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Measurements of $\sin 2\beta$ at *BABAR* with charmonium and penguin decays.

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Abstract

This article summarises measurements of time-dependent CP asymmetries in decays of neutral B mesons to charmonium, open-charm and gluonic penguin-dominated charmless final states. Unless otherwise stated, these measurements are based on a sample of approximately 230 million $\Upsilon(4S)\rightarrow B\overline{B}$ decays collected by the *BABAR* detector at the PEP-II asymmetric-energy B-factory.

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1 Introduction

The Standard Model (SM) of electroweak interactions describes CP violation (CPV) as a consequence of a complex phase in the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. Measurements of CP asymmetries in the proper-time distribution of neutral B decays to CP eigenstates containing a charmonium and K^0 meson provide a precise measurement of $\sin 2\beta$ [2], where β is $\arg\left[-V_{\rm cd}V_{\rm cb}^*/V_{\rm td}V_{\rm tb}^*\right]$ and the V_{ij} are CKM matrix elements. The SM also predicts the amplitude of CPV in $b \to c\bar{c}d$ and $b \to s\bar{q}q$ $(q = d, s)$ decays, defined as $\sin 2\beta_{\rm eff}$, to be approximately $\sin 2\beta$. The $b \to c\bar{c}d$ loop amplitudes have a different weak phase than the $b \to c\bar{c}d$ tree amplitude and if there is a significant penguin amplitude in such $b \to c\bar{c}d$ decays, then one will measure a value of $\sin 2\beta_{\rm eff}$, that differs from $\sin 2\beta$ [3]. $b \to s\bar{q}q$ decays may also be especially sensitive to New Physics since they are dominated by one-loop transitions that can potentially accommodate large virtual particle masses and contributions from physics beyond the SM could invalidate this prediction [3]. However, many of these $b \to s\bar{q}q$ final states are affected by additional SM physics contributions that may obscure the measurement of $\beta_{\rm eff}$ [4]. Precise measurements of $\sin 2\beta_{\rm eff}$ in many $b \to c\bar{c}d$ and $b \to s\bar{q}q$ decays are therefore important either to confirm the SM picture or to search for the possible presence of New Physics.

2 Experimental Technique

The *BABAR* detector [5] is located at the SLAC PEP-II e^+e^- asymmetric energy B-factory. Its program includes the study of CPV in the B-meson system through the measurement of time-dependent CP-asymmetries, A_{CP}. At the $\Upsilon(4S)$ resonance, A_{CP} is extracted from the distribution of the difference of the proper decay times, $t \equiv t_{CP} - t_{tag}$, where t_{CP} refers to the decay time of the signal B meson (B_{CP}) and t_{tag} refers to the decay time of the other B meson in the event (B_{tag}). The decay products of B_{tag} are used to identify its flavour at its decay time. A_{CP} is defined as:

$$A_{CP}(t) \equiv \frac{N(\overline{B^0}(t) \to f_{CP}) - N(B^0(t) \to f_{CP})}{N(\overline{B^0}(t) \to f_{CP}) + N(B^0(t) \to f_{CP})} = S\sin(\Delta m t) - C\cos(\Delta m t), \qquad (1)$$

where $N(\overline{B^0}(t) \to f_{CP})$ is the number of $\overline{B^0}$ that decay into the CP-eigenstate f_{CP} after a time t. A_{CP} can also be expressed in terms of the difference between the B mass eigenstates Δm, where the sinusoidal term describes the interference between mixing and decay and the cosine term is the direct CP asymmetry.

3 Measurements of $\sin 2\beta$ from charmonium decays

The SM predicts that direct CP violation in $b \to c\bar{c}s$ ($B^0 \to$ charmonium $+ K^0$) decays is negligible. It follows that $A_{CP}(t) = -\eta_f \sin 2\beta \sin(\Delta m t)$ where η_f is the eigenvalue corresponding to the CP-eigenstate f_{CP}. $\sin 2\beta$ has been directly measured using B^0 decays to the final states $J/\psi K_S$, ψK_S, $\chi_{c1}K_S$, $\eta_c K_S$, $J/\psi\ K^\star(K^\star \to K_S\pi^0)$ and $J/\psi K_L$ [6]. An extended unbinned maximum-likelihood (ML) fit to the data gives $\sin 2\beta = 0.722 \pm 0.040 \pm 0.023$ [1], which is in agreement with SM expectation. A four-fold ambiguity in β that is obtained from this measurement is reduced to a two-fold ambiguity through the measurement of $\cos 2\beta$. Using 81.9 fb^{-1} of integrated luminosity $\cos 2\beta$ is measured as $2.72\ ^{+0.50}_{-0.79} \pm 0.27$ using $B^0 \to J/\psi\ K^\star$ decays [7]. This determines the sign of

[1] All results are quoted with the first error being statistical and the second being systematic.

$\cos 2\beta$ to be positive at 86% C.L. and is compatible with the sign of $\cos 2\beta$ inferred from SM fits of the unitarity triangle.

4 Measurements of $\sin 2\beta$ from $b \rightarrow c\bar{c}d$ decays

The decay $B^0 \rightarrow D^{*+}D^{*-}$ is an admixture of CP-odd and CP-even components. By performing a transversity analysis [8], the CP-odd fraction is measured to be $0.125 \pm 0.044 \pm 0.007$. The time-dependent CP asymmetry parameters S and C are measured to be $-0.75 \pm 0.25 \pm 0.03$ and $0.06 \pm 0.17 \pm 0.03$ respectively. A preliminary analysis of the decay $B^0 \rightarrow J/\psi\,\pi^0$ also shows it to be consistent with the SM [9]. The signal yield, S and C are simultaneously extracted from a ML fit. 109 ± 12 events are measured with $C = -0.21 \pm 0.26 \pm 0.09$ and $S = -0.68 \pm 0.30 \pm 0.04$.

5 Searches for New Physics

Two $b \rightarrow s\bar{q}q$ ($q = d, s$) decays to CP eigenstates that have been noted as having small theoretical uncertainties in the measurement of β_{eff} are $B^0 \rightarrow \phi K^0$ and $B^0 \rightarrow K_S K_S K_S$ [10]. B^0 decays to ϕK_S and ϕK_L are reconstructed and a ML fit yields 114 ± 12 ϕK_S and 98 ± 18 ϕK_L B^0 candidates. $\sin 2\beta_{eff}$ is measured to be $0.50 \pm 0.25\ ^{+0.07}_{-0.04}$ [11]. A ML fit of reconstructed $B^0 \rightarrow K_S K_S K_S$ candidates (where $K_S \rightarrow \pi^+\pi^-$), finds $C = -0.34\ ^{+0.28}_{-0.25} \pm 0.05$ and $S = -0.71\ ^{+0.38}_{-0.32} \pm 0.04$ [12]. A more recent analysis, where one K_S is reconstructed in the $K_S \rightarrow \pi^0\pi^0$ mode, was combined with [12] to give the preliminary results: $C = -0.10 \pm 0.25 \pm 0.05$ and $S = -0.63\ ^{+0.32}_{-0.28} \pm 0.04$ [13]. The experimental challenge in [13] came from the absence of charged tracks originating from the B^0 decay vertex [14].

The decay $B^0 \rightarrow \eta' K^0$ is also interesting, since additional contributions estimated using SU(3) and QCD factorisation are expected to be small [15]. A ML fit to reconstructed $B^0 \rightarrow \eta' K_L$ and $B^0 \rightarrow \eta' K_S$ candidates yields the preliminary result of 1245 ± 67 candidates, $S = 0.36 \pm 0.13 \pm 0.03$ and $C = -0.16 \pm 0.09 \pm 0.02$. The value of $S = \sin 2\beta_{\text{eff}}$ differs from the *BABAR* value of $\sin 2\beta$ as measured in charmonium + K^0 decays by 2.8 standard deviations [16]. Other $b \rightarrow s\bar{q}q$ decays have been studied at *BABAR*. These include $B^0 \rightarrow f_0 K^0$, $B^0 \rightarrow \pi^0 K^0$, $B^0 \rightarrow \pi^0\pi^0 K^0$, $B^0 \rightarrow \omega K^0$ and $B^0 \rightarrow K^+K^-K^0$ [17, 18]. Small deviations from SM expectations are seen.

6 Conclusion

$\sin 2\beta$ has been measured to 5% accuracy using $B^0 \rightarrow$ charmonium + K^0 decays and is consistent with SM expectations. No deviation from the SM has been observed in $b \rightarrow c\bar{c}d$ decays. Future updates of the $b \rightarrow s\bar{q}q$ analyses on larger datasets will help to understand if the present pattern in the deviation of $b \rightarrow s$ penguins from SM predictions is a statistical effect or a sign of New Physics.

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