MEASUREMENT OF B MIXING FREQUENCY AND CP VIOLATION PARAMETER $\sin 2\beta$ ($\sin 2\phi_1$) AT B FACTORY EXPERIMENTS

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ABSTRACT

Recent results on B mixing and CP violation from the B-factory experiments, BABAR at PEP-II and Belle at KEK-B, are summarized. A discussion of CP violation is then presented which concentrates on the CP parameter $\sin 2\beta$ (also known as $\sin 2\phi_1$). The most recent measurements of this parameter from B-factory data yield

$$\sin 2\beta = 0.741 \pm 0.067 \, \text{(stat)} \pm 0.033 \, \text{(syst)} \, \text{(BaBar)}$$

$$\sin 2\phi_1 = 0.719 \pm 0.072 \, \text{(stat)} \pm 0.035 \, \text{(syst)} \, \text{(Belle)}. $$

These two B-factory results contribute to the current world average of

$$\sin 2\beta = 0.735 \pm 0.055$$
1 Introduction

In the Standard Model, CP violation is made possible by an irreducible complex phase in the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix \([1]\). CP violation is expected if this complex phase is non-zero. The unitarity of the CKM matrix results in six triangles of equal area in the complex plane (Unitarity Triangles). A non-zero area implies the existence of a CP-violating phase – in other words, \textit{if the inner angles of these Unitary Triangles are found to be non-zero, CP-violation is observed}. For the neutral \(B\)-meson system, the angles in question are \(\alpha\), \(\beta\) and \(\gamma\) and are defined by the condition

\[ V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0. \]  

(1)

In particular, the measurement of the angle \(\beta\), defined as

\[ \beta \equiv \arg \left[ -V_{cd}V_{cb}^* / V_{td}V_{tb}^* \right], \]  

(2)

is the main focus of this paper.

Observation of CP violation in neutral \(B\) decays\(^2\) through the measurement of \(\sin^2\beta\) was reported in summer 2001 by both the \(\text{BABAR}\) \([2]\) and Belle \([3]\) collaborations employing data luminosities of 29.7 and 29.1 \(\text{fb}^{-1}\), respectively. By summer 2002, each experiment’s total accumulated luminosity had almost tripled. The more precise \(\sin^2\beta\) results presented in this paper are based on the full samples obtained for summer 2002: 81 \(\text{fb}^{-1}\) (88 million \(B\bar{B}\) decays) for \(\text{BABAR}\) and 78 \(\text{fb}^{-1}\) (85 million \(B\bar{B}\) decays) for Belle.

2 B-Factory Experiments: \(\text{BABAR}\) and Belle

The \(\text{BABAR}\) and Belle B-factory experiments share similar design concepts. Both experiments center around a high luminosity asymmetric electron-positron collider operating at the \(\Upsilon(4S)\) resonance. Each experiment also depends on a high-precision detector designed specifically for high-rate, Lorentz-boosted \(B\bar{B}\) production. The PEP-II collider (\(\text{BABAR}\)) counter-circulates an electron beam of 9.0 GeV against a positron beam of 3.1 GeV, resulting in a center-of-mass boost of \(\beta\gamma = 0.55\). The KEKB collider (Belle) collides electrons and positrons at 8.0 GeV and 3.5 GeV, respectively, resulting in a boost of \(\beta\gamma = 0.425\). B-mesons produced at each collider

\(^1\)BaBar uses notation \(\{\alpha, \beta, \gamma\}\) and Belle uses notation \(\{\phi_2, \phi_1, \phi_3\}\) to address same three CP angles. In this paper, \(\text{BABAR}\) notation is used except for description of Belle-specific results.

\(^2\)Charge-conjugation is implied throughout this document.
are boosted along the $e^-$ direction because of the asymmetric energies, allowing for the measurement of the decay-time difference of the two Bs.

The primary sub-detectors of $\text{BABAR}$ include a drift chamber (DCH) and a silicon vertex tracker (SVT), both operating inside a 1.5 T magnetic field provided by a super-conducting solenoid. Surrounding the tracking volume is a detector of internally reflected Čerenkov radiation (DIRC), an electromagnetic calorimeter (EMC) and an instrumented flux return (IFR).

The Belle apparatus consists of a silicon vertex detector (SVD), a central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) located inside a super-conducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect $K_L^0$ mesons and to identify muons (KLM).

For the CP and mixing measurements, important detector capabilities include tracking, vertexing and particle identification (PID). Details on how each experiment address these requirements can be found in Ref. [4] and Ref. [5].

3 Overview Of Measurement Technique

3.1 Production of $B^0\overline{B}^0$

As a consequence of Bose-Einstein statistics, the $B^0\overline{B}^0$ pairs produced from the $\Upsilon(4S)$ decays remain in a coherent P-wave state until one of the two B-mesons decays. At the moment of the first decay ($t = 0$), the two B-mesons are in opposite flavor states – knowing the flavor state of one B implies knowledge of the other. Between the first decay and its own decay, the second B-meson’s flavor evolves according to a time-dependent oscillatory pattern. If the flavor of one B is known when it decays then the flavor state of the other B at its decay point is solely determined by the proper time between decays ($\Delta t$) and mixing frequency $\Delta m_d$.

3.2 Exclusive Reconstruction of One B-Meson

Given the large number of B-mesons produced at B-Factories, it is conceivable to exclusively reconstruct one of the two B-mesons into a known decay mode. Excluding from consideration the decay products of this reconstructed B ($B_{rec}$), the remaining particles in the event then presumably belong to the “other B”. Often, the flavor of this “other B” can be determined through an inclusive flavor tagging method (B Flavor-Tagging). For this reason, this inclusively “reconstructed” second B-meson is
commonly referred as the \((B_{tag})\). The \(B_{rec}\) and \(B_{tag}\) can be individually vertexed, and the distance between the two vertices used to determine the proper-time difference \(\Delta t(\equiv t_{rec} - t_{tag})\).

The choice of exclusive decay modes is determined according to physics objectives. For a \(B\)-mixing measurement, the \(B_{rec}\) has to decay into one of the (self-tagged) flavor eigenstates. The mixing frequency \(\Delta m_d\) is determined by comparing the flavor of the \(B_{rec}\) and \(B_{tag}\) (both known) in a time-dependent way. For CP measurements, \(B_{rec}\)’s are required to be reconstructed in a CP eigenstate, such as \(J/\psi K_s^0\), etc.

### 3.3 B Decay Time Interval

In asymmetric \(B\bar{B}\) production, as at \(\text{BABAR}\) and Belle, the large boost causes the \(B\) mesons to fly preferentially along the beam direction (conventionally the \(z\)-axis). Accordingly, the time interval \(\Delta t\) between the two \(B\) decays is calculated, to a good approximation, as

\[
\Delta t = \Delta z / (\beta \gamma c),
\]

where \(\Delta z\) is the distance between the decay vertices of \(B_{rec}\) and \(B_{tag}\) along the \(z\)-axis. The \(B_{rec}\) vertex is determined by using the charged tracks from its exclusive decay products; intermediate vertices, such as those from \(K_s^0\) decay, are also reconstructed. The \(B_{tag}\) vertex is obtained by an inclusive fit on charged tracks which do not belong to the exclusive \(B_{rec}\). Constraints from the beam spot locations and \(B_{rec}\) momentum are applied when fitting for \(B_{tag}\).

The \(\Delta t\) resolution is affected by the detector resolution for both the \(B_{rec}\) and \(B_{tag}\) vertices, by a shift on the \(B_{tag}\) vertex due to secondary charmed decays, and by kinematic smearing due to the fact that the \(B\) flight is not exactly in the \(z\)-direction. Accordingly, an empirical resolution function is used to model these effects. In both experiments, the parameters in the resolution functions are determined in data from fits to the neutral and charged \(B\) meson lifetime. An average r.m.s. \(\Delta t\) resolution is 1.1ps for \(\text{BABAR}\) and 1.43ps for Belle, both obtained from data.

### 3.4 Flavor Tagging

The flavor of the \(B_{tag}\) is determined through various flavor signatures among its daughter tracks. High momentum (primary) leptons, kaons and soft pions from \(D^{*+}\) decay are primary sources for flavor tagging. In addition, \(\Lambda\) baryons and lower
Table 1: Efficiencies $\epsilon_i$, average mistag fractions $w_i$, mistag fraction differences $\Delta w_i = w_i(B^0) - w_i(B^0)$, and $Q$ extracted for each tagging category $i$ from the $B_{flav}$ and $B_{CP}$ sample. This data was collected by the BABAR collaboration.

| Category   | $\epsilon$ (%) | $w$ (%) | $\Delta w$ (%) | $Q$ (%) |
|------------|-----------------|---------|----------------|--------|
| Lepton     | 9.1 ± 0.2       | 3.3 ± 0.6 | −1.5 ± 1.1     | 7.9 ± 0.3 |
| Kaon I     | 16.7 ± 0.2      | 10.0 ± 0.7 | −1.3 ± 1.1     | 10.7 ± 0.4 |
| Kaon II    | 19.8 ± 0.3      | 20.9 ± 0.8 | −4.4 ± 1.2     | 6.7 ± 0.4 |
| Inclusive  | 20.0 ± 0.3      | 31.5 ± 0.9 | −2.4 ± 1.3     | 2.7 ± 0.3 |
| All        | 65.6 ± 0.5      |         |                | 28.1 ± 0.7 |

momentum (secondary) leptons can also be used to assist tagging. To obtain optimal tagging efficiency, both experiments use multivariate algorithms to combine various sources of flavor information in an event. Similar events, judged by their physics content or estimated tagging purity, are usually grouped into tagging categories to aid in the study of tagging-based systematic errors.

The figure of merit for B flavor-tagging is the effective tagging efficiency, 

$$Q \equiv \sum_i \epsilon_i (1 - 2w_i)^2,$$

where $i$ sums over tagging categories. Since the CP measurement error and tagging efficiency are related ($\sigma_{asym} \propto 1/\sqrt{Q}$), a higher effective tagging efficiency reduces CP measurement error.

At BABAR, events are grouped into four hierarchical, mutually exclusive tagging categories based on their physics contents. The Lepton category contains events with an identified high momentum lepton. Events with a kaon are assigned to either the Kaon I or Kaon II category. Among the two, the Kaon I category contains events with higher estimated tagging probability, contributed by additional tagging sources such as a soft pion compatible with $D^{*+}$ decay. The Kaon II category also contains remaining events with a soft pion. All other events are assigned to the Inclusive category except for those that have no useful tagging information (which are excluded from further analysis). A set of neural networks have been developed to classify events and to provide estimated mistag probability. The efficiency and mistag probability for each of the four tagging categories can be obtained from data as shown in table 1. Based on these measured efficiencies and mistag probability, the effective tagging efficiency ($Q$) is calculated to be 28.1%.

At Belle, events are instead grouped into tagging categories based solely on estimated tagging probability. A quantity $r$ is assigned to each event. An $r$ value of zero signifies no tagging power and an $r$ value of 1 means perfect tagging.
Events are sorted into six intervals of \( r \) between 0 and 1, according to flavor purity. The event fraction and mistag probability for each category are determined directly from data as summarized in Table 2. The corresponding \( Q \) value for Belle is 28.8\%, similar to that of BABAR’s.

Table 2: The event fractions (\( \epsilon_l \)) and wrong tag fractions (\( w_l \)) for each \( r \) interval. The errors include both statistical and systematic uncertainties. This data was collected by the Belle collaboration.

| Category(l) | \( r \)       | \( \epsilon_l \) | \( w_l \)        |
|------------|---------------|-------------------|------------------|
| 1          | 0.000 – 0.250 | 0.399             | 0.458 ± 0.006   |
| 2          | 0.250 – 0.500 | 0.146             | 0.336 ± 0.009   |
| 3          | 0.500 – 0.625 | 0.104             | 0.229 ± 0.011   |
| 4          | 0.625 – 0.750 | 0.122             | 0.159 ± 0.009   |
| 5          | 0.750 – 0.875 | 0.094             | 0.111 ± 0.009   |
| 6          | 0.875 – 1.000 | 0.137             | 0.020 ± 0.007   |

4 Measurement Of \( B^0B^0 \) Oscillation Frequency

To measure the \( B^0 \) mixing parameter \( \Delta m_d \), the flavors of both the \( B_{\text{rec}} \) and \( B_{\text{tag}} \) need to be determined. The mixing frequency is extracted from the time evolution of opposite-flavor (“unmixed”) and same-flavor (“mixed”) \( B \)-decays. The physics probability density function (PDF), before accounting for detector and background effects, is:

\[
f(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} [1 \pm \cos (\Delta m_d \Delta t)],
\]

where \( \tau_{B^0} \) is the \( B^0 \) lifetime, and “\( \pm \)” denotes “\( + \)” for unmixed events and “\( - \)” for mixed events.

Samples that can be used for the mixing measurement include:

1. “Fully Hadronic”, where \( B_{\text{rec}} \) is completely reconstructed to the exclusive hadronic decays \( D^{(*)-}h \) (where \( h = \pi^+, \rho^+, a_1^+ \)), \( J/\psi K^{*0}(K^{*0} \rightarrow K^+\pi^-) \).
2. “Semileptonic”, where \( B_{\text{rec}} \) is reconstructed to \( D^{*-}l^+\nu \).
3. “Partial \( D^* \pi \)”, where \( B_{\text{rec}} \) is partially reconstructed to \( D^{*-}\pi^+ \) (\( D^{*-} \rightarrow D^0\pi^- \)).
4. “Dilepton”, where instead of attempting to reconstruct one of the \( B \) decays, events with two high momentum leptons are used.

For the first three samples above, the flavor of the \( B_{\text{rec}} \) is determined by the charge of its daughters and the flavor of the \( B_{\text{tag}} \) is provided by flavor tagging.
The time-difference $\Delta t$ is determined using the $B_{\text{rec}}$ and $B_{\text{tag}}$ vertices. For dilepton samples, the charges of the two leptons (which are presumed to be from semileptonic B decays) indicate the flavor of the B-mesons. Proper-time information is obtained using the impact parameters of the two leptons.

BaBar has reported results from three measurements [7]:

- $\Delta m_d = 0.516 \pm 0.016 ($stat$) \pm 0.010 ($syst$) \text{ ps}^{-1}$ (“Hadronic”, 30 fb$^{-1}$)
- $\Delta m_d = 0.492 \pm 0.018 ($stat$) \pm 0.013 ($syst$) \text{ ps}^{-1}$ (“Semileptonic”, 21 fb$^{-1}$)
- $\Delta m_d = 0.493 \pm 0.012 ($stat$) \pm 0.009 ($syst$) \text{ ps}^{-1}$ (“Dilepton”, 21 fb$^{-1}$)

Belle has reported results from four measurements [8]:

- $\Delta m_d = 0.528 \pm 0.017 ($stat$) \pm 0.011 ($syst$) \text{ ps}^{-1}$ (“Hadronic”, 29 fb$^{-1}$)
- $\Delta m_d = 0.494 \pm 0.012 ($stat$) \pm 0.015 ($syst$) \text{ ps}^{-1}$ (“Semileptonic”, 29 fb$^{-1}$)
- $\Delta m_d = 0.505 \pm 0.017 ($stat$) \pm 0.020 ($syst$) \text{ ps}^{-1}$ (“Partial $D^*\pi$”, 29 fb$^{-1}$)
- $\Delta m_d = 0.503 \pm 0.008 ($stat$) \pm 0.009 ($syst$) \text{ ps}^{-1}$ (“Dilepton”, 29 fb$^{-1}$)

Combining BABAR and Belle results yields $\Delta m_d = 0.503 \pm 0.007 \text{ ps}^{-1}$, as compared with combined non B-factory results $\Delta m_d = 0.498 \pm 0.013 \text{ ps}^{-1}$ (LEP+SLD+CDF).

If all results are combined, a world average $\Delta m_d$ value of $0.503 \pm 0.006 \text{ ps}^{-1}$ is obtained.

5 CP Violation Measurement With Charmonium $b \to c\bar{s} s$ Final States

For the measurement of CP asymmetries, the $B_{\text{rec}}$ needs to be reconstructed in a CP eigenstate ($B_{\text{CP}}$) with eigenvalue $\eta_f = -1$ or $+1$. For events where $B_{\text{rec}} = B_{\text{CP}}$ and the flavor of $B_{\text{tag}}$ is known to be $B_0$ ($B_0^*$), the decay rate $f_+ (f_-)$ is given by

$$f_\pm (\Delta t) = \frac{e^{-|\Delta t|/\tau_{B_0}}}{4\tau_{B_0}} \left[ 1 \pm \frac{2 Im \lambda}{1 + |\lambda|^2} \sin (\Delta m_d \Delta t) \mp \frac{1 - |\lambda|^2}{1 + |\lambda|^2} \cos (\Delta m_d \Delta t) \right],$$

(6)

where $\lambda$ is a complex parameter that depends on both the $B_0$-$\bar{B}_0^*$ oscillation amplitude and the amplitudes describing $B_0^*$ and $B_0$ decays to a common CP final state. CP violation arises if $\lambda$ is not unity. In other words, CP violation is manifested with a non vanishing sine or cosine term in the equation. Experimentally, CP violation can be observed as a difference between the $\Delta t$ distributions of $B_0$- and $\bar{B}_0^*$-tagged events or as an asymmetry with respect to $\Delta t = 0$ for either flavor tag.

Among many possible CP modes, $b \to c\bar{s} s$ (charmonium) decays offer the best opportunity for CP violation measurement [6]. These modes include the CP-odd ($\eta_f = -1$) final states $J/\psi K_{S}^0$, $\psi(2S)K_{S}^0$, $\chi_{c1}K_{S}^0$, and $\eta_c K_{S}^0$, and CP-even ($\eta_f = +1$)
state \( J/\psi K^0 \). In addition, a CP-mixed state \( J/\psi K^* \), where \( K^* \) decays to \( K^0 \pi^0 \), can also be used after its CP composition is measured through an angular analysis. For this CP-mixed \( J/\psi K^* \) decay, \( \text{BABAR} \) and Belle find the CP-odd fraction to be \( 16.0 \pm 3.5\% \) and \( 19 \pm 2(\text{stat}) \pm 3(\text{syst})\% \), respectively. This fraction can be used to compute an effective \( \eta_f \) (\( \sim 0.65 \)) for use in the CP extraction.

| Sample | \( N_{\text{tag}} \) | \( P(\%) \) | \( \text{sin}2\beta \) |
|--------|----------------|---------|-----------------|
| \( J/\psi K^0(\psi(2S)K^0_{S}, \chi_{c1}K^0_{S}, \eta_cK^0_{S}) \) | 1506 | 94 | 0.76 ± 0.07 |
| \( J/\psi K^0 (\eta_f = +1) \) | 988 | 55 | 0.72 ± 0.16 |
| \( J/\psi K^0(K^* \rightarrow K^0 \pi^0) \) | 147 | 81 | 0.22 ± 0.52 |
| \( J/\psi K^0 (K^0_S \rightarrow \pi^+ \pi^-) \) | 974 | 97 | 0.82 ± 0.08 |
| \( J/\psi K^0 (K^0_S \rightarrow \pi^0 \pi^0) \) | 170 | 89 | 0.39 ± 0.24 |
| \( \psi(2S)K^0 (K^0_S \rightarrow \pi^+ \pi^-) \) | 150 | 97 | 0.69 ± 0.24 |
| \( \chi_{c1}K^0_{S} \) | 80 | 95 | 1.01 ± 0.40 |
| \( \eta_cK^0_{S} \) | 132 | 73 | 0.59 ± 0.32 |
| Lepton category | 220 | 98 | 0.79 ± 0.11 |
| Kaon I category | 400 | 93 | 0.78 ± 0.12 |
| Kaon II category | 444 | 93 | 0.73 ± 0.17 |
| Inclusive category | 442 | 92 | 0.45 ± 0.28 |
| \( B^0 \) tags | 740 | 94 | 0.76 ± 0.10 |
| \( \overline{B}^0 \) tags | 766 | 93 | 0.75 ± 0.10 |
| \( B_{\text{flav}} \) sample | 25375 | 85 | 0.02 ± 0.02 |
| charged \( B \) sample | 22160 | 89 | 0.02 ± 0.02 |
| Full \( CP \) sample | 2641 | 78 | 0.74 ± 0.07 |

In the Standard Model, \( \lambda \) is expected to be \( \eta_f e^{-2i\beta} \) (\(|\lambda| = 1, \text{Im}(\lambda) = -\eta_f \text{sin}2\beta\)) for these charmonium decays. Thus, a measurement with the time-dependent decay rates in equation \( 8 \) directly reveals the CP parameter \( \text{sin}2\beta \) with little ambiguity.

Both \( \text{BABAR} \) and Belle reconstruct these charmonium modes for use in their \( \text{sin}2\beta \) measurements \([12, 13]\). Yields on each signal mode are summarized in table \( 3 \) for BaBar and in table \( 4 \) for Belle. Shown also in these two tables are measured \( \text{sin}2\beta \) (\( \text{sin}2\phi_1 \)) value for each sub-sample (see text below).

After the flavor of the \( B_{\text{tag}} \) and time-difference \( \Delta t \) are determined for each event in the CP sample, the whole sample is used to construct a likelihood function

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3 Only events with a flavor tag are included, total Tagging efficiency is \( 65.6 \pm 0.5\% \).
Table 4: The numbers of reconstructed $B \rightarrow f_{CP}$ candidates before flavor tagging and vertex reconstruction ($N_{rec}$), the numbers of events used for the $\sin 2\phi_1$ determination ($N_{ev}$), and the estimated signal purity for each $f_{CP}$ mode. (Belle experiment.)

| Sample | $N_{rec}$ | $N_{ev}$ | Purity | $\sin 2\phi_1$ |
|--------|-----------|----------|--------|--------------|
| $J/\psi(\ell^+\ell^-)K^{0}_S(\pi^+\pi^-)$ | 1285 | 1116 | 0.98 | 0.73 ± 0.10 |
| $J/\psi(\ell^+\ell^-)K^{0}_S(\pi^+\pi^-)$ | 188 | 162 | 0.82 | 0.73 ± 0.10 |
| $\psi(2S)(\ell^+\ell^-)K^{0}_S(\pi^+\pi^-)$ | 91 | 76 | 0.96 | 0.73 ± 0.10 |
| $\psi(2S)J/\psi(\pi^+\pi^-)K^{0}_S(\pi^+\pi^-)$ | 112 | 96 | 0.91 | 0.73 ± 0.10 |
| $\chi_{c1}(J/\psi\gamma)K^{0}_S(\pi^+\pi^-)$ | 77 | 67 | 0.96 | 0.73 ± 0.10 |
| $\eta_c(K^0\pi^+\pi^-)K_S^0(\pi^+\pi^-)$ | 72 | 63 | 0.65 | 0.73 ± 0.10 |
| $\eta_c(K^{+}\pi^-\pi^0)K_S^0(\pi^+\pi^-)$ | 49 | 44 | 0.72 | 0.73 ± 0.10 |
| $\eta_c(p\bar{p}K_S^0(\pi^+\pi^-)$ | 21 | 15 | 0.94 | 0.73 ± 0.10 |
| $J/\psi(\ell^+\ell^-)K^{*0}(K_S^0\pi^0)$ | 101 | 89 | 0.92 | 0.73 ± 0.10 |
| $J/\psi(\ell^+\ell^-)K^{*0}(K_S^0\pi^0)$ | 1330 | 1230 | 0.63 | 0.73 ± 0.10 |
| All CP Sample | 3326 | 2958 | 0.81 | 0.73 ± 0.10 |

Based on the PDF

$$f(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left[ 1 - \eta_f q(1 - 2w) \sin \beta \sin (\Delta m_d \Delta t) \right]$$

where $q = +1(-1)$ when $B_{tag}$ is tagged as $B^0 (\bar{B}^0)$ and $w$ is the estimated mistag probability for the tagging category to which the event belongs. As mentioned earlier, both BaBar and Belle obtain $w$ from data. The CP-parameter $\sin 2\beta$ in the PDF serves as a free parameter and is to be extracted from a fit on the data employing the PDF.

The above physics PDF has to be modified to take into account the time resolution function and background time distribution. Details of time resolution treatment and fitting procedure can be found in [10] for BaBar and in [11] for Belle.

The value of $\sin 2\beta$ is determined by an unbinned maximum-likelihood fit to the observed $\Delta t$ distribution. For all CP modes combined, the fitted $\sin 2\beta$ ($\sin 2\phi_1$) values are:

$$\sin 2\beta = 0.741 \pm 0.067 \text{ (stat) } \pm 0.033 \text{ (syst). (BaBar)}$$
$$\sin 2\phi_1 = 0.719 \pm 0.074 \text{ (stat) } \pm 0.035 \text{ (syst). (Belle)}$$

Fitted $\sin 2\beta$ values for various sub-samples are included in table 3 for BaBar and table 4 for Belle. No inconsistency between the samples is observed.
Combining these latest two \( \sin^2 \beta \) results from \( \text{BABAR} \) and Belle with earlier (non B-factory) results, namely \((0.84^{+0.82}_{-1.04} \pm 0.16)\) from Aleph, \((0.79^{+0.41}_{-0.44})\) from CDF and \((3.20^{+1.8}_{-2.0} \pm 0.5)\) from OPAL, a world average of \( \sin^2 \beta = 0.735 \pm 0.055 \) is obtained.

This world average value on (directly measured) \( \sin^2 \beta \) can be compared with the Standard Model constraints in the \( \rho - \eta \) plane, as shown in figure 1. The indirect constraints are realized from measurements on \( |V_{ub}/V_{cb}|, \Delta m_d, \Delta m_s \) and CP-violation in the kaon system. Within the current measurement uncertainties, good agreement is observed. Measurements with improved precision and, in particular, measurements of other CP angles are necessary to provide a more stringent test on the Standard Model CKM theory of CP-violation.

![Figure 1: Directly measured \( \sin^2 \beta \) result shown as straight lines in the CKM \( \eta - \rho \) plane. Contours near \( \eta = 0.3 \) and \( \rho = 0.2 \) are Standard Model prediction fitted with constraints from other measurements.](image)

The \( \sin^2 \beta \) measurements discussed so far are performed with the assumption \( |\lambda| = 1 \), as is predicted by the Standard Model for the \( b \rightarrow c\bar{s}s \) decays. To test this assumption, a more general physics PDF, shown earlier in equation 6, can instead be used. A fitting based on this generalized PDF gives

\[
|\lambda| = 0.948 \pm 0.051 \text{ (stat)} \pm 0.017 \text{ (syst)} \text{ (BaBar)}
\]

\(^4\)Belle uses all \( CP \) modes in this generalized fit while \( \text{BABAR} \) fits only on \( CP \)-odd modes.
$|\lambda| = 0.950 \pm 0.049 \text{ (stat)} \pm 0.026 \text{ (syst) (Belle)}$

The coefficient of $\sin(\Delta m_d \Delta t)$ term is simultaneously fitted to be $0.759 \pm 0.074 \text{ (stat)}$ at \textit{BElLE} and $0.720 \pm 0.074 \text{ (stat)}$ at Belle, respectively. These results are consistent with the original assumption of $|\lambda| = 1$.

6 CP Violation Measurement With Other Modes

In addition to the $b \to c\bar{s}s$ charmonium modes, $CP$ violation measurement can be performed with many other $CP$ decays. In this section, $CP$ results measured from two classes of $\sin^2 \beta$\footnote{Results on $\sin 2\alpha$ are summarized in a separate article in this proceedings.} sensitive samples, the Cabibbo-suppressed $b \to c\bar{s}d$ decays and the penguin dominated $b \to s\bar{s}s$ decays, are briefly summarized. More details can be found in [14, 15].

Unlike the theoretically clean $b \to c\bar{s}s$ decays with which $\sin^2 \beta$ can be directly measured, these additional modes may be affected by more than one $CP$-violating phases. The Standard Model assumption $\lambda = \eta f e^{-2i\beta}$ can not always be applied; often, a generic form of physics PDF as defined in equation 6 has to be used. With this generic PDF, $CP$ asymmetry coefficients $S_f(\equiv \frac{2\Im \lambda}{1+|\lambda|^2})$ and $C_f(\equiv \frac{1-|\lambda|^2}{1+|\lambda|^2})$ can be extracted and compared with theoretical predictions. In the limit that only one weak phase contributes, the coefficient $S_f$ should be equal to $-\eta f \sin^2 \beta$, where $\eta f$ is the eigen value of the corresponding $CP$ mode, and the coefficient $C_f$ should be equal to zero.

6.1 Time Dependent $CP$ Asymmetries With $b \to c\bar{s}d$ Decays

One useful $b \to c\bar{s}d$ mode is the $B^0 \to J/\psi \pi^0$ decay where a $CP$ even ($\eta f = +1$) final state is produced. The decay process receives both tree and penguin contributions. The Cabibbo-suppressed tree contribution has the same weak phase as the $b \to c\bar{s}s$ modes but the penguin contribution of comparable strength may bring in a different weak phase. Both \textit{BElLE} and Belle have reconstructed events in this mode; the measured $CP$ asymmetry coefficients are:

$S_{J/\psi \pi^0} = 0.05 \pm 0.49 \text{ (stat)} \pm 0.16 \text{ (syst) (BElLE)}$

$C_{J/\psi \pi^0} = 0.38 \pm 0.41 \text{ (stat)} \pm 0.09 \text{ (syst) (BElLE)}$

$S_{J/\psi \pi^0} = 0.93 \pm 0.49 \text{ (stat)} \pm 0.08 \text{ (syst) (Belle)}$

$C_{J/\psi \pi^0} = -0.25 \pm 0.39 \text{ (stat)} \pm 0.06 \text{ (syst) (Belle)}.$
In addition to $B^0 \rightarrow J/\psi \pi^0$, BABAR has also constructed the $B^0 \rightarrow D^{*+} D^{*-}$ decay. This decay is also a $b \rightarrow c \bar{c}d$ process but the final state $D^{*+} D^{*-}$ is not a CP eigenstate – an angular analysis is necessary to determine the CP composition. With their $D^{*+} D^{*-}$ sample, BABAR has measured a CP-odd fraction of $0.096 \pm 0.060 \text{(stat)}$ and extracted the effective CP asymmetry parameters as:

$$\text{Im}(\lambda) = 0.31 \pm 0.43 \text{ (stat)} \pm 0.13 \text{ (syst)}$$

$$|\lambda| = 0.98 \pm 0.25 \text{ (stat)} \pm 0.09 \text{ (syst)}$$

If the $B^0 \rightarrow D^{*+} D^{*-}$ decay is a tree-only process, $\text{Im}(\lambda) = -\sin2\beta$ and $|\lambda| = 1$ are expected. In the Standard Model, penguin-induced correction is predicted to be small (< 2%) compared to this tree-only CP asymmetry.

### 6.2 Time Dependent CP Asymmetries With $b \rightarrow s\bar{s}s$ Decays

The penguin dominated $b \rightarrow s\bar{s}s$ process is also sensitive to $\sin2\beta$. If only the Standard Model weak phase contributes, the CP coefficients $S_f$ and $C_f$ are expected to be $-\eta_f \sin2\beta (\sin2\phi_1)$ and zero, respectively. Significant deviations to these expected value probe for new physics (in the penguin loops, for example).

BABAR has reported CP results from the CP-odd $B^0 \rightarrow \phi K^0_S$ decays. The effective $\sin2\beta$ value is found to be $-0.19_{-0.50}^{+0.52} \text{(stat)} \pm 0.09 \text{(syst)}$.

Belle has presented results with two CP-odd, $B^0 \rightarrow \phi K^0_S$ and $B^0 \rightarrow \eta' K^0_S$ modes, and a CP mixed mode $B^0 \rightarrow K^+ K^- K^0_S$ as well. The “$\sin2\phi_1$” ($\equiv -\eta_f S_f$) values measured from these three decays are $0.76 \pm 0.36 \text{(stat)}^{+0.05}_{-0.06} \text{(syst)}$, $-0.73 \pm 0.64 \text{(stat)} \pm 0.18 \text{(syst)}$, and $0.52 \pm 0.46 \text{(stat)} \pm 0.11 \text{(syst)}$, respectively. In the meantime, CP asymmetry parameter $C_f$ is also measured with each mode and found to be consistent with zero.

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\[\text{For this CP mixed mode, Belle has measured its CP composition to be } 97\% \text{ CP-odd and } 3\% \text{ CP-even.}\]

\[\text{The systematic error for the } K^+ K^- K^0_S \text{ mode is subject to an additional } ^{+0.27}_{-0.03} \text{ contribution from the uncertainty in the fraction of the CP-odd component.}\]
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