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Measurement of the Branching Fractions of the Decays $B \to \bar{D}^{(*)} D^{(*)} K$

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We present a measurement of the branching fractions of the 22 decay channels of the B^0 and B^+ mesons to $\bar{D}^{(*)} D^{(*)} K$, where the $D^{(*)}$ and $\overline{D}^{(*)}$ mesons are fully reconstructed. Summing the 10 neutral modes and the 12 charged modes, the branching fractions are found to be $\mathscr{B}(B^0 \to \bar{D}^{(*)} D^{(*)} K) = (3.68 \pm 0.10 \pm 0.24)\%$ and $\mathscr{B}(B^+ \to \bar{D}^{(*)} D^{(*)} K) = (4.05 \pm 0.11 \pm 0.28)\%$, where the first uncertainties are statistical and the second systematic. The results are based on 429 fb^{-1} of data containing $471 \times 10^6 B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the BABAR detector at the SLAC National Accelerator Laboratory.

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1. Introduction

We present the measurement of the branching fractions of the 22 decays of charged and neutral B mesons to $\bar{D}^{(*)}D^{(*)}K$ [1]. Here, $D^{(*)}$ is either a D^0, D^{*0}, D^+ or D^{*+}, $\bar{D}^{(*)}$ is the charge conjugate of $D^{(*)}$ and K is either a K^+ or a K^0. The decays of B mesons to $\bar{D}^{(*)}D^{(*)}K$ final states are interesting for many different reasons. For example, in the past, the hadronic decays of the B meson were in theoretical conflict with the B semileptonic branching fraction due to the inconsistency originating from the number of charmed hadrons per B decay [2]. It was realized [3] that an enhancement in the $b \to c\bar{c}s$ transition was needed to resolve the theoretical discrepancy with the B semileptonic branching fraction. Buchalla *et al.* [3] predicted sizeable branching fractions for decays of the form $B \to \bar{D}^{(*)}D^{(*)}K(X)$. Experimental evidence in support of this picture soon appeared in the literature, including a study by *BABAR* using 76 fb^{-1} of data where the experiment reported the observations or the limits on the 22 decays $B \to \bar{D}^{(*)}D^{(*)}K$ [4]. Furthermore, $\bar{D}^{(*)}D^{(*)}K$ events are interesting for a variety of studies. These events can be used to investigate isospin relations and to extract a measurement of the ratio of $\Upsilon(4S) \to B^+B^-$ and $\Upsilon(4S) \to B^0\bar{B}^0$ decays [5]. *BABAR* used the mode $B^0 \to D^{*-}D^{*+}K^0_S$ with 209 fb^{-1} of data to perform a time-dependent CP asymmetry measurement to determine the sign of $\cos 2\beta$ [6]. The Belle collaboration also published a similar analysis [7]. Although these aspects are not addressed here, it is worth recalling that many $D^{(*)}K$ and $\bar{D}^{(*)}D^{(*)}$ resonant processes are at play in the studied decay channels. Using $B \to \bar{D}^{(*)}D^{(*)}K$ final states, *BABAR* and Belle observed and measured the properties of the resonances $D^+_{s1}(2536)$, $D_{sJ}(2700)$, $\psi(3770)$, and $X(3872)$ [8]. The measurement of the branching fractions here used a method that is insensitive to the possible resonant structure in the final states.

The data were recorded by the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- storage ring operating at the SLAC National Accelerator Laboratory. We analyze the complete *BABAR* data sample collected at the $\Upsilon(4S)$ resonance corresponding to an integrated luminosity of 429 fb^{-1}, with $N_{B\bar{B}} = (470.9 \pm 0.1 \pm 2.8) \times 10^6$ $B\bar{B}$ pairs produced, where the first uncertainties are statistical and the second systematic.

2. Event selection

We reconstruct the B^0 and B^+ mesons in the 22 $\bar{D}^{(*)}D^{(*)}K$ modes. A different optimization of the selection criteria is implemented for each of the final states. We use the following decays of the particles in the final states: $K^0_S \to \pi^+\pi^-$, $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^0$, $D^0 \to K^-\pi^+\pi^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D^{*+} \to D^0\pi^+$, $D^{*+} \to D^+\pi^0$, $D^{*0} \to D^0\pi^0$, and $D^{*0} \to D^0\gamma$. The selection of these particles is based on mass cuts, energies of the decay products, vertexing and particle identification to name a few. The B candidates are reconstructed by combining a $\bar{D}^{(*)}$, a $D^{(*)}$ and a K candidate in one of the 22 modes. For modes involving two D^0 mesons, at least one of them is required to decay to $K^-\pi^+$, except for the decay modes $D^{*-}D^{*+}K^0$, $D^{*-}D^{*+}K^+$, and $D^{*-}D^0K^+$, which have lower background and for which all combinations are accepted. For modes containing a D^{*+} meson, we look only to the decay $D^{*+} \to D^0\pi^+$, except for the modes containing $D^{*-}D^{*+}$, where we also reconstruct $D^{*+} \to D^+\pi^0$. To suppress the background, we use topological variables which allows to discriminate against continuum background. Signal events have $m_{\text{ES}} = \sqrt{s/4 - p^{*2}_B}$ compatible with the known B meson mass (where p^*_B is the center-of-mass momentum of the candidate), and a difference between the candidate energy and the beam energy in the center-of-mass, ΔE, compatible with 0. When we obtain several B candidate, we retain the one with the smallest value of $|\Delta E|$.

3. Fits of the data distributions

For each mode, we fit the $m_{\rm ES}$ distribution between 5.22 and 5.30 GeV/c^2 to get the signal yield. According to their physical origin, four categories of events with differently shaped $m_{\rm ES}$ distributions are separately considered: $\bar{D}^{(*)} D^{(*)} K$ signal events, cross-feed events, combinatorial background events, and peaking background events. To determine the yields and the branching fractions, the shape of each of these contributions are determined.

The shape of the signal is determined from fits to the $m_{\rm ES}$ distributions from signal Monte Carlo (MC) samples. A Crystal Ball function (Gaussian modified to include a power-law tail on the low side of the peak) is used to describe the signal

Another important contribution to the $m_{\rm ES}$ distribution is the "cross-feed" contribution. We call "cross-feed" the events from all of the $\bar{D}^{(*)} D^{(*)} K$ modes, except the one we reconstruct, that pass the complete selection, reconstructed in the given mode and with an $m_{\rm ES}$ value above 5.22 GeV/c^2. We observe from the analysis of simulated samples that most of the cross-feed originates from the combination of an unrelated soft π^0 or γ with the D^0 decayed from the D^{*+} to form a wrong D^{*0} candidate. The peaking component of the cross-feed is either described by a Gaussian function (for modes containing no D^{*0} meson) or a Novosibirsk function [1] (for modes involving D^{*0}). The non-peaking part of the cross-feed contribution is described by an Argus function. The values of the parameters of the cross-feed probability density function (PDF) are determined by fitting the signal MC $m_{\rm ES}$ distributions.

The combinatorial background events are described by an Argus function. A part of this background is peaking in the signal region, and is fitted separately. To extract the peaking background, we fit the $m_{\rm ES}$ distributions from generic MC samples $e^+e^- \to q\bar{q}$ ($q = u, d, s, c, b$) satisfying the $\bar{D}^{(*)} D^{(*)} K$ selection and scale the results to the data luminosity. The simulated distribution is fitted with an Argus function describing the non-peaking part and a Gaussian function describing the peaking part. Only the peaking part is used in the fit to the data, the non-peaking part being included in the combinatorial background.

We fit the $m_{\rm ES}$ distribution using the PDFs for the signal, for the cross-feed, for the combinatorial background, and for the peaking background. The free parameters of the fit are the signal yield, the mean of the signal PDF, the combinatorial background yield, and the shape parameter of the background PDF. All other parameters are fixed to the values obtained from the simulation. Figure 1 shows four examples of fits.

Due to the presence of cross-feed events, the fit for the branching fraction for one channel uses as inputs the branching fractions from other channels. Since these branching fractions are in principle not known, we employ an iterative procedure. In practice, we perform the complete analysis for each B mode, using as a starting point the branching fractions measured by *BABAR* in Ref. [4]. We obtain new measurements of the branching fractions that we use in the next step to fix the cross-feed proportion. We repeat this procedure until the differences between the actual branching fractions and the previous ones are smaller than 2% of the statistical uncertainty. Using this criterion, four iterations are needed. We keep the last iteration as the final result.

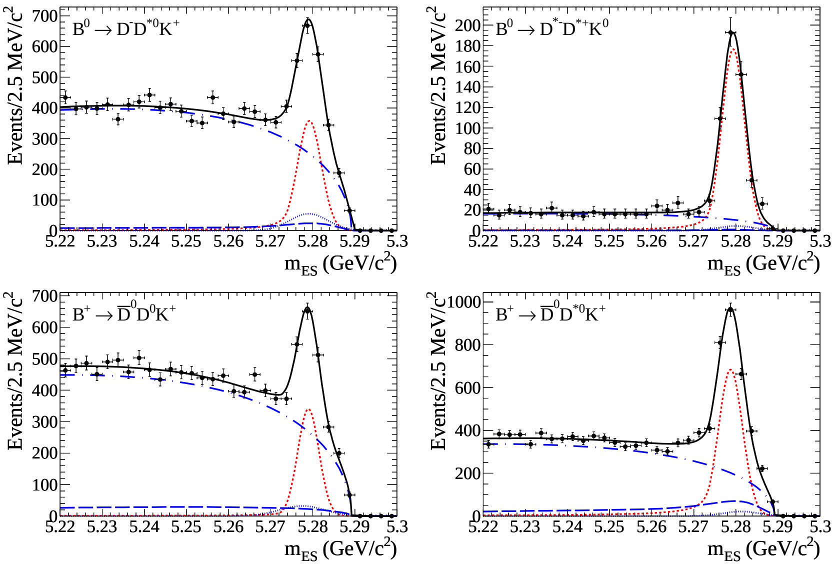

Figure 1: Examples of fits of the $m_{\rm ES}$ data distributions for four modes indicated on the figure. Points with statistical errors are data events, the red dashed line represents the signal, the blue long-dashed line represents the cross-feed event PDF, the blue dashed-dotted line represents the combinatorial background PDF, and the blue dotted line represents the peaking background PDF. The black solid line shows the total PDF.

4. Branching fraction measurements

We measure the branching fractions of the 22 $\bar{D}^{(*)}D^{(*)}K$ modes, including non-resonant and resonant modes. It has been shown that $\bar{D}^{(*)}D^{(*)}K$ events contain resonant contributions [8]. In order to measure the branching fractions inclusively without any assumptions on the resonance structure of the signal, we estimate the efficiency as a function of location in the Dalitz plane of the data $m^2(\bar{D}^{(*)}D^{(*)}) \times m^2(D^{(*)}K)$. We use this efficiency at the event position in the Dalitz plane to reweight the signal contribution. To isolate the signal contribution event-per-event, we use the `sPlot` technique [9]. The `sPlot` technique exploits the result of the $m_{\rm ES}$ fit (yield and covariance matrix) and the PDFs of this fit to compute an event-per-event weight for the signal category and background category.

We consider several sources of systematic uncertainties on the branching fraction measurements: signal shape, cross-feed determination, peaking background, combinatorial background, fit bias, iterative procedure, limited MC statistics, efficiency mapping, difference between data and MC, number of B mesons in the data sample, and secondary branching fractions.

The final results on the data using the full *BABAR* data sample can be found in Table 1. We indicate the significances (including systematic uncertainties) of the observations.

Mode	$\mathscr{B}$	$\mathscr{S}$	Mode	$\mathscr{B}$	$\mathscr{S}$
B^0 decays through external W-emission amplitudes					
$B^0 \to D^- D^0 K^+$	$10.7 \pm 0.7 \pm 0.9$	8.6σ	$B^+ \to \bar{D}^0 D^+ K^0$	$15.5 \pm 1.7 \pm 1.3$	6.6σ
$B^0 \to D^- D^{*0} K^+$	$34.6 \pm 1.8 \pm 3.7$	7.6σ	$B^+ \to \bar{D}^0 D^{*+} K^0$	$38.1 \pm 3.1 \pm 2.3$	10.7σ
$B^0 \to D^{*-} D^0 K^+$	$24.7 \pm 1.0 \pm 1.8$	12.6σ	$B^+ \to \bar{D}^{*0} D^+ K^0$	$20.6 \pm 3.8 \pm 3.0$	3.3σ
$B^0 \to D^{*-} D^{*0} K^+$	$106.0 \pm 3.3 \pm 8.6$	11.4σ	$B^+ \to \bar{D}^{*0} D^{*+} K^0$	$91.7 \pm 8.3 \pm 9.0$	7.5σ
B^0 decays through external+internal W-emission amplitudes					
$B^0 \to D^- D^+ K^0$	$7.5 \pm 1.2 \pm 1.2$	5.1σ	$B^+ \to \bar{D}^0 D^0 K^+$	$13.1 \pm 0.7 \pm 1.2$	8.6σ
$B^0 \to D^{*-} D^+ K^0$	$64.1 \pm 3.6 \pm 3.9$	13.4σ	$B^+ \to \bar{D}^0 D^{*0} K^+$	$63.2 \pm 1.9 \pm 4.5$	12.5σ
$+D^- D^{*+} K^0$			$B^+ \to \bar{D}^{*0} D^0 K^+$	$22.6 \pm 1.6 \pm 1.7$	8.3σ
$B^0 \to D^{*-} D^{*+} K^0$	$82.6 \pm 4.3 \pm 6.7$	12.5σ	$B^+ \to \bar{D}^{*0} D^{*0} K^+$	$112.3 \pm 3.6 \pm 12.6$	6.8σ
B^0 decays through internal W-emission amplitudes					
$B^0 \to \bar{D}^0 D^0 K^0$	$2.7 \pm 1.0 \pm 0.5$	2.3σ	$B^+ \to D^- D^+ K^+$	$2.2 \pm 0.5 \pm 0.5$	2.8σ
$B^0 \to \bar{D}^0 D^{*0} K^0$	$10.8 \pm 3.2 \pm 3.6$	2.2σ	$B^+ \to D^- D^{*+} K^+$	$6.3 \pm 0.9 \pm 0.6$	6.7σ
$+\bar{D}^{*0} D^0 K^0$			$B^+ \to D^{*-} D^+ K^+$	$6.0 \pm 1.0 \pm 0.8$	5.1σ
$B^0 \to \bar{D}^{*0} D^{*0} K^0$	$24.0 \pm 5.5 \pm 6.7$	2.2σ	$B^+ \to D^{*-} D^{*+} K^+$	$13.2 \pm 1.3 \pm 1.2$	7.4σ

Table 1: Branching fractions $\mathscr{B}$ in units of 10^{-4}. The first uncertainties are statistical and the second are systematic. The last column presents the significances $\mathscr{S}$ including the systematic uncertainties.

5. Conclusion

We have analyzed 471 million pairs of B mesons produced in the BABAR experiment, and studied the exclusive decays of $B^0/\bar{B}^0$, $B^\pm$ to $\bar{D}^{(*)}D^{(*)}K^\pm$ and $B^0/\bar{B}^0$, $B^\pm$ to $\bar{D}^{(*)}D^{(*)}K^0$. We measure the branching fractions for the 22 modes. Summing the 10 neutral modes and the 12 charged modes, we observe that $\bar{D}^{(*)}D^{(*)}K$ events represent $(3.68 \pm 0.10 \pm 0.24)\%$ of the B^0 decays and $(4.05 \pm 0.11 \pm 0.28)\%$ of the B^+ decays, where the first uncertainties are statistical and the second systematic.

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