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CP VIOLATION AT *BaBar*

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We report recent measurements of the three CKM angles of the Unitarity Triangle using about 383 millions $b\bar{b}$ pairs collected with the *BABAR* detector at the PEP-II asymmetric-energy B Factory at SLAC.

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1. Unitarity Triangle and Methology in *BABAR*

In the Standard Model, CP violation arises from the complex quark mixing CKM matrix V_{ij}. The unitarity of the CKM matrix results in a triangle in the complex plane. Overconstraining the triangle by measurements of the angles and sides tests its unitarity and the validity of the CKM matrix.

The β angle is the phase of V_{td}, involved in $B^0 - \bar{B}^0$ mixing; the γ angle is the phase of V_{ud}, involved in the $b \to u$ charmless decays. Measurements of $\alpha = \pi - \beta - \gamma$ use processes involving both $B^0 - \bar{B}^0$ mixing and $b \to u$ transitions. In these proceedings, we focus on the most recent measurements at *BABAR* of the angles β, α, and γ and they are mostly based on the analysis of 383 millions $b\bar{b}$ pairs.

The β and α angles of the unitarity triangle are measured using CP violating processes in which amplitudes with different CKM phases interfere. We exploit the interference between the decay of a B^0 directly to a CP eigenstate (f_{CP}) and the decay of a B^0 first mixing to a $\bar{B}^0$ and then decaying into the CP eigenstate. Measuring the time-dependent CP asymmetry $A_{f_{CP}}$ (Eq. 1) allows us to extract the CP parameters S and C.

$$A_{f_{CP}}(\Delta t) = \frac{\Gamma(\bar{B}^0) - \Gamma(B^0)}{\Gamma(\bar{B}^0) + \Gamma(B^0)} = S \sin(\Delta m_d \Delta t) - C \cos(\Delta m_d \Delta t) \qquad (1)$$

If only one decay diagram is involved in the $B^0 \to f_{CP}$ decay, the CP parameters fulfill the following relations: $C = 0$ and $S = -\eta_f \sin(2 \times [\beta + \phi_{CKM}])$ where η_f is the CP eigenvalue of the final state and where ϕ_{CKM} is the CKM phase in the

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decay amplitude $B^0 \to f_{CP}$. This CKM phase is equal to 0 (γ) for $b \to c$ ($b \to u$) transitions used for β (α) measurements.

$B^0 - \bar{B}^0$ pairs are produced at the $\Upsilon(4S)$ resonance in a coherent state. To measure the CP asymmetry, we reconstruct one B meson into a useful decay channel for an angle measurement, while the other B is used to tag the flavor at production. The difference between the two B mesons decay times is reconstructed using the difference in decay flight ($\Delta z \approx 250\mu m$, $\sigma_{\Delta z} \approx 170\mu m$) along the beams direction.

2. Measurements of the β Angle

The golden decay channels $B^0 \to$ charmonium $[J/\Psi,\ \Psi,\ \chi_c,\ \eta_c]\ K^0_{S,L}$ (CP final states) are dominated by a color-suppressed $b \to c$ tree diagram. Their relatively high branching ratio ($\approx 10^{-3}$) and the absence of direct CP violation allows the simple extraction of $S = -\eta_f \sin(2\beta)$ for the CP asymmetry measurement Averaging these analyses, we measures $\sin(2\beta) = 0.714 \pm 0.032 \pm 0.018$[1].

To resolve the $\pi - 2\beta$ ambiguity in $\sin(2\beta)$, different analyses constrain the value of $\cos(2\beta)$ [2,3]. The most recent result is the time-dependent Dalitz analysis of the $D^0(\bar{D}^0) \to K^0_S\pi^+\pi^-$ decay, from the $B^0(\bar{B}^0)$ decay to $D^0(\bar{D}^0)h^0 = \pi^0, \eta, \eta', \omega$. The analysis is sensitive to $\sin(2\beta)$ and $\cos(2\beta)$[4] due to the interference between the D^0 and $\bar{D}^0$ decays and yields $\cos(2\beta) > 0$ @ 86% C.L[5].

Some channels can contain additional loop diagrams that are negligible in the Standard Model. Measuring a value $\eta_f S$ different from the golden mode value is an indication of New Physics. Such channels are $B^0 \to D^+D^-$[6] and $B^0 \to D^{*+}D^{*-}$[7]. Their studies do not indicate any significant direct CP violation, and we measure respectively, $\eta_f S = 0.54 \pm 0.34 \pm 0.06$ and $\eta_f S = 0.72 \pm 0.19 \pm 0.05$, which are consistent with the golden mode.

Several $b \to sq\bar{q}$ penguin modes analyses were updated recently at both *BABAR* and Belle and are summarized in Ref. 8. The "naive" average $\sin(2\beta)_{eff}$ over the penguin modes was 2.5 σ away from the golden mode $\sin(2\beta)$ value at the time of the winter 2007 conferences. But now, for *BABAR* $\sin(2\beta)_{eff} = 0.67 \pm 0.04$ (<1 σ deviation). This is mostly due to the new time-dependent Dalitz analysis of the $B^0 \to K^0_S\pi^+\pi^-$ decay[9]. We fit the phase and magnitude for each component's amplitude ($K^{*+}(892)\pi^-$, $K^{*+}(1430)\pi^-$, $K^0_S\rho^0$, $K^0_S f_0$, non-resonant) and derive the quasi-two-body parameters C and S for the various components. For $K^0_S f_0$, $\eta_f S = 0.94^{+0.02\ +0.04}_{-0.07\ -0.05}$ is the largest deviation from the golden mode. But the errors must be handled with caution, as a constraint to remain in the physical bound was added.

3. Measurements of the α Angle

Measurements of α are more difficult due to the low branching fraction of the charmless $b \to u$ tree transitions, and to non-negligible penguin $b \to d$ diagrams involving a different CKM phase (and a source of direct CP violation). C can be different from zero and S is expressed as a function of an effective angle α_{eff}, not exactly equal to α, by $S = \sqrt{1-C^2} \times \sin(2\alpha_{eff})$. Therefore, time-dependent CP asymmetry of $b \to u$ transitions to $\pi^+\pi^-$ [10] and $\rho^+\rho^-$ [11] CP final states only provide a measurement of α_{eff}. The difference $\alpha - \alpha_{eff}$ is constrained with an isospin analysis[12] using the measured branching fractions and the CP parameters of the other $\pi\pi$ ($\rho\rho$) modes. Neglecting the electroweak penguins contribution, the $SU(2)$ symmetry between the u and d quarks leads to relationships between the amplitudes of the different $\pi\pi$ ($\rho\rho$) modes. The more complicated $\rho\rho$ vector-vector modes are advantageous since the $\rho^+\rho^-$ branching fraction is 5 times higher than for $\pi^+\pi^-$. The $\rho^+\rho^-$ is almost 100% longitudinally polarized (CP-even state), so only the longitudinal components are used in the isospin analysis and the penguin pollution is less than for $\pi^+\pi^-$. Moreover, the CP parameters C and S extracted from the $\rho^0\rho^0$ time-dependent analysis provide additional constraints to the isospin analysis. Fig. 1 shows the constraint on α derived from the $\pi\pi$[13] and $\rho\rho$[14] isospin analyses.

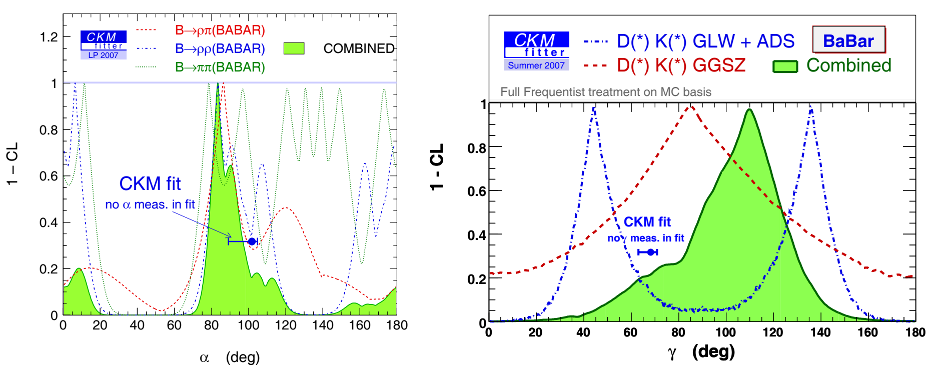

Fig. 1. α scan (left plot) and γ scan (right plot) from CKMFitter frequentist approach for *BABAR*.

Another approach for constraining α is the time-dependant Dalitz analysis of the $B^0 \to (\rho\pi)^0 \to \pi^+\pi^-\pi^0$ [15], which is directly sensitive to α, allowing us to disfavor the $\rho\rho$ mirror solution as shown on Fig. 1. The combined average $\alpha = (83.5^{+13.5}_{-5.7})^\circ$ is in good agreement with global CKM fits[16].

4. Measurements of the γ Angle

The most recent γ results in *BABAR* are from the analysis of $B^+ \to D^{(*)0}K^{(*)+}$ decays which are sensitive to γ due to the interference between two tree diagrams: one color favored $B^+ \to \bar{D}^{(*)0}K^{(*)+}$ $b \to c$ transition and a small (color and CKM) suppressed $B^+ \to D^{(*)0}K^{(*)+}$ $b \to u$ contribution carrying a CKM γ phase. Methods are based on D^0 decay modes for which the D^0 and the $\bar{D}^0$ can not be distinguished: the D^0 or $\bar{D}^0$ can decay into CP eigenstates (GLW method[17]), into the wrong sign $K^+\pi^-$ final state (ADS method[18]), or into three bodies such as $K^0_S\pi^+\pi^-$ in which case a Dalitz analysis is performed (GGSZ method[19]). The challenge of these methods is to disentangle the electroweak part carrying information on γ from the hadronic uncertainties from the B and D meson decays. The sensitivity of the three methods to measure these different contributions are very different. Therefore, these methods complement each other. The best method may be the Dalitz GGSZ analysis. Only the GLW method was updated recently at *BABAR*[20]. The studied CP-even (CP-odd) D^0 decay modes are K^+K^- and $\pi^+\pi^-$ ($K^0\pi^0$ and $K^0\omega$). The direct CP asymmetry between the B^+ and B^- decays for CP-even D decays $A_{CP+} = 0.35 \pm 0.09(stat) \pm 0.05(syst)$ was measured to be significantly different from zero for the first time. The constraints on γ obtained with three approaches is summarized on Fig. 1.

5. Conclusion

The results of the angles (β, α, γ) of the unitarity triangle are consistent[16] with Belle results, and with other CKM constraints such as the measurement of ϵ_K, the length of the sides of the unitarity triangle determined from the measurements of Δm_d, Δm_s, $|V_{ub}|$. This is an impressive confirmation of Standard Model in quark-flavor sector.

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