SLAC-PUB-12073
hep-ex/0607001

MEASUREMENTS OF THE CKM ANGLE β/ϕ_1 AT THE B FACTORIES

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We report measurements of time-dependent CP asymmetries related to the CKM angle β/ϕ_1, using decays of neutral B mesons to charmonium, open charm and in $b \to s$ loop-dominated processes. A preliminary measurement of time-dependent CP asymmetries in $B^0 \to \rho^0(770)K^0_S$ decays from the *BABAR* experiment is given here.

1 Introduction

In the Standard Model (SM), CP violation occurs as a consequence of a complex phase in the 3×3 Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix [1]. The unitarity of the CKM matrix imposes the condition $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$, where V_{ij} are the CKM matrix elements. This condition can be conveniently illustrated as a triangular relation in the $(\bar{\rho}, \bar{\eta})$ complex plane. A non-vanishing phase in the CKM matrix results in a non-zero area for the Unitarity Triangle (UT). Various measurements in the B meson system are sensitive to the CKM angles α, β, and γ of the UT [a].

In the $B^0 - \bar{B}^0$ system, information on the CKM angles can be obtained by measuring the time dependence of B^0 or $\bar{B}^0$ decays to CP eigenstates f_{CP}. The time distribution is given by

$$\frac{dN(B^0(\bar{B}^0) \to f_{CP})}{dt} \propto e^{-t/\tau} \left[1 - (\pm S_f \sin \Delta mt \mp C_f \cos \Delta mt)\right], \tag{1}$$

where τ is the B^0 meson lifetime, and Δm is the $B^0 - \bar{B}^0$ oscillation frequency. The CP-violating coefficients S_f and C_f are functions of the parameter λ_f:

$$\lambda_f = \frac{q}{p} \frac{A(\bar{B}^0 \to f)}{A(B^0 \to f)} \ , \ S_f = \frac{2Im(\lambda_f)}{1 + |\lambda_f|^2} \ , \ C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}. \tag{2}$$

[a] The CKM angles are also called ϕ_2, ϕ_1 ϕ_3. In this report we will indistinctly use either convention.

Contributed to 41st Rencontres De Moriond: QCD And Hadronic Interactions, 11-18 March 2006, La Thuile, Italy

Work supported in part by Department of Energy contract DE-AC02-76SF00515

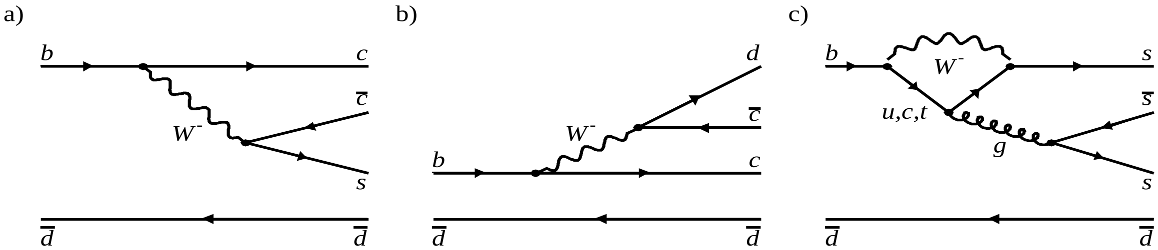

Figure 1: Diagrams mediating the decay amplitudes related to the measurements of the CKM angle β. From left to right: a) $b \to c\bar{c}s$ ("charmonium"), b) $b \to c\bar{c}d$ ("open charm") and c) $b \to q\bar{q}s$ ("penguin-dominated").

In this expression $A(B^0 \to f)$ (resp. $A(\bar{B}^0 \to f)$) is the decay amplitude of B^0 (resp. $\bar{B}^0$) to the final state f_{CP} respectively, and the q/p ratio ratio is given by the admixture of flavour eigenstates B^0 and $\bar{B}^0$ in the neutral B mass eigenstates. The SM predicts $|q/p| \simeq 1$. If only one weak phase enters the decay amplitude, $\lambda_f = \eta_f e^{2\theta}$, where $\eta_f = \pm 1$ is the CP of the final state f.

The CP-violating parameter $\sin 2\beta$ is most accurately measured using $B^0 \to J/\psi K^0$ decays. These decays are dominated by a $b \to c\bar{c}s$ tree amplitude and a $b \to sc\bar{c}$ penguin amplitude. As contributions with different weak phases are doubly Cabibbo-suppressed, the CP violation parameters are $S = \pm\sin 2\beta$ and $C = 0$ to an excellent approximation. Other measurements related to the CKM angle β are given by the $b \to s$ transition decays. In the SM, these decays occur dominantly through pure penguin diagrams, and the CP phase originally acquired in the $B^0 - \bar{B}^0$ mixing is not changed. If new particles contribute in the loop, they introduce new couplings, and the corresponding new phases will shift the CP asymmetry parameter $\sin 2\beta_{eff}$ from its SM value $\sin 2\beta$. Therefore the measurement of $\sin 2\beta_{eff}$ for such decays are a potentially sensitive probe to New Physics.

2 Experimental Technique

The results presented are from the *BABAR* and Belle experiments. *BABAR* runs at the PEP-II asymmetric energy e^+e^- collider, and the Belle detector is located at the KEKB asymmetric collider. Both colliders, usually referred to as B factories, operate at the $\Upsilon(4S)$ resonance, whose mass is slightly above the $B - \bar{B}$ production threshold. At the B factories, the center-of-mass reference frame is boosted with respect to the detector frame, in the direction of the beam line axis z. The boost parameter $\beta\gamma$ is 0.55 for PEP-II and 0.425 for KEKB. The $B - \bar{B}$ pairs being produced almost at rest in the $\Upsilon(4S)$ rest frame, Δt can be determined from the displacement Δz between the B decay vertices: $\gamma\beta c\Delta t \simeq (z_{CP} - z_{TAG})$, where z_{CP} refers to the vertex of the B meson fully reconstructed in the final state f_{CP} , and z_{TAG} to the vertex of the other B meson in the event, whose decay products are also used to identify its flavour at decay time.

At the B factories, CP violation is studied through the measurement of the time-dependent CP asymmetry, $A_{CP}(\Delta t)$. This quantity is defined as

$$A_{CP}(\Delta t) = \frac{N(\bar{B}^0 \to f_{CP}) - N(B^0 \to f_{CP})}{N(\bar{B}^0 \to f_{CP}) + N(B^0 \to f_{CP})}(\Delta t), \tag{3}$$

where $N(\bar{B}^0 \to f_{CP})$ is the number of $\bar{B}^0$ that decay into the final state f_{CP} at the time difference Δt. In general, this asymmetry can be expressed as the sum of two components:

$$A_{CP}(\Delta t) = S_f \sin \Delta m \Delta t - C_f \sin \Delta m \Delta t. \tag{4}$$

When only one amplitude contributes to the final state, the cosine term vanishes, as direct CP violation requires at least two different weak and strong phases to occur. This holds in particular

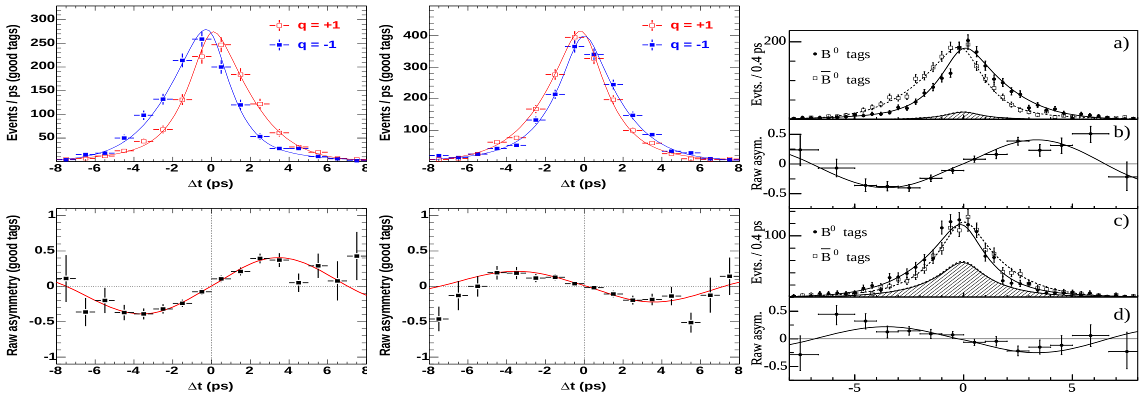

Figure 2: Measurement of $\sin 2\beta$ in the $b \to c\bar{c}s$ modes, form the Belle (left, center) and *BABAR* (right) experiments. The time distributions for events tagged as B^0 or $\bar{B}^0$ in CP-odd or CP-even final states are shown, together with the corresponding raw CP asymmetry, with the projection of the unbinned maximum likelihood fit superimposed.

for decays such as $B^0 \to J/\psi K^0$, where one has $S_f = -\eta_f \sin 2\beta$, η_f being the CP value of the final state considered (i.e. $\eta = -1$ for $J/\psi K^0_S$, and $\eta = +1$ for $J/\psi K^0_L$).

Constraints on the CKM angle β can be obtained through the three types of B^0 decays illustrated in Figure 1: the charmonium modes $b \to c\bar{c}s$, the "open-charm"modes $b \to c\bar{c}d$ and the penguin-dominated $b \to q\bar{q}s$ modes. They are described in the following sections.

3 The CKM angle β/ϕ_1 from $b \to c\bar{c}s$

These modes, also known as "golden" modes, are dominated by a tree level diagram $b \to c\bar{c}s$. Furthermore, the leading penguin contribution to the final state has the same weak phase as the tree, and the largest term with a different weak phase is a doubly Cabibbo-suppressed penguin. This makes $C = 0$ a very good approximation.

The CP eigenstates considered for this analysis are the $J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, $\eta_c K^0_S$ and $J/\psi K^0_L$. These modes also offer experimental advantages, because of their relatively large branching fractions allowing to collect large signal samples, and the presence of narrow charmonium resonances in the final states, that provide a clear experimental signature and a strong rejection of combinatorial background.

The asymmetry between the Δt distributions for B^0 and $\bar{B}^0$ tagged events, clearly visible in Figure 2, establishes CP violation in the B meson system. The average of results are given in the Tables [2] displayed in Figure 3. The latest *BABAR* measurements of $\sin 2\beta$ are performed on a sample of 227×10^6 $B - \bar{B}$ pairs, and the Belle results use a data sample made of 386×10^6 $B - \bar{B}$ pairs [3]. The world average value for $\sin 2\beta$, heavily dominated by the results from *BABAR* and Belle, is $\sin 2\beta = (0.685 \pm 0.032)$. The main sources of systematical errors are uncertainties in the background level and characteristics, in the parametrisation of time resolution, and in the measurement of the wrong tagging rates. Most of these systematics are of statistical nature and will thus decrease with additional statistics.

The direct measurement of $\sin 2\beta$ can be compared with the indirect constraints on the UT [4] originating from World Average values of ε_K,$|V_{ub}/V_{cb}|$, B_d and B_s mixing, as illustrated in Figure 3. The excellent agreement between direct measurements of $\sin 2\beta$ and indirect constraints, is a strong indication that the CKM mechanism is the dominant source for CP violation.

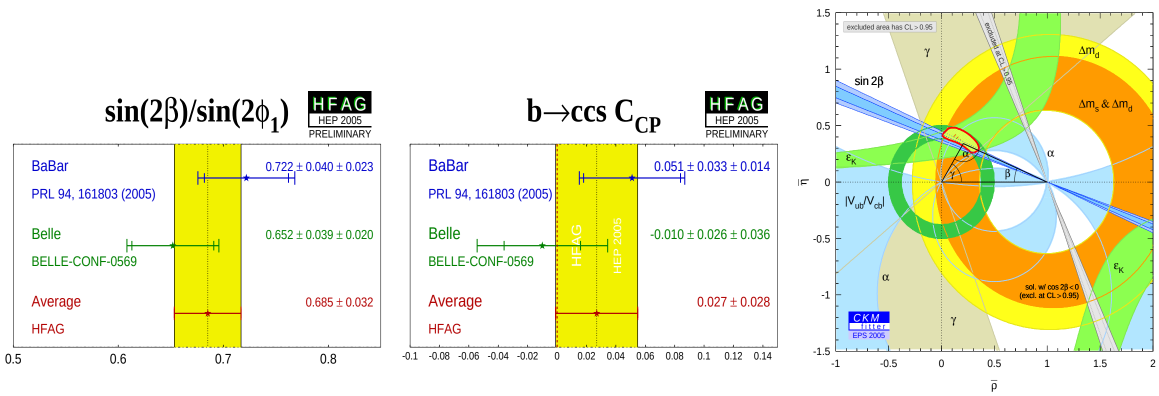

Figure 3: Average of measurements $b \to c\bar{c}s$ processes of the CP violating parameters S (left) and C (center), from the *BABAR* and Belle experiments. Right: constraints on the UT, coming from a global fit to the CKM matrix. The red curve surrounds the $> 95\%$ CL area, from all measurements excluding the direct measurements of $\sin 2\beta$, and the light blue contours represent the direct constraints on the CKM angle β.

3.1 From $\sin 2\beta$ to β

Measurements of the CP violating parameter $\sin 2\beta$ leave a four-fold ambiguity in the CKM angle β itself. The ambiguities can be reduced by measuring the sign of $\cos 2\beta$. This measurement provides a direct test of the SM, since $\cos 2\beta$ is predicted to be positive. The interference of CP-even and CP-odd components in the time-dependent angular distribution $B^0 \to J/\psi K^{*0}$ decays, with $K^{*0} \to K^0_S \pi^0$ provides a measurement of $|\cos 2\beta|$. The *BABAR* experiment has performed an analysis on a data sample of approximately 88 million $B\bar{B}$ pairs, and measures $|\cos 2\beta| = (+2.72^{+0.50}_{-0.79} \pm 0.27)$, with the value of $\sin 2\beta$ fixed to its measured value [5]. For the Belle experiment, 275 million $B\bar{B}$ pairs have been used, providing a result of $|\cos 2\phi_1| = (+0.56 \pm 0.79 \pm 0.11)$. Furthermore, the analysis of the $K^0_S\pi^0$ phase motion can be used as extra input to solve the residual ambiguity. From comparison with the $K\pi$ scattering data from the LASS experiments, only the positive solution for $\cos 2\beta$ shows good agreement with the scattering data, and a negative value for $\cos 2\beta$ is excluded at 86% CL.

Other methods to break the ambiguities have been explored. In particular, it has been shown [6] that in $B^0 \to Dh^0$ with multi-body D decays ($b \to c\bar{u}d$ processes), a time-dependent analysis of the Dalitz plot of the D decay allows a direct determination of the CKM angle ϕ_1. The result from the Belle experiment is $\phi_1 = (16 \pm 21 \pm 12)^o$, and this rules out the $\phi_1 = 68^o$ solution at 97% CL [7].

4 Open-charm decays

The decays $B^0 \to D^{(*)+}D^{(*)-}$ are dominated by a tree level diagram $b \to c\bar{c}d$. Also belonging to the $b \to c\bar{c}d$ class is the $B^0 \to J/\psi\pi^0$ mode [8]. In the SM, the leading penguin contribution to the latter decay is expected to be small. Corrections for the penguin-induced shifts to $S = \sin 2\beta$ and $C = 0$ have been estimated to be a few percent. New Physics beyond the SM could enlarge the penguin contribution and would lead to a measurement of time-dependent CP asymmetries significantly different from the one measured in $b \to c\bar{c}s$ modes. Probing the tree-dominance scenario is an interesting test of the SM.

The extraction of the coefficients S and C is straigthforward in the D^+D^- and $J/\psi\pi^0$ modes, which are pure CP eigenstates. In constrast, as the D^*D^* modes are an admixture of CP-odd and CP-even components, the CP-odd fractions need to be measured for the extraction of S and C parameters. The *BABAR* experiment has performed a transversity analysis giving a CP-odd fraction $R_T = (0.125 \pm 0.044 \pm 0.007)$, and the corresponding result for the Belle experiment [9]

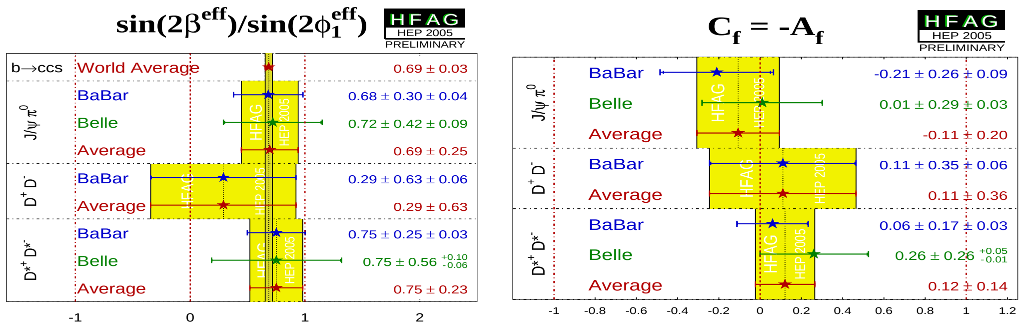

Figure 4: Summary of results on CP violation for the $b \to c\bar{c}d$ processes. All results on S are compatible with the value of $\sin 2\beta$ from $b \to c\bar{c}s$ processes, and no evidence for direct CP violation is observed in the C measurements.

is $R_T = (0.19 \pm 0.08 \pm 0.01)$. The results of the CP fits for all $b \to c\bar{c}d$ modes are summarised in the Table [2] represented in Figure 4. Results are all consistent with the tree-dominance scenario; while small deviations are expected, they still lie below experimental sensitivity, and more data is required for testing the SM.

5 Penguin-dominated decays

In the SM, final states dominated by a $b \to s\bar{s}s$ or a $b \to d\bar{d}s$ transition offer an independent test of the SM, by comparing the CP-violating parameters in loop processes with those obtained in the tree-dominated ones. Examples of final states related to the $b \to q\bar{q}s$ processes are the ϕK^0, $\eta' K^0$, $f_0 K^0$, $\pi^0 K^0$, ωK^0, $K^+K^-K^0$ and $K^0K^0K^0$ modes [10]. These decays are dominated by gluonic penguin amplitudes; depending on the modes considered, other contributions to the amplitudes may be present. In presence of non-SM physics, new particles could contribute to the loop amplitudes and afffect the time-dependent asymmetries.

The decays ϕK^0 provide an example of these studies. In the SM, these decays are almost pure $b \to s\bar{s}s$ penguins, and their CP asymmetry is expected to coincide with the one measured in $b \to c\bar{c}s$ within a few percent. Experimentally, this cannel is also very clean, owing to the narrow ϕ resonance. Although the experimental signature is less clean, the $B^0 \to \phi K^0_L$ final state is also studied. The decay $B^0 \to \eta' K^0$, with its relatively large branching fraction ($\sim 6 \times 10^{-5}$) has drawn attention as well. In the SM, the $\eta' K^0$ decay is expected to be dominated by penguin-mediated amplitudes, and deviations from $S = \sin 2\beta, C = 0$ are therefore expected to be small. Experimental measurements include both the $\eta' K^0_S$ and $\eta' K^0_L$ modes, these last providing an additional 50% data sample. More challenging, the $B^0 \to \pi^0 K^0_S$ and $B^0 \to K^0_S K^0_S K^0_S$ modes are studied by means of a beam-spot constraint technique for the measurement of the B^0 vertex. This technique is validated with a control sample of $B^0 \to J/\psi K^0_S$ decays, ignoring the tracks from the J/ψ in the vertexing. The measurement of the B^0 lifetime provides a supplementary validation. The *BABAR* experiment has also performed a preliminary measurement of time-dependent CP asymmetries in the $B^0 \to \rho^0(770) K^0_S$ mode. While there is a tree contribution to the amplitude, it is both colour- and Cabibbo-suppressed, and deviations from $S = \sin 2\beta$ are expected to be small. The Δt distributions for events tagged as B^0 or $\bar{B}^0$, and the CP asymmetry A_{CP}, are shown in Figure 5. The preliminary values are $S = (0.17 \pm 0.52 \pm 0.26)$, and $C = (0.64 \pm 0.41 \pm 0.25)$.

The Table [2] in Figure 5 summarises the measurements of $b \to s$-penguin modes available (the $\rho^0(770) K^0_S$ mode not being included in the Table). While no significant discrepancies with respect to the $S = \sin 2\beta$, $C = 0$ values are observed in a mode-by-mode basis, a naive

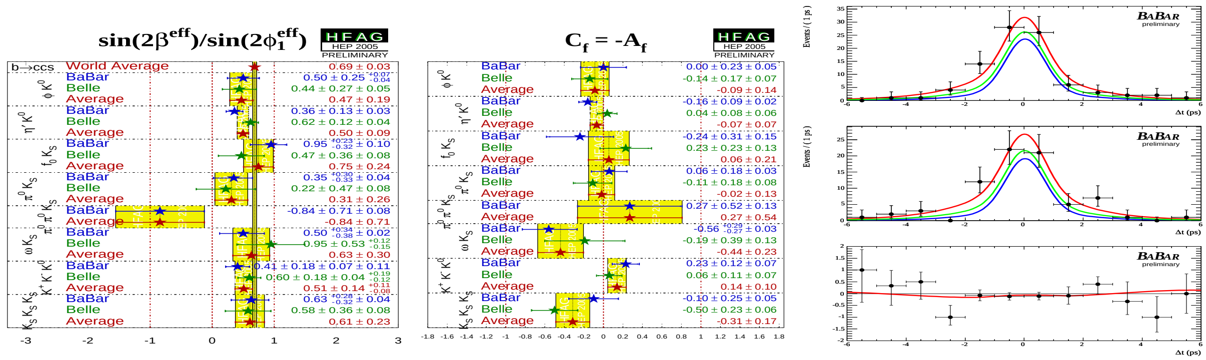

Figure 5: Averages of measurements of the CP-violating parameters S (left) and C (center) in the $b \to q\bar{q}s$ modes. No significant deviation from the $S = \sin 2\beta$, $C = 0$ values from $b \to c\bar{c}s$ is observed. Right: (preliminary result from the *BABAR* experiment) time distributions for $\rho^0(770)K^0_S$ events, tagged as B^0 (top), or $\bar{B}^0$ (center), and raw CP asymmetry (bottom).

averaging of the S and C parameters should be interpreted with extreme caution; each mode is in principle sensitive to different SM contributions, so shifts in $\Delta S = \sin 2\beta_{eff} - \sin 2\beta$ and ΔC are in principle different for each mode. More data is therefore required for drawing conclusions. With increasing data samples integrated by the B factories, new modes from the $b \to q\bar{q}s$ class become accessible, and provide further tests of the SM.

Conclusions

The CP-violating parameter $\sin 2\beta$ in charmonium decays is now measured to a 5% accuracy. The measured value is consistent with SM expectations. No deviation from the "tree-dominance" scenario has been observed in open-charm decays. Time-dependent CP asymmetries in loop-dominated processes are potentially sensitive to contributions from New Physics beyond the SM. Measurements being statistically limited, further studies with larger datasets are required.

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