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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 ($B \to D^{(*)}\pi/\rho$ and $B^0 \to D^{\mp}K_S^0\pi^{\pm}$) or small branching fractions ($B \to D^{(*)}K^{(*)}$). 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 $B^0/\overline{B}^0 \to D^{(*)}X_{u,d,s}$ decays where $X_{u,d,s}$ refers to light and/or strange mesons. In the Standard Model, these decays proceed via Cabibbo suppressed $\underline{\to}\ u$ and favored $\underline{\to}\ c$ 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 $B^0\overline{B}^0$ 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

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

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

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

The decay modes $B^0 \to D^{(*)\mp}\pi^{\pm}$ have been proposed to measure $\sin(2\beta+\gamma)$ [1]. The decay rate distribution for $B \to D^{(*)\mp}\pi^{\pm}$ 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 $S_{\eta}^{\pm}$.

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

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

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

In partially reconstructing $B^0 \to D^{*\mp}\pi^{\pm}$ candidates, only the hard (high-momentum) pions π_h from B decay and soft (low-momentum) pions π_s from $D^{*-} \to \overline{D}^0\pi_s^-$ 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 $B\overline{B}$ pairs is

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

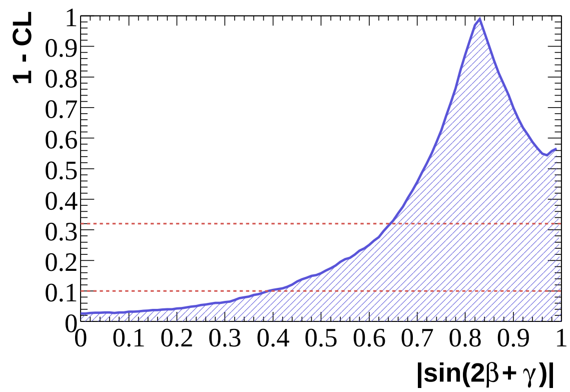

Figure 1: *The shaded region denotes the allowed range of* $|\sin(2\beta+\gamma)|$ *for each confidence level. The horizontal lines show, from top to bottom, the 68% and 90% CL.*

To interpret these results in terms of constraints on $|\sin(2\beta+\gamma)|$, findings from the fully reconstructed $B^0 \to D^{(*)\mp}\pi^{\pm}$, $B^0 \to D^{\mp}\rho^{\pm}$ analysis are combined with those of the partially reconstructed $B^0 \to D^{*\mp}\pi^{\pm}$ 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.

Dalitz plot analysis of $B^0 \to D^{\mp}K^0\pi^{\pm}$

Measurement of $\sin(2\beta+\gamma)$ from three body B decays, such as $B^0 \to D^{\mp}K^0\pi^{\pm}$ 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, $D^{\mp}K^0\pi^{\pm}$, $D^+ \to K^-\pi^+\pi^-$, is reached via the following intermediate states: $B^0 \to D^{**0}K_S^0$ with $D^{**0} = \{D_0^{**}(2400),\ D_2^{**}(2460)\}$, $B^0 \to D^-K^{*+}$ with $K^* = \{K^*(892),\ K_0^*(1430),\ K_2^*(1430),\ K^*(1680)\}$, and a small expected contribution from $B^0 \to D_s^{*+}(2573)\pi^-$. 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

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

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 si

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 $B\overline{B}$ pairs. The central value $2\beta + \gamma$ is stable with respect to the value of r (Fig. 2a).

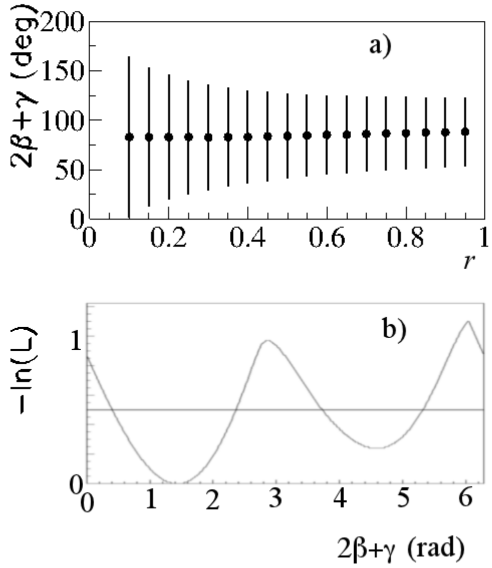

Figure 2: *a): distribution of the values of $2\beta + \gamma$ fitted on data for different hypotheses on the r value. b): variation of the logarithm of the likelihood with $2\beta + \gamma$.*

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

The decay modes $\overline{B}^0 \to D^{(*)0} \bar{K}^0$ have been proposed for determination of $\sin(2\beta + \gamma)$ from measurement of TD *CP* asymmetries [8]. Due to relatively large *CP* asymmetry ($r_B \equiv |A(\overline{B}^0 \to \bar{D}^{(*)0} \bar{K}^0)|/|\overline{B}^0 \to D^{(*)0} \bar{K}^0)| \simeq 0.4$) 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 $B\overline{B}$ pairs finds

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

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

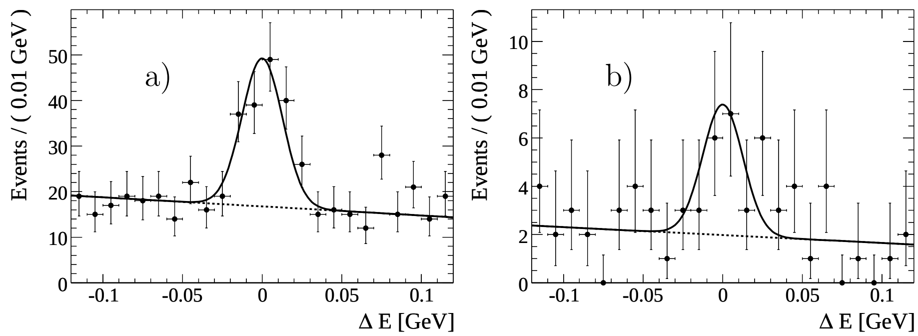

Figure 3: *Distribution of* ΔE *for a)* $\overline{B}^0 \to D^0 \overline{K}^0$*, b)* $\overline{B}^0 \to D^{*0}\overline{K}^0$*, The points are the data, the solid curve is the projection of the likelihood fit, and the dashed curve represents the background component.*

BABAR dataset of 468 million $B\overline{B}$ pairs will only deepen our understanding of the CKM mechanism. We expect an improvement in the measurement of γ with $B \to D^{(*)\mp}\pi^{\pm}/\rho^{\pm}$ since r can be more precisely estimated by using the isospin relation $r = \sqrt{\frac{\tau_B^0}{\tau_B^+}\frac{2\mathcal{B}(B^+ \to D^{*+}\pi^0)}{\mathcal{B}(B^0 \to D^{*-}\pi^+)}} < 0.051$ (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 $\overline{B}^0 \to D^0\ \overline{K}^0$.

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