal{A}_{\rho\pi}$	$-0.114 \pm 0.062 \pm 0.027$	$-0.38^{+0.19+0.04}_{-0.21-0.05}$
$A_{CP}(\rho^+\pi^0)$	$0.23 \pm 0.16 \pm 0.06$	–
$A_{CP}(\rho^0\pi^+)$	$-0.17 \pm 0.11 \pm 0.02$	–
$A_{CP}(\rho^-K^+)$	$0.18 \pm 0.12 \pm 0.08$	$0.22^{+0.22+0.06}_{-0.23-0.02}$
$A_{CP}(K^+\pi^-\pi^0)$	–	$0.07 \pm 0.11 \pm 0.01$

their analysis should help constraining the angle α of the unitarity triangle [16]. A significant *penguin* contribution to the amplitude is however not excluded, which could lead, through the interference with the *tree* amplitude, to a possible direct violation of the *CP* symmetry.

BABAR has released analyses based on 89×10^6 $B\overline{B}$ pairs [17,18] and has updated the asymmetry measurements for $\rho^{\pm}\pi^{\mp}$ and ρ^+K^- with the full sample of 124×10^6 $B\overline{B}$ pairs. Belle has released analyses with 85×10^6 $B\overline{B}$ pairs. As in Sect. 4, a time-dependent analysis is required to study completely the modes $B^0 \to \rho^{\pm}\pi^{\mp}$. Doing this, *BABAR* was able to measure the two parameters $A_{CP}(\rho^-\pi^+)$ and $A_{CP}(\rho^+\pi^-)$, as defined in (1). Belle has not yet performed the full time-dependent analysis and has released only one parameter with the following definition: $\mathcal{A}_{\rho\pi} = \frac{N(\rho^+\pi^-)-N(\rho^-\pi^+)}{N(\rho^+\pi^-)+N(\rho^-\pi^+)}$. This last parameter may be expressed also using the *BABAR* measurements. All results are summarized in Table 4. A significant correlation is found between the two parameters $A_{CP}(\rho^-\pi^+)$ and $A_{CP}(\rho^+\pi^-)$, as can be seen in Fig. 1: on the whole, a 2.5σ effect is seen. Results on *CP* violation are in agreement in the two experiments, however, rather large differences are found for the branching fractions into $\rho^0\pi^0$ and ρ^-K^+.

6 Conclusion

A broad experimental program of search for direct *CP* violation in charmless *B* decays is underway at *BABAR* and Belle and its precision is increasing significantly as luminosity is accumulated. Today, the precision in many modes is such that large new physics effects could be seen experimentally. However, theoretical uncertainties would make the proof still ambiguous. Direct *CP* violation was not yet seen in the *B* system, in spite of the remarkable precision of these measurements.

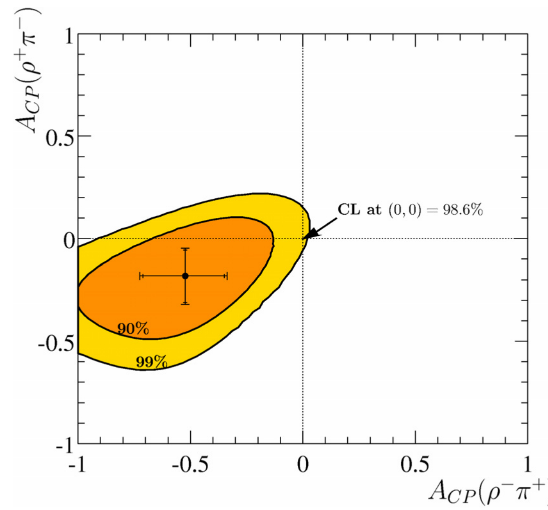

Fig. 1. Confidence intervals for the direct CP asymmetries $A_{CP}(\rho^+\pi^-)$ and $A_{CP}(\rho^-\pi^+)$. The first *error bars* are statistical while the second are total

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