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Time-dependent γ/ϕ_3 measurements by *BABAR*

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Compilation and summary of time-dependent measurements of the CKM angle γ/ϕ_3 with events collected at the *BABAR* detector at the SLAC PEP-II asymmetric *B* factory.

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Introduction

An important goal of flavor physics is to overconstrain the CKM elements. The CKM element γ/ϕ_3 is the least precisely measured of the Unitarity Triangle angles. Decays of B_d mesons that allow one to constrain the CKM angle $\sin(2\beta + \gamma)$ have either small CP asymmetry ($B \rightarrow D^{(*)}\pi/\rho$ and $B^0 \rightarrow D^\mp K_s^0 \pi^\pm$) or small branching fractions ($B \rightarrow D^{(*)}K^{(*)}$). The CP violating effects in these modes, therefore, are difficult to measure.

The quantity $\sin(2\beta + \gamma)$ can be obtained from the study of the time evolution of $B^0/\bar{B}^0 \rightarrow D^{(*)}X_{u,d,s}$ decays where $X_{u,d,s}$ refers to light and/or strange mesons. In the Standard Model, these decays proceed via Cabibbo suppressed $\rightarrow u$ and favored $\rightarrow c$ transitions described by the amplitudes A_u and A_c , respectively. The magnitude of the ratio between the amplitudes A_u and A_c is r . The relative weak phase between these two amplitudes is γ ; it is $2\beta + \gamma$ with $B^0\bar{B}^0$ mixing. Also, there exists the strong phase difference between these two amplitudes, δ . These hadronic parameters in the observables, r and δ , make extraction of the weak phase information difficult.

The time dependent (TD) distribution for B^0 decays to a final state can be written as

$$f^\pm = \frac{e^{-|\Delta t|/\tau}}{4\tau} \times [1 \mp S_\eta^\pm \sin(\Delta m_d \Delta t) \mp \eta C \cos(\Delta m_d \Delta t)] \quad (1)$$

where τ is the B^0 lifetime, Δm_d is the $B^0\bar{B}^0$ mixing frequency and $\Delta t = t_{\text{rec}} - t_{\text{tag}}$ is the time of the reconstructed B (B_{rec}) decay relative to the decay of the other B (B_{tag}) from the $\Upsilon(4S) \rightarrow B\bar{B}$ decay. Δt is calculated from the measured separation along the beam collision axis (z) between the B_{rec} and B_{tag} decay vertices: $\Delta z = \beta\gamma c \Delta t$ where $\beta\gamma = 0.56$ is the Lorentz boost of $B\bar{B}$ pairs along the direction of the high-energy beam. In equation 1 the upper (lower) sign refers to the flavor of B_{tag} as B^0 (\bar{B}^0), while $\eta = +1$ (-1) denotes the final state $D^{(*)}$ ($\bar{D}^{(*)}$). The specifics of the CP parameters, S_η^\pm and C , depend on the physics of the reconstructed B^0 decay mode.

CP asymmetry in $B^0 \rightarrow D^{(*)\mp}\pi^\pm/\rho^\pm$ decays

The decay modes $B^0 \rightarrow D^{(*)\mp}\pi^\pm$ have been proposed to measure $\sin(2\beta + \gamma)$ [1]. The decay rate distribution for $B \rightarrow D^{(*)\mp}\pi^\pm$ is given by equation 1 which is parametrized to account for tag-side interference [2]. The CP parameter C is unity and S^\pm for each tagging category is given by $S_\eta^\pm = (a - \eta c)$ with $a = 2r \sin(2\beta + \gamma) \cos \delta$, $c = 2 \cos(2\beta + \gamma)(r \sin \delta)$. Since A_u is doubly CKM-suppressed with respect to A_c , one expects the ratio to be of order 2%. Due to the small value of r , large data samples are required for a statistically significant measurement of S_η^\pm .

Fully reconstructed $B^0 \rightarrow D^{(*)\mp}\pi^\pm$ and $B^0 \rightarrow D^\mp \rho^\pm$ decays [3] using 232 million $B\bar{B}$ pairs are used to measure the parameters a and c . Results of this analysis from

the TD maximum likelihood fit are

$$\begin{aligned}
a^{D\pi} &= -0.010 \pm 0.023 \pm 0.007, & c_{\text{lep}}^{D\pi} &= -0.033 \pm 0.042 \pm 0.012 \\
a^{D^*\pi} &= -0.040 \pm 0.023 \pm 0.010, & c_{\text{lep}}^{D^*\pi} &= 0.049 \pm 0.042 \pm 0.015 \\
a^{D\rho} &= -0.024 \pm 0.031 \pm 0.009, & c_{\text{lep}}^{D\rho} &= -0.098 \pm 0.055 \pm 0.018
\end{aligned}$$

where the first error is statistical and the second is systematic.

In partially reconstructing $B^0 \rightarrow D^{*\mp}\pi^\pm$ candidates, only the hard (high-momentum) pions π_h from B decay and soft (low-momentum) pions π_s from $D^{*-} \rightarrow \bar{D}^0\pi_s^-$ decays are employed. The ‘‘missing mass’’ of the non-reconstructed D is the kinematic variable used to extract signal events; it peaks at the nominal D^0 mass. This method eliminates the efficiency loss associated with D^0 meson reconstruction. The CP asymmetry measured with this technique [4] using 232 million $B\bar{B}$ pairs is

$$\begin{aligned}
a^{D^*\pi} &= -0.034 \pm 0.014 \pm 0.009, \\
c_{\text{lep}}^{D^*\pi} &= -0.019 \pm 0.022 \pm 0.013
\end{aligned}$$

To interpret these results in terms of constraints on $|\sin(2\beta + \gamma)|$, findings from the fully reconstructed $B^0 \rightarrow D^{(*)\mp}\pi^\pm$, $B^0 \rightarrow D^\mp\rho^\pm$ analysis are combined with those of the partially reconstructed $B^0 \rightarrow D^{*\mp}\pi^\pm$ study using a frequentist method described in Ref. [4]. This method sets the lower limits $|\sin(2\beta + \gamma)| > 0.64$ (0.40) at 68% (90%) C.L. as seen in Figure 1.

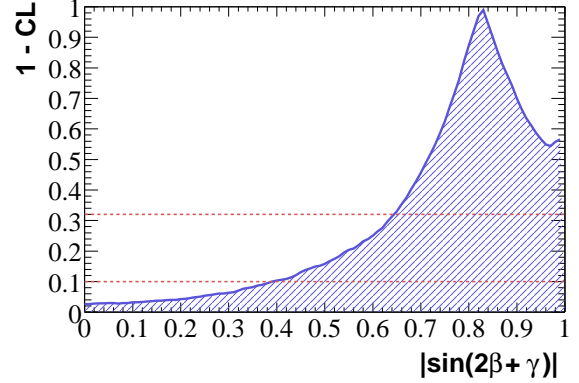


Figure 1: The shaded region denotes the allowed range of $|\sin(2\beta + \gamma)|$ for each confidence level. The horizontal lines show, from top to bottom, the 68% and 90% CL.

Dalitz plot analysis of $B^0 \rightarrow D^\mp K^0 \pi^\pm$

Measurement of $\sin(2\beta + \gamma)$ from three body B decays, such as $B^0 \rightarrow D^\mp K^0 \pi^\pm$ have been suggested as a way to avoid the limitation of small r , since r in these decays could be as large as 0.4 in some regions of the Dalitz plane [5]. The final state, $D^\mp K^0 \pi^\pm$, $D^+ \rightarrow K^- \pi^+ \pi^-$, is reached via the following intermediate states: $B^0 \rightarrow D^{*0} K_S^0$ with $D^{*0} = \{D_0^{*0}(2400), D_2^{*0}(2460)\}$, $B^0 \rightarrow D^- K^{*+}$ with $K^* = \{K^*(892), K_0^*(1430), K_2^*(1430), K^*(1680)\}$, and a small expected contribution from $B^0 \rightarrow D_s^{*+}(2573)\pi^-$. The TD Dalitz plot PDF is of the same form as equation 1, but multiplied by the factor $(A_c^2 + A_u^2)/2$ and with the coefficient of the sin term being

$$S_\eta = \frac{2\text{Im}(A_c A_u e^{i(2\beta + \gamma) + \eta i(\phi_c - \phi_u)})}{A_c^2 + A_u^2}.$$

The amplitudes (A_c, A_u) and strong phases (ϕ_c, ϕ_u) are functions of their positions in the Dalitz plot. The coefficient of the sin

With the ratio of the amplitudes r set to 0.3 for each resonance in the PDF, consistent with the limit $r < 0.4$ (90% CL) reported in Ref.[6], the weak phase is found to be $2\beta + \gamma = (83 \pm 53 \pm 20)^\circ$ and $(263 \pm 53 \pm 20)^\circ$ [7], shown in Fig. 2b, in a sample of 347 million $B\bar{B}$ pairs. The central value $2\beta + \gamma$ is stable with respect to the value of r (Fig. 2a).

$\bar{B}^0 \rightarrow D^{(*)0} \bar{K}^0$ decays

The decay modes $\bar{B}^0 \rightarrow D^{(*)0} \bar{K}^0$ have been proposed for determination of $\sin(2\beta + \gamma)$ from measurement of TD CP asymmetries [8]. Due to relatively large CP asymmetry ($r_B \equiv |A(\bar{B}^0 \rightarrow \bar{D}^{(*)0} \bar{K}^0)|/|A(\bar{B}^0 \rightarrow D^{(*)0} \bar{K}^0)| \simeq 0.4$) these decays appear ideal for such a measurement. The TD decay rate in this case can be parameterized such that $C = (1 - r_B^2)/(1 + r_B^2)$ and $S = r_B \sin(2\beta + \gamma + \delta)/(1 + r_B^2)$. Since r_B can simply be measured by fitting the C coefficient in the decay distributions, the measured asymmetry can be interpreted in terms of $\sin(2\beta + \gamma)$ without additional assumptions. However, the branching fractions of such decays are relatively small, $\mathcal{O}(10^{-5})$. Therefore a large data sample is required.

The most recent measurement [6] of these decays using a data sample of 226 million $B\bar{B}$ pairs finds

$$\begin{aligned} \mathcal{B}(\bar{B}^0 \rightarrow D^0 \bar{K}^0) &= (5.3 \pm 0.7 \pm 0.3) \times 10^{-5} \\ \mathcal{B}(\bar{B}^0 \rightarrow D^{*0} \bar{K}^0) &= (3.6 \pm 1.2 \pm 0.3) \times 10^{-5} \end{aligned}$$

from signal yields to the maximum likelihood fits in Fig. 3. With just over 100 signal events, a TD decay rate analysis is not feasible.

Conclusion

Non-trivial, theoretically clean constraints on $2\beta + \gamma$ come from measurements of time-dependent CP asymmetry in the B decays. Updated measurements to the full

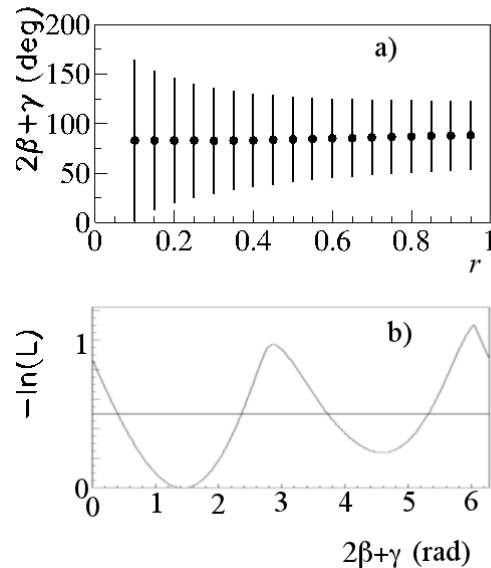


Figure 2: a): distribution of the values of $2\beta + \gamma$ fitted on data for different hypotheses on the r value. b): variation of the logarithm of the likelihood with $2\beta + \gamma$.

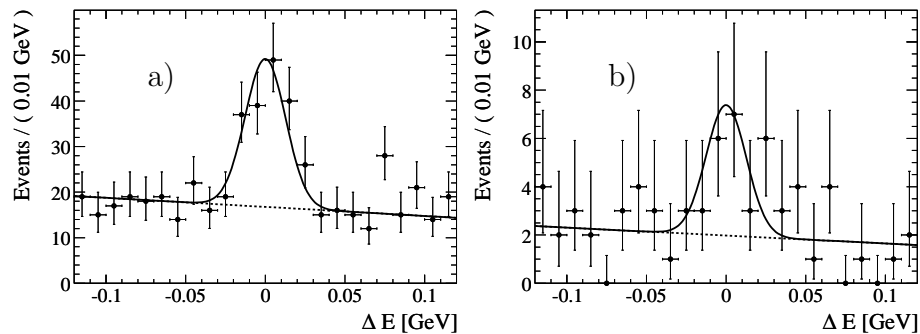


Figure 3: Distribution of ΔE for a) $\bar{B}^0 \rightarrow D^0 \bar{K}^0$, b) $\bar{B}^0 \rightarrow D^{*0} \bar{K}^0$, The points are the data, the solid curve is the projection of the likelihood fit, and the dashed curve represents the background component.

BABAR dataset of 468 million $B\bar{B}$ pairs will only deepen our understanding of the CKM mechanism. We expect an improvement in the measurement of γ with $B \rightarrow D^{(*)\mp} \pi^\pm / \rho^\pm$ since r can be more precisely estimated by using the isospin relation $r = \sqrt{\frac{\tau_B^0}{\tau_B^\pm} \frac{2\mathcal{B}(B^+ \rightarrow D^{*+} \pi^0)}{\mathcal{B}(B^0 \rightarrow D^{*+} \pi^+)}} < 0.051$ (90% C.L.) as suggested by Ref. [9]. It is also possible that the full *BABAR* data sample is just large enough to detect CP asymmetry in the mode $\bar{B}^0 \rightarrow D^0 \bar{K}^0$.

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