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Measurements of Branching Fractions and CP-Violating Asymmetries in B-Meson Decays to the Charmless Two-Body States $K^0\pi^+$, $\overline{K}^0K^+$, and $K^0\overline{K}^0$

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Abstract

We present preliminary measurements of branching fractions and CP-violating asymmetries in decays of B mesons to two-body final states containing a K^0. The results are based on a data sample of approximately 227 million $\Upsilon(4S) \to B\overline{B}$ decays collected with the *BABAR* detector at the PEP-II asymmetric-energy B Factory at SLAC. We measure $\mathcal{B}(B^+ \to K^0\pi^+) = (26.0 \pm 1.3 \pm 1.0) \times 10^{-6}$, $\mathcal{B}(B^+ \to \overline{K}^0K^+) = (1.45^{+0.53}_{-0.46} \pm 0.11) \times 10^{-6} (< 2.35 \times 10^{-6})$, and $\mathcal{B}(B^0 \to K^0\overline{K}^0) = (1.19^{+0.40}_{-0.35} \pm 0.13) \times 10^{-6}$, where the first uncertainty is statistical and the second is systematic, and the upper limit is at a 90% confidence level. The significance of the $\mathcal{B}(B^+ \to \overline{K}^0K^+)$ and $\mathcal{B}(B^0 \to K^0\overline{K}^0)$ results are 3.5σ and 4.5σ, respectively, including systematic uncertainties. In addition, we obtain a measurement of the CP-violating asymmetry for the $B^+ \to K^0\pi^+$ mode and we determine a 90% confidence-level interval for the asymmetry in the $B^+ \to \overline{K}^0K^+$ mode: $\mathcal{A}_{CP}(B^+ \to K^0\pi^+) = -0.087 \pm 0.046 \pm 0.010$ and $\mathcal{A}_{CP}(B^+ \to \overline{K}^0K^+) \in [-0.43, 0.68]$.

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1 Introduction

The decays of B mesons into charmless hadronic final states provide important information for the study of *CP* violation. In particular, the study of the two-body decays $B \to \pi\pi$, $B \to K\pi$, and $B \to KK$ provides crucial ingredients for measuring or constraining the values of the angles α and γ, defined as the following ratios of elements of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix [1]: $\alpha \equiv \arg\left[-V_{td}V_{tb}^{*}/V_{ud}V_{ub}^{*}\right]$ and $\gamma \equiv \arg\left[-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*}\right]$. In this paper, we present measurements of the branching fractions of B-meson decays to the charmless two-body final states $K^0\pi^+$, $\overline{K}^0K^+$, and $K^0\overline{K}^0$. [6] For the $B^+ \to K^0\pi^+$ and $B^+ \to \overline{K}^0K^+$ modes we also report measurements of the direct *CP* asymmetries in the decay rates,

$$\mathcal{A}_{CP} = \frac{\Gamma\left(B^- \to K^0_S h^-\right) - \Gamma\left(B^+ \to K^0_S h^+\right)}{\Gamma\left(B^- \to K^0_S h^-\right) + \Gamma\left(B^+ \to K^0_S h^+\right)}, \tag{1}$$

where $h = K, \pi$.

Measurements of the rates and charge asymmetries for $B \to K\pi$ decays can be used to establish direct *CP* violation and to constrain the angle γ [2]. The decay $B^+ \to K^0\pi^+$ is dominated by the $b \to s$-penguin process and in the Standard Model (SM) is expected to have $\mathcal{A}_{CP} < 1\%$ [3]. Thus, an observation of a sizable charge asymmetry could be an indication of non-SM contributions to the penguin-loop amplitude [3, 4]. The previously unobserved $B \to K\overline{K}$ decays proceed via penguin and W-exchange processes similar to those in $B^0 \to \pi^+\pi^-$ and can help in the determination of α in the measurement of time-dependent CP asymmetries in $B^0 \to \pi^+\pi^-$ [5]. Measurements of the branching fractions for these decay modes also provide important information regarding rescattering processes [6].

2 The *BABAR* detector and dataset

The measurements presented in this paper are based on data collected with the *BABAR* detector [7] at the PEP-II asymmetric-energy e^+e^- collider [8], located at the Stanford Linear Accelerator Center. The sample consists of 226.6 ± 2.5 million $B\overline{B}$ pairs produced at the $\Upsilon(4S)$ resonance ("on-resonance"), which corresponds to an integrated luminosity of about 205 fb^{-1}. An additional $16\,\mathrm{fb}^{-1}$ of data recorded at an e^+e^- center-of-mass (CM) energy approximately $40\,\mathrm{MeV}$ below the $\Upsilon(4S)$ resonance ("off-resonance") is used for background studies.

The *BABAR* detector is described in detail in [7]. Charged-particle momenta are measured in a tracking system consisting of a five-layer, double-sided silicon vertex detector and a 40-layer drift chamber (DCH), which operate in a solenoidal magnetic field of $1.5\,\mathrm{T}$. Particles are identified as pions or kaons based on the Cherenkov angle measured with a detector of internally reflected Cherenkov light (DIRC). The direction and energy of photons are determined from the energy deposits in a segmented CsI(Tl) electromagnetic calorimeter (EMC).

[6] Unless explicitly stated otherwise, charge-conjugate decay modes are assumed throughout this paper and branching fractions are averaged accordingly.

3 Analysis method

Hadronic events are selected on the basis of charged-particle multiplicity and event topology. We reconstruct B-meson candidates decaying to K^0X, where X can be π^+, K^- or $\overline{K}^0$. The K^0 candidates are reconstructed in the mode $K^0 \to K^0_S \to \pi^+\pi^-$.

The following selection criteria are applied to the candidate B-decay products. Charged tracks are required to be within the tracking fiducial volume and to have at least 12 DCH hits and a minimum transverse momentum of $0.1\,\mathrm{GeV}/c$. Tracks that are not K^0_S-decay products are required to originate from the interaction point, to be associated with at least six Cherenkov photons in the DIRC, and to have a Cherenkov angle within $4\,\sigma$ of the expected value for a pion or kaon hypothesis. Candidate K^0_S mesons are reconstructed from pairs of oppositely charged tracks that are consistent with originating from a common vertex, have an invariant mass within $\pm 11.2\,\mathrm{MeV}/c^2$ of the nominal K^0_S mass, and have a measured proper decay time greater than five times its uncertainty.

The B-meson candidate is characterized by two nearly uncorrelated kinematic variables: the energy-substituted mass, $m_{\rm ES} = \sqrt{\left(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B\right)^2 / E_i^2 - p_B^2}$, and the energy difference, $\Delta E = E^*_B - \sqrt{s}/2$, where the subscripts i and B refer to the initial e^+e^- system and the B candidate, respectively. The asterisk denotes the $\Upsilon(4S)$ rest frame (CM frame), and $\sqrt{s}$ is the total CM energy. The pion mass is assigned to all charged particles in the calculation of E^*_B. For $B^0 \to K^0\overline{K}^0$ candidates, we require $|\Delta E| < 0.1\,\mathrm{GeV}$, while for $B^+ \to K^0h^+$ candidates ($h = \pi, K$) we require $-0.115 < \Delta E < 0.075\,\mathrm{GeV}$. The interval is asymmetric in order to select both $B^+ \to K^0\pi^+$ and $B^+ \to \overline{K}^0K^+$ decays with nearly 100% efficiency. The ΔE distribution peaks near zero in the modes not containing charged kaons. In $B^+ \to \overline{K}^0K^+$ decays, the ΔE distribution peaks at $-45\,\mathrm{MeV}$ as a result of the assignment of the pion mass to the charged kaon candidate. The distribution of $m_{\rm ES}$ peaks at the B mass in all modes. We impose a loose selection of $5.20 < m_{\rm ES} < 5.29\,\mathrm{GeV}/c^2$ that includes a background-dominated region used to estimate the level of backgrounds in the signal region.

Simulated events [9], off-resonance data, and events in on-resonance $m_{\rm ES}$- and ΔE-sideband regions are used to study backgrounds. The contribution from other B-meson decays is found to be negligible. The primary source of background are random combinations of tracks and neutral clusters produced in $e^+e^- \to q\overline{q}$ events, where q is a u, d, s, or c quark. In the CM frame, these "combinatorial" events are characterized by a jet-like structure, in contrast to the more uniformly distributed decays of B mesons produced in $\Upsilon(4S)$ decays. We suppress combinatorial backgrounds by exploiting this topological difference through a selection based on θ^*_S, the angle between the sphericity axis of the B-candidate decay products and the sphericity axis of the remaining particles in the event. In the CM frame, this selection is $|\cos\theta^*_S| < 0.8$. To discriminate further between signal decays and combinatorial backgrounds, we employ a Fisher discriminant, $\mathcal{F}$. We define $\mathcal{F}$ as an optimized linear combination of $\sum_i p^*_i$ and $\sum_i p^*_i \cos^2\theta^*_i$ [10], where p^*_i is the momentum of particle i and θ^*_i is the angle between its momentum and the thrust axis of the B-candidate decay products, both calculated in the CM frame. The sums are over all particles in the event except for the B-candidate decay products. The difference between signal and background distributions of $\mathcal{F}$ is present in the probability density functions (PDF's) that model

$\mathcal{F}$ in the fits to the data sample, which we describe below.

Signal yields and charge asymmetries are determined from unbinned extended maximum-likelihood fits. The extended likelihood for a sample of N K^0X candidates is defined as

$$\mathcal{L} = \exp\left(-\sum_i n_i\right)\prod_{j=1}^{N}\left[\sum_i N_i \mathcal{P}_i(\vec{x}_j;\vec{\alpha}_i)\right], \tag{2}$$

where $\mathcal{P}_i(\vec{x}_j;\vec{\alpha}_i)$ is the PDF of a signal or background category i, evaluated at the values of the measured variables $\vec{x}_j$ of candidate j. The sum is over the set of categories. The parameters $\vec{\alpha}_i$ determine the expected distributions of measured variables in each category, and n_i are the yields being determined in the fit. The probability coefficients N_i are defined separately for each mode. We perform separate fits to the two samples of B candidates: $B^0 \to K^0\overline{K}^0$ and $B^+ \to K^0h^+$ ($h = \pi$, K). In the fit to the "neutral-B" ($B^0 \to K^0\overline{K}^0$) sample we include two categories, signal and background. The probability coefficients N_i are set equal to the yields ($N_i = n_i$); the yield in each category is obtained by maximizing the likelihood. In the fit to the "charged-B" ($B^+ \to K^0h^+$) sample, we fit simultaneously two signal categories, $B^+ \to K^0\pi^+$ and $B^+ \to \overline{K}^0K^+$, and two corresponding background categories. In addition, the probability coefficient for each category i is given by $N_i = n_i\,(1 - q_j\mathcal{A}_i)$, where n_i is the total yield, summed over charge states, $\mathcal{A}_i$ is the charge asymmetry, and q_j is the charge of the B candidate. The total yields and charge asymmetries are determined by maximizing $\mathcal{L}$.

As the input variables in the fit are nearly uncorrelated, the PDF in the likelihood function, $\mathcal{P}_i(\vec{x}_j;\vec{\alpha}_i)$, is constructed as the product of the individual PDF's of the input variables $\vec{x}_j$. In both fits, the set of input variables contains $m_{\rm ES}$, ΔE, and $\mathcal{F}$. In the fit to the $B^+ \to K^0h^+$ sample, we include also the normalized Cherenkov-angle residuals $(\theta_c - \theta_c^\pi)/\sigma_{\theta_c}$ and $\left(\theta_c - \theta_c^K\right)/\sigma_{\theta_c}$, where θ_c is the measured Cherenkov angle of the primary daughter h^+, σ_{θ_c} is its measurement uncertainty, and θ_c^π (θ_c^K) is the expected Cherenkov angle for a pion (kaon) hypothesis. The quantities σ_{θ_c}, θ_c^π, and θ_c^K are measured separately for negatively and positively charged pions and kaons from a control sample of $D^0 \to K^-\pi^+$ decays originating from D^{*+} decays.

The parameterization of the PDF's is determined from data and Monte Carlo-simulated (MC) samples. Some PDF parameters are free to vary in the fit as explained below. The signal $m_{\rm ES}$ PDF's for $B^+ \to K^0h^+$ and $B^0 \to K^0\overline{K}^0$ are derived from signal MC samples. The shape of the distribution is modeled as a Gaussian function with an asymmetric variance and a low-side power tail in the K^0h^+ fit, while in the $K^0\overline{K}^0$ fit it is parameterized as a linear combination of two Gaussian functions ("double-Gaussian" function). The mean value of the signal $m_{\rm ES}$ distribution is a free parameter in the $B^+ \to K^0h^+$ fit, as the sample of candidates is sufficiently large. To describe the background $m_{\rm ES}$ PDF, we use an empirical threshold function [11]. The shape parameter of this function is a free parameter in the $B^+ \to K^0h^+$ fit, while in the $B^0 \to K^0\overline{K}^0$ fit it is determined from the on-resonance ΔE-sideband region, defined by the selection $0.1 < |\Delta E| < 0.3\,\mathrm{GeV}$.

The signal ΔE PDF's are derived from MC samples and modeled as double-Gaussian functions for both modes. The signal ΔE distribution is expected to be centered near zero

Table 1: Summary of results for numbers of selected K^0X candidates N, total detection efficiencies ε, fitted signal yields N_S, statistical significances S including systematic uncertainties, charge-averaged branching fractions $\mathcal{B}$, and charge asymmetries $\mathcal{A}_{CP}$. The efficiencies include the branching fractions of intermediate states ($K^0 \to K^0_S \to \pi^+\pi^-$). Branching fractions are calculated assuming equal rates for the $\Upsilon(4S) \to B^0\overline{B}^0$ and $\Upsilon(4S) \to B^+B^-$ processes. The upper limit for the $\overline{K}^0K^+$ branching fraction corresponds to a 90% confidence-level (C.L.), and the central value is given in parentheses. The 90% C.L. asymmetry interval is given for $\overline{K}^0K^+$, including the systematic uncertainty. The 90% C.L. asymmetry interval for $K^0\pi^+$ is $[-0.164, -0.010]$.

Mode	N	ε (%)	N_S	$S(\sigma)$	$\mathcal{B}(10^{-6})$	$\mathcal{A}_{CP}$
$K^0\pi^+$	20441	12.6 ± 0.3	$744\ ^{+37}_{-36}\ ^{+21}_{-17}$	–	$26.0 \pm 1.3 \pm 1.0$	$-0.087 \pm 0.046 \pm 0.010$
$\overline{K}^0K^+$		12.5 ± 0.3	$41\ ^{+15}_{-13}\ ^{+3}_{-2}$	3.5	$< 2.35\,(1.45^{+0.53}_{-0.46} \pm 0.11)$	$[-0.43, 0.68]$
$K^0\overline{K}^0$	1939	8.5 ± 0.5	$23.0\ ^{+7.7}_{-6.7}\ ^{+1.9}_{-2.0}$	4.5	$1.19^{+0.40}_{-0.35} \pm 0.13$	–

for the $K^0\pi^+$ mode, while for $\overline{K}^0K^+$ candidates, the mean of ΔE is shifted because the pion mass is assumed for the charged track. The shift in ΔE is

$$\langle \Delta E \rangle = -\gamma_{\mathrm{boost}} \times \left(\sqrt{M_K^2 + p^2} - \sqrt{M_\pi^2 + p^2} \right) ,$$

where p is the momentum of the track, and M_π and M_K are the nominal values of the pion mass and the kaon mass, respectively. The ΔE mean value is a free parameter in the $B^+ \to K^0h^+$ fit, while in the $B^0 \to K^0\overline{K}^0$ fit it is determined through a comparison of the values obtained in the two MC samples with the value obtained in the fit to the $B^+ \to K^0h^+$ data sample. The background ΔE distribution is modeled as a second- and first-degree polynomial function for the charged-B and neutral-B modes, respectively. The polynomial coefficients are determined from on-resonance events in the m_{ES}-sideband region, defined by the selection $5.20 < m_{\mathrm{ES}} < 5.26\,\mathrm{GeV}/c^2$.

In both modes, the signal $\mathcal{F}$ distribution is modeled as a Gaussian function with an asymmetric variance [12]. Its parameters are free to vary in the K^0h^+ fit; in the $K^0\overline{K}^0$ fit, they are determined from the MC sample. The background $\mathcal{F}$ distribution is parameterized as a double-Gaussian function with its parameters left free to vary in both fits.

In the charged-B modes, the normalized Cherenkov-angle residuals are modeled as double-Gaussian functions; the PDF parameters are taken from the D^* control sample and they are determined separately for π^+, π^-, K^+, and K^- tracks as a function of momentum and polar angle.

4 Physics results and systematic uncertainties

The results of the two maximum-likelihood fits are summarized in Table 1. The $K^0\overline{K}^0$ final state is an equal admixture of $K^0_SK^0_S$ and $K^0_LK^0_L$. We therefore use a 50% probability for the

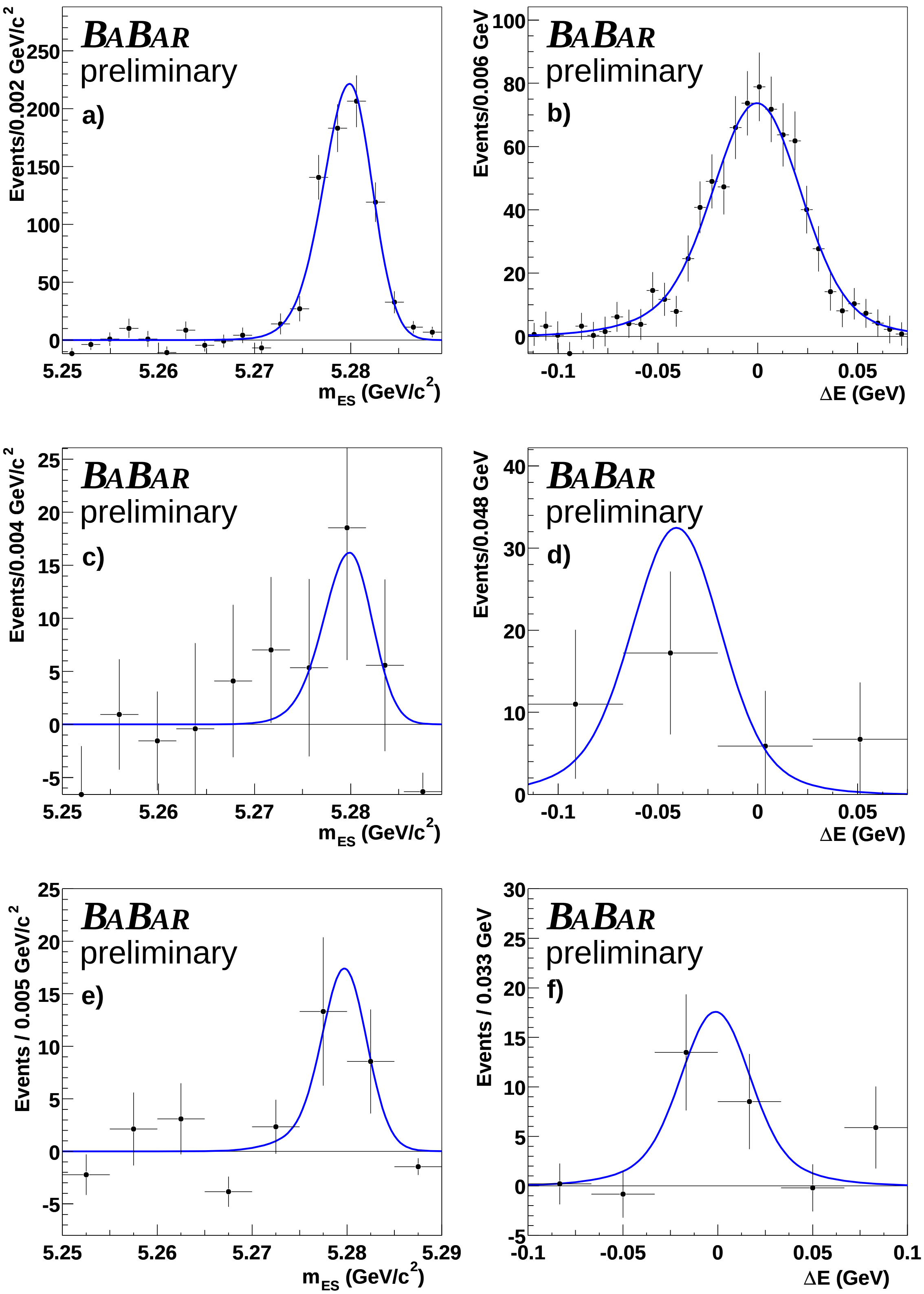

Figure 1: Distributions of $m_{\rm ES}$ and ΔE for (a,b) $B^+ \to K^0_S\pi^+$, (c,d) $B^+ \to K^0_S K^+$ and (e,f) $B^0 \to K^0_S K^0_S$ (histograms) after background subtraction (see text). Projections of the fit PDF's are overlaid (solid curves).

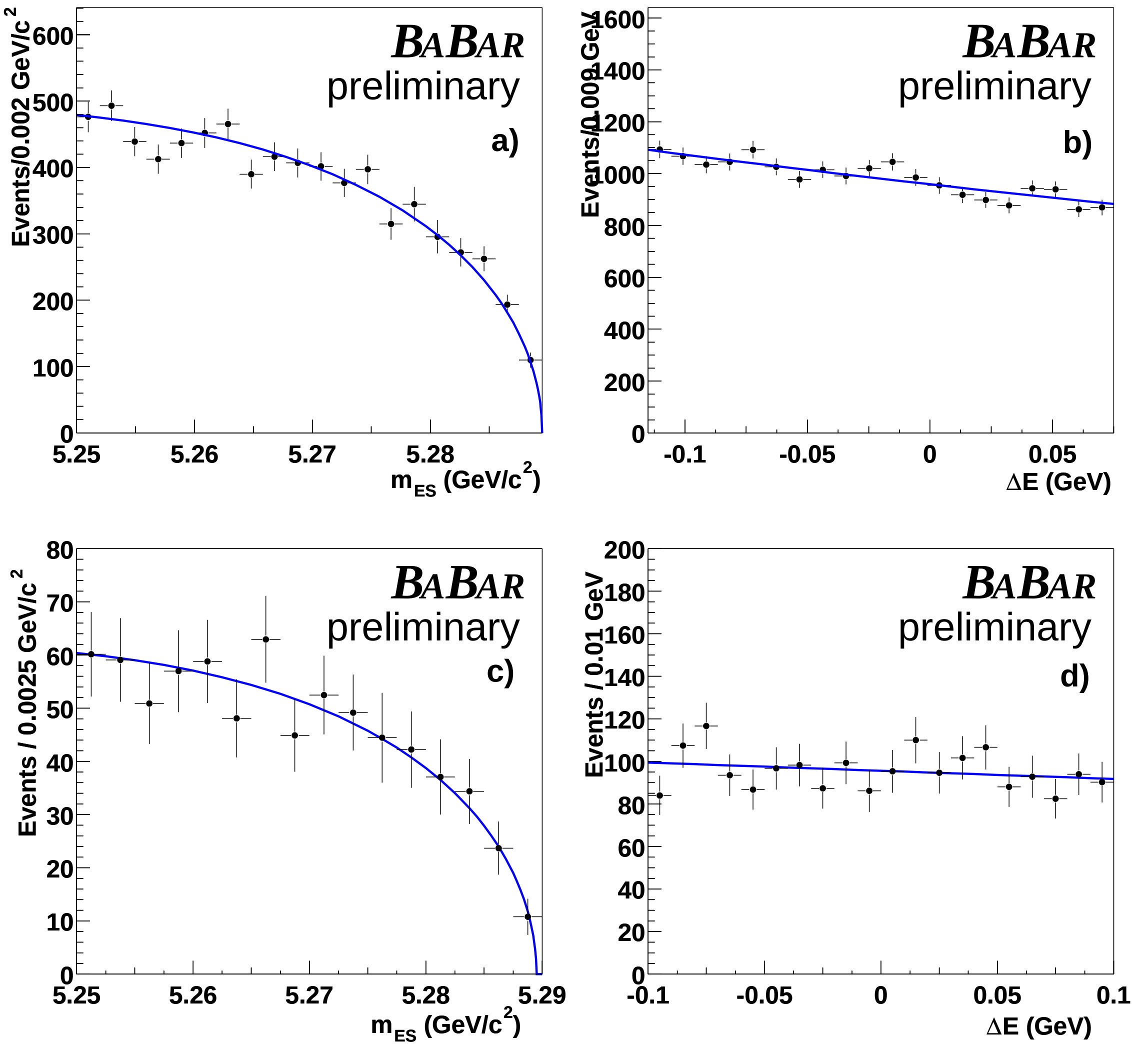

Figure 2: Distributions of m_{ES} and ΔE for (a,b) $B^+ \to K^0_S h^+$ and (c,d) $B^0 \to K^0_S K^0_S$ (histograms) after signal subtraction (see text). Projections of the fit PDF's are overlaid (solid curves).

$K^0\overline{K}^0$ to decay as $K^0_S K^0_S$ in computing the $B^0 \to K^0\overline{K}^0$ branching fraction. We also use the current world averages for $\mathcal{B}(K^0_S \to \pi^+\pi^-)$ [13].

Figure 1 shows background-subtracted distributions of $m_{\rm ES}$ and ΔE for $B^+ \to K^0 h^+$ and $B^0 \to K^0\overline{K}^0$ candidates. The background subtraction is performed by weighting events using the ${}_s\mathcal{P}lot$ technique described in Ref. [14]. The shape of the resulting distribution can be compared with the PDF used in the full fit. We find good agreement in both variables for K^0h^+ and $K^0\overline{K}^0$ candidates. The corresponding signal-subtracted distributions of $m_{\rm ES}$ and ΔE are shown in Figure 2.

The signal significance is defined as the square root of the difference in $-2\ln\mathcal{L}$ between the best fit and the null-signal hypothesis. The upper limit on the signal yield for a given mode i is defined as the value of $n_i^{\rm UL}$ for which $\int_0^{n_i^{\rm UL}} \mathcal{L}_{\rm max} dn_i / \int_0^{\infty} \mathcal{L}_{\rm max} dn_i = 0.9$, where $\mathcal{L}_{\rm max}$ is the likelihood as a function of n_i, maximized with respect to the remaining fit parameters. Branching-fraction upper limits are then calculated by increasing the signal-yield upper limit and reducing the efficiency by their respective systematic uncertainties.

Systematic uncertainties in the signal yields arise primarily from imperfect knowledge of the PDF parameterizations. Such systematic errors are evaluated either by varying the PDF parameters by their measured (1σ) uncertainties or by substituting alternate parameterizations. The significance of each signal yield with the systematic uncertainties included is evaluated by imposing simultaneously in the fit all of the systematic variations of the PDF's that lower that signal yield. Systematic uncertainties in the efficiency include uncertainties in tracking and K^0_S reconstruction.

In the K^0h^+ sample, the dominant systematic uncertainty is that associated with the signal $m_{\rm ES}$ shape, leading to a systematic error of ${}^{+13}_{-15}$ (${}^{+1.3}_{-1.7}$) events, and that associated with the signal ΔE resolution, leading to a systematic error of ${}^{+16}_{-5}$ (${}^{+2.8}_{-0.7}$) events in the $B^+ \to K^0\pi^+$ ($\overline{K}^0K^+$) mode. The significance of the $B^+ \to K^0K^+$ observation with (without) the systematic uncertainty included is $3.5\,\sigma$ ($3.7\,\sigma$). In the $B^0 \to K^0\overline{K}^0$ mode, the main systematic uncertainty is that associated with the background $m_{\rm ES}$ distribution (± 0.8 events). There is also a sizable systematic contribution from the imperfect agreement between MC and data samples (± 1.4 events) and, in the branching-fraction extraction, the uncertainty in the K^0_S efficiency (6.0%). The significance of the $B^0 \to K^0\overline{K}^0$ observation with (without) the systematic uncertainty included is $4.5\,\sigma$ ($4.8\,\sigma$). The systematic uncertainties in the charge asymmetries in the $B^+ \to K^0\pi^+$ mode are evaluated by adding in quadrature the contributions from PDF variations and the upper limit on intrinsic charge bias in the detector (± 0.010).

5 Summary

We present preliminary measurements of the branching fraction and the CP-violating charge asymmetry in the $B^+ \to K^0\pi^+$ decay, and a preliminary measurement of the branching fraction of the $B^0 \to K^0\overline{K}^0$ decay. No evidence of direct CP violation in the $B^+ \to K^0\pi^+$ mode is observed. The $B^0 \to K^0\overline{K}^0$ measurement constitutes the first observation of this decay channel: the probability of obtaining our result assuming the null-signal hypothesis is 3.4×10^{-6}. We have also searched for the $B^+ \to \overline{K}^0K^+$ decay and set an upper limit on its branching fraction at 2.35×10^{-6} at the 90% C.L. The branching-fraction measurements reported here are consistent with previous measurements of the same quantities [15, 17, 18, 16], but are extracted from a data sample larger by a factor of 2.6.

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