The following full text is a publisher's version.

For additional information about this publication click this link.
http://repository.ubn.ru.nl/handle/2066/128228

Please be advised that this information was generated on 2019-10-03 and may be subject to change.
Measurement of the $B^- \to D^0 K^-$ branching fraction

MEASUREMENT OF THE $B^- \to D^0 K^{*-}$ BRANCHING FRACTION  

PHYSICAL REVIEW D 73, 111104(R) (2006)

28Laboratori Nazionali di Frascati dell’INFN, I-00044 Frascati, Italy
29Università di Genova, Dipartimento di Fisica and INFN, I-16146 Genova, Italy
30Harvard University, Cambridge, Massachusetts 02138, USA
31Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany
32Imperial College London, London, SW7 2AZ, United Kingdom
33University of Iowa, Iowa City, Iowa 52242, USA
34Iowa State University, Ames, Iowa 50011-3160, USA
35Universität Karlsruhe, Institut für Experimentelle Kernphysik, D-76021 Karlsruhe, Germany
36Laboratoire de l’Accélérateur Linéaire, IN2P3-CNRS et Université Paris-Sud 11, Centre Scientifique d’Orsay, B.P. 34, F-91898 ORSAY Cedex, France
37Lawrence Livermore National Laboratory, Livermore, California 94550, USA
38University of Liverpool, Liverpool L69 7ZE, United Kingdom
39Queen Mary, University of London, E1 4NS, United Kingdom
40University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
41University of Louisville, Louisville, Kentucky 40292, USA
42University of Manchester, Manchester M13 9PL, United Kingdom
43University of Maryland, College Park, Maryland 20742, USA
44University of Massachusetts, Amherst, Massachusetts 01003, USA
45Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA
46McGill University, Montréal, Québec, Canada H3A 2T8
47Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy
48University of Mississippi, University, Mississippi 38677, USA
49Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7
50Mount Holyoke College, South Hadley, Massachusetts 01075, USA
51Università di Napoli Federico II, Dipartimento di Scienze Fisiche e INFN, I-80126, Napoli, Italy
52NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
53University of Notre Dame, Notre Dame, Indiana 46556, USA
54Ohio State University, Columbus, Ohio 43210, USA
55University of Oregon, Eugene, Oregon 97403, USA
56Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy
57Universités Paris VI et VII, Laboratoire de Physique Nucléaire et de Hautes Energies, F-75252 Paris, France
58University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
59Università di Perugia, Dipartimento di Fisica and INFN, I-06100 Perugia, Italy
60Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy
61Prairie View A&M University, Prairie View, Texas 77446, USA
62Princeton University, Princeton, New Jersey 08544, USA
63Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy
64Universität Rostock, D-18051 Rostock, Germany
65Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom
66DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France
67University of South Carolina, Columbia, South Carolina 29208, USA
68Stanford Linear Accelerator Center, Stanford, California 94309, USA
69Stanford University, Stanford, California 94305-4060, USA
70State University of New York, Albany, New York 12222, USA
71University of Tennessee, Knoxville, Tennessee 37996, USA
72University of Texas at Austin, Austin, Texas 78712, USA
73University of Texas at Dallas, Richardson, Texas 75083, USA
74Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy
75Università di Trieste, Dipartimento di Fisica e INFN, I-34127 Trieste, Italy
76IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain
77Vanderbilt University, Nashville, Tennessee 37235, USA
78University of Victoria, Victoria, British Columbia, Canada V8W 3P6
79Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom
80University of Wisconsin, Madison, Wisconsin 53706, USA

*Also with the Johns Hopkins University, Baltimore, MD 21218, USA
†Also at Laboratoire de Physique Corpusculaire, Clermont-Ferrand, France
‡Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy
§Also with Università della Basilicata, Potenza, Italy
‖Deceased
The decays $B^- \rightarrow D^0 K^{*-} [1]$ are of interest because of their relevance to the Cabibbo-Kobayashi-Maskawa (CKM) model [2] of quark-flavor mixing. Interference effects in specific $D^0$ final states offer a means of observing direct CP violation governed by the angle $\gamma = \arg(-V_{ub}V_{ub}^*/V_{cd}V_{cb}^*)$ [3], where $V$ is the CKM matrix. One way to access $\gamma$ is to measure $R_{CP \pm}$ [4]:

$$R_{CP \pm} = \frac{2}{\Gamma(B^- \rightarrow D^0_{CP \pm} K^{*-}) + \Gamma(B^- \rightarrow D^0_{CP +} K^{+})} \left[ \Gamma(B^- \rightarrow D^0_{CP -} K^{*+}) + \Gamma(B^- \rightarrow D^0_{CP +} K^{*+}) \right].$$

Neglecting $D^0 - \bar{D}^0$ mixing $R_{CP \pm}$ can be expressed in terms of a CP-conserving strong phase difference ($\delta$), the ratio of the magnitude of suppressed and favored amplitudes ($r_B$), and $\gamma$: $R_{CP \pm} = 1 \pm 2r_B \cos \delta \cos \gamma + r_B^2$. Thus a precise determination of the $B^- \rightarrow D^0 K^{*-}$ branching fraction provides the reference for direct CP violation measurements.

The decay $B^- \rightarrow D^0 K^{*-}$ was first observed by CLEO [5], and later by BABAR [6]. In this paper we present a new measurement of the branching fraction $\mathcal{B}(B^- \rightarrow D^0 K^{*-})$ obtained with 2.7 times more data than used for the previous BABAR measurement.

This analysis uses data collected with the BABAR detector at the PEP-II $e^+ e^-$ storage ring. The data corresponds to an integrated luminosity of 211 fb$^{-1}$ at the $\Upsilon(4S)$ peak $(232 \times 10^6 \text{ } BB \text{ } \text{pairs})$ and 16 fb$^{-1}$ at center-of-mass energy 40 MeV below the resonance.

The BABAR detector is described in detail in [7]. We give here a brief description of the components relevant to this analysis. Charged-particle trajectories are measured by a five-layer double-sided silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) inside a 1.5 T solenoid. Charged-particle identification is achieved by combining measurements of the light detected in a ring-imaging Cherenkov device (DIRC) with measurements of the ionization energy loss ($dE/dx$) measured in the DCH and SVT. Photons are detected in a CsI(Tl) electromagnetic calorimeter (EMC) inside the coil. We use GEANT4 [8] based software to simulate the detector response and account for the varying beam and environmental conditions.

To reconstruct $B^- \rightarrow D^0 K^{*-}$ decays we select $K^{*-}$ candidates in the $K^{*-} \rightarrow K^0_S \pi^-$ mode and $D^0$ candidates in three decay channels: $D^0 \rightarrow K^- \pi^+$, $K^- \pi^+ \pi^0$, and $K^- \pi^+ \pi^- \pi^-$. Our event selection follows closely the one reported in [9]. $K^0_S$ candidates are formed from oppositely charged tracks assumed to be pions with a reconstructed invariant mass within 13 MeV/$c^2$ (4 standard deviations) of the known $K^0_S$ mass, $m_{K^0_S}$ [10]. The $K^0_S$ candidates are fitted so that their invariant mass equals $m_{K^0_S}$ (mass constraint). We further require their flight direction and distance to be consistent with a $K^0_S$ coming from the interaction point. The $K^0_S$ candidate’s flight path and momentum vectors must make an acute angle and the flight length in the plane transverse to the beam must be at least 3 times larger than its uncertainty. $K^*$ candidates are formed from a $K^0_S$ and a charged particle, which are required to originate from a common vertex. We select $K^{*-}$ candidates which have an invariant mass within 75 MeV/$c^2$ of the known value [10]. Finally, since the $K^{*-}$ in $B^- \rightarrow D^0 K^{*-}$ is polarized, we require the helicity angle $\theta_H$ to satisfy $|\cos \theta_H| \approx 0.35$, where $\theta_H$ is the angle in the $K^{*-}$ rest frame between the daughter pion and the parent $B$ momentum. The helicity distribution discriminates well between a $B$ meson decay and an event from the $e^+ e^- \rightarrow q\bar{q}(q \in \{u, d, s, c\})$ continuum, since the former is distributed as $\cos^2 \theta_H$ and the latter is almost flat.

In order to reconstruct the $\pi^0$ of the $D^0 \rightarrow K^- \pi^+ \pi^0$ channel, we combine pairs of photons to form candidates with a total energy greater than 200 MeV and an invariant mass between 125 and 145 MeV/$c^2$. A mass-constrained fit is applied to the selected $\pi^0$ candidates. All $D^0$ candidates are mass- and vertex-constrained. Particle identification is required for the charged kaons. We select $D^0$ candidates with an unconstrained invariant mass, $m_{D^0}$, differing from the world average mass, $m_{D^0}^{PDG}$, by less than 12 MeV/$c^2$ for all channels except $K^- \pi^+ \pi^0$ where we require $-29 < m_{D^0} - m_{D^0}^{PDG} < +24$ MeV/$c^2$. To reduce combinatorial background in this channel, we further select candidates in the regions of the Dalitz plane enhanced by the $K^*$ (892), $K^{*0}(892)$ and $\rho^+$ (770) resonances using amplitudes and phases measured by the CLEO experiment [11]. In order to reduce the background from random two track combinations that have masses consistent with a $D^0$ we also require, for the $D^0 \rightarrow K^- \pi^+$ channel, $|\cos \theta_D| \leq 0.9$, where $\theta_D$ is the angle in the $D^0$ rest frame between the daughter kaon and the parent $B$ momentum. Finally, we perform a geometric fit on the $B$ candidate which constrains the $D^0$, the $K^0_S$, and the charged pion from the $K^{*-}$ to originate from a single vertex.

To suppress continuum background we require $|\cos \theta_B^*| \leq 0.9$, where $\theta_B^*$ is defined as the angle between...
the $B$ candidate momentum in the $Y(4S)$ rest frame and the beam axis. The distribution in $\cos \theta_\rho^i$ is flat for $q\bar{q}$ events, while for $B$ mesons it follows a $\sin^2 \theta_\rho^i$ distribution. We also use global event shape variables to distinguish between $q\bar{q}$ continuum events which have a two-jet topology in the $Y(4S)$ rest frame and $B\bar{B}$ events which are more spherical. We require $|\cos \theta_\rho^i| \approx 0.9$ where $\theta_\rho^i$ is the angle between the thrust axes of the $B$ candidate and that of the rest of the event. We construct a linear (Fisher) discriminant [12] from $\cos \theta_\rho^i$ and the $L_0, L_2$ monomials (see below) describing the energy flow in the rest of the event, as in [13]. In the center-of-mass frame (CM) we define $L_j = \sum_i p_i^j |\cos \theta_\rho^i|$, where $i$ indexes the charged and neutral particles in the event once those from the $B$ candidate are removed, and $\theta_\rho^i$ is the angle of the CM-momentum $p_i^j$ with the thrust axis of the $B$ meson candidate.

We identify $B$ candidates using two nearly independent kinematic variables: the beam-energy-substituted mass $m_{ES} = \sqrt{(s/2 + p_B \cdot p_B)^2/E_0^2 - p_B^2}$ and the energy difference $\Delta E = E_B - \sqrt{s}/2$, where $E$ and $p$ are energy and momentum, the subscripts 0 and $B$ refer to the $e^+e^-$ beam-system and the $B$ candidate in the lab frame, respectively; $s$ is the square of the CM energy, and the asterisk labels the CM frame.

In those events where we find more than one acceptable $B$ candidate (less than 25% of selected events depending on the $D^0$ mode), we choose the one with the smallest $\chi^2$ formed from the differences of the measured and world average $D^0$ and $K^{-}\pi^+$ masses scaled by the mass resolution which includes the experimental resolution and, for the $K^{*-}$, its natural width. Simulations show that no bias is introduced by this choice and the correct candidate is picked at least 80% of the time. According to simulation of signal events, the total reconstruction efficiencies are: 13.3%, 4.6%, and 9.0% for the $D^0 \rightarrow K^{-}\pi^+$, $K^{-}\pi^+\pi^0$, and $K^{-}\pi^+\pi^-\pi^+$ modes, respectively.

To study $B\bar{B}$ backgrounds we look at sideband regions away from the signal region in $\Delta E$ and $m_{D^0}$. The $\Delta E$ distributions are centered around zero for signal with a resolution between 11 and 13 MeV for all three channels. We define a signal region $|\Delta E| < 25$ MeV. We also define a $\Delta E$ sideband in the intervals $-100 \leq \Delta E \leq -60$ MeV and $60 \leq |\Delta E| \leq 200$ MeV. The lower limit ($-100$ MeV) is chosen to avoid selecting a region of high background coming from $B^{-} \rightarrow D^{0}K^{*-}$. In this $\Delta E$ sideband we see no significant evidence of a background peaking near the $B$ mass in $m_{ES}$ which could leak into the signal region. The sideband region in $m_{D^0}$ is defined by requiring that this quantity differs from the $D^0$ mass peak by more than 4 standard deviations. It provides sensitivity to doubly-peaking background sources that mimic signal both in $\Delta E$ and $m_{ES}$. This pollution comes from either charmed or charmless $B$ meson decays that do not contain a true $D^0$.

Since many of the possible contributions to this background are not well known, we attempt to measure its size by including the $m_{D^0}$ sideband in the fit described below.

An unbinned extended maximum likelihood fit to $m_{ES}$ distributions in the range $5.2 \leq m_{ES} \leq 5.3$ GeV/c$^2$ is used to determine the event yields. For signal modes, the $m_{ES}$ distributions are described by a Gaussian function $G$ centered at the $B$ mass with resolution ($\sigma$), averaged over the three $D^{0}$ decay modes, of 2.7 MeV/c$^2$. For each $D^{0}$ decay mode $k (= 1, 2, 3)$ we determine the mean and sigma of the Gaussian $G_k$ by fitting to the data. The combinatorial background in the $m_{ES}$ distribution is modeled with a threshold function $A_k$ [14]. Its shape is governed by one parameter $\xi_k$ that is left free in the fit for each $D^{0}$ decay mode. We fit simultaneously $m_{ES}$ distributions of nine samples: the $K^{-}\pi^+$, the $K^{-}\pi^+\pi^0$ and $K^{-}\pi^+\pi^-\pi^+$ samples for (i) the $\Delta E$ signal region, (ii) the $m_{D^0}$ sideband and (iii) the $\Delta E$ sideband. We fit three probability density functions (PDF) weighted by the unknown event yields. For the $\Delta E$ sideband, we use $A_k$. For the $m_{D^0}$ sideband we use $N_{\text{sig}}^k \cdot A_k + N_{\text{Dp}}^k \cdot G_k$, where $G_k$ accounts for the doubly-peaking $B$ decays. For the signal region PDF we use $N_{\text{sig}}^k \cdot A_k + N_{\text{sig}}^k \cdot G_k + N_N^k$ (middle), and $K^{-}\pi^+\pi^-\pi^+$ (bottom). The dashed curve indicates the contribution from the combinatorial background and the peaking $B$-background which is estimated from a simultaneous fit to the $D^{0}$ sideband (not shown).
The uncertainties are statistical only.

TABLE I. Results from the fit and quantities used to derive the $B^- \to D^0 K^-$ branching fraction. For each channel we give the event yield resulting from the fit, the efficiency, and the branching fraction measurement, in units of $10^{-5}$, derived using Eq. (1). The uncertainties are statistical only.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Yield</th>
<th>Efficiency</th>
<th>$B(B^- \to D^0 K^-)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^- \pi^+$</td>
<td>144 ± 13</td>
<td>13.30%</td>
<td>5.15 ± 0.47</td>
</tr>
<tr>
<td>$K^- \pi^+\pi^0$</td>
<td>185 ± 19</td>
<td>4.60%</td>
<td>5.65 ± 0.57</td>
</tr>
<tr>
<td>$K^- \pi^+\pi^-\pi^0$</td>
<td>195 ± 18</td>
<td>8.99%</td>
<td>5.24 ± 0.49</td>
</tr>
</tbody>
</table>

$m_{D^0}$ sideband have the same final states as the signal so we use the same Gaussian shape for the doubly-peaking $B$ background.

The fit results are shown graphically in Fig. 1 and numerically in Table I. For each channel $k$, a measurement $B_k$ of the branching fraction $B(B^- \to D^0 K^-)$ is derived as follows:

$$B_k = \frac{N(D^0 \to X_k) \cdot f}{N_{B^+} \cdot e_{k} \cdot B_{K^-} \cdot B(D^0 \to X_k)},$$

where $N(D^0 \to X_k)$ is the event yield from the fit, $f$ the fraction of $K^-$'s in the sample (discussed below), $N_{B^+}$ is the number of charged $B$ mesons in the data sample, $e_k$ is the efficiency to reconstruct $B^- \to D^0 K^-$ when $D^0 \to X_k$, $B_{K^-} = B(K^- \to K^0_\pi) \cdot B(K^0_\pi \to \pi^+\pi^-)$ and $B(D^0 \to X_k)$ are the branching fractions of the $K^-$ and the $D^0$. We have assumed equal production of pairs of neutral and charged $B$ mesons in $Y(4S)$ decay.

Systematic effects arise from the difference between the actual detector response for the data and the simulation model for the Monte Carlo. Here the main effects stem from the modeling of the tracking efficiency (1.2–1.3% per track), the $K^0_\pi$ reconstruction efficiency (2% per $K^0_\pi$), the $\pi^0$ reconstruction efficiency for the $K^-\pi^+\pi^0$ channel (3%) and the efficiency and misidentification probabilities from the particle identification (2% per kaon). A study of a high-statistics $B^- \to D^0\pi^-$ control sample shows excellent agreement between the data and Monte Carlo sample except for the distributions of $\Delta E$ and the continuum-suppression Fisher discriminant. For these variables, differences of up to (2.5 ± 1.1)% are measured between the data and Monte Carlo. Suitable corrections to the efficiencies are therefore applied and systematic errors assigned. The $K^+$ helicity angle distributions differ significantly between data and simulation because of the nonresonant background under the $K^+$ peak. We describe below how we subtract this background. For the pure $K^+$ events, we estimate that the residual discrepancy between data and simulation in the helicity to be less than 1.6%. We determine using simulations that the $m_{ES}$ signal PDFs deviate from the single Gaussian shape by less than 0.1%.

Substantial systematic uncertainties come from the measured $D^0$ branching fractions [10] and the number of $B^\pm$ pairs in the sample.

The observed number of signal events must be corrected for the nonresonant $K^0_\pi \pi^-$ pairs under the $K^+$ peak. When we remove the requirement on the $K^+$ helicity distribution (Fig. 2) of the selected events manifests a forward-backward asymmetry that indicates an interference with a $K^0_\pi \pi^-$ background [9,15]. We model the $K^0_\pi \pi^-$ system with a $P$-wave and an $S$-wave component. The $P$-wave mass dependence is described by a relativistic Breit-Wigner while the $S$-wave piece is assumed to be a complex constant. This model is fitted to the data and shown in Fig. 2 along with an estimate of the combinatorial background. Neglecting higher resonances, the number of $K^0_\pi \pi^-$ peaking background events is (4 ± 1)% of the total measured number of signal events. We do not quote a systematic error on the contributions of the neglected partial waves (non-$K^+$ $P$-wave and higher order waves) since their expected rates in the $K\pi$ mass window are far below that of the $S$-wave [15]. In Fig. 3 we see that a
TABLE II. Systematic uncertainties. $X_k$ refers to the $D^0$ decay modes given in the columns. $\mathcal{B}_{K^-}^{J/\psi}$ is the branching fraction of the $K^- \rightarrow J/\psi \pi^-$ decay chain.

<table>
<thead>
<tr>
<th>Source</th>
<th>$K^-\pi^+$</th>
<th>$K^-\pi^+\pi^0$</th>
<th>$K^-\pi^+\pi^-\pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking efficiency</td>
<td>3.8%</td>
<td>3.8%</td>
<td>6.3%</td>
</tr>
<tr>
<td>$\pi^0$ efficiency</td>
<td>-</td>
<td>3.1%</td>
<td>-</td>
</tr>
<tr>
<td>Particle Identification</td>
<td>2.0%</td>
<td>2.0%</td>
<td>2.0%</td>
</tr>
<tr>
<td>$K^0_S$ efficiency</td>
<td>1.6%</td>
<td>1.9%</td>
<td>1.8%</td>
</tr>
<tr>
<td>$\cos\theta_1 (K^-\pi^-)$</td>
<td>1.6%</td>
<td>1.6%</td>
<td>1.6%</td>
</tr>
<tr>
<td>Fisher</td>
<td>1.1%</td>
<td>1.1%</td>
<td>1.1%</td>
</tr>
<tr>
<td>$\Delta E$</td>
<td>1.9%</td>
<td>1.8%</td>
<td>2.0%</td>
</tr>
<tr>
<td>$m_{ES}$ PDF shape</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Number of $B^-$</td>
<td>1.1%</td>
<td>1.1%</td>
<td>1.1%</td>
</tr>
<tr>
<td>Simulation statistics</td>
<td>0.9%</td>
<td>1.4%</td>
<td>1.0%</td>
</tr>
<tr>
<td>$\mathcal{B}_{K^-}^{J/\psi}$</td>
<td>0.2%</td>
<td>0.2%</td>
<td>0.2%</td>
</tr>
<tr>
<td>$\mathcal{B}(D^0 \rightarrow X_k)$ [10]</td>
<td>2.4%</td>
<td>6.2%</td>
<td>4.2%</td>
</tr>
<tr>
<td>$K^0_S \pi^- S$-wave subtraction</td>
<td>1.1%</td>
<td>1.1%</td>
<td>1.1%</td>
</tr>
<tr>
<td>Total systematic error</td>
<td>6.1%</td>
<td>9.0%</td>
<td>8.7%</td>
</tr>
</tbody>
</table>

The first error is statistical and the second is systematic. We have compared the results from this analysis using the same data set as in our previously published analysis [6].

The two analyses use different selection criteria and therefore find different numbers of events. The results from the two analyses are consistent to within a half of a (statistical) standard deviation. We have also calculated the branching fraction for the two data sets obtained since the previous analysis. The measurement in each set is consistent with, although lower than the value obtained in [6]. This result supersedes our previously published result.

In summary, we have measured the branching fraction of the decay $B^- \rightarrow D^0 K^-$ in the $D^0 K^0_S \pi^-$ final state and observed the interference of the $K^-\pi^-$ with a small non-resonant $K^0_S$ background.

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), IHEP (China), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), and PPARC (United Kingdom). Individuals have received support from CONACYT (Mexico), Marie Curie EIF (European Union), the A.P. Sloan Foundation, the Research Corporation, and the Alexander von Humboldt Foundation.