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Measurements of branching fraction ratios and CP-asymmetries in suppressed $B^- \to D(\to K^+\pi^-)K^-$ and $B^- \to D(\to K^+\pi^-)\pi^-$ decays

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We report the first reconstruction in hadron collisions of the suppressed decays $B^- \to D(\to K^+\pi^-)K^-$ and $B^- \to D(\to K^+\pi^-)\pi^-$, sensitive to the Cabibbo-Kobayashi-Maskawa phase γ, using data from 7 fb^{-1} of integrated luminosity collected by the CDF II detector at the Tevatron collider. We reconstruct a signal for the $B^- \to D(\to K^+\pi^-)K^-$ suppressed mode with a significance of 3.2 standard deviations, and measure the ratios of the suppressed to favored branching fractions $R(K) = [22.0 \pm 8.6(\text{stat}) \pm 2.6(\text{syst})] \times 10^{-3}$, $R^+(K) = [42.6 \pm 13.7(\text{stat}) \pm 2.8(\text{syst})] \times 10^{-3}$, $R^-(K) = [3.8 \pm 10.3(\text{stat}) \pm 2.7(\text{syst})] \times 10^{-3}$ as well as the direct CP-violating asymmetry $A(K) = -0.82 \pm 0.44(\text{stat}) \pm 0.09(\text{syst})$ of this mode. Corresponding quantities for $B^- \to D(\to K^+\pi^-)\pi^-$ decay are also reported.

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The measurement of CP-violating asymmetries and branching ratios of $B^- \to DK^-$ [1] decay modes allows a theoretically clean extraction of the phase $\gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$ of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix V_{CKM}, a fundamental parameter of the standard model [2]. In these decays the interference between the first-order tree amplitudes of the $b \to c\bar{u}s$ and $b \to u\bar{c}s$ processes leads to observables that depend on their relative weak phase γ, their relative strong phase δ_B, and the magnitude of the amplitude ratio r_B [3]. These quantities can all be extracted from data by combining several experimental observables. This can be achieved in several ways, using a variety of D decay channels [4–6]. An accurate knowledge of the value of γ is instrumental in establishing the possible presence of additional nonstandard model CP-violating phases in processes where higher-order diagrams are involved [7,8]. Its current determination has a relative uncertainty, dominated by statistical uncertainties, between 15 and 20%, depending on the method [9].

A promising class of processes consists of B meson decays that are a coherent superposition of the color favored $B^- \to D^0K^-$ followed by the doubly Cabibbo suppressed decay $D^0 \to K^+\pi^-$, and of the color suppressed $B^- \to \bar{D}^0K^-$ followed by the Cabibbo favored decay $\bar{D}^0 \to K^+\pi^-$. The magnitude of the two amplitudes is comparable, allowing for large CP-violating asymmetries sensitive to the phase γ. The following observables can be defined [5]:

$$R(K) = \frac{\mathcal{B}(B^- \to [K^+\pi^-]_D K^-) + \mathcal{B}(B^+ \to [K^-\pi^+]_D K^+)}{\mathcal{B}(B^- \to [K^-\pi^+]_D K^-) + \mathcal{B}(B^+ \to [K^+\pi^-]_D K^+)},$$

$$R^\pm(K) = \frac{\mathcal{B}(B^\pm \to [K^\mp\pi^\pm]_D K^\pm)}{\mathcal{B}(B^\pm \to [K^\pm\pi^\mp]_D K^\pm)},$$

$$A(K) = \frac{\mathcal{B}(B^- \to [K^+\pi^-]_D K^-) - \mathcal{B}(B^+ \to [K^-\pi^+]_D K^+)}{\mathcal{B}(B^- \to [K^+\pi^-]_D K^-) + \mathcal{B}(B^+ \to [K^-\pi^+]_D K^+)},$$

where $B^- \to [K^+\pi^-]_D K^-$ is the suppressed (sup) mode and $B^- \to [K^-\pi^+]_D K^-$ is the favored (fav) mode. In the approximation of negligible CP violation in D decays and negligible D^0-$\bar{D}^0$ mixing, whose effects were shown to be small in Ref. [10], these quantities are related to the CKM phase γ by the equations [5] $R = r_D^2 + r_B^2 + 2r_Dr_B\cos\gamma \times \cos(\delta_B + \delta_D)$, $R^\pm = r_D^2 + r_B^2 + 2r_Dr_B\cos(\delta_B + \delta_D \pm \gamma)$, and $A = 2r_Br_D\sin\gamma\sin(\delta_B + \delta_D)/R$, where $r_D = |\frac{A(D^0 \to K^+\pi^-)}{A(D^0 \to K^-\pi^+)}|$ and δ_D is the corresponding relative strong phase. The smallness of the product of branching fractions for these suppressed final states ($\mathcal{O}(10^{-7})$) has been a strong limitation to their use in γ determinations. Evidence for the suppressed $B^- \to DK^-$ channel has only recently been obtained by the Belle Collaboration [11]. The large production rate of B mesons available at hadron colliders offers a unique opportunity for improving the experimental determination of the angle γ. Measurements of branching fractions and CP-violating asymmetries of $B^- \to DK^-$ modes in less suppressed final states of the D meson (CP-even modes K^-K^+ and $\pi^-\pi^+$) have already been performed in hadron collisions [12]. However, the small decay rates along with large potential backgrounds from misidentified favored decays, which only differ for the identity of the final particles, make the reconstruction of suppressed modes in hadron collisions significantly more challenging.

In this paper, we describe the first reconstruction of $B^- \to D_{\text{sup}}K^-$ modes performed in hadron collisions, based on data from a total integrated luminosity of 7 fb^{-1} of $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV, collected by the upgraded Collider Detector (CDF II) at the Fermilab Tevatron. We report measurements of $R(K)$, $R^\pm(K)$, and $A(K)$ for those modes. We also report measurements related to the corresponding $D\pi^-$ modes, since measurable, albeit smaller, γ-dependent asymmetries may also be found in these modes [9]. The maximum possible value of the asymmetry is $A_{\max} = 2r_Br_D/(r_B^2 + r_D^2)$, where r_B can be $r_B(K)$ or $r_B(\pi)$. Taking into account the CKM structure of the contributing processes, we expect that $r_B(\pi)$ is suppressed by a factor $|V_{cd}V_{us}/V_{ud}V_{cs}| \sim \tan^2\theta_C$

with respect to $r_B(K)$, where θ_C is the Cabibbo angle, and we assume the same color suppression factor for both DK and $D\pi$ modes. Using $r_B(K) = 0.103^{+0.015}_{-0.024}$ [9], $r_B(\pi) \sim 0.005$ [9], and $r_D^2 = (3.80 \pm 0.18) \times 10^{-3}$ [13], we expect $A_{\max}(K) \approx 0.90$ and $A_{\max}(\pi) \approx 0.16$.

CDF II is a multipurpose magnetic spectrometer surrounded by calorimeters and muon detectors, and is described in detail elsewhere [14–17]. The resolution on transverse momentum of charged particles is $\sigma_{p_T}/p_T \simeq 0.07\% p_T/(\mathrm{GeV}/c)$, corresponding to a typical mass resolution of 18 MeV/c^2 for our signals. The specific ionization energy loss dE/dx of charged particles can be measured from the charge collected by a gaseous drift chamber, the central outer tracker (COT), and provides 1.5σ separation between pion and kaon particles for $p > 2$ GeV/c. Candidate events for this analysis are selected by a three-level online event-selection system (trigger). At level 1, charged particles are reconstructed in the COT by a hardware processor, the extremely fast tracker (XFT) [18]. Two oppositely charged particles are required, with transverse momenta $p_T \geq 2$ GeV/c and scalar sum $p_{T1} + p_{T2} \geq 5.5$ GeV/c. At level 2, another processor, a silicon vertex trigger (SVT) [19], associates r-ϕ position measurements from an inner silicon detector with XFT tracks. This provides a precise measurement of the track impact parameter d_0, the transverse distance of closest approach to the beam line. The resolution of the impact parameter measurement is 50 μm for particles with p_T of about 2 GeV/c, including a ≈ 30 μm contribution due to the transverse beam size, and improves for higher transverse momenta.

We select B hadron candidates by requiring two SVT tracks with $120 \leq d_0 \leq 1000$ μm. To reduce background from light-quark jet pairs, the two trigger tracks are required to have an opening angle in the transverse plane $2° \leq \Delta\phi \leq 90°$, and to satisfy the requirement $L_{xy} > 200$ μm, where L_{xy} is defined as the distance in the transverse plane from the beam line to the reconstructed two-track vertex. The level 1 and 2 trigger requirements are then confirmed at trigger level 3, where the event is fully reconstructed in software.

The events collected by the trigger are further selected by searching for a pair of oppositely charged particles compatible with a two-body D decay. The invariant mass M_D of the pair is reconstructed for both pion and kaon assignments of particle identities. Events are accepted for the analysis only when one of the possible masses is compatible with the nominal D mass $1.8495 \leq M_D \leq 1.8815$ GeV/c^2, and the alternative combination, $M_{\mathrm{SW}}(D)$, is outside a veto region of $1.8245 \leq M_{\mathrm{SW}}(D) \leq 1.9045$ GeV/c^2 around the nominal D mass. The D candidate is then combined with a negatively charged particle in the event with $p_T > 0.4$ GeV/c to form a B^- candidate. A three-dimensional kinematic fit of each decay candidate trajectory is performed by constraining the two tracks forming the D candidate to a common vertex and to the nominal D mass; the D candidate and the remaining track to a separate vertex; and the reconstructed momentum of the B^- candidate to point back to the primary $\bar{p}p$ interaction vertex determined from other tracks in the event.

The events are then divided into two nonoverlapping samples, nominally classified as favored or suppressed, according to the relative charge of the B candidate with the decay product of the D that has been classified as the kaon. The veto requirements applied to the D mass reconstructed with the alternative particle assignment remove a large fraction of the background of favored decays from the sample classified as suppressed, and vice versa, ensuring no overlap between the samples and a complete symmetry of the selection, which is a crucial aspect of the analysis. The small residual contamination of each sample from events with an incorrect identification of D decay products is accounted for as part of the inclusive background $B^- \to D(\to X)\pi^-$, where X are modes other than $K\pi$ (see below). A further veto is applied to the invariant mass formed by the track from the B candidate and the oppositely charged track from the D candidate, again requiring it to be incompatible with the D meson mass, using the same range as the first veto. This requirement suppresses the contamination from tracks from real B decays that have been incorrectly labeled as D decay products, and is applied symmetrically to both samples. A further suppression of this background is achieved by requiring that the transverse distance between B and D decay vertex is greater than 100 μm. This has the additional effect of reducing contamination from nonresonant three-body decays of the type $B^+ \to h^+h^-h^+$, in which all tracks come from a common decay vertex, and where h indicates either K or π.

Additional requirements are applied to the following observables: the impact parameter d_B of the reconstructed B candidate relative to the beam line; the isolation of the B candidate I_B [20]; the goodness of fit of the decay vertex χ^2_B; the significance of the B hadron decay length $L_{xy}(B)/\sigma_{L_{xy}(B)}$; the angle α between the three-dimensional momentum of the B candidate and the three-dimensional decay length; $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$ between the track from the B hadron and the D meson; the cosine of the angle between the D and the flight direction of the B, in the B meson rest frame, $\cos\theta^*_D$; the difference of the kaon probability [21] values of the tracks forming the D to discriminate kaon-pion pairs from pion-pion and kaon-kaon pairs, $\Delta\kappa$. The threshold values for all these requirements, and for the allowed D mass window mentioned above, were determined by an unbiased optimization procedure, maximizing the quantity $N_S/(1.5 + \sqrt{N_B})$ [22], with no use of simulated signal. The signal N_S is defined as the expected rate of suppressed $B^- \to D_{\mathrm{sup}}\pi^-$ events. We take advantage of our large sample of favored $B^- \to D_{\mathrm{fav}}\pi^-$ decays, using it as a model for the kinematical and particle identification properties of the suppressed decay by simply

TABLE I. $B^- \to DK^-$ and $B^- \to D\pi^-$ event yields obtained from the fit to the data. Only statistical uncertainties are quoted.

D mode	$B^+ \to D\pi^+$	$B^- \to D\pi^-$	$B^+ \to DK^+$	$B^- \to DK^-$
$K^-\pi^+$ (favored)	9882 ± 103	9892 ± 103	694 ± 39	767 ± 41
$K^+\pi^-$ (suppressed)	24 ± 9	31 ± 10	29 ± 9	3 ± 8

considering the swap in sign. The resulting requirements are the following: $L_{xy}(B)/\sigma_{L_{xy}(B)} > 12$, $d_B < 50$ μm, $\chi^2_B < 13$, $I_B(\text{cone} = 1) > 0.4$, $I_B(\text{cone} = 0.4) > 0.7$, $\alpha < 0.15$, $\Delta R < 1.5$, $|\cos\theta^*_D| < 0.6$, $\Delta\kappa > -1$. After applying all the above selection criteria, the invariant mass of each $B^- \to Dh^-$ candidate is evaluated using a nominal pion mass assignment to the particle h^- coming from the B decay. Figure 1 shows the distributions for $B^\pm$ candidates.

With the help of large simulated samples of B mesons, we determine that the only modes contributing non-negligible backgrounds are $B^- \to D(\to X)h^-$, $B^- \to D^{*0}\pi^-$, with $D^{*0} \to D^0\gamma/\pi^0$, nonresonant $B^- \to K^-\pi^+\pi^-$, and $B^0 \to D_0^{*-} l^+ \nu_l$. The large contribution of $B^- \to D(\to K^+K^-)h^-$ reported in Refs. [11,23] is strongly suppressed by our selection, since we reconstruct the D mass in the $K\pi$ mass hypothesis.

We use an extended unbinned maximum likelihood fit, exploiting mass and particle identification (PID) information to statistically separate the $B^- \to DK^-$ and $B^- \to D\pi^-$ signals, the combinatorial background, and the physics backgrounds. PID information on the track from the B decay is incorporated in the kaon probability observable [21]. The extended likelihood function is defined as $\mathcal{L} = \prod_i \mathcal{P}_i \mathcal{L}_i$, where i runs over the favored and suppressed modes, positive and negative charges. The Poisson distribution $\mathcal{P}_i$ is equal to $\frac{\mu^{N_i^{\text{tot}}}}{N_i^{\text{tot}}!} e^{-\mu}$, where N_i^{tot} is the number of events of each subsample and μ is the expected mean value. The individual likelihood components have the following structure: $\mathcal{L}_i = \prod_r^{N_i^{\text{tot}}} \sum_j f_j P_j(M_r, \kappa_r|\theta_r)$, where f and $P(M_r, \kappa_r|\theta_r)$ are the fractions and the probability density functions of the signal and background modes, and θ_r are other free parameters of the fit, a mass scale parameter with respect to the nominal B mass and a scale factor multiplying the width of the shapes of the $B^- \to D(\to K^+\pi^-)h^-$ signals. The fit is simultaneously performed on the favored and suppressed samples. Common parameters are the exponential function for the combinatorial background, whose normalization and slope are determined by the fit; the functional expression for signal and background modes; and the ratio between $B^- \to D^{*0}\pi^-$ and $B^- \to D\pi^-$ fractions. The numbers of events and the fractions of signal and background are determined by the fit and the observables are extracted from them. We tested on simulation that our fit does not exhibit any significant bias.

The shape of the mass distribution assigned to each signal and physics background has been modeled using simulated events including the effect of final state QED radiation and parametrized with different functions. Systematic uncertainties are assessed by varying the values of those function parameters within their errors.

A large sample of $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ decays is used to calibrate the average dE/dx response of the detector to kaons and pions, using the charge of the pion in the D^{*+} decay to determine the identity of the D decay products. The shape of the κ distribution is calibrated within our own sample, by using kaons and pions from the decay of the D meson in the favored sample. Uncertainties on the calibration parameters are included in the final systematic uncertainty of A, R, and $R^\pm$, taking into account the full correlation matrix of the parameters characterizing the shape of the κ distribution [24].

The $B^- \to DK^-$ and $B^- \to D\pi^-$ event yields obtained from the fit to the data are reported in Table I. Fit projections on the invariant mass distributions are given in Fig. 1. They provide a consistent description of the observed distributions in the data. We find evidence for a signal in

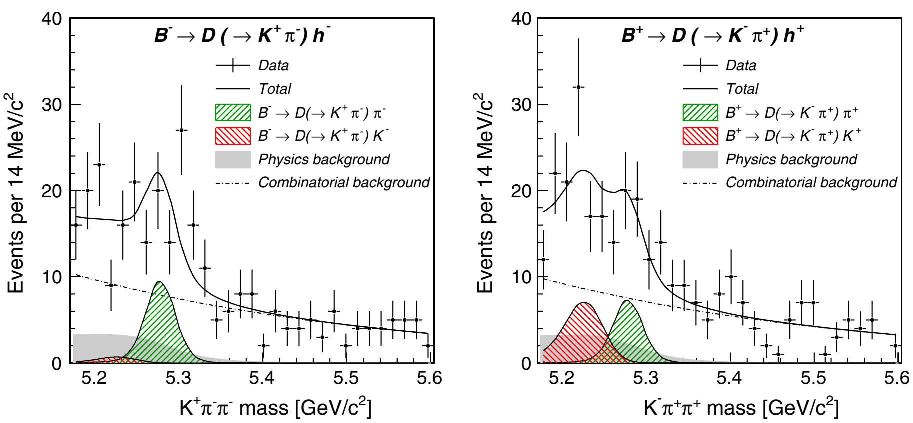

FIG. 1 (color online). Invariant mass distributions of $B^\pm \to Dh^\pm$ for the suppressed mode (bottom meson on the left and antibottom on the right). The pion mass is assigned to the charged track from the B candidate decay vertex. The projections of the common likelihood fit (see text) are overlaid.

TABLE II. Summary of systematic uncertainties.

Source	$R(\pi)$	$R^+(\pi)$	$R^-(\pi)$	$R(K)$	$R^+(K)$	$R^-(K)$	$A(\pi)$	$A(K)$
dE/dx model	<0.0001	<0.0001	<0.0001	0.0001	0.0003	0.0001	<0.01	<0.01
$B^- \to D(\to X)\pi^-$ shape	0.0004	0.0004	0.0004	0.0025	0.0026	0.0026	0.01	0.09
Other backgrounds	<0.0001	<0.0001	<0.0001	0.0006	0.0006	0.0005	<0.01	0.02
Efficiency	<0.0001	<0.0001	<0.0001	0.0003	0.0009	0.0001	0.01	<0.01
Total	0.0004	0.0004	0.0004	0.0026	0.0028	0.0027	0.02	0.09

the $B^- \to DK^-$ suppressed mode with a significance of 3.2σ. The significance is evaluated by comparing the likelihood-ratio observed in data with the distribution expected in statistical trials. Several distributions are generated corresponding to different choices of systematic parameters. The quoted significance corresponds to the distribution yielding the most conservative p value.

The raw fit results are then corrected for the reconstruction efficiency ϵ, due to different probabilities of K^+, K^-, π^+ and π^- to interact with the tracker material. We use previous measurements of $\frac{\epsilon(K^+)}{\epsilon(K^-)} = 1.0178 \pm 0.0023(\text{stat}) \pm 0.0045(\text{syst})$ and $\frac{\epsilon(\pi^+)}{\epsilon(\pi^-)} = 0.997 \pm 0.003(\text{stat}) \pm 0.006(\text{syst})$ [25]. We extract $\frac{\epsilon(K^-\pi^+)}{\epsilon(K^+\pi^-)} = 0.998 \pm 0.015(\text{stat}) \pm 0.016(\text{syst})$ from our own sample of favored $B^- \to D\pi^-$ decays.

Systematic uncertainties are determined by repeating the fit changing the mass and the dE/dx model (Table II). The dominant contribution is the uncertainty on the $B^- \to D(\to X)\pi^-$ shape. This is the largest physics background, and it lies under the signal peak.

In summary, we find evidence for the $B^- \to D(\to K^+\pi^-)K^-$ suppressed mode with a significance of 3.2 Gaussian standard deviations. We measure the ratios of the suppressed $([K^+\pi^-]_D K^-/\pi^-)$ to favored $([K^-\pi^+]_D K^-/\pi^-)$ branching fractions $R(K) = [22.0 \pm 8.6(\text{stat}) \pm 2.6(\text{syst})] \times 10^{-3}$, $R^+(K) = [42.6 \pm 13.7(\text{stat}) \pm 2.8(\text{syst})] \times 10^{-3}$, $R^-(K) = [3.8 \pm 10.3(\text{stat}) \pm 2.7(\text{syst})] \times 10^{-3}$ and $R(\pi) = [2.8 \pm 0.7(\text{stat}) \pm 0.4(\text{syst})] \times 10^{-3}$, $R^+(\pi) = [2.4 \pm 1.0(\text{stat}) \pm 0.4(\text{syst})] \times 10^{-3}$, $R^-(\pi) = [3.1 \pm 1.1(\text{stat}) \pm 0.4(\text{syst})] \times 10^{-3}$ as well as the direct CP-violating asymmetries

$$A(K) = -0.82 \pm 0.44(\text{stat}) \pm 0.09(\text{syst}),$$

$$A(\pi) = 0.13 \pm 0.25(\text{stat}) \pm 0.02(\text{syst}).$$

The observed asymmetry $A(K)$ deviates from zero by 2.2 standard deviations.

These measurements, performed here for the first time in hadron collisions, are in agreement with previous measurements from *BABAR* [23] and Belle [11] with comparable uncertainties. These results can be combined with other $B^- \to DK^-$ measurements to improve the determination of the CKM angle γ.

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