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Evidence for Direct CP Violation in the Measurement of the Cabbibo-Kobayashi-Maskawa Angle $\gamma$ with $B^+ \to D^{(*)}K^{(*)}$ Decays


(BaBar Collaboration)

1Laboratoire d’Annecy-le-Vieux de Physique des Particules (LAPP), Université de Savoie, CNRS/IN2P3, F-74941 Annecy-Le-Vieux, France
2Universitat de Barcelona, Facultat de Fisica, Departament ECM, E-08028 Barcelona, Spain
3aINFN Sezione di Bari, I-70126 Bari, Italy
3bDipartimento di Fisica, Università di Bari, I-70126 Bari, Italy
4University of Bergen, Institute of Physics, N-5007 Bergen, Norway
5Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA
6University of Birmingham, Birmingham, B15 2TT, United Kingdom
7Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany
8University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1
9Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom
10Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia
11University of California at Irvine, Irvine, California 92697, USA
12University of California at Riverside, Riverside, California 92521, USA
13University of California at Santa Barbara, Santa Barbara, California 93106, USA
14University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA
15California Institute of Technology, Pasadena, California 91125, USA
16University of Cincinnati, Cincinnati, Ohio 45221, USA
17University of Colorado, Boulder, Colorado 80309, USA
18Colorado State University, Fort Collins, Colorado 80523, USA
19Technische Universität Dortmund, Fakultät Physik, D-44221 Dortmund, Germany
20Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany
21Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France
22University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
23aINFN Sezione di Ferrara, I-44100 Ferrara, Italy
23bDipartimento di Fisica, Università di Ferrara, I-44100 Ferrara, Italy
24INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy
25aINFN Sezione di Genova, I-16146 Genova, Italy
25bDipartimento di Fisica, Università di Genova, I-16146 Genova, Italy
26Indian Institute of Technology Guwahati, Guwahati, Assam, 781 039, India
27Harvard University, Cambridge, Massachusetts 02138, USA
28Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany
29Humboldt-Universität zu Berlin, Institut für Physik, Newtonstr. 15, D-12489 Berlin, Germany
30Imperial College London, London, SW7 2AZ, United Kingdom
31University of Iowa, Iowa City, Iowa 52242, USA
32Iowa State University, Ames, Iowa 50011-3160, USA
33Johns Hopkins University, Baltimore, Maryland 21218, USA
34Laboratoire de l’Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11, Centre Scientifique d’Orsay, B. P. 34, F-91898 Orsay Cedex, France
35Lawrence Livermore National Laboratory, Livermore, California 94550, USA
36University of Liverpool, Liverpool L69 7EZ, United Kingdom
37Queen Mary, University of London, London, E1 4NS, United Kingdom
38University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
We report the measurement of the Cabibbo-Kobayashi-Maskawa CP-violating angle $\gamma$ through a Dalitz plot analysis of neutral $D$-meson decays to $K^0 \pi^+ \pi^-$ and $K^0_s K^+ K^-$ produced in the processes $B^+ \to D K^+$, $B^0 \to D^0 K^-$ with $D^+ \to D^0 \pi^+$, $D^0$, and $B^+ \to D K^+ K^-$ with $K^0 \to K^0_s \pi^-$, using 468 million $B\bar{B}$ pairs collected by the BABAR detector at the PEP-II asymmetric-energy $e^+ e^-$ collider at SLAC. We measure $\gamma = (68 \pm 14 \pm 4 \pm 3)^\circ$ (modulo 180$^\circ$), where the first error is statistical, the second is the experimental systematic uncertainty, and the third reflects the uncertainty in the description of the neutral $D$ decay amplitudes. This result is inconsistent with $\gamma = 0$ (no direct $CP$ violation) with a significance of 3.5 standard deviations.

The breaking of the $CP$ symmetry in the quark sector of the electroweak interactions arises in the standard model from a single irreducible phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. This phase can be measured using a variety of methods involving $B$-meson decays mediated by either only tree-level or both tree- and loop-level amplitudes. The comparison of these two classes of measurements tests the CKM mechanism, thus offering a strategy to search for new physics [2].

The angle $\gamma$ of the unitarity triangle, defined as $\arg[-V_{ub} V_{cb}^* / V_{cd} V_{cb}^*]$, where $V_{ij}$ are elements of the CKM matrix, is particularly relevant since it is the only $CP$-violating parameter that can be cleanly determined using solely tree-level $B$-meson decays. Its precise determination constitutes an important goal of present and future experiments in flavor physics.

In $B^+ \rightarrow D K^\pm$ decays [3,4] the color-favored $B^+ \rightarrow D^0 K^+$ ($b \rightarrow c \bar{u} s$) and the color-suppressed $B^+ \rightarrow D^0 K^-$ ($b \rightarrow u \bar{c} s$) transitions [5] interfere when the $D^0$ and $\bar{D}^0$ decay to a common final state [6]. The two interfering amplitudes differ by a factor $r_B e^{i(\delta_B - \gamma)}$, where $r_B$ is the magnitude of the ratio of the amplitudes $A(B^+ \rightarrow D^0 K^+)$ and $\bar{A}(B^+ \rightarrow \bar{D}^0 K^-)$, and $\delta_B$ is their relative strong phase. An amplitude analysis of the Dalitz plot (DP) of $D^0$ and $\bar{D}^0$ mesons decaying into the $K_{S}^0 \pi^+ \pi^-$ and $\bar{K}_{S}^0 \pi^+ \pi^-$ self-conjugate final states from $B^+ \rightarrow D K^\pm$ decays offers a unique way to access the complex amplitude ratios and thus the weak and strong phases, and $r_B$. The experimental sensitivity to $\gamma$ arises mostly from regions in the DP where Cabibbo-favored and doubly-Cabibbo-suppressed amplitudes interfere, and from regions populated by $CP$ eigenstates; thus the uncertainty in $\gamma$ depends on $1/r_B$ ($r_B = 0.1 - 0.2$).

In this Letter we study the interference between color-favored and color-suppressed transitions as a function of the position in the DP of squared invariant masses $s_+ = m^2(K_{S}^0 h^-)$, $s_- = m^2(K_{S}^0 h^+)$, where $h$ represents $\pi$ or $K$, for three related $B$ decays, $B^+ \rightarrow D K^\pm$, $B^+ \rightarrow D^* K^\mp$, and $B^+ \rightarrow D K^*_\pm$ [4,7], and report the most precise single measurement of the complex amplitude ratios and evidence for direct $CP$ violation. We use the complete data sample of 425 fb$^{-1}$ of integrated luminosity at the $\Upsilon(4S)$, corresponding to $468 \times 10^9 B \bar{B}$ pairs, and 45 fb$^{-1}$ at a center-of-mass (c.m.) energy 40 MeV below the $\Upsilon(4S)$, recorded by the BABAR experiment [8] at the PEP-II asymmetric-energy $e^+e^-$ collider at SLAC from 1999 to 2008. This measurement updates our previous results based on a partial sample of $383 \times 10^9 B \bar{B}$ pairs, from which we reported a significance of direct $CP$ violation ($\gamma \neq 0$) of 3.0 standard deviations, while most of the analysis details remain unchanged [9]. The Belle Collaboration using $B^+ \rightarrow D^{(*)} K^- \bar{\tau}$, $D \rightarrow K_{S}^0 \pi^+ \pi^-$ alone [10] has also reported $\gamma \neq 0$ with a significance of 3.5 standard deviations.

We reconstruct a total of eight signal samples, $B^+ \rightarrow D^{(*)} K^- \bar{\tau}$ and $B^+ \rightarrow D K^{*+} \bar{\tau}$, with $D^{*+} \rightarrow D \pi^0$, $D \gamma$, $K^{+} \rightarrow K_{S}^0 \pi^+$, with selection criteria nearly identical to our previous analysis. The $DK^{\pm}$ final state, for $D \rightarrow K_{S}^0 K^+ K^-$, has been considered for the first time. For $K_{S}^0 \rightarrow \pi^+ \pi^-$ candidates, we further require the decay length (defined by the $K_{S}^0$ production and decay vertices) projected along the $K_{S}^0$ momentum to be greater than 10 times its error. This additional requirement helps to reduce to a negligible level background events from $D \rightarrow \pi^+ \pi^- h^+ h^-$ decays, and from $a_1(1260)\rightarrow K^+ K^-$. After all the selection criteria the background is completely dominated by random combinations of tracks arising from continuum events, $e^+e^- \rightarrow q \bar{q}$ ($q = u, d, s, o$). Background contributions from $D \rightarrow K_{S}^0 K_{0}^0$ decays are found to be negligible. The $B^{\pm}$ candidates are characterized using the beam-energy substituted $B$ mass $m_{ES}$, the difference between the reconstructed energy of the $B^+$ candidate and the beam energy in the $e^+e^-$ c.m. frame $\Delta E$, and a Fisher discriminant $F$ that combines four topological variables optimized to separate continuum events [9]. We retain candidates with the loose requirements $m_{ES} > 5.2$ GeV/$c^2$, $-80 < \Delta E < 120$ MeV, and $|F| < 1.4$, which provide signal and sideband regions while removing poorly reconstructed candidates [11]. The reconstruction efficiencies in a signal region with $m_{ES} > 5.272$ GeV/$c^2$ and $|\Delta E| < 30$ MeV are 26%, 12%, 15%, and 14%, for the $DK^\pm$, $D^* \rightarrow D^{0} \pi^0 K^\mp$, $D^* \rightarrow D^{0} \sqrt{2} \gamma K^\mp$, and $D^* \rightarrow K^*$$^0 K^\mp$ final states, respectively, for $D \rightarrow K_{S}^0 \pi^+ \pi^-$ (and slightly lower for $D \rightarrow K_{S}^0 K^+ K^-$). These values are about 30%, 40%, 30%, and 20% larger than in our previous analysis, with similar background levels, reflecting improvements in tracking and particle identification. The $m_{ES}$, $\Delta E$, $F$, and $(s_+, s_-)$ distributions for events in the signal region can be found in [11].

The $D^0 \rightarrow K_{S}^0 h^+ h^-$ decay amplitudes $A(s_+, s_-)$ are determined using the same data sample through DP analyses of $D^0$ mesons from $D^{(*)} \rightarrow D^0 \pi^+$ decays produced in $e^+e^- \rightarrow c\bar{c}$ events [9,12]. The charge of the low momentum $\pi^+$ from the $D^0$ decay identifies the flavor of the $D$ meson. The signal purities of the samples are 98.5% and 99.2%, with about 541 000 and 80 000 candidates, for $K_{S}^0 \pi^+ \pi^-$ and $K_{S}^0 K^+ K^-$, respectively. The dynamical properties of the $P$- and $D$-wave amplitudes are parametrized through intermediate resonances with mass-dependent relativistic Breit-Wigner (BW) or Gounaris-Sakurai propagators, Blatt-Weisskopf centrifugal barrier factors, and Zemach tensors for the angular distributions [13]. The $\pi\pi$ S-wave dynamics is described through a $K$-matrix formalism with the $P$-vector approximation and 5 poles [9,14]. For the $K\pi$ S-wave we include a BW for the $K_{S}^0(1430)^-$ state with a coherent nonresonant contribution parametrized by a scattering length and effective range similar to those used to describe $\bar{K}\pi$ scattering data [15]. For the $KK$ S-wave, a coupled-channel BW is used for the $a_0(980)$ with single BWs for $f_0(1370)$ and $a_0(1450)$ states. Overall, the amplitude models reproduce well the DP distributions [12]. Monte Carlo (MC) studies show that a significant contribution to the discrepancies arise from imperfections modeling the efficiency variations at the...
boundaries of the DP and the invariant mass resolution. We account for these and other imperfections in the modeling of the $D^0$ decay amplitudes through our model systematic uncertainties.

We perform a simultaneous, unbinned, and extended maximum-likelihood fit (referred to as CP fit) to the $B^\mp \rightarrow D^{(*)}K^\mp$ and $B^\mp \rightarrow D^0K^*\mp$ decay rates $\Gamma^{(s)}_\mp$ and $\Gamma^{(c)}_\mp$ as a function of $\mu_{\text{RES}}, \Delta E, \bar{f}$, and $(s_-, s_+)$ [9,11]. We extract the signal and background yields, along with the CP-violating parameters $z^{(c)}_\mp = x^{(c)}_\mp + iy^{(c)}_\mp$ and $z^{(s)}_\mp = x^{(s)}_\mp + iy^{(s)}_\mp$, defined as the $B^\mp$ complex amplitude ratios

$$z^{(c)}_\mp = \frac{r^{(c)}_{B^\mp}}{\Delta x^{(c)}_\mp} e^{i(\delta^{(c)}_\mp - \gamma)} \quad \text{and} \quad z^{(s)}_\mp = \kappa r^{(s)}_{B^\mp} e^{i(\delta^{(s)}_\mp - \gamma)},$$

respectively. Here, $r^{(c)}_{B^\mp}$ and $r^{(s)}_{B^\mp}$ are the corresponding magnitude ratios between the $b \rightarrow u$ and $b \rightarrow c$ amplitudes for $B^\mp$ decays, $\delta^{(c)}_B$ and $\delta^{(s)}_B$ the relative strong phases, and $\kappa$ an effective hadronic parameter that accounts for the interference between $B^\mp \rightarrow D^0K^\mp$ and other $B^\mp \rightarrow D^0K^\mp\pi^\mp$ decays, as a consequence of the $K^\mp$ natural width [9,16,17]. Assuming no CP violation and neglecting $D^0 \rightarrow \bar{D}^0$ mixing in $D^0 \rightarrow K^0_s h^+ h^-$ decays [12,18,19], the relation $\mathcal{A}(s_-, s_+) = \mathcal{A}(s_+, s_-)$ holds, where $\mathcal{A}$ is the $B^\mp$ decay amplitude. The $B^\mp \rightarrow D^{(*)}K^\mp$ [and similarly for $B^\mp \rightarrow D^0K^*\mp$ replacing $z^{(c)}_\mp$ and $r^{(s)}_{B^\mp}$ by $z^{(s)}_\mp$ and $r^{(c)}_{B^\mp}$, respectively] signal decay rates are then

$$\Gamma^{(c)}_\mp(s_-, s_+) \propto |\mathcal{A}_\mp|^2 + r^{(c)}_{B^\mp} |\mathcal{A}_\mp|^2 + 2\lambda z^{(c)}_\mp \mathcal{A}_\mp \bar{\mathcal{A}}_\mp,$$

with $\mathcal{A}_\mp = \mathcal{A}(s_-, s_\pm)$, and $\lambda = +1$ except for $B^\mp \rightarrow D^0[D\pi]\bar{K}^\mp$ where $\lambda = -1$ [20]. We apply corrections for efficiency variations and neglect the invariant mass uncertainties in the description of the efficiency variations across the DP [9]. For each signal sample, the following background components are considered: continuum events, $B^\mp \rightarrow D^{(*)}\pi^\mp$ decays where the pion is misidentified as a kaon [only for $B^\mp \rightarrow D^{(*)}\bar{K}^\mp$ samples], and $Y(4S) \rightarrow BB$ [other than $B^\mp \rightarrow D^{(*)}\pi^\mp$] decays. The reference CP fit requires events to satisfy $|\Delta E| < 30$ MeV, but alternative fits are performed varying the requirements on the $\mu_{\text{RES}}, \Delta E, \bar{f}$ variables (e.g. $\mu_{\text{RES}} > 5.272$ GeV/$c^2$ or $\bar{f} > -0.1$) to study the stability of the results. The probability density functions (PDFs) introduced to describe the signal, continuum, and $K/\pi$ misidentification components, along with the $K/\pi$ misidentification yields, are determined using events from signal and $B^\mp \rightarrow D^{(*)}\pi^\mp$, $D_0(1260)^\mp$ control samples. The PDFs for $B\bar{B}$ background events are obtained from large MC samples with full detector simulations [9].

The CP fit yields $896 \pm 35$ (154 \pm 14), $255 \pm 21$ (56 \pm 11), $193 \pm 19$ (30 \pm 7), and $163 \pm 18$ (28 \pm 6) signal $D^0K^\mp$, $D^*[D\pi]\bar{K}^\mp$, $D^*[D\gamma]\bar{K}^\mp$, and $D^0K^*\mp$ events, respectively, for the $K^0_\mp\pi^\mp$ ($K^0_\mp\bar{K}^\mp$) final state. The results for the CP-violating parameters $z^{(c)}_\mp$ and $z^{(s)}_\mp$ are summarized in Table I. Figure 1 shows the 39.3% and 86.5% two-dimensional confidence-level (C.L.) contours in the $z^{(c)}_\mp$ and $z^{(s)}_\mp$ planes, corresponding to one- and two-standard deviation regions, including statistical errors only. The distance between the $z_-$ and $z_+$ central values (and similarly for $z^{(c)}_\mp$ and $z^{(s)}_\mp$) is equal to $2\gamma$, and the angle defined by the lines connecting the central values with the origin is $2\gamma$, and thus is a measurement of direct CP violation. Fitting separately the data for $K^0_\mp\pi^\mp\pi^\mp$ and $K^0_\mp\bar{K}^\mp\bar{K}^\mp$ final states we find consistent results for all the CP-violating parameters [11].

Experimental systematic errors [9,11] originate from uncertainties in the description of the efficiency variations across the DP, the modeling of the DP distributions for background events containing misreconstructed $D$ mesons, the fractions of continuum, and $B\bar{B}$ background events containing a real $D$ meson with either a negatively or positively charged kaon (or $K^*$), and from residual direct CP violation in the $B^\mp \rightarrow D^{(*)}\pi^\mp$ and $B\bar{B}$ background components. We also account for statistical and systematic uncertainties in the $\mu_{\text{RES}}, \Delta E, \bar{f}$ and PDF shapes for signal and background components, and the $K/\pi$ misidentification yields. These uncertainties account for effects that arise from the dependence of the $\mu_{\text{RES}}$ endpoint, the peaking contributions to the small $B\bar{B}$ background, and the $e^+e^-$ c.m. frame. Smaller systematic uncertainties originate from the DP resolution, wrongly reconstructed signal events with a real $D$ and a kaon (or $K^*$) from the other $B$ meson decay, the selection of $B$ candidates sharing tracks with other candidates, and numerical precision in the evaluation of the PDF integrals. We also account for residual cross feed of $B^\mp \rightarrow D^*[D\pi]\bar{K}^\mp$ events into the $B^\mp \rightarrow D^*[D\gamma]\bar{K}^\mp$ sample (about 5%), and the estimated uncertainty on the hadronic parameter $\kappa = 0.9 \pm 0.1$ in the $B^\mp \rightarrow D^0K^*\mp$ sample [9,21].

Assumptions in the $D^0$ decay amplitude models are also a source of systematic uncertainty [9,11,12]. We use alternative $\mathcal{A}(s_-, s_+)$ models where the BW parameters are varied according to their uncertainties or within the ranges allowed by measurements from other experiments, the reference $\bar{K}$-matrix solution [9] is replaced by other solutions [14], and the standard parametrizations are substituted by other related choices. These include replacing the

| TABLE I. CP-violating complex parameters $z^{(c)}_\mp = x^{(c)}_\mp + iy^{(c)}_\mp$ and $z^{(s)}_\mp = x^{(s)}_\mp + iy^{(s)}_\mp$ as obtained from the CP fit. The first error is statistical, the second is the experimental systematic uncertainty, and the third is the systematic uncertainty associated with the $D^0$ decay amplitude models. |
|-------------|-------------|-------------|
| $z_-$       | $6.0 \pm 3.9 \pm 0.7 \pm 0.6$ | $6.2 \pm 4.5 \pm 0.4 \pm 0.6$ |
| $z_+$       | $-10.3 \pm 3.7 \pm 0.6 \pm 0.7$ | $-21.1 \pm 4.8 \pm 0.4 \pm 0.9$ |
| $z^{(c)}_-$ | $-10.4 \pm 5.1 \pm 1.9 \pm 0.2$ | $-5.2 \pm 6.3 \pm 0.9 \pm 0.7$ |
| $z^{(c)}_+$ | $14.7 \pm 5.3 \pm 1.7 \pm 0.3$ | $3.2 \pm 7.7 \pm 0.8 \pm 0.6$ |
| $z^{(s)}_-$ | $7.5 \pm 9.6 \pm 2.9 \pm 0.7$ | $12.7 \pm 9.5 \pm 2.7 \pm 0.6$ |
| $z^{(s)}_+$ | $-15.1 \pm 8.3 \pm 2.9 \pm 0.6$ | $4.5 \pm 10.6 \pm 3.6 \pm 0.8$ |
Gounaris-Sakurai and $K\pi$ S-wave parametrizations by BW line shapes, removing the mass dependence in the $P$ vector [22], changes in form factors such as changes in the Blatt-Weisskopf radius, and adopting a helicity formalism [13] to describe the angular dependence. Other models are built by removing or adding resonances with small or negligible fractions. We find that the overall amplitude model uncertainty on the CP parameters are dominated by alternative models built to account for experimental systematic effects in the determination of $\mathcal{A}(s_+, s_\pi)$ using tagged $D$ mesons [12]. The statistical errors and variations in the $\mathcal{A}(s_-, s_\pi)$ model parameters with and without $D^0 - \bar{D}^0$ mixing are also propagated to $Z^{(\psi)}_\pi$ and $Z_{\gamma\pi}$. Experimental and amplitude model systematic uncertainties [11] have been reduced with respect to our previous measurement [9] as consequence of the use of larger data and MC samples, and the smaller experimental systematic contributions to the model uncertainty resulting from the improvements in the analysis of tagged $D$ mesons [12].

A frequentist construction of one-dimensional confidence intervals of the physically relevant parameters $p \equiv (\gamma, r_B, r_B^\prime, \kappa r_\pi, \delta_B, \delta_B^\prime, \delta_\pi)$ based on the vector of measurements $z = (z, z, z^c, z^c, z, z, z, z)$ and their correlations [11] has been adopted [9]. The procedure takes into account unphysical regions which may arise since we allow $B^-$ and $B^+$ events to have different $r_B^{(s)}$, $r_\pi$, in the $z$ measurements. Figure 2 shows $1 - \text{C.L.}$ as a function of $\gamma$ for each of the three $B$ decays channels separately and their combination. Similar scans for $f_B^{(s)}$, $\kappa r_\pi$, and $\delta_\pi$ can be found in [11]. The method has a single ambiguity in the weak and strong phases. The results for all the $p$ parameters are listed in Table II. The significances of direct CP violation ($\gamma \neq 0$) are $1 - \text{C.L.} = 6.8 \times 10^{-3}$, $5.4 \times 10^{-3}$, $6.3 \times 10^{-2}$, and $4.6 \times 10^{-4}$, which correspond to 2.7, 2.8, 1.9, and 3.5 standard deviations, for $B^+ \rightarrow DK^\pi$, $B^- \rightarrow D^0 K^\pi$, $B^\pm \rightarrow D^\mp K^{\mp \pi}$, and their combination, respectively.

Experimental and amplitude model systematic uncertainties [11] have been reduced with respect to our previous measurement [9] as consequence of the use of larger data and MC samples, and the smaller experimental systematic contributions to the model uncertainty resulting from the improvements in the analysis of tagged $D$ mesons [12].

![FIG. 1 (color online).](image)

FIG. 2 (color online). $1 - \text{C.L.}$ as a function of $\gamma$ for $B^- \rightarrow DK^\pi$, $B^- \rightarrow D^0 K^\pi$, and $B^\pm \rightarrow DK^{\mp \pi}$ decays separately, and their combination, including statistical and systematic uncertainties. The dashed (upper) and dotted (lower) horizontal lines correspond to the one- and two-standard deviation intervals, respectively.

**Table II.** The 68.3% and 95.4% one-dimensional C.L. regions, equivalent to one- and two-standard deviation intervals, for $\gamma$, $r_B$, $r_B^\prime$, $\kappa r_\pi$, and $\delta_B$, including all sources of uncertainty. The values inside $\{}$ brackets indicate the symmetric error contributions to the total error coming from experimental and amplitude model systematic uncertainties.

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<th>95.4% C.L.</th>
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<td>$\gamma$ (°)</td>
<td>$68^{+15}_{-14}$ ${4, 3}$</td>
<td>$[39, 98]$</td>
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<td>$r_B$ (%)</td>
<td>$9.6 \pm 2.9$ ${0.5, 0.4}$</td>
<td>$[3.7, 15.5]$</td>
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<tr>
<td>$r_B^\prime$ (%)</td>
<td>$13.3^{+3.7}_{-3.5}$ ${1.3, 0.3}$</td>
<td>$[4.9, 21.5]$</td>
</tr>
<tr>
<td>$\kappa r_\pi$ (%)</td>
<td>$14.9^{+6.9}_{-6.6}$ ${2.6, 0.6}$</td>
<td>$&lt;28.0$</td>
</tr>
<tr>
<td>$\delta_B$ (°)</td>
<td>$119^{+19}_{-20}$ ${3, 3}$</td>
<td>$[75, 157]$</td>
</tr>
<tr>
<td>$\delta_B^\prime$ (°)</td>
<td>$-82 \pm 21$ ${5, 3}$</td>
<td>$[-124, -38]$</td>
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<tr>
<td>$\delta_\pi$ (°)</td>
<td>$111 \pm 32$ ${11, 3}$</td>
<td>$[42, 178]$</td>
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We have presented a measurement of the $b \to u$ to $b \to c$ complex amplitude ratios in the processes $B^+ \to D^{(*)}K^+$ and $B^+ \to DK^{*+}$, using a combined DP analysis of $D \to K^{0}\pi^+\pi^-$ and $D \to K_S^0K^+K^-$ decays. The results have improved precision and are consistent with our previous measured values [9] and with those reported by the Belle Collaboration with $D \to K^{0}\pi^+\pi^-$ alone [10], and with determinations based on other $D$ meson final states [21-23,24]. From our measurement we determine $\gamma = (68 \pm 14 \pm 4 \pm 3)^\circ$ (modulo 180$^\circ$), exclude the no direct CP-violation hypothesis (i.e., $\gamma = 0$) with a C.L. equivalent to 3.5 standard deviations, and derive the most precise single determinations of the magnitude ratios $r_B^{(*)}$ and $r_{K_S}^{(*)}$.

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*Present address: Temple University, Philadelphia, PA 19122, USA
†Also at Università di Perugia, Dipartimento di Fisica, Perugia, Italy
‡Also at Università di Roma La Sapienza, I-00185 Roma, Italy
§Present address: University of South Alabama, Mobile, AL 36688, USA
¶Also at Università di Sassari, Sassari, Italy
¶Also at University of Oxford, Theoretical Physics Department, Oxford, OX1 3NP, United Kingdom


[4] The symbol $D (D^*)$ indicates either a $D^0 (D^{*0})$ or a $\bar{D}^0 (\bar{D}^{*0})$ meson.

[5] Reference to the charge-conjugate state is implied here and throughout the text unless otherwise specified.


[7] $K^{*0}$, $D^{*+}$, and $D^{*0}$ refer to $K^*(892)^0$, $D^*(2010)^0$, and $D^*(2007)^0$ mesons, respectively.


