CP Violation in B Meson Decays - Experimental Results

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CP violation is intimately connected with the puzzle of matter-antimatter asymmetry and baryogenesis. In the Standard Model of particle physics, the observed CP violation phenomena are accounted for by the Cabibbo-Kobayashi-Maskawa mechanism involving a phase in the quark mixing matrix. This paper is devoted to a review of the experimental status of CP violation in the decays of B mesons.

1. INTRODUCTION

Accelerator experiments, searching for CP violation effects in meson decays, are a crucial counterpart to observations and speculations in astrophysics and cosmology. The striking unbalance between matter and anti-matter in the present Universe calls for an explanation at the level of fundamental interactions, with CP violation among the key ingredients.

The most recent experimental results in this sector have been mainly contributed by two experiments, BABAR and Belle, collecting data on B-meson decays at the B-factories; they are so successful in their CP violation studies, that reviewing their results is both exciting and frustrating.

The excitement comes from an uninterrupted sequence of improvements in the performances of the two B-factories and from the rapidly increasing size of the data samples collected by the two experiments: the initial observation of CP violation already turned into precision measurements, and new, sometimes unanticipated, experimental windows have been opened on future developments in CP phenomenology.

The frustration is entirely due to the difficulty of freezing a picture of new developments in this field, just before a very fruitful Summer 2004 harvest. Both experiments roughly doubled their data samples since Summer 2003, and reported many updates or new measurements at ICHEP 2004: about sixty for BABAR alone!

For this reason, while the written version of this contribution follows the main lines of the talk, emphasizing the same experimental results and trends, I could not resist inserting also summaries from the August ICHEP 2004 updates that followed SSI 2004. At the same time, I did not aim at completeness in covering the many aspects of CP violation phenomenology in B decays, but rather tried to summarize the main trends, in the interdisciplinary spirit of SSI 2004. I apologize in advance for the many interesting theoretical ideas and experimental results that are not covered by this review, and point the interested reader to the up-to date and complete summaries prepared by the Heavy Flavor Averaging Group (HFAG) [1] and to the Standard Model review sections in ref. [2].

2. MATTER AND ANTI-MATTER: THE CP VIOLATION CONNECTION

To first approximation, all fundamental interactions are symmetric under the CP transformation, combining particle-antiparticle exchange or Charge Conjugation (C) and space reflection or Parity (P), but is this really a good symmetry of nature? In 1964 a tiny CP symmetry violation effect was discovered in weak decays of neutral kaons [3]; intensively investigated, this phenomenon remained a peculiarity of the neutral kaon system until the recent observations of CP violation in B decays [4].

CP violation is intimately related with 'Nature's Greatest Puzzle' n.8 of SSI 2004, 'Why is the Universe made of Matter and not Anti-Matter?', since it allows us to distinguish a world of matter from a world of anti-matter in an absolute way. Figure 1 gives a convincing example that this is the case, experimentally. Since CPT is an exact symmetry for local quantum field theories [5], T (time reversal) violation is also expected, and experimentally seen [6].

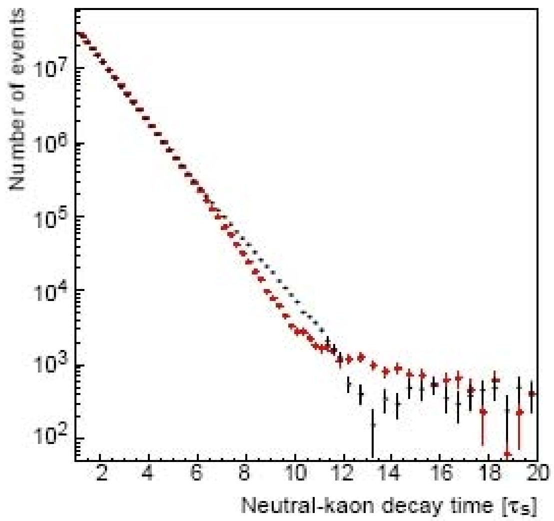

Figure 1: An example of matter-antimatter asymmetry as seen in the different decay time distributions of K^0 and $\bar{K}^0$ mesons to the same $\pi^+\pi^-$ final state, by the CPLEAR experiment [7].

In Cosmology, CP violation was recognized soon as one of three necessary conditions for generating a global excess of matter in the evolution of our Universe, the others being baryon number violation and a departure from thermal equilibrium conditions [8].

In the Standard Model (SM) of particle physics, CP violation is generated entirely by a phase in the quark sector, as proposed by Kobayashi and Maskawa [9]: this mechanism has shown an amazing predictive power. However, as several contributors to this Session of SSI 2004 also pointed out, the SM CP violation fails to explain the observed baryon asymmetry, by many orders of magnitude [10]!

A natural question arises: if the cosmological picture is correct, where are the non-SM CP violation sources? This fundamental question demands a thorough experimental investigation of CP violation to test the SM predictions in the heavy quark sector, looking for evidence of new physics[11].

3. THE CKM PARADIGM AND UNITARITY ANGLES

Back in 1973 M.Kobayashi and T.Maskawa [9] suggested that the non-trivial phase, changing sign under CP and generating observable CP violation effects, could be carried by the quark mixing matrix, connecting the quark mass eigenstates of the full Hamiltonian with the left-handed weak eigenstates coupled by charged-current weak decays. They also noted that the unitarity of the mixing matrix allowed complex phases only for dimension greater or equal to three, and suggested on this basis that a third generation or family (t, b) of quarks should complement the first two, (u, d) and (c, s).

The 3×3 Cabibbo-Kobayashi-Maskawa (CKM) unitary matrix $V_{qq'}$ contains four of the eighteen free parameters of the SM. The most popular CKM parameterization by Wolfenstein [12] explicitly shows the hierarchy of couplings in terms of powers of the sine of the Cabibbo angle [13] $\lambda = |V_{us}| = \sin\theta_C = 0.2243 \pm 0.0016$ [14]; in its simplest form, up to corrections of order $\mathcal{O}(\lambda^4)$,

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

It should be noted that the diagonal elements are close to unity, and that off-diagonal couplings among different quark families get weaker with a 'family-distance' ordering. In this parameterization, the weak CP-violating phase

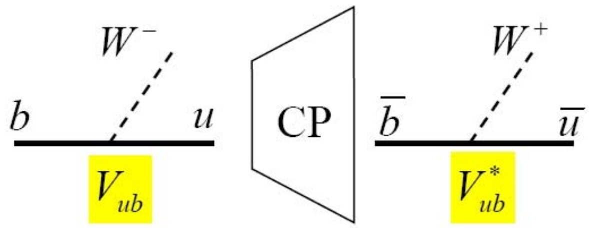

Figure 2: The 'CP mirror' effect on the V_{ub} CKM matrix element in a $b \to u$ transition: the complex-conjugate V_{ub}^* has opposite phase.

is carried by the two elements V_{ub} and V_{td}. From decay rates and branching fraction measurements, constraining the absolute values $|V_{qq'}|$, $A \simeq 0.82$, representing the deviation of $|V_{cb}|$ from λ^2, is known with an uncertainty of about $\pm 5\%$, while $\sqrt{\rho^2 + \eta^2} \simeq 0.4$ is less well known.

CP violation in the SM corresponds to $\eta \neq 0$. Observable CP rate asymmetries are generated by interfering amplitudes, whose relative phase changes sign under CP. Figure 2 shows how the 'CP mirror' changes the sign of the CKM phase in a charged-current transition coupling the b and u quarks to the W weak boson.

The most effective way of comparing experimental results to SM expectations in the CKM sector is by means of the unitarity relations between CKM matrix elements that can be represented by Unitarity Triangles (UT) in the complex plane. The amount of CP violation is linked to the equal areas of these different triangles. When studying $B_u^+ = (\bar{b}u)$ and $B_d^0 = (\bar{b}d)$ meson decays, the relevant triangular relation is between the first and third column of the matrix:

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0. \tag{2}$$

When normalized to $V_{cb}^* V_{cd}$, this relation corresponds to the rescaled triangle shown in Figure 3; its Unitarity Angles or relative phases are labelled in different notations α (ϕ_2), β (ϕ_1), and γ (ϕ_3).

In contrast with the other much flatter triangles that can be constructed from unitarity relations, the three sides of this UT have comparable sizes, all of the same order $\simeq \lambda^3$; they can be measured from decay rates. As a result, the angles are all expected to be significantly different from zero and lead to the SM expectation of large CP asymmetries in some B decays. Recalling that $V_{cd} = \lambda$ and $V_{ud} \simeq V_{tb} \simeq 1$, the same unitarity relation can be written approximately:

$$\frac{V_{ub}^*}{\lambda V_{cb}^*} + 1 + \frac{V_{td}}{\lambda V_{cb}^*} = 0, \tag{3}$$

and shows that, in this parameterization:

$$\gamma \simeq \arg V_{ub} \quad \beta \simeq -\arg V_{td} \quad \alpha = \pi - (\beta + \gamma). \tag{4}$$

For precision tests of the CKM mechanism, one can take into account unitarity at all orders in λ. Defining the so-called 'standard' parameters [15], [14] in terms of λ, A, ρ, and η, one obtains a modified Wolfenstein parameterization [16], where the apex of the rescaled UT (Figure 3) is given to all orders in λ by:

$$\bar{\rho} + i\bar{\eta} \equiv -\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*}, \tag{5}$$

where $\bar{\rho} = \rho(1 - \lambda^2/2 + \mathcal{O}(\lambda^4))$ and $\bar{\eta} = \eta(1 - \lambda^2/2 + \mathcal{O}(\lambda^4))$.

4. EXPERIMENTAL CHALLENGES

The importance of the Unitarity Triangle as a bookkeeping device is clear from Figure 3. The SM predicts that the lines, representing constraints from many different measurements of decay rates and asymmetries, all intersect at the apex $(\bar{\rho}, \bar{\eta})$ of the Unitarity Triangle.

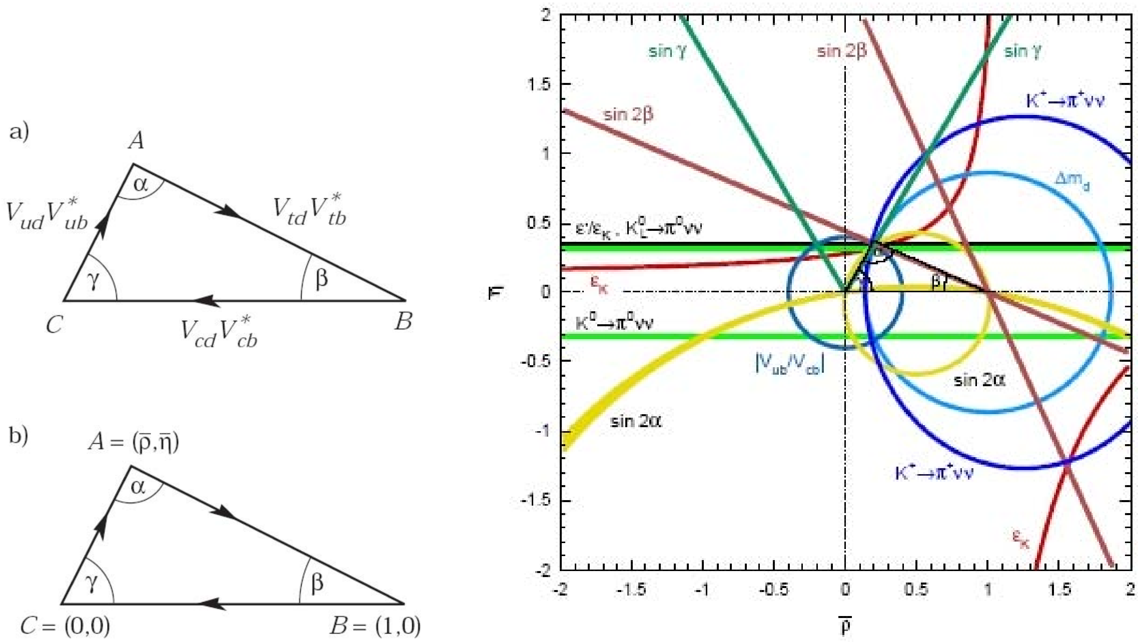

Figure 3: (left) (a) Representation in the complex plane of the Unitarity Triangle formed by the CKM matrix elements $V_{ud}V^*_{ub}$, $V_{td}V^*_{tb}$, and $V_{cd}V^*_{cb}$. (b) Rescaled triangle, all sides divided by $V_{cd}V^*_{cb}$, with vertices A, B, and C at $(\bar\rho,\bar\eta)$, $(1,0)$, and $(0,0)$, respectively.
(right) Experimental paths to the Unitarity Triangle: a compilation of most relevant present and future constraints on the $(\bar\rho,\bar\eta)$ apex; in this paper we are mostly concerned with measurements of $\sin 2\beta$, $\sin 2\alpha$, $\sin\gamma$. A common set of SM parameters is assumed here for all expected constraints, represented with their ambiguities (for instance two straight lines from the $\sin 2\beta$ measurement) but without uncertainties; the figure is reproduced from [17].

Table I: Existing and planned experimental facilities for B-physics studies. At the time of writing this report, the BTeV project [18] had been terminated.

experiment	**BABAR**	**Belle**	**CDF-II, D0**	**LHCb**
Collider	PEP-II	KEK-B	Tevatron	LHC
Beams	e^+e^-, asymm.	e^+e^-, asymm.	$p\bar p$	pp
$\sqrt{s}$(GeV)	10.58	10.58	1800	14000
L (10^{33}cm^{-2}s^{-1})	3	10	$0.2-1.0$	0.15
$\sigma(b\bar b)$(nb)	$\simeq 1$	$\simeq 1$	$\simeq 100000$	$\simeq 500000$
$N_{b\bar b}$ (10^7/year)	$3-10$	$3-10$	20000	75000
$\beta\gamma c\tau$ (μm)	270	210	500	7000
$\sigma(b\bar b)/\sigma(q\bar q)$	0.28	0.28	1×10^{-3}	5×10^{-3}

Most measurements that directly constrain sides and angles of the UT, rely on B-meson decays that are or will be accessible in two types of experimental facilities: asymmetric-energy electron-positron colliders at the $\Upsilon(4S)$ center-of-mass energy (‘B-factories’) and hadron colliders.

Table I lists present and future experimental facilities with important programs in B decay studies, and compares their main parameters: center-of-mass energy $\sqrt{s}$, design luminosity L, $b\bar b$ quark pairs production cross-section $\sigma(b\bar b)$, nominal number $N_{b\bar b}$ of $b\bar b$ pairs produced per year, average boost factor of B mesons in the laboratory frame, and ratio of $b\bar b$ to hadronic background rates. The differences in $N_{b\bar b}$ are compensated, to a large extent, by detection and reconstruction efficiencies.

The $b\bar{b}$ signal cross-section is much larger at hadron colliders, but the same is true for the hadronic backgrounds: as a result of tighter selection criteria, the trigger and reconstruction efficiencies are smaller. Important hadron collider contributions to B physics in the past involved mainly decay channels with leptons. Recently, upgraded detectors became able to trigger on tracks from detached secondary vertices: the reach of these facilities is therefore extended to hadronic decay channels. This progress, together with the unique possibility of copiously producing also B_s^0 mesons, is promising for the future potential of CDF-II and D0, when sufficient luminosity will be integrated, and of the other experiments, when they will become operational, in a few years from now.

The present B physics experimentation is dominated by the very successful operation of the two B-factories. Both are operated at a center-of-mass energy of 10.580 GeV, at the $\Upsilon(4S)$ $b\bar{b}$ resonance, just above the threshold for the production of $B_u^+ B_u^-$ and $B_d^0 \bar{B}_d^0$. The very favorable ratio of $b\bar{b}$ production as compared to lighter quark pairs ($\sigma(b\bar{b})/\sigma(q\bar{q}) \simeq 0.28$), and the clean electron-positron machine environment are compatible with a very inclusive trigger, retaining virtually all B decays, and allow their exclusive reconstruction with high efficiency. The asymmetric beam energy configuration boosts the B mesons in the laboratory frame, allowing their decay vertices to be separately reconstructed, as required in particular by time-dependent CP asymmetry measurements.

PEP-II at SLAC [19] collides 3.1 GeV positrons on 9.0 GeV electrons and in 2004 exceeded the design peak luminosity by about a factor 3, reaching 9.2×10^{33} cm^{-2}s^{-1}. The very efficient operation delivered a total luminosity of about 254 fb^{-1} (10% off-resonance for continuum background measurements), corresponding to about 240 million recorded $B\bar{B}$ pairs. KEK-B at KEK [20] collides 3.5 GeV positrons on 8.0 GeV electrons; their world-record peak luminosity is 13.9×10^{33} cm^{-2}s^{-1}, the total integrated luminosity about 287 fb^{-1} and the recorded $B\bar{B}$ sample reached 280 million pairs.

Both experiments more than doubled their data samples since Summer 2003. In the following we will focus our attention on results from the B-factories only, and we will adopt their notation, dropping the subscripts u and d for B_u^+ and B_d^0 mesons.

4.1. Observables: CP asymmetries

The CKM phases can be directly measured in experiments designed to observe different kinds of CP-violating asymmetries. Each of these observables is the result of the interference of different amplitudes with non-zero relative phase, contributing to the same physical process, similarly to optical interference in a classical two-slit diffraction experiment.

The CP-odd observables in B meson decays are usually classified as CP violation occurring (i) 'directly' in decays, when at least two interfering amplitudes with different electroweak and strong phases describe the same decay process; (ii) in $B^0 - \bar{B}^0$ mixing, if the mass eigenstates $B_L(B_H) = pB^0 \pm q\bar{B}^0$ cannot be chosen to coincide with the CP eigenstates, resulting in $|q/p| \neq 1$; (iii) in the interference between decay and mixing amplitudes, for decays that can proceed directly or via $B^0 - \bar{B}^0$ mixing.

CP asymmetries of type (i) for the decay $i \to f$ are related to the CP-violating CKM phase ϕ by:

$$A_{CP} \equiv \frac{P(i \to f) - P(\bar{i} \to \bar{f})}{P(i \to f) + P(\bar{i} \to \bar{f})} \propto 2|A_1||A_2| \sin\delta \sin\phi, \tag{6}$$

where P are the decay probabilities or rates, A_1 and A_2 are the contributing amplitudes, and δ is a CP-conserving strong relative phase, usually poorly known. A non-zero strong phase is a necessary condition for a CP violation effect to be observable in this case, as illustrated by Figure 4 (top).

CP violation in B mixing (type (ii)) is expected to be very small in the SM, in relation with a decay width difference much smaller than the B_L, B_H mass difference, and is usually neglected.

The B-factory experiments are specially designed to measure time-dependent CP asymmetries of type (iii), with neutral B mesons decaying to a CP eigenstate f, directly or via mixing; Figure 4 (bottom) shows the interference mechanism inducing a different time-dependent decay rate for a decaying meson initially tagged as B^0 or $\bar{B}^0$, and mixing is described in Figure 5.

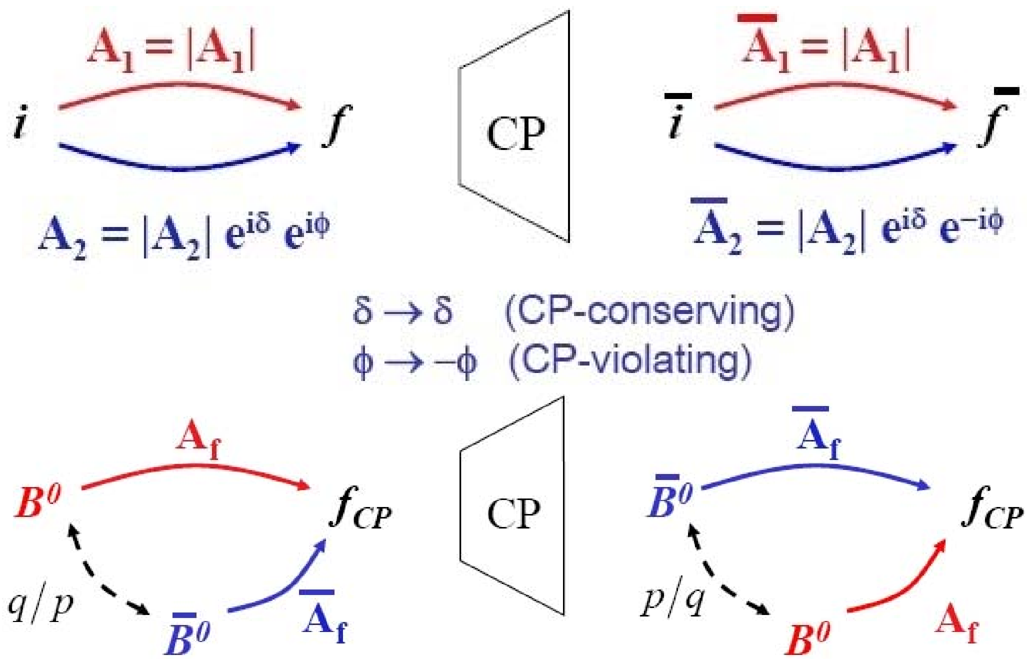

Figure 4: (top) The direct CP asymmetry in the transition between an initial state i and a final state f is due to the interference between two amplitudes A_1 and A_2 with a relative CP-conserving phase δ and a CP-violating phase ϕ; (bottom) CP asymmetry in B^0 decay to a CP eigenstate f_{CP} from the interference between mixing, described by parameters p and q, and the decay amplitudes A_f and $\bar{A}_f$.

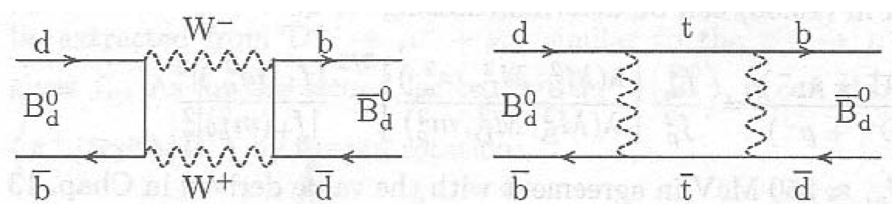

Figure 5: The B^0 mass eigenstates can be expressed as $B^0_{L,H} = pB^0 \pm q\bar{B}^0$. From the box diagrams describing the B^0-$\bar{B}^0$ transition amplitude M_{12}, it can be shown that, from V_{td} appearing twice in each diagram, $(q/p)_B \approx \sqrt{M^*_{12}}/\sqrt{M_{12}} = (V_{td}V^*_{tb})/(V^*_{td}V_{tb}) = \exp(-i2\beta)$.

The B^0 and $\bar{B}^0$ pseudoscalar mesons, pair produced from the decay of the $\Upsilon(4S)$ vector resonance in B-factory experiments, are in a coherent state with opposite flavor, until one of them decays. The proper-time decay-rates $R_\pm$ of a reconstructed $B \to f$ that will be indicated by B_{rec}, when the other meson, called B_{tag}, can be tagged through its decay as a B^0 ($\bar{B}^0$), are given by:

$$R_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left[1 \pm S_f \sin \Delta m_d \Delta t \mp C_f \cos \Delta m_d \Delta t\right], \tag{7}$$

so that the time-dependent asymmetry can be expressed as:

$$A_f(\Delta t) \equiv \frac{R_+ - R_-}{R_+ + R_-} = S_f \sin \Delta m_d \Delta t - C_f \cos \Delta m_d \Delta t. \tag{8}$$

Δt is the difference between proper decay times of B_{rec} and B_{tag}, τ_{B^0} is the B^0 lifetime, and Δm_d, the mass difference between neutral B mass eigenstates, is the parameter governing flavor oscillations. The C and S coefficients in eq. (7)

can be expressed as:

$$S_f = \frac{2\mathcal{I}m\lambda_f}{1+|\lambda_f|^2} \tag{9}$$

$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \tag{10}$$

where the complex CP parameter λ_f takes into account both mixing and decay:

$$\lambda_f = \eta_f \frac{q}{p}\frac{\bar{A}_f}{A_f}, \tag{11}$$

through $q/p = \exp(-i2\beta)$ for B mixing (see Figure 5) and the amplitude ratio $\bar{A}_f/A_f$ for decays; η_f is the CP -parity of the final state. A non-zero value of the S_f coefficient is the signature of CP violation from the interference between mixing and decay, while 'direct' CP violation from the interference of decay amplitudes is characterized by $C_f \neq 0$.

4.2. Analysis methods

The BABAR and Belle detectors are described in detail elsewhere [21]; they share several common features, while differing in some of the adopted techniques. Both cover large fractions of the solid angle in the CM frame around the interaction region. Their multi-layer double-sided inner silicon microstrip detectors sample the charged particle tracks close to the interaction region and to the decay points, with space resolutions down to about $10-20\ \mu$m per point. The five-layer configuration adopted by BABAR is particularly effective also in the reconstruction of tracks from charged particles of low transverse momentum. Both experiments adopt a Drift Chamber as main tracking device to measure angle, momenta and energy deposition per unit path length of charged particle tracks. Charged hadron identification is obtained in BABAR by measuring the particle velocity by a novel Cherenkov ring-imaging device (DIRC, a Detector of Internally Reflected Cherenkov light), while Belle adopted a more conventional combination of Time Of Flight (TOF) counters and aerogel threshold Cherenkov counters. Photon detection and electron identification are provided in both experiments by electromagnetic calorimeters made of CsI(Tl) crystals. A superconducting solenoid provides the magnetic field for momentum analysis. Muons and neutral hadrons are identified by an external detector, using the iron that traps the return of the magnetic flux as a hadron filter, instrumented with Resistive Plate Chambers, partially substituted in BABAR by Streamer Tubes.

While the B-factory environment is extremely clean, as compared to hadron colliders, it is still true that backgrounds are present, and may be relevant when the B-decay channels of interest have very small branching fractions.

One of the B mesons of the $B\bar{B}$ pair from the $\Upsilon(4S)$ resonance, produced almost at rest in the CM frame, is usually reconstructed exclusively, with efficiency typically in the $15-40\%$ range, depending on the final state. Shape variables are used to discriminate the almost isotropically distributed decay products of B decays, from the jet-like configuration of particles in the background events due to 'continuum' production of lighter $q\bar{q}$ pairs. In some cases, at a substantial cost in efficiency, an additional high-momentum lepton is required as a B-tag. Residual continuum backgrounds are statistically subtracted by using data recorded at a slightly lower CM energy ('off-resonance'), where the $\Upsilon(4S)$ does not contribute. Both kinematical constraints and particle identification are relevant in separating different B-decay channels that may produce 'peaking' backgrounds in the discriminating variables m_{ES} and ΔE, defined in Figure 6.

For CP asymmetries, after the reconstruction of the relevant $B \to f$ final state ('B_{rec}'), the second key ingredient is the tagging of the flavor of the other B (B_{tag}). To maximize efficiency, this is achieved by an inclusive tag, using the correlated charge of fast leptons, kaons, or slow pions as a signature. An overall tagging efficiency, corrected for wrong tags, of about 30% is typically obtained.

Finally, the reconstruction of B-decay vertices is required to measure time-dependent CP asymmetries, where the time difference Δt is measured as $\Delta t \simeq \Delta z/(\gamma\beta c)$ from the space separation $\Delta z = z_{rec} - z_{tag}$ of the two B decay vertices along the boost direction. The Δz resolution, of the order of 170 μm, is dominated by the inclusively reconstructed B_{tag} side and is designed to be a fraction of the average separation $< \Delta z > \simeq \gamma\beta c\tau_B \simeq 250 \div 270\ \mu$m.

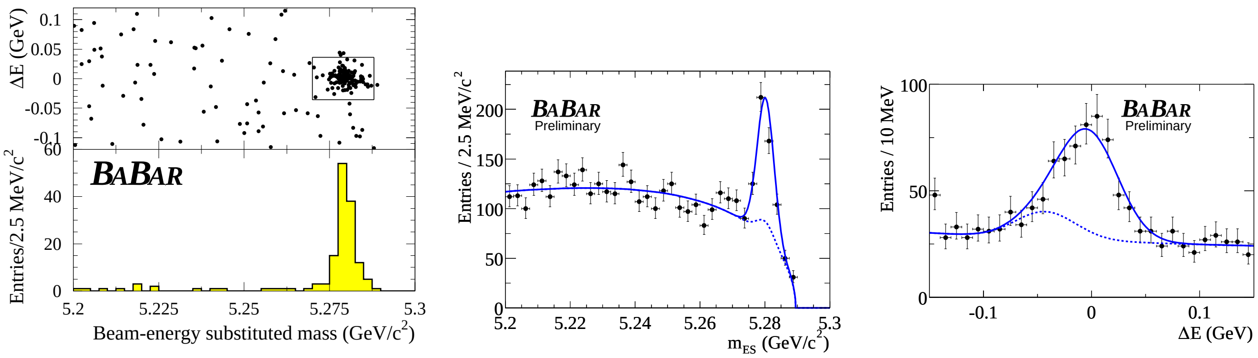

Figure 6: Signal decays are identified using two kinematical variables: the difference ΔE between the reconstructed energy of the B candidate in the e^+e^- center-of-mass (CM) frame and $\sqrt{s}/2$, and the beam-energy substituted-mass $m_{ES} = \sqrt{(s/2 + \vec{p}_i \cdot \vec{p}_B)^2/E_i^2 - p_B^2}$; $\sqrt{s}$ is the total CM energy; the B momentum p_B and the four-momentum $(E_i, \vec{p}_i)$ of the e^+e^- initial state are defined in the laboratory frame. The m_{ES} resolution is dominated by the spread in beam energy of about 2.6 MeV, while the ΔE resolution ($15 - 30$ MeV, depending on the final state) is driven by detector effects. The plot on the left shows an example of the very clean $B^0 \to J/\psi K_S^0$ signal from the first year of data taking [22]; the plots at the center and on the right are taken from a recently updated analysis of $B^0 \to \pi^+\pi^-$ [40], where the signal purity is lower.

It should be noted that a high-luminosity B-factory offers the unique possibility to extend the B tagging concept by requiring a more stringent exclusive tag, obtained by full reconstruction of a large number of hadronic B decay channels, with an overall efficiency of the order of one thousandth and good purity. This method strongly constrains the kinematics of B decays on the opposite side, even in the presence of invisible decay products, such as neutrinos.

5. EXPERIMENTAL RESULTS

5.1. Direct CP Violation in B decays

Direct CP violation, not involving particle-antiparticle oscillations, has been observed in $K_L^0 \to \pi^+\pi^-$ decays [23], where the effect is a few parts per million, due to the smallness of one of the two interfering decay amplitudes. In contrast, if CP violation is due to the Kobayashi-Maskawa mechanism described in Section 3, a large effect is expected in the B-meson system.

A good candidate for the observation of a 'direct' CP asymmetry (Section 4.1) is the decay $B^0 \to K^+\pi^-$: in the Standard Model, this decay occurs through two different amplitudes (penguin and tree), which carry different weak phases and, in general, different strong phases.

A few days before SSI 2004, the BABAR Collaboration announced the results of an updated search for direct CP violation in the decay $B^0 \to K^+\pi^-$. This measurement established direct CP violation in the B^0-meson system at the level of 4.2 standard deviations [24], and was later confirmed by Belle [25] with a significance of 3.9 standard deviations: the combined significance exceeds 5 standard deviations.

The BABAR result is based on a sample of 227 million $B\bar{B}$ pairs. About 68000 events contain pairs of opposite charge tracks identified as pions or kaons, loosely compatible with two-body B decay kinematics and additional topological criteria, rejecting about 80% of the jet-like $q\bar{q}$ background events. An unbinned, extended maximum-likelihood fit based on m_{ES}, ΔE (defined in Figure 6), the Cherenkov angle θ_C from the DIRC, and a combination of several topological variables, determines signal and background yield components for each of the four $\pi^+\pi^-$, $K^+\pi^-$, $K^-\pi^+$, and K^+K^- modes; it also allows the extraction of the signal asymmetry ($A_{K\pi}$), and the background asymmetry ($A^b_{K\pi}$).

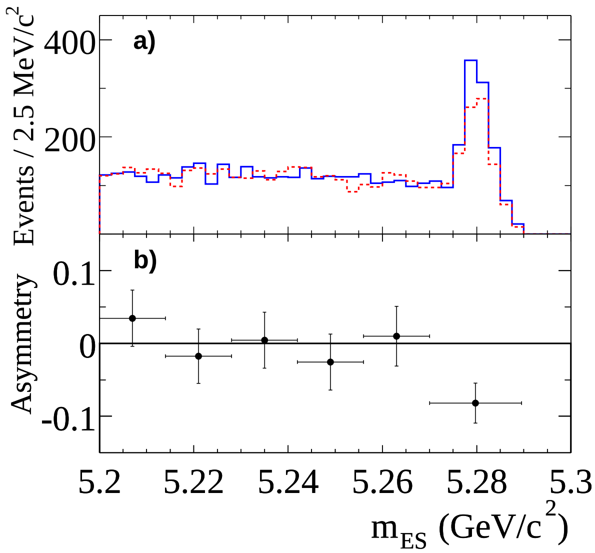

Figure 7: (a) Distribution of the beam-energy substituted mass m_{ES} (defined in Figure 6) enhanced in $K^+\pi^-$ (solid histogram) and $K^-\pi^+$ (dashed histogram). (b) Asymmetry $A_{K\pi}$ calculated for ranges of m_{ES}. The asymmetry in the highest m_{ES} bin is somewhat diluted by the presence of background.

The fitted signal yields are $n_{K\pi} = 1606 \pm 51$, $n_{\pi\pi} = 467 \pm 33$, and $n_{KK} = 3 \pm 12$, consistent with previously published measurements of the flavor averaged branching fractions in these decay modes, in particular $BF(K^+\pi^-) = (1.85 \pm 0.11) \times 10^{-5}$ [2]. The direct CP-violating asymmetry is:

$$A_{K\pi} \equiv \frac{n_{K^-\pi^+} - n_{K^+\pi^-}}{n_{K^-\pi^+} + n_{K^+\pi^-}} = -0.133 \pm 0.030(stat) \pm 0.009(syst), \tag{12}$$

and the background asymmetry is $A^b_{K\pi} = 0.001 \pm 0.008$. The observed signal asymmetry, as opposed to the absence of asymmetry in the background, is qualitatively evident by projecting a subsample of events, enriched in $K\pi$, on one of the variables used in the fit (Figure 7). Control samples and extensive consistency checks exclude possible sources of experimental bias in $A_{K\pi}$.

The ICHEP 2004 world average [1], including the confirmation by Belle, is $A_{K\pi} = -0.109 \pm 0.19$. It should be noted that the observed fairly large $A_{K\pi}$ asymmetry is not at all unexpected [26], and can be traced to the CKM phase in the interference between ‘penguin’ and ‘tree’ amplitudes, the main uncertainties in theoretical predictions being due to the incomplete control of hadronic effects. The experimental observation is indeed important because it supports the validity of the CKM mechanism without particle-antiparticle mixing and helps disentangling penguins, trees, weak and strong phases.

No evidence of direct CP asymmetries is seen yet in other $K\pi$ modes, like $K^\pm\pi^0$ from charged $B^\pm$, where the experimental uncertainty is somewhat larger; within the large theoretical uncertainties due to hadronic effects, an asymmetry with the same sign and comparable magnitude would be expected in these channels [27]. The comparison between measurements in different $K\pi$ modes should ultimately give a handle also on other possible decay mechanisms, such as electroweak penguin amplitudes [28].

Direct CP violation can also be searched for in the time-dependent B-decay asymmetries (Section 4.1). An evidence reported by Belle in the decay channel $\pi^+\pi^-$ will be discussed in Section 5.3.

5.2. The Unitarity Angle β (ϕ_1)

The main initial experimental analysis at the B-factories was a first test of the SM prediction in the B-meson sector: the determination of the unitarity angle β or ϕ_1 ($\simeq -\arg V_{td}$ in the Wolfenstein parameterization), by studying time-

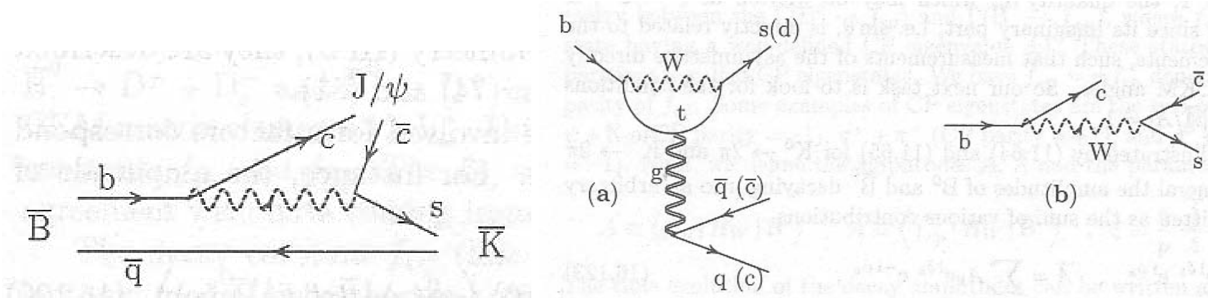

Figure 8: (left) Color-suppressed decay amplitude for the decay $\bar{B} \to J/\psi \bar{K}$. (right) The penguin (a) and tree (b) diagrams for the transition $b \to sc\bar{c}$ have the same weak phase.

dependent CP asymmetries of neutral B-meson decays to CP eigenstates (Section 4.1) containing charmonium ($c\bar{c}$). The decays of neutral B mesons to $J/\psi K^0_S$ and other channels mediated at quark level by $b \to c\bar{c}s$, are particularly clean: theoretically, because the dominating tree and the penguin decay amplitudes (Figure 8) have the same weak phase relative to the mixing amplitude, so that the uncertainty of the prediction for the coefficient $S_f = -\eta_f \sin 2\beta$ is very small, at the percent level; experimentally, because the final state has a relatively large branching fraction ($BF(B \to J/\psi K^0) = (8.5 \pm 0.5) \times 10^{-4}$ [2]) and can be reconstructed with large efficiency and good purity. For the reference channels $B \to J/\psi K^0_{S,L}$ the CP parameter $\lambda_{J/\psi K^0_{S,L}}$ includes the effects of B mixing, B decay, and K mixing, resulting in an overall phase 2β:

$$\lambda_{J/\psi K^0_{S,L}} = \eta_{J/\psi K^0_{S,L}} \left(\frac{q}{p}\right)_B \left(\frac{V_{cb}V^*_{cs}}{V^*_{cb}V_{cs}}\right) \left(\frac{p}{q}\right)_K = \mp \left(\frac{V_{tb}V^*_{td}}{V^*_{tb}V_{td}}\right) \left(\frac{V_{cb}V^*_{cs}}{V^*_{cb}V_{cs}}\right) \left(\frac{V_{cs}V^*_{cd}}{V^*_{cs}V_{cd}}\right) = \mp e^{-2i\beta} \tag{13}$$

The observed interference pattern (Figure 9, left) is a beautiful demonstration of the experimental method and is by now giving a precise determination of $\sin 2\beta$. The ICHEP 2004 world-average experimental value [1] is $\sin 2\beta = 0.725 \pm 0.037$, including systematic uncertainties, in very good agreement with SM expectations based on the assumption of the validity of the CKM mechanism and on the previously available experimental constraints on the sides of the Unitarity Triangle (Figure 9, right). In particular, the two bands representing the CP violation observations in K decays (ϵ_K) and in B decays ($\sin 2\beta$) nicely overlap with the UT apex region predicted by the intersection of bands from measurements of the UT sides ($|V_{ub}|$, $|V_{cb}|$ and B mixing)

After this striking confirmation of the validity of the CKM mechanism, what is the next step? The interest is now focussed on $b \to s\bar{s}s$ decays that receive contributions purely from 'internal' and 'flavor-singlet' penguin diagrams (Figure 10), and are believed to be sensitive to New Physics through new virtual particle contributions in the loops.

The phase in the CP violation parameter $\lambda_{\phi K^0_S}$ from mixing-decay interference in $B \to \phi K^0_S$ is expected to be essentially the same as in $\lambda_{J/\psi K^0_S}$, from $(q/p)_B = \exp(-2i\beta)$:

$$\lambda_{\phi K^0_S} = \left(\frac{q}{p}\right)_B \left(\frac{V_{tb}V^*_{ts}}{V^*_{tb}V_{ts}}\right) \left(\frac{p}{q}\right)_K \approx -e^{-2i\beta}, \tag{14}$$

so that measurement of the asymmetry coefficient S_f should give the essentially the same result for both $b \to c\bar{c}s$ and $b \to s\bar{s}s$, in the absence of New Physics effects, once the SM corrections discussed below are taken into account.

The experimental situation, including BABAR and Belle results shown at ICHEP2004, is summarized in Figure 11, for the S_f coefficient. The total number of tagged events in all penguin modes is by now comparable to the number of events in charmonium mode, used for the initial measurement of $\sin 2\beta$, although with inferior purity.

The departure of the Belle result for $S_{\phi K^0_S}$ [30] that supported in 2003 a claim for evidence of non-SM effects, has been washed out by the addition of more data, and is now closer to the BABAR and SM values. However, an intriguing difference of about 3.7 standard deviations can still be noted comparing the average of BABAR and Belle results for all penguin modes, with respect to the reference charmonium value. Averaging over penguin modes is not justified in the SM, since their S_f coefficients are not expected to be exactly the same; it is even less justified

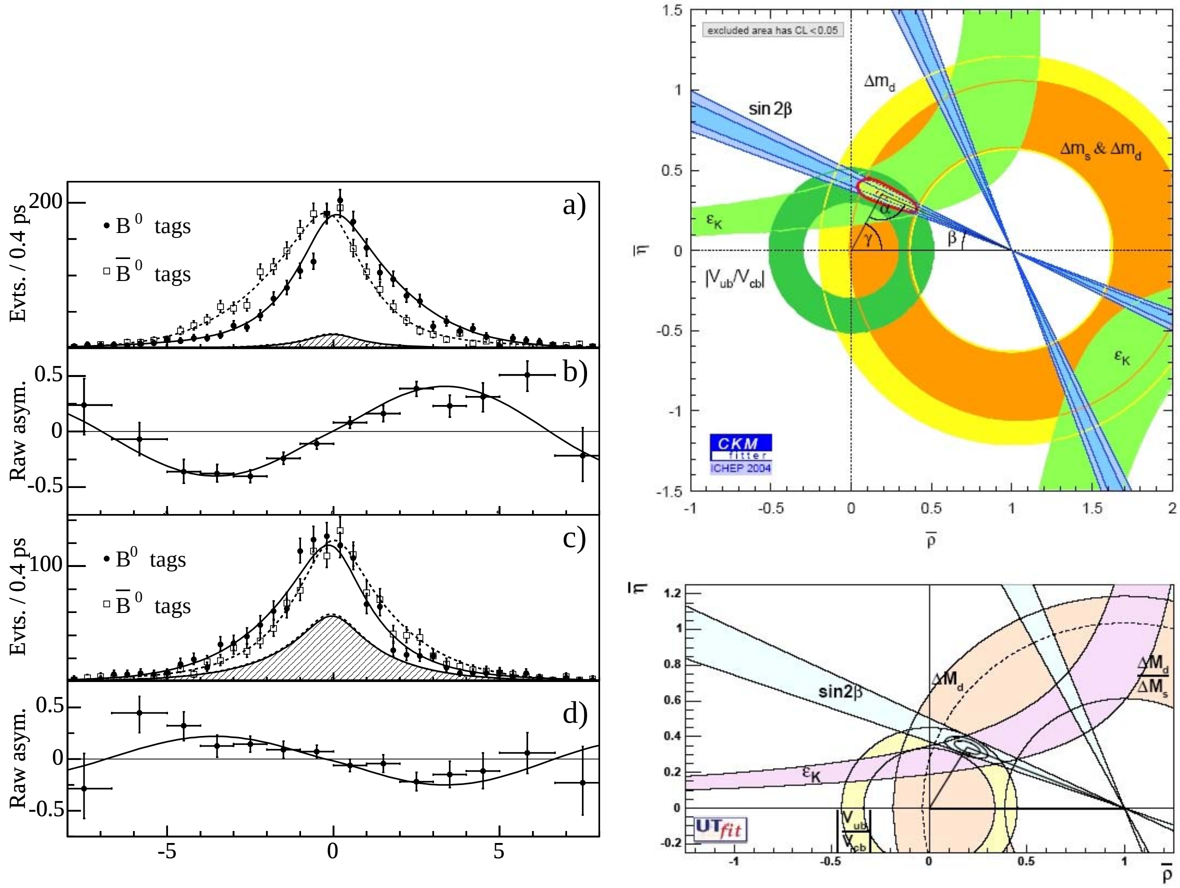

Figure 9: (left) Updated $\sin 2\beta$ measurement from BABAR [29]: a) number of candidates with CP-parity $\eta_f = -1$ ($J/\psi K_S^0$, $\psi(2S)K_S^0$, $\chi_{c1}K_S^0$, and $\eta_c K_S^0$) in the signal region with a B^0 tag N_{B^0} and with a $\bar{B}^0$ tag $N_{\bar{B}^0}$, and b) the raw asymmetry $(N_{B^0} - N_{\bar{B}^0})/(N_{B^0} + N_{\bar{B}^0})$ as functions of Δt, expressed in picoseconds. Figs. c) and d) are the corresponding plots for the $\eta_f = +1$ mode $J/\psi K_L^0$. The solid (dashed) curves represent the fit projections in Δt for B^0 ($\bar{B}^0$) tags. The shaded regions represent the estimated background contributions.
(right) Constraints on the position of the apex of the Unitarity Triangle following from $|V_{ub}|$, B mixing, ϵ_K, and $\sin 2\beta$ (top: [55], bottom: [56]). The value of $\beta = 23.4^o \pm 2^o$ from an overall fit [14] is consistent with the value from the CP-asymmetry measurements of $23.7^o \pm 2.1^o$.

in the presence of New Physics that would affect them differently; still, this can be taken as a very interesting hint, stimulating attention to future progress in these measurements.

In view of systematic experimental investigations of a possible pattern of deviations from the SM, a growing body of theoretical literature [31] reports detailed studies of the SM corrections $\Delta \sin 2\beta$, of order 0.1, that should be applied before a comparison can be made in the relevant penguin modes. The dominant theoretical uncertainty in these estimates comes from suppressed $b \to u \to s$ penguin and $b \to u$ tree diagrams, contributing a different phase through amplitudes proportional to $\lambda^4 e^{-i\gamma}$, doubly CKM-suppressed with respect to the dominant penguin amplitudes of order λ^2. Preliminary naive estimates are now complemented by model calculations and estimates based on SU(3) flavor symmetry; they will eventually provide good limits of the expected SM effects, to be taken into account when searching for New Physics.

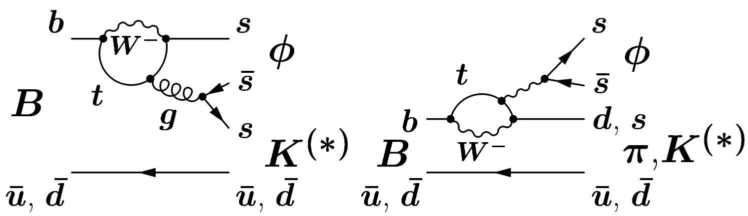

Figure 10: Diagrams describing the decays $B \to \phi K$, ϕK^*, and $\phi\pi$: the dominant gluonic penguin (left), flavor singlet (right). In the latter, the $s\bar{s}$ pair may be connected to the loop either through gluons or an electroweak boson.

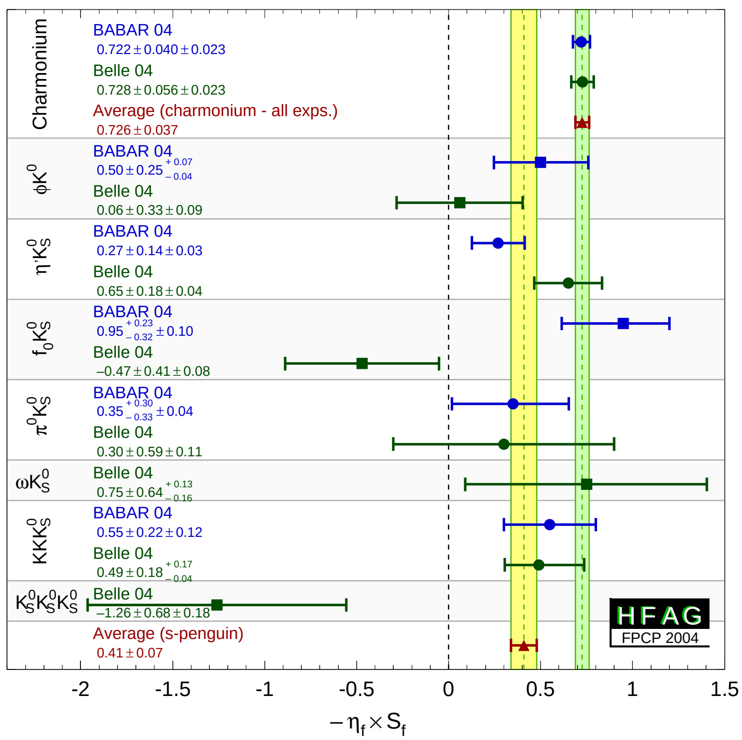

Figure 11: Summary of $\sin 2\beta$ measurements (HFAG, ICHEP 2004) [1]: S_f coefficient for charmonium and penguin-mediated channels, multiplied by the η_f CP-parity of the final state; the average of s-penguin channels is about 3.7 standard deviations away from the reference average value from charmonium modes.

5.3. The Unitarity Angle α (ϕ_2)

The measurement of the unitarity angle α (ϕ_2) poses a more difficult challenge than β (ϕ_1). The interference between mixing and decays to final CP eigenstates involving a $b \to u$ transition, for example $B \to \pi^+\pi^-$ (Figure 12, tree amplitude) would provide sensitivity to $\alpha = \pi - (\beta + \gamma)$ through the CP parameter $\lambda_{\pi\pi}$:

$$\lambda_{\pi\pi} = \left(\frac{q}{p}\right)_B \frac{\bar{A}_{\pi\pi}}{A_{\pi\pi}} = e^{-2i\beta} \frac{\bar{A}_{\pi\pi}}{A_{\pi\pi}}. \tag{15}$$

In the absence of penguin contributions $\bar{A}_{\pi\pi}/A_{\pi\pi} = e^{-2i\gamma}$ and eq. 15 would be reduced to $\lambda_{\pi\pi} = e^{2i\alpha}$. In this case, however, different weak phases are carried by the tree amplitude $T_{\pi\pi}$ and by the penguin amplitude $P_{\pi\pi}$, resulting in:

$$\lambda_{\pi\pi} = e^{i2\alpha} \frac{e^{-i\gamma} + P_{\pi\pi}/T_{\pi\pi}}{e^{+i\gamma} + P_{\pi\pi}/T_{\pi\pi}} \equiv |\lambda_{\pi\pi}| e^{2i\alpha_{eff}}. \tag{16}$$

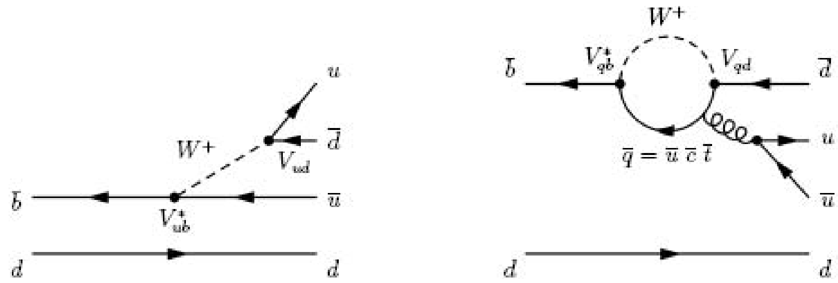

Figure 12: Decay tree and penguin diagrams for $B^0 \to \pi^+\pi^-$: the corresponding amplitudes have the same order $\mathcal{O}(\lambda^3)$. The tree amplitude is proportional to $V_{ub}V^*_{ud}$ with weak phase $\gamma \simeq \arg V_{ub}$, while the phase of the penguin amplitude, proportional to $V_{tb}V^*_{td}$, is related to $\beta \simeq -\arg V_{td}$.

As a consequence, the measurement of the time-dependent asymmetry parameters gives the coefficients $S_{\pi\pi} = \sqrt{1 - C^2_{\pi\pi}} \sin 2\alpha_{eff}$ and $C_{\pi\pi} \propto \sin\delta$, where δ is the strong phase difference between the two contributing decay amplitudes. The effective α_{eff} value obtained from this measurement must be corrected for the deviation due to the so-called 'penguin pollution'.

The canonical method [32] to determine the correction $\Delta\alpha = \alpha_{eff} - \alpha$ experimentally requires separating the different decay amplitudes by measurements of flavor-tagged decay rates of channels related by isospin transformations, for instance $\pi^+\pi^-$, $\pi^+\pi^0$ and $\pi^0\pi^0$, and combining the amplitudes in triangular relations. Complementary approaches to extract α are based on measurements of time-dependent asymmetries of $B \to \rho\rho$, $\rho\pi$.

Because the branching fraction $BF(B^0 \to \pi^0\pi^0) = (1.9 \pm 0.5) \times 10^{-6}$ [33], [2] is comparable to that for $B^+ \to \pi^+\pi^0$ and $B^0 \to \pi^+\pi^-$, the present upper limit on the correction is weak: $\Delta\alpha_{\pi\pi} < 35^o$ at 90% confidence level (CL) [34]. In contrast, the $\rho^0\rho^0$ channel has a much smaller branching fraction than the channels with charged ρ's [35]. As a consequence, it is possible to set a tighter limit on $\Delta\alpha_{\rho\rho} < 14^o$ [36]. This makes the $\rho\rho$ system particularly effective for measuring α in a model-independent way.

The decay $B^0 \to (\rho\pi)^0 \to \pi^+\pi^-\pi^0$, on the other end, offers the opportunity to directly extract both the weak and strong phases by a time-dependent analysis of the three-body final state [37], dominated by ρ resonances and their interference. An initial 'quasi-two-body' analysis [38] was restricted to the charged-ρ regions in the Dalitz plot, with the interference regions removed (Figure 13). At ICHEP 2004 BABAR presented an analysis extended to the entire region of interest in the Dalitz plot, which contains the ρ resonances of all three charges and their interference [41].

A summary of experimental results on $B \to \pi\pi$ is shown in Figure 14. The $S_{\pi\pi}$ and $C_{\pi\pi}$ coefficients (see equation 8) determined By BABAR and Belle differ by about two standard deviations, pointing to a need of more data. Belle [39] rules out the CP-conserving case, $C_{\pi\pi} = S_{\pi\pi} = 0$, at a level of 5.2 standard deviations, and finds evidence for direct CP violation with a significance at or greater than 3.2 standard deviations for any $S_{\pi\pi}$ value. The updated BABAR result [40], consistent with the previous BABAR measurement, does not confirm the large CP violation reported above.

In $B \to \rho\pi$, three CP-violating and two CP-conserving quasi-two-body parameters are determined, where BABAR finds a 2.9σ evidence of direct CP violation. In the complete Dalitz analysis, taking advantage of the interference between the ρ resonances, constraints are derived on the relative strong phase between B^0 decays to $\rho^-\pi^+$ and $\rho^+\pi^-$, and on the angle α of the Unitarity Triangle.

The combined constraints on α that can be derived from $b \to u\bar{u}d$ transitions are consistent with the SM expectations: combining the isospin analyses of $\pi\pi$, $\rho\rho$ and the Dalitz analysis of $\rho\pi$ the following result is obtained [1], using the fitting methods of ref. [17]: $\alpha = (100^{+9}_{-10}[1\sigma]^{+29}_{-20}[2\sigma])^o$, where the first errors are given at one standard deviation, and the second at two, respectively.

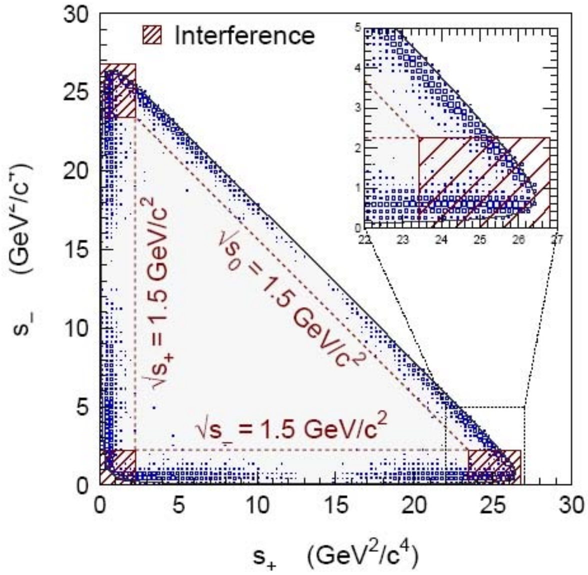

Figure 13: Dalitz plot for $B^0 \to (\rho\pi)^0 \to \pi^+\pi^-\pi^0$ decays; s_+ (s_-) is the invariant mass squared of the $\pi^0\pi^+$ ($\pi^0\pi^-$) pair in the final state. The dashed lines delimit the $\rho^+\pi^-$, $\rho^-\pi^+$, $\rho^0\pi^0$ resonance regions; the shaded areas correspond to the interference regions, initially excluded in the 'quasi-two-body' analysis.

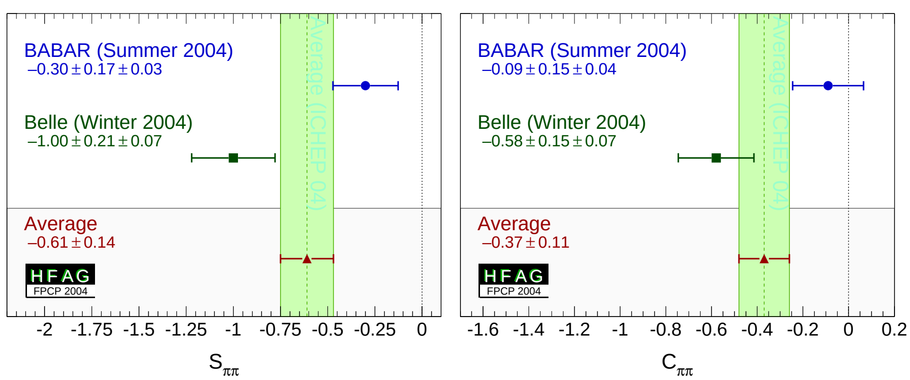

Figure 14: Summary of results for $\sin 2\alpha_{eff}$ from $B^0 \to \pi^+\pi^-$: $S_{\pi\pi}$ (left) and $C_{\pi\pi}$ (right) coefficients from BABAR and Belle; The figure and averages are from [1].

5.4. The Unitarity Angle γ (ϕ_3)

The direct determination of the unitarity angle γ poses the challange of measuring the relative phase of a CKM-suppressed $b \to u$ transition with respect to the dominant $b \to c$ transition.

Figure 15 (top) shows that $B^- \to D^0 K^-$ and $B^- \to \bar{D}^0 K^-$ decays can be used for this purpose, due to two key features: neutral D^0 and $\bar{D}^0$ mesons can decay to a common final state, and both neutral D flavors are produced via $b \to c\bar{u}s$ and $b \to u\bar{c}s$ transitions. The relative phase betwen the interfering amplitudes is the difference $\delta - \gamma$ of strong and weak phases; for the charge conjugate B^+ decay the relative phase is the sum $\delta + \gamma$. The interference term, sensitive to γ, that produces an observable asymmetry between B^- and B^+ decays, is suppressed by a factor $r_b \equiv A(b \to u)/A(b \to c) = R_u F_{cs}$ where $R_u = \sqrt{\bar{\rho}^2 + \bar{\eta}^2} \sim 0.4$ is the left side of the normalized Unitarity Triangle, and $F_{cs} \sim$ is a not well-known 'color suppression' factor [42], expected to be approximately in the range $0.2 \div 0.5$.

Additional suppression factors in useful event rates, and therefore in experimental sensitivity to γ, are due to the restrictions on the final states accessible from both D^0 and $\bar{D}^0$. In the Gronau-London-Wyler (GLW) approach [43],

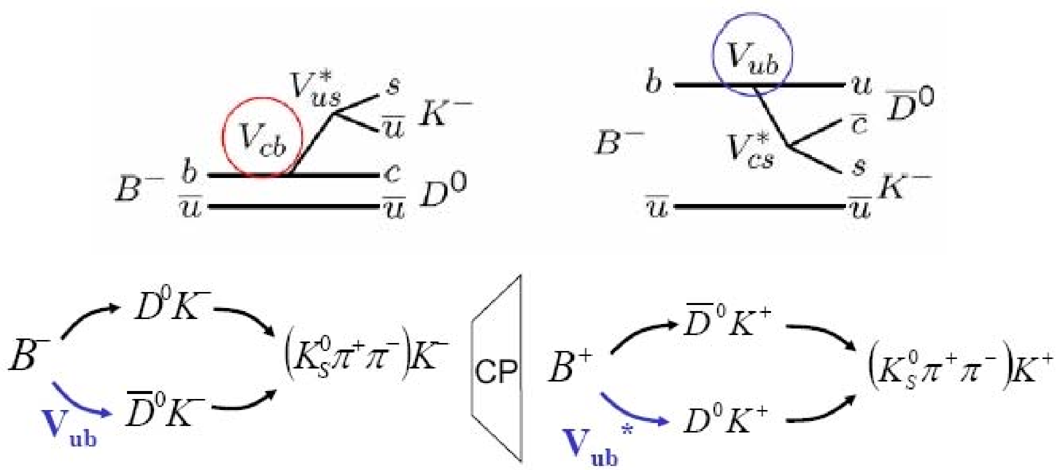

Figure 15: (top) Amplitudes for $B^- \to D^0K^-$ and $B^- \to \bar{D}^0K^-$; (bottom) interference obtained using three-body decays $D^0, \bar{D}^0 \to K_S^0\pi^+\pi^-$.

these are the relatively rare decays to CP eigenstates such as K^+K^-, $\pi^+\pi^-$. The Atwood-Dunietz-Soni (ADS) method [44] compensates for the r_b suppression factor by considering the 'Cabibbo favored' $D^0 \to K^+\pi^-$, 'doubly Cabibbo suppressed' $\bar{D}^0 \to K^+\pi^-$ and the charge conjugate decays. In this case, the favoured ($b \to c$) B decay followed by the doubly-suppressed D decay interferes with the suppressed ($b \to u$) B decay followed by the favored D decay. The resulting combined decay amplitudes are smaller, implying low rates, but the possible CP asymmetry is enhanced.

For both methods, the present experimental uncertainties are still too large. At the cost of some model dependence, a better sensitivity is obtained [45] by using three-body decays $D^0, \bar{D}^0 \to K_S^0\pi^+\pi^-$. The relative phase γ enters via an amplitude proportional to V_{ub}, as shown in Figure 15 (bottom).

This analysis method was pioneered by Belle [46], and later also applied by BABAR [48]. The amplitudes $M_1 \propto V_{cb}^*V_{us}$ (for $\bar{D}^0K^+$) and $M_2 \propto V_{ub}^*V_{cs}$ (for D^0K^+) interfere as the D^0 and $\bar{D}^0$ mesons decay into the same final state $K_S\pi^+\pi^-$. Assuming no CP asymmetry in neutral D decays, the amplitude of the B^+ and charge conjugate B^- decay can be written as

$$M_+ = f(m_+^2, m_-^2) + re^{i\gamma+i\delta}f(m_-^2, m_+^2) \tag{17}$$

$$M_- = f(m_-^2, m_+^2) + re^{-i\gamma+i\delta}f(m_+^2, m_-^2), \tag{18}$$

where m_+^2 and m_-^2 are the squared invariant masses of the $K_S\pi^+$ and $K_S\pi^-$ combinations, respectively, $f(m_+, m_-)$ is the complex amplitude for the $\bar{D}^0 \to K_S\pi{+}\pi{-}$ decay, and the absolute value of the ratio between the two interfering amplitudes, r, is predicted to be in the range $0.1 - 0.2$. The functional form of f is fixed by a $\bar{D}^0 \to K_S\pi^+\pi^-$ decay model, with parametres obtained from a large sample of flavor-tagged D decays produced in continuum e^+e^- annihilation. A simultaneous fit can then be performed for the B^+ and B^- decays with r, γ, and δ as free parameters.

The ICHEP 2004 update by Belle [47], including both DK^- and D^*K^- modes, gives $\phi_3 = (68^{+14}_{-15} \pm 13 \pm 11)^o$; the corresponding result from BABAR [48] is consistent: $\gamma = (70 \pm 26 \pm 10 \pm 10)^o$. In both cases, the first quoted error is statistical, the second accounts for experimental systematic uncertainties, and the third reflects the Dalitz model uncertainty.

A different experimental trade-off is involved in another method [49] that uses the more frequent ($BF \simeq \mathcal{O}(10^{-3})$) decays $B^0 \to D^\pm\pi^\mp$, $B^0 \to D^{*\pm}\pi^\mp$ and $B^0 \to D^\pm\rho^\mp$, where small ($A_{CP} \simeq \mathcal{O}(10^{-2})$) CP asymmetries are expected. The interference in this case is between the Cabibbo-favoured amplitude (e.g. $B^0 \to D^-\pi^+$) with the doubly Cabibbo-suppressed amplitude (e.g. $B^0 \to D^+\pi^-$). The relative weak phase between these two amplitudes is γ and, when combined with the B mixing phase, the total phase difference is $(2\beta + \gamma)$. The size of the time-dependent CP

asymmetry is proportional to the ratio of magnitudes of the suppressed and favoured amplitudes, expected to be about 0.02, that can in principle be obtained experimentally from the corresponding suppressed charged B decays using isospin, or from self-tagging neutral B decays with strangeness using SU(3) symmetry. Both BABAR [50] and Belle [51] reported results on this difficult time-dependent CP asymmetry measurement using exclusive and inclusive reconstruction methods, demonstrating its feasibility and deriving preliminary constraints on the UT, based on assumptions on the ratio of suppressed and favoured amplitudes that cannot be measured directly.

5.5. Other measurements

The sides of the Unitarity Triangle ($|V_{cb}^*V_{cd}|$, $|V_{ub}^*V_{ud}|$ and $|V_{tb}^*V_{td}|$) are experimentally accessible at the B-factories and elsewhere; their measurement, combined with those of the angles discussed above, over-constrain the UT. In particular, $|V_{cb}|$ and $|V_{ub}|$ are determined by the branching fractions of semileptonic B decays with and without charmed hadrons in the final state, and $|V_{td}|$ by B mixing.

A discussion of these measurements is beyond the scope of the present review. It should be noted that also the usual assumptions of CPT conservation and of the absence of CP violation in B mixing (violation of type (ii), as defined in Section 4.1) are subject to experimental tests; although not yet very stringent, upper limits on such effects in the B system have been obtained [52] extending the CPT tests performed in the K system [53].

6. INTERPRETATION: CKM FITTING

Global fits to the existing measurements can test their overall compatibility with the CKM model and determine the best values of the corresponding SM parameters. Several reviews describe the results of fits performed by different authors [54]. The ‘CKMfitter’ [55] and ‘UTfit’ [56] groups maintain up-to-date web-accessible summaries of their fits, using different statistical approaches.

The ‘standard CKM fit’ from the CKMfitter group (Figure 16 (top)) only includes those obervables for which the Standard Model predictions (and hence the CKM constraints) can be considered to be ‘quantitatively under control’ [17]. Comparisons are then made with other available measurements whose interpretation depends significantly on additional theoretical assumptions; including them in the fit gives useful constraints on the corresponding parameters (ratios of penguin to tree amplitudes, strong phases, etc.).

We can share their conclusions [17]: the success of the standard CKM fit strongly supports the CKM mechanism, and the construction of a model-independent Unitarity Triangle is not (yet) precise enough to exclude large non-standard corrections to loop diagrams (mixing, penguins). This situation will improve in the future as soon as more accurate determinations of some of the parameters, in particular the angles α and γ, become available.

Similar results from the UTfit group are also shown in Figure 16 (bottom).

7. OUTLOOK AND CONCLUSIONS

Great progress has been achieved in the last few years: CP-violation has been experimentally established in B-mesons decays by the BABAR and Belle measurements at the B factories, but the interest of the field of flavor physics is far from being exhausted.

The CKM mechanism for CP violation in the Standard Model passed its first test in the B sector with the measurement of the unitarity angle β (ϕ_1) in $B^0 \to J/\psi K^0$; this is now becoming a precision measurement, against which $b \to s\bar{s}s$ channels involving penguin amplitudes can be gauged. Ground-breaking theoretical and experimental work has been adding more options for determining the more elusive α (ϕ_2) and γ (ϕ_3) unitarity angles that are now measured respectively at the 10% and 20% level of accuracy.

At present, these measurements are consistent with the predictions of the Kobayashi-Maskawa mechanism of the Standard Model. However, a dynamically generated matter-antimatter asymmetry of the universe requires additional

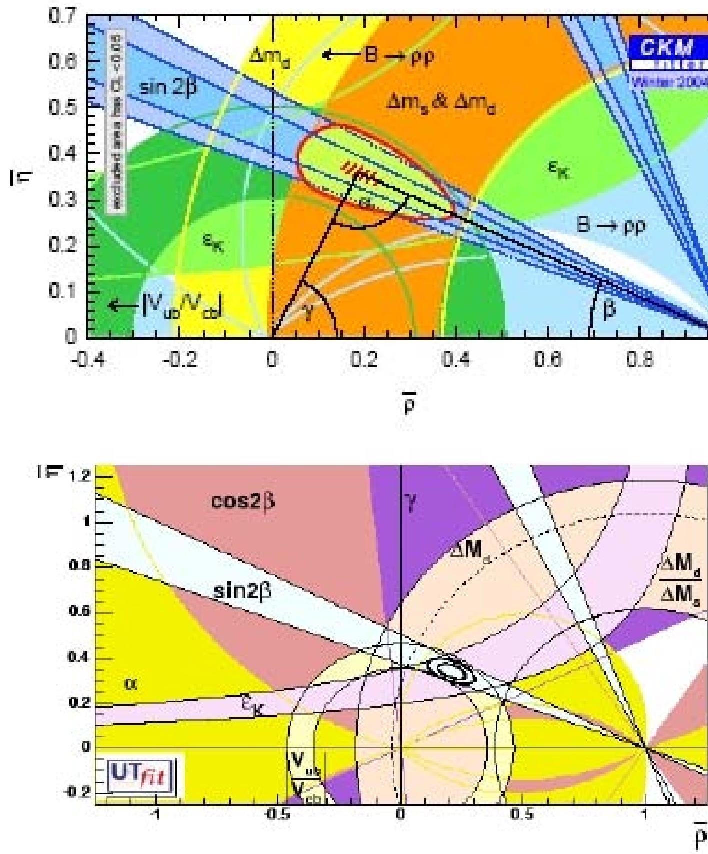

Figure 16: (top) Confidence levels in the $(\bar{\rho}, \bar{\eta})$ plane obtained from the global CKM fit [17] of the CKMfitter group, with a frequentist approach. The constraints from the HFAG averages (ICHEP 2004) of $\sin 2\beta$ and $\sin 2\alpha$ are included in the fit, giving $\bar{\rho} = 0.189^{+0.088}_{-0.070}$ and $\bar{\eta} = 0.358^{+0.046}_{-0.042}$. The shaded areas indicate the regions of $\geq 5\%$ Confidence Levels (CL); for $\sin 2\beta$ also the $\geq 32\%$ constraint is shown. The hatched area in the center of the combined fit result for the apex of the Unitarity Triangle indicates the region where theoretical errors dominate.
(bottom) Allowed regions for $(\bar{\rho}, \bar{\eta})$ from a fit performed by the UTfit group, with a Bayesian method. The closed contours at 68% and 95% probability are shown for the apex of the UT, corresponding to $\bar{\rho} = 0.196 \pm 0.045$ and $\bar{\eta} = 0.347 \pm 0.025$. The full lines correspond to 95% probability regions for the constraints, given by the measurements of $|V_{ub}|/|V_{cb}|$, ϵ_K, Δm_d, Δm_s, $\sin 2\beta$, γ, α and $\cos 2\beta$, respectively. The figure is taken from ref.[57].

sources of CP violation that can be generated by extensions to the Standard Model. Theoretical expectations favor $b \to s$ transitions mediated by loop diagrams for the observation of deviations from the CKM mechanism in meson decays. New CP violation sources might also be observed in the future in different sectors, such as neutrino oscillations or electric dipole moments.

With both B factories planning to double the integrated luminosity to about 500 fb^{-1} by 2006 and again to about 1 ab^{-1} per experiment before the end of the decade, prospects are good for tightening the grip on the Unitarity Triangle and further pushing the CP tests of the Standard Model in the quark sector. Present hints of non-SM effects, lurking in loop diagrams and specifically in $\sin 2\beta$ as measured by penguin-mediated channels, will be under close scrutiny as the available statistics will be increasing. Among the other key observables for overconstraining the UT, the unitarity angle γ and the $B^0_s - \bar{B}^0_s$ mixing parameter are particularly effective and will be the focus of dedicated experimental work.

Experiments at hadron colliders are specially suited for measuring γ and some rare B decays; they are also unique in giving access to B_s production. At the Tevatron at FNAL, the CDF and D0 experiments implemented new triggers, allowing them to record and study hadronic B decays. They have also been tuning their analysis methods on B_d mixing, in order to tackle the measurement of the more rapid and so far unseen B_s oscillations. With LHC expected to start operating at CERN around 2007, a new dedicated facility, the LHCb experiment [58], will join these efforts. Finally, the discovery potential of flavor physics in the LHC era is also actively investigated by a community interested in pursuing the electron-positron approach at a possible future 'Super B-factory' [59], aiming at an order of magnitude increase in luminosity.

Acknowledgments

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