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α AND β AT THE B FACTORIES

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Abstract

We review recent experimental results on time-dependent CP asymmetries in the B system from the *BABAR* and Belle experiments. Measurements of the α and β angles of the Unitarity Triangle of the CKM matrix are discussed. These measurements constitute stringent tests of the Standard Model, and are also used to search for new physics.

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1 Introduction

In the Standard Model (SM) of electroweak interactions, *CP* violation arises as a consequence of a complex phase in the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. Unitarity implies among the elements of *e.g.* the first and third columns of the CKM matrix the relation $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$, which is represented in the complex plane by a Unitarity Triangle (UT) with angles

$$\alpha = arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right], \quad \beta = arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right], \quad \gamma = arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]. \tag{1}$$

To discuss measurements of the first two angles at the B factories, we focus in this report on a particular manifestation of *CP* violation, arising in the decay of a neutral B meson to a *CP* eigenstate f_{CP} from the interference between the decay with and without $B^0\overline{B}^0$ mixing[1]. A time-dependent *CP* asymmetry can be defined as

$$\begin{aligned}\mathcal{A_{CP}} &\equiv \frac{N(\overline{B}^0(\Delta t) \to f_{CP}) - N(B^0(\Delta t) \to f_{CP})}{N(\overline{B}^0(\Delta t) \to f_{CP}) + N(B^0(\Delta t) \to f_{CP})} \\ &= S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t),\end{aligned} \tag{2}$$

where $N(B^0(\Delta t) \to f_{CP})$ denotes the number of B^0 mesons decayed into the *CP* eigenstate at a time Δt after the decay of the $\overline{B}^0$ meson, and the coefficients of the oscillatory terms can be expressed as functions of the $B^0\overline{B}^0$ mixing parameters and of the decay amplitutes:

$$S_f = -\frac{2\,\mathrm{Im}\lambda_f}{1+|\lambda_f|^2}, \qquad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \qquad \lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}. \tag{3}$$

The SM predicts $|q/p| \simeq 1$. If the decay is dominated by a single decay amplitude or by amplitudes with the same weak phase, then $|\lambda_f| = 1$, $C_f = 0$ and $S_f = -\eta_f \mathrm{Im}\lambda_f$, η_f being the *CP* eigenvalue of f_{CP} [2].

2 Experimental techniques

The results discussed in the present paper were obtained by the BABAR [2] and Belle [3] experiments, respectively located at the PEP-II and KEKB e^+e^-

[1]The final state need not be a *CP* eigenstate in general, but just to be common to both B^0 and $\overline{B}^0$.

[2]Some authors, including the Belle collaboration, use the symbols ϕ_2, ϕ_1, ϕ_3 for the angles α, β, γ, and $A_f = -C_f$ for the parameter describing direct *CP* violation. In the present article we will follow the $\alpha, \beta, \gamma, C_f$ nomenclature.

asymmetric-energy B factories. Pairs of $B\overline{B}$ mesons are produced almost at rest in the decay of $\Upsilon(4S)$ resonance. The separation between their decay vertices is increased in the laboratory frame due to the boost given by the asymmetric-energy beams. The results discussed in the present paper refer to about 230 million $B\overline{B}$ pairs (BABAR) and about 386 million $B\overline{B}$ pairs (Belle) unless otherwise noted.

Some basic experimental techniques are common to all time-dependent analyses. The B mesons decaying to the CP eigenstate (B_{CP}) is first reconstructed and then identified against possible backgrounds using two almost uncorrelated kinematic variables: the *energy-substituted* mass $m_{\rm ES} = \sqrt{E^{*2}_{beam} - p^{*2}_B}$, and $\Delta E = E^*_{beam} - E^*_B$, where all quantities are evaluated in the $\Upsilon(4S)$ center-of-mass (CM) frame, E^*_B and p^*_B are the energy and momentum of the reconstructed B meson and E^*_{beam} is the beam energy. The latter is known with excellent precision at the B factories, and provides a constraint which greatly improves the resolution on $m_{\rm ES}$. All tracks not belonging to the reconstructed f_{CP} are assigned to the *tagging* vertex (B_{tag}), which is inclusively reconstructed to measure Δt from the displacement between the B_{CP} and B_{tag} decay vertices: $\Delta t \simeq (z_{CP} - z_{tag})/\beta\gamma c$. The flavor of the B is correlated with the charge of its decay products; we exploit this property to determine whether at the time of its decay it was a B^0 or a $\overline{B}^0$. Finally, $\mathcal{A_{CP}}$ is determined through unbinned maximum-likelihood fits.

3 Measurements of β

The CKM angle β can be measured at the B factories in several processes, broadly belonging to three categories, as schematically shown in Fig. 1. Given the highly predictive power of the Standard Model, where CP violation originates by a single non-vanishing phase in the CKM matrix, comparison of the different angle determinations constitutes a powerful test, possibly leading to effects beyond the SM itself.

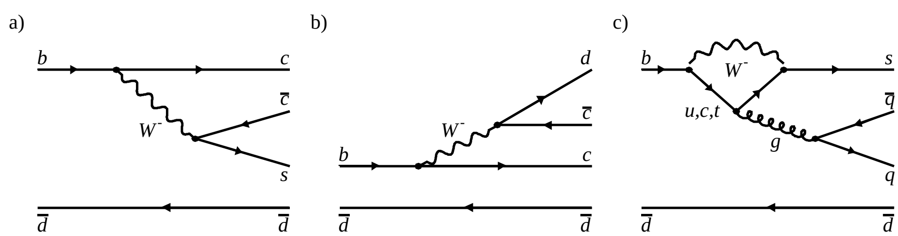

Figure 1: Feynman diagrams for different decay amplitudes used to measure the CKM angle β. From left to right: a) $b \to c\overline{c}s$; b) $b \to c\overline{c}d$; c) penguin-dominated $b \to q\overline{q}s$.

3.1 sin2β from $b \to c\bar{c}s$

For the decays $B^0 \to (c\bar{c})K^{0(*)}$, which are dominated by a single weak phase, the SM predicts that $C = 0$ and that S does not depend on hadronic matrix elements, which are difficult to calculate. Both B factory experiments have analyzed modes with $\eta_{CP} = -1$ ($B^0 \to J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$), with $\eta_{CP} = +1$ ($B^0 \to J/\psi K^0_L$), and $B^0 \to J/\psi K^{*0}(\pi^0 K^0_S)$, which has no definite *CP* parity. The Δt distributions for B^0 and $\overline{B}^0$ tagged events are shown in Fig. 2 for both the *BABAR* [4)] and the Belle [5)] collaborations. The experimental errors are small enough to clearly see the sinusoidal behavior in the asymmetry; note, in η_{CP} =+1 case, the opposite phase in the asymmetry and the reduced amplitude due to the background dilution. As of Winter 2006, the most recent result from

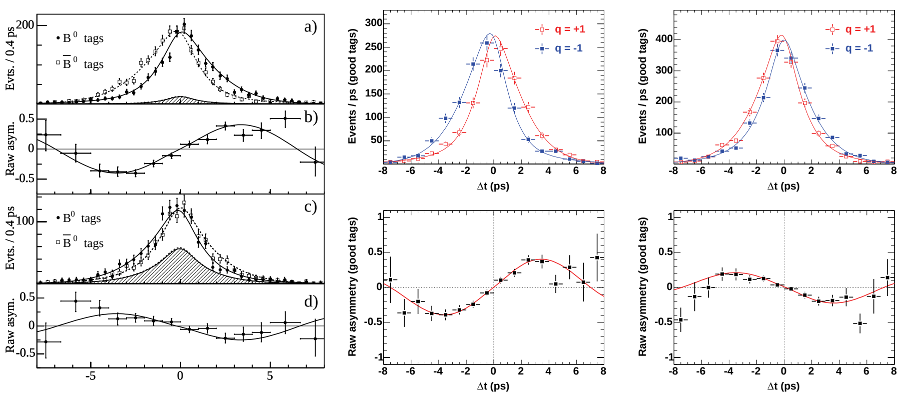

Figure 2: Distribution of the measured Δt for B^0 and $\overline{B}^0$ tagged events and related asymmetry from *BABAR* [4)]: *CP*-odd states (top left), $B^0 \to J/\psi K^0_L$ (bottom left); and from Belle [5)]: $B^0 \to J/\psi K^0_S$ (center); $B^0 \to J/\psi K^0_L$ (right). The projected probability density functions are also shown. The *BABAR* plots use all tagging categories, and also show the estimated background contribution. The Belle plots refer to good-quality tags only.

BABAR [4)] is sin2$\beta = 0.722 \pm 0.040 \pm 0.023$[3] with the systematic uncertainty dominated by the fraction and *CP* asymmetry of the background. Belle [5)] measures (only using the $B^0 \to J/\psi K^0$ modes) $\sin 2\phi_1 = 0.685 \pm 0.039 \pm 0.020$. The systematic error is dominated in this case by uncertainties on vertex reconstruction. The World Average from the Heavy Flavor Averaging Group

[3] Here and in the rest of the paper the first quoted uncertainty is statistical and the second is systematic. They are combined if only one error is given.

(HFAG) [6] is $\sin 2\beta_{WA} = 0.687 \pm 0.032$, as precise as the indirect determination from the sides of the Unitarity Triangle (UT) in the $\bar{\rho} - \bar{\eta}$ plane: $\sin 2\beta_{sides} = 0.793 \pm 0.033$ [7]. The current level of agreement among all UT measurements

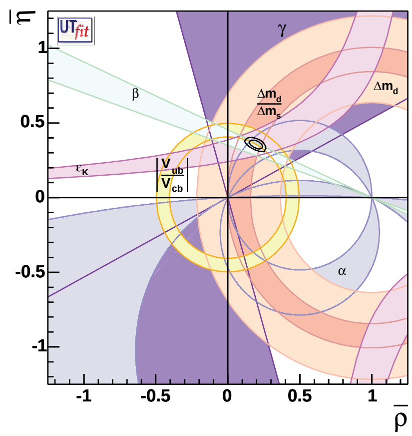

Figure 3: Constraints in the $\bar{\rho} - \bar{\eta}$ plane from measurements on B and K mesons [7].

is shown in Fig. 3. The SM prediction that *CP* violation is indeed described by the single phase in the CKM matrix, and therefore that all determinations of the apex of the UT coincide in the $\bar{\rho} - \bar{\eta}$ plane, is verified with a precision now better than 5%. All measurements of C are also consistent with the SM prediction of no direct *CP* violation in these modes.

3.2 Resolving the four-fold ambiguity in β

The measurement of $\sin 2\beta$ has an intrinsic four-fold ambiguity on the angle β. Two of the possible solutions can be eliminated measuring the sign of $\cos 2\beta$. *BABAR* has published a combined time-dependent and transversity analysis where a term proportional to $\cos 2\beta$ appears in the interference between *CP*-even and *CP*-odd amplitudes in $B^0 \rightarrow J/\psi K^{*0}(\pi^0 K^0_S)$ decays. The results of this analysis, obtained on a sample of approximately 88 million $B\overline{B}$ events [8], favor $\cos 2\beta > 0$ at 86% Confidence Level (CL). A similar measurement published by Belle [9] on 253 million $B\overline{B}$ is consistent with $\cos 2\beta = 0$. Bondar *et al.* [10] suggested to measure $\cos 2\beta$ using the interference between $b \rightarrow c$ and $b \rightarrow u$ amplitudes in $B^0 \rightarrow D^0(K^0_S\pi^+\pi^-)h^0$ decays, where h^0 is a light neutral unflavored meson. Sensitivity to $\cos 2\beta$ requires fitting the time-dependent distribution across the Dalitz plane of the D^0 ($\overline{D}^0$) decay. Belle has recently published this analysis [11], finding $\cos 2\beta = 1.87^{+0.40+0.22}_{-0.53-0.32}$, which rules out the solution $\beta = 67°$ at 98.3% CL.

3.3 $b \to c\bar{c}d$ decays

This class of decays includes both $B^0 \to D^{(*)+}D^{(*)-}$, dominated by the tree amplitude of Fig.1b, and $B^0 \to J/\psi\pi^0$, whose expected main contribution is a color-suppressed internal spectator tree diagram. In either case the phase of the involved CKM matrix elements is the same as in charmonium decays, and the SM would predict $C = 0$ and $S = \sin 2\beta$ in the absence of penguin-mediated contributions. Testing the validity of the SM predictions in the widest possible range of final states is part of the B factory mission.

BABAR [12] has recently published updated measurements of the $B^0 \to J/\psi\pi^0$ branching fraction and *CP* parameters: $\mathcal{B}(B^0 \to J/\psi\pi^0) = (1.94 \pm 0.22 \pm 0.17) \times 10^{-5}$, $S = -0.68 \pm 0.30 \pm 0.04$, $C = -0.21 \pm 0.26 \pm 0.09$, which have been used to contrain in a model-independent way the size of penguin-mediated long distance effect in $B^0 \to J/\psi K^0_S$ [13]. *BABAR* has also updated the *CP* asymmetry measurements in $B^0 \to D^{*\pm}D^{\mp}$ decays, and measured for the first time the asymmetry in D^+D^- [14]. The $B^0 \to D^{*+}D^{*-}$ decay is a Vector-Vector (VV) final state, which analogously to $J/\psi K^{*0}$ can have $L = 0, 1, 2$ angular momentum and therefore both even and odd *CP* components. *BABAR* [15] has updated the measurement of the *CP*-odd fraction $f_{odd} = 0.125 \pm 0.044 \pm 0.070$, and that of $S = -0.75 \pm 0.25 \pm 0.03$, $C = +0.06 \pm 0.17 \pm 0.03$. All results are consistent so far with the SM expectation of tree dominance [16], which however could receive sizeable corrections in some models [17]. It is therefore important to keep reducing the experimental uncertainties.

3.4 New Physics search in penguin-dominated $b \to q\bar{q}s$ decays

The quark transition $b \to s$ is forbidden in the SM at the tree level, and proceeds dominantly through penguin diagrams with CKM coefficients proportional to $V_{cb}V^*_{cs}$ and therefore with the same weak phase as in $B^0 \to J/\psi K^0_S$ decays. Since the tree amplitude is missing, small effects such as those expected from additional diagrams due to heavy particles circulating in the loop are in principle more easily detectable. For this reason these decays are especially sensitive probes of New Physics (NP). Before concluding that a deviation from the simple pattern $S = \sin 2\beta$, $C = 0$ is due to NP, contributions due to diagrams present in the SM must be properly accounted for. Bounds derived from simmetry considerations, such SU(3), are more general but usually weaker than calculations made for specific models. Among the many recent calculations we cite those in the framework of QCD factorization for 2-body decays [18] and

3-body decays [19]. Modes where the calculated corrections $\Delta\sin2\beta$ and the related uncertainties are smaller include $B^0 \to \phi K^0, \eta' K^0$, and $K^0_S K^0_S K^0_S$.

In addition to the above theoretical difficulties, the decays dominated by $b \to s$ penguin diagrams are also experimentally challenging. The branching fractions are considerably lower, and the signature less clean than for B decays into charmonium, so that light-quark production from e^+e^- continuum constitutes an important background. Event-shape topological variables exploiting the spherical shape of $B\overline{B}$ decays are used to suppress such background sources. Some channels finally, such as $B^0 \to \pi^0 K^0_S$, do not even have charged tracks emerging from the B^0 decay vertex. A new technique was developed by *BaBar* to reconstruct the decay vertex by extrapolating back the K^0_S reconstructed momentum constraining it to intersect the beam profile in the $x-y$ plane.

Belle has presented in 2005 updated measurements [5] in the channels $B^0 \to \phi K^0, \eta' K^0, f_0 K^0_S, \omega K^0_S, K^+K^-K^0_S$. The Δt and time-asymmetry distributions for $B^0 \to \phi K^0$ and $\eta' K^0$ which are among the cleanest and most abundant modes are shown in Fig. 4.

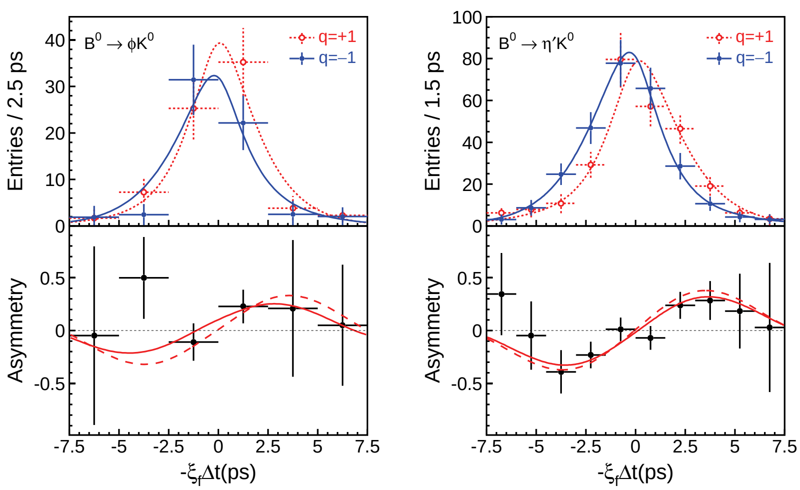

Figure 4: Distribution of the measured Δt for B^0 and $\overline{B}^0$ tagged events and related asymmetry from Belle [5], for good-quality tags. Left: $B^0 \to \phi K^0$; right: $B^0 \to \eta' K^0$. The result of the unbinned maximum-likelihood fit is also shown. The dashed curves in the bottom figure show the SM expectation from Belle's measurement of *CP*-violation parameters for the $B^0 \to J/\psi K^0$ mode ($\sin2\beta = 0.652$).

BABAR has mainly focused on increasing the statistical power of its data by exploring new submodes. Examples include using K^0_L mesons *e.g.* in ϕK^0 and $\eta' K^0$, $K^+K^-K^0_L$, and $K^0_S K^0_S K^0_S(\pi^0\pi^0)$. The energy of K^0_L candidates is not measured in the B-factory detectors, and is inferred from the direction making use of the B-mass constraint. *BABAR* [20] finds 777 ± 80 $K^+K^-K^0_L$ candidates in its sample of 230 milliom $B\overline{B}$ pairs, with $S = 0.07 \pm 0.28 \pm 0.12$ and $C = 0.54 \pm 0.22 \pm 0.09$. Since $K^+K^-K^0$ is not a *CP* eigenstate, its *CP* content must be determined independently. This is done by an angular momentum analysis of the clean $K^+K^-K^0_S$. The result $f_{CPeven} = 0.89 \pm 0.08 \pm 0.06$ is consistent with Belle's isospin analysis [21]. Using this *CP* dilution, the value $\sin 2\beta_{K^+K^-K^0} = 0.41 \pm 0.18 \pm 0.07 \pm 0.11$, where the last error is due to the uncertainty on the *CP* content. In spite of having the largest branching fraction among all $b \to s$ modes, $K^+K^-K^0$ has also a fairly large theoretical uncertainty. The situation is somewhat reversed for $B^0 \to K^0_S K^0_S K^0_S$ which, although being a 3-particle state, is a pure *CP* eigenstate. This state has an estimated $\Delta \sin 2\beta < 0.05$, but has a branching fraction of only $\sim 3.1 \times 10^{-6}$. Using also events where one of the K^0_S is reconstructed in the $(\pi^0\pi^0)$ mode, *BABAR* measures [22] $S_{3K^0_S} = +0.58^{+0.28}_{-0.32} \pm 0.04$; Belle measures [5] $S_{3K^0_S} = +0.63 \pm 0.36 \pm 0.08$.

The $B^0 \to \eta'\pi^0$ and $\eta\pi^0$ decays are dominated by the 'flavor-singlet' diagram, the $\eta\eta'$ mode by the color-suppressed diagram. More precise branching fraction measurements can reduce the theoretical uncertainty of the color-suppressed tree amplitude for $\eta' K^0$ decays in SU(3)-based calculations [23]. *BABAR* [24] has not found signals for any of these modes in its dataset of 230 million $B\overline{B}$ pairs, and set 90% CL upper limits on the branching fractions of $\eta'\eta$ ($< 1.7 \times 10^{-6}$), $\eta\pi^0$ ($< 1.3 \times 10^{-6}$), and $\eta'\pi^0$ ($< 2.1 \times 10^{-6}$), while Belle in their larger dataset [25] find $\mathcal{B}(B^0 \to \eta'\pi^0) = (2.79\ ^{+1.02}_{-0.96}\ ^{+0.35}_{-0.34}) \times 10^{-6}$.

The HFAG compilation of the effective $\sin 2\beta$ measurements in $b \to s$ is shown in the left plot of Fig. 5. A very good agreement between the two experiments is observed. Note that despite the smaller *BABAR* dataset, also the errors are comparable. The different channels are consistent among each other, and almost all are within about one standard deviation from the reference charmonium measurement. The discrepancy between the $b \to s$ and $b \to c\bar{c}s$ modes, which has aroused a lot of interest in the past years, has become smaller, but persists. The C measurements (right plot of Fig. 5) are consistent with no direct *CP* violation in any of these channels. Reducing the experimental errors with new data and the inclusion of new decay modes with smaller branching fractions will eventually help elucidating if the timid hints of New Physics are real.

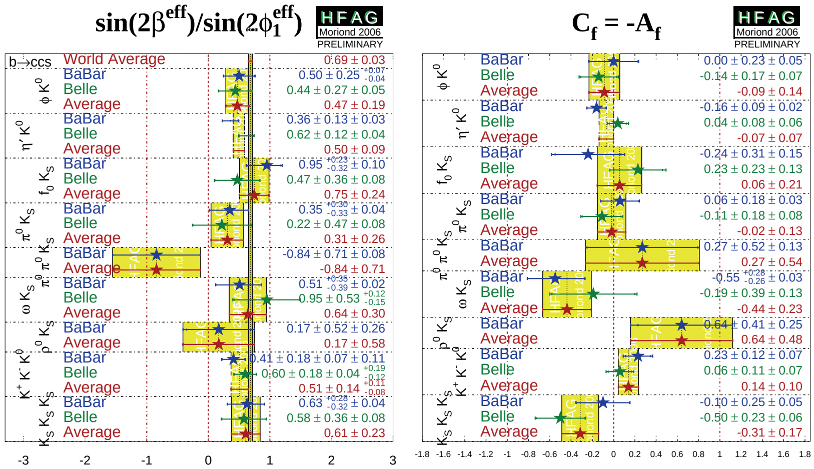

Figure 5: Left: summary of effective $\sin 2\beta$ measurements in penguin-dominated $b \to s$ decay modes; right: summary of C measurements. The reference $b \to c\bar{c}s$ measurements are shown for comparison.

4 Measurements of α

The tree amplitude in charmless $b \to u$ decays is proportional to the CKM element V_{ub}, with phase γ, and can interfere with $B^0\overline{B}^0$ mixing (which introduces a phase β). The time-dependent $B^0 \to h^+h^-$ decays, where $h^\pm = \pi^\pm$ or $\rho^\pm$, are therefore sensitive to $\beta + \gamma$, or $\alpha = \pi - (\beta + \gamma)$ if the Unitary Triangle is closed in the $\bar{\rho} - \bar{\eta}$ plane as predicted by the SM.

The $B^0 \to h^+h^-$ decays can in principle receive contributions from both tree (T) and penguin (P) diagrams, and this complicates the interpretation of the measured parameters: unlike in charmonium decays, in general $C_{hh} \neq 0$ and $S_{hh} \neq \sin 2\alpha$, and one actually measures $S_{hh} = \sqrt{1 - C_{hh}^2}\,\sin(2\alpha_{eff})$, where α_{eff} is related to α by the unknown ratio of penguin and tree contributions:

$$\lambda_{hh} = \frac{q}{p}\frac{\bar{A}}{A} = -e^{2i\alpha}\frac{1 - P/T\; e^{-i\alpha}}{1 - P/T\; e^{i\alpha}} \equiv |\lambda_{hh}| e^{2i\alpha_{eff}}. \quad (4)$$

As shown in [26], one can in principle determine the shift $\Delta\alpha = \alpha - \alpha_{eff}$ induced by the penguin amplitudes using the isospin-related decays $B^0 \to \pi^+\pi^-$, $B^0 \to \pi^0\pi^0$ and $B^\pm \to \pi^0\pi^\pm$. This requires measuring six branching fractions from *tagged* samples, and still leaves with an eight-fold ambiguity which requires very large data samples to be resolved. A relation less stringent, but more accessible with the current data sample since it does not require to tag the flavor of the decaying B also holds [27]: $\sin^2(\alpha_{eff}) \leq \mathcal{B}(B^0 \to \pi^0\pi^0)/\mathcal{B}(B^\pm \to \pi^0\pi^\pm)$, which is particularly useful for small values of the numerator.

4.1 α from $B \to \pi\pi$

The agreement between the *BABAR* and Belle measurements was poor in the past years, when Belle observed large direct *CP* violation. The discrepancy has somewhat reduced as of late (see Tab. 1).

Table 1: *CP asymmetries and branching fractions for* $B \to \pi\pi$ [6].

	BABAR	Belle	HFAG ave.
$S_{\pi\pi}$	$-0.30 \pm 0.17 \pm 0.03$	$-0.67 \pm 0.16 \pm 0.06$	-0.50 ± 0.12
$C_{\pi\pi}$	$-0.09 \pm 0.15 \pm 0.04$	$-0.56 \pm 0.12 \pm 0.06$	-0.37 ± 0.10
$\mathcal{B}(\pi^+\pi^-) \times 10^6$	$1.17 \pm 0.32 \pm 0.10$	$2.3^{+0.4}_{-0.5}{}^{+0.2}_{-0.3}$	1.45 ± 0.29
$\mathcal{B}(\pi^0\pi^0) \times 10^6$	$1.17 \pm 0.32 \pm 0.10$	$2.3^{+0.4}_{-0.5}{}^{+0.2}_{-0.3}$	1.45 ± 0.29
$\mathcal{B}(\pi^0\pi^\pm) \times 10^6$	$5.8 \pm 0.6 \pm 0.4$	$5.0 \pm 1.2 \pm 0.5$	5.5 ± 0.6

The ratio $\mathcal{B}(\pi^0\pi^0)/\mathcal{B}(\pi^0\pi^+)$ is unfortunately found to be large, indicating a non negligible penguin contribution. The constraints on α derived from the time-dependent and isospin analysis in the $\pi\pi$ system are shown in the left plot of Fig. 6.

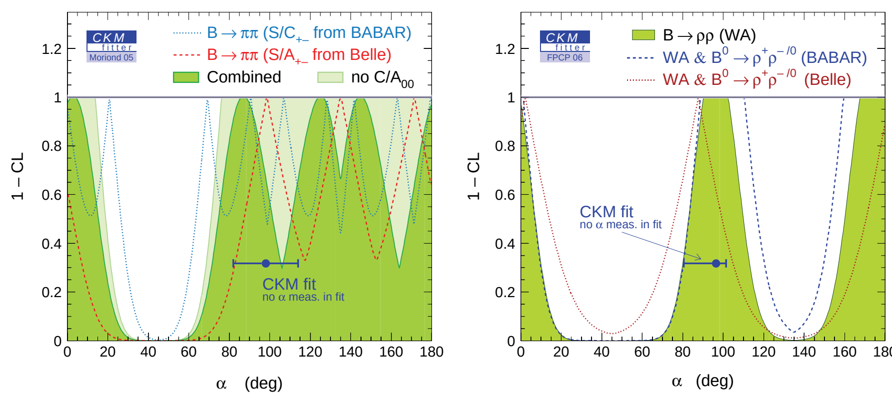

Figure 6: Confidence level for the UT angle α obtained from the isospin analysis. Left: constraints from $B \to \pi\pi$; right: constraints from $B \to \rho\rho$.

4.2 α from $B \to \rho\rho$

The decay channel $B^0 \to \rho^+\rho^-$ has the same quark content as $\pi^+\pi^-$ and can also be used to measure α. There are non-trivial experimental complications due to the presence of two neutral pions in the final state, with just weak mass constraints from the wide intermediate resonances. Moreover, $\rho^+\rho^-$ is a VV state and necessitates in principle a complete angular analysis to disentangle the effect of the three possible helicity states. On the other hand, the branching fraction is about six times larger than $\mathcal{B}(B^0 \to \pi^+\pi^-)$, and the state is found to be almost purely longitudinally polarized, so that a per-event transversity analysis can be avoided and only the longitudinal *CP* parameters need to be determined. The relevant measurements in the $\rho\rho$ decays are summarised in Tab. 2.

Table 2: *CP asymmetries, branching fractions and longitudinal polarization fraction for* $B \to \rho\rho$ [6].

	BaBar	Belle	HFAG ave.
$S_{\rho\rho}$	$-0.33 \pm 0.24^{+0.08}_{-0.14}$	$+0.08 \pm 0.41 \pm 0.09$	-0.21 ± 0.22
$C_{\rho\rho}$	$-0.03 \pm 0.18 \pm 0.09$	$0.00 \pm 0.30 \pm 0.09$	-0.03 ± 0.17
$\mathcal{B}(\rho^0\rho^0) \times 10^6$	< 1.1 at 90 %CL		< 1.1 at 90 %CL
$\mathcal{B}(\rho^+\rho^0) \times 10^6$	$17.2 \pm 2.5 \pm 2.8$	$31.7 \pm 7.1^{+3.8}_{-6.7}$	19.1 ± 3.5
$\mathcal{B}(\rho^+\rho^-) \times 10^6$	$30 \pm 4 \pm 5$	$22.8 \pm 3.8^{+2.3}_{-2.6}$	$25.2^{+3.6}_{-3.7}$
f_L	$0.978 \pm 0.014^{+0.021}_{-0.029}$	$0.941^{+0.034}_{-0.040} \pm 0.030$	

The constraints on α derived from the time-dependent and isospin analysis in the $\rho\rho$ system are shown in the right plot of Fig. 6. These constraints are observed to be considerably more precise than for $\pi\pi$, mainly due to the low value of $\mathcal{B}(B^0 \to \rho^0\rho^0)$.

4.3 α from $B \to \rho\pi$

The third mode used to measure the angle α is $B^0 \to \pi^+\pi^-\pi^0$. This is not a *CP* eigenstate, and four flavor-charge configurations $(B^0(\overline{B}^0) \to \rho^\pm\pi^\mp)$ must be considered. The corresponding isospin analysis is extremely complicated involving pentagonal relations among the different amplitudes, and cannot be solved for the 12 unknowns with the present statistics. It was however pointed out [28] that the variation of the strong phase of the interfering ρ resonances in the Dalitz plot provides the necessary degrees of freedom to constrain α with only the irreducible $(\alpha \to \alpha + \pi)$ ambiguity. BaBar [29] has performed this analysis, including the interfering $\rho^+\pi^-$, $\rho^-\pi^+$ and $\rho^0\pi^0$ amplitudes. The result of the combined time-dependent and Dalitz plot analysis is $\alpha = (113^{+27}_{-17} \pm 6)^\circ$.

4.4 Combining the α measurements

The $\pi\pi$, $\rho\rho$ and $\rho\pi$ modes give consistent and complementary measurements of the angle α. As discussed previously, the most precise constraint is given by the $\rho\rho$ mode. The bound given by $\rho\pi$ is less precise, but helps disfavoring the mirror solution near 170°. The interpretation of the experimental results depends to a certain extent on the method, and on the underlying assumptions used. The combined constraint from the CKMfitter collaboration [30], which uses a frequentistic approach, is shown on the left plot of Fig. 7. The right plot of the same figure shows the results, based on Bayesian statistics, obtained by the UTFit collaboration [7]. The latter fit prefers the "non-SM" solution for

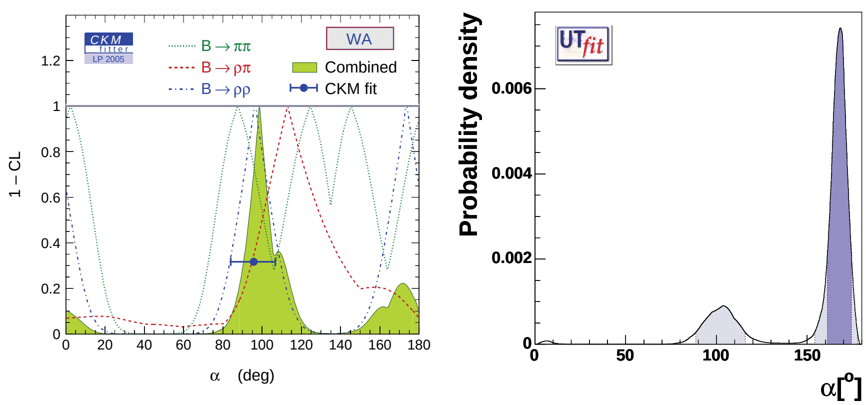

Figure 7: Confidence level for the UT angle α obtained from the combined analysis of $B \to \pi\pi, \rho\rho$ and $\rho\pi$ decays. Left: plot obtained by the CKMfitter collaboration; right: plot obtained by the UTFit collaboration.

α. The SM solution is however similar in the two approaches: $\alpha_{CKMfitter} = (99^{+12}_{-9})^\circ$, $\alpha_{UTFit} = (102 \pm 9)^\circ$, and in very good agreement with the indirect determination $\alpha_{ind} = (95^{+10}_{-13})^\circ$.

5 Summary and outlook

The B factories have established that CP violation is violated in B decays, and measured sin2β in charmonium decays with 5% precision. The experimental measurement is consistent with the indirect determination derived from all other measurements in the B and K systems, which is an important confirmation of the validity of the Standard Model. The paradigm has now shifted to searching for deviations among different sin2β measurements. Penguin-dominated $b \to s$ modes are particularly promising because they are expecially sensitive to heavy virtual states. All sin2β measurements are limited by statistical uncertainties, and will therefore become more precise with increased datasets. Theoretical calculations are often fed by experimental measurements, and will also improve with more data.

The precision of the UT angle α depends crucially on the still unmeasured branching fraction of the decay $B^0 \to \rho^0\rho^0$, which is needed to bound the effect of penguin amplitudes.

BABAR and Belle plan to accumulate by the end of 2008 data samples four times bigger than those used in the analyses discussed in the present report, and are therefore expected to deliver many more important results.

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