PROCEEDINGS OF SCIENCE

SLAC-PUB-16031

# Recent BABAR results on CP violation in B decays

**Denis Derkach***
*Laboratoire de l'Accélérateur Linéaire, Orsay, France*
*E-mail:* derkach@lal.in2p3.fr

We will review the latest developments in determining the *CP*-violating phase $\gamma$ of the CKM matrix from measurements by the *BABAR* collaborations. The emphasis is given to recent results obtained with the analyses of the full dataset obtained by the experiment.

*The 2011 Europhysics Conference on High Energy Physics-HEP 2011,*
*July 21-27, 2011*
*Grenoble, Rhône-Alpes France*

*Speaker.



PoS(EPS-HEP2011)138

SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025
Work supported by US Department of Energy under contract DE-AC02-76SF00515 and HEP.

## 1. Introduction

The precise measurements of the *CP* violation processes is one of the way to look for the deviations from the Standard Model (SM). This goal can be achieved in the experiments aiming to study the *B*-meson decays. The *BABAR* experiment was constructed at the SLAC National Accelerator Laboratory on the PEP-II accelerator with primary goal to perform the first precision tests of the Kobayashi-Maskawa theory using *CP* asymmetry measurements in *B*-meson decays. The accelerator PEP-II operated at the energy close to the mass of $\Upsilon(4S)$ resonance, which subsequently decays to a pair of *B* mesons.

The *BABAR* detector is described in detail elsewhere [1]. During the last decade the *BABAR* detector was able to collect more than 430 $\text{fb}^{-1}$ of data before the shutdown in 2008. This dataset can be interpreted as 470 billions of $B\bar{B}$ pairs.

The angle $\gamma = -\arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$ is defined in terms of the matrix elements $V_{ij}$ of the CKM matrix. Its measurements provide a good test of the Standard Model (SM) extensions, as $\gamma$ can be extracted from the processes well described in the SM with a tree-level diagrams.

Various methods related to $B^+ \to D^{(*)0}K^{(*)+}$ decays have been proposed to determine the UT angle $\gamma$. These methods exploit the fact that the $B^+$ meson can decay either a $D^0$ (from a $\bar{b} \to c\bar{u}\bar{s}$ transition), or a $\bar{D}^0$ (from a $\bar{b} \to u\bar{c}\bar{s}$ transition; or vice versa for $b$ decays). If the final state is chosen such that both $D^0$ and $\bar{D}^0$ can contribute, the interference between these amplitudes is sensitive to the phase $\gamma$, allowing $\gamma$ to be determined with essentially no theoretical assumptions. Choices for the final state include $D^0$ meson decaying to:

- a singly Cabibbo-suppressed *CP* eigenstate, like $D^0 \to h^+h^-$ ($h = \pi, K$) for Gronau-London-Wyler (GLW) method [2];
- a doubly Cabibbo-suppressed flavor eigenstate, like $D^0 \to K^+\pi^-$ for Atwood-Dunietz-Soni (ADS) method [3];
- a Cabibbo-allowed self-conjugate 3-body state, like $D^0 \to K_S^0\pi^+\pi^-$ for Giri-Grossman-Soffer-Zupan (GGSZ) method [4].

Generally, the observables of the methods also depend on the amplitude ratio $r_{\rm B} \equiv \frac{A(b\to u)}{A(b\to c)}$ and the relative *CP* conserving phase $\delta_{\rm B}$ between the two amplitudes. These parameters depend on the *B* decay under investigation.

One of the advantages of studying *B* physics in an $e^+e^-$ collider at the $\Upsilon(4S)$ resonance is the kinematic constraint provided by the initial state. The energy of each B meson in the $\Upsilon(4S)$ frame must be equal to $\sqrt{s}/2$, where $\sqrt{s}$ is the total $e^+e^-$ CM energy. This constraint is exploited by introducing two almost uncorrelated kinematic variables: the energy-substituted mass $m_{\rm ES} \equiv \sqrt{(E_0^{*2}/2 + \vec{p}_0\cdot\vec{p}_B)^2/E_0^2 - p_B^2}$ and the energy difference $\Delta E \equiv E_B^* - E_0^*/2$, where $E$ and $p$ are the energy and the momentum respectively, the subscripts $B$ and 0 refer to the candidate $B$ and to the $e^+e^-$ system respectively and the asterisk denotes the $e^+e^-$ CM frame.

In the analyses presented, additional continuum background discrimination is achieved through inclusion into the maximum likelihood fit a variable from the combination (either a linear for Fisher discriminant, $\mathscr{F}$, or a non-linear neural network, NN) of several event-shape quantities and proper-time interval between two *B* meson decays. The selection is optimized maximizing the ratio $\frac{S}{S+B}$, where $S$ and $B$ are the expected number of signal and background events. In case of the ADS method, the selection optimization is performed on the suppressed channel sample.

In the following, the most recent results from the *BABAR* collaboration are discussed.

## 2. Recent Results with the GLW Method

The Gronau-London-Wyler (GLW) method [2] is based on the reconstruction of the $B$ decay to $D^0K$, where $D^0$ and $\bar{D}^0$ decay to $CP$-even or $CP$-odd eigenstates. The $D^0$ modes normally used are:

- $CP+$: $K^+K^-$, $\pi^+\pi^-$;
- $CP-$: $K_S^0\pi^0$, $\phi K_S^0$, $\eta K_S^0$, $\rho K_S^0$, and $\omega K_S^0$.

For the normalization, $B^+ \to \bar{D}^0K^+$, with $\bar{D}^0 \to K^+\pi^-$ is also reconstructed.

The four observables for this method are formed in the following way:

$$\begin{aligned} R_{CP^\pm} &= \frac{\Gamma(B^+ \to D^0_\pm K^+) + \Gamma(B^- \to D^0_\pm K^-)}{\Gamma(B^+ \to D^0K^+) + \Gamma(B^- \to \bar{D}^0K^-)} = 1 + r_\mathrm{B}^2 \pm 2r_\mathrm{B}\cos\gamma\cos\delta_\mathrm{B}, \\ A_{CP^\pm} &= \frac{\Gamma(B^+ \to D^0_\pm K^+) - \Gamma(B^- \to D^0_\pm K^-)}{\Gamma(B^+ \to D^0_\pm K^+) + \Gamma(B^- \to D^0_\pm K^-)} = \frac{\pm 2r_\mathrm{B}\sin\gamma\sin\delta_\mathrm{B}}{R_{CP^\pm}}. \end{aligned} \quad (2.1)$$

This set can provide an information on $\gamma$, $\delta_\mathrm{B}$, and $r_\mathrm{B}$ with an 8-fold ambiguity for the phases. In the recent *BABAR* analysis [5], the partial decay rates are obtained from maximum likelihood fits to $\Delta E$, $m_\mathrm{ES}$, and $\mathscr{F}$. We obtain around 500 signal events in both $CP$-odd and $CP$-even final states. An example of the fit is shown in Fig. 1. We measure $A_{CP+} = 0.25 \pm 0.06 \pm 0.02$ and 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 $R_{CP-} = 1.07 \pm 0.08 \pm 0.04$.

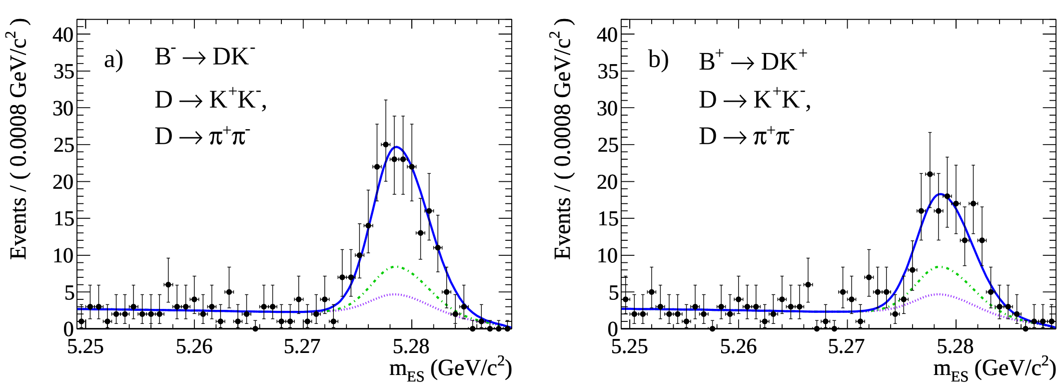


**Figure 1:** $m_\mathrm{ES}$ projections of the fits to the data: (a) $B^- \to D_{CP+}K^-$, (b) $B^+ \to D_{CP+}K^+$. The curves are the full PDF (solid, blue), and $B \to D\pi$ (dash-dotted, green) stacked on the remaining backgrounds (dotted, purple). Only a subrange of the whole fit range is shown in order to provide a closer view of the signal peak.

Following the frequentist approach and combining the statistical and systematic errors, we obtain $0.24 < r_{\rm B} < 0.45$ and $11.3^\circ < \gamma < 22.7^\circ$ or $80.9^\circ < \gamma < 99.1^\circ$ or $157.3^\circ < \gamma < 168.7^\circ$, modulus $180^\circ$.

## 3. Recent Results with the ADS Method

In the ADS method [3], $\gamma$ is measured from the study of $B \to DK$ decays, where $D$ mesons decay into non $CP$ eigenstate final states. The suppression of $b \to u$ transition with respect to the $b \to c$ one is partly overcome by the study of decays of the $B$ meson in final states which can proceed in two ways: either through a favored $b \to c$ $B$ decay followed by a doubly-Cabibbo-suppressed $D$ decay, or through a suppressed $b \to u$ $B$ decay followed by a Cabibbo-favored $D$ decay.

Neglecting $D$-mixing effects, which in the SM give very small corrections to $\gamma$ and do not affect the $r_{\rm B}$ measurement, the measured ratios $R^+$ and $R^-$ are related to the $B$ and $D$ mesons' decay parameters through the following relations:

$$
\begin{aligned}
R^+ &= \frac{\Gamma(B^+ \to [\overline{f}]_{D^0} K^+)}{\Gamma(B^+ \to [f]_{D^0} K^+)} = r_{\rm B}^2 + r_{\rm D}^2 + 2 r_{\rm B} r_{\rm D} k_{\rm D} \cos(\gamma + \delta), \\
R^- &= \frac{\Gamma(B^- \to [f]_{D^0} K^-)}{\Gamma(B^+ \to [f]_{D^0} K^+)} = r_{\rm B}^2 + r_{\rm D}^2 + 2 r_{\rm B} r_{\rm D} k_{\rm D} \cos(\gamma - \delta),
\end{aligned}
\tag{3.1}
$$

with

$$
\begin{aligned}
r_{\rm D}^2 &\equiv \frac{\Gamma(D^0 \to f)}{\Gamma(D^0 \to \overline{f})} = \frac{\int dm A_{\rm DCS}(m)}{\int dm A_{\rm CA}(m)}, \\
k_{\rm D} e^{i\delta_{\rm D}} &\equiv \frac{\int dm A_{\rm DCS}(m) A_{\rm CA} e^{i\delta(m)}}{\sqrt{\int dp A_{\rm DCS}^2(p) \int dp A_{\rm CA}^2(p)}},
\end{aligned}
\tag{3.2}
$$

The used observables are connected to the "classical" $R_{\rm ADS}$ and $A_{\rm ADS}$ set by simple relations: $R_{\rm ADS} = \frac{R^+ + R^-}{2}$ and $A_{\rm ADS} = \frac{R^- - R^+}{R^- + R^+}$. Since $R^+$ and $R^-$ are two independent observables, while $R_{\rm ADS}$ and $A_{\rm ADS}$ are correlated we prefer to extract the physical parameters from $(R^+, R^-)$ rather than $(R_{\rm ADS}, A_{\rm ADS})$. The values of $k_{\rm D}$ and $\delta_{\rm D}$ measured by the CLEO-c collaboration [6], are used in the signal yield estimation and $r_{\rm B}$ extraction. The ratio $r_{\rm D}$ has been measured in different experiments and we take the average value [7].

The BABAR collaboration has recently published the analyses of $B^\pm \to D^{(*)} K^\pm$ decay channels with $D^* \to D\gamma$ and $D^* \to D\pi^0$. We have reconstructed the $D \to K\pi$ [8] and $D \to K\pi\pi^0$ [9] decay channels.

The yields are determined from the maximum likelihood fit to $m_{\rm ES}$ and Neural Network (for the $D \to K\pi$ mode) or Fisher (for the $D \to K\pi\pi^0$ mode). The measured values of $R^+$ and $R^-$ are shown in Table 1. Some fit projections are shown in Fig. 2.

Following Bayesian and frequentist approach for the $K\pi$ and $K\pi\pi^0$ $D$-meson decay, respectively, we obtain the following results: $r_{\rm B}(B \to DK, D \to K\pi) = (9.5^{+5.1}_{-4.1})\%$, $r_{\rm B}(B \to D^*K, D \to K\pi) = (9.6^{+3.5}_{-5.1})\%$, and $r_{\rm B}(B \to DK, D \to K\pi\pi^0) = (7.8^{+3.2}_{-6.8})\%$. The extraction of $\gamma$ can be performed from these data using combination with other methods.

**Table 1:** Results of extraction of $R^+$ and $R^-$ for different decay channels and their statistical and systematic errors.

| Sample | $R^+$, $10^{-3}$ | $R^-$, $10^{-3}$ |
|---|---|---|
| $B \to DK$, $D \to K\pi$ | $22 \pm 9 \pm 3$ | $2 \pm 6 \pm 2$ |
| $B \to D^*K$,$D^* \to D\gamma$, $D \to K\pi$ | $9 \pm 16 \pm 7$ | $19 \pm 23 \pm 12$ |
| $B \to D^*K$, $D^* \to D\pi^0$, $D \to K\pi\pi^0$ | $5 \pm 8 \pm 3$ | $37 \pm 18 \pm 9$ |
| $B \to DK$, $D \to K\pi\pi^0$ | $5^{+12}_{-10}{}^{+2}_{-4}$ | $12^{+12}_{-10}{}^{+3}_{-5}$ |

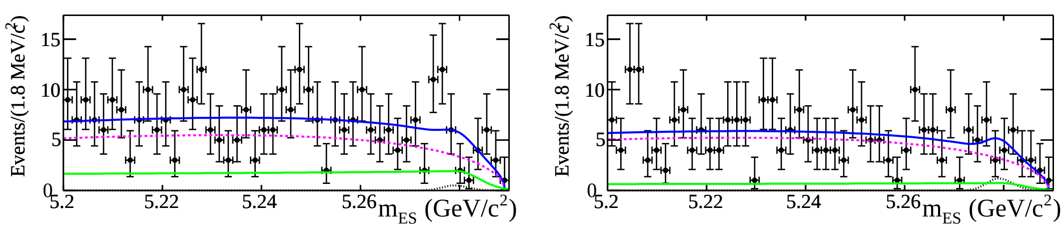


**Figure 2:** Projections of the 2D likelihood for $m_{\text{ES}}$ with the additional requirement $\mathscr{F} > 0.5$, obtained from the fit to the $B^+$ (left) and $B^-$ (right) data sample for the suppressed mode. The data are well described by the overall fit result (solid blue line) which is the sum of the signal, continuum, non-peaking, and peaking $B\bar{B}$ backgrounds.

## 4. Conclusions

The *BABAR* collaboration remains active and continues to analyze the large dataset obtained during last decade. The full *BABAR* dataset has already been exploited by several analysis attempting to measure $\gamma$. The most probable value of this *CP* violating parameter is measured to be around 70° in full accordance to the SM expectations as obtained from the CKM fits.

## References

[1] B. Aubert *et al.* (*BABAR* Collaboration), Nucl. Instr. Methods **A479**, 1 (2002).

[2] M. Gronau, D. Wyler, Phys. Rev. Lett. B **253** (1991) 483; M. Gronau, D. London, Phys. Rev. Lett. B **265** (1991) 172.

[3] I. Dunietz, Phys. Rev. Lett. B **270** (1991) 75; Phys. Rev. Lett. D **52** (1995) 3048; D. Atwood, I. Dunietz and A. Soni, Phys. Rev. Lett. **78**, 3257 (1997).

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

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

[6] N. Lowrey et al. (CLEO Collaboration), Phys. Rev. D **80**, 031105(R) (2009).

[7] K. Nakamura *et al.* (Particle Data Group), J. Phys. G 37, 075021 (2010).

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

[9] J. P. Lees *et al.* (*BABAR* Collaboration), Phys. Rev. D **84**, 012002 (2011)