Measurement of the branching fraction ratios and $CP$ asymmetries in $B^- \to D^0_{CP} K^-$ decays

The BaBar Collaboration

February 1, 2008

Abstract

We present a preliminary study of $B^- \to D^0_{CP} \pi^- \, \text{and} \, B^- \to D^0_{CP} K^-$ decays, with the $D^0_{CP}$ reconstructed in the $CP$-odd eigenstates $K_s \pi^0$, $K_s \omega$, in the $CP$-even eigenstates $K^+ K^-$, $\pi^+ \pi^-$, and in the (non-$CP$) flavor eigenstate $K^\mp \pi^\pm$. Using a sample of about 382 million $\Upsilon(4S)$ decays into $B\overline{B}$ pairs, collected with the BaBar detector operating at the PEP-II asymmetric-energy $B$ Factory at SLAC, we measure the ratios of the branching fractions

$$R_{CP\pm} \equiv \frac{\mathcal{B}(B^- \to D^0_{CP\pm} K^-) + \mathcal{B}(B^+ \to D^0_{CP\pm} K^+)}{[\mathcal{B}(B^- \to D^0 K^-) + \mathcal{B}(B^+ \to D^0 K^+)]/2}$$

and the direct $CP$ asymmetry

$$A_{CP\pm} \equiv \frac{\mathcal{B}(B^- \to D^0_{CP\pm} K^-) - \mathcal{B}(B^+ \to D^0_{CP\pm} K^+)}{\mathcal{B}(B^- \to D^0_{CP\pm} K^-) + \mathcal{B}(B^+ \to D^0_{CP\pm} K^+)}.$$

The results are:

$$R_{CP^-} = 0.81 \pm 0.10(\text{stat}) \pm 0.05(\text{syst})$$
$$R_{CP^+} = 1.07 \pm 0.10(\text{stat}) \pm 0.04(\text{syst})$$
$$A_{CP^-} = -0.19 \pm 0.12(\text{stat}) \pm 0.02(\text{syst})$$
$$A_{CP^+} = 0.35 \pm 0.09(\text{stat}) \pm 0.05(\text{syst})$$

Contributed to the XXIIIrd International Symposium on Lepton and Photon Interactions at High Energies, 8/13 – 8/18/2007, Daegu, Korea

Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

Work supported in part by Department of Energy contract DE-AC03-76SF000515.
The **BaBar** Collaboration,

B. Aubert, M. Bona, D. Boutigny, Y. Karyotakis, J. P. Lees, V. Poireau, X. Prudent, V. Tisserand, A. Zghiche

*Laboratoire de Physique des Particules, IN2P3/CNRS et Université de Savoie, F-74941 Annecy-Le-Vieux, France*

J. Garra Tico, E. Grauges

*Universitat de Barcelona, Facultat de Fisica, Departament ECM, E-08028 Barcelona, Spain*

L. Lopez, A. Palano, M. Pappagallo

*Università di Bari, Dipartimento di Fisica and INFN, I-70126 Bari, Italy*

G. Eigen, B. Stugu, L. Sun

*University of Bergen, Institute of Physics, N-5007 Bergen, Norway*

G. S. Abrams, M. Battaglia, D. N. Brown, J. Button-Shafer, R. N. Cahn, Y. Groysman, R. G. Jacobsen, J. A. Kadyk, L. T. Kerth, Yu. G. Kolomensky, G. Kukartsev, D. Lopes Pegna, G. Lynch, L. M. Mir, T. J. Orimoto, I. L. Osipenkov, M. T. Ronan, K. Tackmann, T. Tanabe, W. A. Wenzel

*Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA*

P. del Amo Sanchez, C. M. Hawkes, A. T. Watson

*University of Birmingham, Birmingham, B15 2TT, United Kingdom*

H. Koch, T. Schroeder

*Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany*

D. Walker

*University of Bristol, Bristol BS8 1TL, United Kingdom*

D. J. Asgeirsson, T. Cuhadar-Donszelmann, B. G. Fulsom, C. Hearty, T. S. Mattison, J. A. McKenna

*University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1*

A. Khan, M. Saleem, L. Teodorescu

*Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom*

V. E. Blinov, A. D. Bukin, V. P. Druzhinin, V. B. Golubev, A. P. Onuchin, S. I. Serednyakov, Yu. I. Skovpen, E. P. Solodov, K. Yu. Todyshev

*Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia*

M. Bondioli, S. Curry, I. Eschrich, D. Kirkby, A. J. Lankford, P. Lund, M. Mandelkern, E. C. Martin, D. P. Stoker

*University of California at Irvine, Irvine, California 92697, USA*

S. Abachi, C. Buchanan

*University of California at Los Angeles, Los Angeles, California 90024, USA*

S. D. Foulkes, J. W. Gary, F. Liu, O. Long, B. C. Shen,¹ G. M. Vitug, L. Zhang

*University of California at Riverside, Riverside, California 92521, USA*

¹Deceased
H. P. Paar, S. Rahatlou, V. Sharma

University of California at San Diego, La Jolla, California 92093, USA

J. W. Berryhill, C. Campagnari, A. Cunha, B. Dahmes, T. M. Hong, D. Kovskly, J. D. Richman

University of California at Santa Barbara, Santa Barbara, California 93106, USA

T. W. Beck, A. M. Eisner, C. A. Heusch, J. Kroseberg, W. S. Lockman, T. Schalk,
B. A. Schumm, A. Seiden, M. G. Wilson, L. O. Winstrom

University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA

E. Chen, C. H. Cheng, F. Fang, D. G. Hitlin, I. Narsky, T. Piatenko, F. C. Porter

California Institute of Technology, Pasadena, California 91125, USA

R. Andreassen, G. Mancinelli, B. T. Meadows, K. Mishra, M. D. Sokoloff

University of Cincinnati, Cincinnati, Ohio 45221, USA

F. Blanc, P. C. Bloom, S. Chen, W. T. Ford, J. F. Hirschauer, A. Kreisel, M. Nagel, U. Nauenberg,
A. Olivas, J. G. Smith, K. A. Ulmer, S. R. Wagner, J. Zhang

University of Colorado, Boulder, Colorado 80309, USA

A. M. Gabareen, A. Soffer, W. H. Toki, R. J. Wilson, F. Winklemeier

Colorado State University, Fort Collins, Colorado 80523, USA

D. D. Altenburg, E. Feltresi, A. Hauke, H. Jasper, M. Karbach, J. Merkel, A. Petzold, B. Spaan, K. Wacker

Universität Dortmund, Institut für Physik, D-44221 Dortmund, Germany

V. Klose, M. J. Kobel, H. M. Lacker, W. F. Mader, R. Nogowski, J. Schubert, K. R. Schubert, R. Schwierz,
J. E. Sundermann, A. Volk

Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany

D. Bernard, G. R. Bonneau, E. Latour, V. Lombardo, Ch. Thiebaut, M. Verderi

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France

P. J. Clark, W. Gradl, F. Muheim, S. Playfer, A. I. Robertson, J. E. Watson, Y. Xie

University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom

M. Andreotti, D. Bettoni, C. Bozzi, R. Calabrese, A. Cecchi, G. Cibinetto, P. Franchini, E. Luppi,
M. Negrini, A. Petrella, L. Piemontese, E. Preci, V. Santoro

Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy

F. Anulli, R. Baldini-Ferroli, A. Calcaterra, R. de Sangro, G. Finocchiaro, S. Pacetti, P. Patteri,
I. M. Peruzzi, M. Piccolo, M. Rama, A. Zallo

Laboratori Nazionali di Frascati dell’INFN, I-00044 Frascati, Italy

A. Buzzo, R. Contri, M. Lo Vetere, M. M. Macri, M. R. Monge, S. Passaggio, C. Patrignani, E. Robutti,
A. Santroni, S. Tosi

Università di Genova, Dipartimento di Fisica and INFN, I-16146 Genova, Italy

2Now at Tel Aviv University, Tel Aviv, 69978, Israel

3Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy
L. Gladney  
*University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*

M. Biasini, R. Covarelli, E. Manoni  
*Università di Perugia, Dipartimento di Fisica and INFN, I-06100 Perugia, Italy*

C. Angelini, G. Batignani, S. Bettarini, M. Carpinelli, R. Cenci, A. Cervelli, F. Forti, M. A. Giorgi, A. Lusiani, G. Marchiori, M. A. Mazur, M. Morganti, N. Neri, E. Paoloni, G. Rizzo, J. J. Walsh  
*Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy*

J. Biesiada, P. Elmer, Y. P. Lau, C. Lu, J. Olsen, A. J. S. Smith, A. V. Telnov  
*Princeton University, Princeton, New Jersey 08544, USA*

E. Baracchini, F. Bellini, G. Cavoto, D. del Re, E. Di Marco, R. Faccini, F. Ferrarotto, F. Ferroni, M. Gaspero, P. D. Jackson, L. Li Gioi, M. A. Mazzoni, S. Morganti, G. Piredda, F. Polci, F. Renga, C. Voena  
*Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy*

M. Ebert, T. Hartmann, H. Schröder, R. Waldi  
*Universität Rostock, D-18051 Rostock, Germany*

T. Adye, G. Castelli, B. Franek, E. O. Olaiya, W. Roethel, F. F. Wilson  
*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom*

S. Emery, M. Escalier, A. Gaidot, S. F. Ganzhur, G. Hamel de Monchenault, W. Kozanecki, G. Vasseur, Ch. Yèche, M. Zito  
*DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France*

X. R. Chen, H. Liu, W. Park, M. V. Purohit, R. M. White, J. R. Wilson  
*University of South Carolina, Columbia, South Carolina 29208, USA*

M. T. Allen, D. Aston, R. Bartoldus, P. Bechtle, R. Claus, J. P. Coleman, M. R. Convery, J. C. Dingfelder, J. Dorfan, G. P. Dubois-Felsmann, W. Dunwoodie, R. C. Field, T. Glanzman, S. J. Gowdy, M. T. Graham, P. Grenier, C. Hast, W. R. Innes, J. Kaminski, M. H. Kelsey, H. Kim, P. Kim, M. L. Kocian, D. W. G. S. Leith, S. Li, S. Luitz, V. Luth, H. L. Lynch, D. B. MacFarlane, H. Marsiske, R. Messner, D. R. Muller, C. P. O’Grady, I. Ofte, A. Perazzo, M. Perl, T. Pulliam, B. N. Ratcliff, A. Roodman, A. A. Salnikov, R. H. Schindler, J. Schwiening, A. Snyder, D. Su, M. K. Sullivan, K. Suzuki, S. K. Swain, J. M. Thompson, J. Va’vra, A. P. Wagner, M. Weaver, W. J. Wisniewski, M. Wittgen, D. H. Wright, A. K. Yarritu, K. Yi, C. C. Young, V. Ziegler  
*Stanford Linear Accelerator Center, Stanford, California 94309, USA*

P. R. Burchat, A. J. Edwards, S. A. Majewski, T. S. Miyashita, B. A. Petersen, L. Wilden  
*Stanford University, Stanford, California 94305-4060, USA*

S. Ahmed, M. S. Alam, R. Bula, J. A. Ernst, V. Jain, B. Pan, M. A. Saeed, F. R. Wappler, S. B. Zain  
*State University of New York, Albany, New York 12222, USA*

M. Krishnamurthy, S. M. Spanier  
*University of Tennessee, Knoxville, Tennessee 37996, USA*

---

5 Also with Universita’ di Sassari, Sassari, Italy
1 INTRODUCTION

A measurement of the processes $B^- \to D^0 K^-$ \cite{1} and $B \to D^0_{CP\pm} K$, where $D^0_{CP\pm}$ indicates the CP-even or CP-odd states $1/\sqrt{2}(D^0 \pm \bar{D}^0)$, has been attracting the attention of theorists for the last fifteen years \cite{2}. These decay rates are fundamental ingredients in some of the proposed methods to extract the $\gamma$ angle of the CKM matrix in a theoretically clean way. To this end, one needs to measure the two direct $CP$ asymmetries

$$A_{CP\pm} \equiv \frac{B(B^- \to D^0_{CP\pm} K^-) - B(B^+ \to D^0_{CP\pm} K^+)}{B(B^- \to D^0_{CP\pm} K^-) + B(B^+ \to D^0_{CP\pm} K^+)},$$

and the two ratios of charge-averaged branching fractions in $D^0$ decays to $CP$ eigenstates

$$R_{CP\pm} \equiv \frac{B(B^- \to D^0_{CP\pm} K^-) + B(B^+ \to D^0_{CP\pm} K^+)}{[B(B^- \to D^0 K^-) + B(B^+ \to D^0 K^+)]/2}.$$ \(1\)\(2\)

In fact, $\gamma$ is constrained by the following set of equations in the three unknowns $\gamma$, $\delta$, $r$:

$$R_{CP\pm} = 1 + r^2 \pm 2r \cos \delta \cos \gamma$$ \(3\)

$$A_{CP\pm} = \frac{\pm 2r \sin \delta \sin \gamma}{1 + r^2 \pm 2r \cos \delta \cos \gamma},$$ \(4\)

where $r \equiv |A(B^- \to D^0 K^-)/A(B^+ \to D^0 K^+)| \approx O(0.1)$ is the magnitude of the ratio of the amplitudes for $B^- \to D^0 K^-$ and $B^- \to D^0 K^-$ and $\delta$ the difference between their strong phases. The asymmetries $A_{CP\pm}$, in addition to being ingredients for the extraction of $\gamma$, are of special relevance because they would indicate, if significantly different from zero, direct $CP$ violation in charged $B$ decays. To measure $R_{CP\pm}$ and $A_{CP\pm}$ we reconstruct $B \to D^0_{CP\pm} K$ and $B \to D^0_{CP\pm} \pi$ decays with the $D^0_{CP\pm}$ decaying to two $CP$-odd and two $CP$-even eigenstates, and $B^- \to D^0 K^-$ and $B^- \to D^0 \pi^-$ decays with $D^0$ decaying to one non-$CP$ state. Previous measurements of these quantities were performed by BABAR \cite{3} and Belle \cite{4}. We update the result by BABAR from 211 fb$^{-1}$ to 348 fb$^{-1}$ of data. Compared to the previous analysis, the current study does not include the decay mode $D^0 \to K^0_S \phi$, since it is going to be explored by the Dalitz analysis method using $B^- \to D K^-$, $D \to K^0_S K^+ K^-$ decays. Dropping $D^0 \to K^0_S \phi$ allows to combine the results of both measurements in the future. We also express the $CP$-sensitive observables in terms of three Dalitz related independent quantities:

$$x_\pm = \frac{R_{CP+}(1 + A_{CP+}) - R_{CP-}(1 + A_{CP-})}{4},$$ \(5\)

$$r^2 = x_\pm^2 + y_\pm^2 = \frac{R_{CP+} + R_{CP-} - 2}{2},$$ \(6\)

where the Cartesian coordinates $x_\pm = r \cos(\delta \pm \gamma)$ and $y_\pm = r \sin(\delta \pm \gamma)$ are the same $CP$ parameters as were measured by the BABAR Collaboration using $B^- \to D K^-$, $D \to K^0_S \pi^- \pi^+$ decays \cite{5}. We reduce the systematic uncertainties from $D^0$ branching fractions and reconstruction efficiencies of different $D^0$ modes by measuring the double branching fraction ratios

$$R_\pm = \frac{R_{CP\pm}}{R_{K^0/\pi}}$$ \(7\)
rather than the quantities $R_{CP\pm}$. Here,

$$R_{CP\pm}^{K/\pi} \equiv \frac{B(B^- \to D_{CP\pm}^0 K^-) + B(B^+ \to D_{CP\pm}^0 K^+)}{B(B^- \to D_{CP\pm}^0 \pi^-) + B(B^+ \to D_{CP\pm}^0 \pi^+)} ,$$

(8)

and

$$R_{CP\pm}^{K/\pi} \equiv \frac{B(B^- \to D^0 K^-) + B(B^+ \to D^0 K^+)}{B(B^- \to D^0 \pi^-) + B(B^+ \to D^0 \pi^+)} .$$

(9)

$R_{\pm}$ and $R_{CP\pm}$ are equivalent discarding a term of the order of $\approx 0.01$, which will be accounted for by assigning a systematic uncertainty when quoting the result in terms of $R_{CP\pm}$.

2 THE BaBar DETECTOR AND DATASET

This measurement uses 348 fb$^{-1}$ of data taken at the $\Upsilon(4S)$ resonance by the BaBar detector with the PEP-II asymmetric $B$ factory. The BaBar detector is described in detail elsewhere [6]. Tracking of charged particles is provided by a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH). A ring-imaging Cherenkov detector (DIRC) provides improved particle identification (PID). An electromagnetic calorimeter (EMC), comprised of CsI crystals, is used to identify electrons and photons. These systems are mounted inside a 1.5 T solenoidal magnetic field. The instrumented flux return of the magnet allows discrimination of muons from other particles. We use a GEANT4-based Monte Carlo (MC) simulation [7] to model the response of the detector, taking into account the varying accelerator and detector conditions.

3 EVENT SELECTION

We reconstruct $B^- \to D^0 h^-$ decays where the prompt track $h^-$ is a kaon or a pion. Candidates for $D^0$ are reconstructed in the $CP$-even eigenstates $\pi^- \pi^+$ and $K^- K^+$, in the $CP$-odd eigenstates $K^0_S \pi^0$, $K^0_S \omega$ and in the non-$CP$ flavor eigenstate $K^- \pi^+$. $K^0_S$ and $\omega$ candidates are selected in the $\pi^- \pi^+$ and $\pi^+ \pi^- \pi^0$ channels, respectively.

PID information from the DCH and, when available, from the DIRC must be consistent with the kaon hypothesis for the $K$ meson candidate in all $D^0$ modes and with the pion hypothesis for the $\pi^\pm$ meson candidates in the $D^0 \to \pi^- \pi^+$ mode. For the prompt track to be identified as a pion or a kaon, we require at least five Cherenkov photons to be detected to ensure a good measurement of the Cherenkov angle. We reject a candidate track if its Cherenkov angle is not within 4$\sigma$ of the expected value for either a kaon or pion mass hypothesis. We also reject candidate tracks that are identified as electrons by the DCH and the EMC or as muons by the DCH and the muon system.

Photon candidates are clusters in the EMC that are not matched to any charged track, have a raw energy greater than 30 MeV and lateral shower shape consistent with the expected pattern of energy deposit from an electromagnetic shower. Photon pairs with invariant mass within the range 115–150 MeV/$c^2$ (~3$\sigma$) and total energy greater than 200 MeV are considered $\pi^0$ candidates. To improve the momentum resolution, the $\pi^0$ candidates are kinematically fit with their mass constrained to the nominal $\pi^0$ mass [8].

Neutral kaons are reconstructed from pairs of oppositely charged tracks with invariant mass within 10 MeV/$c^2$ from the nominal $K^0_S$ mass [8]. We also require the ratio between the flight

\footnote{The double branching fraction ratios, in the approximation $A(B^+ \to D_{CP\pm}^0 \pi^+)$ $\approx A(B^- \to D_{CP\pm}^0 \pi^-)$ $\approx \bar{c} \sqrt{2} A(B^- \to D^0 \pi^-)$, are equivalent to $R_{CP\pm}$, discarding a term $r_B |V_{us}|^2 / |V_{ud}|^2 |V_{us}| |V_{us}| \approx 0.01.$}
distance in the plane transverse to the beam direction and its expected uncertainty to be greater than 2.

The invariant mass of a $D^0$ candidate must agree within 2.5σ of its mass resolution to the nominal $D^0$ mass \[5\]. The $D^0$ mass resolution is about 7.5 MeV/c² in the $K\pi, K^+K^-$ and $\pi^+\pi^-$ modes, and about 21 MeV/c² and 9 MeV/c² in the $K_s^0\pi^0$ and $K_s^0\omega$ modes, respectively. Selected $D^0$ candidates are fit with a constraint to the nominal $D^0$ mass.

We reconstruct $B$ meson candidates by combining a $D^0$ candidate with a charged track $h^-$. For the $K^-\pi^+$ mode, the charge of the track $h^-$ must match the one of the kaon from the $D^0$ decay. We select $B$ meson candidates by using two kinematically independent variables: the beam-energy-substituted mass

$$m_{ES} = \sqrt{(E_i^2/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/(E_i^2 - p_B^2)}$$

and the energy difference

$$\Delta E = E_B^* - E_i^*/2,$$

where the subscripts $i$ and $B$ refer to the initial $e^+e^-$ system and the $B$ candidate, respectively, and the asterisk denotes the beams center-of-mass (CM) frame. The $m_{ES}$ distributions for $B^- \to D^0 h^-$ signal events are Gaussian distributions centered at the $B$ mass with a width of 2.6 MeV/c², which does not depend on the decay mode or on the nature of the prompt track. In contrast, the $\Delta E$ distributions depend on the mass assigned to the prompt track. We evaluate $\Delta E$ with the kaon mass hypothesis so that the distributions are centered near zero for $B^- \to D^0 K^-$ events and shifted on average by approximately 50 MeV/c to the positive direction for $B^- \to D^0 \pi^-$ events. The $\Delta E$ resolution depends on the momentum resolutions of the $D^0$ meson and the prompt track $h^-$, and is typically 16 MeV for all the $D^0$ decay modes. All $B$ candidates are required to have $m_{ES}$ within 2.5σ of the mean value and $\Delta E$ in the range $-0.15 < \Delta E < 0.20\text{GeV}$.

To reduce background from continuum production of light quarks, we construct a Fisher discriminant based on the following four quantities: (i) The Legendre polynomials, a set of momentum-weighted sums of the tracks and neutrals not associated with the reconstructed candidate, i.e. coming from the rest of the event (ROE):

$$L_j = \sum_{i}^{\text{ROE}} p_i^* \times |\cos(\theta_i^*)|^{j},$$

where $\theta_i^*$ is the CM angle between $\mathbf{p}_i^*$ and the thrust axis $\hat{T}^B$ of the $B$ candidate. We have considered only the $L_0, L_2$ pair, since previous studies have shown that adding other $L_j$ to the set of discriminating variables does not improve the sensitivity. In particular we use the ratio $L_2/L_0$;

(ii) $R_{B^0}^{\text{ROE}}$, the ratio of the Fox-Wolfram moments $H_2^{\text{ROE}}/H_0^{\text{ROE}}$, computed using tracks and photons in the ROE. $H_i^{\text{ROE}}$ is defined as \[11\]:

$$H_i^{\text{ROE}} = \sum_{i,j}^{\text{ROE}} \frac{|\mathbf{p}_i^*||\mathbf{p}_j^*|}{E_{\text{vis}}^2} P_i(\cos \theta_{ij}^*),$$

where $P_i$ is a Legendre polynomial, $\theta_{ij}$ is the opening angle between $\mathbf{p}_i^*$ and $\mathbf{p}_j^*$, and $E_{\text{vis}}$ is the total visible energy of the event. (iii) $|\cos(\mathbf{p}_B^*, z)|$ is the cosine of the angle of the $B$ candidate momentum with respect to the beam ($z$) axis. (iv) $|\cos(\hat{T}^B, z)|$ is the cosine of the angle of the $B$ candidate thrust axis with respect to the $z$ axis. A cut on the value of the Fisher discriminant
rejects more than 75% of the continuum background while retaining about 85% of the signal in all modes.

Another source of background is related to $B\bar{B}$ events. Its main contributions come from the processes $B\rightarrow D^*h$ ($h = \pi, K$) and $B^-\rightarrow D^0\rho^-$ mis-reconstructed as $B^-\rightarrow D^0h^-$ candidates. For $D^0\rightarrow K^-K^+$, $D^0\rightarrow \pi^-\pi^+$, $D^0\rightarrow K_S^0\pi^0$ and $D^0\rightarrow K_S^0\omega$ decays, there are peaking backgrounds caused by $B$ mesons decaying into the same final state particles. The peaking backgrounds have $\Delta E$ and $m_{ES}$ distributions similar to the signal. Their yields are estimated from the $D^0$ invariant mass sideband data and are taken into account in the fit.

When reconstructing $B$ candidates, it is possible that more than one combination satisfies the selection criteria in the same event. In order to select only one candidate per event, we define a criterion that allows to identify the combination with the largest probability to be a true signal $B^-\rightarrow D^0h^-$ decay. The $D^0$ invariant mass and the energy-substituted mass are chosen as discriminating quantities in all the channels. When $D^0$ decays into the $CP$-odd channels we also include the invariant masses of the $\omega$ and $\pi^0$ candidates. These variables are combined in a $\chi^2$ function whose minimization defines the best candidate choice. In the end, the fraction of rejected background candidates in the selected samples is 2% in the $K\pi$, less than 1% for $KK$ and $\pi^+\pi^-$ modes, while it is about 5% in the $K_S^0\pi^0$ mode and 8% in the $K_S^0\omega$.

The total reconstruction efficiencies, based on simulated signal events, are about 35%($K^-\pi^+$), 32%($K^-K^+$), 33%($\pi^-\pi^+$), 20%($K_S^0\pi^0$) and 8%($K_S^0\omega$).

4 FIT PROCEDURE

We determine the signal and background yields for each $D^0$ decay mode from a two-dimensional extended unbinned maximum-likelihood fit to the selected data events determines the signal and background yields. The input variables to the fit are $\Delta E$ and a particle identification probability for the prompt track based on the Cherenkov angle $\theta_C$, the momentum $p$ and the polar angle $\theta$ of the track. The extended likelihood function $L$ for the selected sample is given by the product of the probabilities for each individual candidate and a Poisson factor:

$$L = e^{-N'(N')^N} \prod_{i=1}^{N} p_i. \quad (12)$$

The probability $p_i$ for a candidate in the event $i$ is the sum of the signal and background terms:

$$p_i(\Delta E, \theta_C) = \frac{N_{D^0\pi}}{N'} p_i^{D^0\pi} + \frac{N_{D^0K}}{N'} p_i^{D^0K} + \frac{N_{\rho\pi}}{N'} p_i^{\rho\pi} + \frac{N_{\rho(K)}}{N'} p_i^{\rho(K)} + \frac{N_{BB\pi}}{N'} p_i^{BB\pi} + \frac{N_{BBK}}{N'} p_i^{BBK} + \frac{N_{X_1X_2K}}{N'} p_i^{X_1X_2K}, \quad (13)$$

where $N' = N_{D^0\pi} + N_{D^0K} + N_{\rho\pi} + N_{\rho(K)} + N_{BB\pi} + N_{BBK} + N_{X_1X_2K}$. Each addendum on the right-hand side of equation (13) is the product of two different terms. The ratio $N_J/N'$ ($J = D^0\pi, D^0K, ...$) represents the probability to choose a candidate of type $J$ after the selection criteria
are applied; the term $P^J_i$ is the probability to measure the particular set of physical quantities $\{\Delta E, \theta_C\}_i$ in the $i^{th}$ event, once the candidate of type $J$ has been selected:

$$P^J_i = P^J_{\Delta E,i} P^J_{\theta_C,i}. \quad (14)$$

The $\Delta E$ distribution for $B^- \rightarrow D^0 K^-$ signal is parameterized with a double Gaussian function. The mean and width of the narrow Gaussian are denoted in the following with $\mu(D^0 K)$ and $\sigma(D^0 K)$. The $B^- \rightarrow D^0 \pi^- \Delta E$ probability density function (PDF) would be the same as the $B^- \rightarrow D^0 K^-$ one, if the prompt track had been assigned the pion mass. Since $\Delta E$ is computed by assigning the kaon mass, it is shifted by a quantity

$$\Delta E_{\text{shift}}(\gamma, |\vec{p}|) = \gamma \left( \sqrt{m_K^2 + |\vec{p}|^2} - \sqrt{m_\pi^2 + |\vec{p}|^2} \right)$$

which depends on the momentum $|\vec{p}|$ of the prompt track in the lab frame. $\gamma$ is the Lorentz parameter characterizing the boost of the center of mass frame relative to the lab frame. Therefore we parameterize the $B^- \rightarrow D^0 \pi^- \Delta E$ shape with a double Gaussian whose mean is computed, event-by-event, as $\mu(D^0 \pi) = \mu(D^0 K) + \Delta E_{\text{shift}}(\gamma, |\vec{p}|)$, and whose width is the same as for the $B^- \rightarrow D^0 K^-$ signal component. The fraction of the wide component of the signal shape, its offset from the narrow component and the ratio between its width and the width of the narrow component are fixed using the mode-dependent numbers obtained from the MC simulation. The $\Delta E$ distributions for the continuum background are parameterized with a first order polynomial. The $\Delta E$ distribution for the $B\overline{B}$ background is empirically parametrized with a “Crystal-Ball” lineshape [10]: a Gaussian with an exponential tail at higher $\Delta E$ values. The parameters of the background shapes are determined from MC simulated events and are fixed in the fit.

The particle identification PDF is obtained from MC simulation. Its parametrization is performed by means of a double Gaussian distribution as a function of $\theta_C^{\text{pull}}$, which is the difference between the measured Cherenkov angle and its expected value for a given mass hypothesis, divided by the expected error.

We independently fit five samples corresponding to each of the five $D^0$ decay modes under study. The fit simultaneously evaluates separate likelihood functions for $B^+$ and $B^-$ categories. In the fit the free parameters are $D^0 K$ and $D^0 \pi$ signal yield asymmetries, total number of signal events in $D^0 \pi$ ($N_{D^0 \pi}$), ratio $R_{K/\pi} = N_{D^0 K}/N_{D^0 \pi}$, eight background yields: $N_{q\overline{q}(\pi)}$, $N_{q\overline{q}(K)}$, $N_{B\overline{B}(\pi)}$, $N_{B\overline{B}(K)}$ (one for each charge, i.e. $4 \times 2 = 8$), and two parameters of the $\Delta E$ signal shape (shared between positive and negative samples). The number of peaking background events $N_{X_1 X_2 K}$ is fixed to the values obtained from the study using $D^0$ mass sidebands. We assume no charge asymmetry in the peaking background (a small systematic error due to this assumption is considered later).

5 PHYSICS RESULTS AND SYSTEMATIC STUDIES

The results of the fit are summarized in Table[1] Figure[1] shows the distributions of $\Delta E$ and $\theta_C$ for the $K^- \pi^+$, CP-even and CP-odd modes. The projections of the likelihood fits are overlaid on the plots. On Figure[2] we show the $\Delta E$ projections produced with a kaon identification requirement applied to the prompt track. Hence the $B^- \rightarrow D^0 K^-$ signals become prominently visible on the plots, while $B^- \rightarrow D^0 \pi^-$ contributions significantly decrease.

The double ratios $R_{CP \pm}$ are computed by calculating a weighted mean of the ratios $R_{K/\pi}$ for CP-even and CP-odd modes and dividing it by $R_{K/\pi}$ for the non-CP mode. Correction factors
Table 1: $B^- \rightarrow D^0 K^-$ and $B^- \rightarrow D^0 \pi^-$ signal event yields obtained from the fit to the data. All values are preliminary.

| $D^0$ mode | $N(B \rightarrow D^0 \pi)$ | $N(B \rightarrow D^0 K)$ | $N(B^+ \rightarrow D^0 K^+)$ | $N(B^- \rightarrow D^0 K^-)$ |
|------------|-----------------|-----------------|-----------------|-----------------|
| $K^- \pi^+$ | 24965 ± 169     | 1859 ± 52       | 951 ± 36        | 909 ± 35        |
| $K^- K^+$  | 2412 ± 54       | 189 ± 20        | 61 ± 11         | 128 ± 16        |
| $\pi^- \pi^+$ | 876 ± 38       | 73 ± 15         | 24 ± 9          | 49 ± 12         |
| $K_S^0 \pi^0$ | 2967 ± 69     | 184 ± 25        | 107 ± 19        | 77 ± 16         |
| $K_S^0 \omega$ | 1023 ± 44     | 59 ± 14         | 36 ± 12         | 23 ± 9          |

(ranging from 1.006 to 1.027 depending on the $D^0$ mode) that account for small differences in the efficiency between the $B^- \rightarrow D^0 K^-$ and $B^- \rightarrow D^0 \pi^-$ selections are taken into account. An additional factor is applied to the results in the $D^0 \rightarrow K^0_s \omega$ mode to correct for a dilution due to the S-wave non-resonant contribution. These corrections were estimated using a fit to the $\omega$ helicity angle in the selected data events and found to be 1.10 ± 0.11 for $A_{CP}^{K^0_s \omega}$ and 0.98 ± 0.02 for $R_{CP}^{K^0_s \omega}$. The uncertainties in the correction factors are included in the systematic errors (±0.006 and ±0.008 for $R_{CP}$ and $A_{CP}$, respectively). The results for each mode separately and combined by $CP$-even and $CP$-odd categories are listed in Table 2.

Table 2: Measured double branching fraction ratios $R_{CP \pm}$ and $CP$ asymmetries $A_{CP \pm}$ for different $D^0$ decay modes. In the combined results, the first error is statistical, the second is systematic. For individual modes, only statistical errors are shown. All values are preliminary.

| $D^0$ decay mode | $R_{CP}$          | $A_{CP}$          |
|------------------|------------------|------------------|
| $K^- K^+$        | 1.05 ± 0.11      | 0.36 ± 0.10      |
| $\pi^- \pi^+$    | 1.13 ± 0.22      | 0.33 ± 0.20      |
| $CP$-even combined | 1.07 ± 0.10 ± 0.04 | 0.35 ± 0.09 ± 0.05 |
| $K_S^0 \pi^0$    | 0.84 ± 0.11      | -0.16 ± 0.13     |
| $K_S^0 \omega$   | 0.75 ± 0.18      | -0.24 ± 0.26     |
| $CP$-odd combined | 0.81 ± 0.10 ± 0.05 | -0.19 ± 0.12 ± 0.02 |

Systematic uncertainties in the double ratios $R_{CP \pm}$ and in the $CP$ asymmetries $A_{CP \pm}$ arise primarily from uncertainties in signal yields due to the estimate of the peaking backgrounds (±0.03 for $R_{CP \pm}$ and ±0.05 for $R_{CP \mp}$) and from the imperfect knowledge of the PDF shapes. The parameters of the PDFs that are fixed in the nominal fit are varied by ±1σ and the observed difference in the parameters $R_{K/\pi}$, signal yield asymmetries and $N_{D^0 K}$ is taken as a systematic uncertainty (±0.003 for $A_{CP \pm}$, ±0.002 for $A_{CP \mp}$, ±0.010 for $R_{CP \pm}$ and ±0.007 for $R_{CP \mp}$). Possible $CP$ asymmetries up to 20% in the peaking backgrounds are also taken into account (±0.04 for $A_{CP \pm}$). An estimate of the intrinsic detector charge bias due to acceptance, tracking, and particle identification efficiency has been obtained from the weighted average of the measured asymmetries in the processes $B^- \rightarrow D^0 \rightarrow K^- \pi^+ h^-$ and $B^- \rightarrow D^0_{CP \pm} \pi^-$, where $CP$ violation is expected to be negligible. This asymmetry estimate (±0.02) has been added in quadrature to the total systematic uncertainties on
the \( CP \) asymmetries \( A_{CP\pm} \) (this is a correlated part of the systematics for \( A_{CP+} \) and \( A_{CP-} \)). The accuracy in the equivalence between \( R_\pm \) and \( R_{CP\pm} \) is evaluated to be \( \pm 0.03 \) for \( R_{CP+} \) and \( \pm 0.02 \) for \( R_{CP-} \) (these uncertainties are correlated).

### 6 SUMMARY

In conclusion, we reconstruct \( B^- \rightarrow D^0K^- \) decays with \( D^0 \) mesons decaying to non-\( CP \) \( K^+\pi^- \), \( CP \)-even \( K^+K^- \) and \( \pi^+\pi^- \) and \( CP \)-odd \( K^0\pi^0 \) and \( K^0\omega \) eigenstates. We have measured the \( CP \) asymmetries \( A_{CP+} = 0.35 \pm 0.09 \) (stat) \( \pm 0.05 \) (syst) and \( A_{CP-} = -0.19 \pm 0.12 \) (stat) \( \pm 0.02 \) (syst). Our result for \( A_{CP+} \) is 3.4\( \sigma \) away from 0. This constitutes the first evidence for direct \( CP \) violation in \( B^- \rightarrow D^0K^- \) decays. The double ratios of branching fractions are measured to be \( R_{CP+} = 1.07 \pm 0.10 \) (stat) \( \pm 0.04 \) (syst) and \( R_{CP-} = 0.81 \pm 0.10 \) (stat) \( \pm 0.05 \) (syst).

The corresponding values of \( x_\pm \) and \( \tau_B^2 \) are extracted using equations 5 and 6, separately propagating correlated and uncorrelated errors on \( A_{CP+} \) and \( R_{CP\pm} \). We obtain \( x_+ = -0.065 \pm 0.047 \) (stat) \( \pm 0.020 \) (syst), \( x_- = 0.199 \pm 0.052 \) (stat) \( \pm 0.020 \) (syst), \( \tau_B^2 = -0.060 \pm 0.070 \) (stat) \( \pm 0.039 \) (syst).

The results obtained in this analysis are statistically in agreement with the previous measurements as demonstrated in Table 3. All results presented in this document are preliminary.

Table 3: Comparison of the preliminary results of this analysis to the previous measurements by \( BaBar \) [3] and Belle [4]. The decay mode \( D^0 \rightarrow K^0_S\phi \), used in the previous analyses, is not included in the present measurement.

| Parameter | Present analysis | \( BaBar \) (2006) [3] | Belle (2006) [4] |
|-----------|----------------|--------------------------|-----------------|
| \( R_{CP-} \) | \( 0.81 \pm 0.10 \pm 0.05 \) | \( 0.86 \pm 0.10 \pm 0.05 \) | \( 1.17 \pm 0.14 \pm 0.14 \) |
| \( R_{CP+} \) | \( 1.07 \pm 0.10 \pm 0.04 \) | \( 0.90 \pm 0.12 \pm 0.04 \) | \( 1.13 \pm 0.16 \pm 0.08 \) |
| \( A_{CP-} \) | \( -0.19 \pm 0.12 \pm 0.02 \) | \( -0.06 \pm 0.13 \pm 0.04 \) | \( -0.12 \pm 0.14 \pm 0.05 \) |
| \( A_{CP+} \) | \( 0.35 \pm 0.09 \pm 0.05 \) | \( 0.35 \pm 0.13 \pm 0.04 \) | \( 0.06 \pm 0.14 \pm 0.05 \) |

### 7 ACKNOWLEDGMENTS

We are grateful for the extraordinary contributions of our PEP-II colleagues in achieving the excellent luminosity and machine conditions that have made this work possible. The success of this project also relies critically on the expertise and dedication of the computing organizations that support \( BaBar \). The collaborating institutions wish to thank SLAC for its support and the kind hospitality extended to them. This work is supported by the US Department of Energy and National Science Foundation, the Natural Sciences and Engineering Research Council (Canada), Institute of High Energy Physics (China), the Commissariat à l‘Energie Atomique and Institut National de Physique Nucléaire et de Physique des Particules (France), the Bundesministerium für Bildung und Forschung and Deutsche Forschungsgemeinschaft (Germany), the Istituto Nazionale di Fisica Nucleare (Italy), the Foundation for Fundamental Research on Matter (The Netherlands), the Research Council of Norway, the Ministry of Science and Technology of the Russian Federation, and the Particle Physics and Astronomy Research Council (United Kingdom). Individuals have
received support from CONACyT (Mexico), the A. P. Sloan Foundation, the Research Corporation, and the Alexander von Humboldt Foundation.

References

[1] Charge conjugation is implied here and throughout the text unless explicitly stated otherwise.

[2] M. Gronau and D. Wyler, Phys. Lett. B265, 172 (1991); M. Gronau and D. London, Phys. Lett. B253 483 (1991); D. Atwood, I. Dunietz and A. Soni, Phys. Rev. Lett. 78, 3257 (1997); A. Giri, Y. Grossman, A. Soffer, J. Zupan Phys. Rev. D68 054018 (2003).

[3] BABAR Collaboration, B. Aubert et al., Phys. Rev. D73, 051105(R) (2006).

[4] Belle Collaboration, K. Abe et al, Phys. Rev. D 73, 051106(R) (2006)

[5] BABAR Collaboration, B. Aubert et al., Phys. Rev. Lett. 95, 121802 (2005).

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

[7] GEANT4 Collaboration, S. Agostinelli et al., Nucl. Instr. and Methods A506 250 (2003).

[8] Particle Data Group, W.-M. Yao et al., Journal of Physics G, 1 (2006).

[9] G.C. Fox and S. Wolfram, Phys. Rev. Lett. 41 1581 (1978).

[10] M.J. Oreglia, Ph.D Thesis, Stanford University [Report No. SLAC-236, 1980], Appendix D; J.E. Gaiser, Ph.D Thesis, Stanford University [Report No. SLAC-255, 1982], Appendix F; T. Skwarnicki, Ph.D Thesis, Institute for Nuclear Physics, Krakow, [Report No. DESY F31-86-02, 1986], Appendix E.
Figure 1: $\Delta E$ (left) and $\theta_C$ (right) distributions of selected $B^- \rightarrow D^0 h^-$ events. The blue line represents the projection of the likelihood in the plotted variable. The red line represents the $B^- \rightarrow D^0 K^-$ component. In the left hand plots, the green and light blue lines indicate $B\bar{B}$ and continuum backgrounds, respectively. The brown line refers to the peaking background (when present).
Figure 2: $\Delta E$ distributions of $B^- \to D^0 K^-$ signal enhanced $B^- \to D^0 h^-$ events. The blue line represents the projection of the likelihood, the red line indicates the $B^- \to D^0 K^-$ component, the green line shows the total background contribution. The remaining $B^- \to D^0 \pi^-$ signal is visible as a small shoulder on the right hand side of the $B^- \to D^0 K^-$ signal peak.