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 $\Upsilon(4S) \to B\bar{B}$ 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 $\beta$ is $\arg[-V_{cb}^*V_{tb}^T/V_{td}^*V_{tb}]$ and the $V_{ij}$ are CKM matrix elements. The SM also predicts the amplitude of CPV in $b \to \bar{c}d$ and $b \to s\bar{q}q$ ($q = d, s$) decays, defined as $\sin 2\beta_{\text{eff}}$, to be approximately $\sin 2\beta$. The $b \to \bar{c}d$ loop amplitudes have a different weak phase than the $b \to \bar{c}d$ tree amplitude and if there is a significant penguin amplitude in such $b \to \bar{c}d$ decays, then one will measure a value of $\sin 2\beta_{\text{eff}}$, 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 $\beta_{\text{eff}}$ [4]. Precise measurements of $\sin 2\beta_{\text{eff}}$ in many $b \to \bar{c}d$ 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 B\(\bar{A}\)B\(\bar{A}\)R 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 $T(4S)$ 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:

$$A_{CP}(t) \equiv \frac{N(\bar{B}^0(t) \to f_{CP}) - N(B^0(t) \to \bar{f}_{CP})}{N(\bar{B}^0(t) \to f_{CP}) + N(B^0(t) \to \bar{f}_{CP})} = S \sin(\Delta mt) - C \cos(\Delta mt),$$  

(1)

where $N(\bar{B}^0(t) \to f_{CP})$ is the number of $\bar{B}^0$ 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 $\Delta m$, 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 $b \to \bar{c}s$ ($B^0 \to$ charmonium + $K^0$) decays is negligible. It follows that $A_{CP}(t) = -\eta_f \sin 2\beta \sin(\Delta mt)$ where $\eta_f$ 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 $J/\psi K_s, \psi K_s, \chi_{c1} K_s, \eta_c K_s, J/\psi K^* (K^* \to K_S\pi^0)$ 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 $\beta$ 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 $B^0 \to J/\psi K^*$ 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 \( b \to \bar{c}d \) decays

The decay \( B^0 \to D^*+D^- \) is an admixture of \( CP \)-odd and \( CP \)-even components. By performing a transversity analysis, 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 \( B^0 \to J/\psi \pi^0 \) also shows it to be consistent with the SM. The signal yield, \( S \) and \( C \) are simultaneously extracted from a ML fit. 109 \pm 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 \( b \to s\bar{q}q \) \((q = d, s)\) decays to \( CP \) eigenstates that have been noted as having small theoretical uncertainties in the measurement of \( \beta_{\text{eff}} \) are \( B^0 \to \phi K^0 \) and \( B^0 \to K_SK_SK_S \). \( B^0 \) decays to \( \phi K_S \) and \( \phi K_L \) are reconstructed and a ML fit yields \( 114 \pm 12 \phi K_S \) and \( 98 \pm 18 \phi K_L \). \( B^0 \) candidates, \( \sin 2\beta_{\text{eff}} \) is measured to be \( 0.50 \pm 0.25 \pm 0.07 \). A ML fit of reconstructed \( B^0 \to K_SK_SK_S \) candidates (where \( K_S \to \pi^+\pi^- \)), finds \( C = -0.34 \pm 0.25 \pm 0.05 \) and \( S = -0.71 \pm 0.38 \pm 0.04 \). A more recent analysis, where one \( K_S \) is reconstructed in the \( K_S \to \pi^0\pi^0 \) mode, was combined with \( [12] \) to give the preliminary results: \( C = -0.10 \pm 0.25 \pm 0.05 \) and \( S = -0.63 \pm 0.32 \pm 0.04 \). The experimental challenge in \( [13] \) came from the absence of charged tracks originating from the \( B^0 \) decay vertex. \( [14] \)

The decay \( B^0 \to \eta'K^0 \) is also interesting, since additional contributions estimated using SU(3) and QCD factorisation are expected to be small \( [15] \). A ML fit to reconstructed \( B^0 \to \eta'K_L \) and \( B^0 \to \eta'K_S \) candidates yields the preliminary result of \( 1245 \pm 67 \) 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 \( b \to s\bar{q}q \) decays have been studied at \( BABAR \). These include \( B^0 \to f_0K^0 \), \( B^0 \to \pi^0K^0 \), \( B^0 \to \pi^0\pi^0K^0 \), \( B^0 \to \omega K^0 \) and \( B^0 \to K^+K^-K^0 \). \( [17] [18] \). Small deviations from SM expectations are seen.

6 Conclusion

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

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