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MEASUREMENT OF BRANCHING FRACTIONS AND CP VIOLATION

IN $B \rightarrow \eta_c K$ AND OBSERVATION OF $B^\pm \rightarrow ppK^\pm$

A DISSERTATION SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAI'I IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

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Fang Fang

Dissertation Committee:

Thomas Browder, Chairperson
Stephen Olsen
Sandip Pakvasa
Pui Lam
Brent Tully
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Abstract

We report measurements of branching fractions for charged and neutral $B \to \eta_c K$ decays, and determine the $\eta_c$ mass and width. The results are based on an analysis of 29.1 fb$^{-1}$ of data collected by the Belle detector at KEKB. We also report a measurement of the $CP$ violation parameter $\sin(2\phi_1)$ in $B^0 \to \eta_c K_S^0$ based on an analysis of a 78 fb$^{-1}$ of data sample.

We report the observation of the decay mode $B^\pm \to ppK^\pm$ based on an analysis of 29.4 fb$^{-1}$ of data collected by the Belle detector at KEKB. This is the first example of a $b \to s$ transition with baryons in the final state. The $pp$ mass spectrum in this decay is inconsistent with phase space and is peaked at low mass. The branching fraction for this decay is measured to be $B(B^\pm \to ppK^\pm) = (4.7^{+1.1}_{-0.9}(\text{stat}) \pm 0.5(\text{syst})) \times 10^{-6}$. We also report upper limits for the decays $B^0 \to ppK_S$ and $B^\pm \to pp\pi^\pm$. 
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Chapter 1

Introduction

1.1 The Standard Model

The Standard Model for particle physics is the theory of fundamental particles and their interactions. It has been tremendously successful and has survived all experimental tests since it was developed in the 60’s and 70’s.

In the Standard Model, the elementary building blocks of particles are quarks and leptons, which are fermions with spin angular momentum equal to $\frac{1}{2}$. There are altogether three generations of quarks and leptons and their antiparticle counterparts. Their masses and electric charges are listed in Table 1.1. Quarks, carrying a fractional electric charge, are only found inside composite particles known as hadrons. There are two classes of hadrons: baryons composed of three quarks or antiquarks, and mesons composed of a quark and an antiquark. In contrast to quarks, leptons can be observed as free particles.

Particles interact via the strong, the electromagnetic, the weak and the gravitational forces. At the subatomic scale, the gravitational force is much weaker than the other forces and is negligible in the Standard Model. These forces are transmitted between particles by exchange of the gauge bosons listed in Table 1.2. The strong
interaction, carried by gluons, is responsible for binding quarks together to form hadrons. Leptons do not feel the strong force. Quantum chromodynamics (QCD) is the field theory that describes the strong interaction. The Standard Model incorporates QCD and the theory of the electroweak interaction, the unified electromagnetic and weak interactions, into a $SU(3) \otimes SU(2) \otimes U(1)$ gauge theory.

Table 1.1: Table of the Standard Model fundamental particles [1]. Each has an antiparticle counterpart with the same mass and opposite quantum numbers. The first generation of quarks (u and d) and leptons ($e$ and $\nu_e$) is by far the most common in nature.

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Flavor</th>
<th>Charge</th>
<th>Mass (GeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>+2/3</td>
<td>0.0015</td>
<td>0.0045</td>
</tr>
<tr>
<td>d</td>
<td>−1/3</td>
<td>0.005</td>
<td>0.0085</td>
</tr>
<tr>
<td>c</td>
<td>+2/3</td>
<td>1.0 − 1.4</td>
<td></td>
</tr>
<tr>
<td>s</td>
<td>−1/3</td>
<td>0.080 − 0.155</td>
<td></td>
</tr>
<tr>
<td>t</td>
<td>+2/3</td>
<td>174.3 ± 5.1</td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>−1/3</td>
<td>4.0 − 4.5</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Leptons</th>
<th>Flavor</th>
<th>Charge</th>
<th>Mass (GeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>−1</td>
<td>0.000511</td>
<td></td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>0</td>
<td>&lt; 3 × 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>$\mu$</td>
<td>−1</td>
<td>0.106</td>
<td></td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>0</td>
<td>&lt; 0.00019</td>
<td></td>
</tr>
<tr>
<td>$\tau$</td>
<td>−1</td>
<td>1.777</td>
<td></td>
</tr>
<tr>
<td>$\nu_\tau$</td>
<td>0</td>
<td>&lt; 0.0182</td>
<td></td>
</tr>
</tbody>
</table>

Table 1.2: Table of the Standard Model gauge bosons.

<table>
<thead>
<tr>
<th>Gauge boson</th>
<th>Interaction</th>
<th>Charge</th>
<th>Mass (GeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$</td>
<td>electroweak</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$W^{\pm}$</td>
<td>electroweak</td>
<td>±1</td>
<td>80.4</td>
</tr>
<tr>
<td>$Z^0$</td>
<td>electroweak</td>
<td>0</td>
<td>91.19</td>
</tr>
<tr>
<td>g</td>
<td>strong</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
The quark mass eigenstates are different from the weak interaction eigenstates. The mixing of the three generations of quarks can be described by a $3 \times 3$ unitary matrix known as the Cabibbo-Kobayashi-Maskawa (CKM) matrix [2, 3],

$$
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix} =
\begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix},
$$

where $(d,s,b)$ are the mass eigenstates. The CKM matrix describes the flavor-changing electroweak interactions. The nine elements represent the couplings of the quarks to the $W$ bosons.

The CKM matrix is determined from four independent parameters that include an irreducible phase angle that breaks $CP$ symmetry in the weak interactions. They are part of the free parameters of the Standard Model. In the commonly used Wolfenstein parameterization [4], the CKM matrix elements are approximated in terms of the parameters labeled as $A$, $\lambda$, $\rho$ and $\eta$,

$$
V = \begin{pmatrix}
  1 - \frac{1}{2} \lambda^2 & \lambda & A \lambda^3 (\rho - i \eta) \\
  -\lambda & 1 - \frac{1}{2} \lambda^2 & A \lambda^2 \\
  A \lambda^3 (1 - \rho - i \eta) & -A \lambda^2 & 1
\end{pmatrix} + \mathcal{O}(\lambda^4).
$$

The weak phase appears in the transitions between the first and the third generations. These parameters have to be measured. They can be extracted by measuring the CKM matrix elements via relevant decay processes. Assuming only three generations and unitarity, 90% confidence limits on the magnitudes of each element are found to be [1]

$$
|V| = \begin{pmatrix}
  0.9741 - 0.9756 & 0.219 - 0.226 & 0.0025 - 0.0048 \\
  0.219 - 0.226 & 0.9732 - 0.9748 & 0.038 - 0.044 \\
  0.004 - 0.014 & 0.037 - 0.044 & 0.9990 - 0.9993
\end{pmatrix}.
$$
Figure 1.1: (a) The unitarity triangle in the complex plane representing Eqn. (1.4). (b) The rescaled unitarity triangle in the \( \rho-\eta \) plane where \( \bar{\rho} = \rho(1 - \lambda^2/2) \) and \( \bar{\eta} = \eta(1 - \lambda^2/2) \).

While the parameter \( \lambda \), which is the sine of the Cabibbo angle \( \theta_C \), and \( A \) are well determined with better than 5% accuracy, the other two parameters, \( \rho \) and \( \eta \) are poorly determined.

The unitarity condition, \( VV^\dagger = 1 \), on the CKM matrix leads to six orthogonality relations among the matrix elements. They can be represented by six triangles in the complex plane. The unitarity triangle representing the orthogonality relation between the first and the third column,

\[
V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0, \tag{1.4}
\]

is shown in Fig. 1.1. This unitarity triangle controls \( b \) quark decays. In the \( \rho-\eta \) plane,
it is convenient to rescale the three sides of the triangle by $|V_{cd}V_{cb}^*|$ to make the side on the real axis of unit-length. The interior angles of the triangle, $\phi_1$, $\phi_2$ and $\phi_3$, are defined by

$$\phi_1 = \pi - \arg\left(\frac{-V_{td}V_{tb}^*}{-V_{cd}V_{cb}^*}\right),$$
$$\phi_2 = \arg\left(\frac{V_{td}V_{tb}^*}{-V_{ud}V_{ub}^*}\right),$$
$$\phi_3 = \arg\left(\frac{V_{ud}V_{ub}^*}{-V_{cd}V_{cb}^*}\right).$$

(1.5)

A nonzero value of the angle $\phi_1$, $\phi_2$ or $\phi_3$ indicates a non-vanishing phase in the CKM matrix and, hence, a $CP$ violation.

Although the Standard Model has successfully predicted and explained all experimental results, it has known flaws. For example, it does not explain why a particle has a certain mass, and why there are exactly three generations of fundamental particles. It requires the input of a set of 19 free parameters, including the particle masses and the coupling constants, that have to be determined experimentally. Exploration of the Standard Model at ever deeper levels and searches for new phenomena beyond its predictions are essential for a better theory.

1.2 $CP$ Violation

$CP$ symmetry consists in the invariance of physics laws under the combined transformations of charge conjugation $C$ and space-inversion $P$. Violation of $CP$ symmetry means the violation of symmetry between particle and antiparticle. A $CP$ violating process is necessary to generate the matter-antimatter asymmetry of the Universe [5].

$CP$ had been found to be a good symmetry until Christenson, Cronin, Fitch and Turlay discovered that it is violated in the neutral-kaon system in 1964 [6]. The short-lived neutral kaon, $K_S$, decays dominantly to a $2\pi$ state that has $CP = 1$. If $CP$ was
conserved, the long-lived neutral kaon $K_L$ would be the $CP$ eigenstate with eigenvalue $-1$, and, $K_L \rightarrow 2\pi$ is forbidden by $CP$ symmetry. Completely unexpectedly, they found that $K_L$ can also decay to the $2\pi$ state with the ratio of branching fractions

$$\frac{B(K_L \rightarrow \pi^+\pi^-)}{B(K_S \rightarrow \pi^+\pi^-)} = (2.0 \pm 0.4) \times 10^{-3}. \quad (1.6)$$

The result indicates that $CP$ is violated by a small amount for neutral-kaon decays.

The small violation of $CP$ symmetry in the neutral-kaon system can be accommodated by the Standard Model. Much larger $CP$ violation is also expected in the $B$ meson system [7, 8]. However, the $CP$ violation allowed by the Standard Model is too small to explain the matter-antimatter asymmetry of the Universe, the magnitude of which is expressed as

$$\eta = \frac{n_B}{n_\gamma}, \quad (1.7)$$

where $n_B$ is the difference between the density of baryons and antibaryons and $n_\gamma$ is the photon density. The Standard Model $CP$ violation generates a $\eta$ [9, 10] that is more than ten orders of magnitude smaller than the observed range of values, $(2.6-6.3) \times 10^{-10}$ [1].

Two classes of $CP$ violations exist: direct and indirect. In the $B$ meson system, direct $CP$ violation may arise from a difference in decay rates of $B^+$ ($B^0$) and $B^-$ ($\bar{B}^0$) to charge conjugate states. Whereas, indirect $CP$ violation may arise from an interference between $B^0-\bar{B}^0$ mixing and direct decay amplitudes.

### 1.3 $B$ Meson Decays

The $b$ quark, discovered at Fermilab in 1977, is the second heaviest quark. It exists inside $B$ mesons, which are bound states of a $b$ quark and a light anti-quark. In this thesis we study only $B^+ (u\bar{b})$ and $\bar{B}^0 (d\bar{b})$ mesons\footnote{The inclusion of the charge conjugate state is implied throughout this thesis} and refer to them hereafter as
$B$ mesons. The lifetimes and masses of $B^+$ and $\bar{B}^0$ mesons are listed in Table 1.3. Although the $b$ quark is massive, $B$ mesons have relatively long lifetimes because they decay only via the weak interaction, and furthermore primarily through the quite weak $b \to c$ transition specified by the $V_{cb}$ element of the CKM matrix. $B$ meson decays provide a unique experimental environment to measure the unitarity triangle and to search for physics beyond the Standard Model.

<table>
<thead>
<tr>
<th>B meson</th>
<th>Lifetime ($10^{-12}$ s)</th>
<th>Mass (GeV/c$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+$</td>
<td>1.674 ± 0.018</td>
<td>5.2790 ± 0.0005</td>
</tr>
<tr>
<td>$B^0$</td>
<td>1.542 ± 0.016</td>
<td>5.2794 ± 0.0005</td>
</tr>
</tbody>
</table>

### 1.3.1 $B^0$-$\bar{B}^0$ Mixing and $CP$ Violation

The $B^0$ and $\bar{B}^0$ mesons can transform from one to the other, like the neutral $K$ mesons, by the second order weak interaction shown in Fig. 1.2. This phenomenon is known as mixing. The diagrams with an intermediate $t$ quarks are dominant because of the large $t$ quark mass. The mass eigenstates of the neutral $B$ system are mixtures of the flavor eigenstates $B^0$ and $\bar{B}^0$. Assuming $CPT$ symmetry, they can be expressed as

$$|B_H\rangle = p|B^0\rangle + q|\bar{B}^0\rangle$$

$$|B_L\rangle = p|B^0\rangle - q|\bar{B}^0\rangle,$$

where the eigenvalues are $\mu_{H,L} = M_{H,L} - \frac{i}{2} \Gamma_{H,L}$. Hence, a state starting with pure $|B^0\rangle$ or $|\bar{B}^0\rangle$ at $t = 0$ evolves with time as

$$|B^0(t)\rangle = g_+(t)|B^0\rangle + \frac{2}{p} g_-(t)|\bar{B}^0\rangle$$
Consider the decays of $B^0$ and $\bar{B}^0$ into a final state $f$ that is common to both mesons. $CP$ violation occurs if there is an asymmetry in the time-dependent decay rates of $B^0 \to f$ and $\bar{B}^0 \to f$. The time-dependent asymmetry is derived to be

$$A_{CP}(t) = \frac{\Gamma[\bar{B}^0(t) \to f] - \Gamma[B^0(t) \to f]}{\Gamma[\bar{B}^0(t) \to f] + \Gamma[B^0(t) \to f]} \approx \frac{1}{1 + |\lambda_f|^2} [(1 - |\lambda_f|^2)\cos(\Delta m_B t) + 2\text{Im}\lambda_f \sin(\Delta m_B t)],$$

(1.11)

where $\Delta m_B$ is the mass difference of $B^0$ and $\bar{B}^0$, and $\lambda_f$ is defined as

$$\lambda_f = \frac{q\bar{A}_f}{pA_f}.$$

(1.12)

The quantities $A_f$ and $\bar{A}_f$ represent the decay amplitudes for $B^0 \to f$ and $\bar{B}^0 \to f$, respectively. The first term in Eqn. (1.11) proportional to $\cos(\Delta m_B t)$ arises from direct $CP$ violation, while the second term proportional to $\sin(\Delta m_B t)$ arises from indirect $CP$ violation.
1.3.2 \( B \to \) Charmonium

In 1974, teams led by Burton Richter [11] and Samuel Ting [12] independently discovered the \( J/\psi \) particle and confirmed the existence of a fourth quark, the charm quark (c), for the first time. The \( J/\psi \) meson is the \( 1^3S_1 \) bound state of a c quark and an anti-c quark, which have parallel spins. The \( cc \) system is called charmonium. The \( \eta_c \) meson is the ground state charmonium, \( 1^1S_0 \), with the quarks having antiparallel spins. Fig. 1.3 shows the spectrum of the charmonium states and their transitions. The masses and widths are given in Table 1.4.

<table>
<thead>
<tr>
<th>( cc ) meson</th>
<th>Mass (MeV/c(^2))</th>
<th>Width (MeV/c(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta_c ) ( (1^1S_0) )</td>
<td>2979.7 ± 1.5</td>
<td>( 16.0^{+3.6}_{-3.2} )</td>
</tr>
<tr>
<td>( J/\psi ) ( (1^3S_1) )</td>
<td>3096.87 ± 0.04</td>
<td>( 0.087 \pm 0.05 )</td>
</tr>
<tr>
<td>( \chi_{c0} ) ( (1^3P_0) )</td>
<td>3415.1 ± 0.8</td>
<td>( 14.9^{+2.6}_{-2.3} )</td>
</tr>
<tr>
<td>( \chi_{c1} ) ( (1^3P_1) )</td>
<td>3510.51 ± 0.12</td>
<td>( 0.88 \pm 0.14 )</td>
</tr>
<tr>
<td>( \chi_{c2} ) ( (1^3P_2) )</td>
<td>3556.18 ± 0.13</td>
<td>( 2.00 \pm 0.18 )</td>
</tr>
<tr>
<td>( \eta'_c ) ( (2^1S_0) )</td>
<td>3654 ± 10</td>
<td>&lt; 55 [13]</td>
</tr>
<tr>
<td>( \psi' ) ( (2^3S_1) )</td>
<td>3685.96 ± 0.09</td>
<td>( 0.306 \pm 0.39 )</td>
</tr>
</tbody>
</table>

\( B \) decays to charmonium proceed mainly via \( b \to cc\bar{s} \) transitions. For \( B^0 \to J/\psi K^0 \), the dominant Feynman diagram is the color suppressed \( b \to c \) tree transition shown in Fig. 1.4 (a). The \( b \to s \) penguin diagram in Fig. 1.4 (b) is suppressed by a loop factor with respect to the tree diagram. The effective weak Hamiltonian has the form [14]

\[
H_{\text{eff}} = \frac{G_F}{\sqrt{2}} [V_{cb}^* V_{cs}(C_1(\mu)\mathcal{O}_1 + C_2(\mu)\mathcal{O}_2) - V_{tb}^* V_{ts} \sum_{i=3}^{10} C_i(\mu)\mathcal{O}_i],
\]

(1.13)

where \( C_i(\mu) \) are Wilson coefficients and \( \mathcal{O}_i \) are local operators defined as follows:

\[
\mathcal{O}_1 = (\bar{s}_i b_j)_{V-A}(\bar{c}_j c_i)_{V-A},
\]
Figure 1.3: Charmonium spectrum and transitions below the $D\bar{D}$ threshold. States that have not been observed are indicated with a dashed line.

\begin{align}
\mathcal{O}_2 &= (\bar{s}b)_{V-A}(\bar{c}c)_{V-A}, \\
\mathcal{O}_3(5) &= (\bar{s}b)_{V-A} \sum_q (\bar{q}q)_{V-A(V+A)}, \\
\mathcal{O}_4(6) &= (\bar{s}_ib_j)_{V-A} \sum_q (\bar{q}_jq_i)_{V-A(V+A)}, \\
\mathcal{O}_7(9) &= \frac{3}{2} (\bar{s}b)_{V-A} \sum_q e_q (\bar{q}q)_{V+A(V-A)}, \\
\mathcal{O}_8(10) &= \frac{3}{2} (\bar{s}_ib_j)_{V-A} \sum_q e_q (\bar{q}_jq_i)_{V+A(V-A)}. 
\end{align}

In Eqn. 1.13, the first part describes the current-current interactions, and the second term describes the QCD and electroweak penguin interactions.
Neglecting the penguin contributions, the decay amplitude of $B \to J/\psi K$ is proportional to $(J/\psi K|C_1(\mu)O_1 + C_2(\mu)O_2|B)$. While the Wilson coefficients are rather well determined, evaluations of the hadronic matrix elements suffer from large theoretical uncertainties. In the naive factorization model, the assumption is made that gluon exchange between the final states can be neglected. Hence, the matrix elements of the four-quark operators are reduced to the product of the matrix elements of two-quark operators,

$$\langle J/\psi K | (\bar{s}b)_{V-A}(\bar{c}c)_{V-A}|B \rangle \to \langle K | (\bar{s}b)_{V-A}|B \rangle \langle J/\psi |(\bar{c}c)_{V-A}|0 \rangle . \quad (1.15)$$

Other QCD approaches based on the factorization ansatz have also been used to predict $B$ decays to charmonium, with efforts to include non-factorizable corrections [15, 16, 17].

In the factorization approximation, the $B \to \eta_c K$ and $B \to J/\psi K$ decay rates are related by

$$R = \frac{\Gamma(B \to \eta_c K)}{\Gamma(B \to J/\psi K)} = a \cdot \left( \frac{f_{\eta_c}}{f_{J/\psi}} \right)^2 \cdot \left[ \frac{F_0(m_{\eta_c}^2)}{F_1(m_{J/\psi}^2)} \right]^2 , \quad (1.16)$$

where $a$ is the dimensionless coefficient that depends on the $B$, $J/\psi$ and $\eta_c$ masses,
and $F_0(m_{\eta_c}^2)$ and $F_1(m_{J/\psi}^2)$ are form factors. The decay constants $f_{J/\psi}$ and $f_{\eta_c}$ are defined by

$$
\langle 0|\bar{c}\gamma_\mu c|J/\psi\rangle = m_{J/\psi}f_{J/\psi}\varepsilon_\mu
$$
$$
\langle 0|\bar{c}\gamma_\mu\gamma_5 c|\eta_c\rangle = if_{\eta_c}p_\mu
$$

(1.17)

where $\varepsilon_\mu$ is the polarization vector of $J/\psi$ and $p_\mu$ is the momentum of $\eta_c$. Theoretical predictions for the ratio $R$ vary from 0.9 to 1.6 [18, 19, 20, 21, 22]. Experimental tests of these predictions are limited by the large statistical uncertainties in the branching fractions for $B \rightarrow \eta_c K$ [23]. It is important to measure $B$ decays to $\eta_c$ precisely because they can provide a testing ground for various QCD models.

The charmonium mesons are $CP$ eigenstates. Both $B^0$ and $\bar{B}^0$ decay to the common final states $charmonium + K_S$. However, in the spectator diagram, $B^0$ only decays to $K^0$ and $\bar{B}^0$ only decays to $\bar{K}^0$. Therefore,

$$
\frac{\bar{A}_{J/\psi K_S}}{A_{J/\psi K_S}} = - \left(\frac{q}{p}\right)_K \frac{\bar{A}_{J/\psi \bar{K}^0}}{A_{J/\psi K^0}},
$$

(1.18)

and

$$
\lambda_{J/\psi K_S} = - \left(\frac{q}{p}\right)_B \left(\frac{q}{p}\right)_K \frac{\bar{A}_{J/\psi \bar{K}^0}}{A_{J/\psi K^0}} \sim \frac{V_{tb}^* V_{td}}{V_{cb}^* V_{cs}} \frac{V_{cs} V_{cd}^*}{V_{tc}^* V_{td}} \frac{V_{cb} V_{cs}^*}{V_{cb} V_{cs}} = -\xi_f e^{-2i\phi_1}.
$$

(1.19)

The quantity $\xi_f = \pm 1$ is the $CP$ eigenvalue of the final state, which is $-1$ for $J/\psi K_S$.

Substituting Eqn. (1.19) into Eqn. (1.11), one finds

$$
A_{CP}(t) = -\xi_f \sin(\Delta m_B t)\sin(2\phi_1).
$$

(1.20)

The two diagrams in Fig. 1.4 have the same weak phase and the color suppressed tree diagram is the dominant contribution. The penguin diagram with an intermediate $u$ quark also contributes and it has a different weak phase. However, it is
highly suppressed with respect to the $t$ quark penguin due to the small $u$ quark mass. The theoretical uncertainty in Eqn. (1.20) is less than 1% [24]. Furthermore, the $B^0 \rightarrow J/\psi K_S$ channel is experimentally clean and easy to access. It has been recognized as the “golden” mode for observing $CP$ violation in the $B$ meson system. Fig. 1.5 shows the indirect constraints on the apex $(\bar{\rho}, \bar{\eta})$ of the unitarity triangle. The angle $\phi_1$ is expected to lie in the region $0.47 < \sin(2\phi_1) < 0.89$ at the 95% confidence level [25]. Hence, $B^0 \rightarrow J/\psi K_S$ provides us a unique opportunity to observe possible large $CP$ violation and to constrain further the unitarity triangle.

Eqn. (1.20) also applies to $B^0 \rightarrow \eta_c K_S$ and these decays can be used to measure $\sin(2\phi_1)$. As predicted, the branching fraction for $B^0 \rightarrow \eta_c K_S$ is comparable to that for $B^0 \rightarrow J/\psi K_S$. Thus, the decay mode $B^0 \rightarrow \eta_c K_S$ is a promising mode to study time dependent $CP$ violation in the $B$ meson system.
1.3.3 \( B \to \) Baryons

In contrast to charm meson decay, final states with baryons are allowed in \( B \) meson decays. A few low-multiplicity \( B \) decay modes with baryons in the final state from \( b \to c \) transitions have been observed [26]. Rare decays due to \( b \to s \) and \( b \to u \) transitions should also lead to final states with baryons. A number of searches for such modes have been carried out by CLEO [27], ARGUS [28] and LEP [29, 30], but only upper limits were obtained. Stringent upper limits for two body modes such as \( B \to p\bar{p}, B \to \Lambda p \) and \( B \to \Lambda\bar{\Lambda} \) have been recently reported by Belle [31].

Fig. 1.6 shows the spectator diagrams that contribute to \( B^+ \to p\bar{p}K^+ \) and \( B^+ \to p\bar{p}\pi^+ \). The \( B \to p\bar{p}K \) decay mode is expected to proceed mainly via \( b \to s \) penguin diagrams [32, 33, 34]; \( B \to p\bar{p}\pi \) is expected to proceed mainly via the external \( b \to u \) tree diagrams. The magnitude of the non-dominant contributions is not known accurately and they could be comparable to those of the dominant contributions [35].

CLEO also carried out a search for non-resonant \( B^+ \to p\bar{p}K^+ \) and \( B^+ \to p\bar{p}\pi^+ \) decay modes. They found the 90% confidence level upper limits of \( \mathcal{B}(B^+ \to p\bar{p}K^+) < 8.9 \times 10^{-5} \) and \( \mathcal{B}(B^+ \to p\bar{p}\pi^+) < 5.3 \times 10^{-5} \) [36]. Observation of these decays will provide valuable information towards the understanding of the mechanism of charmless baryonic \( B \) decays.

Once these modes are established, they may be used to either constrain or observe direct \( CP \) violation in \( B \) decay [37]. The interference between the tree and the penguin contributions makes it possible to look for direct \( CP \) violation. The decay amplitudes may be written as

\[
A_{B^+ \to f} = T e^{i\phi_T} + P e^{i(\phi_P + \delta)}
\]

\[
A_{B^- \to f} = T e^{-i\phi_T} + P e^{i(-\phi_P + \delta)}
\]

(1.21)

where \( T (P) \) and \( \phi_T (\phi_P) \) represent the magnitude and the weak phase of the tree
(penguin) amplitude, \( \delta \) represents the strong phase. As a result, one derives

\[
A_{CP} = \frac{\Gamma(B^- \to f) - \Gamma(B^+ \to f)}{\Gamma(B^- \to f) + \Gamma(B^+ \to f)} = \frac{2\sin(\phi_P - \phi_T)\sin\delta}{\frac{F}{T} + \frac{T}{F} + 2\cos(\phi_P - \phi_T)\cos\delta}. \quad (1.22)
\]

This equation shows that we may expect sizable direct \( CP \) violation in these decay modes if the following conditions are satisfied:

- The tree and the penguin contributions are comparable.
- The strong phase \( \delta \) is large.
The relative weak phases for $B \to p\bar{p}K$ and $B \to p\bar{p}\pi$ are

$$\langle \phi_P - \phi_T \rangle_{B^\pm \to p\bar{p}K^\pm} = \arg \left( \frac{V_{ub}^* V_{us}}{V_{tb}^* V_{ts}} \right) = \phi_3$$

$$\langle \phi_P - \phi_T \rangle_{B^\pm \to p\bar{p}\pi^\pm} = \arg \left( \frac{V_{ub}^* V_{ud}}{V_{tb}^* V_{td}} \right) = \phi_2$$  \hspace{1cm} (1.23)

A $CP$ asymmetry is related to $\sin \phi_3$ or $\sin \phi_2$.

### 1.4 Thesis Outline

The outline is as follows. The experimental apparatus used to collect data for this work is described in chapter 2. In chapter 3, we measure branching fractions for $B^+ \to \eta_c K^+$ and $B^0 \to \eta_c K^0$. We also determine the $\eta_c$ mass and width. In chapter 4, we measure the $CP$ violation parameter $\sin(2\phi_1)$ in the decay mode $B^0 \to \eta_c K^0$. In chapter 5, searches for the nonresonance $B \to p\bar{p}K$ and $B \to p\bar{p}\pi$ are presented. We have observed the decay mode $B^\pm \to p\bar{p}K^\pm$ for the first time. Finally, we summarize the work in chapter 6.
Chapter 2

Experimental Apparatus

The data sample used for this thesis was collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider. The KEKB accelerator accelerates electrons and positrons to desired energies and collides them. The Belle detector detects particles produced in the collisions.

The KEKB accelerator operates at the $\Upsilon(4S)$ resonance, $\sqrt{s} = 10.58$ GeV. The $e^+e^-$ hadronic cross-section in the region of $\Upsilon$ resonances is shown in Fig. 2.1. The $\Upsilon$ mesons are $b\bar{b}$ triplet states with orbital angular momentum equal to 1. The ratio of the $\Upsilon(4S)$ on-resonance to continuum $u\bar{u}$, $d\bar{d}$, $c\bar{c}$ and $s\bar{s}$ production is about 1 to 3. The $\Upsilon(4S)$ resonance lies only 20 MeV above the threshold for $B\bar{B}$ pair production, and decays mostly to $B^0\bar{B}^0$ or $B^+B^-$; non-$B\bar{B}$ decays of the $\Upsilon(4S)$ are less than 4% at 95% confidence level [38]. Assuming isospin invariance and $\tau_{B^+}/\tau_{B^0} = 1.066 \pm 0.024$, the ratio of the $\Upsilon(4S) \to B^+B^-$ to the $\Upsilon(4S) \to B^0\bar{B}^0$ branching fractions is found to be completely consistent with 1 [1].
2.1 The KEKB Accelerator

The configuration of the KEKB accelerator is illustrated in Fig. 2.2. Two separate rings are used, one for the 8 GeV electrons (HER) and one for the 3.5 GeV positrons (LER).

The asymmetric energies of the electron and position beams are specifically tuned for observation of the time-dependent $CP$ violation in $B$ meson decays. At $\beta\gamma = 0.425$, the decay length of $B$ mesons reaches 200 $\mu$m in the laboratory frame. This allows us to separate the decay vertices of the two $B$ mesons and, hence, to measure the time-dependent asymmetry $A_{CP}$ defined in Chapter 1.

The electrons and positrons are brought into collision at a crossing angle of $\pm 11$ mrad. The crossing angle is used to separate the incoming and outgoing beams and avoid parasitic collisions. In contrast to magnetic separation, the crossing angle allows for higher luminosity and lower beam related backgrounds. The machine parameters
Figure 2.2: The KEKB accelerator system. There is only one interaction point, around which the Belle detector is installed [40].

of KEKB are carefully determined to ensure the design peak luminosity of $1 \times 10^{34}$ cm$^{-2}$s$^{-1}$. KEKB has achieved the world record for peak luminosity of $1.05 \times 10^{34}$ cm$^{-2}$s$^{-1}$ and has accumulated a total integrated luminosity of 158 fb$^{-1}$ as of July 2003.

### 2.2 The Belle detector

The Belle detector is primarily designed to study $CP$ violation in $B$ decay [41]. It is a multipurpose cylindrical particle detector that provides the maximum solid-angle coverage. Fig. 2.3 shows the configuration of the Belle detector, which is constructed surrounding the interaction point. A silicon vertex detector (SVD) located radially
outside a beryllium beam pipe measures $B$ meson decay vertices. It is followed by a central drift chamber (CDC) which provides tracking information of charged particles. Particle identification information is provided by energy-loss ($dE/dx$) in the CDC, and measurements from aerogel Cerenkov (ACC) counters and time-of-flight counters (TOF) surrounding the CDC. An electromagnetic calorimeter (ECL) located outside the TOF detects photons and electrons. These sub-detectors are enclosed inside a 1.5 Tesla superconducting solenoid. Outside the superconducting solenoid is a $K_L$ and muon detector (KLM) which makes use of the iron magnet return yoke as the absorber material.

Figure 2.3: Side view of the Belle detector.
2.2.1 Beam Pipe

The beam pipe is a double-wall beryllium cylinder with an inner radius of 2 cm. The cooling for the beam pipe is provided by helium-gas flowing between the walls. To reduce multiple Coulomb scattering, the material in the beam pipe has been minimized. For example, a helium cooling system is used instead of water. The beam pipe is coated with 20 \( \mu \)m gold in order to reduce synchrotron radiation background from the high energy ring. The total thickness of the beryllium walls is 0.3\% of a radiation length.

2.2.2 Silicon Vertex Detector

The silicon vertex detector (SVD) is an essential component of the Belle detector because it measures \( B \) meson decay vertices [42]. Fig. 2.4 shows the side and end views of the SVD. It consists of three layers of double-sided silicon strip detectors (DSSDs) and covers the polar angle range \( 23^\circ < \theta < 139^\circ \). Each DSSD consists of 1280 sense strips and 640 readout pads on both sides. The readout electronics for the DSSDs is based on the VA1 integrated circuit. The vertex resolution of SVD is limited by multiple Coulomb scattering since most particles of interest have low momentum. To minimize the effect of multiple scattering, the innermost layer has to be placed as close as possible to the interaction point, and the amount of the detector material has to be minimized.

When a charged particle passes through the DSSDs, it produces electron-hole pairs along its track. The charges are then collected at the sense strips by the applied electrical field. The charge distributions on the orthogonally segmented strips allow one to determine three-dimensional hit positrons and, hence, to reconstruct the particle track. The impact parameters of a reconstructed track are defined as the \( r-\phi \) and \( z \) distances of the closest approach of the track to the interaction point. Fig. 2.5 shows the impact parameter resolutions, which are directly related to the vertex resolutions,
of tracks associated with SVD hits. The SVD provides a $\Delta z$ resolution for $B$ meson vertices of about 100 $\mu$m.

2.2.3 Central Drift Chamber

The Belle central drift chamber (CDC) has been designed to meet the following requirements:

- Reconstruct charged particle tracks and hence measure their momenta precisely. The path of a charged particle moving in a uniform magnetic field is a helix with its axis parallel to the direction of the magnetic field. The particle momentum can be determined from the curvature of the helix.

- Measure the energy loss $dE/dx$ precisely for the particle identification system.

- Provide important trigger information.
Figure 2.5: Impact parameter resolutions as functions of the pseudo-momentum $p\beta\sin(\theta)^{3/2}$ and $p\beta\sin(\theta)^{5/2}$, where $p$ is the track momentum and $\theta$ is the track dip angle [43].

The configuration of the cylindrical CDC is shown in Fig. 2.6. The CDC covers a polar angle region of $17^\circ \leq \theta \leq 150^\circ$ and consists of 32 axial layers, 18 small-angle-stereo layers and 3 cathode strip layers. In total it has 8400 drift cells, each of which contains one sense wire and eight field wires and is filled with a 50% helium-50% ethane gas mixture. A charged particle passing through the drift cells ionizes the atoms of the gas along its path. When the ionized electrons drift towards the nearest sense wire, they can gain enough energy from the electric field to ionize additional gas atoms and form electron avalanches. These electrons generate a large electronic pulse, a hit, at the sense wire. The signal is amplified and sent to a Shaper/Discriminator/QTC module for readout. Hits on axial wires provide the $r$-$\phi$ track information, and those on cathode strips and stereo wires provide the $z$ information [44].
Figure 2.6: The Belle central drift chamber: (a) overview schematic, (b) cell structure, (c) the cathode sector.
The drift velocity of electrons in the helium-ethane gas mixture is about 40 $\mu$m/ns as shown in Fig. 2.7. The time of a hit is used to determine how far the ionizing track was from the sense wire. A track segment finder is used to select hits belonging to the same track and determine the track positions with respect to the sense wires. The helix parameters are extracted using a $\chi^2$ fit. The SVD information, if available, is then included to improve the measurement of the helix. The CDC provides a $r$-$\phi$ spatial resolution of approximately 130 $\mu$m, which is limited by diffusion of the ionization electrons. The transverse momentum resolution is measured to be $(0.19p_t + 0.30)\%$ using cosmic ray data.

The energy loss $dE/dx$ by ionization for an incident particle is a function of its velocity. For a given momentum, different particle species have different $dE/dx$ because their masses are different. The height of a hit corresponds to the amount of ionization charge collected and is used to determine $dE/dx$. The $dE/dx$ performance is illustrated in Fig. 2.8. The $dE/dx$ resolution is 6.9% for minimum ionizing pions from $K_S$ decays. The $dE/dx$ measurements provide over $3\sigma$ separation between $K$ and $\pi$ for momenta below 0.8 GeV/c and $2\sigma$ separation for momenta above 2.0 GeV/c.

![Drift velocity of electrons in the helium-ethane gas mixture used in the Belle CDC.](image-url)
2.2.4 Aerogel Cerenkov Counter

A threshold silica aerogel Cerenkov counter (ACC) is an important component of the Belle particle identification system. It is capable of identifying high momentum particles that are beyond the reach of $dE/dx$ and time-of-flight measurements. A charged particle moving with a velocity $v > c/n$ inside a medium, e.g. silica aerogel, with refractive index $n$ produces Cerenkov radiation. For a fixed $n$, the threshold energies for particles to emit Cerenkov photons are proportional to their masses. Therefore, $K/\pi$ separation in the desired momentum region can be achieved by selecting media with appropriate refractive index values [45].

The configuration of the ACC is shown in Fig. 2.9. It consists of 960 counter modules in the barrel region and 228 modules in the forward end-cap region, covering a total polar angle range from $17^\circ$ to $127^\circ$. Cerenkov photons are measured by fine-mesh photomultiplier tubes. Aerogels of 6 different refractive indices are used to accommodate several different kinematical ranges. A detailed description of the ACC can be found elsewhere [46]. For kaons of momenta from 1.5 GeV/$c$ to 4.0 GeV/$c$, the ACC can provide a good $K/\pi$ separation with a kaon detection efficiency of 73% and the pion fake rate of 7% [47].

2.2.5 Time-of-Flight

The time-of-flight technique can be used to identify particles of different masses by measuring their flight time differences. Two particles of different masses have, for the same momentum $p$, different velocities. In the relativistic limit ($E \gg mc^2$), the time difference for traveling the same distance $L$ is

\[ \Delta t = \frac{Lc}{2p^2} (m_1^2 - m_2^2). \]  (2.1)
Figure 2.8: Measured $dE/dx$ versus momentum for different particle species in collision data. The solid curves are the expected distributions.

Figure 2.9: The side view of the Belle aerogel Cerenkov counter.
Particle identification with a time-of-flight system requires good time resolution. For a kaon and a pion of momentum equal to 1.2 GeV/c and flight path equal to 1.2 m, the flight time difference is about 300 ps. A time-of-flight system (TOF) with 100 ps time resolution is effective for particle momentum below 1.2 GeV/c, which encompasses 90% of particles produced in $\Upsilon(4S)$ decays.

To achieve the design goal of 100 ps, fast plastic scintillation counters are used and read out with fine-mesh-dynode photomultiplier tubes (FM-PMTs) [48]. A TOF module is composed of two TOF counters and one thin trigger scintillation counter (TSC). Each TOF counter is readout with two phototubes. A total 64 modules are located at a radius of 1.2 m, forming a cylindrical structure that covers the polar angle range from 33° to 121°. Light signals from the TOF scintillators are converted into photoelectrons and amplified by the PMTs. The readout electronics takes PMT signals into a charge-to-time converter and then to a multihit TDC for charge measurements. Fig. 2.10 shows the mass distribution for particles of momenta below 1.2 GeV/c in hadron events. The $K$, $\pi$ and $p$ signals are clearly separated. The TOF and TSC counters also provide fast trigger signals [49, 50].

2.2.6 Electromagnetic Calorimeter

An electromagnetic calorimeter (ECL) [51] is used to measure precisely the energy and position of photons, and to provide important particle identification information for electrons and positrons. At high energy, electrons lose their energy in the calorimeter by bremsstrahlung, and photons lose their energy by electron-positron pair production. These processes repeat over and over again, producing electromagnetic showers of deposited energy in the absorbing material.

The ECL consists of 8736 CsI(Tl) counters. They form a barrel section that is 3.0 m in length with an inner radius of 1.25 m and annular end-caps at $z = +2.0$ m and $z = -1.0$ m from the interaction point, as illustrated in Fig. 2.11. The ECL
Figure 2.10: Mass distribution from TOF measurement for particle momentum below 1.2 GeV/c. The points with error bars are data, and the histogram is the MC prediction assuming the TOF time resolution is 100 ps.

covers a polar angle region of $17^\circ < \theta < 150^\circ$, corresponding to a total solid-angle coverage of 91% of $4\pi$. Each CsI(Tl) crystal has a small tilt angle in the $\theta$ and $\phi$ directions in order to avoid photons escaping through the gaps between crystals. The size of each crystal is limited by the trade-off between position resolution and energy resolution. Signals from the crystals are readout with silicon photodiodes. Photons are reconstructed if they do not match extrapolated charged tracks and have a lateral shape consistent with that of an electromagnetic shower.

The ECL has good performance over a wide energy range of $20 \text{ MeV} < E_\gamma < 5.4 \text{ GeV}$. The energy resolution is $\sigma_E/E = (1.3 \oplus 0.07/E \oplus 0.8/E^{1/4})\%$. The two-photon invariant mass distribution in the $\pi^0$ mass region is shown in Fig. 2.12. A clear $\pi^0$ peak is seen at its nominal mass with a resolution of $5 \text{ MeV}/c^2$. Electrons and charged pions can be separated in the ECL because electrons deposit most of their energies while charged pions deposit only a fraction of their energies. Measurements from the
ECL combined those from the CDC, ACC and TOF provide an electron detection efficiency of about 80% and a $\pi$ fake rate of less than 1% in the momentum range from 500 MeV/c to 2 GeV/c.

### 2.2.7 Superconducting Solenoid

A superconducting solenoid provides a magnetic field of 1.5 T in a cylindrical volume 3.4 m in diameter and 4.4 m in length. The coil consists of a single layer of superconducting coil with high purity (99.99%) aluminum stabilizer.
2.2.8 $K_L$ and Muon System

A $K_L$ and muon detection system (KLM) has been designed to have high efficiency over a broad momentum range, greater than 600 MeV/$c$. It consists of glass-electrode resistive plate counters (RPCs) sandwiched between 4.7 cm-thick iron plates. The barrel and endcap KLM covers a polar angle range from 25° to 145°. $K_L$'s that interact in the iron or ECL produces a shower of ionizing particles. A detected shower that does not match extrapolated tracks is identified as $K_L$. The location of the shower determines the direction of $K_L$, but fluctuations in the size of the shower do not allow a useful measurement of the $K_L$ energy. Muons can be discriminated from strongly interaction hadrons because muons travel much further with smaller deflections on average. For momentum between 1 GeV/$c$ and 3 GeV/$c$, the KLM provides effective muon identification with an efficiency of 89% and a kaon or pion fake rate less than 2% [52].
2.3 Trigger and Data Acquisition

A trigger system is used to select good events and reject background events as efficiently as possible. For the Belle experiment, we are interested in hadronic, Bhabha, $\mu$ and $\tau$ pair and two photon processes. At a luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$, the total event rate of these physical processes is around 100 Hz\(^1\). The background events are dominated by spent electrons and positrons from the beams and occur at a rate of about 100 Hz. This leads to a total trigger rate of 200 Hz. The trigger system is capable of handling unexpected high beam background rates within the limits of the data acquisition system.

The online trigger system consists of the Level-1 hardware trigger and the Level-3 software trigger. Fig. 2.13 shows the signal flow of the Level-1 trigger system. The CDC and SVD trigger systems provide charged track signals. The TOF trigger system provides an event timing signal. The ECL trigger system provides triggers for both neutral and charged particles based on total energy deposit and cluster counting of crystal hits. The KLM trigger system gives additional information on muons. The global decision logic (GDL) \cite{53} takes the trigger signals from the sub-detectors and makes the global trigger decision. The Level-1 trigger signal is provided at a fixed time, 2.2 $\mu$s after the event occurrence. The efficiency of the Level-1 trigger is $\sim$ 100%. The Level-3 trigger was introduced in January 2001 to reduce the number of background events that pass the Level-1 trigger. It uses a fast track fitting algorithm to find tracks coming from the interaction point. Background events that do not produce such tracks are rejected. The Level-3 trigger has an efficiency of about 99% and an event rate reduction of 40% $\sim$ 50% \cite{54}.

A block diagram of the Belle data acquisition system is shown in Fig. 2.14. It is a distributed-parallel system and can work at 500 Hz with a dead time fraction of less than 10%. Multi-hit FASTBUS TDC modules are used to read out signals from all

\(^1\)The Bhabha and two photon events are prescaled by a factor of $\sim 1/100$. 

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detectors except SVD, which uses flash ADC modules. The GDL sends a timing signal to the central sequence controller which then distributes it to the Timing Distributor Model (TDM) in the master VME for each detector and initiates a readout sequence. The event builder converts the parallel sub-detector data into a complete event data, which is then sent to the online computer farm. The computer farm converts the raw event data into the offline data format, and then carries out the Level-3 trigger. The final data is sent to a mass storage system via optical fibers. Details of the Belle data acquisition system can be found elsewhere [55].

Figure 2.13: The trigger system for the Belle detector.
Figure 2.14: The Belle data acquisition system.
Chapter 3

Measurement of Branching Fractions for $B \rightarrow \eta_c K$ Decays and Determination of $\eta_c$ Mass & Width

3.1 Introduction

In this chapter, we describe a measurement of branching fractions for $B^0 \rightarrow \eta_c K^0$ and $B^+ \rightarrow \eta_c K^+$. In contrast to $B \rightarrow J/\psi K$, the $\eta_c$ meson must be reconstructed from hadronic decays rather than from a leptonic final state with relatively low combinatorial background. We reconstruct $\eta_c$ candidates via the decay modes: $\eta_c \rightarrow K^+ K^- \pi^0$, $\eta_c \rightarrow pp$ and $\eta_c \rightarrow K^{*0} K^- \pi^+$. Branching fractions for these $\eta_c$ decay modes are given in Table 3.1. To obtain the branching fractions for $B \rightarrow \eta_c K$, we combine the results for the $\eta_c \rightarrow K_S^0 K^- \pi^+$ [56] and $\eta_c \rightarrow K^+ K^- \pi^0$ modes.
Table 3.1: PDG branching fractions for the $\eta_c$ decay modes [57].

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Branching Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_c \rightarrow K\bar{K}\pi$</td>
<td>$(5.5 \pm 1.7)$%</td>
</tr>
<tr>
<td>$\eta_c \rightarrow p\bar{p}$</td>
<td>$(1.2 \pm 0.4)$%</td>
</tr>
<tr>
<td>$\eta_c \rightarrow K^{*0}K^-\pi^+$</td>
<td>$(2.0 \pm 0.7)$%</td>
</tr>
</tbody>
</table>

3.2 Event Selection Requirements

We use a 29.1 fb$^{-1}$ data sample, which contains 31.3 million produced $B\bar{B}$ pairs, collected at the $\Upsilon(4S)$ resonance with the Belle detector. Event selection criteria are determined using the figure of merit, which is defined as $S/\sqrt{S + B}$, where $S$ and $B$ are the number of signal and background events, respectively. We determined $S$ from a GEANT based Monte Carlo simulation, and $B$ from the sideband data.

3.2.1 Hadronic Events

In $e^+e^-$ collisions at the $\Upsilon(4S)$ resonance, non-hadronic events are produced via $e^+e^- \rightarrow \tau^+\tau^-$, $e^+e^- \rightarrow e^+e^-q\bar{q}$, QED and beam gas interactions. To remove these events, we apply the following hadronic event selection criteria [58]:

- The number of well-reconstructed tracks is required to be greater than 2.
- The distance between the primary vertex and the beam spot is required to be smaller than 1.5 cm in the x-y plane, and smaller than 3.5 cm in the z direction.
- The visible energy, $E_{vis}$, which is the sum of the energies of all well reconstructed tracks and photons, is required to be greater than or equal to $0.2\sqrt{s}$.
- The vector sum of the $z$ momentum of all well reconstructed tracks and photons is required to be smaller than $0.5\sqrt{s}$.
• The number of good clusters in the barrel region of the ECL is required to be greater than 1.

• The energy sum of good clusters in the central barrel section of the ECL is required to be between $0.1\sqrt{s}$ and $0.8\sqrt{s}$.

• Either the energy sum of all ECL clusters is required to be greater than $0.18\sqrt{s}$, or the heavy jet mass is required to be greater than 1.8 GeV.

• The heavy jet mass is required to be greater than either $0.25E_{vis}$ or 1.8 GeV.

• The average cluster energy is required to be smaller than 1.0 GeV.

These requirements retain 99% of $B\bar{B}$ events and a non-hadronic component of less than 5%.

3.2.2 Charged Tracks

A helix in a magnetic field along $z$-axis is fully determined by five parameters, $dr$, $\phi_0$, $\kappa$, $dz$ and $\tan\lambda$. The impact parameters $dr$ and $dz$ are the radial and $z$ positions, respectively, of the point of closest approach of the helix to a specified vertex. We use a right-handed coordinate system where the $z$-axis is anti-parallel to the positron beam direction. Charged tracks are selected with $|dr|$ less than 0.5 cm and $|dz|$ less than 3 cm with respect to the interaction point. These requirements suppress background tracks that do not originate from the interaction point. To remove badly reconstructed tracks, we require all tracks to have transverse momenta $p_T > 50$ MeV/c and have more than 6 axial and 2 stereo CDC hits.

3.2.3 Particle Identification

Particle identification likelihoods for the pion and kaon particle hypotheses are calculated by combining information from the TOF and ACC systems with the $dE/dx$
measurements in the CDC. To identify kaons, we require the kaon likelihood ratio,
\[ \frac{L_K}{L_K + L_\pi} \], to be greater than 0.6, which is 88% efficient for kaons with a 8.5% misidentification rate for pions. For the \( \eta_c \rightarrow K^+K^-\pi^0 \) mode, the kaon likelihood ratio is required to be greater than 0.8 for those charged kaons that come directly from the \( B \) rather than from the \( \eta_c \) candidate. In addition, we remove all kaon candidates that are consistent with being either protons or electrons. To identify pions, we require \( \frac{L_K}{L_K + L_\pi} \) to be smaller than 0.9.

Protons and antiprotons are identified using all particle identification systems and are required to have proton likelihood ratios \( \frac{L_p}{L_p + L_K} \) and \( \frac{L_{\bar{p}}}{L_{\bar{p}} + L_\pi} \) greater than 0.4. Proton candidates that are electron-like according to the information recorded by CsI(Tl) calorimeter are vetoed. This selection is 95% efficient for protons with a 12% kaon misidentification rate. Fig. 3.1 shows the invariant mass of \( p\pi^- \) in the \( \Lambda \) mass region. The background in the \( \Lambda \) signal region is dramatically reduced by the requirement that the proton likelihood ratio to be greater than 0.4.

3.2.4 \( K_S^0 \)

We select \( K_S^0 \rightarrow \pi^+\pi^- \) candidates from pairs of oppositely charged tracks that satisfy the pion hypothesis and lie within the mass window \( 0.482 \text{ MeV}/c^2 < M(\pi^+\pi^-) < 0.514 \text{ MeV}/c^2 \), which corresponds to \( \pm 4\sigma \). The distance of closest approach of the two pion tracks in the \( z \) direction is required to be less than 20 cm. The \( \pi^+ \) and \( \pi^- \) must satisfy a vertex constrained fit with an acceptable \( \chi^2 \). The \( K_S^0 \) flight length of is required to be between 0.2 and 50 cm. The difference in the angle, in the \( x - y \) plane, between a vector from the beam spot to the \( K_S^0 \) vertex and the \( K_S^0 \) flight direction is required to satisfy \( \Delta \phi < 0.1 \) radian. Other details of the \( K_S^0 \) reconstruction can be found in the Appendix.
Figure 3.1: Invariant mass of $p\pi^-$ in the $\Lambda$ mass region without (solid histogram) and with (dashed histogram) the requirement that the proton likelihood ratio be greater than 0.4.

3.2.5 $\pi^0$

Neutral pion candidates are selected from pairs of ECL clusters with invariant mass within $\pm 16$ MeV/c$^2$, which is $\pm 3\sigma$, of the nominal $\pi^0$ mass and momenta above 350 MeV/c. The photons are required to have energies above 50 MeV if they lie in the central barrel region of the calorimeter and above 200 MeV if they are detected in the endcap region. The daughter photons from $\pi^0 \rightarrow \gamma\gamma$ must satisfy a constrained fit with $\chi^2$ smaller than 50.
3.2.6 $K^{*0}$ Reconstruction

$K^{*0}$ candidates are reconstructed in the $K^{*0} \rightarrow K^+\pi^-$ decay mode. We require the $K^+\pi^-$ invariant mass to be between 0.817 and 0.967 GeV/c$^2$. Fig. 3.2 shows the reconstructed $K^{*0}$ signals.

![Graph showing reconstructed $K^{*0}$ candidates for the $B \rightarrow \eta_c K$ decay modes.](image)

Figure 3.2: Reconstructed $K^{*0}$ candidates for the $B \rightarrow \eta_c K$ decay modes.

3.2.7 $\eta_c$ Reconstruction

We reconstruct $\eta_c$ candidates in the $K^+K^-\pi^0$, $p\bar{p}$ and $K^{*0}K^-\pi^+$ decay modes. The $\eta_c$ candidate is required to have invariant mass in the range $2.920 < M_{\eta_c} < 3.035$ GeV/c$^2$ for the $K^+K^-\pi^0$ mode and $2.935 < M_{\eta_c} < 3.035$ GeV/c$^2$ for all other modes. In order to reduce the combinatorial background, the charged daughters of the $\eta_c$ are required to satisfy a vertex constrained fit with $\chi^2$ smaller than 50. For the $K^{*0}K^-\pi^+$ mode, which suffers a higher combinatorial background, the transverse momenta of
the charged daughters of the $\eta_c$ are required to be greater than 300 MeV/c. Fig. 3.3 shows the invariant mass of reconstructed $\eta_c$'s for $B^+ \to \eta_c K^+$ Monte Carlo data.

Figure 3.3: Reconstructed $\eta_c$ signals for (a) $\eta_c \to K^+K^-\pi^0$, (b) $\eta_c \to p\bar{p}$ and (c) $\eta_c \to K^{*0}K^-\pi^+$ decay modes in $B^+ \to \eta_c K^+$ Monte Carlo data.
3.2.8 \( B \) Reconstruction

The \( B \) signal candidates in the \( B^+ \rightarrow \eta_c K^+ \) and \( B^0 \rightarrow \eta_c K^0 \) modes are reconstructed by combining charged or neutral kaons and \( \eta_c \) candidates. In order to isolate the signal, we form two variables in the \( \Upsilon(4S) \) center of mass frame, the beam-energy constrained mass \( M_{bc} \) and the energy difference \( \Delta E \). They are defined as

\[
M_{bc} = \sqrt{E_{\text{beam}}^2 - \vec{P}_{\text{recon}}^2}, \\
\Delta E = E_{\text{recon}} - E_{\text{beam}},
\]

(3.1)

where \( E_{\text{beam}} \), \( E_{\text{recon}} \) and \( \vec{P}_{\text{recon}} \) are the beam energy, the reconstructed energy and the reconstructed momentum of the signal candidates, respectively. By conservation of energy, \( M_{bc} \) is centered at the nominal \( B \) mass, and \( \Delta E \) is centered at zero. Fig. 3.4 shows the distributions of \( M_{bc} \) and \( \Delta E \) for \( B^+ \rightarrow \eta_c K^+ \) Monte Carlo data.

The signal region for \( \Delta E \) is \( \pm 2.5\sigma \), where \( \sigma \) is the mode-dependent resolution, and the values are listed in Table 3.2 for all decay modes. The signal region for \( M_{bc} \) is \( 5.27 < M_{bc} < 5.29 \) GeV/\( c^2 \). The resolution in beam-energy constrained mass is 2.8 MeV/\( c^2 \) and is dominated by the beam energy spread of KEKB.

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>( \Delta E ) Range (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta_c \rightarrow K^+ K^- \pi^0 )</td>
<td>([-55, +45])</td>
</tr>
<tr>
<td>( \eta_c \rightarrow p\bar{p} )</td>
<td>([-25, +25])</td>
</tr>
<tr>
<td>( \eta_c \rightarrow K^{*0} K^- \pi^+ )</td>
<td>([-30, +30])</td>
</tr>
</tbody>
</table>

Table 3.2: The \( \Delta E \) signal regions for \( B \rightarrow \eta_c K \) decay modes.
Figure 3.4: The $M_{bc}$ and $\Delta E$ distributions for (a) $\eta_c \rightarrow K^+K^-\pi^0$, (b) $\eta_c \rightarrow p\bar{p}$ and (c) $\eta_c \rightarrow K^{*0}K^-\pi^+$ decay modes in $B^+ \rightarrow \eta_cK^+$ Monte Carlo data.
3.2.9 Selection of Best Candidate

For the $\eta_c \rightarrow K^+K^-\pi^0$ decay mode, 4% of the events have two $B$ candidates. Monte Carlo study shows that for most of the fake $B$ candidates, the $\eta_c$ is reconstructed from a misidentified $\pi^0$. We select the $B$ candidate with the best $\chi^2$ of the $\pi^0$ constrained fit. For the $\eta_c \rightarrow p\bar{p}$ and $\eta_c \rightarrow K^{*0}K^-\pi^+$ decay modes, 1% of the events have two $B$ candidates. For these modes, we select the $B$ candidate with the best $\chi^2$ of the $\eta_c$ vertex constrained fit.

3.3 Continuum Suppression

The continuum processes $e^+e^- \rightarrow q\bar{q}$ (where $q = u, d, c$ and $s$) are the dominant background for this measurement. Continuum and $B\bar{B}$ events have different event topologies, which provide discrimination between them. In the $\Upsilon(4S)$ center of mass frame, the $B\bar{B}$ pairs are produced with small energy release and therefore tend to have a nearly spherical event topology. The $q\bar{q}$ pairs are produced with large recoil energy and result in a jet-like event topology, which tends to be collimated along the original quark or anti-quark direction.

Several event topology variables provide discrimination between the large continuum background and the $B\bar{B}$ events. The $R_2$ variable [59] is the ratio of $H_2$ to $H_0$, where $H_2$ and $H_0$ are the Fox-Wolfram moments following the definition

$$H_l = \sum_{i,j} \frac{|\vec{p}_i||\vec{p}_j|}{E^2} P_l(\cos\theta_{ij}),$$

where $i$ and $j$ run over all final state particles, $E$ is the total visible energy of the event, $\theta_{ij}$ is the opening angle between particle $i$ and $j$, and $P_l$ is the $l$-th Legendre polynomial. Fig. 3.5 shows the $R_2$ distributions for $B\bar{B}$ and continuum Monte Carlo. We reject events with $R_2 < 0.5$. This requirement removes 21% of the continuum while retaining 99% of the signal.
Figure 3.5: The $R_2$ distributions for $B\bar{B}$ (solid histogram) and continuum (dashed histogram) Monte Carlo.

To further suppress the remaining continuum events, we first form a Fisher discriminant [60, 61] with the following event topology variables:

- Modified Fox-Wolfram moments $H_l^{SO}$ and $H_l^{OO}$, which have the same form as Equation 3.2 but where the indices $i$ and $j$ run over only the particles that originate from the reconstructed $B$ (represented by the superscript $S$) or the other $B$ (represented by the superscript $O$). We use the six moments with $l = 1, 2, 3, \text{ and } 4$ except for $H_1^{SO}$ and $H_3^{SO}$, which are found to be correlated with $M_{bc}$ and $\Delta E$. 

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• The cosine of thrust angle, $\cos \theta_T$, which is the cosine of the angle between the thrust axis of the particles coming from the reconstructed $B$ candidate and that of the remaining particles. The $\cos \theta_T$ distribution is flat for $B\bar{B}$ events and peaks at $\pm 1$ for the continuum background.

The Fisher discriminant is defined as

$$\mathcal{F} = \sum_{i=1}^{7} a_i X_i,$$  \hspace{1cm} (3.3)

where $X_i$ are the seven topology variables, and $a_i$ are weight coefficients that are optimized for maximal separation between signal Monte Carlo and continuum data.

We also use the cosine of the $B$ flight direction with respect to the $z$ axis ($\cos \theta_B$) to distinguish signal from background. The $\Upsilon(4S)$ is spin 1 and the $B$ meson is spin 0. The conservation of angular momentum requires the $B\bar{B}$ pair to be in a p-wave state. Therefore, the signal has a $(1 - \cos^2 \theta_B)$ angular distribution while the continuum background has a flat angular distribution. We then form probability density functions for the Fisher discriminant and $\cos \theta_B$. The probability density functions for the Fisher discriminant are bifurcated Gaussians, and that for $\cos \theta_B$ has the form of $(a - bx^2)$ for signal Monte Carlo and is a linear function for continuum data. Since the Fisher discriminant and $\cos \theta_B$ are uncorrelated, the signal (background) probability density functions are multiplied together to form a signal (background) likelihood $\mathcal{L}_S$ ($\mathcal{L}_{BG}$). A likelihood ratio is defined as

$$\mathcal{L}_R = \frac{\mathcal{L}_S}{\mathcal{L}_S + \mathcal{L}_{BG}}$$  \hspace{1cm} (3.4)

In Fig. 3.6, we show the distributions of $\cos \theta_B$, $\mathcal{F}$ and $\mathcal{L}_R$ for the $B^+ \rightarrow \eta_c K^+$, $\eta_c \rightarrow K^+K^-\pi^0$ signal Monte Carlo and continuum data. We require the likelihood ratio $\mathcal{L}_R$ to be greater than 0.5. This selects 85% of the signal events and rejects 77% of the continuum background that survives the $R_2$ cut.

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3.4 Backgrounds from Other B Decays

Using a sample of $57 \times 10^6$ $B\bar{B}$ Monte Carlo events with a model of all $b \to c$ decays, we investigate backgrounds from other $B$ decay modes. In the $\eta_c \to p\bar{p}$ mode, no such backgrounds are found.

In the $B^+ \to \eta_c K^+, \eta_c \to K^+ K^- \pi^0$ mode, we find there is background from the decay chain $B^+ \to \bar{D}^0 \rho^+, \bar{D}^0 \to K^+ K^-, \rho^+ \to \pi^+ \pi^0$. This background peaks in the $M_{bc}$ distribution. We reject the events where the $K^+ K^-$ invariant mass lies within 15 MeV/$c^2$ of the $D^0$ mass.

In the $B^+ \to \eta_c K^+, \eta_c \to K^{*0} K^- \pi^+$ mode, we found there is background from the decay chain $B^+ \to \bar{D}^0 D_s^+, \bar{D}^0 \to K^+ \pi^-, D_s^+ \to K^+ K^{\ast0}$, which has the same final state particles as the signal. Therefore, this background has the same $M_{bc}$ and $\Delta E$
peak positions as the signal. It is removed by requiring the $K^+\pi^-$ invariant mass be inconsistent with the $D^0$ mass.

In the $B^0 \rightarrow \eta_c K^0_S$, $\eta_c \rightarrow K^{*0}K^-\pi^+$ mode, we found there is background from the decay chain $B^0 \rightarrow J/\psi K^{*0}$, $\eta_c$ or $J/\psi \rightarrow K^0_S K^-\pi^+$, which has the same final state particles as the signal. We reject the events where the $K^0_S K^-\pi^+$ invariant mass lies between 2.92 and 3.14 GeV/c$^2$.

### 3.5 Signal Yield

We fit the $M_{bc}$ distribution to the sum of a signal Gaussian and an ARGUS background function that behaves like phase space near the kinematic boundary [62]. The width of the Gaussian is fixed from Monte Carlo simulation while the mean is determined from $B^+ \rightarrow D^{(*)+}\pi^+$ and $B^0 \rightarrow D^{(*)-}\pi^+$ signal events in the data [63]. The shape parameters of the background function is determined from $\Delta E$ sideband data. The signal yields are determined by fits to the individual $M_{bc}$ distributions for each mode. The statistical significance is defined as $\sqrt{-2\log(L(0)/L_{\text{max}})}$, where $L_{\text{max}}$ is the best likelihood value and $L(0)$ is the likelihood with the signal yield fixed at zero.

The detection efficiencies for all modes are determined from Monte Carlo simulation. We generate 10,000 $B^+ \rightarrow \eta_c K^+$ signal events, and 15,000 $B^0 \rightarrow \eta_c K^0_S$ signal events for each $\eta_c$ decay mode. We then apply the event selection procedure to the Monte Carlo data, and fit the $M_{bc}$ distributions to obtain the MC signal yields. The detection efficiencies are calculated using

$$\epsilon = \frac{\text{MC signal yield}}{\text{Number of generated } B's}.$$  \hspace{1cm} (3.5)

The yields, significances and detection efficiencies for these fits are given in Table 3.3, where the results for the $\eta_c \rightarrow K^0_S K^-\pi^+$ mode are also included [56]. Significant signals are observed in all decay modes except for $B^0 \rightarrow \eta_c K^0$, $\eta_c \rightarrow K^{*0}K^-\pi^+$. 48
As a consistency check, we also determine the yield from a fit to the $\Delta E$ distribution with a double Gaussian for signal and a linear background function. The width of the Gaussian is determined from Monte Carlo simulation, and the slope of the linear function is determined from the $M_{bc}$ sideband. The results of these fits are also given in Table 3.3. In the fits to the $\Delta E$ distribution, the region with $\Delta E < -120$ MeV is excluded to avoid contributions from modes with additional particles such as $B \rightarrow \eta_c K^*$.

Using the $M_{bc}$ yields and detection efficiencies for the $B^+ \rightarrow \eta_c K^+$ decay modes, we find

$$\frac{B(\eta_c \rightarrow p\bar{p})}{B(\eta_c \rightarrow K_S^0 K^- \pi^+)} = 0.072 \pm 0.020,$$

and

$$\frac{B(\eta_c \rightarrow K^{*0} K^- \pi^+)}{B(\eta_c \rightarrow K_S^0 K^- \pi^+)} = 0.84 \pm 0.24,$$

where the errors are statistical only. These results are in good agreement with the values calculated from the world averages [1], which are $0.065 \pm 0.030$ and $1.09 \pm 0.51$ respectively.

The $M_{bc}$ and $\Delta E$ distributions and the fit results are shown in Fig. 3.7, 3.8 and 3.9. For illustration, in Fig. 3.10, we show the beam-energy constrained mass and $\Delta E$ distributions for the signal candidates in all the decay modes. In the $M_{bc}$ distribution including the $\eta_c \rightarrow K_S^0 K^- \pi^+$ mode, we observe a signal of $195 \pm 17$ events. The fit to the $\Delta E$ distribution for all modes combined gives an integrated yield of $188 \pm 17$ events in the signal region.
Table 3.3: Signal yields from $M_{bc}$ and $\Delta E$ fits, statistical significances, and MC reconstruction efficiencies. Errors are statistical only.

<table>
<thead>
<tr>
<th></th>
<th>$\Delta E$ Yield</th>
<th>$M_{bc}$ Yield</th>
<th>Signif.$(M_{bc})$</th>
<th>$\epsilon$(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow \eta_c K^+$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta_c \rightarrow K^+ K^- \pi^0$</td>
<td>26.5 ± 7.8</td>
<td>31.8 ± 7.0</td>
<td>6.3$\sigma$</td>
<td>8.8%</td>
</tr>
<tr>
<td>$\eta_c \rightarrow p\bar{\rho}$</td>
<td>16.3 ± 4.2</td>
<td>17.7 ± 4.4</td>
<td>7.5$\sigma$</td>
<td>34.0%</td>
</tr>
<tr>
<td>$\eta_c \rightarrow K^{*0} K^- \pi^+$</td>
<td>22.0 ± 5.8</td>
<td>20.8 ± 5.4</td>
<td>5.8$\sigma$</td>
<td>5.1%</td>
</tr>
<tr>
<td>$\eta_c \rightarrow K_S^0 K^- \pi^+$ [56]</td>
<td>74.8 ± 10.4</td>
<td>81.6 ± 10.3</td>
<td>12.2$\sigma$</td>
<td>16.4%</td>
</tr>
<tr>
<td>$B^0 \rightarrow \eta_c K_S^0$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta_c \rightarrow K^+ K^- \pi^0$</td>
<td>19.9 ± 5.7</td>
<td>17.1 ± 5.1</td>
<td>4.7$\sigma$</td>
<td>9.5%</td>
</tr>
<tr>
<td>$\eta_c \rightarrow p\bar{\rho}$</td>
<td>7.0 ± 3.0</td>
<td>6.8 ± 2.6</td>
<td>5.0$\sigma$</td>
<td>34.9%</td>
</tr>
<tr>
<td>$\eta_c \rightarrow K^{*0} K^- \pi^+$</td>
<td>0.2 ± 1.7</td>
<td>2.2 ± 1.8</td>
<td>1.6$\sigma$</td>
<td>3.75%</td>
</tr>
<tr>
<td>$\eta_c \rightarrow K_S^0 K^- \pi^+$ [56]</td>
<td>19.6 ± 5.4</td>
<td>23.0 ± 5.4</td>
<td>6.8$\sigma$</td>
<td>15.5%</td>
</tr>
</tbody>
</table>
Figure 3.7: The $M_{bc}$ and $\Delta E$ distributions for the $\eta_c \to K^+K^-\pi^0$ modes: (a) $B^0 \to \eta_c K^0$, (b) $B^+ \to \eta_c K^+$. 
Figure 3.8: The $M_{bc}$ and $\Delta E$ distributions for the $\eta_c \rightarrow p\bar{p}$ modes: (a) $B^0 \rightarrow \eta_c K_S^0$, (b) $B^+ \rightarrow \eta_c K^+$. 
Figure 3.9: The $M_{bc}$ and $\Delta E$ distributions for the $\eta_c \rightarrow K^{*0}K^-\pi^+$ modes: (a) $B^0 \rightarrow \eta_c K^0_S$, (b) $B^+ \rightarrow \eta_c K^+$. 
Figure 3.10: $M_{bc}$ and $\Delta E$ distributions for $B \rightarrow \eta_c K$ candidates in all the decay modes: (a) without, (b) with the $\eta_c \rightarrow K_s^0 K^- \pi^+$ mode.
3.6 Observation of the $\eta_c$ Signal

After removing the requirements on $\eta_c$ invariant mass, we also verify that the signal yield for $\eta_c$ candidates in the $M_{bc}, \Delta E$ region is consistent with the result used for the branching fraction determination. The $\eta_c$ invariant mass distributions for signal candidates for the individual decay modes are shown in Fig. 3.11, and in Fig. 3.12 for all decay modes combined except for $B^0 \rightarrow \eta_c K_S^0$, $\eta_c \rightarrow K^{*0} K^- \pi^+$. The curve in the plot is a fit to a Breit-Wigner convolved with the resolution (11 MeV/$c^2$) determined from MC to represent the $\eta_c$, a Gaussian to represent the $J/\psi$, and a first-order polynomial to represent the background. We find an intrinsic width $\Gamma_{\eta_c} = 29 \pm 8 \pm 6$ MeV/$c^2$ and a mass $M(\eta_c) = 2979.6 \pm 2.3 \pm 1.6$ MeV/$c^2$. The systematic errors in the width and mass measurements are given in Table 3.4; they include the effects of varying the background shape, the small difference between data and MC detector resolutions, and possible binning effects. The results are consistent with world averages and comparable in precision to the best individual measurements [1].

The $\eta_c$ yield is 182 \pm 25 events. We also observe a clear signal of 66 \pm 18 events from $B \rightarrow J/\psi K$, where the $J/\psi$ is reconstructed in hadronic decay modes. The $J/\psi$ mass is found to be 3.096 \pm 0.002 (stat) MeV/$c^2$, which is in very good agreement with the world average [1]. The width of the Gaussian is 7.8 \pm 1.9 (stat) MeV/$c^2$ and agrees with the MC expectation of 8.6 \pm 0.2 MeV/$c^2$.

3.7 Systematic Errors

The dominant contributions to the systematic error include the uncertainties due to the tracking efficiency (2\% per track) and particle identification efficiency (4-14\%, depending on the mode). The discrepancy in the track finding efficiencies between experimental data and Monte Carlo were determined using $\eta \rightarrow \pi^+ \pi^- \pi^0$ and $\eta \rightarrow \gamma \gamma$ samples [64]. The error in kaon identification efficiency is obtained from kinematically
selected $D^*+ \to D^0 \pi^+, D^0 \to K^- \pi^+$ in the data [47]. The error in proton/antiproton identification is determined using $\Lambda/\bar{\Lambda}$ samples. The results are given in Table 3.5. We quote 2% error per kaon, 4% per pion and 3% per proton.

![Histograms](image)

**Figure 3.11:** The $\eta_c$ invariant mass distributions for (a) $B^0 \to \eta_c K_S^0$ and (b) $B^+ \to \eta_c K^+$.  

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Figure 3.12: Candidate $M(\eta_c)$ invariant mass distribution for events in the $M_{bc}$ and $\Delta E$ signal region: (a) without, (b) with the $\eta_c \rightarrow K_S^0 K^- \pi^+$ mode. Signal at the $\eta_c$ and $J/\psi$ masses from $B \rightarrow \eta_c K$ and $B \rightarrow J/\psi K$ decays are visible.
Table 3.4: Results for the $M(\eta_c)$ fit for different choices of the background function, resolutions and $M(\eta_c)$ bins. The resolution is varied by ± 2 MeV/$c^2$. The bin size is varied by ± 2 MeV/$c^2$, and the bin center is shifted by a half bin.

<table>
<thead>
<tr>
<th>2nd order poly. resolution</th>
<th>$M_{\eta_c}$ (MeV/$c^2$)</th>
<th>$\Gamma_{\eta_c}$ (MeV/$c^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+2 MeV/$c^2$</td>
<td>2979.6 ± 2.3</td>
<td>24 ± 7</td>
</tr>
<tr>
<td>-2 MeV/$c^2$</td>
<td>2979.7 ± 2.3</td>
<td>31 ± 8</td>
</tr>
<tr>
<td>Bin choice</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+2 MeV/$c^2$ shifted</td>
<td>2980.3 ± 2.6</td>
<td>29 ± 8</td>
</tr>
<tr>
<td>+2 MeV/$c^2$ shifted</td>
<td>2979.0 ± 2.5</td>
<td>30 ± 7</td>
</tr>
<tr>
<td>-2 MeV/$c^2$</td>
<td>2978.5 ± 2.3</td>
<td>29 ± 7</td>
</tr>
<tr>
<td>-2 MeV/$c^2$ shifted</td>
<td>2980.2 ± 2.4</td>
<td>29 ± 8</td>
</tr>
</tbody>
</table>

The systematic error due to the modeling of the likelihood ratio cut is determined using $B^+ \rightarrow \bar{D}^0\pi^+$ events reconstructed in data. We applied the same continuum suppression procedure, and determined the discrepancy in $B^+$ reconstruction efficiencies between data and Monte Carlo. The results are given in Table 3.6. We quote a 2% systematic error for the likelihood ratio cut.

To estimate the systematic errors in the vertex constrained fit, we use a $\phi \rightarrow K^+K^-$ sample. The reconstructed $\phi$ candidates are shown in Fig. 3.13. A vertex constrained fit is applied to the $\phi$ daughters. We require the $\chi^2$ be smaller than 50, and determined the reconstruction efficiencies. The difference between data and Monte Carlo is taken as the systematic error, which is 2%. The results are summarized in Table 3.7.

The systematic errors in the yields of the $M_{bc}$ fit were determined by varying the mean of the signal by 0.5 MeV/$c^2$, and the width of the signal and the shape parameter (EFACT) of the background by 1σ of the fitting errors. The results are summarized in Table 3.8.
To check for the possibility of background from non-resonant modes that may contribute to the $M_{bc}$ distribution, we use the $\eta_c$ mass sideband data. No statistically significant signals are observed. To be conservative, we include the yields as an asymmetric systematic error, which are given in Table 3.9.

The sources of systematic error are combined in quadrature to obtain the total systematic error, which is given in Table 3.10.

Table 3.5: The systematic errors in the proton likelihood ratio cuts, $L_p/(L_p + L_K) > 0.4$ and $L_p/(L_p + L_\tau) > 0.4$, determined using $\Lambda \rightarrow p\pi^-$ events.

<table>
<thead>
<tr>
<th>$P_p \text{ (GeV}/c)$</th>
<th>Efficiency</th>
<th>$\epsilon_{\text{Data}}/\epsilon_{\text{MC}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2 – 0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC</td>
<td>0.965</td>
<td>0.964 ± 0.003</td>
</tr>
<tr>
<td>Data</td>
<td>0.930</td>
<td></td>
</tr>
<tr>
<td>0.7 – 1.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC</td>
<td>0.974</td>
<td>0.988 ± 0.005</td>
</tr>
<tr>
<td>Data</td>
<td>0.962</td>
<td></td>
</tr>
<tr>
<td>1.8 – 3.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC</td>
<td>0.807</td>
<td>1.028 ± 0.025</td>
</tr>
<tr>
<td>Data</td>
<td>0.823</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.6: The systematic errors in the event shape likelihood ratio cuts determined from $B^+ \rightarrow \bar{D}^0\pi^+$ events.

<table>
<thead>
<tr>
<th>LR</th>
<th>Efficiency (Data)</th>
<th>Efficiency (MC)</th>
<th>$\epsilon_{\text{Data}}/\epsilon_{\text{MC}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 0.5</td>
<td>0.8548</td>
<td>0.8482</td>
<td>1.007 ± 0.009</td>
</tr>
<tr>
<td>&gt; 0.6</td>
<td>0.8181</td>
<td>0.8148</td>
<td>1.004 ± 0.010</td>
</tr>
<tr>
<td>&gt; 0.7</td>
<td>0.7740</td>
<td>0.7630</td>
<td>1.014 ± 0.012</td>
</tr>
</tbody>
</table>
Table 3.7: The errors in the vertex constrained fit for $\chi^2 < 50$ determined using $\phi \rightarrow K^+K^-$ events. $P_\phi^*$ is the $\phi$ momentum in the $\Upsilon(4S)$ center of mass frame.

<table>
<thead>
<tr>
<th>$P_\phi^*$ (GeV/c)</th>
<th>Efficiency</th>
<th>$\epsilon_{\text{Data}}/\epsilon_{\text{MC}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC</td>
<td>0.9582</td>
<td>1.003 ± 0.001</td>
</tr>
<tr>
<td>Data</td>
<td>0.9610</td>
<td></td>
</tr>
<tr>
<td>1.5 – 2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC</td>
<td>0.9624</td>
<td>0.986 ± 0.002</td>
</tr>
<tr>
<td>Data</td>
<td>0.9492</td>
<td></td>
</tr>
<tr>
<td>2.0 – 2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC</td>
<td>0.9522</td>
<td>0.986 ± 0.003</td>
</tr>
<tr>
<td>Data</td>
<td>0.9390</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.13: The $M(K^+K^-)$ invariant mass distribution in the $\phi$ mass region in data with a $\chi^2 < 50$ cut.
Table 3.8: The systematic errors in the $M_{bc}$ fit. The total error is the sum in quadrature of the individual errors.

<table>
<thead>
<tr>
<th></th>
<th>Mean (%)</th>
<th>Width (%)</th>
<th>EFACT (%)</th>
<th>Total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow \eta_c K^+$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta_c \rightarrow K^+ K^- \pi^0$</td>
<td>0.5</td>
<td>0.2</td>
<td>1.7</td>
<td>1.8</td>
</tr>
<tr>
<td>$\eta_c \rightarrow p\bar{p}$</td>
<td>0.9</td>
<td>0.1</td>
<td>0.3</td>
<td>1.0</td>
</tr>
<tr>
<td>$\eta_c \rightarrow K^{*0} K^- \pi^+$</td>
<td>2.8</td>
<td>2.2</td>
<td>2.0</td>
<td>4.1</td>
</tr>
<tr>
<td>$B^0 \rightarrow \eta_c K^0_S$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta_c \rightarrow K^+ K^- \pi^0$</td>
<td>0.2</td>
<td>1.5</td>
<td>3.4</td>
<td>3.7</td>
</tr>
<tr>
<td>$\eta_c \rightarrow p\bar{p}$</td>
<td>0.4</td>
<td>0.1</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>$\eta_c \rightarrow K^{*0} K^- \pi^+$</td>
<td>0.7</td>
<td>0.9</td>
<td>3.1</td>
<td>3.3</td>
</tr>
</tbody>
</table>

Table 3.9: The errors due to the yields observed in the $\eta_c$ invariant mass sideband.

<table>
<thead>
<tr>
<th></th>
<th>Systematic error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow \eta_c K^+$</td>
<td></td>
</tr>
<tr>
<td>$\eta_c \rightarrow K^+ K^- \pi^0$</td>
<td>$-11.9%$</td>
</tr>
<tr>
<td>$\eta_c \rightarrow p\bar{p}$</td>
<td>$-10.4%$</td>
</tr>
<tr>
<td>$\eta_c \rightarrow K^{*0} K^- \pi^+$</td>
<td>$-8.7%$</td>
</tr>
<tr>
<td>$B^0 \rightarrow \eta_c K^0_S$</td>
<td></td>
</tr>
<tr>
<td>$\eta_c \rightarrow K^+ K^- \pi^0$</td>
<td>$-0.8%$</td>
</tr>
<tr>
<td>$\eta_c \rightarrow p\bar{p}$</td>
<td>$-9.7%$</td>
</tr>
<tr>
<td>$\eta_c \rightarrow K^{*0} K^- \pi^+$</td>
<td>$-$</td>
</tr>
</tbody>
</table>

3.8 Consistency Check

To verify the analysis procedure, we measured the branching fraction for $B^+ \rightarrow J/\psi K^+$, where the $J/\psi$ is reconstructed from the $J/\psi \rightarrow p\bar{p}$ mode. Fig. 3.14 shows a clear signal in the $M_{bc}$, $\Delta E$ and $M(p\bar{p})$ distributions. We obtain $27.4 \pm 5.3$ signal
Table 3.10: The total systematic errors.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Systematic error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow \eta_c K^+$</td>
<td></td>
</tr>
<tr>
<td>$\eta_c \rightarrow K^+ K^- \pi^0$</td>
<td>$+10.0% -15.5%$</td>
</tr>
<tr>
<td>$\eta_c \rightarrow p\bar{p}$</td>
<td>$+10.5% -14.8%$</td>
</tr>
<tr>
<td>$\eta_c \rightarrow K^{*0} K^- \pi^+$</td>
<td>$+17.9% -19.9%$</td>
</tr>
<tr>
<td>$B^0 \rightarrow \eta_c K_S^0$</td>
<td></td>
</tr>
<tr>
<td>$\eta_c \rightarrow K^+ K^- \pi^0$</td>
<td>$+10.9% -10.9%$</td>
</tr>
<tr>
<td>$\eta_c \rightarrow p\bar{p}$</td>
<td>$+10.4% -14.2%$</td>
</tr>
<tr>
<td>$\eta_c \rightarrow K^{*0} K^- \pi^+$</td>
<td>$+17.5% -17.5%$</td>
</tr>
</tbody>
</table>

events from a fit to the $M_{bc}$ distribution. The statistical significance of the fit is 10.5$sigma$. We observe 27.6 ± 5.2 events in the $\Delta E$ spectrum, and 26.5 ± 5.2 events in the $M(pp)$ invariant mass distribution. We use the $M_{bc}$ yield, the Monte Carlo detection efficiency of 32.5%, and $B(J/\psi \rightarrow pp) = (2.12 \pm 0.10) \times 10^{-3}$ [57] to determine the branching fraction

$$B(B^+ \rightarrow J\psi K^+) = (12.6 \pm 2.4) \times 10^{-4},$$  \hspace{1cm} (3.8)

where the error is statistical only. This is in good agreement with the PDG world average $B(B^+ \rightarrow J\psi K^+) = (10.1 \pm 0.5) \times 10^{-4}$ [1], where $J/\psi$ is reconstructed from the $J/\psi \rightarrow l^+l^-$ modes.
Figure 3.14: The (a) $\Delta E$, (b) $\Delta E$ vs. $M_{bc}$, (c) $M(p\bar{p})$ invariant mass and (d) $M_{bc}$ distributions for $B^+ \to J/\psi K^+$, $J/\psi \to p\bar{p}$. The curves are results of fits.
3.9 Branching Fractions

To calculate the product branching fractions, we use the formula

\[
B = \frac{\text{Signal yield}}{\text{Number of } B\text{'s} \times \text{Detection efficiency}}.
\] (3.9)

The results are given in Table 3.11 for all modes in which signals are observed. For \( B^0 \to \eta_c K^0, \eta_c \to K^{*0} K^- \pi^+ \) mode, we calculate an upper limit based on the number of events observed in the \( M_{bc} \) signal region (4) and the expected number of background events (2) based on the fit. We use the Feldman-Cousins procedure [65], and reduce the efficiency by one sigma of the systematic error in the calculation. Using an implementation of the Cousin-Highland method [66] to incorporate systematic uncertainties in the upper limit, we obtain a slightly more restrictive limit of 7.1 events on the yield. This corresponds to an upper limit of \( 26 \times 10^{-6} \) rather than the value \( 29 \times 10^{-6} \) given in the table.

Since many of the \( \eta_c \) branching fractions are poorly determined and in some cases there are conflicting measurements, we quote \( B \) branching fractions for the \( \eta_c \to K_S^0 K^- \pi^+ \) and \( \eta_c \to K^- K^+ \pi^0 \) modes only. The \( \eta_c \to K_S^0 K^- \pi^+ \) mode is the most precisely and reliably measured mode and the branching fraction for the \( \eta_c \to K^- K^+ \pi^0 \) mode is related by isospin. We use \( B(\eta_c \to K_S^0 K^- \pi^+) = 1/3 \times (0.055 \pm 0.017) \) where \( 1/3 \) is the relevant Clebsch-Gordon coefficient squared. We assume that the experimental systematic errors in the \( \eta_c \to K_S^0 K^- \pi^+ \) and \( \eta_c \to K^- K^+ \pi^0 \) modes are uncorrelated. We assume equal production of \( B^+ B^- \) and \( B^0 \bar{B}^0 \) pairs and do not include an additional systematic error for the uncertainty in this assumption. We find

\[
B(B^+ \to \eta_c K^+) = (1.25 \pm 0.14^{+0.10}_{-0.12} \pm 0.38) \times 10^{-3}
\] (3.10)

and

\[
B(B^0 \to \eta_c K^0) = (1.23 \pm 0.23^{+0.12}_{-0.16} \pm 0.38) \times 10^{-3}.
\] (3.11)
The first error is statistical, the second error is systematic and the third error is due to the uncertainty in the $\eta_c$ branching fraction scale. When the $\eta_c$ branching fractions for the other modes are better determined, absolute $B$ branching fractions for these modes can be extracted from our results.

Table 3.11: Product branching fractions for $B \to \eta_c K$ decay modes ($10^{-6}$).

<table>
<thead>
<tr>
<th>Branching Fraction</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(B^+ \to \eta_c K^+) \times B(\eta_c \to K^0_S K^0 K^- \pi^+)$ [56]</td>
<td>$(23.2 \pm 2.9^{+2.8}_{-3.8})$</td>
</tr>
<tr>
<td>$B(B^+ \to \eta_c K^+) \times B(\eta_c \to K^+ K^- \pi^0)$</td>
<td>$(11.4 \pm 2.5^{+1.1}_{-1.8})$</td>
</tr>
<tr>
<td>$B(B^+ \to \eta_c K^+) \times B(\eta_c \to p\bar{p})$</td>
<td>$(1.64 \pm 0.41^{+0.17}_{-0.24})$</td>
</tr>
<tr>
<td>$B(B^+ \to \eta_c K^+) \times B(\eta_c \to K^{*0} K^- \pi^+)$</td>
<td>$(19.3 \pm 5.0^{+3.4}_{-3.8})$</td>
</tr>
<tr>
<td>$B(B^0 \to \eta_c K^0) \times B(\eta_c \to K^0_S K^- \pi^+)$ [56]</td>
<td>$(20.1 \pm 4.7^{+3.0}_{-4.5})$</td>
</tr>
<tr>
<td>$B(B^0 \to \eta_c K^0) \times B(\eta_c \to K^+ K^- \pi^0)$</td>
<td>$(16.6 \pm 5.0^{+1.8}_{-1.5})$</td>
</tr>
<tr>
<td>$B(B^0 \to \eta_c K^0) \times B(\eta_c \to p\bar{p})$</td>
<td>$(1.79 \pm 0.68^{+0.19}_{-0.25})$</td>
</tr>
<tr>
<td>$B(B^0 \to \eta_c K^0) \times B(\eta_c \to K^{*0} K^- \pi^+)$</td>
<td>$(8.1 \pm 6.6 \pm 1.4)$</td>
</tr>
<tr>
<td></td>
<td>&lt; 29 at 90% C.L.</td>
</tr>
</tbody>
</table>
Chapter 4

Measurement of $\sin(2\phi_1)$ in $B^0 \rightarrow \eta_c K^0_S$

4.1 Introduction

Here we present a measurement of the CP violation parameter $\sin(2\phi_1)$ in the $B^0 - \bar{B}^0$ system where one of the $B$ mesons decays to the CP-eigenstate $\eta_c K^0_S$. We reconstruct $B$ meson decays to $\eta_c K^0_S$ while we identify the flavor of the other $B$ meson from its decay products. We then reconstruct the decay vertex positions of both $B$ mesons. We obtain $\sin(2\phi_1)$ from an unbinned maximum likelihood fit to the distribution of the proper time difference between the two $B$ mesons.

4.2 Analysis Principle

For $B^0 \rightarrow \eta_c K^0_S$, the time-dependent CP asymmetry is defined as

$$A_{CP}(t) = \frac{\Gamma[\bar{B}^0(t) \rightarrow \eta_c K^0_S] - \Gamma[B^0(t) \rightarrow \eta_c K^0_S]}{\Gamma[\bar{B}^0(t) \rightarrow \eta_c K^0_S] + \Gamma[B^0(t) \rightarrow \eta_c K^0_S]}.$$  \hspace{1cm} (4.1)
where \( \Gamma[B^0(t), B^0(t) \rightarrow \eta_c K^0_S] \) is the \( B^0 \) or \( B^0 \) decay rate at proper time \( t \). Since the final state \( \eta_c K^0_S \) is common to both \( B^0 \) and \( B^0 \), it does not reveal the flavor of the fully reconstructed \( B \) (\( B_{CP} \)). Instead, we can tag the flavor of the other \( B \) (\( B_{tag} \)) if it decays to a flavor specific final state. The \( B^0-\bar{B}^0 \) pair produced at the \( \Upsilon(4S) \) resonance are correlated, and therefore evolve coherently. Hence the two \( B \)'s have opposite flavors at any time instant \( t \). Thus, the flavor of \( B_{CP} \) is identified at the instant \( t = t_{tag} \), the time when \( B_{tag} \) decays and is tagged. The time-dependent \( CP \) asymmetry can then be rewritten as a function of \( \Delta t = t_{CP} - t_{tag} \), where \( t_{CP} \) is the decay time of \( B_{CP} \), and is given by

\[
A_{CP}(\Delta t) = -\xi_f \sin(\Delta m_B \Delta t) \sin(2\phi_1) .
\] (4.2)

In the above equation, the \( CP \) eigenvalue \( \xi_f \) is \(-1\) for \( \eta_c K^0_S \) and the world average for \( \Delta m_B \) is \( 0.489 \pm 0.008 \) ps\(^{-1} \) [1].

Experimentally, the proper time difference \( \Delta t \) is determined as \( \Delta t \simeq \Delta z/(\beta\gamma)c \), where \( \Delta z \) is the \( z \) distance between the decay vertices of \( B_{CP} \) and \( B_{tag} \), and \( \beta\gamma \) is the boost for the \( B \) mesons. The KEKB asymmetric-energy \( e^+e^- \) collision provides, along the \( z \) axis, a boost of 0.425, which leads to an average decay length of the \( B^0 \) meson in the lab frame of approximately 200 \( \mu m \). This compares to the \( \Delta z \) resolution of the SVD of about 100 \( \mu m \).

The decay rate of \( B_{CP} \) as a function of \( \Delta t \) is related to \( \sin(2\phi_1) \) by the equation

\[
\Gamma[B_{CP}(\Delta t) \rightarrow \eta_c K^0_S] \propto \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}[1 - q\xi_f(1 - 2w)\sin(\Delta m_B \Delta t)\sin(2\phi_1)] .
\] (4.3)

where \( q \) equals \(+1\) if \( B_{tag} \) is identified as a \( B^0 \) and \(-1\) if \( B_{tag} \) is identified as a \( \bar{B}^0 \). Since it is experimentally impossible to tag the \( B \)-flavor perfectly, the \( CP \) asymmetry is diluted by a factor of \((1 - 2w)\), where \( w \) is the probability that the \( B \) meson is assigned the wrong flavor. To extract \( \sin(2\phi_1) \), we perform an unbinned maximum
likelihood fit to the $\Delta t$ distribution of the sum of the signal contribution, which is the function on the right side of Equation (4.3) convoluted with the detector resolution, and the background contributions.

4.3 $B_{CP}$ Reconstruction

We use a 78 $fb^{-1}$ data sample, which contains 85 million produced $B^0\bar{B}^0$ pairs, collected at the $\Upsilon(4S)$ resonance with the Belle detector. We reconstruct the $B_{CP}$ candidates via the $B^0 \rightarrow \eta_c K^0_S$ decay mode, where the $K^0_S$ decays to $\pi^+\pi^-$. To reconstruct the $\eta_c$, we use the decay modes $\eta_c \rightarrow K^0_S K^-\pi^+$, $\eta_c \rightarrow K^+ K^-\pi^0$ and $\eta_c \rightarrow p\bar{p}$. All events are required to pass the event selection cuts described in the previous chapter. The $M_{bc}$ and $\Delta E$ distributions for the fully reconstructed $B$ candidates are shown in Fig. 4.1. The signal region is $5.27 < M_{bc} < 5.29$ GeV/$c^2$ and $-35 < \Delta E < 35$ MeV for $K^0_S K^-\pi^+$, $-55 < \Delta E < 45$ MeV for $K^+ K^-\pi^0$ and $-25 < \Delta E < 25$ MeV for $p\bar{p}$.

![Figure 4.1: The $M_{bc}$ and $\Delta E$ distributions for $B_{CP}$ candidates in all the $B^0 \rightarrow \eta_c K^0_S$ decay modes.](image)
4.4 \( B \)-flavor Tagging

We can identify the flavor of neutral \( B \) mesons that decay to a flavor-specific state. For example, in the semileptonic decay \( \bar{b} \to \bar{c}l^+\nu \), the high momentum positively charged lepton is associated with a \( B^0 \) meson while the negatively charged lepton is associated with a \( \bar{B}^0 \) meson. The flavor of \( B_{CP} \) can also be tagged by a secondary lepton in \( \bar{b} \to \bar{c} \to \bar{s}l^-\bar{\nu} \), a charged kaon or a \( \Lambda \) in \( \bar{b} \to \bar{c} \to \bar{s} \), a fast pion in \( B^0 \to D^{(*)-}\pi^+X \) or a slow pion in \( B^0 \to D^{*-}X, D^{*-} \to \bar{D}^0\pi^- \). We use a multidimensional likelihood method for the \( B \)-flavor tagging [67]. In this method, the well reconstructed tracks that do not belong to \( B_{CP} \) are divided into four categories: leptons, slow pions, \( \Lambda \)’s, and kaons or fast pions. The \( B \)-flavor information are determined independently for each particle category, and then combined taking into account their correlations.

The overall flavor tagging information is represented by two parameters, \( q \) and \( r \). We define \( q \) as a discrete variable with value +1 for \( B^0 \) tag, -1 for \( \bar{B}^0 \) tag and 0 for no flavor discrimination. Monte Carlo study shows that less than 0.3% of signal events have \( q = 0 \). The parameter \( r \) is the event-by-event flavor tagging dilution factor determined from Monte Carlo simulation. We use \( r \) to sort the data into six bins, \( 0 < r \leq 0.25, 0.25 < r \leq 0.5, 0.5 < r \leq 0.625, 0.625 < r \leq 0.75, 0.75 < r \leq 0.875 \) and \( 0.875 < r \leq 1.0 \). For each \( r \) bin, the wrong tag probability \( w_l \) (\( l = 1', 2', 3', 4', 5', 6' \)) used in the \( \sin(2\phi_1) \) fit are determined from the 78 \( fb^{-1} \) data sample using the self-tagging decay modes \( B \to D^*l\nu, B \to D^{(*)-}\pi^+ \) and \( B \to D^{(*)-}\rho^+ \) [68, 69].

4.5 Vertex Reconstruction

In order to measure the \( B \) decay vertex positions precisely, we first remove the tracks that have less than one \( r-\phi \) hit or less than two \( z \) hits in the SVD. We obtain the \( B_{CP} \) vertex position by applying a vertex constrained fit to the remaining charged daughter particles from the \( \eta_c \). We then remove the tracks that are associated with the
$B_{CP}$ candidate. For the remaining tracks, we require that the error on the $z$ impact parameter ($e_{dz}$) for these tracks be smaller than 500 $\mu$m. In order to eliminate the tracks from secondary vertices, we also require the tracks to have radial impact parameters $|dr|$ smaller than 500 $\mu$m, and be inconsistent with $K^{0}_{S} \rightarrow \pi^{+}\pi^{-}$. To reconstruct the $B_{tag}$ vertex, we apply a vertex constrained fit to the tracks that satisfy all these requirements. If the $\chi^{2}/n.d.f.$ for the fit is greater than 20, we remove the track that has the largest contribution to the $\chi^{2}$ and redo the fit. The fit repeats until $\chi^{2}/n.d.f. \leq 20$. Details of the tag-side vertex reconstruction can be found elsewhere [70].

The $B$ vertices are constrained to be consistent with the interaction point profile. For each run or every 60000 events, whichever comes first, the IP profile is determined by a fit to the distribution of reconstructed IP's, where the smearing effect in the $r$-$\phi$ direction due to the $B$ decay length is included. A typical value of the IP profile is $\sigma_{x} = 80 \mu$m, $\sigma_{y} = 5 \mu$m and $\sigma_{z} = 3.4$ mm. With the IP profile, we are able to reconstruct single-track vertices.

We remove the events with poorly reconstructed vertex positions by requiring the $\chi^{2}/n.d.f.$ in the $z$ direction ($\xi_{z}$) for the vertex constrained fits for both $B$ mesons be smaller than 100. We also remove the events that have $|\Delta t| > 70$ ps. The $CP$-side vertex reconstruction is 92% efficient for the signal, and the tag-side is 86% efficient. The combined efficiency is about 85%. The resolution for the $B_{CP}$ vertex is 107 $\mu$m for the $K^{0}_{S}K^{-}\pi^{+}$ mode, 99 $\mu$m for the $K^{+}K^{-}\pi^{0}$ mode and 83 $\mu$m for the $p\bar{p}$ mode. The resolution for the $B_{tag}$ vertex is 150 $\mu$m due to the inclusion of charm decay products.

### 4.6 Signal Probability

After flavor tagging and vertex reconstruction, we find, in the $M_{bc}$ and $\Delta E$ signal region, 63 candidates for the $K^{0}_{S}K^{-}\pi^{+}$ mode, 44 candidates for the $K^{+}K^{-}\pi^{0}$ mode
and 15 candidates for the $p\bar{p}$ mode; 65 have $q = 1$ and 57 have $q = -1$. We use these events to measure $\sin(2\phi_1)$.

The probability that an event is signal as a function of $M_{bc}$ and $\Delta E$ is written as

$$f_{\text{sig}}(M_{bc}, \Delta E) = \frac{f P_{\text{sig}}(M_{bc}, \Delta E)}{f P_{\text{sig}}(M_{bc}, \Delta E) + (1 - f) P_{\text{bkg}}(M_{bc}, \Delta E)},$$

(4.4)

where $f$ is the purity of the candidate events. The signal probability density function (PDF), $P_{\text{sig}}$, is the product of a single Gaussian in $M_{bc}$ and a single or double Gaussian in $\Delta E$, depending on the decay channel. The parameters for the signal PDF are determined in the region with $5.2 < M_{bc} < 5.3$ GeV/$c^2$ and $-0.1 < \Delta E < 0.2$ GeV. For the $M_{bc}$ Gaussian, the mean is fixed from the $B^0 \rightarrow \bar{D}^{(*)}-\pi^+$ data, and the width is determined from an unbinned fit to the $\Delta E$ vs $M_{bc}$ distribution for $B^+ \rightarrow \eta_c K^+$, taking into account the resolution difference between the $B^0 \rightarrow \eta_c K^0_S$ and $B^+ \rightarrow \eta_c K^+$ decay modes, which is determined from Monte Carlo. For the $\Delta E$ Gaussian, the parameters are fixed from Monte Carlo simulation except for the mean and the main width, which are also determined from the $B^+ \rightarrow \eta_c K^+$ data. The background PDF, $P_{\text{bkg}}$, is the product of an ARGUS background function in $M_{bc}$ and a linear background function in $\Delta E$. The shape parameter for the ARGUS function is determined from the sideband data in the region with $0.1 < \Delta E < 0.2$ GeV, and that for the linear function is determined from the sideband data in the region with $5.2 < M_{bc} < 5.265$ GeV/$c^2$.

In order to determine $f$, we then perform an unbinned 2D maximum likelihood fit to the individual $\Delta E$ vs $M_{bc}$ distribution for each decay mode. The signal and background normalization factors are the only free parameters in the fit. Fig. 4.2 shows the projections in $M_{bc}$ and $\Delta E$ for the data and the results of the fits.
Figure 4.2: The distributions of $M_{bc}$ for events in the $\Delta E$ signal region and $\Delta E$ for events in the $M_{bc}$ signal region for the (a) $K^0 \bar{K}^{-} \pi^+$, (b) $K^+ K^- \pi^0$ and (c) $p\bar{p}$ modes. The curves are the projections of the unbinned 2D fit.

### 4.7 Determination of $\sin(2\phi_1)$

To extract $\sin(2\phi_1)$, we perform an unbinned maximum likelihood fit to the $\Delta t$ distribution. The likelihood value for event $i$ is given by:

$$P_i(\Delta t, q, w_i) = f_{ol} P_{ol}(\Delta t) + (1 - f_{ol}) \int [f_{sig} P_{sig}(\Delta t', q, w_i) R_{sig}(\Delta t - \Delta t')] d\Delta t' + (1 - f_{sig}) P_{bkg}(\Delta t') R_{bkg}(\Delta t - \Delta t')] d\Delta t'. \quad (4.5)$$
The right side of the equation is the sum of three components: the signal likelihood, the background likelihood and the likelihood due to a small component of broad outliers in the \( \Delta z \) distribution, which is represented by a Gaussian \( (P_{ol}) \) of width \( 42^{+5}_{-4} \) ps.

The signal likelihood is the convolution of the signal PDF \( P_{\text{sig}} \) with the signal resolution function \( R_{\text{sig}} \). \( P_{\text{sig}} \) is a function of \( \sin(2\phi) \):

\[
P_{\text{sig}}(\Delta t', q, w) = \frac{e^{-|\Delta t'|/\tau_{B_0}}}{4\tau_{B_0}}[1 + q(1 - 2w)\sin(\Delta m_B \Delta t')\sin(2\phi)]_i, \tag{4.6}
\]

where \( \tau_{B_0} = 1.542 \pm 0.016 \) ps [1] is the \( B^0 \) lifetime. \( R_{\text{sig}} \) is the convolution of four components: the detection resolutions of the \( z \) vertex positions for \( B_{CP} \) and \( B_{tag} \), the shift in the \( z \) vertex position for \( B_{tag} \) due to the tracks originating from secondary vertices, and the kinematic approximation that the \( B \) mesons are at rest in the center of mass frame. Details of the parameterization of \( R_{\text{sig}} \) can be found in reference [71]. \( R_{\text{sig}} \) is determined from a lifetime fit of the decays \( B^0 \rightarrow D^0\pi^0, D^{*0}\pi^0, J/\psi K^0, J/\psi K^{*0} \). These decay modes have better vertex resolutions than the \( K^0 S K^- \pi^+ \) and \( K^+ K^+ \pi^0 \) modes. We introduce scale factors of 1.09 for the \( K^0 S K^- \pi^+ \) mode and 1.06 for the \( K^+ K^- \pi^0 \) mode, which are determined from Monte Carlo simulation.

The background likelihood is the convolution of the background PDF \( P_{\text{bkgr}} \) with the resolution function for background events, \( R_{\text{bkgr}} \). For \( P_{\text{bkgr}} \), we use the sum of a \( \delta \) function and an exponential function:

\[
P_{\text{bkgr}}(\Delta t') = f_\delta \delta(\Delta t' - \mu) + (1 - f_\delta)e^{-|\Delta t' - \mu|/\tau_{\text{bkgr}}}. \tag{4.7}
\]

For \( R_{\text{bkgr}} \), we use the sum of two Gaussians

\[
R_{\text{bkgr}}(\Delta t - \Delta t') = (1 - f_{\text{tail}})G(\Delta t - \Delta t'; s_{\text{main}}\sigma) + f_{\text{tail}}G(\Delta t - \Delta t'; s_{\text{tail}}\sigma), \tag{4.8}
\]

where \( \sigma \) is the event-by-event error on \( \Delta t \), and \( s_{\text{main}}\sigma \) and \( s_{\text{tail}}\sigma \) are widths of the
Gaussians. The parameters for $P_{bkg}$ and $R_{bkg}$ are determined from a fit to the $\Delta t$ distribution for the sideband data in the region with $5.200 < M_{bc} < 5.265$ GeV/c$^2$ and $-0.1 < \Delta E < 0.2$ GeV. We divide the candidate events into two categories: first, the events that have the two vertices reconstructed from multiple tracks, and, second, the events that have at least one of the vertices reconstructed from a single track. We have 80 events in the first category and 42 events in the second category. In the fit, the $s_{\text{tail}}$ and $f_{\text{tail}}$ values for the events in the second category are fixed to Monte Carlo simulation. The fitted values of the parameters are given in Table 4.1. The $\Delta t$ distribution of the sideband data and the result of the fit are shown in Fig. 4.3.

Table 4.1: The fitted values of the parameters for $P_{bkg}$ and $R_{bkg}$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$P_{bkg}$:</th>
<th>Fitted value</th>
<th>$R_{bkg}$:</th>
<th>Multi-track Vertex</th>
<th>Single-track Vertex</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$</td>
<td></td>
<td>$-0.532 \pm 0.044$</td>
<td>$s_{\text{main}}$</td>
<td>$0.83 \pm 0.17$</td>
<td>$1.07 \pm 0.10$</td>
</tr>
<tr>
<td>$\tau_{bkg}$</td>
<td></td>
<td>$1.08 \pm 0.20$</td>
<td>$s_{\text{tail}}$</td>
<td>$1.80 \pm 0.36$</td>
<td>$3$ (fixed)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$f_{\text{tail}}$</td>
<td>$0.46 \pm 0.23$</td>
<td>$0$ (fixed)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$f_{\delta}$</td>
<td>$0.66 \pm 0.19$</td>
<td>$0.43 \pm 0.18$</td>
</tr>
</tbody>
</table>

The likelihood function for the fit is $L = \prod_i P_i$ where $i$ runs over all events. In the final fit, $\sin(2\phi_1)$ is the only free parameter and is determined by maximizing $L$. The result of the fit is shown in Fig. 4.4. The $CP$ asymmetry parameter $\sin(2\phi_1)$ is found to be $1.26^{+0.27}_{-0.39}$ from the fit. The error is statistical only.
Figure 4.3: The $\Delta t$ distribution for the sideband data. The curve is the fitted result.

4.8 Systematic Errors

The largest contributions to the systematic error come from the uncertainties in the vertex reconstruction, the signal resolution function, and $w_l$. In order to estimate the systematic error in the vertex reconstruction, we vary the $\Delta t$ cut by ±50 ps, the $\xi_z$ cut by ±50, the $|dr|$ cut by ±50 $\mu$m and the $e_{dz}$ cut by ±50 $\mu$m and combine the results in quadrature. The error associated with flavor tagging is determined by varying each $w_l$ by $1\sigma$ and combining the results in quadrature. The errors due to the uncertainties in the physics parameters, $m_{B^0}$, $\tau_{B^0}$ and $\Delta m_B$, and the parameters for signal resolution function, background shape and $f_{\text{sig}}$ are also obtained by varying their values by $1\sigma$. To determine the possible fit bias, we perform fits to signal Monte Carlo samples generated for different values of $\sin(2\phi_1)$. We find that the fitted values statistically agree with the generated values as shown in Fig. 4.5. To be conservative, we take their differences as the possible fit bias. The contributions to the systematic error are given in Table 4.2. The sources of systematic error are combined in quadrature to obtain the final systematic error, which is 0.06.0.
Figure 4.4: The $\Delta t$ distributions for the events with $B_{tag}$ identified as $B^0 (q = +1)$ and $\bar{B}^0 (q = -1)$. The results of the fit with $\sin(2\phi_1) = 1.26 \pm 0.34$ are also shown. The shaded areas are the background contributions.

4.9 Consistency Check

We apply the $\sin(2\phi_1)$ fit to the $B^+ \rightarrow \eta_c K^+$ mode, which does not have any time dependent $CP$ asymmetry and, hence, has $A_{CP}(t) = 0$. The fit gives $\sin(2\phi_1) = -0.04 \pm 0.12$, which is in good agreement with the expected value of 0. We also apply the fit to the sideband data in the region with $5.20 < M_{bc} < 5.26$ GeV/c$^2$ and $-0.1 < \Delta E < 0.2$ GeV. The $\sin(2\phi_1)$ value is found to be $-0.11 \pm 0.28$, which is consistent with 0. These results show that there is no significant bias in the fit. The raw asymmetry and the fit result for the $B^0 \rightarrow \eta_c K^0_S$ mode are plotted in Fig. 4.6(a), where a non-zero time-dependent $CP$ asymmetry is visible. The corresponding results for the $B^+ \rightarrow \eta_c K^+$ mode and the sideband data are plotted in Figs. 4.6(b) and 4.6(c), which show no time dependent $CP$ asymmetry.
Table 4.2: Contributions to the systematic error for $\sin(2\phi_1)$ in $B \rightarrow \eta_c K_S^0$.

<table>
<thead>
<tr>
<th>Uncertainty Source</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertex reconstruction</td>
<td>0.039</td>
</tr>
<tr>
<td>Resolution function</td>
<td>0.030</td>
</tr>
<tr>
<td>Wrong tag probability</td>
<td>0.023</td>
</tr>
<tr>
<td>Possible fit bias</td>
<td>0.023</td>
</tr>
<tr>
<td>Background shape</td>
<td>0.0039</td>
</tr>
<tr>
<td>$m_{B^0}, \tau_{B^0}, \Delta m_B$</td>
<td>0.0064</td>
</tr>
<tr>
<td>Signal probability</td>
<td>0.0058</td>
</tr>
<tr>
<td>Total</td>
<td>0.060</td>
</tr>
</tbody>
</table>

To check the modeling of the signal resolution function, the background shape and the signal probability, we fit the $\Delta t$ distributions for $B^0 \rightarrow \eta_c K_S^0$ and $B^+ \rightarrow \eta_c K^+$ to determine the $B$ meson lifetimes. The likelihood value for the lifetime fit has the same form as Eqn. (4.5) with

$$P_{\text{sig}}(\Delta t') = \frac{e^{-|\Delta t'|/\tau_B}}{2\tau_B}.$$  \hspace{1cm} (4.9)

The $\Delta t$ distributions and the fit results are shown in Fig. 4.7. From the fit, we find
Figure 4.6: The raw asymmetry plots for (a) $B^0 \rightarrow \eta_c K_S^0$, (b) $B^+ \rightarrow \eta_c K^+$ and (c) the sideband data. The curves are the results of the unbinned maximum likelihood fits.

$\tau_{B^0} = 1.46 \pm 0.20$ ps and $\tau_{B^+} = 1.53 \pm 0.11$ ps, where the errors are statistical only. They are in good agreement with the world averages $\tau_{B^0} = 1.542 \pm 0.016$ ps and $\tau_{B^+} = 1.674 \pm 0.018$ ps [1].

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Figure 4.7: The $\Delta t$ distributions for (a) $B^0$, $\bar{B}^0$ and (b) $B^+$, $B^-$ mesons. The curves are the results of the fits with $\tau_{B^0} = 1.46 \pm 0.20$ ps and $\tau_{B^+} = 1.53 \pm 0.11$ ps, respectively. The shaded areas are the background contributions.

4.10 Result

From the unbinned maximum likelihood fit to the proper time difference distribution, we find

$$\sin(2\phi_1) = 1.26^{+0.27}_{-0.39} \pm 0.06.$$  \hspace{1cm} (4.10)

This result is $3\sigma$ away from a zero value of $\sin(2\phi_1)$. It is statistically consistent with Belle’s measurement using the $J/\psi K^0_S$ mode [72], which gives $\sin(2\phi_1) = 0.72 \pm 0.10$ (stat).
Chapter 5

Observation of $B^\pm \rightarrow p\bar{p}K^\pm$

5.1 Introduction

We report the results of searches for the decay modes $B^+ \rightarrow p\bar{p}K^+$ and $B^0 \rightarrow p\bar{p}K^0$. These modes are expected to proceed mainly via $b \rightarrow s$ penguin diagrams. We also search for $B^+ \rightarrow p\bar{p}\pi^+$, which is expected to occur primarily via a $b \rightarrow u$ tree process.

To reconstruct the signal, we form combinations of protons, antiprotons and kaons or pions that are inconsistent with the $b \rightarrow c\bar{c}s$ transitions: $B^+ \rightarrow \psi K^+$, $\psi \rightarrow p\bar{p}$; $B^+ \rightarrow \eta_cK^+$, $\eta_c \rightarrow p\bar{p}$; $B^+ \rightarrow \psi' K^+$, $\psi' \rightarrow p\bar{p}$ and $B^+ \rightarrow \chi_{c[0,1]}K^+$, $\chi_{c[0,1]} \rightarrow p\bar{p}$. We then fit the $\Delta E$ distributions to establish the existence of a signal and determine its branching fraction.

5.2 Selection Criteria

We use a 29.4 $fb^{-1}$ data sample, which contains 31.9 million produced $B\bar{B}$ pairs, collected at the $\Upsilon(4S)$ resonance with the Belle detector. The data are required to pass the hadronic selection cuts.
To determine the selection criteria, we maximize the figure of merit $S/\sqrt{S+B}$ where $S$ is taken from signal Monte Carlo simulation and $B$ is taken from the sideband data. Two Monte Carlo models of signal are considered, a model where the $B^+ \to p\bar{p}K^+$ decay is non-resonant three-body phase space and a second model where the $p\bar{p}$ system is produced from the decay of a high mass state with mass 2.3 GeV/$c^2$ and width 300 MeV/$c^2$. The Monte Carlo momentum distributions expected for protons and kaons are shown in Fig. 5.1. For the second Monte Carlo, kaons have momenta above 1.2 GeV/$c$. We determine the final optimization of selection requirements with this Monte Carlo. The figure of merit, $S/\sqrt{S+B}$, that is used to determine the selection criteria is shown in Fig. 5.2 for three of the most important cuts.

![Figure 5.1](image)

**Figure 5.1:** The distributions of proton momenta and kaon momenta for the two Monte Carlo models used: (a) $B^+ \to p\bar{p}K^+$ non-resonant three-body phase space decay, (b) $B^+ \to XK^+$ where $X$ is a high mass state that decays to $p\bar{p}$.
Figure 5.2: The figure of merit for (a) kaon likelihood ratio \( L_K/(L_K + L_\pi) \), (b) proton likelihood ratio \( L_p/(L_p + L_K) \) and \( L_p/(L_p + L_\pi) \) and (c) signal event likelihood ratio \( LR \) cuts for the mode \( B^+ \rightarrow ppK^+ \).

We select well measured charged tracks with impact parameters with respect to the interaction point of less than 0.3 cm in the radial direction and less than 3 cm in the z direction. The tracks are required to have \( p_T > 50 \text{ MeV}/c \) and have greater than 6 axial and 2 stereo CDC hits.

To identify kaons that have momenta above 1.2 GeV/c, we do not use the TOF system and require \( L_K/(L_K + L_\pi) > 0.6 \). We also veto kaon candidates that are consistent with being protons. For the \( B^+ \rightarrow p\bar{p}\pi^+ \) mode, we require pions to have \( L_K/(L_K + L_\pi) \) smaller than 0.8. Protons and antiprotons are identified using all particle identification systems and are required to have proton likelihood ratios
\[ \frac{L_p}{(L_p + L_K)} \text{ and } \frac{L_p}{(L_p + L_\pi)} \] greater than 0.2. This rather loose requirement optimizes the figure of merit. Fig. 5.3 shows that this proton likelihood ratio requirement is very effective in removing the background for a sample of \( \Lambda \to p\pi^- \) candidates. Proton candidates that are electron-like according to the information recorded by the CsI(Tl) calorimeter are vetoed. This selection is 98% efficient for protons with a 15% kaon misidentification rate.

For the \( B^0 \to p\bar{p}K_S^0 \) mode, we select \( K_S \) candidates from \( \pi^+\pi^- \) candidates that lie within the mass window \( 0.482 \text{ GeV}/c^2 < M(\pi^+\pi^-) < 0.514 \text{ GeV}/c^2 \) which corresponds to \( \pm 4\sigma \), and satisfy the “good \( K_S \)” requirements described in the appendix. The distance of closest approach between the two daughter tracks is required to be less than 2.4 cm. The impact parameter of each track in the radial direction should have magnitude greater than 0.02 cm, and the flight length should be greater than 0.22 cm. The difference in the angle between the vertex direction and the \( K_S \) flight direction in the \( x-y \) plane is required to satisfy \( \Delta\phi < 0.03 \) radians.

To reconstruct \( B^+ \to p\bar{p}K^+ \) signal candidates, we form combinations of a kaon, proton and antiproton that are inconsistent with the following \( b \to c\bar{c}s \) transitions: \( B^+ \to J/\psi K^+, J/\psi \to p\bar{p}; B^+ \to \eta_c K^+; \eta_c \to p\bar{p}; B^+ \to \psi' K^+, \psi' \to p\bar{p} \) and \( B^+ \to \chi_{c[0,1]} K^+, \chi_{c[0,1]} \to p\bar{p} \). This set of requirements is referred to as the charm veto. The regions \( 2.85 < M(pp) < 3.128 \text{ GeV}/c^2 \) and \( 3.315 < M(pp) < 3.735 \text{ GeV}/c^2 \) are excluded to remove background from modes with \( \eta_c, \psi \) and \( \chi_{c0}, \chi_{c1}, \psi' \) mesons, respectively. Similar charm vetoes are applied in the analysis of the other decay modes. In the case of \( B^0 \to p\bar{p}K_S^0 \), events with \( pK_S \) or \( p\bar{K}_S \) invariant masses that lie between 2.262 and 2.310 \( \text{GeV}/c^2 \) are rejected to remove \( B^0 \to \Lambda^+_c \bar{p} \) candidates.

To isolate the signal, we form the beam constrained mass \( M_{bc} \) and energy difference \( \Delta E \) in the \( \Upsilon(4S) \) center of mass frame. The signal region for \( \Delta E \) is \( \pm 25 \text{ MeV} \), which corresponds to \( \pm 2.5\sigma \) where \( \sigma \) is the resolution determined from a Gaussian fit to the Monte Carlo simulation. The signal region for \( M_{bc} \) is \( 5.270 < M_{bc} < 5.290 \text{ GeV}/c^2 \).

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5.3 Continuum Suppression

To suppress the large continuum background, we first remove events with $R_2 < 0.5$. We then form a likelihood ratio using two variables. The six modified Fox-Wolfram moments and the cosine of the thrust angle are combined into a Fisher discriminant $\mathcal{F}$. For signal Monte Carlo and continuum data, we then form probability density functions for this Fisher discriminant, and the cosine of the $B$ decay angle with respect to the $z$ axis ($\cos \theta_B$). In Fig. 5.4, we show distributions of $\cos \theta_B$, $\mathcal{F}$ and the likelihood ratio $\mathcal{L}_S/\mathcal{L}_S + \mathcal{L}_{BG}$ for the $B^+ \rightarrow p\bar{p}K^+$ signal Monte Carlo and continuum data. The likelihood ratio $\mathcal{L}\mathcal{R}$ is required to be greater than 0.7. The event topology requirements retain 74% of the signal while removing 90% of the continuum background. For the $B^+ \rightarrow p\bar{p}\pi^+$ mode, which suffers from a higher continuum background, we require $\mathcal{L}\mathcal{R}$ to be greater than 0.8.
5.4 Backgrounds from Other $B$ decays

To check for $B\bar{B}$ backgrounds that might peak in the signal region, we used two large $B\bar{B}$ Monte Carlo samples. These samples contain $36 \times 10^6 B^0\bar{B}^0$ events and $40 \times 10^6 B^+B^-$ events, which correspond to an integrated luminosity about twice the size of the data sample. For $B^+ \rightarrow ppK^+$, three candidates in the signal region were observed from the $B^+B^-$ sample and none from the $B^0\bar{B}^0$ sample. No backgrounds that peak in the signal region were found. For the $B^0 \rightarrow ppK_S^0$ mode, no candidates in the signal region were observed.
We also generated dedicated Monte Carlo samples of $b \to c$ decay modes with baryons in the final state. We restricted our attention to low multiplicity decay modes. We generated samples of $33,000 \, \bar{B}^0 \to \Lambda_c^+ \bar{p}$, $105,000 \, B^- \to \Lambda_c^+ \bar{p} \pi^-$ and $B^- \to \Lambda_c^+ \bar{p} e^- \bar{\nu}_e$. The charmed baryon $\Lambda_c$ was allowed to decay into all measured decay modes that contain a proton. These samples correspond to an integrated luminosity about a factor of ten larger than the data sample. In these samples, we find no significant background in $p\bar{p}K^+$ except for the two body mode $\Lambda_c^+ \bar{p}$, where $\Lambda_c \to pK^-\pi^+$. However, because of the presence of an additional pion, this background is displaced from the signal by 100 MeV in $\Delta E$. In the $B^0 \to p\bar{p}K^0_S$ mode, we observe background in the signal region from $\Lambda_c^+ \bar{p}$, where $\Lambda_c^+ \to pK^0_S$. However, the expected background is of order two events. We therefore introduce an explicit veto for this decay chain.

We have also examined Monte Carlo simulations of $B^+ \to K^+ K^- K^+$ and $B^+ \to K^+\pi^-\pi^+$ decays. Due to the large shift in $\Delta E$ that occurs when we assign a proton mass to a kaon or pion, we observe no background from these decay modes.

We have run on the continuum Monte Carlo samples but, as expected, do not observe any peaking backgrounds.

### 5.5 Signal Yields and Fits

In Fig. 5.5, we show the $\Delta E$ and beam-constrained mass distributions for the signal candidates. We fit the $\Delta E$ distribution with a double Gaussian signal function and a linear background function, with slope determined from the $M_{bc}$ sideband. The mean of the Gaussian is determined from $\bar{B}^0 \to \Lambda_c p \pi^+ \pi^-$, $\Lambda_c \to pK^-\pi^+$ decays. The fit to the $\Delta E$ distribution gives a yield of $51.4^{+11.0}_{-10.3}$ with a significance of 5.8 standard deviations. In the fit to the $\Delta E$ distribution, the region with $\Delta E < -120$ MeV is excluded to avoid feed-downs from modes such as $B \to p\bar{p}K^*$. As a consistency check, we fit the $M_{bc}$ distribution to the sum of a signal Gaussian and a background
Figure 5.5: (a) $\Delta E$, (b) $\Delta E$ vs. $M_{bc}$ and (c) $M_{bc}$ distributions for $B^+ \to ppK^+$.

function with kinematic threshold. The width of the Gaussian is fixed from Monte Carlo simulation and the mean is determined from $B^+ \to \bar{D}^0\pi^+$ data. The shape parameter of the background function is determined from $\Delta E$ sideband data. In the $M_{bc}$ distribution, we observe a signal of $58.6^{+10.3}_{-9.6}$ events. The signal yields and the branching fractions are determined from fits to the $\Delta E$ distribution rather than $M_{bc}$ in order to minimize possible biases from $B\bar{B}$ backgrounds that tends to peak in $M_{bc}$ but not in $\Delta E$.

We also examine the $M(pp)$ invariant mass distributions for events in the $\Delta E$, $M_{bc}$ signal region. The signal yield as a function of $M(pp)$ is shown in Fig. 5.6. These
yields were determined by fits to the $\Delta E$ distribution in bins of $p\bar{p}$ invariant mass. The distribution from a three-body phase space Monte Carlo normalized to the area of the signal is superimposed. It is clear that the observed mass distribution is not consistent with three-body phase space but instead is peaked at low $p\bar{p}$ mass.

To avoid model dependence in the determination of the branching fraction for $B^+ \to p\bar{p}K^+$, we fit the $\Delta E$ signal yield in bins of $M(p\bar{p})$ and correct for the detection efficiency in each bin using the three-body phase space $B^+ \to p\bar{p}K^+$ Monte Carlo model. The results of the fits are given in Table 5.1.

We also examined two related decay modes $B^0 \to p\bar{p}K_S^0$ and $B^+ \to p\bar{p}\pi^+$ that may help clarify the interpretation of the signal. Measurement of $B^0 \to p\bar{p}K_S^0$ will help to determine the role of the spectator quark in $b \to s$ decays with baryons, while
observation of $B^+ \rightarrow p\bar{p}\pi^+$ will constrain the ratio of the $b \rightarrow u$ tree and $b \rightarrow s$ penguin diagrams in decays with baryons.

For $B^0 \rightarrow p\bar{p}K_0^*$, after the application of the charm and $\Lambda_c$ vetoes, no significant signal is observed in either the $\Delta E$ or $M_{bc}$ distribution. A fit to the $\Delta E$ distribution shown in Fig. 5.7 gives $6.4^{+4.4}_{-3.7}$ events. We calculate an upper limit by applying the Feldman-Cousins procedure [65]. In this case, the total number of events in the signal region is 16, and if the background is taken to be 8 (the fits gives $9.9^{+1.5}_{-1.3}$) then we obtain an upper limit of less than 16 events at the 90% confidence level. The detection efficiency for $B^0 \rightarrow p\bar{p}K_0^*$, $K_s \rightarrow \pi^+\pi^-$ is 23.0%.

In the $B^+ \rightarrow p\bar{p}\pi^+$ mode, the $M_{bc}$ and $\Delta E$ distributions after the application of the charm veto are shown in Fig. 5.8. We fit the $\Delta E$ distribution with a double Gaussian for $B^+ \rightarrow p\bar{p}\pi^+$ signal, an asymmetric double Gaussian for misidentified $B^+ \rightarrow p\bar{p}K^+$ decays and a linear background function. When the kaon in $B^+ \rightarrow p\bar{p}K^+$ is misidentified as a pion, it produces a peak centered at $-50$ MeV in the $\Delta E$ distribution. This fit gives a signal yield of $16.2^{+8.6}_{-8.0}$ events and a significance of $2.1\sigma$. A corresponding excess of $17.9^{+7.4}_{-6.7}$ events in the $M_{bc}$ distribution is also observed. The detection efficiency is 26.9%, which is similar to the $B^+ \rightarrow p\bar{p}K^+$ mode.

<table>
<thead>
<tr>
<th>$M(pp)(\text{GeV}/c^2)$</th>
<th>$M_B$ yield</th>
<th>$\Delta E$ yield</th>
<th>$\varepsilon_{\text{detect}}$</th>
<th>$B \times 10^{-6}$</th>
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</thead>
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<tr>
<td>&lt;2.0</td>
<td>10.9^{+4.1}_{-3.4}</td>
<td>10.8^{+4.2}_{-3.6}</td>
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<td>0.97^{+0.38}_{-0.32}</td>
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<tr>
<td>2.0-2.2</td>
<td>13.0^{+4.7}_{-4.1}</td>
<td>12.3^{+4.7}_{-4.0}</td>
<td>0.33</td>
<td>1.16^{+0.44}_{-0.38}</td>
</tr>
<tr>
<td>2.2-2.4</td>
<td>11.1^{+4.2}_{-3.5}</td>
<td>10.4^{+4.3}_{-3.6}</td>
<td>0.31</td>
<td>1.06^{+0.33}_{-0.37}</td>
</tr>
<tr>
<td>2.4-2.6</td>
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<td>0.30</td>
<td>0.40^{+0.33}_{-0.27}</td>
</tr>
<tr>
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<td>1.5^{+2.7}_{-2.1}</td>
<td>0.30</td>
<td>0.16^{+0.28}_{-0.22}</td>
</tr>
<tr>
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<td>0.30</td>
<td>0.63^{+0.39}_{-0.31}</td>
</tr>
<tr>
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<td>0.33</td>
<td>0.21^{+0.32}_{-0.25}</td>
</tr>
<tr>
<td>4.0-4.8</td>
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<td>1.5^{+5.1}_{-4.4}</td>
<td>0.32</td>
<td>0.15^{+0.50}_{-0.47}</td>
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Figure 5.7: (a) $\Delta E$ and (b) $M_{bc}$ distributions for $B^0 \rightarrow p\bar{p}K^0_S$.

Figure 5.8: (a) $\Delta E$ and (b) $M_{bc}$ distributions for $B^+ \rightarrow p\bar{p}\pi^+$. 
5.6 Systematic Errors

The largest contributions to the systematic error are the uncertainties in the tracking efficiency, particle identification efficiency and the modeling of the likelihood ratio cut. The particle identification systematic includes contributions of 3% for the proton and antiproton, 2% for the charged kaon and 4% for the charged pion. The error in proton/antiproton identification is determined using $\Lambda/\bar{\Lambda}$ samples, while the error in kaon identification efficiency is obtained from kinematically selected $D^*+ \rightarrow D^0\pi^+, D^0 \rightarrow K^-\pi^+$ decays in the data. The systematic error due to the modeling of the likelihood ratio cut is determined using $B^+ \rightarrow D^0\pi^+$ events reconstructed in data. The systematic error in the yield from the $\Delta E$ fit was determined by varying the mean and $\sigma$ of the signal and the shape parameter of the background. The contributions to the systematic error are given in Table 5.2. The sources of systematic error are combined in quadrature to obtain the final systematic error, which is 11.0% for $B^+ \rightarrow p\bar{p}K^+$, 12.3% for $B^0 \rightarrow p\bar{p}K^0_S$ and 13.5% for $B^+ \rightarrow p\bar{p}\pi^+$. 

<table>
<thead>
<tr>
<th>Uncertainty Source</th>
<th>$p\bar{p}K^+$</th>
<th>$p\bar{p}K^0_S$</th>
<th>$p\bar{p}\pi^+$</th>
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</thead>
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<td>10.0</td>
</tr>
<tr>
<td>Tracking efficiency</td>
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<td>8.0</td>
<td>6.0</td>
</tr>
<tr>
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<td>6.2</td>
</tr>
<tr>
<td>L.R. cut efficiency</td>
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<td>2.6</td>
<td>2.6</td>
</tr>
<tr>
<td>$\mathcal{N}_{B\bar{B}}$</td>
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<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>11.0</strong></td>
<td><strong>12.3</strong></td>
<td><strong>13.5</strong></td>
</tr>
</tbody>
</table>
5.7 Consistency Checks

To check the consistency of the signal, we examine the distributions of particle identification variables for events in the signal region. Fig. 5.9 shows the likelihood ratio $L_K/(L_p + L_K)$ for the proton candidate and the antiproton candidate, and $L_K/(L_K + L_π)$ for the kaon candidate with the particle identification cuts removed. No discrepancies between data and Monte Carlo are observed. We note that the distributions for data events contain some background that is responsible for the peaks near one in the proton and antiproton distributions. In Fig. 5.10, we show the ECL shower widths for the signal candidates. As expected from Monte Carlo, the widths of the ECL showers produced by antiprotons are larger than those of protons.

If we examine the $B^+ \rightarrow p\bar{p}K^+$ signal with the charmonia vetoes removed, we find clear signals in the $η_c$, $ψ$, and $ψ'$ mass regions. These are shown in Fig. 5.11. The band due to $B^+ \rightarrow ψK^+$ and the low mass enhancement from the $B^+ \rightarrow p\bar{p}K^+$ signal are both clearly visible in the Dalitz plot. We also examine the $pK^-$ mass distribution but do not observe any obvious narrow structures such as the $Λ(1520)$.

To verify the analysis procedure and branching fraction determination, we remove the $ψ$ veto and examine the decay chain $B^+ \rightarrow ψK^+$, $ψ \rightarrow p\bar{p}$. A clear signal of $23.2 ± 4.7$ events is then observed in the $ΔE$ distribution. In the $M_{bc}$ spectrum, we observe $24.1 ± 5.0$ events. The signal for $ψK^+$ is shown in Fig. 5.12. We use the $ΔE$ yield and the Monte Carlo detection efficiency of 0.309 to determine the branching fraction $B(B^+ \rightarrow ψK^+) = (11.0 ± 2.2) \times 10^{-4}$. This is in very good agreement with the PDG world average, $B(B^+ \rightarrow ψK^+) = (10.1±0.5) \times 10^{-4}$ [1], which was obtained by experiments that reconstruct the $J/ψ$ in dilepton modes.
Figure 5.9: The distribution of (a) $L_K/(L_p + L_K)$ for the proton candidate and (b) the antiproton candidate, and (c) $L_K/(L_K + L_\pi)$ for the kaon candidate. The distributions in the left column are for signal Monte Carlo while those in the right column are for data events in the signal region. The particle likelihood ratio cuts are removed.
Figure 5.10: The distribution of (a) shower width for the proton candidate (b) shower width for the antiproton candidate and (c) shower width for the kaon candidate. The distributions in the left column are for signal Monte Carlo while those in the right column are for data events in the signal region.
Figure 5.11: With the charmonia vetoes removed, (a) the distribution of $M(pp)$ with sideband superimposed and (b) the Dalitz plot.

### 5.8 Branching Fractions

We sum the partial branching fractions in each $M(pp)$ bin given in Table 5.1 to obtain

$$B(B^+ \rightarrow p\bar{p}K^+) = (4.7^{+1.1}_{-0.9}\text{(stat)} \pm 0.5\text{(syst)}) \times 10^{-6}. \quad (5.1)$$

For $M(pp) < 3.4 \text{ GeV}/c^2$, the mass region below the $\chi_c$ and $\psi'$ resonances, we obtain $B(B^+ \rightarrow p\bar{p}K^+) = (4.4^{+0.9}_{-0.8}\text{(stat)} \pm 0.5\text{(syst)}) \times 10^{-6}$ with the charm veto applied.

For $M(pp) < 2.8 \text{ GeV}/c^2$, the region below charm threshold, we obtain $B(B^+ \rightarrow p\bar{p}K^+) = (3.8^{+0.8}_{-0.7}\text{(stat)} \pm 0.4\text{(syst)}) \times 10^{-6}$. For $B^0 \rightarrow p\bar{p}K^0_S$, we reduce the detection
efficiency by the systematic error and obtain an upper limit at 90% confidence level of

\[ B(B^0 \rightarrow p\bar{p}K^0) < 7.2 \times 10^{-6}. \]  

(5.2)

In the \( B^+ \rightarrow p\bar{p}\pi^+ \) mode, the excess in the \( \Delta E \) fit corresponds to a branching fraction

\[ B(B^+ \rightarrow p\bar{p}\pi^+) = (1.9_{-0.3}^{+1.0} \pm 0.3) \times 10^{-6} \]  

or an upper limit of

\[ B(B^+ \rightarrow p\bar{p}\pi^+) < 3.7 \times 10^{-6} \]  

(5.3)

at 90% confidence level after taking into account the systematic error.

We find that the branching fraction for the \( b \rightarrow s \) penguin dominant decay, \( B^+ \rightarrow p\bar{p}K^+ \), is greater than that for \( b \rightarrow u \) tree dominant decay, \( B^+ \rightarrow p\bar{p}\pi^+ \). This agrees with the pattern found in measurements of \( B \rightarrow K\pi \) and \( B \rightarrow \pi\pi \) [73, 74, 75].
Chapter 6

Conclusions

6.1 Measurement of Branching Fractions and $CP$ Violation in $B \to \eta_c K$

We have measured the branching fractions for $B^+ \to \eta_c K^+$ and $B^0 \to \eta_c K^0$. The $\eta_c$ candidates are reconstructed via the decay modes, $\eta_c \to K^+K^-\pi^0$, $\eta_c \to p\bar{p}$ and $\eta_c \to K^{*0}K^-\pi^+$. Combining the $\eta_c \to K^+K^-\pi^0$ and $\eta_c \to K^0 S K^-\pi^+$ [56] decay modes, we find

$$B(B^+ \to \eta_c K^+) = (1.25 \pm 0.14^{+0.10}_{-0.12} \pm 0.38) \times 10^{-3} \quad (6.1)$$

and

$$B(B^0 \to \eta_c K^0) = (1.23 \pm 0.23^{+0.12}_{-0.16} \pm 0.38) \times 10^{-3}. \quad (6.2)$$

These results are more precise than previous results [23]. The result for the $B^+ \to \eta_c K^+$ branching fraction is somewhat higher than the CLEO measurement, while the $B^0 \to \eta_c K^0$ result is consistent. When the absolute branching fractions for $\eta_c \to p\bar{p}$ and $\eta_c \to K^{*0}K^-\pi^+$ are better determined, absolute $B$ branching fractions for these
modes can be extracted from our results. Using the world averages for the branching fractions for $B \to J/\psi K$ [1], we obtain

$$\frac{B(B^+ \to \eta_c K^+)}{B(B^+ \to J/\psi K^+)} = 1.2 \pm 0.2 \pm 0.4$$

$$\frac{B(B^0 \to \eta_c K^0)}{B(B^0 \to J/\psi K^0)} = 1.4 \pm 0.3 \pm 0.4.$$ (6.3)

The results agree with the calculations of these ratios in models based on factorization. The dominant sources of errors in Eqn. (6.3) are uncertainties in the $\eta_c$ decay branching fractions. More precise measurements of the $B \to \eta_c K$ decays as well as the $\eta_c$ decay branching fractions are needed to test various QCD models [18, 19, 20, 21, 22].

We also find an intrinsic width $\Gamma_{\eta_c} = 29 \pm 8 \pm 6$ MeV/$c^2$ and a mass $M(\eta_c) = 2979.6 \pm 2.3 \pm 1.6$ MeV/$c^2$. The results are consistent with the world averages, which are $\Gamma_{\eta_c} = 16.1^{+3.1}_{-2.8}$ MeV/$c^2$ and $M(\eta_c) = 2979.2 \pm 1.3$ MeV/$c^2$ [1]. Fig. 6.1 shows the comparison between our result and the world average for the $\eta_c$ width. Discrepancies exist among different measurements. Our result is comparable in precision to the best individual measurements.

We have measured the $CP$ asymmetry parameter $\sin(2\phi_1)$ in neutral $B$ meson decays to $\eta_c K_S^0$ using a 78 fb$^{-1}$ data sample. The $\eta_c$ is reconstructed in the $\eta_c \to K_S^0 K^-\pi^+$, $\eta_c \to K^+K^-\pi^0$ and $\eta_c \to pp$ decay modes. From an unbinned maximum likelihood fit to the proper time difference distribution, we find

$$\sin(2\phi_1) = 1.26^{+0.27}_{-0.39} \pm 0.06.$$ (6.4)

This is $3\sigma$ away from a zero value of $\sin(2\phi_1)$, and is consistent with the Standard Model prediction. The $B^0 \to \eta_c K_S^0$ mode has been used in Belle’s measurements of $\sin(2\phi_1)$ to increase statistics [72, 76, 77]. Our result is statistically consistent with the measurement using the $B^0 \to J/\psi K_S^0$ decay in the same data sample, which is $\sin(2\phi_1) = 0.72 \pm 0.10$(stat). A difference between the $\sin(2\phi_1)$ values for $B^0 \to$
Figure 6.1: Comparison between our measurement and measurements that are used to obtain the world average of $\eta_c$ width. The vertical lines show the world average with errors.

$J/\psi K_S^0$ and $B^0 \rightarrow \eta_c K_S^0$ would indicate new physics beyond the Standard Model [78]. This possibility can be probed by measuring $\sin(2\phi_1)$ in $B^0 \rightarrow \eta_c K_S^0$ precisely with more data to come.

6.2 Observation of $B^\pm \rightarrow p\bar{p}K^\pm$

We have observed a significant signal (5.8$\sigma$) for the decay $B^+ \rightarrow p\bar{p}K^+$. To avoid model dependence in the determination of the branching fraction for $B^+ \rightarrow p\bar{p}K^+$, we measure the partial branching fractions in bins of $M(p\bar{p})$ and then sum them to obtain

$$B(B^+ \rightarrow p\bar{p}K^+) = (4.7^{+1.1}_{-0.9}(\text{stat}) \pm 0.5(\text{syst})) \times 10^{-6}. \quad (6.5)$$

We have also searched for two related modes $B^0 \rightarrow p\bar{p}K_S^0$ and $B^+ \rightarrow p\bar{p}\pi^+$ and have set upper limits of

$$B(B^0 \rightarrow p\bar{p}K^0) < 7.2 \times 10^{-6} \quad (6.6)$$
and

\[ B(B^+ \rightarrow p\bar{p}\pi^+) < 3.7 \times 10^{-6} \]  

at 90% confidence level. The branching fraction for the \( b \rightarrow s \) penguin dominant decay, \( B^+ \rightarrow p\bar{p}K^+ \), is greater than that for \( b \rightarrow u \) tree dominant decay, \( B^+ \rightarrow p\bar{p}\pi^+ \). This agrees with the pattern found in measurements of \( B \rightarrow K\pi \) and \( B \rightarrow \pi\pi \). \( B^+ \rightarrow p\bar{p}K^+ \) is the first \( b \rightarrow s \) decay mode with baryons in the final state. We need more statistics to observe the \( B^0 \rightarrow p\bar{p}K^0_S \) and \( B^+ \rightarrow p\bar{p}\pi^+ \) decays, and to search for the \( CP \) asymmetry in \( B^\pm \rightarrow p\bar{p}K^\pm \) and \( B^\pm \rightarrow p\bar{p}\pi^\pm \).

We find that the \( M(p\bar{p}) \) mass spectrum is inconsistent with phase space and is peaked toward low mass. This feature has also now been observed in \( \bar{B}^0 \rightarrow D^{(*)0}p\bar{p} \) [79] and \( B^0 \rightarrow p\Lambda\pi^- \) [80] decays. The feature of the \( M(p\bar{p}) \) may due to a singlet penguin process or a fragmentation process [81]. It may also be a baryon form factor effect [82, 83, 84]. Recently, a narrow enhancement near the \( M(p\bar{p}) \) threshold has been observed in the decay \( J/\psi \rightarrow \gamma p\bar{p} \) [85]. It is also possible that we have observed two body \( B^\pm \rightarrow XK^\pm \) decays, where \( X \) is a low-mass \( p\bar{p} \) resonance. These possibilities can be further clarified by examining the \( M(p\bar{p}) \) spectrum and the Dalitz plots of \( B \rightarrow p\bar{p}K \) with more statistics in the future.
Appendix A

$K_S^0 \rightarrow \pi^+\pi^-$ Reconstruction and Selection Optimization

A.1 Reconstruction of $K_S^0$

In particle physics experiments, particles that decay into a pair of oppositely charged particles are generally referred to as "$V^0$" particles. In the Belle experiment, $V^0$ particles can be $K_S^0 \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow p\pi^-$ and from photon conversions. Strange particles have long lifetimes and decay to two oppositely charged daughters. In Belle reconstruction software, the $v0$finder module is used to reconstruct $V^0$ candidates. This algorithm associates a pair of oppositely charged tracks, and determines the decay vertex, momentum and invariant mass of the $V^0$ candidate from the helix parameters.

The charged track helix is a circle in the $x$-$y$ plane. Pairs of helices are divided into the following categories:

- They intersect at two crossing points as shown in Fig. A.1(a). $B\bar{B}$ Monte Carlo simulation shows that, for real $K_S^0$'s that have both daughter tracks reconstructed in the CDC, 98% fall into this category. The crossing point with the
smaller distance in the $z$ direction between the two tracks is chosen as the $V^0$ decay vertex. For 95% of the real $K^0_s$'s, the crossing point we choose is closest to the generated decay vertex of the $K^0_s$.

- They are outside each other as shown in Fig. A.1(b). If they are tangential, the point of tangency is chosen to be the $V^0$ decay vertex. Otherwise, the midpoint of closest approach of the two tracks is taken to be the $V^0$ decay vertex.

- One helix is inside the other as shown in Fig. A.1(c). Candidates that have this type of configuration are discarded. This causes an inefficiency of less than 1% for $K^0_s$ reconstruction.

![Diagram](image)

Figure A.1: The three categories of for helix pairs.

In the determination of the $V^0$ decay vertex, the helix parameters used are calculated assuming that the tracks originate from the IP. The energy loss and multiple scattering effects for the $V^0$ particles are not properly considered because they often decay far away from the IP. Based on the position of the vertex found by v0finder, we use the helix parameters that are corrected taking into account any material traversed between the IP and the decay vertex. We then perform a vertex constrained fit [86, 87] to the daughters of the $V^0$ candidate. The vertex constrained fit improves the track parameters and their errors by requiring that the two tracks come from a
common vertex. If the fit converges, we use the resulting fitted track parameters and decay vertex to reconstruct the $V^0$ candidate. If the fit fails, we use the unfitted track parameters and decay vertex. This method is implemented in the v0finder2 module.

To check the performance of v0finder2, we use a sample of 10,000 $B^0 \rightarrow J/\psi K^0_S$ Monte Carlo events. Fig. A.2 shows the $K^0_S$ candidates reconstructed with v0finder and v0finder2. The $K^0_S$ candidates reconstructed with v0finder2 have a narrower width. We fit the $K^0_S$ candidate invariant mass distribution to the sum of a double Gaussian for signal and a linear background function. The effective width of the double Gaussian is defined as

$$\sigma = \sqrt{\frac{A_1 \sigma_1^2 + A_2 \sigma_2^2}{A_1 + A_2}}, \quad (A.1)$$

where $A_1$, $A_2$ and $\sigma_1$, $\sigma_2$ are the areas and widths of the two Gaussians. The results of the fits are given in Table A.1. The reconstruction efficiency and mean of the $K^0_S$ mass distribution are also improved with v0finder2.

We define the $K^0_S$ reconstruction efficiency to be

$$\varepsilon = \frac{\text{# of real } K^0_S\text{'s reconstructed with v0finder2}}{\text{# of real } K^0_S\text{'s with both daughters reconstructed in the CDC}}. \quad (A.2)$$

For $K^0_S$'s in $B\bar{B}$ Monte Carlo events, the reconstruction efficiency is $87.5\pm0.5\%$, where the error is statistical only. Fig. A.3 shows the $K^0_S$ reconstruction efficiencies as a function of the momentum and the flight length in the $x$-$y$ plane. In v0finder and

**Table A.1:** Results of the fits to the invariant mass distributions of $K^0_S$ candidates reconstructed with v0finder and v0finder2.

<table>
<thead>
<tr>
<th></th>
<th># of $K^0_S$</th>
<th>Mean (MeV/$c^2$)</th>
<th>$\sigma$ (MeV/$c^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>v0finder</td>
<td>8275</td>
<td>498.12 ± 0.05</td>
<td>4.51 ± 0.14</td>
</tr>
<tr>
<td>v0finder2</td>
<td>8445</td>
<td>497.83 ± 0.04</td>
<td>3.67 ± 0.14</td>
</tr>
</tbody>
</table>
Figure A.2: The $K_S^0$ candidates reconstructed with v0finder (dashed line) and v0finder2 (solid line) in $B^0 \rightarrow J/\psi K_S^0$ Monte Carlo events.

v0finder2, $K_S^0$ candidates are required to have invariant masses within $\pm 30$ MeV/c$^2$ of the nominal mass. The main source of inefficiency are the $K_S^0$'s reconstructed from poorly measured tracks that, as a result, have masses outside the above region.

### A.2 $K_S^0 \rightarrow \pi^+\pi^-$ Selection Optimization

The $K_S^0$ candidates reconstructed with v0finder or v0finder2 include large backgrounds. Our study shows that the following four variables are effective in suppressing these backgrounds:

- $\Delta \phi$, which is the difference in the angle, in the $x$ - $y$ plane, between a vector from the beam spot to the $K_S^0$ vertex and the $K_S^0$ flight direction,
- $dr$, which is the smaller of the impact parameters $dr$ of the $K_S^0$ daughters,
Figure A.3: The $K_S^0$ reconstruction efficiencies as a function of the momentum and the flight length in the $x$-$y$ plane.

- $z_{\text{dist}}$, which is the distance in the $z$ direction between the two daughter tracks at their intersection point or the midpoint of closest approach,

- $f l$, which is the flight length of the $K_S^0$ candidate in the $x$-$y$ plane.

Fig. A.4 shows the distributions of the above variables for $K_S^0$ signals and backgrounds in $B\bar{B}$ Monte Carlo. $K_S^0$'s have long lifetimes and hence the decay vertex is usually displaced from the IP. For the background, the tracks are randomly associated and mostly originate from the IP. Therefore, $d r$ and $f l$ are displaced from zero for real $K_S^0$, while for fake $K_S^0$, they peak at zero. For signal events, the $K_S^0$ flight direction is nearly the same as the direction of the vector from the IP to the $K_S^0$ vertex, except for physical effects such as multiple scattering, and hence the $\Delta \phi$ distribution peaks at zero. For the background, one of the intersections of the two tracks is randomly selected. This leads to peaks at zero and $\pi$ in the $\Delta \phi$ distribution. The fake $K_S^0$'s also tend to have a large $z_{\text{dist}}$. 

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Figure A.4: Distributions of the variables used to suppress the $K_S^0$ background. The left column is for real $K_S^0$'s and the right column is for fake $K_S^0$'s.
To determine the selection criteria, we use $2 \times 10^5$ continuum and $5 \times 10^4 \ B\overline{B}$ Monte Carlo events. We optimize the $K^0_S$ selection requirements by maximizing the figure of merit $S/\sqrt{S + B}$. The number of signal and background events ($S$ and $B$) are determined from fits to the $K^0_S$ invariant mass distributions. The $K^0_S$ candidates are required to have invariant masses that lie within $\pm 3\sigma$ of the nominal mass. We divide the $K^0_S$'s into three momentum bins, $p < 0.5 \ \text{GeV}/c$, $0.5 \leq p < 1.5 \ \text{GeV}/c$ and $p \geq 1.5 \ \text{GeV}/c$, and determine the optimal requirements for each bin. The results are given in Table A.2.

We apply the "good" (optimal) $K^0_S$ cuts to a 432 pb$^{-1}$ data sample that passes the hadronic event selection criteria. The results are shown in Fig. A.5. This set of requirements is 76% efficient for the $K^0_S$ signal, while removing 99% of the background. The $K^0_S$ candidates that pass the good $K^0_S$ cuts are also shown in Fig. A.6 with the result of the fit superimposed.

Table A.2: The $K^0_S$ requirements that maximize the figure of merit $S/\sqrt{S + B}$.

<table>
<thead>
<tr>
<th>$p$ (GeV/c)</th>
<th>$d r$ (cm)</th>
<th>$\Delta\phi$ (rad.)</th>
<th>$z_{\text{dist}}$ (cm)</th>
<th>$f l$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt; 0.5$</td>
<td>$&gt; 0.05$</td>
<td>$&lt; 0.3$</td>
<td>$&lt; 0.8$</td>
<td>none</td>
</tr>
<tr>
<td>$0.5 - 1.5$</td>
<td>$&gt; 0.03$</td>
<td>$&lt; 0.1$</td>
<td>$&lt; 1.8$</td>
<td>$&gt; 0.08$</td>
</tr>
<tr>
<td>$&gt; 1.5$</td>
<td>$&gt; 0.02$</td>
<td>$&lt; 0.03$</td>
<td>$&lt; 2.4$</td>
<td>$&gt; 0.22$</td>
</tr>
</tbody>
</table>

A.3 Other Considerations for $K^0_S$ Selection Optimization

We divide reconstructed $K^0_S$'s into three categories:

- The first category are the $K^0_S$'s that have both the daughter tracks associated with SVD hits. These $K^0_S$'s are reconstructed from well measured tracks and,
Figure A.5: The $K_S^0$ candidates in experimental data without (open histogram) and with (shaded histogram) the good $K_S^0$ cuts.

as a result, have a narrow width in the invariant mass distribution as shown in Fig. A.7(a).

- The second are the $K_S^0$'s where one of the daughter tracks has associated SVD hits. Monte Carlo simulation shows that 94% of the $K_S^0$'s in this category decay inside the SVD. The tracks that are not associated with SVD hits are often badly reconstructed. These $K_S^0$'s have a wide width and a large tail in the invariant mass distribution as shown in Fig. A.7(b).
Figure A.6: The invariant mass distribution of the $K_S^0$ candidates that pass the good $K_S^0$ selection criteria. The curve is the result of a double Gaussian fit.

- The third are $K_S^0$'s that have both the daughter tracks not associated with any SVD hits. The daughters of these $K_S^0$'s are outside the fiducial volume of the SVD. They also have a tail in the invariant mass distribution as shown in Fig. A.7(c). The distributions of the variables $\Delta \phi$, $dr$, $z_{dist}$ and $f I$ for the three categories of $K_S^0$'s are different, and are shown in Fig. A.8. We, therefore, optimize the $K_S^0$ selection criteria for each category. The results are given in Table A.3. This set of $K_S^0$ requirements is 83% efficient for the signal, while removing 98% of the background.
Figure A.7: The invariant mass distributions for real $K_S^0$'s that have (a) both the daughter tracks associated with SVD hits, (b) one of the daughter tracks associated with SVD hits and (c) both of the daughter tracks not associated with any SVD hits. The left column is for $B\bar{B}$ MC and the right column is for continuum MC.

Table A.3: The $K_S^0$ requirements that are optimized for the three $K_S^0$ categories.

<table>
<thead>
<tr>
<th>$K_S^0$ category</th>
<th>$d r$ (cm)</th>
<th>$\Delta \phi$ (rad.)</th>
<th>$z_{dist}$ (cm)</th>
<th>$f l$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$&gt; 0.03$</td>
<td>$&lt; 0.35$</td>
<td>$&lt; 2$</td>
<td>$&gt; 0.08$</td>
</tr>
<tr>
<td>II</td>
<td>$&gt; 0.10$</td>
<td>$&lt; 0.40$</td>
<td>$&lt; 40$</td>
<td>$&lt; 9.0$</td>
</tr>
<tr>
<td>III</td>
<td>$&gt; 0.10$</td>
<td>$&lt; 0.05$</td>
<td>$&lt; 6.5$</td>
<td>$&gt; 1.5$</td>
</tr>
</tbody>
</table>
Figure A.8: The $dr$, $\Delta\phi$, $z_{\text{dist}}$ and $fl$ distributions for the three categories of $K_S^0$'s in MC.
Appendix B

Publications
Measurement of Branching Fractions for $B \to \eta_c K^{(*)}$ Decays


1Budker Institute of Nuclear Physics, Novosibirsk
2Chiba University, Chiba
3Chuo University, Tokyo
4University of Cincinnati, Cincinnati, Ohio
5University of Frankfurt, Frankfurt
6Gyeongguk National University, Chinni
7University of Hawaii, Honolulu, Hawaii
8High Energy Accelerator Research Organization (KEK), Tsukuba
9Hiroshima Institute of Technology, Hiroshima
10Institute of High Energy Physics, Chinese Academy of Sciences, Beijing
11Institute of High Energy Physics, Vienna
12Institute for Theoretical and Experimental Physics, Moscow
13J. Stefan Institute, Ljubljana
14Kanagawa University, Yokohama
15Korea University, Seoul
16Ktoyo University, Kyoto
17Kyungpook National University, Taegu
18Institut de Physique des Hautes Énergies, Université de Lausanne, Lausanne
19University of Ljubljana, Ljubljana
20University of Maribor, Maribor
21University of Melbourne, Victoria
22Nagoya University, Nagoya
23Nara Women's University, Nara
24National Lien-Ho Institute of Technology, Miao Li
25National Taiwan University, Taipei
26H. Niewodniczanski Institute of Nuclear Physics, Krakow
27Nihon Dental College, Niigata

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We report measurements of branching ratios for charged and neutral $B \to \eta K$ decays where the $\eta$ meson is reconstructed in the $K^0\bar{K}^0\pi^\pm$, $K^-\bar{K}^+\pi^0$, and $pp$ decay channels. The neutral $B^0$ channel is a $CP$ eigenstate and can be used to measure the $CP$ violation parameter $\sin 2\phi_1$. We also report the first observation of the $B^0 \to \eta K^{\ast 0}$ mode. The results are based on an analysis of 29.1 fb$^{-1}$ of data collected by the Belle detector at KEKB.

The decay mode $B \to \eta K$ proceeds by a spectator $b \to c\bar{s}$ transition with internal $W$ emission as in the $CP$ eigenstate $B^0 \to J/\psi K_S^0$. The neutral decay mode $B^0 \to \eta K_S^0$ has therefore been used to measure the $CP$ violation parameter $\sin 2\phi_1$ [1–3]. Measurements of branching fractions for $B \to \eta K^{\ast 0}$ decay modes are also useful in the study of the dynamics of hadronic $B$ decay [4]. However, in contrast to $B^0 \to J/\psi K_S^0$, the $\eta$ meson must be reconstructed from hadronic decays rather than from a leptonic final state with relatively low combinatorial background. In this Letter, we report new measurements of $B \to \eta K$ branching fractions with the $\eta$ meson reconstructed in the $K_S^0\bar{K}^0\pi^\pm$, $K^-\bar{K}^+\pi^0$, and $pp$ channels [5]. These signals are large enough to be used to determine the mass and width of the $\eta$ meson. We also report the first observation of the related decay mode $B^0 \to \eta K^{\ast 0}$. When $K^{\ast 0} \to K_S^0\pi^0$, this decay mode is also a $CP$ eigenstate.

We use a 29.1 fb$^{-1}$ data sample, which contains $31.3 \times 10^6$ produced $B\bar{B}$ pairs, collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ (3.5 on 8 GeV) collider [6]. KEKB operates at the $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58$ GeV) with a peak luminosity that now exceeds $7 \times 10^{33}$ cm$^{-2}$s$^{-1}$. The Belle detector is a large, solid-angle magnetic spectrometer that consists of a three-layer silicon vertex detector, a 50-layer central drift chamber (CDC), a mosaic of aerogel threshold Čerenkov counters (ACC), time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to identify $K_L$ and muons. The detector is described in detail elsewhere [7].

We select well measured charged tracks with impact parameters with respect to the interaction point of less than 0.5 cm in the radial direction and less than 3 cm in the beam direction ($z$). These tracks are required to have $p_T > 50$ MeV/$c$.

Particle identification likelihoods for the pion and kaon particle hypotheses are calculated by combining information from the TOF and ACC systems with $dE/dx$ measurements in the CDC. To identify kaons (pions), we apply a mode-dependent requirement on the kaon (pion) likelihood ratio, $L_K/(L_\pi + L_K)$ [$L_\pi/(L_\pi + L_K)$]. The requirement $L_K/(L_\pi + L_K) > 0.5$ is used for the $\eta \to K_S^0\bar{K}^0\pi^0$ mode. For other modes, we require $L_K/(L_\pi + L_K) > 0.6$, which is 88% efficient for kaons with a 8.5% misidentification rate for pions. For the $\eta \to K^+K^-\pi^0$ mode, the kaon likelihood ratio is required to
be greater than 0.8 for those charged kaons that come directly from the $B$, rather than from the $\eta_s$ candidate. In addition, we remove all kaon candidates that are consistent with being either protons or electrons.

Protons and antiprotons are identified using all particle identification systems and are required to have proton likelihood ratios $[L_p/(L_p + L_k)]$ and $L_p/(L_p + L_n)$ greater than 0.4. Proton candidates that are electronlike according to the information recorded by the CsI(Tl) calorimeter are vetoed. This selection is 99% efficient for protons with a 12% kaon misidentification rate.

We select $K_S$ candidates from $\pi^+\pi^-$ candidates that lie within the mass window 0.482 GeV/c$^2$ < $M(\pi^+\pi^-)$ < 0.514 GeV/c$^2$. The flight length of the $K_S$ is required to be greater than 0.2 cm. The difference in the angle, in the $x$-$y$ plane, between a vector from the beam spot to the $K_S$ vertex and the $K_S$ flight direction is required to satisfy $\Delta \phi < 0.1$ rad.

$K^{*0}$ candidates are reconstructed in the $K^+\pi^-$ mode. For $\eta_s \rightarrow K^{*0}K^+$, we require the $K^+\pi^-$ invariant mass to be between 0.817 and 0.967 GeV/c$^2$. For the $B^0 \rightarrow \eta_sK^{*0}$ mode, the $K^{*0}$ mass must lie in the range between 0.801 and 0.991 GeV/c$^2$.

Neutral pion candidates are selected from pairs of ECL clusters with invariant mass within $\pm 16$ MeV of the nominal $\pi^0$ mass and momenta above 350 MeV/c. The photons must have energy above 50 MeV if they lie in the barrel region of the calorimeter and above 200 MeV if they are detected in the end cap.

To reconstruct signal candidates in the $B^+ \rightarrow \eta_sK^+$ and $B^0 \rightarrow \eta_sK^0$ modes, we form combinations of charged or neutral kaons and $\eta_s$ candidates. The $\eta_s$ is reconstructed in the $K^0\bar{K}^0\pi^+$, $K^-\pi^+\pi^0$, $K^0\pi^-\pi^0$, and $p\bar{p}$ decay modes. The $\eta_s$ candidate is required to have invariant mass in the range 2.920 < $M_{\eta_s}$ < 3.035 GeV/c$^2$ for the $K^+\pi^-\pi^0$ mode and 2.935 < $M_{\eta_s}$ < 3.035 GeV/c$^2$ for all other modes. The charged daughters of the $\eta_s$ are required to satisfy a vertex constrained fit with a mode-dependent $x^2$ requirement.

To isolate the signal, we form the beam-energy constrained mass $M_{bc} = \sqrt{E^2_{beam} - P^2_{rec}}$ and energy difference $\Delta E = E_{rec} - E_{beam}$ in the $Y(4S)$ center of mass frame. Here $E_{beam}$ and $P_{beam}$ are the beam energy, the reconstructed energy, and the reconstructed momentum of the signal candidate, respectively. The signal region for $\Delta E$ in all modes except for $\eta_s \rightarrow K^0\bar{K}^0\pi^+$ is $\pm 2.5\sigma$, where $\sigma$ is the mode-dependent resolution and ranges from $\pm 25$ MeV for $\eta_s \rightarrow p\bar{p}$ to the range $\pm 55, +45$ MeV for $\eta_s \rightarrow K^-\pi^+\pi^0$. In the low background $\eta_s \rightarrow K^0\bar{K}^0\pi^+$ mode, the region is extended to $\pm 35$ MeV ($\pm 3.5\sigma$). The signal region for $M_{bc}$ is 5.270 GeV/c$^2$ < $M_{bc}$ < 5.290 GeV/c$^2$. The resolution in beam-energy constrained mass is 2.8 MeV/c$^2$ and is dominated by the beam-energy spread of KEKB.

Several event topology variables provide discrimination between the large continuum (e$^+e^-$ $\rightarrow q\bar{q}$, where $q = u, d, s, c$) background, which tends to be collimated along the original quark direction, and more spherical $B\bar{B}$ events. We first remove events with $R_z > 0.5$, where $R_z$ is the normalized second Fox-Wolfram moment. We form a likelihood ratio using two variables. Six modified Fox-Wolfram moments and the cosine of the thrust angle are combined into a Fisher discriminant [8]. For signal Monte Carlo (MC) and continuum data, we then form probability density functions for this Fisher discriminant and the cosine of the $B$ decay angle with respect to the $z$ axis ($\cos \theta_B$). The signal (background) probability density functions are multiplied together to form a signal (background) likelihood $L_S(L_B)$. A mode-dependent likelihood ratio requirement $L_S(L_S + L_B)$ is then imposed.

Using a sample of 57 $\times 10^6$ $B\bar{B}$ Monte Carlo events with a model of $b \rightarrow c$ decays, we investigate backgrounds from other $B$ decay modes. In the $\eta_s \rightarrow p\bar{p}$ mode, no such backgrounds are found. In other modes, some background is observed but it can be removed by application of mode-dependent vetoes on invariant mass combinations that are consistent with the $D^0, \chi_{c1}, J/\psi, \phi(2S)$, or $\eta(2550)$ masses. For example, in the $B^0 \rightarrow \eta_s K^+, \eta_s \rightarrow K^-\pi^+\pi^0$ mode, we remove background from the decay chain $B^+ \rightarrow D^0\rho^+, D^0 \rightarrow K^-\pi^+\pi^0 \rightarrow \pi^-\pi^+\pi^0$. This background is removed by requiring that the $K^-\pi^+$ invariant mass be inconsistent with the $D^0$ mass.

We fit the $M_{bc}$ distribution to the sum of a Gaussian and a background function that behaves like phase space near the kinematic boundary [9]. The width of the Gaussian is fixed from MC simulation while the mean is determined from $B^+ \rightarrow \eta_s K^+$ data. The shape parameter of the background function is determined from $\Delta E$ sideband data. The signal yield was determined by fits to the individual $M_{bc}$ distributions for each mode. The yields and significances [10] for these fits are given in Table I. Significant signals are observed in all decay modes except for $B^0 \rightarrow \eta_s K^0, \eta_s \rightarrow K^0K^-\pi^+$. For this mode, we calculate an upper limit based on the number of events observed in the $M_{bc}$ signal region (4) and the expected number of background events (2) based on the fit. We use the Feldman-Cousins procedure [11] and reduce the efficiency by one sigma of the systematic error in the calculation. The detection efficiencies for all modes were determined from a GEANT based Monte Carlo simulation. For illustration, in Fig. 1, we show the beam-energy constrained mass and $\Delta E$ distributions for the signal candidates in all the decay modes except for $B^0 \rightarrow \eta_s K^0, \eta_s \rightarrow K^0K^-\pi^+$. In the $M_{bc}$ distribution, we observe a signal of 195 $\pm 17$ events.

As a consistency check, we also determine the yield from a fit to the $\Delta E$ distribution with a double Gaussian for signal and a linear background function with slope determined from the $M_{bc}$ sideband. The results of these
TABLE I. Signal yields from $M_{bc}$ and $\Delta E$ fits, statistical significances, and MC reconstruction efficiencies. Errors are statistical only.

<table>
<thead>
<tr>
<th>$\Delta E$ Yield</th>
<th>$M_{bc}$ Yield</th>
<th>Signif. ($M_{bc}$)</th>
<th>$\epsilon$(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow \eta K^*$</td>
<td>74.8 ± 10.4</td>
<td>81.6 ± 10.3</td>
<td>12.2σ</td>
</tr>
<tr>
<td>$\eta \rightarrow K^0 K^- \pi^+$</td>
<td>26.5 ± 7.8</td>
<td>31.8 ± 7.0</td>
<td>6.3σ</td>
</tr>
<tr>
<td>$\eta \rightarrow K^0 K^- \eta^0$</td>
<td>16.3 ± 4.2</td>
<td>17.7 ± 4.4</td>
<td>7.5σ</td>
</tr>
<tr>
<td>$\eta \rightarrow K^0 K^- \pi^+$</td>
<td>22.0 ± 5.8</td>
<td>20.8 ± 5.4</td>
<td>5.8σ</td>
</tr>
<tr>
<td>$B^0 \rightarrow \eta K^0_L$</td>
<td>19.6 ± 5.4</td>
<td>23.0 ± 5.4</td>
<td>6.8σ</td>
</tr>
<tr>
<td>$\eta \rightarrow K^0_L K^- \pi^+$</td>
<td>19.9 ± 5.7</td>
<td>17.1 ± 5.1</td>
<td>4.7σ</td>
</tr>
<tr>
<td>$\eta \rightarrow p\bar{p}$</td>
<td>7.0 ± 3.0</td>
<td>6.8 ± 2.6</td>
<td>5.0σ</td>
</tr>
<tr>
<td>$\eta \rightarrow K^0 K^- \eta^0$</td>
<td>0.2 ± 1.7</td>
<td>2.2 ± 1.8</td>
<td>1.6σ</td>
</tr>
</tbody>
</table>

The contributions to the systematic error include the uncertainties due to the tracking efficiency (2% per track), particle identification efficiency (4%–14%, depending on the mode), and the modeling of the likelihood ratio requirement (2%). The error in kaon identification efficiency is obtained from kinematically selected $D^*+\rightarrow D^0 \pi^+$, $D^0 \rightarrow K^- \pi^+$ in the data while the error in proton/antiproton identification is determined using $\Lambda/\bar{\Lambda}$ samples. The systematic error due to the modeling of the likelihood ratio cut is determined using $B^+\rightarrow D^0 \pi^+$ events reconstructed in data. The systematic error in the yields of the $M_{bc}$ fit were determined by varying the mean and $\sigma$ of the signal and the shape parameters of the background. To account for the possibility of background from nonresonant modes that may contribute to the $M_{bc}$ distribution, we include the yields observed in the $\rho$ mass sideband (8%–14% of the signal depending on the mode) as an asymmetric systematic error. The sources of the contributions to the systematic error include the uncertainties due to the tracking efficiency (2% per track), particle identification efficiency (4%–14%, depending on the mode), and the modeling of the likelihood ratio requirement (2%). The error in kaon identification efficiency is obtained from kinematically selected $D^*+\rightarrow D^0 \pi^+$, $D^0 \rightarrow K^- \pi^+$ in the data while the error in proton/antiproton identification is determined using $\Lambda/\bar{\Lambda}$ samples. The systematic error due to the modeling of the likelihood ratio cut is determined using $B^+\rightarrow D^0 \pi^+$ events reconstructed in data. The systematic error in the yields of the $M_{bc}$ fit were determined by varying the mean and $\sigma$ of the signal and the shape parameters of the background. To account for the possibility of background from nonresonant modes that may contribute to the $M_{bc}$ distribution, we include the yields observed in the $\rho$ mass sideband (8%–14% of the signal depending on the mode) as an asymmetric systematic error. The sources
of systematic error are combined in quadrature to obtain the total systematic error, which is given in Table II.

The product branching fractions are given in Table II for all modes in which signals are observed. Since many of the \( \eta_c \) branching fractions are poorly determined and in some cases there are conflicting measurements, we quote \( B \) branching fractions for the \( \eta_c \to K^0S \pi^0 \) and \( \eta_c \to K^-\pi^+ \) modes only. The \( \eta_c \to K^0S \pi^0 \) mode is the most precisely and reliably measured mode; the branching fraction for the \( \eta_c \to K^-\pi^+ \) mode is related by isospin. We use \( B(\eta_c \to K^0S \pi^0) = 1/3 \times (0.055 \pm 0.017) \), where 1/3 is the product of the appropriate Clebsch-Gordon coefficient and intermediate \( K^0 \) branching fraction. We assume that the experimental systematic errors in the \( \eta_c \to K^0S \pi^0 \) and \( \eta_c \to K^-\pi^+ \) modes are uncorrelated. We assume equal production of \( B^+B^- \) and \( B^0\bar{B}^0 \) pairs and do not include an additional systematic error for the uncertainty in this assumption. We find

\[
B(B^+ \to \eta_c K^+) = (1.25 \pm 0.14^{+0.10}_{-0.12} \pm 0.38) \times 10^{-3}
\]

and

\[
B(B^0 \to \eta_c K^0) = (1.23 \pm 0.23^{+0.12}_{-0.13} \pm 0.38) \times 10^{-3}
\]

The first error is statistical, the second error is systematic, and the third error is due to the uncertainty in the \( \eta_c \) branching fraction scale. When the \( \eta_c \) branching fractions for the other modes are better determined, absolute \( B \) branching fractions for these modes can be extracted from our results.

In the \( B^0 \to \eta_c K^0 \to K^-\pi^+ \) channel, the \( \eta_c \) is reconstructed in the \( K^0S \pi^0 \) mode. Since this mode is a pseudoscalar to pseudoscalar-vector decay, by angular momentum conservation, the cosine of the \( K^0 \) helicity angle \( \cos(\theta_K) \) follows a \( \cos^2(\theta_K) \) distribution; we select events with \( \cos(\theta_K) > 0.4 \). We also investigate \( B\bar{B} \) background and find that this background can be removed by applying vetoes to events with combinations that are consistent with \( J/\psi \to K^0S \pi^0 \), \( J/\psi \to K^-\pi^+ \pi^- \), \( \psi(2S) \to K^0S \pi^0 \), \( \eta_c(2S) \to K^0S \pi^0 \), \( \chi_c \to K^0S \pi^0 \), \( \eta_c \to K^-\pi^+ \pi^- \), \( D_s^+ \to K^0S \pi^0 \), and \( D_s^- \to K^-\pi^+ \pi^- \). The detection efficiency for these selection requirements is \( 7.95 \pm 0.12\% \).

After applying these requirements, a fit to the \( M_{BC} \) distribution yields a signal of \( 33.7 \pm 6.7 \) events for \( B^0 \to \eta_c K^0 \) with a statistical significance of \( 7.7\sigma \) [10]. The \( M_{BC} \) distribution is shown in Fig. 3(a). The yields from the \( \Delta E \) fit, shown in Fig. 3(b) (30 ± 7 events), the \( \eta_c \) invariant mass distribution (24 ± 7 events), and the \( K^-\pi^+ \) invariant mass distribution (27 ± 8 events) are consistent with the yield from the \( M_{BC} \) fit.

To evaluate the contribution from nonresonant \( B^0 \to K^0S \pi^0 \) as well as the remaining \( B\bar{B} \) backgrounds that peak in the \( M_{BC} \) distribution, we select events in the \( \eta_c \) sideband [13] and repeat the \( M_{BC} \) fit. We find no significant signal. By using the ratio of the yields in the \( \eta_c \) signal and sideband regions determined from MC, we estimate the contributions of such backgrounds to be \( 3.9 \pm 4.2 \) events, consistent with zero. We use the \( K^0S \) sideband [13] to estimate the nonresonant \( B^0 \to \eta_c K^0 \) decay component and obtain \(-0.6 \pm 3.3 \) events. These possible background contributions are not subtracted in the branching fraction measurement, but instead are treated as systematic uncertainties. We find

\[
B(B^0 \to \eta_c K^0) = (1.62 \pm 0.32^{+0.34}_{-0.34} \pm 0.50) \times 10^{-3}
\]

To take into account the possibility of \( B\bar{B} \) background, we conservatively include asymmetric systematic errors from the results of the fits to the \( \eta_c \) (\( \pm 1\% \)) and \( K^0S \) (\( \pm 5\% \)) sidebands. Other sources of systematic error are the uncertainties in the track reconstruction efficiency (\( \pm 2\% \) per track), the parameters in the \( M_{BC} \) fit (\( \pm 7\% \)), particle identification (\( \pm 6\% \)), and the number of \( B\bar{B} \) events.

From the results for the branching fractions for \( B^0 \to \eta_c K^0 \) and \( B^0 \to \eta_c K^{*0} \) determined above, we can determine the ratio

\[
R_{BC} = \frac{B(B^0 \to \eta_c K^{*0})}{B(B^0 \to \eta_c K^0)}
\]

The uncertainty from the \( \eta_c \) branching fraction scale cancels in the ratio. We find...
Our result can be compared to calculations of this ratio in models based on factorization and is consistent with the range 1.02–2.57 predicted by Gourdin, Keum, and Pham [14].

The branching fractions reported in this Letter for $B^+ \rightarrow \eta \pi K^+$ and $B^0 \rightarrow \eta K^0$ using $\eta \rightarrow K\bar{K}\pi$ decays are more precise than previous results [15]. The result for the $B^+ \rightarrow \eta K^+$ branching fraction is somewhat higher than the CLEO measurement, while the $B^0 \rightarrow \eta K^0$ result is consistent. Several additional $\eta$ modes including $\eta \rightarrow p\bar{p}$, $\eta \rightarrow K^- K^+ \pi^0$, and $\eta \rightarrow K^{*0} K^- \pi^+$ have been used and increase the fraction of $\eta$ decays that can be reconstructed for CP violation measurements. With the large samples of $B \rightarrow \eta K$ decays now available, we are able to determine the mass and width of the $\eta$ meson. We find $M(\eta) = 2979.6 \pm 2.3 \pm 1.6$ MeV and $\Gamma(\eta) = 29 \pm 8 \pm 6$ MeV. In addition, we report the first observation of the $B^0 \rightarrow \eta K^{*0}$ decay, which is a CP eigenstate when $K^{*0} \rightarrow K^0 \pi^0$.

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Observation of $B^{\pm} \rightarrow p\bar{p}K^\pm$


(Belle Collaboration)

1Aomori University, Aomori
2Budker Institute of Nuclear Physics, Novosibirsk
3Chiba University, Chiba
4Chuo University, Tokyo
5University of Cincinnati, Cincinnati, Ohio
6University of Frankfurt, Frankfurt
7Gyeongang National University, Chinju
8University of Hawaii, Honolulu, Hawaii
9High Energy Accelerator Research Organization (KEK), Tsukuba
10Hiroshima Institute of Technology, Hiroshima
11Institute for Cosmic Ray Research, University of Tokyo, Tokyo
12Institute of High Energy Physics, Chinese Academy of Sciences, Beijing
13Institute of High Energy Physics, Vienna
14Institute for Theoretical and Experimental Physics, Moscow
15J. Stefan Institute, Ljubljana
16Kagawa University, Kagawa
17Korea University, Seoul
18Kyoto University, Kyoto
19IPHE, University of Lausanne, Lausanne
20University of Ljubljana, Ljubljana
21University of Maribor, Maribor
22University of Melbourne, Victoria
23Nagoya University, Nagoya
24Nara Women's University, Nara
25National Kaohsiung Normal University, Kaohsiung
26National Lien-Ho Institute of Technology, Miao Li

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We report the results of searches for the decay modes $B^+ \rightarrow p\bar{p}K^+$ [1] and $B^0 \rightarrow p\bar{p}K_S$. These modes are expected to proceed mainly via $b \rightarrow s$ penguin diagrams [2]. We also search for $B^+ \rightarrow p\bar{p}\pi^+$ which is expected to occur primarily via a $b \rightarrow u$ tree process. Once they are established, these baryonic modes may be used to either constrain or observe direct CP violation in $b$ decay [3].

In contrast to charm meson decay, final states with baryons are allowed in $B$ meson decay. To date, a few low multiplicity $B$ decay modes with baryons in the final state from $b \rightarrow c$ transitions have been observed [4]. Rare $B$ decays due to charmless $b \rightarrow s$ and $b \rightarrow u$ transitions should also lead to final states with baryons. A number of searches for such modes have been carried out by CLEO [5], ARGUS [6], and LEP [7], but only upper limits were obtained. Stringent upper limits for two-body modes such as $B^0 \rightarrow p\bar{p}$, $B^+ \rightarrow \Lambda p$, and $B^0 \rightarrow \Lambda\bar{\Lambda}$ have recently been reported by Belle [8].

We use a 29.4 fb$^{-1}$ data sample, which contains $31.9 \times 10^6$ produced $B\bar{B}$ pairs, collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider [8]. KEKB operates at the $Y(4S)$ resonance ($\sqrt{s} = 10.58$ GeV) with a peak luminosity that exceeds $5 \times 10^{30}$ cm$^{-2}$s$^{-1}$. The Belle detector is a large-solid-angle magnetic spectrometer that consists of a three-layer silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), a mosaic of aerogel threshold Cerenkov counters (ACC), time-of-flight scintillation counters (TOF), and an array of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux return located outside of the coil is instrumented to identify $K_L$ and muons (KLM). The detector is described in detail elsewhere [10].

To avoid bias, the event selections were chosen on the basis of a Monte Carlo (MC) study before examining the data. The agreement between data and MC is checked and included in the systematic error.

We select well measured charged tracks with impact parameters with respect to the interaction point of less than 0.3 cm in the radial direction and less than 3 cm in the beam direction ($z$). These tracks are required to have $p_T > 50$ MeV/c.

Particle identification likelihoods for each particle hypothesis are calculated by combining information from the TOF, ACC system with $dE/dx$ measurements in the CDC. Protons and antiprotons are identified using all particle ID systems and are required to have proton likelihood ratios $|L_p/L_\bar{p} + L_p| > 1.5$ and $L_p/L_\bar{p} + L_p > 0.66$. Proton candidates that are electronlike according to the information recorded by the CsI(Tl) calorimeter are vetoed.
This selection is 89% efficient for protons with a 7% kaon misidentification rate. To identify kaons (pions), we require the kaon (pion) likelihood ratio to be greater than 0.6. This requirement is 88% efficient for kaons with a 8.5% misidentification rate for pions. In addition, we remove kaon candidates that are consistent with being protons.

For the $B^0 \rightarrow p \bar{p} K_S$ mode, we select $K_S$ candidates from $\pi^- \pi^-$ candidates that lie within the mass window $0.482 \text{ GeV/c}^2 < M(\pi^- \pi^-) < 0.514 \text{ GeV/c}^2 (\pm 4\sigma)$. The distance of closest approach between the two daughter tracks is required to be less than 2.4 cm. The impact parameter of each track in the radial direction should have a magnitude greater than 0.02 cm, and the flight length should be greater than 0.22 cm. The difference in the angle between the vertex direction and the $K_S$ flight direction in the $x$-$y$ plane is required to satisfy $|\Delta \theta| < 0.03$ rad.

To reconstruct signal candidates in the $B^+ \rightarrow p \bar{p} K^+$ mode, we form combination of a kaon, proton, and anti-proton that are inconsistent with the following $b \rightarrow c\bar{c} s$ transitions: $B^+ \rightarrow J/\psi K^+$, $J/\psi \rightarrow p\bar{p}$; $B^+ \rightarrow \eta_c K^+$, $\eta_c \rightarrow p\bar{p}$; $B^+ \rightarrow \psi' K^+$, $\psi' \rightarrow p\bar{p}$; and $B^+ \rightarrow \chi_{(c)1} K^+$, $\chi_{(c)1} \rightarrow p\bar{p}$. This set of requirements is referred to as the charm veto [11]. Similar charm vetoes are applied in the analysis of the other decay modes. In the case of $B^0 \rightarrow p \bar{p} K_S$ events with $pK_S$ or $\bar{p} K_S$ masses consistent with the $\Lambda_c$ are rejected [12].

To isolate the signal, we form the beam-constrained mass, $M_{bc} = \sqrt{E_{\text{beam}}^2 - \vec{p}_{\text{recon}}^2}$, and energy difference $\Delta E = E_{\text{recon}} - E_{\text{beam}}$ in the $Y(4S)$ center of mass frame. Here $E_{\text{beam}}$, $E_{\text{recon}}$, and $\vec{p}_{\text{recon}}$ are the beam energy, the reconstructed energy, and the reconstructed momentum of the signal candidate, respectively. The signal region for $\Delta E$ is $\pm 50$ MeV which corresponds to $\pm 5\sigma$ where $\sigma$ is the resolution determined from a Gaussian fit to the MC simulation. The signal region for $M_{bc}$ is $5.270 \pm 0.03 \text{ GeV/c}^2$. The resolution in beam-constrained mass is $2.8 \text{ MeV/c}^2$ and is dominated by the beam energy spread of KEKB.

Several event topology variables provide discrimination between the large continuum ($e^+ e^- \rightarrow q\bar{q}$, where $q = u, d, s, c$) background, which tends to be collimated along the original quark direction, and more spherical $B \bar{B}$ events. We form a likelihood ratio using two variables. Six modified Fox-Wolfram moments and the cosine of the thrust angle are combined into a Fisher discriminant [13]. For signal MC and continuum data, we then form probability density functions for this Fisher discriminant, and the cosine of the $B$ decay angle with respect to the $z$ axis ($\cos \theta_B$). The signal (background) probability density functions are multiplied together to form a probability distribution over $L_z$ ($L_{BG}$). The likelihood ratio $L_z/L_{BG}$ is then required to be greater than 0.6. The event topology requirements retain 78% of the signal while removing 87% of the background.

In Fig. 1, we show the $\Delta E$ distribution (with $5.270 \text{ GeV/c}^2 < M_{bc} < 5.290 \text{ GeV/c}^2$) and the beam-constrained mass distribution (with $|\Delta E| < 50$ MeV) for the signal candidates. We fit the $\Delta E$ distribution with a double Gaussian for signal and a linear background function with slope determined from the $M_{bc}$ sideband. The mean of the Gaussian is determined from $B^+ \rightarrow \Lambda_c^+ p \pi^- \pi^0$, $\Lambda_c^- \rightarrow p K^- \pi^0 \pi^0$ decays. The fit to the $\Delta E$ distribution gives a yield of $42.8^{+3.9}_{-6.6}$ with a significance of 5.6 standard deviations [14]. In the fit to the $\Delta E$ distribution, the region with $\Delta E < -120$ MeV is excluded to avoid feed-downs from modes such as $B \rightarrow p K^+$. As a consistency check, we fit the $M_{bc}$ distribution to the sum of a signal Gaussian and a background function with kinetic threshold. The width of the Gaussian is fixed from MC simulation while the mean is determined from $B^+ \rightarrow D^0 \pi^+$ data. The shape parameter of the background function is determined from $\Delta E$ sideband data. In the $M_{bc}$ distribution, we observe a signal of $42.9^{+3.9}_{-6.6}$ events. The signal yields and the branching fractions are determined from fits to the $\Delta E$ distribution rather than $M_{bc}$ to minimize possible biases from $B \bar{B}$ background which tends to peak in $M_{bc}$ but not in $\Delta E$.

The background in these modes is predominantly due to continuum events. To check for $B \bar{B}$ backgrounds that might peak in the signal region, we used two large $B \bar{B}$ MC samples that correspond to an integrated luminosity that is about twice the size of the data sample. The estimated background is of the order of one event and no backgrounds that peak in the $\Delta E$ signal region were found. We also examined MC samples of $b \rightarrow c$ decay modes with baryons in the final state. We restricted our attention to low multiplicity decay modes. We generated samples of $B \rightarrow \Lambda_c^+ p$, $B \rightarrow \Lambda_c^- p \pi^-$, and $B \rightarrow \Lambda_c^- p e^+ \nu_e$ that correspond to an integrated luminosity about a factor of 10 larger than the data sample used here. The $\Lambda_c$ charmed baryon was allowed to decay into all measured decay modes that contain a proton. Again no peaking backgrounds were observed.

We also examine the $M(p \bar{p})$ mass distributions for events in the $\Delta E, M_{bc}$ signal region. The signal yield as a function of $p \bar{p}$ mass is shown in Fig. 2. These yields were determined by fits to the $\Delta E$ distribution in bins of $p \bar{p}$ invariant mass. The distribution from a three-body phase space MC normalized to the area of the signal is
The distribution from nonresonant $B^+ \rightarrow p \bar{p} K^+$ MC simulation is superimposed. The inset shows the $p \bar{p}$ mass distribution for the $J/\psi K^+$ signal region.

To avoid model dependence in the determination of the branching fraction for $p \bar{p} K^+$, we fit the $\Delta E$ signal yield in bins of $M(p \bar{p})$ and correct for the detection efficiency in each bin using a three-body phase space $B^+ \rightarrow p \bar{p} K^+$ MC model. The results of the fits are given in Table I. We then sum the partial branching fractions in each bin to obtain

$$B(B^+ \rightarrow p \bar{p} K^+) = [4.3^{+1.1}_{-0.9} \text{(stat)} \pm 0.5 \text{(syst)}] \times 10^{-6}.$$  

For $M(p \bar{p}) < 3.4 \text{ GeV/c}^2$, the mass region below the $\chi_c$ and $\psi'$ resonances, $B(B^+ \rightarrow p \bar{p} K^+) = [4.4^{+0.9}_{-0.8} \text{(stat)} \pm 0.4 \text{(syst)}] \times 10^{-6}$.  

TABLE 1. Fit results in bins of $M(p \bar{p})$. The detection efficiency ($\epsilon_{\text{detect}}$) and the partial branching fraction ($B$) for each bin are also listed.

<table>
<thead>
<tr>
<th>$M(p \bar{p})$ (GeV/c$^2$)</th>
<th>$\Delta E$ yield</th>
<th>$\epsilon_{\text{detect}}$</th>
<th>$B(\times 10^{-6})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;2.0$</td>
<td>10.2$^{+11}_{-9.4}$</td>
<td>0.33</td>
<td>0.97$^{+0.09}_{-0.09}$</td>
</tr>
<tr>
<td>2.0–2.2</td>
<td>7.8$^{+11}_{-8.9}$</td>
<td>0.34</td>
<td>0.73$^{+0.08}_{-0.09}$</td>
</tr>
<tr>
<td>2.2–2.4</td>
<td>11.9$^{+10}_{-8.3}$</td>
<td>0.30</td>
<td>1.24$^{+0.08}_{-0.07}$</td>
</tr>
<tr>
<td>2.4–2.6</td>
<td>5.5$^{+10}_{-8.3}$</td>
<td>0.29</td>
<td>0.61$^{+0.08}_{-0.09}$</td>
</tr>
<tr>
<td>2.6–2.8</td>
<td>3.3$^{+10}_{-8.3}$</td>
<td>0.30</td>
<td>0.34$^{+0.08}_{-0.09}$</td>
</tr>
<tr>
<td>2.8–3.4</td>
<td>4.6$^{+10}_{-8.3}$</td>
<td>0.29</td>
<td>0.50$^{+0.08}_{-0.09}$</td>
</tr>
<tr>
<td>3.4–4.0</td>
<td>$1.2^{+9.6}_{-1.3}$</td>
<td>0.27</td>
<td>$-0.14^{+0.08}_{-0.09}$</td>
</tr>
<tr>
<td>4.0–4.8</td>
<td>$0.3^{+10}_{-8.3}$</td>
<td>0.25</td>
<td>$0.04^{+0.08}_{-0.09}$</td>
</tr>
</tbody>
</table>

We also examined two related decay modes $B^0 \rightarrow p \bar{p} K_S$ and $B^0 \rightarrow p \bar{p} \pi^+$ that may help clarify the interpretation of the signal. Measurement of $B^0 \rightarrow p \bar{p} K_S$ will help determine the role of the spectator quark in $b \rightarrow s$ decays with baryons, while observation of $B^0 \rightarrow p \bar{p} \pi^+$ will constrain the ratio of the $b \rightarrow u$ tree and $b \rightarrow s$ penguin diagrams in decays with baryons. For $B^0 \rightarrow p \bar{p} K_S$, after the application of the charm and $\Lambda_c$ vetoes, no significant signal is observed in either the $\Delta E$ or $M_{bc}$ distribution. A fit to the $\Delta E$ distribution gives $6.4^{+5}_{-4}$ events. Applying the Feldman-Cousins procedure [16], we obtain an upper limit of less than 16 events at the 90% confidence level (C.L.). After reducing the detection 0.5(syst) $\times 10^{-6}$ with the charm veto applied. For $M(p \bar{p}) < 2.8 \text{ GeV/c}^2$, the region below charm threshold, we obtain $B(B^+ \rightarrow p \bar{p} K^+) = [3.9^{+1.3}_{-0.8} \text{(stat)} \pm 0.4 \text{(syst)}] \times 10^{-6}$.  

The contributions to the systematic error for the $B^+ \rightarrow p \bar{p} K^+$ mode are the uncertainties due to the tracking efficiency (6%), particle identification efficiency (8%), and the modeling of the likelihood ratio cut (2.6%). The particle identification systematic includes contributions of 3% for the proton and antiproton and 2% for the charged kaon. The error in proton/antiproton identification is determined using $\Lambda/\bar{\Lambda}$ samples, while the error in kaon identification efficiency is obtained from kinematically selected $D^{*+} \rightarrow D^0 \pi^+, D^0 \rightarrow K^- \pi^+$ in the data. The systematic error due to the modeling of the likelihood ratio cut is determined using $B^+ \rightarrow D^0 \pi^+$ events reconstructed in data. The systematic error in the yield of the $\Delta E$ fit (3.8%) was determined by varying the mean and $\sigma$ of the signal and the shape parameter of the background. The sources of systematic error are combined in quadrature to obtain the final systematic error of 11.0%.

For events in the $\Delta E$, $M_{bc}$ signal region we examine the proton, antiproton, and kaon particle identification likelihood distributions and compare to signal MC simulation. No discrepancy is observed. We also verify that the ECL shower width distribution is consistent with MC expectations for the proton and antiproton candidates. In addition, we check the branching fraction as the cuts on the proton and antiproton probabilities and likelihood ratio are varied. We do not observe any systematic trends beyond statistics.  

To verify the analysis procedure and branching fraction determination, we remove the $J/\psi$ veto and examine the decay chain $B^+ \rightarrow J/\psi K^+$, $J/\psi \rightarrow p \bar{p}$. A clear signal of $26.4 \pm 5.2$ events is then observed in the $\Delta E$ spectrum. We also observe $25.9 \pm 5.1$ events in the $M_{bc}$ distribution. The $p \bar{p}$ invariant mass spectrum for $J/\psi K^+$ signal candidates is shown as an inset in Fig. 2. We use the $\Delta E$ yield and the MC detection efficiency of 0.30 to determine the branching fraction $B(B^+ \rightarrow J/\psi K^+) = (13.1 \pm 2.6) \times 10^{-4}$. This is in good agreement with the PDG world average, $B(B^+ \rightarrow J/\psi K^+) = (10.0 \pm 1.0) \times 10^{-4}$ [15], which was obtained by experiments that reconstruct the $J/\psi$ in dilepton modes. We also examined two related decay modes $B^0 \rightarrow p \bar{p} K_S$ and $B^0 \rightarrow p \bar{p} \pi^+$ that may help clarify the interpretation of the signal. Measurement of $B^0 \rightarrow p \bar{p} K_S$ will help determine the role of the spectator quark in $b \rightarrow s$ decays with baryons, while observation of $B^0 \rightarrow p \bar{p} \pi^+$ will constrain the ratio of the $b \rightarrow u$ tree and $b \rightarrow s$ penguin diagrams in decays with baryons.
efficiency by the systematic error, we obtain an upper limit at 90% C.L. of \( B(B^0 \rightarrow p\bar{p}K^0) < 7.2 \times 10^{-6} \).

In the \( B^+ \rightarrow p\bar{p}\pi^+ \) mode, after the application of the charm veto we perform a fit to the \( \Delta E \) distribution that allows for \( B^+ \rightarrow p\bar{p}\pi^+ \) signal and a reflection from misidentified \( B^+ \rightarrow p\bar{p}K^- \) decays. This fit gives a signal yield of 16.2^{+6}_{-5.0} \) events and a significance of 2.1\( \sigma \). The excess in the \( \Delta E \) fit corresponds to a branching fraction \( B(B^+ \rightarrow p\bar{p}\pi^+) = (1.9^{+0.9}_{-0.7} \pm 0.3) \times 10^{-6} \) or an upper limit of \( B(B^+ \rightarrow p\bar{p}\pi^+) < 3.7 \times 10^{-6} \) at 90% C.L. after taking into account the systematic error.

We have observed a significant signal (5.6\( \sigma \)) for the decay \( B^+ \rightarrow p\bar{p}K^- \). This is the first \( b \rightarrow s \) decay mode with baryons in the final state. In the future, this mode can be used to search for direct CP violation [3]. We find that its \( p\bar{p} \) mass spectrum is inconsistent with phase space and is peaked toward low mass. This feature is suggestive of a genuine three-body process and that this feature of the \( M(p\bar{p}) \) spectrum is a baryon form factor effect [17,18].

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[1] Hereafter, the inclusion of the charge conjugate mode is implied.
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