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Measurements of the CKM angle γ at *BABAR*

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The recent measurements of the CKM angle γ by the *BABAR* experiment are reported. The analyses have been performed using the full sample of 468 million $B\bar{B}$ pairs collected by the *BABAR* detector at the SLAC PEP-II asymmetric-energy B factory during the years 1999-2007.

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In the standard model (SM) of particle physics *CP* violation in the quark sector of weak interactions arises from a single irreducible phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix V that describes the mixing of quarks [1]. The unitarity of the CKM matrix defines a unitarity triangle (UT) in the complex plane. *CP* violation measurements and semileptonic decay rates (and other methods) can be conveniently displayed and compared as constraints on the angles and sides, respectively, of this triangle. Inconsistencies between all these (in general) precise and redundant measurements can be used to search for new physics (NP). As today, there is an impressive overall agreement between all measurements [2]. Among these, the angle γ defined as the phase of V_{ub} in the Wolfenstein parametrization [1], is particularly relevant since it is the only *CP*-violating measurement that, together with the measurement of the *CP*-conserving magnitude of V_{ub}, selects a region of the UT apex independently of most types of NP, and thus constitutes a SM candle type of measurement. Current constraints, provided by the *BABAR* and Belle experiments, make use of $B^{\pm} \to D^{(*)}K^{\pm}$ and $B^{\pm} \to DK^{*\pm}$ decays, and are still weak ($\sim 15^{\circ}$). Neutral B decays have also been proposed, although do not yet provide significant constraints.

The angle γ from $B^{\pm} \to D^{(*)}K^{\pm}$ and $B^{\pm} \to DK^{*\pm}$ decays is determined measuring the interference between the amplitudes $b \to u$ and $b \to c$, when the neutral D meson is reconstructed in a final state accessible from both D^0 and $\bar{D}^0$ decays. Since both amplitudes are tree level, the interference is unaffected by NP appearing in the loops, making the theoretical interpretation of observables in terms of γ very clean. The disadvantage is that the branching fractions of the involved decays are small due to CKM suppression ($10^{-5} - 10^{-7}$), and the size of the interference, given by the ratio r_B between the magnitudes of the $b \to u$ and $b \to c$ amplitudes, is small due to further CKM and color suppressions ($\sim 10\%$). As a consequence, the measurements are statistically limited and one has to combine complementary methods applied on the same B decay modes sharing the same hadronic parameters (r_B and δ_B, i.e. the relative magnitude and phase of the $b \to u$ and $b \to u$ transitions) and γ, and use as many as possible different B decay modes to improve the overall sensitivity to γ.

In this talk we present the most recent determinations of γ obtained by *BABAR*, based on the full data sample of charged B meson decays produced in $e^+e^- \to \Upsilon(4S) \to B^+B^-$ and recorded in the years 1999-2007, about 468×10^6 B^+B^- pairs. We have studied $B^{\pm} \to D^{(*)}K^{\pm}$ and $B^{\pm} \to DK^{*\pm}$ decays, with the neutral D mesons reconstructed in a number of different final states: $D \to K^0_S h^+h^-$, with $h = \pi, K$ (Dalitz plot method); $D \to K^{\pm}\pi^{\mp}$ (ADS method); and $D \to f_{CP}$, with f_{CP} a *CP*-eigenstate (GLW method) [3].

One of the B mesons produced in the $\Upsilon(4S)$ decay is fully reconstructed, with efficiencies ranging between 40% (for low-multiplicity with no neutrals) and 5% (for high-multiplicity decays with neutrals). The selection is optimized to maximize the statistical sensitivity. The reconstruction efficiencies have substantially improved (20% to 60% relative) with respect to our previous measurements based on about 384×10^6 B^+B^- pairs, reflecting improvements in tracking and particle identification, and optimization of the analysis procedures. Signal B decays are characterized by means of two nearly independent kinematic variables exploiting the constraint from the known beam energies: the beam-energy $m_{\mathrm{ES}} \equiv \sqrt{E^{*2}_{\mathrm{beam}} - |p^*_B|^2}$ and the energy-difference $\Delta E \equiv E^*_B - E^*_{\mathrm{beam}}$. Since the main source of background comes from $q\bar{q}$ continuum production, additional discrimination is achieved using multivariate analysis tools, from the combination (either a linear Fisher discriminant $\mathscr{F}$, or a non-linear neural network, NN) of several event-shape quantities. These variables distinguish between spherical $B\bar{B}$ events from more jet-like events and exploit the different angular correlations in the two event categories. The signal is finally separated from background through unbinned maximum likelihood (UML) fits to the $B^\pm \to D^{(*)}K^\pm$ and $B^\pm \to DK^{*\pm}$ data using $m_{\rm ES}$, ΔE, and $\mathscr{F}$ or NN. Some analyses make also use of tagging information from the recoiling B meson. $B^\pm \to D^{(*)}\pi^\pm$ decays, which are about 12 times more abundant than $B^\pm \to D^{(*)}K^\pm$, have a similar topology and show negligible CP-violating effects ($r_B \sim 1\%$), are discriminated by means of excellent pion and kaon identification provided by dE/dx and Cerenkov measurements, and are used as calibration and control samples (negative tests of CP violation).

In the Dalitz plot (DP) method the amplitude for a B^- decay has for the $b \to c$ transition the DP of the D^0 decay, while for the $b \to u$ transition the DP is the corresponding to the $\bar{D}^0$ decay. If we assume no D mixing nor CP violation in the D decay, and use as independent kinematic variables $s_\pm = m^2(K^0_S\pi^\pm)$, then the two DPs are identical but one rotated 90° with respect to the other. This is of critical importance since allows to determine directly from data the strong charm phase variation for D^0 and $\bar{D}^0$, as well as well as the hadronic parameters r_B and δ_B, and the week phase γ, provided that a D decay amplitude model is assumed. For B^+ decays one has to interchange the D^0 and $\bar{D}^0$ DPs, and change the sign of γ. This results in an interference term proportional to our observables $x_\pm \equiv r_B \cos(\delta_B \pm \gamma)$ and $y_\pm \equiv r_B \sin(\delta_B \pm \gamma)$, i.e. the real and imaginary parts of the ratio of $b \to u$ to $b \to c$ amplitudes for $B^\pm$ decays. We reconstruct $B^\pm \to DK^\pm$, $D^*K^\pm$ with $D^* \to D\pi^0, D\gamma$, and $DK^{*\pm}$ with $K^{*\pm} \to K^0_S\pi^\pm$ decays, followed by neutral D meson decays to the 3-body self-conjugate final states $K^0_S h^+h^-$, with $h = \pi, K$. From the UML fit we determine the signal and background yields in each of the eight different final states for each B charge, along with the CP-violating parameters $x_\pm$ and $y_\pm$ [4]. We find 1507 $B^\pm$ signal candidates with $K^0_S\pi^+\pi^-$, and 268 with $K^0_S K^+K^-$. Prior to the CP fit, we model the D^0 and $\bar{D}^0$ decay amplitudes as a coherent sum of S-, P-, and D-waves, and determine their amplitudes and phases (along other relevant parameters) relative to dominant CP-eigenstates $K^0_S\rho(770)$ (for $K^0_S\pi^+\pi^-$) and $K^0_S a_0(980)$ (for $K^0_S K^+K^-$), using a large ($\approx 6.2 \times 10^5$) and very pure ($\approx 99\%$) signal sample of flavor tagged neutral D mesons from $D^{*+} \to D^0\pi^+$ decays produced in $e^+e^- \to c\bar{c}$ events [5]. From the $(x_\pm, y_\pm)$ confidence regions for

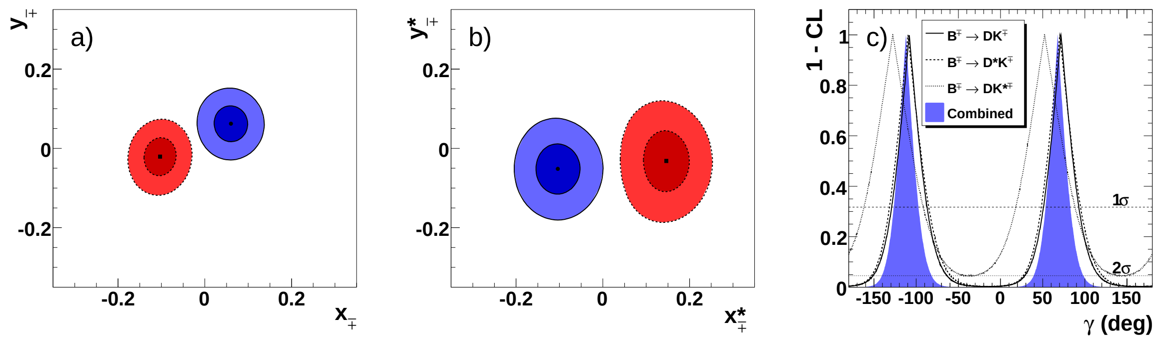

Figure 1: 1σ and 2σ contours (statistical only) in the $(x_\mp, y_\mp)$ planes for (a) $B^\mp \to DK^\mp$ and (b) $B^\mp \to D^*K^\mp$, for B^- (solid lines) and B^+ (dotted lines) decays. (c) $1 - \text{CL}$ as a function of γ for $B^\mp \to DK^\mp, D^*K^\mp, DK^{*\mp}$ decays, including statistical and systematic uncertainties. The dashed (upper) and dotted (lower) horizontal lines correspond to the 1σ and 2σ intervals, respectively.

each of the 3 different B decay modes –Fig. 1.(a)(b)– we determine, using a frequentist procedure,

1σ $[2\sigma]$ intervals for γ –Fig. 1.(c)–. We obtain $\gamma\,(\mathrm{mod}\ 180^\circ) = (68\pm14\pm4\pm3)^\circ$ $[39^\circ, 98^\circ]$, where the three uncertainties are statistical, experimental systematic, and amplitude model systematic. We also determine the hadronic parameters $r_B^{DK^\pm} = (9.6\pm2.9)\%$ $[3.7, 15.5]\%$, $r_B^{D^*K^\pm} = (13.3^{+4.2}_{-3.9})\%$ $[4.9, 21.5]\%$, $\kappa r_B^{DK^{*\pm}} = (14.9^{+6.6}_{-6.2})\%$ $[0, 28.0]\%$ ($\kappa = 0.9\pm0.1$ takes into account the K^* intrinsic width), and the strong phases $\delta_B^{DK^\pm}$, $\delta_B^{D^*K^\pm}$, and $\delta_B^{DK^{*\pm}}$ [4]. A 3.5σ evidence of direct *CP* violation ($\gamma \neq 0$) is found from the combination of the 3 channels, which corresponds to the significance of the separation between the (x_+, y_+) and (x_-, y_-) solutions in Fig. 1.(a)(b).

In the ADS method, we reconstruct $B^\pm \to DK^\pm$, $D^*K^\pm$ with $D^* \to D\pi^0, D\gamma$, followed by D decays to both doubly-Cabibbo-suppressed (DCS) D^0 final state $K^+\pi^-$ and the Cabibbo-favored (CF) $K^-\pi^+$, which is used as normalization and control sample. Final states with opposite-sign kaons arise either from the CKM favored B decay followed by the DCS D neutral D decay or from the CKM- and color-suppressed B decay followed by the CF D decay, producing an interference which can be potentially large since the magnitudes of the interfering amplitudes are similar. However, their overall branching ratios are very small ($\sim 10^{-7}$) and background suppression becomes crucial. The UML fit directly determines the three branching fraction ratios R_{ADS} between B decays with opposite-sign and same-sign kaons, and the three yields of B decays with same-sign kaons, using m_{ES} and NN. The three *CP* asymmetries A_{ADS} are inferred from all these. We obtain first indications of signals for the $B^\pm \to DK^\pm$ and $B^\pm \to D^*K^\pm$ (with $D^* \to D\pi^0$) opposite-sign modes –Fig. 2–, with significances of 2.1σ and 2.2σ, respectively [6]. The measured branching fraction ratios are $R_{ADS}^{DK} = (1.1\pm0.5\pm0.2)\times10^{-2}$, $R_{ADS}^{[D\pi^0]K} = (1.8\pm0.9\pm0.4)\times10^{-2}$, and $R_{ADS}^{[D\gamma]K} = (1.3\pm1.4\pm0.8)\times10^{-2}$, and the *CP* asymmetries are $A_{ADS}^{DK} = -0.86\pm0.47^{+0.12}_{-0.16}$, $A_{ADS}^{[D\pi^0]K} = 0.77\pm0.35\pm0.12$, and $A_{ADS}^{[D\gamma]K} = 0.36\pm0.94^{+0.25}_{-0.41}$. From these results and external measurements of the relative amplitude and phase of $\bar{D}^0$ to D^0 mesons decaying into the $K^-\pi^+$ final state [7] we infer, using a frequentist procedure similar to that used in the DP method, $r_B^{DK^\mp} = (9.5^{+5.1}_{-4.1})\%$ $[0, 16.7]\%$, $r_B^{D^*K^\mp} = (9.6^{+3.5}_{-5.1})\%$ $[0, 15.0]\%$, and $54^\circ < \gamma\,(\mathrm{mod}\ 180^\circ) < 83^\circ$, with no constraints at 2σ level.

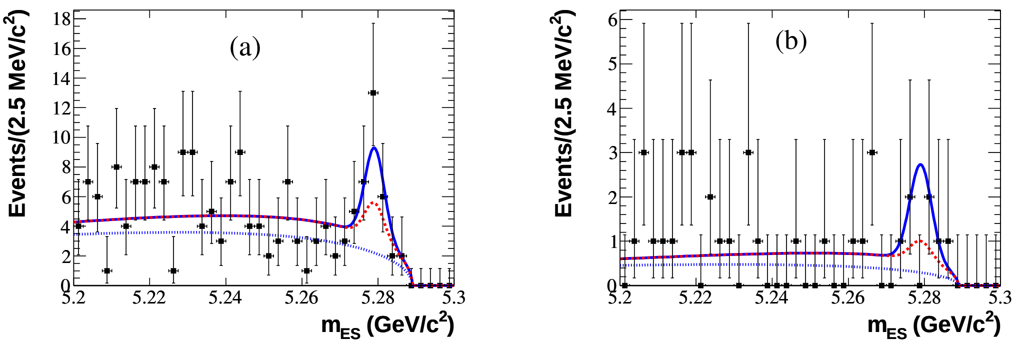

Figure 2: Projections on m_{ES} for (a) $B^\pm \to DK^\pm$ and (b) $B^\pm \to D^*[D\pi^0]K^\pm$, $D \to K^\mp\pi^\pm$ opposite-sign decays, for ADS samples enriched in signal ($NN > 0.94$). The points with error bars are data while the curves represent the fit projections for signal plus background (solid), the sum of all background components (dashed), and $q\bar{q}$ background only (dotted).

In the GLW method, we reconstruct $B^\pm \to DK^\pm$ decays, followed by D decays to non-*CP*

($D^0 \to K^-\pi^+$), *CP*-even (K^+K^-, $\pi^+\pi^-$), and *CP*-odd ($K^0_S\pi^0$, $K^0_S\phi$, $K^0_S\omega$) eigenstates. 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* ($R^{\pm}_{K/\pi}$) and non-*CP* ($R_{K/\pi}$) decays (normalized to the corresponding $B^\pm \to D\pi^\pm$ decays, to cancel systematic uncertainties related to absolute reconstruction efficiencies) provide four observables from which the three unknowns γ, r_B and δ_B can be extracted (up to an 8-fold ambiguity for the phases). The signal yields, expressed in terms of $A_{CP\pm}$, $R^{\pm}_{K/\pi}$ and $R_{K/\pi}$ are extracted from UML fits to $m_{\rm ES}$, ΔE, and $\mathscr{F}$. We identify about 500 $B^\pm \to DK^\pm$ decays with *CP*-even D final states and a similar amount for *CP*-odd D final states, and measure [8] $A_{CP+} = 0.25 \pm 0.06 \pm 0.02$, $A_{CP-} = -0.09 \pm 0.07 \pm 0.02$, $R_{CP+} = 1.18 \pm 0.09 \pm 0.05$, and $R_{CP-} = 1.07 \pm 0.08 \pm 0.04$. The parameter A_{CP+} is different from zero with a significance of 3.6σ, and constitutes evidence for direct *CP* violation in $B^\pm \to DK^\pm$ decays. These results can be written in terms of the observables $x_\pm$ using the relationship $x_\pm = [R_{CP+}(1 \mp A_{CP+}) - R_{CP-}(1 \mp A_{CP-})]/4$. Excluding the $D \to K^0_S\phi$, $\phi \to K^+K^-$ channel to facilitate the combination with the DP method, we find $x_+ = -0.057 \pm 0.039 \pm 0.015$ and $x_- = 0.132 \pm 0.042 \pm 0.018$, which are consistent (and of similar precision) with the DP method. From these results and using a frequentist procedure similar to that used previously we infer $24\% < r_B < 45\%$ $[6,51]\%$, and mod 180°, $11^\circ < \gamma < 23^\circ$ or $81^\circ < \gamma < 99^\circ$ or $157^\circ < \gamma < 169^\circ$ $[7^\circ, 173^\circ]$.

We have reported the recent progress in the determination of the CKM angle γ, using the full *BABAR* data sample and three different and complementary methods (DP, ADS, and GLW). A coherent and consistent set of results on γ and the hadronic parameters characterizing the B decays has been obtained. The central value for γ, around 70° with a precision around 15°, is consistent with indirect determinations from CKM fits [2]. A proper average of all the three methods using the full *BABAR* sample of $B^\mp \to D^{(*)}K^\mp$, $DK^{*\mp}$ decays is foreseen. We obtain $x_- - x_+ = 0.175 \pm 0.040$ by combining the $x_\pm$ measurements from the DP and GLW methods for $B^\mp \to DK^\mp$ decays, which is different from zero with a significance of 4.4σ, thus constitutes strong evidence for direct *CP* violation in these charged B decays. Finally, we have the first sign of an ADS signal in $B^\mp \to DK^\mp$ and $B^\mp \to D^{(*)}K^\mp$ decays.

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