Measurements of Branching Fractions and Dalitz Distributions for $B^0 \to D^{(*)\pm} K^0 \pi^\mp$ Decays

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We present measurements of the branching fractions for the three-body decays $B^0 \to D^{(*)\mp} K^0 \pi^\pm$ and their resonant submodes $B^0 \to D^{(*)\mp} K^{*\pm}$ using a sample of approximately 88×10^6 $B\bar{B}$ pairs collected by the *BABAR* detector at the SLAC PEP-II asymmetric energy storage ring. We measure: $\mathcal{B}(B^0 \to D^\mp K^0 \pi^\pm) = (4.9 \pm 0.7_{\rm stat} \pm 0.5_{\rm syst}) \times 10^{-4}$, $\mathcal{B}(B^0 \to D^{*\mp} K^0 \pi^\pm) = (3.0 \pm 0.7_{\rm stat} \pm 0.3_{\rm syst}) \times 10^{-4}$, $\mathcal{B}(B^0 \to D^\mp K^{*\pm}) = (4.6 \pm 0.6_{\rm stat} \pm 0.5_{\rm syst}) \times 10^{-4}$, $\mathcal{B}(B^0 \to D^{*\mp} K^{*\pm}) = (3.2 \pm 0.6_{\rm stat} \pm 0.3_{\rm syst}) \times 10^{-4}$.

From these measurements we determine the fractions of resonant events to be $f(B^0 \to D^{\mp}K^{*\pm}) = 0.63 \pm 0.08_{\rm stat} \pm 0.04_{\rm syst}$ and $f(B^0 \to D^{*\mp}K^{*\pm}) = 0.72 \pm 0.14_{\rm stat} \pm 0.05_{\rm syst}$.

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Several independent measurements are needed to test the standard model description of CP violation. The angle γ can be determined using decays of the type $B \to D^{(*)}K^{(*)}$ [1]. The experimental challenges are color suppression of the $b \to u$ transition, reconstruction of D^0 CP eigenstates, and interfering doubly-Cabibbo-suppressed decays (DCSD) [2]. Also, two-body mode analyses are complicated because there are eight degenerate solutions for γ in the interval $[0, 2\pi]$.

In recent papers [3,4] three-body decays have been suggested for measuring γ, since these do not suffer from the color suppression penalty. Furthermore, the channels $B^0 \to D^{(*)\mp}K^0\pi^{\pm}$ do not have the above problems with CP states and DCSD interference, and can resolve most of the ambiguities [3]. The angle γ can be extracted from a time-dependent Dalitz analysis of these decay modes.

The analysis presented here is based on 81.8 fb^{-1} of data taken at the $\Upsilon(4S)$ resonance, corresponding to approximately 88×10^6 $B\bar{B}$ pairs, with the *BABAR* detector [5] at the SLAC PEP-II storage ring. We measure the branching fractions of the $B^0 \to D^{(*)\mp}K^0\pi^{\pm}$ decays and consider their distribution in the Dalitz plot.

We reconstruct D^+ mesons in the decay mode $K^-\pi^+\pi^+$ and D^{*+} mesons in the mode $D^0\pi^+$, with the D^0 decaying to $K^-\pi^+$, $K^-\pi^+\pi^0$, and $K^-\pi^+\pi^-\pi^+$. Here and throughout the Letter charge conjugate states are implied. Tracks from the D decay are required to originate from a common vertex. Positive kaon identification is enforced on kaons from D meson decays, except for the $D^0 \to K^-\pi^+$ mode.

The D^+ candidates are required to have a mass within 12 MeV$/c^2$ (2σ) of the D^+ mass, while the mass of D^0 candidates decaying to charged daughters only is required to lie within 15 MeV$/c^2$ (2.5σ) of the D^0 mass, where σ is the experimental resolution. The $D^0 \to K^-\pi^+\pi^0$ candidates are required to have a mass within 30 MeV$/c^2$ (2.5σ) of the D^0 mass and to be located at a point in the D^0 Dalitz plot where the density of events is larger than 1.4% of the maximum density.

The D^{*+} candidates are accepted if the mass difference $m_{D^{*+}} - m_{D^0}$ is within 2 MeV$/c^2$ (3σ) of the nominal value, except for the $D^0 \to K^-\pi^+\pi^0$ candidates where we use 1.5 MeV$/c^2$ to reduce this mode's larger combinatoric background.

We combine oppositely charged tracks from a common vertex into K_S^0 candidates. The K_S^0 candidates are required to have a mass within 7 MeV$/c^2$ (3σ) of the K_S^0 mass and a transverse flight length that is significantly (4σ) greater than zero.

To form B^0 candidates, the $D^{(*)+}$ candidates are combined with a K_S^0 candidate and a π^-, for which the particle identification (PID) is inconsistent with being a kaon or an electron. The probability of a common vertex is required to be above 0.1%. Using the beam energy, two almost-independent kinematic variables are constructed: the beam-energy substituted mass $m_{\rm ES} \equiv \sqrt{(\sqrt{s}/2)^2 - p_B^{*2}}$, and the difference between the B^0 candidate's measured energy and the beam energy, $\Delta E \equiv E_B^* - \sqrt{s}/2$. The asterisk denotes evaluation in the $\Upsilon(4S)$ c.m. frame. B^0 candidates are required to have ΔE in the range $[-0.1, 0.1]$ GeV, and $m_{\rm ES}$ in the range $[5.24, 5.29] \times$ ($[5.20, 5.288]$) GeV$/c^2$ for $D^{\mp}K^0\pi^{\pm}$($D^{*\mp}K^0\pi^{\pm}$).

To suppress the dominant continuum background events, which have a more jetlike shape than $B\bar{B}$ events, we use a linear combination, $\mathcal{F}$, of four variables: $L_0 = \sum_i p_i$, $L_2 = \sum_i p_i |\cos\theta_i|^2$, and the absolute values of the cosine of the polar angles of the B momentum and of the B thrust direction [6]. Here, p_i is the momentum and θ_i is the angle with respect to the thrust axis of the signal B candidate of the tracks and clusters not used to reconstruct the B. All of these variables are calculated in the c.m. frame. The coefficients are chosen to maximize the separation between the signal Monte Carlo distribution and 9.6 fb^{-1} of continuum events from data taken 40 MeV below the $\Upsilon(4S)$ resonance (off-resonance data). $\mathcal{F}$ has negligible correlations with $m_{\rm ES}$ and ΔE.

After the event selection, approximately 5% of the events have more than one B^0 candidate. We choose the one with m_D closest to the expected value and correct for differences between data and simulation. In simulated signal events, the final selection is 19.3% efficient for $B^0 \to D^{\mp}K^0\pi^{\pm}$ and 15.5%, 3.9%, and 8.2% efficient for $B^0 \to D^{*\mp}K^0\pi^{\pm}$ in the three D^0 decay modes $K^-\pi^+$, $K^-\pi^+\pi^0$, and $K^-\pi^+\pi^-\pi^+$, respectively.

We perform an unbinned extended maximum likelihood fit with the variables $m_{\rm ES}$, ΔE, and $\mathcal{F}$ on the selected candidates, using the logarithm of the likelihood

$$\ln\mathcal{L} = \sum_{i={\rm events}} \ln\left(\sum_j N_j P_{ij}(m_{\rm ES}^i, \Delta E^i, \mathcal{F}^i)\right) - \sum_j N_j, \quad (1)$$

where P_{ij} is the product of probability density functions (PDFs) for event i of $m_{\rm ES}^i$, ΔE^i, and $\mathcal{F}^i$, and N_j is the number of events of each sample component j: signal, continuum, combinatoric $B\bar{B}$ decays, and $B\bar{B}$ events that peak in $m_{\rm ES}$ but not in ΔE signal region (denoted peaking $B\bar{B}$ background).

The signal is described by a Gaussian distribution in $m_{\rm ES}$, two Gaussian distributions with common mean in ΔE, and a Gaussian distribution with different widths on each side of the mean (''bifurcated Gaussian distribution'') in $\mathcal{F}$. Their shape is obtained from the high-statistics data control samples $B^0 \to D^{(*)\mp} a_1^\pm$ (similar topology of the final state as the signal) for m_{ES} and ΔE, and $B^0 \to D^{*\mp}\pi^\pm$ for $\mathcal{F}$, and all nine parameters are fixed in the fit.

The continuum and combinatoric $B\bar{B}$ backgrounds are described by empirical endpoint functions [7] in m_{ES}, linear functions in ΔE, and bifurcated Gaussian distributions in $\mathcal{F}$. The $\mathcal{F}$ distribution of continuum is obtained from off-resonance data, while the $\mathcal{F}$ distribution of the $B\bar{B}$ backgrounds is obtained from Monte Carlo simulation, and compared with data in high-statistics samples to ensure that there is no significant difference. The two $\mathcal{F}$ distributions and the common endpoint in m_{ES} are fixed in the fit, while the m_{ES} shape and ΔE distributions are left free to float, leaving four out of 11 parameters free in the fit.

The peaking $B\bar{B}$ background is parametrized by a Gaussian distribution in m_{ES}, an exponential distribution in ΔE, and shares the PDF in $\mathcal{F}$ with the nonpeaking $B\bar{B}$ background. The mean and width in m_{ES} of the peaking $B\bar{B}$ background are fixed to values obtained from Monte Carlo simulation, which are consistent with values measured in the ΔE sideband of data, thus adding one free and two fixed parameters.

The likelihood function is determined by the 27 parameters described above, of which all four yields and five background shape parameters are fitted. Subsequent to the fit, possible residual backgrounds from combinatoric D and K_S^0 candidates are estimated using the sidebands of m_D and $m_{K_S^0}$, and subtracted.

The three-body and quasi-two-body [that is $B^0 \to D^{(*)\mp} K^{*\pm}$]) branching fractions are obtained by fitting first without regard to event positions in the Dalitz plot, and then with the requirement that the $K_S^0\pi^+$ invariant mass lie within 100 MeV$/c^2$ of the $K^{*+}(892)$ mass. Because of the relatively small number of background events in the second fit, all $B\bar{B}$ shape parameters are kept fixed to the value obtained in the first fit.

The results are shown in Fig. 1, while yields and purities [defined as $N_{\rm sig}/\sigma^2(N_{\rm sig})$] are listed in Table I, with the K^{*+} resonant part included in the three-body state. To determine the three-body branching fractions optimally, a mapping of the efficiency across the Dalitz plot is needed. This is obtained from simulated signal events. Incorporating the efficiency variations ($\sim \pm 30\%$) across the Dalitz plot requires a measure of the (*a priori* unknown) event distribution in the Dalitz plot. We obtain the number of signal events from the likelihood fit using weights defined as

$$W_{\rm sig}^i \equiv \frac{\sum_j \mathbf{V}_{{\rm sig},j} P_{ij}(m_{ES}^i, \Delta E^i, \mathcal{F}^i)}{\sum_j N_j P_{ij}(m_{ES}^i, \Delta E^i, \mathcal{F}^i)}, \quad (2)$$

where N_j and P_{ij} are defined as in Eq. (1), and $\mathbf{V}_{{\rm sig},j}$ is the signal row of the covariance matrix of the component yields obtained from the likelihood fit. These weights $W_{\rm sig}^i$, which in the absence of correlations are signal probabilities $P_{\rm sig}/P_{\rm total}$, contain the signal distribution and its uncertainty for any quantity, uncorrelated with the variables in the likelihood fit [8]. It has been checked that the Dalitz variables have no significant correlation with the likelihood fit variables. It should be noted that because of

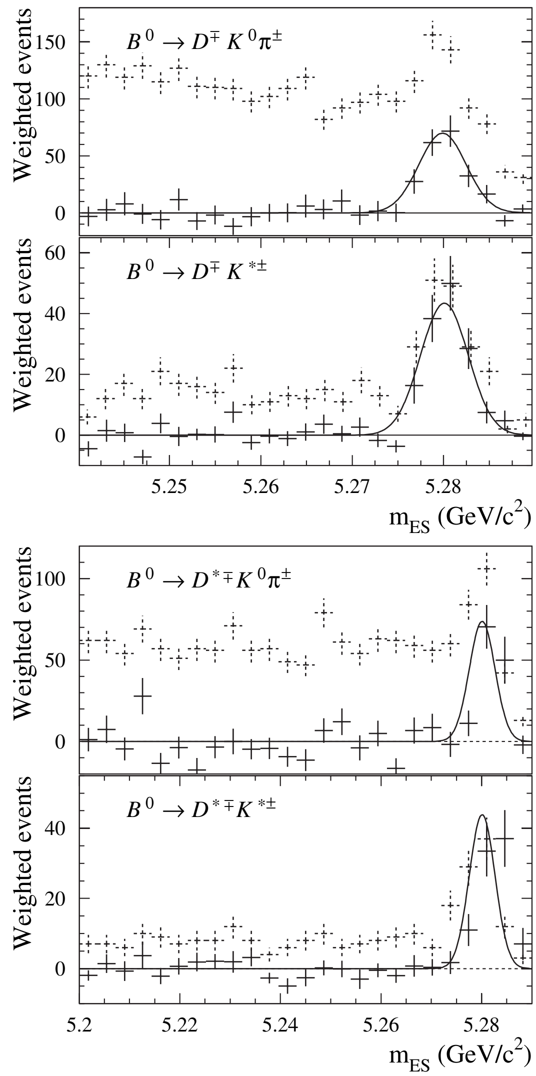

FIG. 1. m_{ES} distributions in data for the four decay modes. In solid markers are shown events weighted by $W_{\rm sig}$ (see text). Following the presciption of [8] the m_{ES} variable was removed from the likelihood to perform the second fit needed to obtain the m_{ES} free yields and covariance matrix entering into $W_{\rm sig}$. The PDF used in the main fit is superimposed for comparison. For comparison, the m_{ES} distribution obtained with $|\Delta E| < 25$ MeV (2σ) is included (dotted points).

TABLE I. Signal yields and purities.

Decay mode	Signal yield	Purity
$B^0 \to D^\mp K^0 \pi^\pm$	230 ± 24	40%
$B^0 \to D^\mp K^{*\pm}$	143 ± 14	73%
$B^0 \to D^{*\mp} K^0 \pi^\pm$	134 ± 17	46%
$B^0 \to D^{*\mp} K^{*\pm}$	78 ± 10	78%

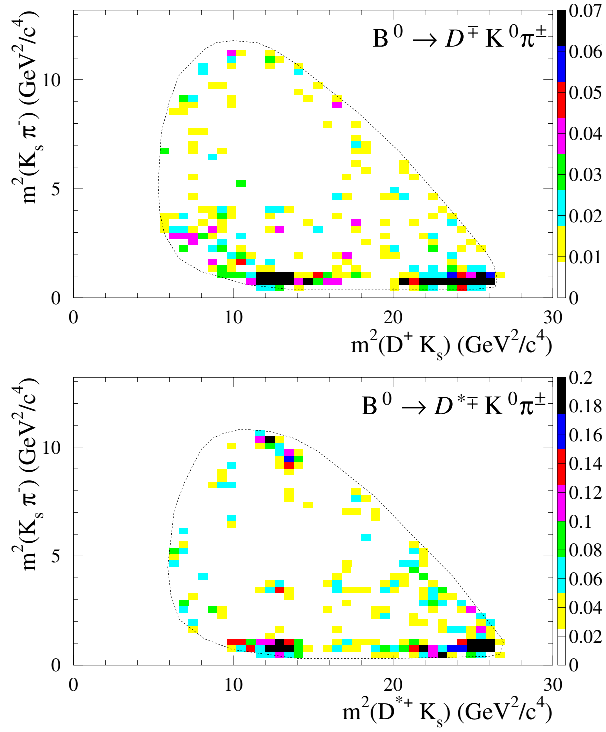

FIG. 2 (color online). Signal Dalitz distributions with events weighted by $W_{\rm sig}$ and corrected for efficiency variations. Each bin is colored according to its contribution to the branching fraction. The bins in white also include the contributions which are negative but still statistically compatible with zero.

the use of the covariance matrix, the weight can be negative especially for backgroundlike events.

The efficiency-corrected Dalitz distributions, weighted by $W_{\rm sig}$, are shown in Fig. 2. The $K^*(892)^+$ resonance is dominant in both the $B^0 \to D^\mp K^0 \pi^\pm$ and $B^0 \to D^{*\mp} K^0 \pi^\pm$ modes, while no other resonant structures are significant. In the $B^0 \to D^\mp K^0 \pi^\pm$ channel, the spin-1 $K^{*\pm}$ meson has the helicity distribution $dN/d\cos\theta \propto \cos^2\theta$, where θ is the angle between the $K^{*\pm}$ and the K^0 in the $K^{*\pm}$ center of mass frame. This can be seen in Fig. 3.

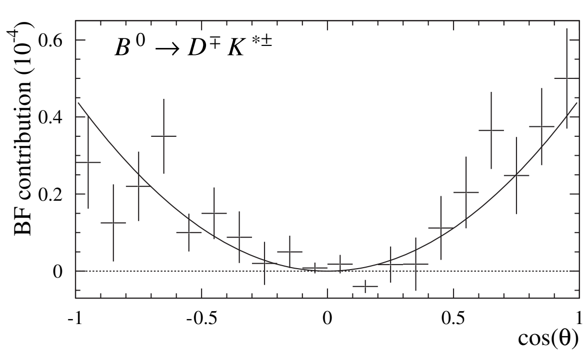

FIG. 3. Distribution of $\cos\theta$ for data for the $B^0 \to D^\mp K^0 \pi^\pm$ decay mode in the $K^{*\pm}$ region using the signal weights $W_{\rm sig}$ and correcting for efficiency variations. The solid curve shows the expected spin-1 distribution $dN/d\cos\theta \propto \cos^2\theta$.

The systematic errors are summarized in Table II. Most systematic errors are due to possible differences between data and Monte Carlo calculations. The tracking efficiency residuals and associated systematic error are obtained from a large sample of τ decays. The efficiency correction as a function of the position in the Dalitz plot obtained from simulated signal events comes with systematic uncertainties due to resolution effects and binning, which are mostly of statistical origin. A $\pm 1\sigma$ variation of all fixed variables in the fit, including relevant correlations, is used to obtain the systematic from the uncertainty in the PDFs.

Our final branching fraction results, weighting the three D^0 modes according to their combined statistical and uncorrelated systematic error, are

$$\mathcal{B}(B^0 \to D^\mp K^0 \pi^\pm) = (4.9 \pm 0.7_{\rm stat} \pm 0.5_{\rm syst}) \times 10^{-4},$$
$$\mathcal{B}(B^0 \to D^{*\mp} K^0 \pi^\pm) = (3.0 \pm 0.7_{\rm stat} \pm 0.3_{\rm syst}) \times 10^{-4},$$
$$\mathcal{B}(B^0 \to D^\mp K^{*\pm}) = (4.6 \pm 0.6_{\rm stat} \pm 0.5_{\rm syst}) \times 10^{-4},$$
$$\mathcal{B}(B^0 \to D^{*\mp} K^{*\pm}) = (3.2 \pm 0.6_{\rm stat} \pm 0.3_{\rm syst}) \times 10^{-4}.$$

To summarize, a clear signal is seen in both the $B^0 \to D^\mp K^0 \pi^\pm$ and $B^0 \to D^{*\mp} K^0 \pi^\pm$ channels, and in both modes the $K^*(892)^+$ resonance is dominant. Defining the K^* resonant fractions, f, as $\mathcal{B}(B^0 \to D^{(*)\mp} K^{*\pm})\mathcal{B}(K^{*+} \to K^0\pi^+)/\mathcal{B}(B^0 \to D^{(*)\mp} K^0 \pi^\pm)$, we obtain the fractions $f(B^0 \to D^\mp K^{*\pm}) = 0.63 \pm 0.08_{\rm stat} \pm 0.04_{\rm syst}$ and $f(B^0 \to D^{*\mp} K^{*\pm}) = 0.72 \pm 0.14_{\rm stat} \pm 0.05_{\rm syst}$, respectively, where the systematic errors are mainly from correcting for any possible nonresonant contributions.

Both the method of this analysis and the resulting three-body branching fraction measurements are the first of their kind, while the resonant decay modes have been measured before [9]. To determine the sensitivity to γ of these modes, a time-dependent Dalitz fit is required, for which the data sample is inadequate. However, the branching

TABLE II. Sources and sizes of systematic errors. The combined errors take correlations into account. All numbers are in percent.

Systematic	$DK\pi$	DK^*	$D^*K\pi$	D^*K^*
Tracking efficiency	5.9	5.9	6.1	6.3
PID efficiency	2.2	2.0	2.0	2.0
$\mathcal{B}(D^{*+})$	···	···	0.7	0.7
$\mathcal{B}(D^{+/0})$	6.5	6.5	3.4	3.8
$D^{(*)}$ reconstruction	0.7	0.7	1.2	1.2
K^{*+} fraction fit	···	3.7	···	5.1
$\mathcal{B}(K_S^0)$	0.2	0.2	0.2	0.2
K_S^0 reconstruction	1.8	1.9	1.9	1.9
π^0 reconstruction	···	···	0.8	1.2
PDF parametrization	4.5	2.9	7.1	3.7
Efficiency variation	3.5	4.9	6.3	5.6
$B\bar{B}$ counting	1.1	1.1	1.1	1.1
Combined error	11.0	11.6	12.6	12.2

fractions and Dalitz distributions suggest that these modes will be useful for measuring γ at the B factories.

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