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SIN 2β AND MIXING: RESULTS FROM B-FACTORIES

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ABSTRACT

First observation and subsequent more precise measurements of CP violation in the B meson system have been recently reported by experiments at asymmetric B-factories. Time-dependent measurements are performed by these experiments to study CP-violation and $B^0\overline{B}^0$ oscillation. Their results on the CP asymmetry amplitude, sin2β, and the $B^0\overline{B}^0$ mixing frequency, Δm_d, are reviewed.

1 Introduction

In the Standard Model of electroweak interaction the origin of CP violation is a non-zero complex phase in the three-generation CKM matrix [1] which describes quark mixing. Since 1981 [2] large CP-violating asymmetries have been predicted in the time distribution of B^0 decays to charmonium final states.

Asymmetries in experimentally easy-to-detect decays like $B^0 \to J/\psi K_S^0$ provide a direct measurement of sin2β, where $\beta = arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*]$. However large samples of $B^0\overline{B}^0$ events ($> 10^7$) are necessary to unambiguosly observe CP violation and the first results [3] were statistically limited. Non-zero values of sin2β with a significance higher than 4σ were published only 20 years later by dedicated experiments at asymmetric e^+e^- colliders, BaBar [4] at PEP-II and Belle [5] at KEKB. PEP-II and KEKB are high luminosity ($> 10^{33} cm^{-2}s^{-1}$) e^+e^- storage rings operating at the $\Upsilon(4S)$ resonance. A $B^0\overline{B}^0$ pair produced in an $\Upsilon(4S)$ decay evolves in a coherent P-wave state. The decay of one B meson to a self-tagging state, which distinguishes between B^0 and $\overline{B}^0$ at a certain time, projects the other B, at that time, onto the opposite flavor as a consequence of Bose symmetry. The probabilities for observing $B^0\overline{B}^0$, B^0B^0 and $\overline{B}^0\overline{B}^0$ pairs are oscillatory functions of Δt, the difference of time between the two B decays. This allows mixing frequencies and CP asymmetries to be determined if Δt is measured, if the flavor of the tagging B, B_{tag}, is ascertained and if the other neutral B decay, B_{rec}, is fully reconstructed. If B_{rec} is found in a flavor eigenstate ($B_{rec} = B_{flav}$), the mass difference between the neutral B mass eigenstates, Δm_d, can be measured from the time-dependent mixing asymmetry

$$A_{mixing}(\Delta t) \equiv \frac{h_+(\Delta t) - h_-(\Delta t)}{h_+(\Delta t) + h_-(\Delta t)} = cos(\Delta m_d \Delta t) \tag{1}$$

where $h_+(h_-)$ is the decay rate for events with opposite(same) flavor for B_{flav} and B_{tag}.

If the fully reconstructed neutral B is found in a CP eigenstate ($B_{rec} = B_{CP}$), a time dependent CP-violating observable can be constructed

$$A_{CP}(\Delta t) \equiv \frac{f_+(\Delta t) - f_-(\Delta t)}{f_+(\Delta t) + f_-(\Delta t)} = \frac{2Im\lambda}{1+|\lambda|^2} sin(\Delta m_d \Delta t) - \frac{1-|\lambda|^2}{1+|\lambda|^2} cos(\Delta m_d \Delta t) \tag{2}$$

measuring the decay rate asymmetry between B^0-tagged (f_+) and $\overline{B}^0$-tagged (f_-) events, where the complex parameter λ depends on both $B^0\overline{B}^0$ mixing and the decay amplitudes of B^0 and $\overline{B}^0$ to the common final state.

In the Standard Model, $\lambda = \eta_f e^{-2i\beta}$ for $b \to c\overline{c}s$ decays containing a charmonium state, where η_f is the CP eigenvalue of the final state. Therefore for these decays the time-dependent CP violating asymmetry is

$$A_{CP}(\Delta t) = -\eta_f \sin 2\beta sin(\Delta m_d \Delta t) \quad (3)$$

and its amplitude is a direct measurement of sin2β.

2 Experimental aspects

Time dependent asymmetries are modified by detector effects and their measurement requires a determination of the experimental Δt resolution and the fraction of events, w, in which the tag assignement is incorrect. The observed amplitudes for the CP asymmetry in B_{CP} sample and the mixing asymmetry in the B_{flav} sample are reduced by the same factor $(1 - 2w)$ due to mistags. Since the Δt resolution is dominated by B_{tag}, as it will be mentioned later, the Δt distributions for the B_{CP} and the B_{flav} sample can be convoluted with a common Δt resolution function, $R(\delta t)$, where δt is the difference between the measured and true Δt value.

Neglecting the lifetime difference between mass eigenstates, and indicating the B^0 lifetime with τ, the observed decay rates can be written as

$$h_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}[1 \pm (1 - 2w)cos(\Delta m_d \Delta t)] \otimes R(\delta t) \quad (4)$$

for opposite flavor (+) and same flavor (−) signal events, and

$$f_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}[1 \pm \eta_f (1 - 2w) \sin 2\beta sin(\Delta m_d \Delta t)] \otimes R(\delta t) \quad (5)$$

for B^0 tagged (+) and $\overline{B}^0$-tagged (−) decays to CP eigenstates.

The Belle collaboration performs indepedent fits for the mistag fractions and $R(\delta t)$, extracting the first from the amplitude of the mixing asymmetry of the B_{flav} sample, and the second from a fit of charged and neutral B meson lifetimes. The BaBar collaboration performs a simultaneous fit to the B_{CP} sample and to the high statistics B_{flav} sample with sin2β, w and $R(\delta t)$ as free parameters. Both experiments fix Δm_d and τ to the PDG [6)] value in the sin2β fit.

In all cases the measurement of Δm_d, in addition to being of theoretical interest, has common elements with the analysis for the measurement of sin2β

and therefore it constitutes an essential validation test of the whole analysis chain, including flavor tagging, Δt determination and resolution.

2.1 Δt measurement

Neglecting the small B momentum in the $\Upsilon(4S)$ center of mass system, Δt can be determined by the $\Upsilon(4S)$ boost, $\beta\gamma$, and the measurement of the distance Δz between the two B decay vertices along the electron beam direction from

$$\Delta t = \Delta z/\beta\gamma c.$$

The average value for Δz is approximately 200 μm at KEKB where $\beta\gamma \approx 0.425$ and 260 μm at PEP-II where $\beta\gamma \approx 0.55$. The Δz resolution is dominated by the z position resolution for the B_{tag} vertex, which is tipically 140 - 170 μm on the B_{tag} side compared to about 70 μm on B_{rec} side.

3 $B^0\overline{B}^0$ mixing results

The $B^0\overline{B}^0$ mixing frequency Δm_d is determined with a simultaneous likelihood fit to the Δt distributions of opposite flavor ($B^0\overline{B}^0$) and same flavor (B^0B^0 or $\overline{B}^0\overline{B}^0$) events.

For fully-reconstructed B^0 decays to hadrons, BaBar has measured [7]

$$\Delta m_d = 0.519 \pm 0.016(stat) \pm 0.010(syst)ps^{-1}.$$

This is consistent with previous measurements from other experiments [6] and with other results from Belle and Babar, the most precise of which are based on a different technique and a dilepton data sample to give

$$\Delta m_d = 0.493 \pm 0.012(stat) \pm 0.009(syst)ps^{-1}$$

for Babar [8] and

$$\Delta m_d = 0.463 \pm 0.008(stat) \pm 0.016(syst)ps^{-1}$$

for Belle [9].

Including all these measurements, the new world average [10] is

$$\Delta m_d = 0.489 \pm 0.008$$

and it is dominated by the results from BaBar and Belle here reported.

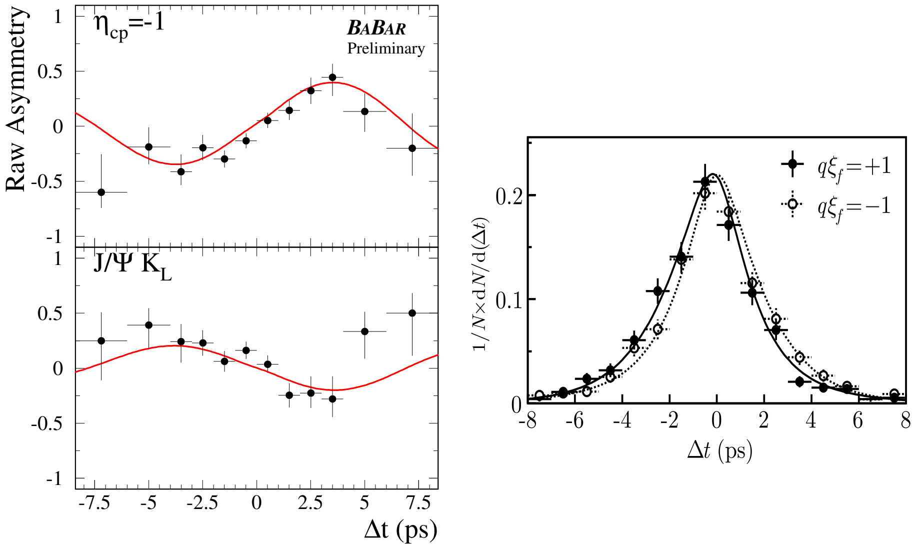

Figure 1: *On the left, raw asymmetry in the number of B^0 and $\overline{B}^0$ tags, $(N^0_B - N_{\overline{B}^0})/(N^0_B + N_{\overline{B}^0})$, as a function of Δt from Babar. The upper plot is for CP odd final states, the lower plot for the CP even $J/\psi\, K^0_L$. The solid curves represent the result of the combined fit which has determined the central* $\sin 2\beta$ *value (0.75). On the right, Δt distributions from Belle for the events with $q\xi_f = 1$ and $q\xi_f = -1$, where ξ_f is the CP eigenvalue and $q = 1(-1)$ for B^0 ($\overline{B}^0$) tag. The result of the global fit for* $\sin 2\beta$ *= 0.82 is shown as solid and dashed curves respectively.*

4 $\sin 2\beta$ results with golden decay modes

From 62 million $B\overline{B}$ events collected between 1999 and 2001, which correspond to an integrated luminosity of approximately 56 fb^{-1}, the BaBar collaboration has measured [11]

$$\sin 2\beta = 0.75 \pm 0.09(stat) \pm 0.04(syst)$$

The B_{CP} sample used in this measurement consists of B mesons decaying to the final states $J/\psi\, K^0_S(K^0_S \to \pi^+\pi^-, \pi^0\pi^0)$, $\psi(2S)K^0_S(K^0_S \to \pi^+\pi^-)$, $\chi_{c1}K^0_S(K^0_S \to \pi^+\pi^-)$, $J/\psi\, K^{*0}(K^{*0} \to K^0_S\pi^0, K^0_S \to \pi^+\pi^-)$, and $J/\psi\, K^0_L$. The J/ψ and $\psi(2S)$ mesons are reconstructed through their decays to e^+e^- and $\mu^+\mu^-$; the $\psi(2S)$ is also reconstructed through its decay to $J/\psi\,\pi^+\pi^-$. The χ_{c1} is reconstructed in the decay mode $J/\psi\,\gamma$.

The observed time-dependent asymmetries for this B_{CP} data sample are shown in fig.1 (plots on the left).

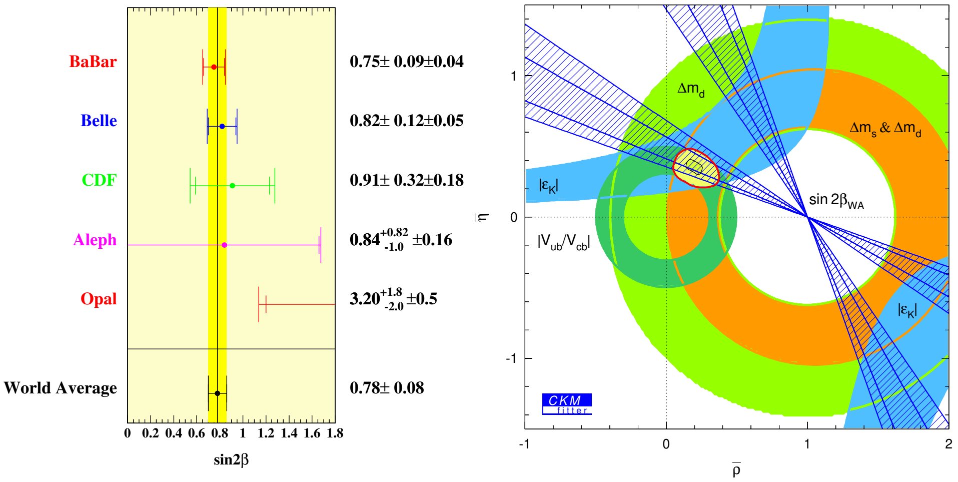

Figure 2: *On the left, most recent* sin2β *results by experiment. On the right, present indirect constraints on the position of the apex of the Unitarity Triangle in the* $(\bar{\rho}, \bar{\eta})$ *plane, not including the* sin2β *measurement. The fitting procedure is described in* [13]*. The* sin2β *World Average is represented by the hatched regions, corresponding to one and two statistical standard deviations.*

The η_c K^0_S final state, with $\eta_c \rightarrow K^0_S K^{\pm}\pi^{\mp}$ and $\eta_c \rightarrow K^{\pm}K^{\mp}\pi^0$, has not been included in the global fit yet but the preliminary result for sin2β with these purely hadronic decays, sin2β = 0.43 ± 0.46(stat) ± 0.08(syst) is consistent with other golden modes.

The final state in vector-vector decays like $B^0 \rightarrow J/\psi\ K^{*0}$ $(\rightarrow K^0_S\ \pi^0)$ is a mixture of even and odd CP, depending on the relative orbital angular momentum of the J/ψ and K^{*0}. An angular analysis is performed to disantangle the two components.

The result from the Belle experiment [12], based on a luminosity of about 42 fb^{-1} and the same modes, including decays to η_c K^0_S, is

$$\sin 2\beta \ = \ 0.82 \ \pm \ 0.12(stat) \ \pm \ 0.05(syst)$$

The likelihood fit is overlaid to the observed Δt asymmetries in the plot on the right of fig. 1. Present sin2β results and constraints on the Standard Model Unitarity Triangle are shown in fig.2.

For both experiments the dominant sources of systematic error are the parameterization of the Δt resolution function, possible differences in the mistag fractions between the B_{CP} and B_{flav} samples and uncertainties in the level, composition and CP asymmetry of the background.

By floating $|\lambda|$ in the fit to the $\eta_f = -1$ sample, which has high purity and requires minimal assumptions on backgrounds, the BaBar collaboration has obtained

$$|\lambda| = 0.93 \pm 0.06(stat) \pm 0.02(syst)$$

consistent with Standard Model expectation of no direct CP violation.

5 sin2β results with other modes

As the size of the data sample increases, more tests of the Standard Model and independent measurements of sin2β with other decay modes can be performed.

An example is given by neutral B decaying to $D^{*\pm}D^{*\mp}$, where the leading sub-quark process is the Cabibbo-suppressed tree decay $b \to c\bar{c}d$ and the penguin contribution is expected to be small [14]. However no assumption is made on the penguin contribution by fitting for the sinus and cosinus coefficients in

$$A_{CP}(\Delta t) = Ssin(\Delta m_d \Delta t) + Ccos(\Delta m_d \Delta t)$$

and BaBar preliminary results are

$$S = -0.05 \pm 0.45 \pm 0.05$$

$$C = -0.12 \pm 0.30 \pm 0.05$$

Preliminary results by Belle on the CP asymmetry when the final state is $\eta' K^0_S$, a penguin-dominated decay mode ($b \to s\bar{s}d$), are

$$S = 0.27 \pm 0.54 \pm 0.07$$

$$C = 0.12 \pm 0.32 \pm 0.07$$

6 Conclusions and Outlook

Time-dependent measurements by experiments at B-factories allow the most precise measurements of the CP-violating amplitude sin2β and the $B^0\overline{B}^0$ mixing frequency, Δm_d. Present results on sin2β are consistent with the Standard Model predictions, as given by CKM global fits of indirect measurements, and have now reached a level of precision that offers significant constraint on the position of the apex of the Unitarity Triangle in the $(\bar{\rho}, \overline{\eta})$ plane.

Results on sin2β by BaBar and Belle are still limited by the data sample size and are expected to improve in the near future.

Over the next few years, indepedent measurements of the CP violation parameters with $b \to c\bar{c}d$ or $b \to s\bar{s}d$, if in disagreement with sin2β, can probe the effects of new physics beyond the Standard Model.

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