Time-dependent $\gamma/\phi_3$ measurements by $\text{BaBar}$

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Compilation and summary of time-dependent measurements of the CKM angle $\gamma/\phi_3$ with events collected at the $\text{BaBar}$ 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 $\gamma/\phi_3$ 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 $B^0 \to D^{\mp}K^0_s\pi^\pm$) 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 $B^0/\bar{B}^0 \to D^{(*)}X_{u,d,s}$ decays where $X_{u,d,s}$ refers to light and/or strange mesons. In the Standard Model, these decays proceed via Cabibbo suppressed $\to u$ and favored $\to c$ 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 $\gamma$; it is $2\beta + \gamma$ with $B^0\bar{B}^0$ mixing. Also, there exists the strong phase difference between these two amplitudes, $\delta$. These hadronic parameters in the observables, $r$ and $\delta$, 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

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

where $\tau$ is the $B^0$ lifetime, $\Delta m_d$ is the $B^0\bar{B}^0$ mixing frequency and $\Delta t = t^{\text{rec}} - t^{\text{tag}}$ is the time of the reconstructed $B$ ($B^{\text{rec}}$) decay relative to the decay of the other $B$ ($B^{\text{tag}}$) from the $Y(4S) \to B\bar{B}$ decay. $\Delta t$ is calculated from the measured separation along the beam collision axis ($z$) between the $B^{\text{rec}}$ and $B^{\text{tag}}$ 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 $B^{\text{tag}}$ as $B^0$ ($\bar{B}^0$), while $\eta = +1$ ($-1$) denotes the final state $D^{(*)}$ ($D^{(*)}$). 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 $B^0 \to D^{(*)}\pi^\pm/\rho^\pm$ decays**

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

\[
\begin{align*}
  a^{D\pi} &= -0.010 \pm 0.023 \pm 0.007, \\
  c^{D\pi}_{\text{lep}} &= -0.033 \pm 0.042 \pm 0.012, \\
  a^{D^*\pi} &= -0.040 \pm 0.023 \pm 0.010, \\
  c^{D^*\pi}_{\text{lep}} &= 0.049 \pm 0.042 \pm 0.015, \\
  a^{D\rho} &= -0.024 \pm 0.031 \pm 0.009, \\
  c^{D\rho}_{\text{lep}} &= -0.098 \pm 0.055 \pm 0.018.
\end{align*}
\]

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

In partially reconstructing \(B^0 \rightarrow D^{*+}\pi^\pm\) candidates, only the hard (high-momentum) pions \(\pi_h\) from \(B\) decay and soft (low-momentum) pions \(\pi_s\) from \(D^{*-} \rightarrow \overline{D}^0\pi^-\) 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

\[
\begin{align*}
  a^{D^*\pi} &= -0.034 \pm 0.014 \pm 0.009, \\
  c^{D^*\pi}_{\text{lep}} &= -0.019 \pm 0.022 \pm 0.013.
\end{align*}
\]

To interpret these results in terms of constraints on \(|\sin(2\beta + \gamma)|\), findings from the fully reconstructed \(B^0 \rightarrow D^{(*)+}\pi^\pm\), \(B^0 \rightarrow D^{(*)}\rho^\pm\) analysis are combined with those of the partially reconstructed \(B^0 \rightarrow D^{*+}\pi^\pm\) 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 [4].

**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% C.L.

### Dalitz plot analysis of \(B^0 \rightarrow D^+K^0\pi^\pm\)

Measurement of \(\sin(2\beta + \gamma)\) from three body \(B\) decays, such as \(B^0 \rightarrow D^+K^0\pi^\pm\) 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, \(D^+K^0\pi^\pm\), \(D^+ \rightarrow K^-\pi^+\pi^-\), is reached via the following intermediate states: 

\(B^0 \rightarrow D^{*+}\pi^\pm\), 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 \(B^0 \rightarrow D_2^{*+}(2573)\pi^-\). The TD Dalitz plot PDF is of the same form as equation [11], but multiplied by the factor \((A_e^2 + A_u^2)/2\) and with the coefficient of the sin term being

\[
S_\gamma = \frac{2\text{Im}(A_eA_u e^{i(2\beta + \gamma)} + \eta\delta)}{A_e^2 + A_u^2}.
\]
The amplitudes \((A_c, A_u)\) and strong phases \((\phi_c, \phi_u)\) are functions of their positions in the Dalitz plot. The coefficient of the \(\sin\) term is \(C = (A^2_c - A^2_u)/(A^2_c + A^2_u)\).

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 \(2\beta + \gamma\).

\[ B^0 \rightarrow D^{(*)0} \bar{K}^0 \text{ decays} \]

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

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

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

$\bar{B}\Lambda\bar{B}$ 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 $\gamma$ with $B \rightarrow D^{(*)\pm} \pi^\pm/\rho^\pm$ since $r$ can be more precisely estimated by using the isospin relation $r = \sqrt{\frac{\tau_{D^{(*)}}}{{\tau_B}}} \frac{2\beta(B^0 \rightarrow D^{(*)}\pi^0)}{\beta(B^0 \rightarrow D^0\pi^0)} < 0.051$ (90% C.L.) as suggested by Ref. [9]. It is also possible that the full $\bar{B}\Lambda\bar{B}$ data sample is just large enough to detect $CP$ asymmetry in the mode $\bar{B}^0 \rightarrow D^0 K^0$.

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