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CP violation in the B meson system: recent experimental results

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ABSTRACT: Recent experimental results on CP violation in the study of B meson decays are reviewed. The emphasis is put on the recent measurements of the CP parameter $\sin 2\beta$ by the *BABAR* and BELLE experiments at asymmetric B factories, which establish for the first time CP violation in the B meson system.

1. Introduction

CP violation has been extensively studied in the K^0 system since the discovery of the phenomenon in K_L^0 decays thirty seven years ago [1], while the last fifteen years have been rich in experimental and theoretical developments in Heavy Flavor physics [2]. The consistency of the experimental results with the general scheme of charged weak interactions and CP violation in the Standard Model of particle physics is highly non-trivial. Now is the time to challenge the model experimentally in its prediction of large CP violation effects in the B meson system. This paper gives an overview of the present experimental knowledge on the subject. We start with a status report on the new generation of B factory experiments, followed by an introduction to the $B^0\overline{B}^0$ system and the CKM matrix, and an overview of present experimental constraints on the Unitarity Triangle from CP-violating K and CP-conserving B observations. We then review in turn searches for CP violation in the B system: direct CP violation, CP violation in $B^0\overline{B}^0$ mixing and, finally, CP violation in the interference between mixing and decay, with an emphasis on the recent $\sin 2\beta$ measurements by *BABAR* and BELLE. We conclude the review by an overview of experimental prospects in the domain.

2. Status of B factory experiments

The three e^+e^- B factories in activity are CESR at Cornell, PEP-II at SLAC and KEK-B at KEK at which B meson pairs are produced in e^+e^- annihilations in the $\Upsilon(4S)$ resonance energy region at $\sqrt{s} \approx 10.58 \, \text{GeV}$.

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The new-generation machines, PEP-II and KEK-B, are energy-asymmetric: the electron and positron beams are stored at different energies in two separate storage rings so that the proper time difference between the two B meson decays can be deduced from the measurable distance between the two decay vertices along the boost axis. Both machines have started operation in late Spring 1999 and have improved steadily their performances. At the time of the Conference in July 2001, the two machines had already demonstrated very high instantaneous luminosities with tolerable backgrounds for the detectors: $4.5 \times 10^{33} \, \text{cm}^{-2}\text{s}^{-1}$ for KEK-B (for a design luminosity of 10^{34}) and 3.5×10^{33} for PEP-II (already beyond the design luminosity of 3×10^{33}). The data samples recorded by the *BABAR* and BELLE experiments were of comparable size: about $30 \, \text{fb}^{-1}$ at the $\Upsilon(4S)$ resonance (corresponding to about 32 million $B\overline{B}$ pairs).

3. The $B^0 \overline{B}^0$ system

The light B_L and heavy B_H mass eigenstates of the neutral B_d meson system (made of b and d quarks) are given by [1]:

$$|B_L\rangle = p\,|B^0\rangle + q\,|\overline{B}^0\rangle, \quad |B_H\rangle = p\,|B^0\rangle - q\,|\overline{B}^0\rangle. \tag{3.1}$$

where B^0 and $\overline{B}^0$ are the flavor eigenstates of the system, related through CP transformation according to: $CP\,|B^0\rangle = e^{2i\xi_B}\,|\overline{B}^0\rangle$ (the phase ξ_B is arbitrary, due to b-flavor conservation by strong interactions). The complex coefficients p and q are normalized ($|p|^2 + |q|^2 = 1$). The phase of q/p, which also depends on phase conventions, is not an observable; only the modulus of this quantity, $|p/q|$, has a physical significance.

The mass difference Δm_{B_d} and width difference $\Delta\Gamma_{B_d}$ between the two mass eigenstates are defined as:

$$\Delta m_{B_d} \equiv m_{B_H} - m_{B_L}, \quad \Delta\Gamma_{B_d} \equiv \Gamma_{B_H} - \Gamma_{B_L}. \tag{3.2}$$

Based on model-independent considerations, the two mesons are expected to have a negligible difference in lifetime, $\Delta\Gamma_{B_d}/\Gamma_{B_d} \sim 10^{-2}$[3]. In particular, $\Delta\Gamma_{B_d}/\Gamma_{B_d} \ll x_d$ where $x_d \equiv \Delta m_{B_d}/\Gamma_{B_d} = 0.73 \pm 0.05$. Neglecting $\Delta\Gamma_{B_d}$ versus Δm_{B_d} the time evolution of a state prepared initially (*i.e.* at time $t = 0$) in a pure B^0 or $\overline{B}^0$ state, respectively, can be written as follows:

$$|B^0_{\text{phys}}(t)\rangle = e^{-i\,mt}\,e^{-\Gamma\,t/2}\{\,\cos(\Delta m_{B_d}\,t/2)\,|B^0\rangle + i\,(q/p)\,\sin(\Delta m_{B_d}\,t/2)\,|\overline{B}^0\rangle\,\}$$
$$|\overline{B}^0_{\text{phys}}(t)\rangle = e^{-i\,mt}\,e^{-\Gamma\,t/2}\{\,\cos(\Delta m_{B_d}\,t/2)\,|\overline{B}^0\rangle + i\,(p/q)\,\sin(\Delta m_{B_d}\,t/2)\,|B^0\rangle\,\} \tag{3.3}$$

where $m = \frac{1}{2}(m_{B_H} + m_{B_L})$ and $\Gamma = \frac{1}{2}(\Gamma_{B_H} + \Gamma_{B_L})$.

4. CP violation in the Standard Model

In the Standard Model of strong and electro-weak interactions, CP violation arises from the presence of a single irremovable phase in the unitary complex mixing matrix for the

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[1]CPT invariance is assumed throughout this paper

three quark generations [4][5]. This phase is called the Kobayashi-Maskawa phase, and the matrix, the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix.

The unitarity of the CKM matrix can be expressed in geometric form as six triangles of equal areas in the complex plane. A non-zero area directly implies the existence of a *CP*-violating phase [6]. One of the six triangles, the Unitarity Triangle, represents the most experimentally accessible of the unitarity relations, which involves the two smallest elements of the CKM matrix, V_{ub} and V_{td}. V_{ub} is involved in $b \to u$ transitions such as in B meson decays to charmless final states, and V_{td} appears in $b \to d$ transitions that can proceed via diagrams involving virtual top quarks, examples of which are the box diagrams describing the $B^0 \overline{B}^0$ mixing. Because the lengths of the sides of the Unitarity Triangle are of the same order, the angles can be large, leading to potentially large *CP*-violating asymmetries from phases between CKM matrix elements.

The CKM matrix can be described by four real parameters. Using the sine of the Cabibbo angle λ as an expansion parameter, the Wolfenstein parameterization is given by [7]:

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\,\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\,\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4) \quad , \quad (4.1)$$

where A, $\bar{\rho} = \rho(1 - \lambda^2/2)$ and $\bar{\eta} = \eta(1 - \lambda^2/2)$ are the remaining three parameters. It should be noted that, in this parameterization, the usual (but arbitrary) phase convention under which all the CKM matrix elements are real except V_{ub} and V_{td} is implicitly made.

5. Experimental situation before the B factories

The sine of the Cabibbo angle λ is known at the percent level ($\lambda \simeq 0.2230$). The parameter A, determined mostly from measurements of semileptonic decays of strange and beauty particles, is known at the 5% level ($A \simeq 0.830$). The coordinates of the apex of the Unitarity Triangle, $\bar{\rho}$ and $\bar{\eta}$, are constrained by $|\varepsilon_K|$, $|V_{ub}/V_{cb}|$, Δm_{B_d} measurements, and by the limit on $\Delta m_{B_d}/\Delta m_{B_s}$. These constraints depend on additional measurements and theoretical inputs. Many critical studies of the CKM constraints are available in the recent literature (see for instance Ref. [8]-[13]); they differ in the way theoretical uncertainties and experimental systematic errors are handled, and in the statistical treatment in the combination of the available information. The conclusions of the various analyses are quite consistent however [1]. Reference [8] for instance gives 95% confidence intervals $\bar{\rho} \in [0.04, 0.38]$ and $\bar{\eta} \in [0.21, 0.49]$. The allowed range for $\bar{\eta}$ is an experimental indication that the CKM matrix indeed contains a non-zero phase.

The side of the Unitarity Triangle that is proportional to $V_{td}V_{tb}^*$ forms an angle β with the side proportional to $V_{cd}V_{cb}^*$ and an angle α with the side proportional to $V_{ud}V_{ub}^*$. Experimental sensitivity to the angles β and α can therefore arise from interferences between the $B^0\overline{B}^0$ mixing amplitude (which involves V_{td}) and decay amplitudes that involve V_{cb} and V_{ub} respectively. The third angle, γ, is the argument of V_{ub}^* in the usual phase convention. The experimental programme for testing the CKM model with three generations of leptons, in

particular its description of *CP* violation in the charged weak current sector, involves as many measurements of the sides, angles and other quantities constraining the position of the apex of the Unitarity Triangle, and checking that the results are indeed consistent. The *CP*-violating observable $\sin 2\beta$ is already constrained by the allowed region in $(\bar{\rho}, \bar{\eta})$ from *CP*-conserving measurements: $\sin 2\beta \in [0.47, 0.89]$ at the 95% confidence level [8].

6. *CP* violation in the decay

CP violation in the decay (also referred to as direct *CP* violation) is due to interference among decay amplitudes which differ in both weak and strong phases. Direct *CP* violation is now firmly established in K_L^0 decays: the amount of direct *CP* violation recently reported by NA48 and KTeV is consistent with predictions based on the Standard Model within large theoretical uncertainties [1].

For B decays, one builds time-independent *CP* asymmetry observables:

$$\mathcal{A}_{CP} \equiv \frac{\Gamma(\overline{B} \to \overline{f}) - \Gamma(B \to f)}{\Gamma(\overline{B} \to \overline{f}) + \Gamma(B \to f)} = \frac{1 - |\overline{A}_{\overline{f}}/A_f|^2}{1 + |\overline{A}_{\overline{f}}/A_f|^2} . \tag{6.1}$$

Direct *CP* violation is the only type of *CP* violation for charged modes, while for neutral modes it competes with the other two types of *CP* violation. Sizable direct *CP* violation effects ($|\overline{A}_{\overline{f}}/A_f| \neq 1$) require the contribution to the decay of at least two amplitudes of comparable size with of course different weak phases, but also a non-zero relative strong phase (the latter is in general difficult to estimate theoretically). The rule of thumb is that larger *CP* violation effects are potentially expected for very rare processes for which the dominant amplitude (*e.g.* a tree amplitude) is suppressed at the level of higher-order amplitudes (*e.g.* penguin amplitudes).

	CLEO [14]	*BABAR* [15]	BELLE [16]	World average
$B^0 \to \pi^+\pi^-$	$4.3^{+1.6}_{-1.4} \pm 0.5$	$4.1 \pm 1.0 \pm 0.7$	$5.6^{+2.3}_{-2.0} \pm 0.4$	$4.44^{+0.89}_{-0.86}$
$B^0 \to K^+\pi^-$	$17.2^{+2.5}_{-1.4} \pm 1.2$	$16.7 \pm 1.6 \pm 1.3$	$19.3^{+3.4}_{-3.2}{}^{+1.5}_{-0.6}$	$17.37^{+1.47}_{-1.30}$
$B^0 \to K^+K^-$	< 1.9	< 2.5	< 2.7	
$B^+ \to \pi^+\pi^0$	< 12.7	$5.7^{+2.0}_{-1.8} \pm 0.8$	< 13.4	
$B^+ \to K^+\pi^0$	$11.6^{+3.0}_{-2.7}{}^{+1.4}_{-1.3}$	$10.8^{+2.1}_{-1.9} \pm 1.0$	$16.3^{+3.5}_{-3.3}{}^{+1.6}_{-1.8}$	$12.13^{+1.70}_{-1.67}$
$B^+ \to K^0\pi^+$	$18.2^{+4.6}_{-4.0} \pm 1.6$	$18.2^{+3.3}_{-3.0} \pm 2.0$	$13.7^{+5.7}_{-4.8}{}^{+1.9}_{-1.8}$	$17.41^{+2.60}_{-2.51}$
$B^0 \to K^0\pi^0$	$14.6^{+5.9}_{-5.1}{}^{+2.4}_{-3.3}$	$8.2^{+3.1}_{-2.7} \pm 1.2$	$16.0^{+7.2}_{-5.6}{}^{+2.5}_{-2.7}$	$10.73^{+2.66}_{-2.66}$

Table 1: Recent measurements of branching ratios for B meson decays to charmless two-body final states containing pions or kaons, in units of 10^{-6}. In certain cases, 90% confidence limits are given.

In charmless hadronic decays for instance, the tree $b \to u$ amplitude is highly suppressed and competes with $b \to s$ or $b \to d$ penguin amplitudes: asymmetries for these modes could be as large as 10%. The various $B \to \pi\pi$ and $B \to K\pi$ modes have all been recently observed by CLEO [14] and confirmed by *BABAR* [15] and BELLE [16] (see Table 1), with branching ratios in the 10^{-6}-10^{-5} region. *CP* asymmetries in the self-tagged modes have been measured [15][17][18] consistent with zero within errors (see Table 2).

CP asymmetries have also been measured in a variety of other charmless *B* decays [19] and again no significant deviation from zero has been observed. For all these modes, the sensitivity on $\mathcal{A}_{CP}$ is at best at the 10%-15% level.

	CLEO [17]	*BABAR* [15] [52]	BELLE [18]
$B \to K^{\pm}\pi^{\mp}$	-0.04 ± 0.16	-0.19 ± 0.10	$0.04^{+0.19}_{-0.17}$
$B^{\pm} \to K^{\pm}\pi^{0}$	-0.29 ± 0.23	0.00 ± 0.18	$-0.06^{+0.22}_{-0.20}$
$B^{\pm} \to K^{0}_{s}\pi^{\pm}$	0.18 ± 0.24	-0.21 ± 0.18	$0.10^{+0.43}_{-0.34}$

Table 2: Recent measurements of charge *CP* asymmetries in self-tagged $B \to K\pi$ decay modes.

Is is interesting to look for asymmetries where none is expected. Examples are the loop-induced $b \to s\gamma$ modes, for which $\mathcal{A}_{CP}$ is strongly suppressed within the Standard Model. Combining two statistically independent measurements, one based on the pseudo-reconstruction of the X_s system, the other on tagging the flavor of the other *B* with leptons, CLEO measures [20]: $\mathcal{A}_{CP}(b \to s\gamma) = -0.079 \pm 0.108 \pm 0.022$. *CP* asymmetries have also been measured the exclusive $B^{\pm} \to K^{*\pm}\gamma$ mode by CLEO and *BABAR* [21]: $\mathcal{A}_{CP}(B^{\pm} \to K^{*\pm}\gamma) = +0.08 \pm 0.13 \pm 0.03$ and $-0.035 \pm 0.076 \pm 0.012$, respectively. In both inclusive and exclusive $b \to s\gamma$ analyses, much higher statistics are needed to challenge the SM on the prediction of very small *CP* asymmetries. Similarly, an order of magnitude more data would be needed to test the prediction of a strong $\mathcal{A}_{CP}$ suppression in pure penguin $b \to s\bar{s}s$ decays, such as the recently observed $B \to \phi K$ modes [22][23][24].

The copious $b \to c\bar{c}s$ decays are in general dominated by the tree amplitude. In modes such as $B^{\pm} \to J/\psi K^{\pm}$, the tree amplitude is colored-suppressed but the dominant penguin contribution has nearly the same weak phase and direct *CP* violation further suppressed. This is experimentally confirmed at the 4% level by CLEO [25]: $\mathcal{A}_{CP}(B^{\pm} \to J/\psi K^{\pm}) = (+1.8 \pm 4.3 \pm 0.4)\%$ and at the 3% level by *BABAR* [21]: $\mathcal{A}_{CP}(B^{\pm} \to J/\psi K^{\pm}) = (-0.9 \pm 2.7 \pm 0.5)\%$.

7. *CP* violation in mixing

CP (or *T*) violation in $B^0\overline{B}^0$ mixing (also referred to as indirect *CP* violation) manifests itself as an asymmetry in the transitions $B^0 \to \overline{B}^0$ and $\overline{B}^0 \to B^0$, as a consequence of the mass eigenstates being different from the *CP* eigenstates:

$$|q/p| \neq 1 \implies \text{Prob}(B^0_{phys}(t) \to \overline{B}^0) \neq \text{Prob}(\overline{B}^0_{phys}(t) \to B^0).$$

This effect can be studied by investigating time-dependent differences in mixing rates in decays to flavor-specific final states such as semileptonic neutral *B* decays:

$$\mathcal{A}_T(t) = \frac{\Gamma(\,|\overline{B}^0_{\text{phys}}(t)\rangle \to \ell^+\nu X\,) - \Gamma(\,|B^0_{\text{phys}}(t)\rangle \to \ell^-\nu X\,)}{\Gamma(\,|\overline{B}^0_{\text{phys}}(t)\rangle \to \ell^+\nu X\,) + \Gamma(\,|B^0_{\text{phys}}(t)\rangle \to \ell^-\nu X\,)}. \tag{7.1}$$

Starting from equations 3.3, one finds that the proper time dependence cancels out in the ratio 7.1 and the asymmetry is independent of t:

$$\mathcal{A}_T(t) = a_T \quad \text{with} \quad a_T \equiv \frac{1 - |q/p|^4}{1 + |q/p|^4}. \tag{7.2}$$

The *CP* asymmetry parameter a_T can be extracted from both time-integrated and time-dependent measurements. At LEP and the Tevatron, time-dependent asymmetries are studied using either flavor-tagged samples of semileptonic decays or fully inclusive samples of B^0 decays. In the latter case, the time-integrated rate vanishes due to *CPT* symmetry but some sensitivity to a_T exists in the time-dependence of the asymmetry, as shown in Ref. [26]. Averaging the results of their various analyses, CDF [27], OPAL [28] and ALEPH [29] obtain $a_T = 0.024 \pm 0.063 \pm 0.033$, $a_T = 0.004 \pm 0.056 \pm 0.012$ and $a_T = -0.013 \pm 0.026(\text{stat} + \text{syst})$, respectively. At the $\Upsilon(4S)$, CLEO has recently measured the integrated like-sign dilepton charge asymmetry [30]; the result is in agreement with its previous measurement of a_T via partial hadronic reconstruction. The weighted average of the two CLEO measurements gives: $a_T = 0.014 \pm 0.041 \pm 0.006$. At this Conference, *BABAR* has presented a time-dependent analysis of its like-sign dilepton sample based on $20.7\,\text{fb}^{-1}$ of data [31], obtaining: $a_T = 0.0048 \pm 0.0116 \pm 0.0144$. This preliminary result demonstrates that asymmetric B factory experiments are already close to sensitivities needed to test theoretical predictions on indirect *CP* violation ($a_T \leq 10^{-2}$), and that systematic uncertainties can be controlled at the required level.

To conclude, no significant indirect *CP* violation effect in the neutral B meson system has been seen to date. This experimental constraint allows us to express, to a very good approximation, the ratio q/p in term of a pure phase ϕ_M: $q/p = e^{2i\phi_M} e^{2i\xi_B}$ (ξ_B is maintained to express the arbitrariness of the phase convention). The phase ϕ_M results from CKM factors involved in the box diagrams that describe the dispersive part of the $B^0 \to \overline{B}^0$ amplitude. In the Standard Model, to a very good approximation:

$$\frac{q}{p} = \frac{V_{td}V_{tb}^*}{V_{td}^*V_{tb}} e^{2i\xi_B} \tag{7.3}$$

and therefore $\phi_M = \arg(V_{td}V_{tb}^*) = \pi - \beta + \arg(V_{cd}V_{cb}^*)$, which, in the usual phase convention, reduces to $\phi_M = -\beta$. New Physics can possibly manifest itself as a phase shift with respect to the Standard Model expectation for ϕ_M.

8. *CP* violation in interference between decay with/without mixing

In order to calculate the time-dependent decay rates to a specific final state f accessible to both B^0 and $\overline{B}^0$ decays, one introduces the phase-independent complex parameter λ_f:

$$\lambda_f \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f}, \tag{8.1}$$

where $A_f \equiv \langle f|H|B^0 \rangle$ and $\overline{A}_f \equiv \langle f|H|\overline{B}^0 \rangle$. Particularly interesting is the situation where $|A_f|^2 \approx |\overline{A}_f|^2$. This condition is fulfilled in the case that we consider now, where the final state f is a *CP* eigenstate, f_{CP}. Using equations 3.3, one obtains

$$\rho_\pm(t) = \left\{\frac{1}{2}\left(1 + |\lambda_{f_{CP}}|^2\right) \pm \frac{1}{2}\left(1 - |\lambda_{f_{CP}}|^2\right)\cos\left(\Delta m_{B_d}t\right) \mp \text{Im}(\lambda_{f_{CP}})\sin\left(\Delta m_{B_d}t\right)\right\} e^{-\Gamma t},$$
$$\tag{8.2}$$

with $\rho_+(t) \equiv |\langle f_{CP}|H|B^0_{\text{phys}}(t)\rangle|^2 / |A_{f_{CP}}|^2$ and $\rho_-(t) \equiv |\langle f_{CP}|H|\overline{B}^0_{\text{phys}}(t)\rangle|^2 / |\overline{A}_{f_{CP}}|^2$. One finds that the conditions for no *CP* violation at any time t are $|\lambda_{f_{CP}}| = 1$ and $\text{Im}\,\lambda_{f_{CP}} = 0$:

$$\lambda_{f_{CP}} \neq \pm 1 \implies \text{Prob}(B^0_{phys}(t) \to f_{CP}) \neq \text{Prob}(\overline{B}^0_{phys}(t) \to f_{CP}). \tag{8.3}$$

The time-dependent *CP* asymmetry:

$$\mathcal{A}_{f_{CP}}(t) \equiv \frac{\Gamma(\,|\overline{B}^0_{\text{phys}}(t)\rangle \to f_{CP}) - \Gamma(\,|B^0_{\text{phys}}(t)\rangle \to f_{CP})}{\Gamma(\,|\overline{B}^0_{\text{phys}}(t)\rangle \to f_{CP}) + \Gamma(\,|B^0_{\text{phys}}(t)\rangle \to f_{CP})} \tag{8.4}$$

can be written as:

$$\mathcal{A}_{f_{CP}}(t) = S_{f_{CP}} \cdot \sin(\Delta m_{B_d} t) - C_{f_{CP}} \cdot \cos(\Delta m_{B_d} t), \tag{8.5}$$

where the coefficients of the sine and cosine terms are:

$$S_{f_{CP}} = \frac{2\,\text{Im}\lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2} \quad \text{and} \quad C_{f_{CP}} = \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2}. \tag{8.6}$$

The cosine term vanishes in absence of both *CP* violation in mixing ($|q/p| = 1$) and direct *CP* violation in the decay ($|\overline{A}_{f_{CP}}/A_{f_{CP}}| = 1$). Even in that case, *CP* violation can arise from the weak phase difference between q/p and $\overline{A}_{f_{CP}}/A_{f_{CP}}$, resulting in a non-vanishing sine term ($\text{Im}\,\lambda_{f_{CP}} \neq 0$). In the language of flavor eigenstates, this is interpreted as an interference between the decay of a B^0 meson with and without mixing [2].

In the case of a single *CP*-violating phase in the disintegration process, ϕ_D, one finds:

$$\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = \eta_{f_{CP}}\, e^{2i\phi_D}\, e^{-2i\xi_B}, \tag{8.7}$$

where $\eta_{f_{CP}}$ is the *CP* parity of the f_{CP} final state, $\eta_{f_{CP}} = \pm 1$. It follows that:

$$\lambda_{f_{CP}} = \eta_{f_{CP}}\, e^{2i(\phi_D + \phi_M)}, \quad S_{f_{CP}} = \text{Im}\,\lambda_{f_{CP}} = \eta_{f_{CP}} \sin 2(\phi_D + \phi_M), \quad C_{f_{CP}} = 0, \tag{8.8}$$

and

$$\mathcal{A}_{f_{CP}}(t) = \eta_{f_{CP}} \sin 2(\phi_D + \phi_M) \sin(\Delta m_{B_d} t). \tag{8.9}$$

The "gold-plated" $J/\psi K^0_{S,L}$ modes provide a theoretically clean way of extracting $\sin 2\beta$: the branching ratio are relatively high ($\sim 10^{-4}$) and the experimental signatures are clear. The quark subprocess at the tree level for the $\overline{B}^0 \to J/\psi\,\overline{K}^0$ is $b \to c\overline{c}s$, which involves the $V^*_{cs}V_{cb}$ product of CKM factors. The interference in $B^0(\overline{B}^0) \to J/\psi K^0_{S,L}$ is possible due to $K^0\overline{K}^0$ mixing which introduces another CKM product, $V^*_{cd}V_{cs}$. With negligible theoretical uncertainty, direct *CP* violation is ruled out in these modes (this is supported experimentally by the non-observation of direct *CP* violation in the SU(3)-related $B^\pm \to J/\psi K^\pm$ decay). In the usual phase convention, the ratio of amplitudes is

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[2] note that, if the interpretation of this *CP*-violating effect is somewhat convention-dependent, the phase of $\lambda_{f_{CP}}$ is not.

made real, $\phi_D = 0$, and all the effect comes from the phase $\phi_M = -\beta$ in q/p, *i.e.* from the fact that the mass eigenstates are not *CP*-even and *CP*-odd. One finds:

$$\mathcal{A}_{J/\psi K^0_{S,L}} = -\eta_{J/\psi K^0_{S,L}} \sin 2\beta \sin (\Delta m_{B_d} t) , \qquad (8.10)$$

where $\eta_{J/\psi K^0_S}$ and $\eta_{J/\psi K^0_L}$ are equal to -1 and $+1$, respectively. At LEP, OPAL [32] with 24 $B^0 \to J/\psi K^0_S$ candidates (60% purity) selected out of 4.4 million hadronic Z^0 decays measures: $\sin 2\beta = 3.2^{+1.8}_{-2.0}(\text{stat}) \pm 0.5(\text{syst})$. ALEPH [33] with 23 candidates (71% purity) selected out of 4 million hadronic Z^0 decays measures: $\sin 2\beta = 0.84^{+0.82}_{-1.04}(\text{stat}) \pm 0.16(\text{syst})$. At the Tevatron (FNAL), CDF [34] using 400 $B^0 \to J/\psi K^0_S$ events out of the entire Run I data sample ($110 \, \text{pb}^{-1}$ at $\sqrt{s} = 1.8 \, \text{TeV}$) measures: $\sin 2\beta = 0.79^{+0.41}_{-0.44}(\text{stat} + \text{syst})$.

8.1 The concept of an asymmetric B factory

The cleanest source of B mesons is in $e^+ e^-$ collisions at the energy of the $\Upsilon(4S)$ resonance ($\sqrt{s} \approx 10.58 \, \text{GeV}$). The $\Upsilon(4S)$ resonance is the lightest Υ resonance ($b\bar{b}$ bound state with $J^{PC} = 1^{--}$) above B meson pair production threshold. To present knowledge, the $\Upsilon(4S)$ decays exclusively into $B^+ B^-$ or $B^0 \overline{B}^0$ final states in equal amounts. The $e^+ e^- \to \Upsilon(4S)$ process, with a cross-section close to $1 \, \text{nb}$, competes with the QED pair production of light quarks $e^+ e^- \to q\bar{q}$ (where $q = u$, d, s or c). The background from QED continuum constitutes 75% of the hadronic cross-section, but can be reduced thanks to distinct topological characteristics. Furthermore, the QED continuum can be studied with data taken at energies under the $B\overline{B}$ threshold, typically $40 \, \text{MeV}$ below the $\Upsilon(4S)$ resonance (*off-resonance data*).

Due to the intrinsic spin of the $\Upsilon(4S)$, $B\overline{B}$ states produced in the $\Upsilon(4S) \to B\overline{B}$ reaction are in a coherent $L = 1$ state. In the case of the $\Upsilon(4S) \to B^0 \overline{B}^0$ reaction, each meson evolves according to the time evolution of single B meson equations 3.3. However, the two mesons evolve in phase, and the correlation between both sides of the $B^0 \overline{B}^0$ system holds at any time after production until one of the two mesons decays. If the first meson decays into a flavor specific decay mode, the other meson in the pair, at that same instant, must have the opposite flavor. If the first meson decays into a *CP* eigenstate, the other meson in the pair, at that same instant, must have opposite *CP*.

Let us consider the case where one of the two mesons (called B_{tag}) decays into a flavor-specific final state at proper time t_{tag}, while the other meson (called B_{rec}, because it is usually fully-reconstructed) decays into the final state f at proper time t_{rec}. After integration on $t_{\text{rec}} + t_{\text{tag}}$, the decay rate writes:

$$\rho(\Delta t, \varepsilon_{\text{tag}}) \propto e^{-|\Delta t|/\tau_{B_d}} \cdot \{ \, (|A_f|^2 + |\overline{A}_f|^2)$$
$$+ \, \varepsilon_{\text{tag}} \, [\, 2 \, \text{Im}(\frac{q}{p} A_f^* \overline{A}_f) \sin (\Delta m_{B_d} \Delta t) - (|A_f|^2 - |\overline{A}_f|^2) \cos (\Delta m_{B_d} \Delta t) \,] \, \} \, , \quad (8.11)$$

where $\Delta t = t_{\text{rec}} - t_{\text{tag}}$ is the proper decay time difference and ε_{tag} equals 1 or -1 depending or whether the B_{tag} is identified as a B^0 or a $\overline{B}^0$.

If the final state f is also a flavor-specific final state ($B_{\text{rec}} = B_{\text{flav}}$), one obtains from the above equation the normalized $B^0 \overline{B}^0$ mixing time distribution:

$$h(\Delta t, \varepsilon_{\text{tag}} \times \varepsilon_f) = \frac{1}{4\tau_{B_d}} e^{-|\Delta t|/\tau_{B_d}} \{ 1 - \varepsilon_{\text{tag}} \times \varepsilon_f \cdot \cos (\Delta m_{B_d} \Delta t) \} , \qquad (8.12)$$

where $\varepsilon_f = +1$ or -1 depending on whether f is a B^0 decay final state ($|\overline{A}_f| = 0$) or a $\overline{B}^0$ decay final state ($|A_f| = 0$). The cases $\varepsilon_{\text{tag}} \times \varepsilon_f = +1$ and $\varepsilon_{\text{tag}} \times \varepsilon_f = -1$ define the mixed and the unmixed samples, respectively. (If one considers the mixed and unmixed samples together, one obtains a pure lifetime distribution.) Similarly, if the final state f is a CP eigenstate ($B_{\text{rec}} = B_{CP}$), the normalized decay distributions writes:

$$f(\Delta t,\, \varepsilon_{\text{tag}}) = \frac{1}{4\tau_{B_d}} e^{-|\Delta t|/\tau_{B_d}} \left\{ 1 + \varepsilon_{\text{tag}} \left(S_{f_{CP}} \cdot \sin \Delta m_{B_d} \Delta t - C_{f_{CP}} \cdot \cos \Delta m_{B_d} \Delta t \right) \right\} \ .$$

(8.13)

The time distributions at the $\Upsilon(4S)$ are therefore obtained by substituting the proper time difference Δt to the B^0 decay time t, with the difference that Δt is an algebraic quantity which takes values from $-\infty$ to $+\infty$. When integrating over Δt, one loses the information on the coefficient of the sine term. As a result of the coherent production of B^0 mesons at the $\Upsilon(4S)$, a time-integrated CP asymmetry measurement is insensitive to $\text{Im}(\lambda_{f_{CP}})$; the study the CP asymmetry as a function of Δt is required. Experimentally, the variable Δt can be related to the distance between the locations of the two B meson decays. In practice, at an energy-symmetric machine like CESR, the flight distance of the B mesons ($\sim 30\,\mu$m) is too small compared to the interaction region size, and such a time-dependent study is impossible even with perfect vertex resolution.
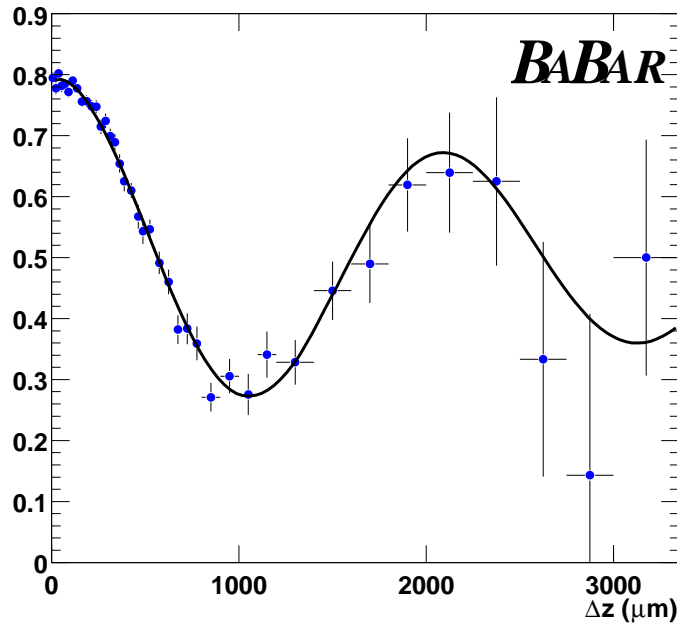
Figure 1: Time-dependent relative rate of unlike-sign dilepton events (*BABAR* data, $20.7\,\text{fb}^{-1}$) and the overlaid binned maximum likelihood fit from which the $B^0\overline{B}^0$ oscillation frequency Δm_d is measured [36]: $\Delta m_{B_d} = 0.499 \pm 0.010 \pm 0.012\,\hbar\,\text{ps}^{-1}$. The full scale, expressed here in μm, covers more than 15 lifetimes of the B^0 meson (about 1.5 oscillation period).

In the late 1980s, to resolve this problem, the concept of a machine operating at the

$\Upsilon(4S)$ in an asymmetric mode, *i.e.* with beams of unequal energies, was proposed [35]. PEP-II and KEK-B were built on this model. At asymmetric B factories, the $\Upsilon(4S)$ is produced in motion in the laboratory frame, and the two B mesons travel measurable distances along the boost axis before they decay. The relation between the proper time difference Δt and the distance between the two B decay vertices along the boost axis Δz is (to a very good approximation) $\Delta z = \beta\gamma c \Delta t$. The center-of-mass frame boosts for PEP-II and KEK-B are similar: $\beta\gamma = 0.56$ and $\beta\gamma = 0.45$, respectively. One lifetime of the B^0 meson corresponds to a distance of the order of $250\,\mu\mathrm{m}$ along the boost axis and a complete $B^0\,\overline{B}^0$ mixing period $2\pi/\Delta m_{B_d}$ to about $2\,\mathrm{mm}$. (This is illustrated on Fig. 1, which shows the time-dependent $\ell^\pm\ell^\mp$ relative rate for dilepton events in *BABAR* data as a function of Δz.) Time-dependent CP asymmetries are expected to be maximal when mixed and unmixed samples are of equal size, around a quarter period ($\sim 500\,\mu\mathrm{m}$).

8.2 Mis-tagging probability and time-resolution function

Flavor tagging of selected events requires the determination of $\varepsilon_{\mathrm{tag}}$, the flavor of the B_{tag} [3]. In practice, of course, flavor tagging is imperfect. Let w be the probability for a signal event to be incorrectly assigned a flavor tag $\varepsilon_{\mathrm{tag}}$. The perfect time-dependent probability density for this event $\rho(\Delta t, \varepsilon_{\mathrm{tag}})$ has to be replaced by $(1-w) \times \rho(\Delta t, \varepsilon_{\mathrm{tag}}) + w \times \rho(\Delta t, -\varepsilon_{\mathrm{tag}}) = \rho(\Delta t, (1-2w) \times \varepsilon_{\mathrm{tag}})$, where we use the fact that ρ is linear in $\varepsilon_{\mathrm{tag}}$. The effect of the imperfect flavor tagging is therefore to replace $\varepsilon_{\mathrm{tag}}$ by $\mathcal{D} \times \varepsilon_{\mathrm{tag}}$ in front of oscillatory terms in Eq. 8.11- 8.13, where $\mathcal{D} \equiv 1 - 2w$ is a dilution factor due to mis-tagging.

Flavor tagging is principally based on charge correlations of daughter particles with the flavor of the decaying B_{tag}. For example, the presence of the following particles would identify a $\overline{B}^0$ decay: high-momentum ℓ^- leptons (e^- and μ^-) from $b \to c\ell^-\nu$ semileptonic decays; intermediate-momentum ℓ^+ lepton from cascade decays; K^+ from charm decays; high-momentum π^- from $\overline{B}^0 \to D^{*+}\pi^-$ decays; soft π^+ from $D^{*+} \to D^0\pi^+$ decays. *BABAR* and BELLE use different strategies to combine this information. *BABAR* defines four tagging categories based on the physical content of the event (such as the presence of a lepton or a kaon) while BELLE uses a multi-dimensional likelihood method and defines six tagging categories based on the value of a continuous flavor tagging dilution factor. The tagging performances of the two experiments are very similar, with an effective tagging efficiency $Q \approx 27\%$ (this means that a sample of 100 signal events is statistically equivalent to a sample of 27 perfectly tagged events).

The vertex resolution in z for the fully-reconstructed B_{rec} is of the order of $60\,\mu\mathrm{m}$, depending on the mode. The position of the vertex of the B_{tag} is determined using the charged tracks not belonging to the B_{rec}, and by exploiting energy-momentum conservation and the knowledge of the beam spot position. A precision on Δz of the order of $180\,\mu\mathrm{m}$ is obtained (this is to be compared to the average flight distance $\sim 250\,\mu\mathrm{m}$). The Δz determination algorithms have high efficiencies, typically greater than 97%.

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[3]thanks to the coherent evolution of B^0 mesons at the $\Upsilon(4S)$, tagging the flavor of the B_{tag} when it decays is equivalent to tagging the flavor of the B_{rec} at $\Delta t = 0$.

The final probability density functions $\varrho(\Delta t)$ are obtained by convoluting the ideal time distributions $\rho(\Delta t)$ with a time resolution function $\mathcal{R}(\delta_{\Delta t})$:

$$\varrho(\Delta t) \equiv (\rho \otimes \mathcal{R})(\Delta t) = \int_{-\infty}^{+\infty} \rho(\Delta t) \times \mathcal{R}(\delta_{\Delta t}) \cdot d\delta_{\Delta t} , \qquad (8.14)$$

where $\delta_{\Delta t} = \Delta t - \Delta t_{\text{true}}$. The time resolution functions are parameterized as a normalized sum of two (BELLE) or three (*BABAR*) Gaussian distributions with different means and widths. (In *BABAR*, the third Gaussian has a fixed very large width and no offset, and accounts for fewer than 1% of events with badly reconstructed vertices.) In both analyses, the core and tail distributions are allowed to have non-zero means to account for the bias due to the flight of charm particles whose decay products are used to determine the position of the B_{tag} decay vertex, and their widths are scaled by event-by-event errors derived from the vertex fits. In *BABAR*, the parameters of the resolution function are evaluated independently for each tagging category.
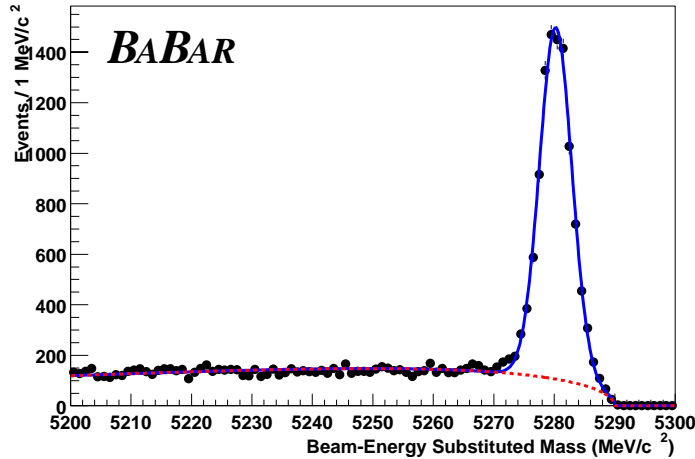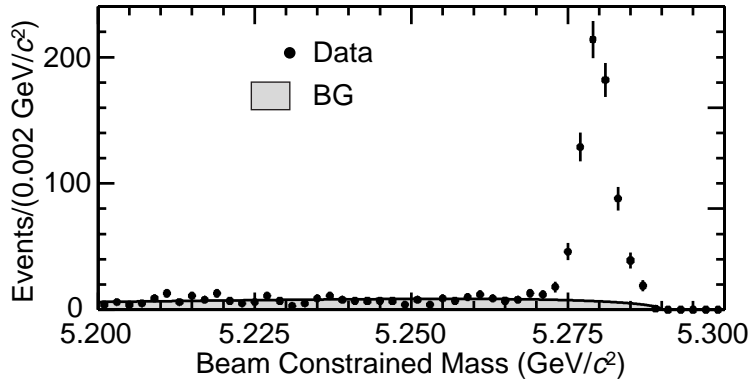

Figure 2: Mass distribution for *BABAR*'s sample of flavor-specific fully-reconstructed hadronic B^0 decays, called the B_{flav} sample in the text. (The mass is computed with the beam energy substituted to the measured energy of the candidates.) This sample, composed of 9360 signal events selected out of $29.1\,\text{fb}^{-1}$ of data, is used for lifetime and mixing measurements (see text).

8.3 Flavor and *CP* samples

The flavor B_{flav} sample (Fig. 2) is composed of events where the final state f is a flavor-specific hadronic state, such as $B^0 \to D^{(*)-}\pi^+$, $D^{(*)-}\rho^+$, $D^{(*)-}a_1^+$, $J/\psi K^{*0}(\to K^+\pi^-)$ and charge conjugates. (Similar decay modes are considered for charged B mesons.) The selection rate for these Cabbibo-favored modes is of the order of 300 events per fb^{-1}, with purities around 85%.

The *CP* sample is divided into three categories: $\eta_{CP} = -1$, $\eta_{CP} = +1$ and mixed-*CP*. BELLE uses all selected events for the *CP* sample while *BABAR* applies further cuts, rejecting 30% of events with poor or very poor flavor tagging information. The $\eta_{CP} = -1$

Figure 3: Beam energy-constrained mass distribution for BELLE's high-purity sample of $\eta_{CP} = -1$ events for the sin2β fit (706 events selected out of $30 \, \text{fb}^{-1}$ of data).

sample (Fig. 3) is composed of events selected in the $B^0 \to J/\psi K_S^0$, $\psi(2S) K_S^0$ and $\chi_{c1} K_S^0$ modes. Are considered the decays: $J/\psi \to \ell^+ \ell^-$; $K_S^0 \to \pi^+ \pi^-$ (and in certain cases $\pi^0 \pi^0$); $\psi(2S) \to \ell^+ \ell^-$ and $J/\psi \pi^+ \pi^-$; $\chi_{c1} \to J/\psi \gamma$. BELLE also considers $B^0 \to \eta_c K_S^0$ decays, with $\eta_c \to K_S^0 K\pi$ and $K^+ K^- \pi^0$. BELLE selects 706 events with 93% purity, while *BABAR* keeps 480 events with 96% purity after tagging cuts. The $\eta_{CP} = +1$ sample is composed of events selected in the $B^0 \to J/\psi K_L^0$ mode: 569 events with 60% purity for BELLE and 273 events for 51% purity after tagging cuts for *BABAR*. The mixed-CP sample is composed of events selected in the $B^0 \to J/\psi K^{*0}$ mode with $K^{*0} \to K_S^0 \pi^0$: 41 events with 84% purity for BELLE and 50 events with 74% purity after tagging cuts for *BABAR*. For this VV mode, the CP content can be extracted from an analysis of angular distributions of the related non-CP $J/\psi K^*$ modes. *BABAR* [37] and BELLE [38] each use their own values of R_T, the fraction of CP-odd in the decay. The results, $R_T = 0.16 \pm 0.03 \pm 0.03$ and $R_T = 0.19 \pm 0.04 \pm 0.04$, respectively, are consistent with less-precise previous measurements.

The information on the interesting physical quantities (for instance τ_{B_d}, Δm_{B_d} or sin2β) is extracted from un-binned maximum likelihood fits to the Δt spectra of either flavor or CP samples (or a combination of the two samples) using the probability density functions defined above for the signal. The fits also include empirical descriptions of background Δt distributions, the parameters of which are determined mostly from events in the sidebands of the signal region or from events selected in off-resonance data. τ_{B_d} and Δm_{B_d} are fixed to their PDG value [39] in the fits for sin2β. The mis-tagging probabilities and the parameters of the resolution function for the signal and the background are fit parameters. *BABAR* also fits for a possible difference between B^0 and $\overline{B}^0$ tags. For the fit to the $J/\psi K^*$ sample, BELLE includes the event-by-event information of the K^* helicity angle in the CP fit. *BABAR* performs a global fit to the flavor and CP sample in order to get a correct estimate for the errors and their correlations: the largest correlation between sin2β and any combination of the other fitted parameters is found to be as small as 13%.

8.4 Observation of CP violation in the B meson system

Lifetimes measurements with fully-reconstructed decays are performed using the first two

building blocks of the sin2β analysis: the reconstruction of B mesons in flavor eigenstates, and the Δz determination. Using its B_{flav} and charged B samples, *BABAR* has produced precision measurements of B^0 and $B^\pm$ lifetimes and their ratio at the 2% level [40]: $\tau_{B^0} = 1.546 \pm 0.032 \pm 0.022\,\text{ps}$, $\tau_{B^\pm} = 1.673 \pm 0.032 \pm 0.023\,\text{ps}$ and $\tau_{B^\pm}/\tau_{B^0} = 1.082 \pm 0.026 \pm 0.012$. BELLE has lifetime results using $B \to D^* \ell \nu$ semileptonic decays with comparable precision [41]: $\tau_{B^0} = 1.55 \pm 0.02\,\text{ps}$, $\tau_{B^\pm} = 1.64 \pm 0.03\,\text{ps}$. Mixing measurements use in addition the third building block which is flavor tagging. Using its B_{flav} sample, *BABAR* [42] measures $\Delta m_{B_d} = 0.519 \pm 0.020 \pm 0.016\,\hbar\,\text{ps}^{-1}$ (see Fig. 6).

The first results of *BABAR* and BELLE concerning B lifetimes and Δm_{B_d} are not only consistent with world averages [39], but in many cases competitive in precision with the combination of all previous results. This constitutes an important demonstration of the feasibility of time-dependent studies at asymmetric B factories and validates the experimental technique for the sin2β measurement. Important byproducts of these measurements are the determination of the parameters of the time resolution function and of the mis-tagging probabilities. *These quantities are evaluated from the data on the high-statistics flavor sample rather than determined from Monte-Carlo simulation.*

The results from *BABAR* [36][43] and BELLE [44] on sin2β are:

$$\text{sin}2\beta_{BABAR} = 0.59 \pm 0.14 \pm 0.05$$
$$\text{sin}2\beta_{\text{BELLE}} = 0.99 \pm 0.14 \pm 0.06$$

These two results independently establish CP violation in the B meson system at more than 4 standard deviations. (There is an unpleasant 2σ discrepancy between the two results which will hopefully be resolved with increased statistics.) The CP violation effect is large, and can be seen from the raw time distributions (and the resulting time-dependent asymmetry) as a clear excess of $\varepsilon_{\text{tag}} \times \eta_{CP} = -1$ tags (resp. $\varepsilon_{\text{tag}} \times \eta_{CP} = +1$ tags) at positive (resp. negative) Δt values (see Fig. 4 and 5).
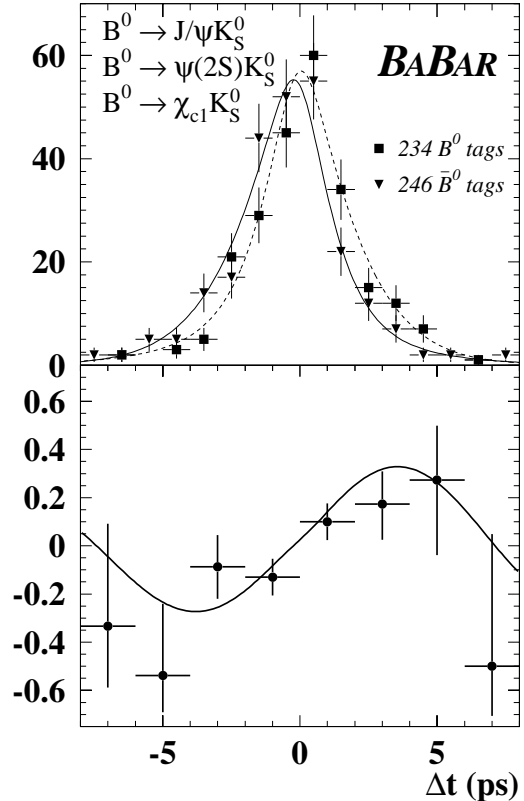
Figure 4: Time distributions and raw asymmetry for *BABAR*'s $\eta_{CP} = -1$ sample with, superimposed, the projection of the un-binned maximum likelihood fits. The top plot shows the time distributions for the B^0-tagged (triangles) and $\overline{B}^0$-tagged CP samples (squares). The bottom plot shows the resulting raw asymmetry, which is diluted with respect to Eq. 8.10 due to unperfect flavor tagging and finite time resolution.
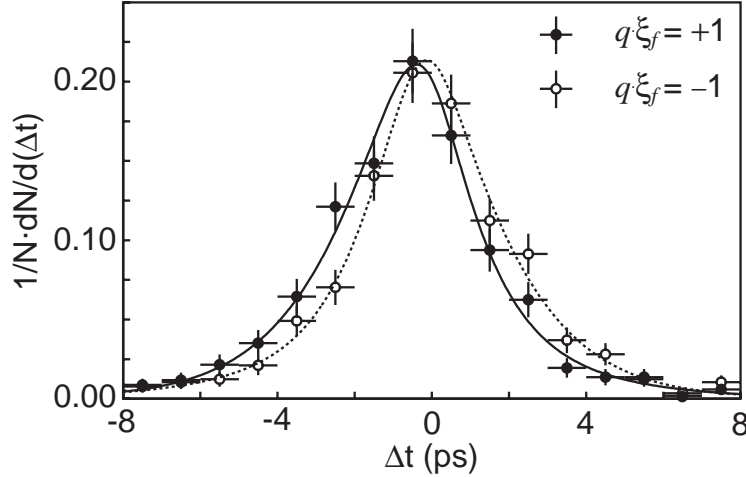
Figure 5: Time distributions for BELLE's full *CP* sample after background substraction, with, superimposed, the projection of the un-binned maximum likelihood fit to each distribution (open circles: $\varepsilon_{\text{tag}} \times \eta_{CP} = -1$ tags; full circles: $\varepsilon_{\text{tag}} \times \eta_{CP} = +1$ tags).

Various cross-checks have been performed, including internal consistency of various sub-samples and tagging categories, null asymmetry with high statistics charged and B_{flav} samples, etc. Systematic uncertainties are small since the time resolution and the tagging performance are extracted from the data themselves. Main residual systematic uncertainties come from resolution models, vertex algorithms, detector misalignments and possible difference between the flavor and the *CP* samples. The contribution to the systematics from the fraction, shape and *CP* content of the background is sizable for the $J/\psi K_L^0$ and $J/\psi K^{*0}$ modes, but is negligible overall. Systematics from the uncertainty on τ_{B_d} and Δm_{B_d} are negligible.

Averaging these results with previous measurements from CDF, ALEPH and OPAL, one obtains $\sin 2\beta_{\text{WA}} = 0.79 \pm 0.11 (\text{stat} + \text{syst})$. Figure 7 shows how the present knowledge of the $\sin 2\beta$ parameter constrains the apex of the Unitarity Triangle in the $(\bar{\rho}, \bar{\eta})$ plane. The constraint from direct $\sin 2\beta$ measurements is represented by four branches, due to the four-fold ambiguity in deriving a value of β from a measurement of $\sin 2\beta$; one of the four possible solutions, in the upper left quadrant, is obviously consistent with the allowed region determined from the interpretation of previous experimental results in the context of the Standard Model.

9. Prospects

At this point, the knowledge of $\sin 2\beta$ is not accurate enough to reduce the allowed region in the $(\bar{\rho}, \bar{\eta})$ plane significantly. However, $\sin 2\beta$ constitutes potentially one of the best constraints on position of the apex of the Unitarity Triangle since, as opposed to other quantities, its measurement is not limited by theoretical uncertainties but by statistics. Future, highly precise, measurements of $\sin 2\beta$ will allow a correspondingly precise test of the CKM model.
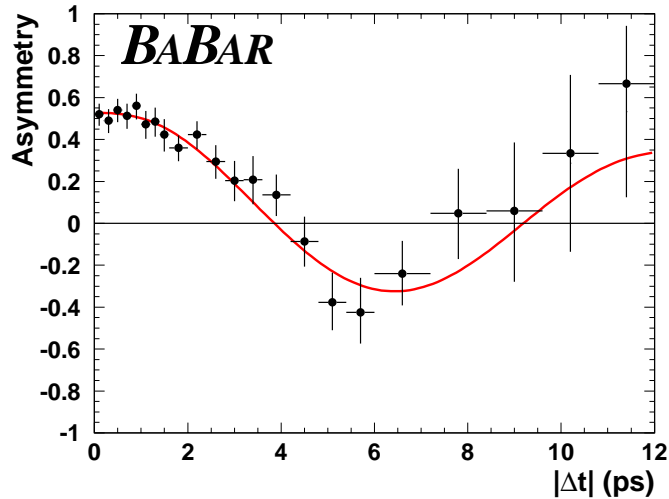
Figure 6: Time-dependent asymmetry for the flavor sample (*BABAR*, 20.7 fb^{-1}), with, superimposed, the projection of the un-binned maximum likelihood fit, from which a competitive measurement of the $B^0\overline{B}^0$ mixing frequency is extracted (see text). This sample is included in the global fit for sin2β and dominates the determination of the mis-tagging probabilities and parameters of the time resolution function.

The two teams at SLAC and KEK are presently accumulating data at a unprecedented high rate. PEP-II has recently (early October 2001) delivered a record 263 pb^{-1} of data in one day; KEK-B holds the record of instantaneous luminosity for an e^+e^- collider, 4.9×10^{33} cm^{-1}s^{-1}. If the machines keep with their schedule, each experiment should have registered close to 100 fb^{-1} of data (with 10% to 15% off-resonance) by early summer 2002. The current results from BELLE and *BABAR* for roughly 30 fb^{-1} have a statistical uncertainty of $\sigma^{\text{stat}}_{\text{sin2}\beta} \simeq 0.14$. Assuming no further improvements in reconstruction efficiency and data analysis, we can infer statistical uncertainties of $\sigma^{\text{stat}}_{\text{sin2}\beta} \simeq 0.08$ for 100 fb^{-1}. Most of the systematic uncertainties will be reduced with larger statistics, and other systematics dominated by detector effects are likely to improve as well. It is believed that the total systematic uncertainties can be controlled at the level of $\sigma^{\text{syst}}_{\text{sin2}\beta} \simeq 0.03$ for 100 fb^{-1}. The next round of sin2β measurements at B factories will still be statistics dominated.

9.1 Comparison of sin2β in other decay modes

A comparison of the asymmetry in the pure penguin $b \to s\overline{s}s$ decay $B \to \phi K^0_S$ with that in $b \to c\overline{c}s$ decays is sensitive to new particles with complex couplings. Typically, the experiments can detect one ϕK^0_S event for 2 fb^{-1} of data at the $\Upsilon(4S)$ [22][23][24]. Using the results from the sin2β measurement, and scaling from the observed yields in that mode, the estimated uncertainty using the ϕK^0_S mode is $\sigma^{\text{stat}}_{\text{sin2}\beta} \simeq 0.56$ for 100 fb^{-1}. Clearly, much larger statistics is needed to probe new physics appearing in loop diagrams by the measurement of sin2β with that mode. Asymmetries in other modes such as $B^0 \to J/\psi\,\pi^0$ can also potentially measure sin2β, but even larger statistics are needed. The $b \to c\overline{c}d$ modes $B^0 \to D^{(*)+}D^{(*)-}$ can also (to leading terms) measure sin2β: most of these modes

have been observed by CLEO [45] and recently a first measurement of the polarization in the VV mode $B^0 \to D^{*+}D^{*-}$ has been presented [46].
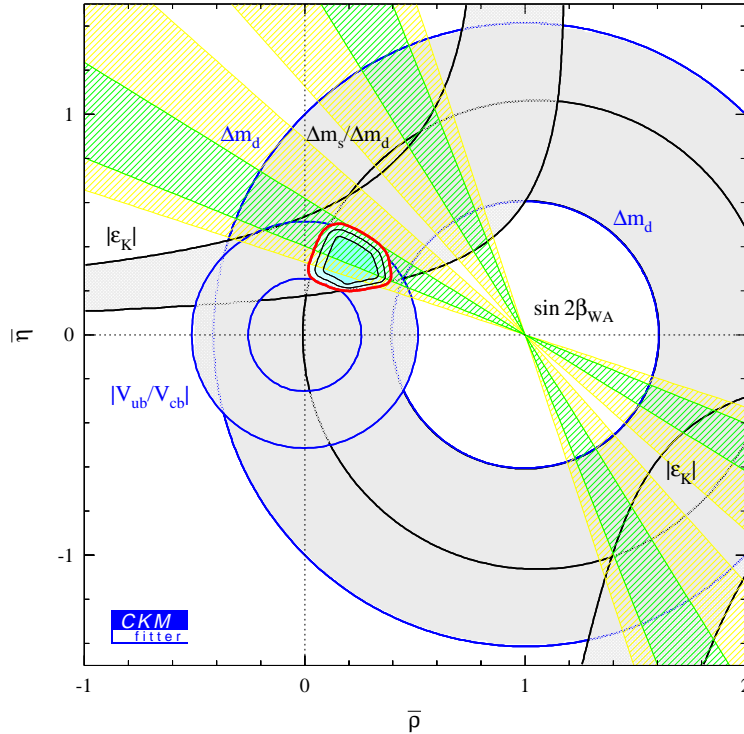
Figure 7: Present constraints on the position of the apex of the Unitarity Triangle in the $(\bar{\rho}, \bar{\eta})$ plane [8]. The world average of direct measurements of $\sin 2\beta$, represented by green and yellow hatched regions corresponding to one and two statistical standard deviations, is not included in the determination of the allowed region for the apex of the Unitarity Triangle.

9.2 Measurements of $\sin 2\alpha$

The CP decay mode $B^0 \to \pi^+\pi^-$ receives competing contributions from tree and penguin diagrams. If the decay were dominated by the tree amplitude, the asymmetry would be proportional to $\sin 2\alpha$. However, the competing penguin amplitudes have different weak phases and as a result, the CP asymmetry in this mode measures $\sin 2\alpha_{\text{eff}} = \sin 2(\alpha + \delta_{\text{peng}})$, where δ_{peng} accounts for the penguin contribution. This contribution can in principle be estimated using isospin relations among $B \to \pi\pi$ amplitudes [47]. However, the so-called isospin analysis is in practice jeopardized by the requirement of measuring flavor-tagged branching ratios $B^0 \to \pi^0\pi^0$ and $\overline{B}^0 \to \pi^0\pi^0$ (which could be as small as 10^{-6}), and by the possible contribution of electroweak penguin amplitudes. Methods have been developed to bound experimentally the penguin contribution from a limit on non-tagged $B^0 \to \pi^0\pi^0$ [48]-[50]. Methods allowing the determination of δ_{peng} theoretically, such as the QCD factorization [51], are promising but need to be confronted to experiment [1][2]. Experimentally, the measurement is significantly more challenging than that of $\sin 2\beta$: branching fraction of order 5×10^{-6}, large background from continuum, competition with the 4-times more

copious mode $B^0 \to K^+\pi^-$. *BABAR* has however performed the first measurement of the time-dependent *CP* asymmetry in this mode [52] based on 65^{+12}_{-11} signal $\pi^+\pi^-$ events selected out of 31 fb^{-1} of on-peak data:

$$S_{\pi\pi} = 0.03^{+0.53}_{-0.56} \pm 0.11, \quad C_{\pi\pi} = -0.25^{+0.45}_{-0.47} \pm 0.14, \qquad (9.1)$$

where $S_{\pi\pi}$, the coefficient of the sine term (see Eq. 8.5), is equal to $\sin 2\alpha_{\text{eff}}$. From this result, one can anticipate with 100 fb^{-1} an error of the order of 0.30 on $\sin 2\alpha_{\text{eff}}$ (moreover, it is conceivable that the $B^0 \to \pi^0\pi^0$ mode will be observed, and the $B^+ \to \pi^+\pi^0$ confirmed).

9.3 Measurements of γ

The study of charmless two-body B decays into pions and kaons (such as $B \to K\pi$) offers methods for the determination of the *CP* angle γ. Non-trivial constraints (bounds) on γ (which is the relative weak phase between tree and penguin amplitudes for these decays) can be extracted from *CP*-averaged ratios of branching fractions using only isospin considerations. The general analysis is however complicated by possible contribution of electroweak penguin amplitudes, SU(3) breaking effects and final state interactions, so that predictions suffer from some amount of model dependence (see for instance Ref. [51] and [53]). Different models make predictions on direct *CP* asymmetries in the $B \to K\pi$ modes that can be tested experimentally.

The combination of CKM angles $2\beta + \gamma$ can be measured in decays of the type $B \to D^*\pi$. Here, the basic idea is to exploit the interference between the direct decay, $B^0 \to D^{*+}\pi^-$, and the decay after $B^0\overline{B}^0$ mixing, $B^0 \to \overline{B}^0 \to D^{*+}\pi^-$ [54]. The difficulty with this approach is the necessity of measuring the ratio r of the doubly-Cabibbo-suppressed to the dominant decay amplitudes, in order to interpret the small expected amplitude of the time-dependent asymmetry. To overcome the problems specific to this decay mode, several other strategies based on the mixing-induced interference between the dominant $b \to c\overline{u}d$ and the suppressed $\overline{b} \to \overline{u}c\overline{d}$ process (the relative weak phase of which is γ), have been proposed [55][56]. Experimentally, analyses are based on both full and partial reconstruction techniques, where the ratio r is determined from measurements in related less-suppressed modes. Preliminary studies are encouraging: one can anticipate accuracies $\sigma_{\sin(2\beta+\gamma)}$ of the order of 0.4 with 100 fb^{-1}.

At longer term, the $B^\pm \to DK^\pm$ modes can be exploited to extract the *CP* angle γ (the relative weak phase between the $b \to c\overline{u}s$ and $b \to u\overline{c}s$ quark level amplitudes contributing to these decays). The original construction suggested in [57] is using exact isospin relations which link the modes $B \to D^0_{CP}K$, $B \to D^0K$ and $B \to \overline{D}^0K$ (D^0_{CP} represents a *CP* eigenstate), but suffers from intrinsic difficulties [58]; several variants of the original method have been proposed [59][60], but all require the measurement of very rare processes, at the 10^{-7} level. In addition, this type of construction suffers from an eight-fold ambiguity in the value of γ, so even higher precision is necessary to separate the multiple solutions for γ. Experimentally, evidence for $B \to D_{CP}K$ decays has been reported [61].

10. Conclusions

The last two years have been rich in important experimental results on CP violation. The asymmetric B factories have come online with outstanding beginnings: the *BABAR* and BELLE collaborations have already published world class results in the domain of B physics, and have established independently CP violation in the B system. Their measurements of $\sin 2\beta$, obtained with $30\,\mathrm{fb}^{-1}$ each, dominate the present world average, $\sin 2\beta_{\mathrm{WA}} = 0.79 \pm 0.11(\mathrm{stat} + \mathrm{syst})$. The encouraging *BABAR* result on $\sin 2\alpha_{\mathrm{eff}}$ demonstrates the feasibility of time-dependent CP analyses with small signals and large backgrounds at B factories. The data samples are expected to be multiplied by three before next summer, and by ten in the next three years, bringing sensitivities to direct and indirect CP violation effects to the level of theoretical expectations. Experiments at hadron colliders benefit from much higher statistics in B mesons (but with different levels of backgrounds and different systematics), and the possibility of studying the B_s system. The upgraded CDF and D0 experiments at the Tevatron are starting up again and will produce competitive measurements of $\sin 2\beta$ and probably the measurement of x_s, as soon as in 2002. The collider experiments of the next generation, BTeV at the Tevatron and LHCB at the LHC, are planned to come online around year 2006 .

Complementary approaches of B factories and collider experiments will be needed to perform the rich programme of redundant precision measurements in the domain of charged weak interactions for testing the CKM sector of the Standard Model, and probing the origin of the CP violation phenomenon.

11. Acknowledgements

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