Measurement of Branching Fractions and Resonance Contributions for $B^0 \rightarrow D^0 K^+ \pi^-$ and Search for $B^0 \rightarrow D^0 K^+ \pi^- \pi^0$ Decays


(The BABAR Collaboration)

1Laboratoire de Physique des Particules, F-74941 Annecy-le-Vieux, France
2IFAE, Institut d’Estudis Àtomiques de Barcelona, E-08193 Bellaterra, Barcelona, Spain
3Università di Bari, Dipartimento di Fisica e INFN, I-70126 Bari, Italy
4Institute of High Energy Physics, Beijing 100039, China
5University of Bergen, Institute of Physics, N-5007 Bergen, Norway
6Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA
7University of Birmingham, Birmingham, B15 2TT, United Kingdom
8Ruhr Universit¨at Bochum, Institut f¨ur Experimentalphysik 1, D-44780 Bochum, Germany
9University of Bristol, Bristol BS8 1TL, United Kingdom
10University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1
11Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom
12Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia
13University of California at Irvine, Irvine, California 92697, USA
14University of California at Los Angeles, Los Angeles, California 90024, USA
15University of California at Riverside, Riverside, California 92521, USA
16University of California at San Diego, La Jolla, California 92093, USA
17University of California at Santa Barbara, Santa Barbara, California 93106, USA
18Institute for Particle Physics, University of California at Santa Cruz, Santa Cruz, California 95064, USA
Using $226 \times 10^6 \ Y(4S) \to BB$ events collected with the BABAR detector at the PEP-II $e^+e^-$ storage ring at the Stanford Linear Accelerator Center, we measure the branching fraction for $B^0 \to \bar{D}^0 K^+\pi^-$, excluding $B^0 \to D^{*-}K^+$, to be $B(B^0 \to \bar{D}^0 K^+\pi^-) = (88 \pm 15 \pm 9) \times 10^{-6}$. We observe $B^0 \to \bar{D}^0 K^*(892)^0$ and $B^0 \to \bar{D}^0_s(2460)^- K^+$ contributions. The ratio of branching fractions $B(B^0 \to D^{*-}K^+)/B(B^0 \to D^+\pi^-) = (7.76 \pm 0.34 \pm 0.29)\%$ is measured separately. The branching fraction for the suppressed mode $B^0 \to \bar{D}^0 K^+\pi^-$ is $B(B^0 \to \bar{D}^0 K^+\pi^-) < 19 \times 10^{-6}$ at the 90% confidence level.

The $D^0$ candidate is reconstructed through $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$ channels, where the measured invariant mass is required to be within 20, 35, and 20 MeV/$c^2$, respectively, of the nominal $D^0$ mass [12], corresponding to 3.0, 2.5, and 3.0 $\sigma$. A vertex fit is performed with the mass constrained to the nominal value. The $\pi^0$ candidate is formed from two photon candidates with invariant mass between 115 and 150 MeV/$c^2$.

For the measurement of the ratio $r$, the $D^0$ is combined with a low momentum $\pi$ to form a $D^*$ candidate, with its vertex constrained to the interaction point (beam spot). Candidates with mass difference $m_{D^*\pi} - m_{D^0\pi}$ between 144 and 147 MeV/$c^2$ are retained. A charged track, assumed to have the pion mass, is combined with the $D^*$ to form a $B^0$ candidate. The $\chi^2$ probabilities for both the $D^*$ and $B^0$ vertex fits are required to be greater than 0.1%. To reject jetlike continuum background, the normalized Fox-Wolfram second moment $R_2$ [13], computed with charged tracks and neutral clusters, is required to be less than 0.5, and $|\cos \theta_T| \leq 0.85$, where $\theta_T$ is the thrust angle between the $B^0$ candidate and the rest of the event in the $e^+e^-$ center-of-mass (c.m.) frame.

For $B^0 \to \bar{D}^0 K^+\pi^-$ and $\bar{D}^0 K^+\pi^+$ measurements, the $B^0$ candidate is formed by combining a $D^0$ candidate with oppositely charged pion and kaon candidates. We select candidates outside the $D^{*-}K^+$ region (142.5 $< m_{D^*\pi} < 148.5$ MeV/$c^2$, a 2$\sigma$ window). The measured $D^0$ invariant mass must be within 12, 28, and 8.5 MeV/$c^2$ of the nominal $D^0$ mass for $K^+\pi^0$, $K^+\pi^0\pi^0$, and $K^+\pi^0\pi^0\pi^0$ modes, respectively. Candidates are rejected if the $D^0 \to \bar{K}^0\pi^0\pi^0$ decay probability, computed with the Dalitz parameters measured in Ref. [14], is less than 6% of the maximum value. The $\chi^2$ probability of the $D^0$ ($B^0$) vertex fit is required to be greater than 0.5% (2%). All charged tracks are required to have at least 12 hits in the drift chamber and transverse momentum greater than 100 MeV/$c$. Both kaon candidates are required to be consistent with the kaon hypothesis. Prompt pion candidates consistent with the kaon hypothesis are rejected.

To further reduce the continuum background, $|\cos \theta_B|$ must be less than 0.9, where $\theta_B^p$ is the polar angle of the $B^0$ candidate in the c.m. frame. A Fisher discriminant $\mathcal{F}$ is formed based on $R_2$, $\cos \theta_T$, $\theta_B^p$, and two moments $L_0$ and $L_2$, where $L_i = \sum_j P_j^i |\cos \theta_B^p|^j$, summed over the remaining
particles $j$ in the event, where $\theta_j^*$ and $p_j^*$ are the angle with respect to the $B^0$ thrust and the momentum in the c.m. frame. Different cuts on $F$ are applied for each mode to optimize the signal significance based on simulated event samples. Candidates used in the subsequent fits have beam-energy substituted mass $m_{ES} = \sqrt{\left(\sqrt{s}/2\right)^2 - (p^*)^2} > 5.2$ GeV/c$^2$ and energy difference $|\Delta E| = |E^* - \sqrt{s}/2| < 150$ MeV, where $E^*$ and $p^*$ are the energy and momentum of the $B^0$ candidate and $\sqrt{s}$ is the total energy in the c.m. frame.

We study five samples separately: (a) $B^0 \rightarrow \bar{D}^0 K^+ \pi^-$ excluding the $D^+ K^+$ contribution, (b) $B^0 \rightarrow D^0 K^+ \pi^-$, (c) $B^0 \rightarrow \bar{D}^0 K^*(892)^0$, (d) $B^0 \rightarrow D_s^+(2460)^0 K^+$, and (e) $B^0 \rightarrow D^+ h^+$, where $h^+$ is a pion or kaon. Samples (c) and (d) are subsets of (a), where the resonances are selected within 1.5 times their full widths [12].

For samples (a)–(d), a two-dimensional ($m_{ES}, \Delta E$) unbinned-maximum-likelihood fit is used to determine the signal yields. The signal component is the product of a Gaussian in $m_{ES}$ centered at the $B^0$ mass and a Crystal Ball line shape [15] in $\Delta E$ centered near zero. The combinatorial background component is modeled with an Argus threshold function [16] in $m_{ES}$ and a second-order polynomial in $\Delta E$. Two background components peak in $m_{ES}$: peaking background $A$ describes the $B^0 \rightarrow D^+ \pi^- \pi^+$ contribution, which also peaks in $\Delta E$ but the peak is shifted by about +50 MeV because the pion is misidentified as a kaon; peaking background $B$ uses a second-order polynomial in $\Delta E$ to accommodate events such as $D^+ K^+ \pi^-$, and $D^+ \rho$, where one or more pions or photons are missed in the reconstruction and/or a pion is misidentified as a kaon. The probability density function (PDF) is the sum of the signal and three background components. A large $B^0 \rightarrow D^+ \pi^+$ data control sample is used to determine the signal shape in both $\Delta E$ and $m_{ES}$, and the peaking background $A$ in $\Delta E$, where we assign the kaon mass to the pion candidate. We use the same parameters for signal and peaking backgrounds in $m_{ES}$ since they are consistent in simulation. The $\Delta E$ distributions and yields for the four components in the signal region are shown in Fig. 1 and Table I, respectively.

The signal yield for $B^0 \rightarrow \bar{D}^0 K^+ \pi^-$ is corrected for variations in signal efficiency across the $DK\pi$ Dalitz plot. Each event $k$ with variables $\tilde{q}_k = (m_{ES,k}, \Delta E_k)$ is assigned a signal weight $[17]$

$$w_{sig}(\tilde{q}_k) = \frac{\sum_{j=1}^{4} V_{sig,j}P_j(\tilde{q}_k)}{\sum_{j=1}^{4} N_jP_j(\tilde{q}_k)},$$

calculated from the four PDF components $P_j$, their yields $N_j$ from the fit, and the covariance matrix elements $V_{sig,j}$ between $N_{sig}$ and $N_j$. The efficiency-corrected signal yield is then $\sum_k w_{sig}(\tilde{q}_k)/\epsilon_k$, where the efficiency $\epsilon_k$ is estimated from the simulated events in the vicinity of each data point in the Dalitz plot.

Figure 2 shows the signal weight distribution as a function of $m_{K^+\pi^-}$ and $m_{D_s^+(2460)^0}$. The peaks near $m_{K^+\pi^-}$ and $m_{D_s^+(2460)^0}$ are clearly visible. We use the ($m_{ES}, \Delta E$) fit

### Table I. The yields of signal, combinatorial (comb.), and peaking (peak A, peak B) background PDFs of the samples (a)–(d) described in the text; values and errors are rescaled to represent the yields in the signal region ($m_{ES} > 5.27$ GeV/c$^2$, $|\Delta E| < 40$ MeV). The bottom row shows the branching fractions with statistical errors.

<table>
<thead>
<tr>
<th>$D^0$ mode</th>
<th>$B^{0} \rightarrow D^{0}K^{+}\pi^{-}$</th>
<th>$B^{0} \rightarrow D^{0}K^{+}\pi^{-}$</th>
<th>$B^{0} \rightarrow D^{0}K^{*}(892)^{0}$</th>
<th>$B^{0} \rightarrow D_{s}^{+}(2460)^{0}K^{+}$</th>
<th>$B^{0} \rightarrow D_{s}^{+}(2460)^{0}K^{+}$</th>
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<tr>
<td>Signal</td>
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<td>58 ± 20</td>
<td>69 ± 19</td>
<td>17 ± 13</td>
<td>34 ± 24</td>
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<td></td>
<td>8 ± 22</td>
<td>35 ± 7</td>
<td>21 ± 7</td>
<td>31 ± 7</td>
<td>15 ± 6</td>
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<tr>
<td></td>
<td>15 ± 6</td>
<td>15 ± 6</td>
<td>16 ± 5</td>
<td>16 ± 5</td>
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<tr>
<td>Comb.</td>
<td>229 ± 4</td>
<td>500 ± 5</td>
<td>528 ± 5</td>
<td>608 ± 5</td>
<td>918 ± 6</td>
</tr>
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<td></td>
<td>989 ± 6</td>
<td>17 ± 1</td>
<td>29 ± 1</td>
<td>30 ± 1</td>
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<td>16 ± 1</td>
<td>16 ± 1</td>
<td>22 ± 1</td>
<td></td>
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<tr>
<td>Peak A</td>
<td>5 ± 6</td>
<td>0 ± 1</td>
<td>0 ± 2</td>
<td>0 ± 0</td>
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</tr>
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<tr>
<td></td>
<td>2 ± 2</td>
<td>5 ± 2</td>
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<tr>
<td>Peak B</td>
<td>45 ± 9</td>
<td>76 ± 12</td>
<td>42 ± 10</td>
<td>50 ± 11</td>
<td>54 ± 14</td>
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<td></td>
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<tr>
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<td>7 ± 3</td>
<td>7 ± 3</td>
<td>0 ± 1</td>
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<tr>
<td>$B(10^{-6})$</td>
<td>88 ± 15</td>
<td>−4 ± 12</td>
<td>38 ± 6</td>
<td>18.3 ± 4.0</td>
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FIG. 1 (color online). $\Delta E$ distributions and PDF projections with $m_{ES} > 5.27$ GeV/c$^2$ for (a) $B^0 \rightarrow \bar{D}^0 K^+ \pi^-$ excluding $D^+ K^+$ candidates, (b) $B^0 \rightarrow D^0 K^+ \pi^-$, (c) $B^0 \rightarrow \bar{D}^0 K^*(892)^0$, and (d) $B^0 \rightarrow D_s^+(2460)^0 K^+$, for the three $D^0$ modes combined. Circles with error bars are data points. Four curves from top to bottom represent the total PDF (solid line), total background (dashed line), combinatorial background plus peaking background $B$ described in the text (dot-dashed line), and combinatorial background only (dotted line). In (a)–(c), the middle two curves overlap because the peaking background $A$ is negligible.
results and signal efficiencies estimated from simulated $B^0 \rightarrow D^{0} K^{*}(892)^0$ and $B^0 \rightarrow D_s^{*}(2460)^- K^+$ samples to compute corresponding branching fractions. For the $B^0 \rightarrow D^0 K^+ \pi^-$ mode, we assume a flat distribution on the Dalitz plot when determining the signal efficiency.

For modes in which we do not observe a significant signal, the 90% confidence level (C.L.) branching fraction upper limit (UL) is determined by integrating the signal, the 90% confidence level (C.L.) branching fraction upper limit (UL) is determined by integrating the signal efficiency.

To measure $r$, we select events with $m_{ES} > 5.27$ GeV/$c^2$ from sample (c). A two-dimensional PDF of $\Delta E$ and $\theta_C$ (the reconstructed Cherenkov-light angle of the prompt track) is used to separate $D^0 K$ from $D^* \pi$ decays. Tracks with an estimated $\theta_C$ uncertainty $\sigma_C > 4 \text{ mrad}$ or $n_{y,s}/\sqrt{n_{y,b}} < 3$ are removed, where $n_{y,s}$ and $n_{y,b}$ are the numbers of signal and background photons determined from a likelihood fit to the ring of Cherenkov photons associated with the track [11]. Finally, events are rejected if $\theta_C$ is smaller than the predicted Cherenkov angle for kaons by more than $4 \sigma_C$, in order to remove particles heavier than kaon.

The $\Delta E$ signal peak PDF is a Crystal Ball line shape and the background is a linear function plus a Gaussian peaked near $-150$ MeV to accommodate background events such as $D^0 \rho$ and $D^{*\pi}$ where a soft $\pi$ is missed in the reconstruction. The distribution of $(\theta_C - \theta_C^X)/\sigma_C$ is modeled by Gaussian functions. For the pion component, we use three Gaussian functions centered near zero. For the kaon component, a single Gaussian function centered near $(\theta_K - \theta_{K}^X)/\sigma_C$ is sufficient, where $\theta_K^X$ and $\theta_{K}^X$ are the expected Cherenkov angle for kaon and pion, respectively, based on the measured momentum. Most of the parameters are obtained from a fit to the pion or kaon tracks in a large $c\bar{c} \rightarrow D^0 X \rightarrow D^0 \pi X$, $D^0 \rightarrow K^- \pi^+$ data control sample, except the total width of the distribution, which is free in the final fit to accommodate a small difference in width due to differences in momentum spectra between signal and control samples.

Figure 3 shows the $\Delta E$ and $(\theta_C - \theta_C^X)/\sigma_C$ distributions and PDF projections for $B^0 \rightarrow D^{-} h^+ (h = \pi$ or $K)$ candidates. We find 13,400 signal events, of which $f = (6.80 \pm 0.28\%)$ are $D^* \pi$ events, and 4850 background events in the sample. The ratio $r = f/(1-f)$ is corrected by the signal efficiency ratio $r_{e\pi} = e_{\pi} K/e_{\pi} \pi = (94.0 \pm 2.3\%)$ obtained from simulation. This ratio is smaller than unity because $\theta_C$ for kaons is smaller (resulting in fewer Cherenkov photons) and more kaons than pions decay in flight within the tracking volume. The uncertainty on $r_{e\pi}$ includes simulation statistics and systematic uncertainties due to the two aforementioned effects.

For samples (a)–(d), the systematic uncertainties on the signal efficiency are studied with large $\tau$ lepton decay samples (for track reconstruction efficiency) and comparisons between signal simulation and the $B^0 \rightarrow D^{*\pi}$ data control sample. The fractional uncertainty, common to all four samples, on signal efficiency is 5% including the uncertainties on the number of $BB$ events and the $D^0$ branching fractions. For the $B^0 \rightarrow D^0 K^+ \pi^-$ mode, the uncertainty of efficiency variation on the Dalitz plot contributes an additional systematic error of 8%. In addition, we vary the control sample shapes in each fit by one standard error and sum the changes in signal yield in quadrature. The total signal yield variations are 8, 2.0, 3.4, and 2.6 events for $D^0 K^+ \pi^-$, $D^0 K^- \pi^+$, $D^0 K^{*}(892)^0$, and $D_s^{*}(2460)^- K^+$, respectively. For the $B^0 \rightarrow D^0 K^{*}(892)^0$ and $D_s^{*}(2460)^- K^+$ measurements, we consider possible contamination from each other and from the nonresonance contribution. Using the signal yields for $B^0 \rightarrow D^0 K^{*}(892)^0$ and $D_s^{*}(2460)^- K^+$, and the cross-feed efficiencies determined from simulation, we find that six events in each of these two $B^0$ modes could be attributed to the other mode and to nonresonance contributions. This contributes a 6% uncertainty for $B^0 \rightarrow D^0 K^{*}(892)^0$ and 11% for $B^0 \rightarrow D_s^{*}(2460)^- K^+$. The uncertainty due to the full width of the $D_s^{*}(2460)^-$ and $K^{*}(892)^0$ resonances is 8% for $B^0 \rightarrow D_s^{*}(2460)^- K^+$ and less than 1% for $B^0 \rightarrow D^0 K^{*}(892)^0$. 

FIG. 2 (color online). The signal weight distribution as a function of $m_{c\bar{c}}$, $m_{D^0}$, and $m_{D^*}$. The shaded histograms include only events with (a) $|m_{D^0} - 2460 \text{ MeV}/c^2| < 75 \text{ MeV}/c^2$, and (b) $|m_{K^+} - 896 \text{ MeV}/c^2| < 150 \text{ MeV}/c^2$. 

FIG. 3 (color online). (a) $\Delta E$ and (b) Cherenkov angle $(\theta_C - \theta_C^X)/\sigma_C$ distributions for $D^*- h^+$ candidates and PDF projections. Circles with error bars are data points. Shaded distribution is the combinatorial background, the dotted curve adds the $D^* \pi$ contribution, and the solid curve is the full PDF. The dashed curve represents the $D^0 K$ contribution only. $\Delta E$ for $D^* \pi$ is centered near zero, while for $D^0 K$ it is shifted to lower values because the prompt track is assumed to be a pion.
The largest systematic uncertainties cancel in the branching ratio measurement [sample (e)]. The remaining systematic errors are from PDF shapes, control sample distributions and contaminations (1.9%), residual uncertainties in the signal efficiency ratio (2.4%), and potential fit bias (2.1%). The last item has been evaluated with simulation samples including background.

In conclusion, we have measured the branching fraction for the $B^0 \rightarrow \bar{D}^0 K^+ \pi^-$ decay excluding $D^+ K^-$,
\[
\mathcal{B}(B^0 \rightarrow \bar{D}^0 K^+ \pi^-) = (88 \pm 15 \pm 9) \times 10^{-6},
\]
as well as its two significant resonances,
\[
B(B^0 \rightarrow \bar{D}^0 K^+(892)^0) \times B(K^+(892)^0 \rightarrow K^+ \pi^-) = (38 \pm 6 \pm 4) \times 10^{-6},
\]
and
\[
B(B^0 \rightarrow D_s^-(2460)^- K^-)
\]
\[
\times B(D_s^-(2460)^- \rightarrow \bar{D}^0 \pi^-) = (18.3 \pm 4.0 \pm 3.1) \times 10^{-6}.
\]
The signal significances are 8.7, 8.3, and 5.0 standard deviations, respectively, determined from the change in the likelihood between the best fit and a fit with the signal yield fixed to zero (the first case) or the possible cross feed from other sources (six events for the latter two cases). From a fit excluding the observed resonances, assuming flat distribution on the Dalitz plot, we find $\mathcal{B}(B^0 \rightarrow \bar{D}^0 K^+ \pi^-) = (26 \pm 8 \pm 4) \times 10^{-6}$, whose signal significance is $3.1 \sigma$ and 90% confidence level upper limit is $37 \times 10^{-6}$. We do not observe a significant signal for the CKM-suppressed $B^0 \rightarrow D^+ K^- \pi^+$ mode. The 90% confidence level upper limit is $\mathcal{B}(B^0 \rightarrow D^0 K^+ \pi^-) < 19 \times 10^{-6}$. The event yields in this channel are lower than anticipated [5], indicating that a significantly larger data sample is required to constrain $\gamma$ through this method.

The ratio of branching fractions for $B^0 \rightarrow D^- K^+$ to $B^0 \rightarrow D^+ \pi^+$ is measured to be
\[
r = (7.76 \pm 0.34 \pm 0.29)\%,
\]
a nearly fourfold improvement compared to the previous result [8]. This ratio is consistent with $(f_K/f_\pi)^2 \tan^2 \theta_{\text{Cab}} = 0.072$ [18], expected at tree level if factorization and flavor-SU(3) symmetry hold, where $\theta_{\text{Cab}}$ is the Cabibbo angle and $f_K$ and $f_\pi$ are the decay constants of the kaon and pion, respectively.

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*Also at Dipartimento di Fisica, Università di Perugia, Perugia, Italy.
†Also at Università della Basilicata, Potenza, Italy.
‡Deceased.
[7] The charge conjugate state is implied throughout this Letter.
[15] The Crystal Ball line shape is a modified Gaussian distribution with a transition to a tail function on one side $[\ln(1-x)]^a \exp(-x/\sigma)/((\bar{x}-\alpha)/\sigma + n(\alpha-\bar{x}))$ when $\alpha \lesssim \bar{x} - \alpha \sigma$, where $\bar{x}$ and $\sigma$ are the mean and width of the Gaussian for $x > \bar{x} - \alpha \sigma$.
[18] The value is calculated from $\Gamma(\tau^+ \rightarrow K^- \nu_\tau)/\Gamma(\tau^- \rightarrow \pi^- \nu_\tau)$, corrected for phase space factors.