Time-integrated measurements of the CKM angle $\gamma/\phi_3$ in $\text{BABAR}$

**Giovanni Marchiori**\textsuperscript{1}

on behalf of the $\text{BABAR}$ Collaboration

*Laboratoire de Physique Nucléaire et de Hautes Energies*  
*IN2P3/CNRS, F-75252 Paris, FRANCE*

The most recent determinations of the CKM angle $\gamma/\phi_3$ by the $\text{BABAR}$ Collaboration, using time-integrated observables measured in charged $B \to D^{(*)}K^{(*)}$ decays, are presented. The measurements have been performed on the full sample of 468 million $B \bar{B}$ pairs collected by the $\text{BABAR}$ detector at the SLAC PEP-II asymmetric-energy $B$ factory in the years 1999-2007.

PROCEEDINGS OF

CKM2010, the 6th International Workshop on the CKM Unitarity Triangle  
University of Warwick, UK  
6-10 September 2010

\textsuperscript{1}e-mail: giovanni.marchiori@lpnhe.in2p3.fr
1 Introduction

A theoretically clean measurement of the angle $\gamma \equiv \arg \left[ \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right]$ (also denoted as $\phi_3$ in the literature) can be obtained using $CP$-violating $B \rightarrow D(\ast)K(\ast)$ decays. The interference between the $b \rightarrow c\pi s$ and $b \rightarrow u\pi s$ tree amplitudes results in observables that depend on the relative weak phase $\gamma$, the magnitude ratio $r_B \equiv \left| \frac{A(b\rightarrow u)}{A(b\rightarrow c)} \right|$, and the relative strong phase $\delta_B$ between the two amplitudes. The hadronic parameters, $r_B$ and $\delta_B$, depend on the $B$ decay under investigation; they can not be precisely calculated from theory, but can be extracted directly from data by simultaneously reconstructing several different $D$ final states.

In this contribution we present the most recent $\gamma$ determinations obtained by BABAR, based on the full sample ($\approx 468 \times 10^6$ $B^\pm$ decays) of charged $B$ mesons produced in $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^+B^-$ and accumulated in the years 1999-2007. The following decays have been reconstructed: (i) $B^\pm \rightarrow D(\ast)K^\pm$ and $B^\pm \rightarrow DK^\ast(\ast)K^\pm \rightarrow K_0^0(\pi^\pm \pi^\mp)$, with $D \rightarrow K_0^0 h^+h^-$, $h = \pi, K$; (ii) $B^\pm \rightarrow DK^\pm$, with $D$ decaying to $CP$-eigenstates $f_{CP}$; (iii) $B^\pm \rightarrow D(\ast)K^\pm$, with $D$ decaying to $K^\pm\pi^\mp$. The results are statistically limited, as the effects that are being searched for are tiny, since: (i) the branching fractions of the $B$ meson decays considered here are on the order of $5 \times 10^{-4}$ or lower; (ii) the branching fractions for $D(\ast)$ decays, including secondary decays, range between $O(10^{-2})$ and $O(10^{-4})$; (iii) the interference between the $b \rightarrow c$ and $b \rightarrow u$ mediated $B$ decay amplitudes is low, as the ratios $r_B$ are around 0.1 due to CKM factors and the additional color-suppression of $A(b \rightarrow u)$.

The $B$ decay final states are completely reconstructed, with efficiencies between 40% (for low-multiplicity, low-background decay modes) and 5% (for high-multiplicity decays). The selection is optimized to maximise the statistical sensitivity $S/\sqrt{S+B}$, where the number of expected signal $(S)$ and background $(B)$ events is estimated from simulated samples and data control samples. Signal $B$ decays are distinguished from $B\bar{B}$ and continuum $q\bar{q}$ background by means of maximum likelihood fits to two variables exploiting the kinematic constraint from the known beam energies: the energy-substituted invariant mass $m_{ES} \equiv \sqrt{E_{beam}^2 - p_T^2}$ and the energy difference $\Delta E \equiv E^*_B - E_{beam}^*$. Additional continuum background discrimination is achieved by including in the likelihood a variable built, using multivariate analysis tools, from the combination (either a linear Fisher discriminant, $F$, or a non-linear neural-network, $NN$) of several event-shape quantities. These variables distinguish spherical $B\bar{B}$ events from more jet-like $q\bar{q}$ events and exploit the different angular correlations in the two event categories. $B \rightarrow D(\ast)\pi$ decays, which are 12 times more abundant than $B \rightarrow D(\ast)K$ and are expected to show negligible $CP$-violating effects ($r_B \approx 0.01$ in such decays), are discriminated by means of the excellent pion and kaon identification provided by $dE/dx$ measured in the charged particle tracking devices and by the radiation detected in the Cherenkov detector, and are used as control samples.
2 Dalitz-plot method: $B^{\pm} \to D^{(*)}K^{(*)\pm}$, $D \to K_{S}^{0}h^{+}h^{-}$

We reconstruct $B^{\pm} \to DK^{\pm}$, $D^{*}K^{\pm}$ ($D^{*} \to D\gamma$ and $D\pi^{0}$), and $DK^{*\pm}$ ($K^{*\pm} \to K_{S}^{0}\pi^{\pm}$) decays, followed by neutral $D$ meson decays to the 3-body self-conjugate final states $K_{S}^{0}h^{+}h^{-}$ ($h = \pi, K$) \footnote{1}. From an extended maximum likelihood fit to $m_{ES}$, $\Delta E$ and $F$ (Fig. 1\footnote{1}) we determine the signal and background yields in each channel: we find 268 $B$ candidates with $D \to K_{S}^{0}K^{+}K^{-}$ and 1507 $B$ candidates with $D \to K_{S}^{0}\pi^{+}\pi^{-}$.

![Figure 1: The $m_{ES}$ (a), $\Delta E$ (b), and $F$ (c) distributions for $B^{\pm} \to DK^{\pm}$, $D \to K_{S}^{0}\pi^{+}\pi^{-}$, for events in the signal region ($m_{ES} > 5.272$ GeV/c$^2$, $|\Delta E| < 30$ MeV, and $F > -0.1$), after all the selection criteria, except the one on the plotted variable, are applied. The curves represent the fit projections: signal plus background (solid black lines), $q\bar{q} + B\bar{B}$ background (dotted red lines), $q\bar{q} + B\bar{B} + B \to D\pi$ background (dashed blue lines).

Following the technique proposed in \footnote{2}, from a fit to the Dalitz-plot distribution of the $D$ daughters we determine 2D confidence regions for the variables $x_{\pm} \equiv r_{B}\cos(\delta_{B} \pm \gamma)$ and $y_{\pm} \equiv r_{B}\sin(\delta_{B} \pm \gamma)$ (Fig. 2\footnote{2}). In the fit we model the $D^{0}$ and $\bar{D}^{0}$ decay amplitudes to $K_{S}^{0}h^{+}h^{-}$ as the coherent sum of a non-resonant part and several intermediate two-body decays that proceed through known $K_{S}^{0}h$ or $h^{+}h^{-}$ resonances. The model is determined from large ($\approx 6.2 \times 10^{5}$) and very pure ($\approx 99\%$) control samples of $D$ mesons produced in $D^{*}\to D\pi$ decays \footnote{3}. The results for $x$ and $y$ are summarized in Table 1\footnote{1}.

| Parameter | $B^{\pm} \to DK^{\pm}$ | $B^{\pm} \to D^{*}K^{\pm}$ | $B^{\pm} \to DK^{*\pm}$ |
|-----------|----------------|----------------|----------------|
| $x_{\pm}$ | $-0.103 \pm 0.037 \pm 0.006 \pm 0.007$ | $0.147 \pm 0.033 \pm 0.017 \pm 0.003$ | $-0.151 \pm 0.083 \pm 0.029 \pm 0.006$ |
| $y_{\pm}$ | $-0.021 \pm 0.048 \pm 0.004 \pm 0.009$ | $-0.032 \pm 0.077 \pm 0.008 \pm 0.006$ | $0.045 \pm 0.106 \pm 0.036 \pm 0.008$ |
| $x_{-}$ | $0.060 \pm 0.039 \pm 0.007 \pm 0.006$ | $-0.104 \pm 0.051 \pm 0.019 \pm 0.002$ | $0.075 \pm 0.106 \pm 0.029 \pm 0.007$ |
| $y_{-}$ | $0.062 \pm 0.045 \pm 0.004 \pm 0.006$ | $-0.052 \pm 0.063 \pm 0.009 \pm 0.007$ | $0.127 \pm 0.095 \pm 0.027 \pm 0.006$ |

Table 1: Values of $x_{\pm}$ and $y_{\pm}$ measured with the Dalitz-plot analysis of $B^{\pm}\to D^{(*)}K^{(*)\pm}$

From the $(x_{\pm}, y_{\pm})$ confidence regions we determine, using a frequentist procedure, $1\sigma$ confidence intervals for $\gamma$, $r_{B}$ and $\delta_{B}$ (Fig. 3\footnote{3}). We obtain $\gamma \mod 180^\circ = (68 \pm 14 \pm$
Figure 2: 1σ and 2σ contours in the $x\pm, y\pm$ planes for (a) $B \rightarrow DK$, (b) $B \rightarrow D^*K$ and (c) $B \rightarrow DK^*$, for $B^-$ (solid lines) and $B^+$ (dotted lines) decays.

$4\pm 3)^\circ$, where the three uncertainties are respectively the statistical, the experimental systematic and the Dalitz-model systematic ones. We find values of $r_B$ around 0.1, confirming that interference is low in these channels: $r_B^{DK^\pm} = 0.096\pm 0.029$; $r_B^{D^*K^\pm} = 0.133^{+0.042}_{-0.039}$; $kr_B^{DK^\pm} = 0.149^{+0.066}_{-0.062}$ ($k=0.9\pm 0.1$ takes into account the $K^*$ finite width).

We also measure the strong phases (modulo 180°): $\delta_B^{DK^\pm} = (119^{+13}_{-20})^\circ$; $\delta_B^{D^*K^\pm} = (-82 \pm 21)^\circ$; $\delta_B^{DK^*\pm} = (111 \pm 32)^\circ$. A 3.5σ evidence of direct CP violation is found from the distance between $(x_+, y_+)$ and $(x_-, y_-)$ (0 in absence of CPV) in the three $B$ decay channels.

Figure 3: 1-confidence level (CL) as a function of $\gamma$ (left), $r_B$ (center) and $\delta_B$ (right) from the $B \rightarrow D^{(*)} K^{(*)}$ Dalitz-plot analysis.

3 GLW method: $B^\pm \rightarrow DK^{(*)\pm}, D \rightarrow f_{(CP)}$

We reconstruct $B^\pm \rightarrow DK^{\pm}$ decays, with $D$ mesons decaying to non-CP ($D^0 \rightarrow K^-\pi^+$), CP-even ($K^+K^-, \pi^+\pi^-$) and CP-odd ($K^0_{S\pi^0}, K^0_{S\phi}, K^0_{S\omega}$) eigenstates [4].
The partial decay rate charge asymmetries $A_{CP\pm}$ for $CP$-even and $CP$-odd $D$ final states and the ratios $R_{CP\pm}$ of the charged-averaged $B$ meson partial decay rates in $CP$ and non-$CP$ decays provide a set of four observables from which the three unknowns $\gamma$, $r_B$ and $\delta_B$ can be extracted (with an 8-fold discrete ambiguity for the phases) [5].

The signal yields, from which the partial decay rates are determined, are obtained from maximum likelihood fits to $m_{ES}$, $\Delta E$ and $F$. An example is shown in Fig. 4. We identify about 500 $B^\pm \rightarrow DK^\pm$ decays with $CP$-even $D$ final states and a similar amount of $B^\pm \rightarrow DK^\mp$ decays with $CP$-odd $D$ final states. We measure $A_{CP+} = 0.25 \pm 0.06 \pm 0.02$ and $A_{CP-} = -0.09 \pm 0.07 \pm 0.02$, respectively, where the first error is the statistical and the second is the systematic uncertainty. The parameter $A_{CP+}$ is different from zero with a significance of 3.6 standard deviations, constituting evidence for direct $CP$ violation. We also measure $R_{CP+} = 1.18 \pm 0.09 \pm 0.05$ and $R_{CP-} = 1.07 \pm 0.08 \pm 0.04$.

![Figure 4: ΔE projections of the fits to the data: (a) $B^-\rightarrow D_{CP+}K^-$, (b) $B^+\rightarrow D_{CP+}K^+$. The curves are the full PDF (solid, blue), and $B\rightarrow D\pi$ (dash-dotted, green) stacked on the remaining backgrounds (dotted, purple). We require candidates to lie inside a signal-enriched region: 0.2 < $F$ < 1.5, 5.275 < $m_{ES}$ < 5.285 GeV/c$^2$, charged particle from the $B$ passing kaon identification criteria.](image)

Using a frequentist technique, including statistical and systematic uncertainties, we obtain $0.24 < r_B < 0.45$ ($0.06 < r_B < 0.51$) and, modulo $180^\circ$, $11.3^\circ < \gamma < 22.7^\circ$ or $80.9^\circ < \gamma < 99.1^\circ$ or $157.3^\circ < \gamma < 168.7^\circ$ ($7.0^\circ < \gamma < 173.0^\circ$) at the 68% (95%) confidence level (Fig. 5). To facilitate the combination of these measurements with the results of the Dalitz-plot analysis, we exclude the $D \rightarrow K^0_s\phi$, $\phi \rightarrow K^+K^-$ channel from this analysis – thus removing events common to the two measurements – and express our results in terms of the variables $x_{\pm}$ using $x_{\pm} = \frac{1}{4}[R_{CP+}(1 \mp A_{CP+}) - R_{CP-}(1 \mp A_{CP-})]$. We find: $x_{+} = -0.057 \pm 0.039 \pm 0.015$ and $x_{-} = 0.132 \pm 0.042 \pm 0.018$, in good agreement with the results from the Dalitz-plot analysis.
Figure 5: 1-CL as a function of $\gamma \mod 180^\circ$ (left) and $r_B$ (right) from the $B \to DK$ GLW study.

4 ADS method: $B^\pm \to D(\ast)^\pm K^\pm$, $D \to K^\pm \pi^\mp$

We reconstruct $B^\pm \to DK^\pm$ and $D^\ast K^\pm$ ($D^\ast \to D\gamma$ and $D\pi^0$), followed by $D$ decays to both the doubly-Cabibbo-suppressed $D^0$ final state $K^+\pi^-$ and the Cabibbo-allowed final state $K^-\pi^+$, which is used as normalization and control sample [6]. Final states with opposite-sign kaons are produced from the interference of the CKM favored $B$ decay followed by the doubly Cabibbo-suppressed $D$ decay and the CKM- and color-suppressed $B$ decay followed by the Cabibbo-allowed $D$ decay, and the $CP$ asymmetries may be potentially very large. On the other hand, their overall branching fractions are very small ($O(10^{-7})$) and background suppression is crucial. The three branching fraction ratios ($R_{ADS}$) between $B$ decays with opposite-sign and same-sign kaons and the three charge asymmetries ($A_{ADS}$) in $B$ decays with opposite-sign kaons provide six observables that can be used, together with the measurements by $c$- and $B$-factories of the amplitude ratio $r_D$ and the strong phase difference $\delta_D$ between the two $D$ decay amplitudes, to determine $\gamma$ (with a 4-fold discrete ambiguity) and the two sets of $r_B, \delta_B$ [7].

The yields are determined from fits to $m_{ES}$ and $NN$ (Fig. 6). We see indications of signals for the $B \to DK$ and $B \to D_{D^\ast K^0}^\ast K$ opposite-sign modes, with significances of 2.1$\sigma$ and 2.2$\sigma$, respectively. The measured branching fraction ratios are $R^{DK}_{ADS} = (1.1\pm0.5\pm0.2) \times 10^{-2}$ and $R^{D_{\ast K}^0}_{ADS} = (1.8\pm0.9\pm0.4) \times 10^{-2}$. The $CP$ asymmetries are large, $A^{DK}_{ADS} = -0.86\pm0.47_{-0.12}^{+0.12}$ and $A^{D_{\ast K}^0}_{ADS} = +0.77\pm0.35_{-0.12}^{+0.12}$. We see no evidence of opposite-sign $B \to D_{\ast D}^\ast K$ decays, and measure $R^{D_{\ast K}}_{ADS} = (1.3\pm1.4\pm0.8) \times 10^{-2}$ and $A^{D_{\ast K}}_{ADS} = +0.36 \pm 0.94_{-0.25}^{+0.25}$. From these results we infer $r_B^{DK} = 0.095^{+0.051}_{-0.041}$, $r_B^{D_{\ast K}} = 0.096^{+0.035}_{-0.051}$ and $54^\circ < \gamma < 83^\circ$ (Fig. 7).
Figure 6: \( m_{ES} \) projection of the fit to the data for the \( B^\pm \rightarrow DK^\pm, D \rightarrow K^\mp \pi^\pm \) decays, for samples enriched in signal \((N/N > 0.94)\), for (a) \( B^+ \) and (b) \( B^- \) candidates. The curves represent the fit projections for signal plus background (solid), the sum of all background components (dashed), and the \( q\bar{q} \) background only (dotted).

Figure 7: 1-CL as a function of \( \gamma \) (left) and \( r_B \) (right) from the \( B \rightarrow D^{(*)} K \) ADS study.

5 Conclusion

The full BABAR dataset has been exploited to measure the CKM angle \( \gamma \) in several \( B^\pm \rightarrow D^{(*)} K^{(*)\pm} \) decays using three alternative techniques. A coherent set of results on \( \gamma \) and on the hadronic parameters characterizing the \( B \) decay amplitudes has been obtained. The central value for \( \gamma \), around 70\(^\circ\), is consistent with indirect determinations from the CKM fits. We attained a precision on \( \gamma \) around 15\(^\circ\), and confirm the theoretical expectations of significant suppression \((r_B \approx 0.1)\) of the \( b \rightarrow u \) mediated decay amplitude with respect to the \( b \rightarrow c \) one. Finally, two direct CP violation evidences at the level of 3.5\(\sigma\) have been observed.
References

[1] P. del Amo Sanchez et al. [BABAR Collaboration], Phys. Rev. Lett. 105, 121801 (2010).

[2] A. Giri, Y. Grossman, A. Soffer and J. Zupan, Phys. Rev. D 68, 054018 (2003).

[3] P. del Amo Sanchez et al. [BABAR Collaboration], Phys. Rev. Lett. 105, 081803 (2010).

[4] P. del Amo Sanchez et al. [BABAR Collaboration], Phys. Rev. D 82, 072004 (2010).

[5] M. Gronau and D. Wyler, Phys. Lett. B265, 172; M. Gronau and D. London, Phys. Lett. B253, 483 (1991).

[6] P. del Amo Sanchez et al. [BABAR Collaboration], Phys. Rev. D 82, 072006 (2010).

[7] D. Atwood, I. Dunietz and A. Soni, Phys. Rev. Lett. 78, 3257 (1997).