

# Measurement of the CKM-angle $\gamma$ at *BABAR*

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We present the results of the measurements employed by the *BABAR* Collaboration, to determine the value of the Cabibbo-Kobayashi-Maskawa (CKM)  $CP$ -violating phase  $\gamma$  ( $\equiv \arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*]$ ). These measurements are based on the studies performed with the charged B-decays  $B^- \rightarrow \tilde{D}^0 K^-$ ,  $B^- \rightarrow \tilde{D}^{*0} K^-$ , and  $B^- \rightarrow \tilde{D}^0 K^{*-}$ , where  $\tilde{D}^0$  indicates either a  $D^0$  or a  $\bar{D}^0$  meson. A sample of about 230 million  $B\bar{B}$  pairs collected by the *BABAR* detector [1], at the PEP-II asymmetric-energy  $e^+e^-$  collider at SLAC, is used.

Three methods are exploited [2, 3, 4], where the  $\tilde{D}^0$  decays either to a  $CP$ -eigenstate ( $GLW$ ), or to a Cabibbo-suppressed flavor decay ("wrong sign",  $ADS$ ), or to the  $K_S^0 \pi^- \pi^+$  final state, for which a Dalitz analysis has to be performed ( $GGSZ$ ). To extract  $\gamma$ , those 3 methods are all based on the fact that a  $B^-$  meson can decay into a color-allowed  $D^{(*)0} K^- / K^{*-}$  (color-suppressed  $\bar{D}^{(*)0} K^- / K^{*-}$ ) final state via  $b \rightarrow c\bar{u}s$  ( $b \rightarrow u\bar{c}s$ ) transitions. The amplitude  $\mathcal{A}("V_{cb}")$  of the  $b \rightarrow c\bar{u}s$  transition is proportional to  $\lambda^3$  and the amplitude  $A("V_{ub}")$  of the  $b \rightarrow u\bar{c}s$  transition to  $\lambda^3 \sqrt{\bar{\eta}^2 + \bar{\rho}^2} e^{i(\delta_{B^-} - \gamma)}$ . The second amplitude therefore carries both the  $EW$   $\gamma$   $CP$ -phase and the relative strong phase of those 2 transitions. As the total measured amplitude for  $B^- \rightarrow \tilde{D}^0 K^-$ ,  $B^- \rightarrow \tilde{D}^{*0} K^-$ , and  $B^- \rightarrow \tilde{D}^0 K^{*-}$  decays is the sum of the 2 amplitudes  $\mathcal{A}("V_{cb}")$  and  $\mathcal{A}("V_{ub}")$ , the 2 amplitudes interfere when the  $D^0$  and  $\bar{D}^0$  decay into the same final state. This interference can lead to different  $B^+$  and  $B^-$  decay rates (direct  $CP$ -violation).

The various methods are "theoretically clean" because the main contributions to the amplitudes come from tree-level transitions. In addition to the CKM parameters and to the strong phase,  $\mathcal{A}("V_{ub}")$  is significantly reduced with respect to  $\mathcal{A}("V_{cb}")$  by the color suppression phenomenon. One usually defines the parameter  $r_B \equiv |\mathcal{A}("V_{ub"}) / \mathcal{A}("V_{cb"})|$  that determines the size of the direct  $CP$  asymmetry. It is the critical parameter for these analyzes. Its value is predicted [5] to lie in the range 0.1 – 0.3. The smaller  $r_B$  is, the smaller is the experimental sensitivity to  $\gamma$ .

A combination of the various constraints obtained with these methods is performed. It is based on a frequentist approach [6] where the world average of the  $GLW$  and  $ADS$  methods is combined with the result of the *BABAR* Dalitz analysis [7]. It constrains the angle  $\gamma$  to have a value equal to  $[51_{-18}^{+23}]^\circ$  and consistent with the overall indirect prediction obtained for the standard model CKM triangle fit:  $[57_{-13}^{+7}]^\circ$ . The *BABAR* Dalitz analysis alone measures  $\gamma = [67 \pm 28(stat.) \pm 13(syst.) \pm 11(Dalitz\ model)]^\circ$ . Incidentally, It should be emphasized that these somewhat precise measurements were considered as unreachable at B-factories a few years ago.

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## 1. Introduction to the various physical quantities

The 2 parameters " $r_B$ " and " $\delta_B$ " depend on the studied decay:  $B^- \rightarrow \tilde{D}^0 K^-$  ( $\delta_B$  and  $r_B$ ) or  $B^- \rightarrow \tilde{D}^{*0} K^-$  ( $\delta_B^*$  and  $r_B^*$ ) or  $B^- \rightarrow \tilde{D}^0 K^{*-}$  ( $\delta_{sB}$  and  $r_{sB}$ ). The CKM-angle  $\gamma$ , and the parameters " $r_B$ ", and " $\delta_B$ " can be measured experimentally through the 2 observable quantities (Asymmetry and Ratio of Branching Ratios):

$$\mathbf{A} \equiv \frac{\Gamma(B^- \rightarrow \tilde{D}^{(*)0} K^{(*)-}) - \Gamma(B^+ \rightarrow \tilde{D}^{(*)0} K^{(*)+})}{\Gamma(B^- \rightarrow \tilde{D}^{(*)0} K^{(*)-}) + \Gamma(B^+ \rightarrow \tilde{D}^{(*)0} K^{(*)+})}, \quad (1.1)$$

$$\mathbf{R} \equiv \frac{\Gamma(B^- \rightarrow \tilde{D}^{(*)0} K^{(*)-}) + \Gamma(B^+ \rightarrow \tilde{D}^{(*)0} K^{(*)+})}{\Gamma(B^- \rightarrow D^{(*)0} K^{(*)-}) + \Gamma(B^+ \rightarrow \bar{D}^{(*)0} K^{(*)+})}. \quad (1.2)$$

Both *BABAR* [8] and Belle [9] Collaborations have produced results for these three methods at the time of spring 2005. We essentially present here new results for the decay  $B^- \rightarrow \tilde{D}^0 K^{*-}$  ( $K^*(892)^-$  decays where  $K^{*-} \rightarrow K_S^0 \pi^-$ ). The analyzes are described in details in [10, 11, 7].

## 2. The *GLW* analysis [2, 8, 10]

The  $\tilde{D}^0$  is reconstructed in various *CP*-eigenstates decay channels:  $K^+ K^-$ ,  $\pi^+ \pi^-$  (*CP*+ eigenstates); and  $K_S^0 \pi^0$ ,  $K_S^0 \phi$ ,  $K_S^0 \omega$  (*CP*- eigenstates). The  $\mathbf{R}_{CP}$  is normalized to the branching ratios as obtained from 3 flavor state decays:  $D^0 \rightarrow K^- \pi^+$ ,  $K^- \pi^+ \pi^0$ , and  $K^- \pi^+ \pi^+ \pi^-$ . One has 4 observable quantities, for 3 unknown ( $\gamma$ ,  $r_B$ , and  $\delta_B$ ):  $\mathbf{R}_{CP\pm} = 1 \pm 2r_B \cos \delta \cos \gamma + r_B^2$  and  $\mathbf{A}_{CP\pm} = \frac{\pm 2r_B \sin \delta \sin \gamma}{\mathbf{R}_{CP\pm}}$ . Only 3 are independent, as:  $\mathbf{R}_{CP-} \mathbf{A}_{CP-} = -\mathbf{R}_{CP+} \mathbf{A}_{CP+}$ . In principle with infinite statistics this method is very clean to determine  $\gamma$  (with 8 fold-ambiguities). But the small *CP*-asymmetry (small  $r_B \simeq 0.1 - 0.3$ ) and the small secondary branching ratios to produce the  $D^0$  *CP*-eigenstates, make this method difficult with the present B-factories dataset.

For the  $B^- \rightarrow \tilde{D}^0 K^{*-}$  decay [10], we measure:  $\mathbf{A}_{CP+} = -0.08 \pm 0.19 \pm 0.08$ ,  $\mathbf{R}_{CP+} = -0.26 \pm 0.40 \pm 0.12$ ,  $\mathbf{A}_{CP-} = 1.96 \pm 0.40 \pm 0.11$ , and  $\mathbf{R}_{CP-} = 0.65 \pm 0.26 \pm 0.08$ , where the first uncertainty is statistical and the second systematic. The (peaking)-background is estimated from the  $m_{ES}$  and  $m_{D^0}$  side-bands. The *CP*+ pollution for *CP*- eigenstate from decays  $K_S^0 [K^+ K^-]_{\text{non } \phi}$  and  $K_S^0 [\pi^+ \pi^- \pi^0]_{\text{non } \omega}$  is estimated using data. Finally, we take into account in the systematic uncertainties the possible strong phases as generated by probable  $K\pi$  S-waves in the  $K^{*-} \rightarrow K_S^0 \pi^-$  decays. From  $\mathbf{R}_{CP\pm}$  we also derive  $rs_B^2 = 0.30 \pm 0.25$ . When one defines the so-called *Cartesian coordinates*:  $xs^\pm \equiv rs_B \cos(\delta_s \pm \gamma)$ , we find:  $xs^+ = 0.32 \pm 0.18$  (*stat.*)  $\pm 0.07$  (*syst.*),  $xs^- = 0.33 \pm 0.16$  (*stat.*)  $\pm 0.06$  (*syst.*). At the present time, the measured values of  $\mathbf{A}_{CP}$  ( $\mathbf{R}_{CP}$ ) are not precise enough to differ significantly from 0 (1) so that a strong constraint on  $\gamma$  can be obtained from the *GLW* method alone.

## 3. The *ADS* analysis [3, 8, 11]

The  $D^0$  meson as generated from the  $b \rightarrow c\bar{u}s$  transition is required to decay to the doubly Cabibbo-suppressed  $K^+ \pi^-$  mode ("wrong sign"), while the  $\bar{D}^0$  meson, from the interfering  $b \rightarrow u\bar{c}s$  transition, decays to Cabibbo-favored final state  $K^+ \pi^-$ . The overall branching ratio for a final state  $B^- \rightarrow [K^+ \pi^-]_{\tilde{D}^0} K^{(*)-}$  is expected to be small ( $\sim 10^{-6}$ ), but the 2 interfering diagrams

are now of the same order of magnitude. The challenge in this method is therefore to detect  $B$  candidate in this final state with 2-opposite charge kaons. The total amplitude is complicated by an additional unknown relative strong phase  $\delta_D$  in the  $D^0\text{-}\bar{D}^0 \rightarrow [K^+\pi^-]$  system, while the ratio of their respective amplitude  $r_D$  is precisely measured at the level of 6 % [12]. It can be written as  $A([K^+\pi^-]_{\bar{D}^0}K^{(*)-}) \propto r_B e^{i(\delta_B-\gamma)} + r_D e^{-i\delta_D}$ . Using the  $B^- \rightarrow [K^-\pi^+]K^{(*)-}$  modes as normalisation for  $\mathbf{R}_{ADS}$ , one can write the equations for the 2 experimental observable quantities:  $\mathbf{R}_{ADS} = r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D) \cos(\gamma)$  and  $\mathbf{A}_{ADS} = \frac{2 r_B r_D \sin(\delta_B + \delta_D) \sin(\gamma)}{\mathbf{R}_{ADS}}$ . Where  $\mathbf{R}_{ADS}$  is clearly highly sensitive to  $r_B^2$ .

For the  $B^- \rightarrow \tilde{D}^0 K^-$  and  $B^- \rightarrow \tilde{D}^{*0} K^-$  channels [8], no significant  $ADS$  signal has been measured yet. At 90 % of confidence level, we set the upper limits  $r_B < 0.23$  and  $r_B^{*2} < (0.16)^2$ , respectively for the 2 decay modes. For the  $B^- \rightarrow \tilde{D}^0 K^{*-}$  decay [11], we have also not seen any significant  $ADS$  signal, we measure  $\mathbf{R}_{ADS} = 0.046 \pm 0.031 \pm 0.008$ ,  $\mathbf{A}_{ADS} = -0.22 \pm 0.61 \pm 0.17$ , where the first uncertainty is statistical and the second systematic. As part of the systematic uncertainties, we consider effect of the possible strong phases as generated by probable  $K\pi$  S-waves in the  $K^{*-} \rightarrow K_S^0 \pi^-$  decays. It is the dominant contribution.

Using a frequentist approach [6], and combining both the  $GLW$  and  $ADS$  methods for the  $B^- \rightarrow \tilde{D}^0 K^{*-}$  channel [11], we determine  $rs_B = 0.28_{-0.10}^{+0.06}$ , and we can exclude at the two-standard deviation level the interval  $75^\circ < \gamma < 105^\circ$ .

#### 4. The $K_S^0 \pi^- \pi^+$ Dalitz analysis [4, 8, 7]

Among the  $\tilde{D}^0$  decay modes studied so far the  $K_S^0 \pi^- \pi^+$  channel is the one with the highest sensitivity to  $\gamma$  because of the best overall combination of branching ratio magnitude,  $D^0 - \bar{D}^0$  interference and background level. This mode offers a reasonably high branching ratio ( $10^{-5}$ , including secondary decays) and a clean experimental signature (only charged tracks in the final state). The decay mode  $K_S^0 \pi^- \pi^+$  can be accessed through many intermediate states: "wrong sign" or "right"  $K^*$  resonances,  $K_S^0 \rho^0$   $CP$ - eigenstate, ... Therefore, an analysis of the the amplitude of the  $\tilde{D}^0$  decay over the  $m^2(K_S^0 \pi^-)$  vs.  $m^2(K_S^0 \pi^+)$  ( $m_-^2$  vs.  $m_+^2$ ) Dalitz plane structure is sensitive to the same kind of observable as for both the  $GLW$  and  $ADS$  methods. The sensitivity to  $\gamma$  varies strongly over the Dalitz plane. The contribution from the  $b \rightarrow u\bar{c}s$  transition in the  $B^- \rightarrow D^{(*)0} K^- / K^{*-}$  ( $B^+ \rightarrow \bar{D}^{(*)0} K^+ / K^{*+}$ ) decay can significantly be amplified by the amplitude  $\mathcal{A}_{D^+}$  ( $\mathcal{A}_{D^-}$ ) of the  $\bar{D}^0 \rightarrow K_S^0 \pi^- \pi^+$  ( $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ ) decay ( $\mathcal{A}_{D^\mp} \equiv \mathcal{A}_D(m_\mp^2, m_\pm^2)$ ). Assuming no  $CP$  asymmetry in  $D$  decays, the decay rate of the chain  $B^- \rightarrow D^{(*)0} K^- / K^{*-}$  ( $B^+ \rightarrow \bar{D}^{(*)0} K^+ / K^{*+}$ ), and  $\tilde{D}^0 \rightarrow K_S^0 \pi^- \pi^+$ , can be written as:  $\Gamma_\mp(m_-^2, m_+^2) \propto |\mathcal{A}_{D^\mp}|^2 + r_B^2 |\mathcal{A}_{D^\pm}|^2 + 2 \{x_\mp \text{Re}[\mathcal{A}_{D^\mp} \mathcal{A}_{D^\pm}^*] + y_\mp \text{Im}[\mathcal{A}_{D^\mp} \mathcal{A}_{D^\pm}^*]\}$ .

We have introduced the *Cartesian coordinates*:  $\{x_\mp, y_\mp\} = \{\text{Re}, \text{Im}\}[r_B e^{i(\delta_B \mp \gamma)}]$ , for which the constraint  $r_B^2 = x_\mp^2 + y_\mp^2$  holds. These are natural parameters to describe the amplitude of the decay. A simultaneous fit both to the  $B^\pm$  decays and  $\tilde{D}^0 \rightarrow K_S^0 \pi^- \pi^+$  decays is then performed to extract 12 parameters:  $\{x_-, y_-\}$  from  $B^- \rightarrow \tilde{D}^0 K^-$ ,  $\{x^*, y^*\}$  from  $B^- \rightarrow \tilde{D}^{*0} K^-$ , and  $\{x_s, y_s\}$  from  $B^- \rightarrow \tilde{D}^0 K^{*-}$ . In the last case, we deal with  $(K_S^0 \pi^\mp)_{\text{non-}K^*}$  contribution, by defining an effective dilution parameter  $\kappa$  as  $x_{s^\mp}^2 + y_{s^\mp}^2 = \kappa^2 r_B^2$ , with  $0 \leq \kappa \leq 1$ .

Since the measurement of  $\gamma$  arises from the interference term in  $\Gamma_\mp(m_-^2, m_+^2)$ , the uncertainty in the knowledge of the complex form of  $\mathcal{A}_D$  can lead to a systematic uncertainty. Two different models describing the  $D^0 \rightarrow K_S^0 \pi^- \pi^+$  decay have been used in the recent  $BABAR$  analysis [7].

The first model (also referred to as Breit-Wigner model) is the same as used for our previously reported measurement of  $\gamma$  on  $B^- \rightarrow \tilde{D}^{(*)0} K^-, \tilde{D}^0 \rightarrow K_s^0 \pi^- \pi^+$  decays [8], and expresses  $\mathcal{A}_D$  as a sum of two-body decay-matrix elements and a non-resonant contribution. In the second model (hereafter referred to as the  $\pi\pi$  S-wave K-matrix model) the treatment of the  $\pi\pi$  S-wave states in  $D^0 \rightarrow K_s^0 \pi^- \pi^+$  uses a K-matrix formalism to account for the non-trivial dynamics due to the presence of broad and overlapping resonances. The two models have been obtained using a high statistics flavor tagged  $D^0$  sample ( $D^{*+} \rightarrow D^0 \pi_s^+$ ) selected from  $e^+e^- \rightarrow c\bar{c}$  events recorded by BABAR.

At the end of the analysis, the 7 parameters:  $\gamma$ ,  $\delta_B$ ,  $\delta_B^*$ ,  $\delta_{sB}$ ,  $r_B$ ,  $r_B^*$ , and  $\kappa.r_{sB}$ , are extracted from the 12 *Cartesian coordinates* using a frequentist approach that defines a 7 – *D* Neyman Confidence Region. The values for all these parameters can be found in the documents [8] and [7]. But it should be noticed that the values of  $r_B$  and  $r_B^*$  stand in the range 0 – 0.35 ( 2-standard deviation interval) while  $\kappa.r_{sB}$  is presently less constrained ( $< 0.75$ ).

The overall value for the *EW CP* phase is:  $\gamma = [67 \pm 28(stat.) \pm 13(syst.) \pm 11(Dalitz\ model)]^\circ$ . Where it can be noticed that the uncertainty coming from the employed *Dalitz model* would limit the measurement at infinite statistic. Though so far we have used the "Breit-Wigner model" to perform the fit, it has been checked that the relative systematic uncertainty of that measurement with respect to a fit to the "the  $\pi\pi$  S-wave K-matrix model" is  $3^\circ$  (incorporated in the above result). This indicates that the Dalitz model uncertainty could eventually be strongly reduced in a future analysis.

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