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Search for inclusive charmless $B \to K^+X$ and $B \to K^0X$ decays

The *BABAR* Collaboration

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Abstract

We present preliminary results from a search for inclusive charmless $B \to KX$ decays. These decays occur dominantly via one-loop $b \to s$ penguin transitions, and can provide useful information about these processes. Using a sample of 288.5 fb^{-1} collected with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- B Factory at SLAC, we search for high-energy kaons recoiling against fully reconstructed B decays. We measure the partial branching fractions for kaons with momentum $p^\star(K) > 2.34\,\mathrm{GeV}$ in the B rest frame, and obtain (in units of 10^{-6}): $\mathcal{B}(B \to K^+X, p^\star > 2.34\,\mathrm{GeV}) = 196^{+37}_{-34}(\mathrm{stat.})^{+31}_{-30}(\mathrm{syst.})$ and $\mathcal{B}(B \to K^0X, p^\star > 2.34\,\mathrm{GeV}) = 154^{+55}_{-48}(\mathrm{stat.})^{+55}_{-41}(\mathrm{syst.})$ (< 266 at 90% C.L.).

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1 INTRODUCTION

B-meson decays proceed dominantly through $b \to c$ transitions, while the tree-level $b \to u$ and one-loop $b \to s$ transitions are suppressed. In the Standard Model (SM), the branching fractions for $b \to u$ and $b \to s$ transitions are approximately $1\% - 2\%$ [1, 2, 3]. It has been suggested that loop transitions are a window on the effects of new physics, as virtual non-SM particles in the loop can couple to the quarks [4, 5]. The branching fraction for $b \to sg^{\star}$ ($g^{\star}$ = gluon) decays could be as large as 10% in certain models [4, 5].

In recent years, exclusive B decays dominated by $b \to sg^{\star}$ ($b \to sq\overline{q}$, $q = u, d, s$) have been used to measure the CKM unitarity triangle angle β. The amplitude S of the sine component of the time-dependent CP asymmetry in these decay modes is measured to be systematically shifted low relative to the expected values from SM calculations ($S \simeq \sin 2\beta$), although this shift is currently not statistically significant [6].

A good understanding of the dynamics of $b \to s$ transitions is needed to make accurate predictions of related quantities within the framework of the SM [7]. This understanding currently comes from branching fractions and CP measurements of $b \to s$ dominated exclusive decays and from inclusive and exclusive $b \to s\gamma$ transitions. The measurement of inclusive $b \to sg^{\star}$ decays would provide additional information to the current picture [8], and could help us understand the discrepancies seen in the measurements of $\sin 2\beta$ [7].

Previous experimental attempts to measure inclusive $b \to sg^{\star}$ decays have been statistically limited [9, 10, 11, 12]. The B-factory experiments present new opportunities to make a significant measurement of this process.

In this paper, we present a preliminary result from a search for inclusive charmless $B \to K^{+}X$ and $B \to K^{0}X$ decays, which can in principle be related to the $b \to sg^{\star}$ rate. The neutral kaon in $B \to K^{0}X$ is reconstructed through the decay $K^{0}_{S} \to \pi^{+}\pi^{-}$. We define as signal $B \to KX$ all the charmless decays that contain at least one kaon. These decays can occur via $b \to s$ (dominant), $b \to u$, and $b \to d$ transitions. The signal yields are extracted with an unbinned maximum likelihood (ML) fit to samples of $B \to KX$ decays recoiling against fully reconstructed hadronic B decays.

2 THE *BABAR* DETECTOR AND DATASET

The data used in this analysis were collected with the *BABAR* detector [13] at the PEP-II asymmetric-energy $e^{+}e^{-}$ collider located at the Stanford Linear Accelerator Center (SLAC). The analysis uses an integrated luminosity of $288.5\,\mathrm{fb}^{-1}$ recorded at the $\Upsilon(4S)$ resonance (center-of-mass energy $\sqrt{s} = 10.58$ GeV).

In the *BABAR* detector, charged particles are detected and their momenta measured by a combination of a vertex tracker consisting of five layers of double-sided silicon microstrip detectors and a 40-layer central drift chamber, both operating in the 1.5-T magnetic field of a superconducting solenoid. We identify photons and electrons using a CsI(Tl) electromagnetic calorimeter (EMC). Charged particle identification (PID) is provided by an internally reflecting ring imaging Cherenkov detector (DIRC) covering the central region of the detector, the average energy loss (dE/dx) in the tracking devices and by the EMC. Additional information that we use to identify and reject electrons and muons is provided by the EMC and the detectors of the solenoid flux return (IFR).

3 ANALYSIS METHOD AND EVENT SELECTION

The experimental identification of the inclusive $b \to sg^\star$ decay is complicated by the fact that the gluon is a virtual intermediate state with no good experimental signature. We instead rely on the hadronization of the primary strange quark into a charged or neutral kaon to identify decays dominated by $b \to s$ transitions. The analysis is therefore effectively a search for the decays $B \to K^+X$ and $B \to K^0X$. The momentum $p^\star(K)$ of the primary kaon in the B rest frame is limited for $b \to c$ background by the D-meson mass, and cannot be larger than $\sim 2.3\,\mathrm{GeV}$, while $p^\star(K)$ can be as large as $\sim 2.6\,\mathrm{GeV}$ for signal $B \to KX$ decays. We use this difference as the primary signature to look for charmless inclusive $B \to KX$ decays, as was first suggested in Ref. [14].

In this analysis we reject the large $e^+e^- \to q\overline{q}$ $(q = u, d, s, c)$ continuum background very efficiently by reconstructing one of the two B mesons (B_{reco}) in $e^+e^- \to \Upsilon(4S) \to B\overline{B}$, and searching for the $B \to KX$ signal (B_{signal}) recoiling against B_{reco}. We select a large sample of events containing a B_{reco} meson which decays into a hadronic final state as $B_{\mathrm{reco}} \to \overline{D}^{(*)}Y^\pm$, and is fully reconstructed. The system $Y^\pm$ consists of a combination of hadrons containing one, three, or five charged pions or kaons, up to two neutral pions, and at most two $K^0_S \to \pi^+\pi^-$ candidates. We reconstruct $D^{*-} \to \overline{D}^0\pi^-$; $D^{*0} \to \overline{D}^0\pi^0$; $\overline{D}^0 \to K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^-\pi^+$, $K^0_S\pi^+\pi^-$; and $D^- \to K^+\pi^-\pi^-$, $K^+\pi^-\pi^-\pi^0$, $K^0_S\pi^-$, $K^0_S\pi^-\pi^0$, $K^0_S\pi^-\pi^-\pi^+$. The B_{reco} candidates are characterized kinematically by the energy-substituted mass $m_{\mathrm{ES}} = (\frac{1}{4}s - \mathbf{p}_B^2)^{\frac{1}{2}}$ and energy difference $\Delta E = E_B - \frac{1}{2}\sqrt{s}$, where $(E_B, \mathbf{p}_B)$ is the B-meson 4-momentum vector, and all values are expressed in the $\Upsilon(4S)$ frame. We require the value of ΔE to be consistent with zero within three standard deviations (σ), as measured for each decay mode (10 to $35\,\mathrm{MeV}$). We require $5.25 < m_{\mathrm{ES}} < 5.29\,\mathrm{GeV}$, and use this variable in the ML fit described below. We define the purity for each B_{reco} decay mode as the ratio $S/(S + B)$ measured in control samples, where S is the number of reconstructed signal B_{reco} and B is the number of background events. We require the purity of the selected B_{reco} candidates to be at least 20%. In events containing more than one B_{reco} candidate, we select the decay mode with the highest purity.

To further reject $q\overline{q}$ continuum background, we make use of the angle θ_{T} between the thrust axis of the B_{reco} candidate in the $\Upsilon(4S)$ frame and that of the rest of the charged tracks and neutral clusters in the event. The distribution of $|\cos\theta_{\mathrm{T}}|$ is sharply peaked near 1 for combinations drawn from jet-like $q\overline{q}$ pairs, and nearly uniform for the almost isotropic B-meson decays; we require $|\cos\theta_{\mathrm{T}}| < 0.9$. Further discrimination from continuum in the ML fit is obtained from a Fisher discriminant $\mathcal{F}$, which is an optimized linear combination of four variables: the angles with respect to the beam axis of the B momentum and B thrust axis (in the $\Upsilon(4S)$ frame), and the zeroth and second angular moments $L_{0,2}$ of the energy flow about the B thrust axis. The moments are defined by $L_j = \sum_i p_i \times |\cos\theta_i|^j$, where θ_i is the angle with respect to the B thrust axis of track or neutral cluster i, p_i is its momentum, and the sum excludes the B_{reco} candidate.

We select 2.99×10^6 B_{reco} candidates with the above criteria, and apply an unbinned ML fit to the m_{ES} and $\mathcal{F}$ variables to separate $B\overline{B}$ events from $q\overline{q}$ continuum background. We find $N(B_{\mathrm{reco}}) = (1.78 \pm 0.09) \times 10^6$, where the uncertainty includes a conservative preliminary estimate of the systematics due to the modeling of the data.

We search for the signal B meson (B_{signal}) using the charged tracks and the neutral clusters that are not part of the B_{reco} candidate. We reject B_{signal} candidates containing charged tracks compatible with an electron or muon hypothesis, or that contain a reconstructed D meson candidate with mass within 30 MeV of the nominal mass. We also require $m_{\mathrm{ES}}(B_{\mathrm{signal}}) > 5.1\,\mathrm{GeV}$.

The measured $\Upsilon(4S)$ and $B_{\rm reco}$ 4-momentum vectors are used to determine accurately the 4-momentum vector of $B_{\rm signal}$, independently of its decay products. We then select charged K^+ and neutral $K^0_S \to \pi^+\pi^-$ candidates with momentum $p^\star(K)$ larger than 2.34 GeV, calculated in the $B_{\rm signal}$ rest frame.

The DIRC Cherenkov angle θ_c for charged kaon candidates must satisfy $-5\sigma_c < \theta_c < +2\sigma_c$, where σ_c is the resolution on θ_c, and the upper limit is designed to reject contamination from charged pions. To exclude secondary kaons, the distance of closest approach of the K^+ candidate must be within three standard deviations of the $B_{\rm signal}$ vertex, as determined inclusively from all tracks recoiling against $B_{\rm reco}$.

We require the mass of K^0_S candidates to be within $\pm 4.5\sigma$ of the nominal mass ($0.486 < m_{K^0_S} < 0.510\,{\rm GeV}$). The reconstructed $K^0_S \to \pi^+\pi^-$ must have a vertex χ^2 probability $\mathcal{P}_{\rm vertex} > 0.001$, and its lifetime significance (τ/σ_τ) must be larger than 3.

The above selection has an efficiency of $(16.1 \pm 1.5)\%$ for the decays $B \to K^+X$ with $p^\star(K^+) > 2.34\,{\rm GeV}$, and $(6.7 \pm 1.1)\%$ for the decays $B \to K^0X$ with $p^\star(K^0) > 2.34\,{\rm GeV}$ and reconstructed as $B \to K^0_SX$, $K^0_S \to \pi^+\pi^-$. The selected samples contain 246 $B \to K^+X$ and 76 $B \to K^0_SX$ candidates. We estimate from Monte Carlo simulation that $10-20\%$ of the selected candidates come from $b \to c$ decays, which can produce kaons of momentum higher than 2.34 GeV in the decay of D mesons. Contamination from unflavored $b \to u$ and $b \to d$ transitions is negligible for $B \to K^0_SX$, and estimated to contribute to 2.4% of the $B \to K^+X$ sample via K/π mis-identification.

4 MAXIMUM LIKELIHOOD FIT

We obtain yields for each decay from an extended unbinned ML fit with the following input observables: $m_{\rm ES}$, $\mathcal{F}$, and $p^\star(K)$. As described below, the fit is first applied with several probability density function (PDF) parameters floating to samples obtained with $p^\star(K) > 1.8\,{\rm GeV}$. The signal yield is then extracted from a fit to the $p^\star(K) > 2.34\,{\rm GeV}$ samples, in which the $B\overline{B}$ background yield and $p^\star(K)$ PDF are fixed to the results of the first fit.

For each event i and hypothesis j (signal $B \to KX$, $B\overline{B}$ background, continuum background), we define the probability density function (PDF)

$$\mathcal{P}^i_j = \mathcal{P}_j({m_{\rm ES}}^i)\mathcal{P}_j(\mathcal{F}^i)\mathcal{P}_j(p^{\star i}). \tag{1}$$

The likelihood function is

$$\mathcal{L} = \exp\,(-\sum_j Y_j) \prod_i^N \left[\sum_j Y_j \mathcal{P}^i_j\right] \,, \tag{2}$$

where Y_j is the yield of events of hypothesis j, to be found by maximizing $\mathcal{L}$. N is the number of events in the sample.

The $m_{\rm ES}$ and $\mathcal{F}$ variables discriminate between $B\overline{B}$ and $q\overline{q}$ continuum events. For these variables, the same PDF is used for the $B \to KX$ signal and $B\overline{B}$ background components. The $m_{\rm ES}$ PDF for $q\overline{q}$ continuum is parametrized by an empirical phase-space function [15] of the form

$$f(x) \propto x\sqrt{1-x^2}\exp\left[-\xi(1-x^2)\right] \tag{3}$$

where $x \equiv 2m_{\rm ES}/\sqrt{s}$, and ξ is a parameter determined by the fit. For B decays, $m_{\rm ES}$ is modeled by the sum of two Gaussians and the function of Eq. 3 with a different value of ξ. The $\mathcal{F}$ PDF is parametrized as a bifurcated Gaussian plus a Gaussian for $B\overline{B}$ events, and as two Gaussians for

$q\overline{q}$ continuum. The $p^\star(K)$ PDF is defined over the wider range $p^\star(K) > 1.8\,\mathrm{GeV}$. For the signal $B \to KX$, the PDF is the sum of a phase-space function given by Eq. 3, with $x \equiv p^\star(K)/2.62\,\mathrm{GeV}$, and a Gaussian to account for the contribution from exclusive 2-body decays such as $B \to \eta' K$. The parameters of the signal $p^\star(K)$ PDF will be varied in the evaluation of the systematic errors, as the $p^\star(K)$ spectrum is not well known. The $B\overline{B}$ background PDF is the sum of three Gaussians, two of them used to model the $B \to DK$ and $B \to D^* K$ contributions. The $q\overline{q}$ component is described by the sum of an exponential and a Gaussian. All the PDF distributions are illustrated in Figs. 1 and 2.

The PDF for each variable and each component is initially determined from Monte Carlo (MC) simulation. A preliminary ML fit with several free PDF parameters is applied to the sample obtained with the relaxed requirement $p^\star(K) > 1.8\,\mathrm{GeV}$. This range of $p^\star(K)$ includes too much background for an accurate determination of the signal yield, but it allows the measurement of the yield and the $p^\star(K)$ PDF for the $B\overline{B}$ component. The free parameters of this fit are the three yields, the fractions of neutral B_{reco} candidates for each component, the size of the $p^\star(K)$ secondary Gaussians for the signal and $B\overline{B}$ components, the width of the $p^\star(K)$ main Gaussian for the $B\overline{B}$ component, and the m_{ES} exponent parameter for the $q\overline{q}$ component. The results are illustrated in Fig. 1, which shows the projections onto $p^\star(K^+)$ and $p^\star(K^0_S)$ of subsamples enriched with a threshold requirement on the signal likelihood computed without the variable plotted.

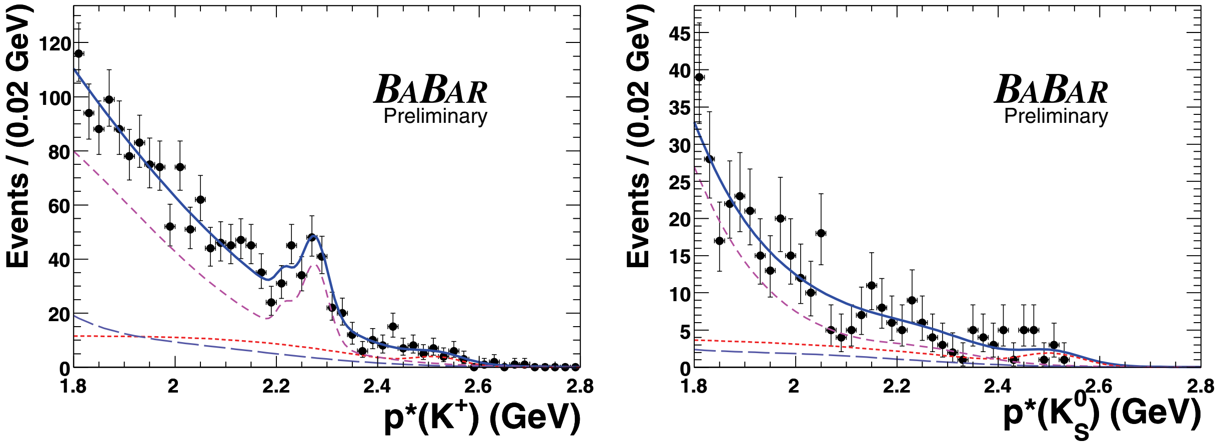

Figure 1: Projection plots for the $p^\star(K^+)$ (left) and $p^\star(K^0_S)$ (right) variables from the fits to the $p^\star(K) > 1.8\,\mathrm{GeV}$ samples. The projections are obtained with a cut on the signal likelihood (see text) retaining about 80% of the signal events. The points are from the data, the full line shows the full fit, the dotted line the signal, the short-dashed line the $B\overline{B}$ background, and the long-dashed line the $q\overline{q}$ continuum background.

The PDFs determined in the first fit are then used in a second ML fit to the sample obtained with $p^\star(K) > 2.34\,\mathrm{GeV}$. Free parameters are the signal and $q\overline{q}$ continuum background yields, while the $B\overline{B}$ yield is fixed to the fraction of the value measured in the first fit ($p^\star(K) > 1.8\,\mathrm{GeV}$). Systematic errors account for the uncertainties in the fixed $B\overline{B}$ yield, as determined in the first fit and which include the affect of correlations with the signal component.

Monte Carlo simulated experiments are used to validate the fit procedure, and to evaluate possible biases in the yields due to our neglect of small residual correlations among discriminating variables. The bias is determined by fitting ensembles of simulated $q\overline{q}$ experiments drawn from the PDF into which we have embedded the expected number of signal and $B\overline{B}$ background events, randomly extracted from the fully simulated MC samples. The measured biases are listed in Table 1.

5 RESULTS

The partial branching fractions are calculated as

$$\mathcal{B}(B \to KX, p^{\star}(K) > 2.34\,\mathrm{GeV}) = \frac{Y_{KX} - Y_b}{\epsilon \cdot N(B_{\mathrm{reco}})}, \tag{4}$$

where Y_{KX} is the measured yield, Y_b is the fit bias, and ϵ is the reconstruction efficiency. The results of the fits to the $p^{\star}(K) > 2.34\,\mathrm{GeV}$ samples and the quantities used in the determination of the branching fractions are presented in Table 1. The significance is taken as the square root of the difference between the value of $-2\ln\mathcal{L}$ (with additive systematic uncertainties included) for zero signal and the value at its minimum. In Fig. 2 we show projections onto m_{ES}, $\mathcal{F}$ and $p^{\star}(K)$ of subsamples enriched with a threshold requirement on the signal likelihood computed without the variable plotted.

Table 1: Number of events to fit N_{cand}, fitted signal yield Y_{KX} in events (ev.), measured bias Y_b (see text), detection efficiency ϵ, significance $\mathcal{S}$ (with systematic uncertainties included), and measured partial branching fraction $\mathcal{B}$ for each mode. The first errors are statistical and the second are systematic. The quantity in parentheses is the 90% C.L. upper limit for the branching fraction $\mathcal{B}(B \to K^0X)$.

Mode	N_{cand}	Y_{KX} (ev.)	Y_b (ev.)	ϵ (%)	$\mathcal{S}$ (σ)	$\mathcal{B}$ (10^{-6})
$B \to K^+X$	246	$58.4^{+10.5}_{-9.7}$	2.2	16.1	6.0	196^{+37+31}_{-34-30}
$B \to K^0X$	76	$21.1^{+6.5}_{-5.7}$	2.8	6.7	3.1	154^{+55+55}_{-48-41} (< 266)

6 SYSTEMATIC STUDIES

We determine systematic uncertainties affecting the measurement of the yields, the estimation of the selection efficiencies, and the measurement of the number of B_{reco} candidates. The systematic uncertainties are summarized in Table 2.

The signal yield systematic errors arise from the fixed $B\overline{B}$ yields (31.0 ± 6.8 events for the charged decay mode and 13.8 ± 4.2 events for the neutral mode), which are varied within their uncertainties; the fit bias correction, for which we assign as systematic error the quadratic sum of the statistical uncertainty on the correction and one half of the correction itself; and the PDF parameter uncertainties, which are left free one by one in the fit and the variation in signal yield recorded. The dominant contribution to the PDF parameter uncertainties arises from the poorly known signal $p^{\star}(K)$ spectrum. We evaluate this uncertainty by floating in the fit the relative size and the mean of the Gaussian used in the description of the signal $p^{\star}(K)$ PDF.

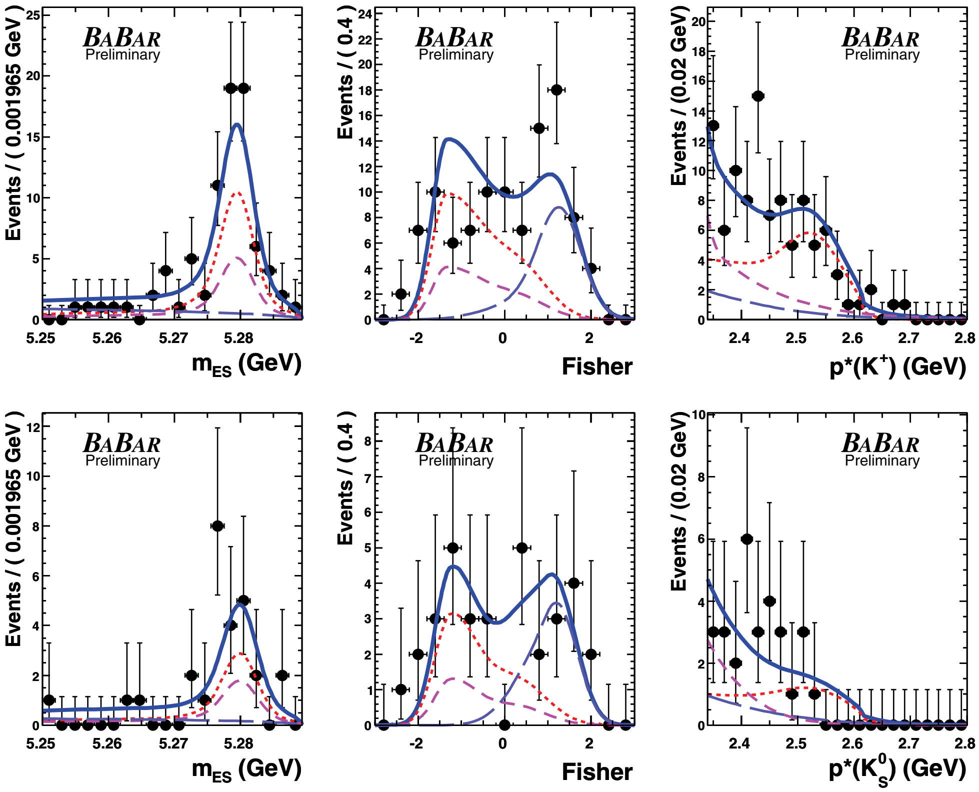

Figure 2: Projection plots for $m_{\rm ES}$ (left), $\mathcal{F}$ (center), and $p^\star(K)$ (right) from the fits to the $p^\star(K) > 2.34\,{\rm GeV}$ samples. The top plots are for the $B \to K^+X$ decay, and the bottom plots for $B \to K^0_S X$. The projections are obtained with a cut on the signal likelihood (see text) retaining about 85% of the $B \to K^+X$ signal events and 75% of the $B \to K^0_S X$ signal events. The points are from the data, the full line shows the full fit, the dotted line the signal, the short-dashed line the $B\overline{B}$ background, and the long-dashed line the $q\overline{q}$ continuum background.

Uncertainties on the selection efficiencies are dominated by the statistics of the inclusive $B \to KX$ Monte Carlo samples. We also include 0.5% uncertainty per track, 2.1% for the K^0_S, and 2.4% for the K^+ particle identification criteria.

The uncertainty in the number of fitted $B_{\rm reco}$ candidates is taken from the results of that fit (5%).

7 CONCLUSIONS

We have presented preliminary results for a study of inclusive charmless $B \to K^+X$ and $B \to K^0X$ decays, recoiling against fully reconstructed hadronic B decays from $\Upsilon(4S)$ decays. We measure the partial branching fractions for charged and neutral kaons with momentum above the end-point for $b \to c$ backgrounds ($p^\star(K) > 2.34\,{\rm GeV}$):

$$\mathcal{B}(B \to K^+X, p^\star > 2.34\,{\rm GeV}) = (196^{+37}_{-34}({\rm stat.})^{+31}_{-30}({\rm syst.})) \times 10^{-6}, \text{ and}$$
$$\mathcal{B}(B \to K^0X, p^\star > 2.34\,{\rm GeV}) = (154^{+55}_{-48}({\rm stat.})^{+55}_{-41}({\rm syst.})) \times 10^{-6} \ (< 266 \times 10^{-6} \text{ at 90\% C.L.}).$$

Table 2: Systematic uncertainties for the $B \to K^+X$ and $B \to K^0X$ decay modes. The multiplicative errors are fractional, and apply to the efficiency and to the B_{reco} counting, while the additive errors are in units of events and apply to the signal yields.

	$B \to K^+X$	$B \to K^0X$
Multiplicative errors (%)		
MC eff	9.4	16.1
Tracking eff/qual	0.5	1.0
K^0_S eff	–	2.1
Kaon PID	2.4	–
Number B_{reco}	5.0	5.0
Total multiplicative (%)	10.9	17.0
Additive errors (events)		
Fixed $b \to c$ yield	$^{+6.0}_{-5.6}$	$^{+4.1}_{-3.5}$
PDF parametrization	$^{+2.6}_{-2.4}$	$^{+3.9}_{-0.8}$
Fit bias	±1.2	±1.4
Total additive (events)	$^{+6.6}_{-6.2}$	$^{+5.8}_{-3.9}$

Known exclusive charmless two-body decays, dominated by the decays $B^+ \to \eta' K^+$ and $B^0 \to \eta' K^0$, account for approximately 60% of these branching fractions. Similar two-body decays with a K^* meson and three-body decays, such as $B^+ \to K^+K^-K^+$ and $B^0 \to K^+K^-K^0$, probably account for much of the remainder.

A theoretical model is necessary to extrapolate these results to the full $p^\star(K)$ spectrum, and ultimately to extract a measurement of the inclusive $b \to sg^\star$ branching fraction. Completing this extrapolation and assigning the theoretical systematic error from the shape of the $p^\star(K)$ spectrum is the focus of ongoing effort.

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