

# MEASUREMENTS OF $\phi_1$ AND $\phi_2$ BY BELLE AND BABAR

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We report recent measurements of the Unitarity triangle angles  $\phi_1$  and  $\phi_2$  using large data samples collected with Belle and BaBar detectors at  $e^+e^-$  asymmetric-energy colliders.

## 1 Introduction

In the Standard Model (SM),  $CP$  violation in  $B^0$  meson decays originates from an irreducible complex phase in the  $3 \times 3$  Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix<sup>1</sup>. The angles  $\phi_1$  and  $\phi_2$  of the CKM unitarity triangle have been measured in several  $B$  decay modes<sup>2,3,4,5</sup>. Extra studies in different decay modes are important to check the self-consistence between measurements to probe the existence of New Physics.

The results reported in this paper were obtained by two experiments, Belle and BaBar, working at  $e^+e^-$  asymmetric-energy colliders, KEKB<sup>6</sup> and PEP-II, correspondingly, with the center-of-mass (CM) energy at  $\Upsilon(4S)$  resonance ( $\sqrt{s} = 10.58$  GeV). The Belle detector<sup>7</sup> is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), a mosaic of aerogel threshold Cherenkov counters (ACC), time-of-flight scintillation counters (TOF), and an array of CsI(Tl) crystals (ECL) 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  $K_L$  mesons and to identify muons (KLM). For the results from Belle experiment the data sample of 657 million  $B\bar{B}$  pairs is used.

The BaBar detector is described in detail elsewhere<sup>8</sup>. Charged particle momenta are measured with a tracking system consisting of a five-layer silicon vertex tracker (SVT) and a 40-layer

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drift chamber (DCH) surrounded by a 1.5 T solenoidal magnet. An electromagnetic calorimeter (EMC) comprising 6580 CsI(Tl) crystals is used to measure photon energies and positions. Charged hadrons are identified with a detector of internally reflected Cherenkov light (DIRC) and ionization measurements in the tracking detectors. The results from BaBar experiment are based on 383 million  $B\bar{B}$  pairs data sample.

## 2 Study of $B^+ \rightarrow D^+\bar{D}^0$ and search for $B^0 \rightarrow D^0\bar{D}^0$

Recently, evidence of direct  $CP$  violation in the decay  $B^0 \rightarrow D^+D^-$  was observed by Belle<sup>9</sup>, while BaBar measured an asymmetry consistent with zero<sup>10</sup>. A similar effect might occur in the charged mode  $B^+ \rightarrow D^+\bar{D}^0$ <sup>11</sup>. This decay has already been observed by Belle<sup>12</sup> and confirmed by BaBar<sup>13</sup>.

Now, Belle updated their result with larger data sample<sup>14</sup>.  $366 \pm 32$  events were found from the fit to the  $\Delta E - M_{bc}$  distribution (Fig. 1(a,b)), where  $\Delta E = E_B - E_{\text{beam}}$ ,  $M_{bc} = \sqrt{E_{\text{beam}}^2 - p_B^{*2}}$ ,  $E_B(p_B^*)$  is the energy (momentum) of  $B$  candidate in the CM system,  $E_{\text{beam}}$  is the CM beam energy. The branching fraction of  $B^+ \rightarrow D^+\bar{D}^0$  is measured to be  $\mathcal{B}(B^+ \rightarrow D^+\bar{D}^0) = (3.85 \pm 0.31 \pm 0.38) \times 10^{-4}$ , where the first error is statistical and the second one is systematic. The charge asymmetry for this decay is measured to be consistent with zero:  $A_{CP}(B^+ \rightarrow D^+\bar{D}^0) = 0.00 \pm 0.08 \pm 0.02$ . Belle also searched for the decay  $B^0 \rightarrow D^0\bar{D}^0$ . An upper limit is established for the branching fraction:  $\mathcal{B}(B^0 \rightarrow D^0\bar{D}^0) < 0.43 \times 10^{-4}$  (Fig. 1(c,d)).

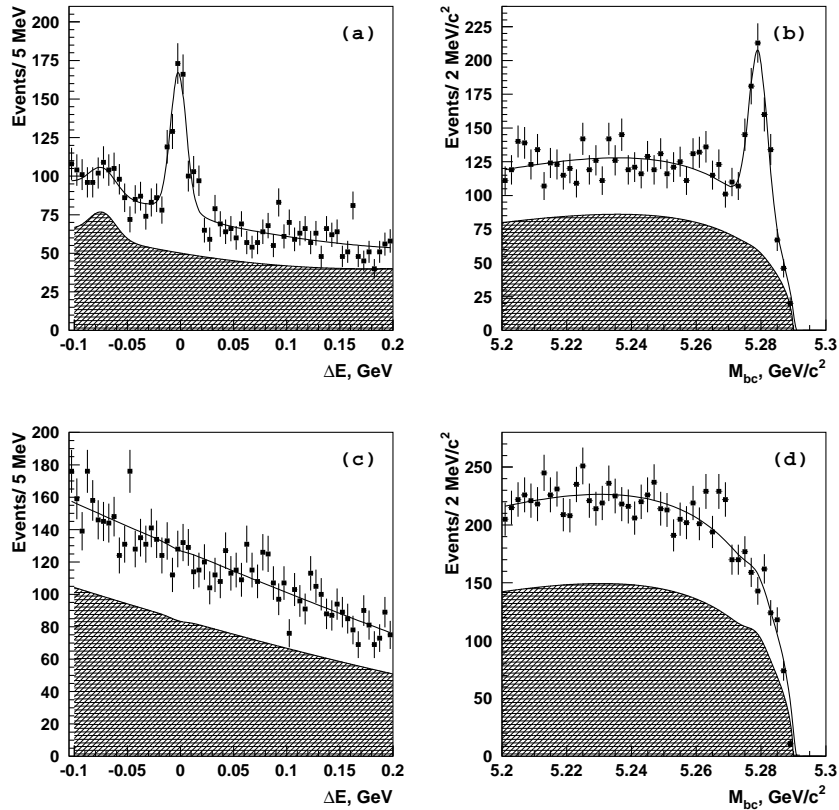


Figure 1:  $\Delta E$  (a,c) and  $M_{bc}$  (b,d) distributions for the  $B^+ \rightarrow D^+\bar{D}^0$  (a,b) and  $B^0 \rightarrow D^0\bar{D}^0$  (c,d) candidates. Each distribution is the projection of the signal region of the other parameter. Points with errors represent the experimental data, open curves show projections from the 2D fits and cross-hatched curves show the  $B\bar{B}$  background component only.

### 3 Study of $B^0 \rightarrow D^{*+}D^{*-}$

Another interesting decay mode to study the  $CP$  asymmetry is  $B^0 \rightarrow D^{*+}D^{*-}$ . Both experiments have updated their results for this decay mode and obtained high statistics signals shown in Fig. 2(a,c)<sup>15</sup>. The time-dependent decay rates of  $B^0$  and  $\bar{B}^0$  to a  $CP$  eigenstate, like  $D^{*+}D^{*-}$ , is given by formula:

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

where  $q$  is the  $b$ -flavor charge:  $q = +1(-1)$  when the tagging  $B$  meson is a  $B^0$  ( $\bar{B}^0$ ),  $\tau_{B^0}$  is the neutral  $B$  lifetime,  $\Delta m_d$  is the mass difference between two  $B^0$  mass eigenstates,  $\Delta t_{B^0} = t_{CP} - t_{\text{tag}}$ . The tree diagram dominates in this decay mode, which according to the SM gives  $\mathcal{S}_{f_{CP}} = \xi_{D^{*+}D^{*-}} \sin 2\phi_1$  and  $\mathcal{A}_{f_{CP}} = 0$ . The parameter  $\xi_{D^{*+}D^{*-}}$  is the  $CP$  eigenvalue of the  $D^{*+}D^{*-}$ , which is  $+1$  when the decay proceeds via  $S$  and  $D$  waves, or  $-1$  for a  $P$  wave. Therefore, the  $CP$  measurement requires helicity study to obtain the  $CP$ -odd fraction  $R_{\text{odd}}$  of the decay. It is done in both analyses from Belle and BaBar in the so-called transversity basis. The fit results are presented in Fig. 2(b,d). The parameter  $R_{\text{odd}}$  is found to be equal to  $0.143 \pm 0.034(\text{stat}) \pm 0.008(\text{syst})$  by BaBar and  $0.116 \pm 0.042(\text{stat}) \pm 0.004(\text{syst})$  by Belle.

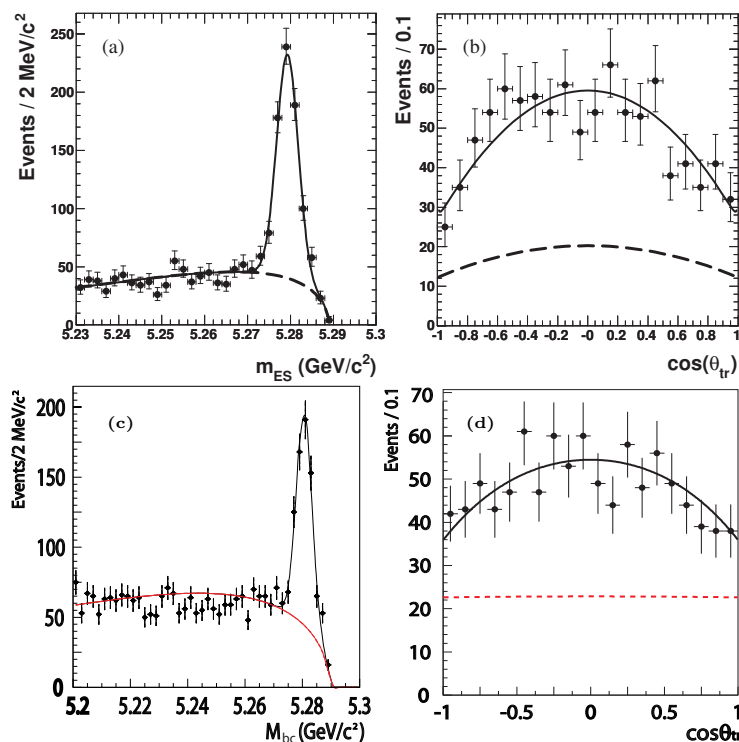


Figure 2: Measured distributions of  $M_{bc}$  (a, c) and  $\cos \theta_{\text{tr}}$  in the region  $M_{bc} > 5.27 \text{ GeV}/c^2$  (b, d) for BaBar (a, b) and Belle (c, d) of  $B^0 \rightarrow D^{*+}D^{*-}$  events. The solid lines are the projections of the fit results. The dotted lines represent the background components.

Finally, the unbinned maximum likelihood fit was performed to obtain the  $CP$ -violating parameters. The results of the fits are summarized in Table 1 and presented in Fig. 3. Both experiments obtained the results well consistent with each other in both the  $CP$ -odd fraction and the  $CP$ -violating parameters. Note that in the BaBar parametrization  $\mathcal{A} = -\mathcal{C}$ . The Belle results are preliminary.

Table 1: Results for  $B^0 \rightarrow D^{*+}D^{*-}$  decay mode.

	Yield	$R_{\text{odd}}$	$\mathcal{A} = -\mathcal{C}$	$\mathcal{S}$
Belle	$545 \pm 29$	$0.116 \pm 0.042 \pm 0.004$	$+0.16 \pm 0.13 \pm 0.02$	$-0.93 \pm 0.24 \pm 0.15$
BaBar	$638 \pm 38$	$0.143 \pm 0.034 \pm 0.008$	$+0.02 \pm 0.11 \pm 0.02$	$-0.66 \pm 0.19 \pm 0.04$

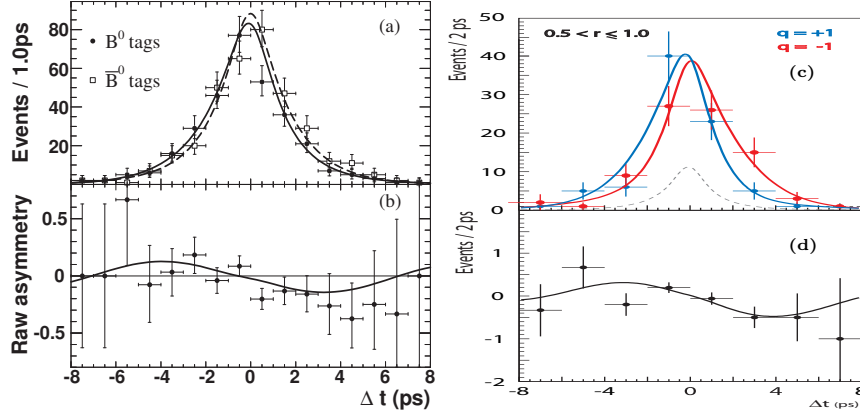


Figure 3: The  $\Delta t$  distributions of  $B^0 \rightarrow D^{*+}D^{*-}$  events in the region  $M_{bc} > 5.27 \text{ GeV}/c^2$  for  $B^0(\bar{B}^0)$  tagged candidates (a, c) and the raw asymmetry  $(N_{B^0} - N_{\bar{B}^0})/(N_{B^0} + N_{\bar{B}^0})$ , as a function of  $\Delta t$  (b, d) for BaBar (a, b) and Belle (c, d). The lines represent the fit results.

#### 4 $CP$ -violation in $B^0 \rightarrow K_S\pi^0\pi^0$ and $B^0 \rightarrow K_S\pi^0$

In the SM, the  $CP$  violation parameters in  $b \rightarrow s$  ‘‘penguin’’ and  $b \rightarrow c$  ‘‘tree’’ transitions are predicted to be the same,  $\mathcal{S}_f \approx -\xi_f \sin 2\phi_1$  and  $\mathcal{A}_f \approx 0$ , with small theoretical uncertainties. Recent measurements however, indicate that the effective  $\sin 2\phi_1$  value,  $\sin 2\phi_1^{\text{eff}}$ , measured with penguin processes is different from  $\sin 2\phi_1 = 0.687 \pm 0.025$  measured in tree decays by  $2.6\sigma$ <sup>16</sup>. New particles in loop diagrams may shift the weak phase.

Recently, Belle and BaBar measured the  $CP$  asymmetry in  $B^0 \rightarrow K_S^0\pi^0\pi^0$  and  $B^0 \rightarrow K_S\pi^0$  decays that proceed through  $b \rightarrow s\bar{q}q$  ( $q = u, d$ ) transitions<sup>17,18,19,20</sup>. The results of  $CP$ -violating parameters measurements are presented in Table 2. Both experiments are perfectly consistent with each other. In the case of  $B^0 \rightarrow K_S^0\pi^0\pi^0$  the central value of  $\mathcal{S}$  has a sign opposite to what we expect from the SM, but the errors are still too large to claim the contradiction. The estimated deviation of the average value from the SM is more than  $2\sigma$ . The fit to the data for Belle for  $B^0 \rightarrow K_S^0\pi^0\pi^0$  is presented in Fig. 4(a-c) and the BaBar result for  $B^0 \rightarrow K_S^0\pi^0$  is shown in Fig. 4(d-f).

 Table 2: Results for  $B^0 \rightarrow K_S^0\pi^0\pi^0$  and  $B^0 \rightarrow K_S\pi^0$  decay modes.

	$\mathcal{A} = -\mathcal{C}$	$\mathcal{S} = -\sin 2\phi_1$
$B^0 \rightarrow K_S^0\pi^0\pi^0$		
Belle	$-0.17 \pm 0.24 \pm 0.06$	$+0.43 \pm 0.49 \pm 0.09$
BaBar	$-0.23 \pm 0.52 \pm 0.13$	$+0.72 \pm 0.71 \pm 0.08$
Average	$-0.18 \pm 0.22$	$+0.52 \pm 0.41$
$B^0 \rightarrow K_S\pi^0$		
Belle	$-0.05 \pm 0.14 \pm 0.05$	$+0.33 \pm 0.35 \pm 0.08$
BaBar	$-0.24 \pm 0.15 \pm 0.03$	$+0.40 \pm 0.23 \pm 0.03$

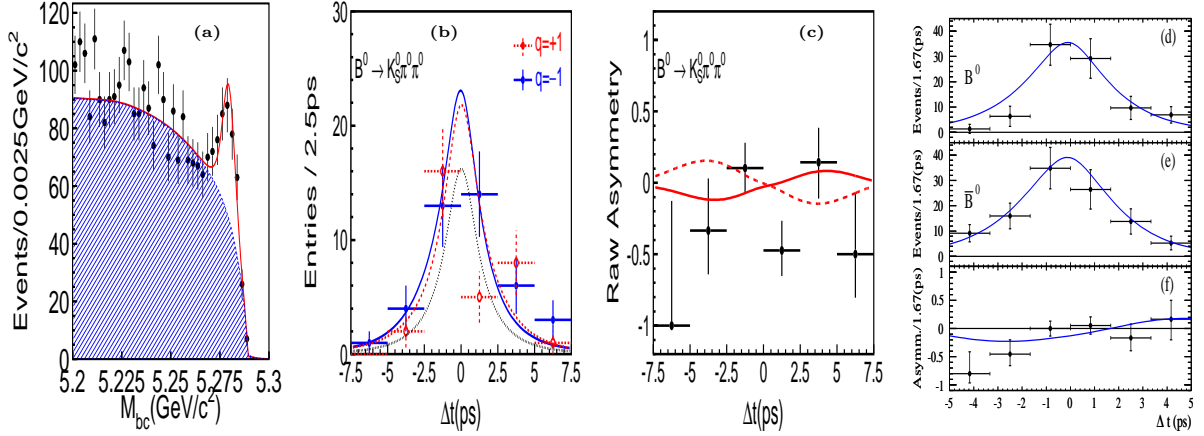


Figure 4: Distributions for the  $M_{bc}$  (a), the  $\Delta t$  (b) and the raw asymmetry (c) for  $B^0 \rightarrow K_S^0 \pi^0 \pi^0$  decay mode from Belle.  $\Delta t$  distributions for the  $B^0$  (d) and  $\bar{B}^0$  (e) tagged events and the raw asymmetry (f) for the decay  $B^0 \rightarrow K_S^0 \pi^0$  from BaBar. The lines represent the fit result.

## 5 $\phi_2$ measurements

The CKM angle  $\phi_2$  have been measured in decay modes like  $B^0 \rightarrow \pi\pi, \rho\rho, \rho\pi$  <sup>21</sup>. Addition of new decay modes allows to improve an accuracy of  $\phi_2$  measurement and to check a consistency of measurements in different final states. The decay  $B^0 \rightarrow a_1^\pm(1260)\pi^\mp$  proceeds through  $b \rightarrow u$  transitions, hence its time-dependent  $CP$  violation is also sensitive to  $\phi_2$ . Belle measured the branching fraction for this decay mode to be  $\mathcal{B}(B^0 \rightarrow a_1^\pm(1260)\pi^\mp)\mathcal{B}(a_1^\pm(1260) \rightarrow \pi^\pm\pi^\pm\pi^\mp) = (14.9 \pm 1.6 \pm 2.3) \times 10^{-6}$  <sup>22</sup>, while BaBar has updated their previous measurements now with  $CP$  violation study:  $\mathcal{A}_{CP} = -0.07 \pm 0.07 \pm 0.02$  and  $\mathcal{S} = +0.37 \pm 0.21 \pm 0.07$  <sup>23</sup>. The angle  $\phi_2$  was measured to be  $\phi_2^{\text{eff}} = 78.6^\circ \pm 7.3^\circ$ . The result is presented in Fig. 5(a-c).

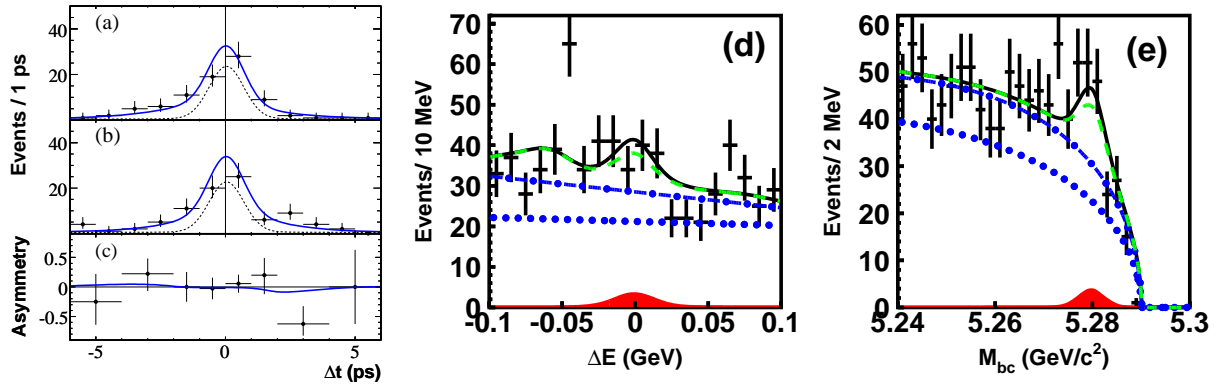


Figure 5:  $\Delta t$  distributions of the decay  $B^0 \rightarrow a_1^\pm \pi^\mp$  for  $B^0$  (a) and  $\bar{B}^0$  (b) tagged events, and the raw asymmetry (c). The solid lines show the fit results, while the dotted lines show the background component. Projection of the signal region onto (d)  $\Delta E$  and (e)  $M_{bc}$  for  $B^0 \rightarrow \rho^0 \rho^0$  candidates. The fit result is shown as the thick solid curve; the hatched region represents the signal component. The dotted, dot-dashed and dashed curves represent, respectively, the cumulative background contributions from continuum processes,  $b \rightarrow c$  decays, and charmless  $B$  decays.

Belle also performed the search for the decay  $B^0 \rightarrow \rho^0 \rho^0$  and other decay modes with four pions in the final state. In the absence of the signals, the upper limits on the branching fraction were established. The signal distributions for the  $B^0 \rightarrow \rho^0 \rho^0$  are shown in Fig. 5(a,b). All

Table 3: Fit results for decays relevant to  $\phi_2$  measurements.

Mode	Yield	$\epsilon$ (%)	$\mathcal{S}(\sigma)$	$\mathcal{B}(\times 10^{-6})$	UL( $\times 10^{-6}$ )@90% C.L.
Belle results					
$\rho^0 \rho^0$	$24.5^{+23.6+9.7}_{-22.1-9.9}$	9.16	1.0	$0.4 \pm 0.4^{+0.2}_{-0.2}$	$< 1.0$
$\rho^0 \pi^+ \pi^-$	$112.5^{+67.4+51.5}_{-65.6-53.7}$	2.90	1.3	$5.9^{+3.5+2.7}_{-3.4-2.8}$	$< 11.9$
$4\pi^\pm$	$161.2^{+61.2+26.0}_{-59.4-28.5}$	1.98	2.5	$12.4^{+4.7+2.0}_{-4.6-2.2}$	$< 19.0$
$\rho^0 f^0$	$-11.8^{+14.5+4.9}_{-12.9-3.6}$	5.10	—	—	$< 0.6$
$f^0 f^0$	$-7.7^{+4.7+3.0}_{-3.5-2.9}$	2.75	—	—	$< 0.4$
$f^0 \pi^+ \pi^-$	$6.3^{+37.0+18.0}_{-34.7-18.1}$	1.55	—	$0.6^{+3.6}_{-3.4} \pm 1.8$	$< 7.3$
BaBar results					
$b_1^0 \pi^+$	$178^{+39}_{-37}$	6.78	4.0	$6.7 \pm 1.7 \pm 1.0$	
$b_1^0 K^+$	$219^{+38}_{-36}$	6.73	5.3	$9.1 \pm 1.7 \pm 1.0$	
$b_1^\mp \pi^\pm$	$387^{+41}_{-39}$	9.54	8.9	$10.9 \pm 1.2 \pm 0.9$	
$b_1^- K^+$	$267^{+33}_{-32}$	9.43	6.1	$7.4 \pm 1.0 \pm 1.0$	
$a_1^0 \pi^+$	$382 \pm 79$	7.2	3.8	$20.4 \pm 4.7 \pm 3.4$	
$a_1^- K^0$	$241 \pm 32$	9.6	6.2	$34.9 \pm 5.0 \pm 4.4$	
$a_1^+ \pi^0$	$459 \pm 78$	12.5	4.2	$26.4 \pm 5.4 \pm 4.2$	
$a_1^- K^+$	$272 \pm 44$	7.9	5.1	$16.3 \pm 2.9 \pm 2.3$	

results are preliminary.

Also a number of the decay modes potentially usable for the  $\phi_2$  measurements have been studied by BaBar<sup>24,25,26</sup>. All the results of these studies are summarized in Table 3.

## 6 $CP$ -violation in $\Upsilon(4S)$ decays

In the decay  $\Upsilon(4S) \rightarrow B^0 \bar{B}^0 \rightarrow f_1 f_2$ , where  $f_1$  and  $f_2$  are  $CP$  eigenstates, the  $CP$  eigenvalue of the final state  $f_1 f_2$  is  $\xi = -\xi_1 \xi_2$ . Here the minus sign corresponds to odd parity from the angular momentum between  $f_1$  and  $f_2$ . If  $f_1$  and  $f_2$  have the same  $CP$  eigenvalue, i.e.  $(\xi_1, \xi_2) = (+1, +1)$  or  $(-1, -1)$ ,  $\xi$  is equal to  $-1$ . Such decays, for example  $(f_1, f_2) = (J/\psi K_S^0, J/\psi K_S^0)$ , violate  $CP$  conservation since the  $\Upsilon(4S)$  meson has  $J^{PC} = 1^{--}$  and thus has  $\xi_{\Upsilon(4S)} = +1$ . The branching fraction within the SM is suppressed by the factor

$$F \approx \frac{x^2}{1+x^2} (2 \sin 2\phi_1)^2 = 0.68 \pm 0.05,$$

where  $x = \Delta m_d / \Gamma = 0.776 \pm 0.008$ <sup>27</sup>.

This decay was studied by Belle. Due to a small branching fractions to the final state and low reconstruction efficiencies the expected yield is very small, 0.04 events. In order to increase the signal yield, a partial reconstruction technique was used<sup>28</sup>. One  $B^0$  was fully reconstructed, while only  $K_S^0$  was reconstructed from another one. The signal was searched in the recoil mass distribution to the reconstructed particles where, in principle, signals from  $\eta_c, J/\psi, \chi_{c1}$ , or  $\psi(2S)$  can be seen. The method was checked using charged  $B$  decay control samples,  $\Upsilon(4S) \rightarrow B^+ B^- \rightarrow (f_{B^+}, J/\psi^{\text{tag}} K^- \text{ and } \eta_c^{\text{tag}} K^-)$ , where  $f_{B^+}$  stands for  $J/\psi K^+$  and  $\bar{D}^0 \pi^+$ . Also neutral  $B$  decays were examined in the decay  $\Upsilon(4S) \rightarrow B^0 \bar{B}^0 \rightarrow (f_{B^0}, J/\psi^{\text{tag}} K_S^0 \text{ and } \eta_c^{\text{tag}} K_S^0)$  with  $f_{B^0} = B^0 \rightarrow D^{(*)-} h^+$ . The fit yields  $206 \pm 57$  for charged  $B$  and  $35 \pm 16$  for neutral  $B$  signal events, which is in good agreement with the MC expectation (Fig. 6(a,b)). The results of the final fit are shown in Fig. 6(c). The extracted signal yield,  $-1.5^{+3.6}_{-2.8}$  events, is consistent with zero as well as with the SM prediction (1.7 events). An upper limit for the branching fraction was obtained  $\mathcal{B}(\Upsilon(4S) \rightarrow B^0 \bar{B}^0 \rightarrow J/\psi K_S^0, (J/\psi, \eta_c) K_S^0) < 4 \times 10^{-7}$  at the

90% confidence level, where the SM prediction is  $1.4 \times 10^{-7}$ . This corresponds to  $F < 2$  at the 90% confidence level.

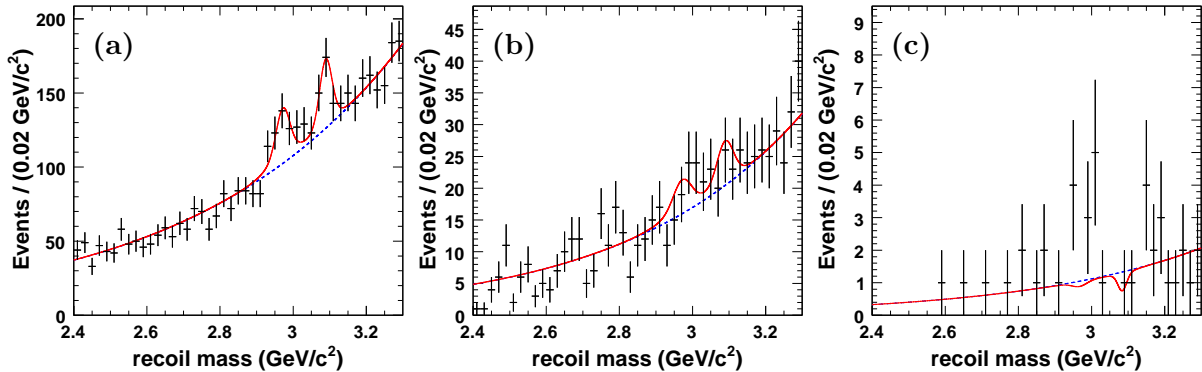


Figure 6: Recoil mass distributions for samples reconstructed as  $\Upsilon(4S) \rightarrow (B^+, (J/\psi, \eta_c)^{\text{tag}} K^-)$  (a),  $(B^0 \rightarrow D^{(*)-} h^+, (J/\psi, \eta_c)^{\text{tag}} K_S^0)$  (b) and  $(J/\psi K_S^0, (J/\psi, \eta_c)^{\text{tag}} K_S^0)$  (c). The solid lines show the fits to signal plus background distributions while the dashed lines show the background distributions.

## 7 Summary

The  $CP$  violating parameters have been measured in various decay modes. Most of the measurements are in a good agreement with the SM expectations. Although a room for New Physics becomes smaller and smaller, there is still some sign that it can be found in  $b \rightarrow s$  transitions. More statistics is necessary to test these possibilities.

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