Search for $B_s^0 \to hh$ Decays at the $\Upsilon(5S)$ Resonance

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We have searched for $B_s^0 \to hh$ decays, where h stands for a charged or neutral kaon, or a charged pion. These results are based on a 23.6 fb^{-1} data sample collected with the Belle detector on the $\Upsilon(5S)$ resonance at the KEKB asymmetric-energy e^+e^- collider, containing 1.25 million $B_s^{(*)}\bar{B}_s^{(*)}$ events. We observe the decay $B_s^0 \to K^+K^-$ and measure its branching fraction, $\mathcal{B}(B_s^0 \to K^+K^-) = [3.8^{+1.0}_{-0.9}(\text{stat}) \pm 0.5(\text{syst}) \pm 0.5(f_s)] \times 10^{-5}$. The first error is statistical, the second is systematic, and the third error is due to the uncertainty in the B_s^0 production fraction in $e^+e^- \to b\bar{b}$ events. No significant signals are seen in other decay modes, and we set upper limits at 90% confidence level: $\mathcal{B}(B_s^0 \to K^-\pi^+) < 1.2 \times 10^{-5}$, $\mathcal{B}(B_s^0 \to \pi^+\pi^-) < 2.6 \times 10^{-5}$ and $\mathcal{B}(B_s^0 \to K^0\bar{K}^0) < 6.6 \times 10^{-5}$.

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The recent observation [1] of a significant difference in the direct CP violation of $B \to K\pi$ between B^0 and B^+ [2] was unexpected and has generated much discussion. Possible explanations for this difference include a large color-suppressed tree amplitude [3], new physics in the electroweak penguin loop [4], or both [5]. Similar measurements of charmless two-body B_s^0 decays may provide additional insight into this and other aspects of B decays. For instance, a comparison of the CP violating asymmetries between the B^0 and B_s^0 may discriminate among new physics models [6]; the angles $\phi_1(\beta)$ and $\phi_3(\gamma)$ of the unitarity triangle may be extracted using the time evolution of the decays $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ [7]; the branching fractions and CP violating asymmetries of these two decays provide information on U-spin symmetry breaking [8]; and the decay $B_s^0 \to K^-\pi^+$ can be used to determine $\phi_3(\gamma)$ [9].

The decay $B_s^0 \to K^+K^-$ is of particular interest because its branching fraction is expected to be large, in analogy to that of $B^0 \to K^+\pi^-$, and the final state is a CP eigenstate. The time-dependent CP asymmetry of this decay is sensitive to the $B_s^0 - \bar{B}_s^0$ mixing phase (ϕ_s) and the width difference of the two B_s^0 mass eigenstates ($\Delta\Gamma_s$); these two parameters provide a clean probe to new physics beyond the Standard Model. CDF and DØ have performed a time-dependent CP analysis using $B_s^0 \to J/\psi\phi$ events to measure ϕ_s and $\Delta\Gamma_s$. The results are limited by statistics and no significant deviations from the SM expectation are observed [10].

Experimental results to date on charmless B_s^0 decay have been limited to just a few measurements from CDF [11–13] and Belle [14]. In this paper, we report on a search for B_s^0 decays to K^+K^-, $K^0\bar{K}^0$, $K^-\pi^+$ and $\pi^+\pi^-$ based on (23.6±0.3) fb^{-1} (L_{int}) of data collected at the Υ(5S) resonance with the Belle detector operated at the KEKB asymmetric-energy (3.6 GeV on 8.2 GeV) e^+e^- collider [15]. In an earlier study, half of the center-of-mass (c.m.) energy was measured to be $E^*_{\text{beam}} = (5433.5 \pm 0.5)$ MeV [16]. At this energy, the cross section for $b\bar{b}$ events is $\sigma_{b\bar{b}}^{\Upsilon(5S)} = (0.302 \pm 0.014)$ nb, of which a fraction $f_s = (19.5^{+3.0}_{-2.3})\%$ contains B_s^0 mesons [18]. Three production modes are kinematically allowed: $B_s^0\bar{B}_s^0$, $B_s^*\bar{B}_s^0$ and $B_s^*\bar{B}_s^*$, where the fraction of $B_s^*\bar{B}_s^*$ is $f_{B_s^*\bar{B}_s^*} = (90.1^{+3.8}_{-4.0} \pm 0.2)\%$ [19]. The number of $B_s^*\bar{B}_s^*$ pairs is thus computed as $N_{B_s^*\bar{B}_s^*} = L_{\text{int}} \times \sigma_{b\bar{b}}^{\Upsilon(5S)} \times f_s \times f_{B_s^*\bar{B}_s^*} = (1.25 \pm 0.19) \times 10^6$.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised 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 detect K_L^0 mesons and to identify muons (KLM). The detector is described in detail elsewhere [20].

Charged kaons and pions are required to have a distance of closest approach to the interaction point (IP) of less than 3.0 cm in the beam direction and less than 0.3 cm in the transverse plane. Charged kaons and pions are identified using dE/dx measurements from the

CDC, Cherenkov light yields in the ACC, and timing information from the TOF. This information is combined in a likelihood ratio, $\mathcal{R}_{K/\pi} = \mathcal{L}_K/(\mathcal{L}_\pi + \mathcal{L}_K)$, where $\mathcal{L}_K$ ($\mathcal{L}_\pi$) is the likelihood that the track is a kaon (pion). Charged tracks with $\mathcal{R}_{K/\pi} > 0.6$ are treated as kaons, and with $\mathcal{R}_{K/\pi} < 0.6$ as pions. Furthermore, charged tracks positively identified as electrons or muons [21] are rejected. With these selections, the kaon (pion) identification efficiency is about 83% (88%), while 12% (8%) of kaons (pions) are misidentified as pions (kaons). Neutral kaons are reconstructed in the $K^0_S \to \pi^+\pi^-$ decay channel and are required to have an invariant mass in the range 490 MeV/c^2 $< M_{\pi^+\pi^-} <$ 510 MeV/c^2. The intersection point of the $\pi^+\pi^-$ pair must be displaced from the IP [22].

B^0_s candidates are selected by combining kaons and pions in appropriate pairs and separated from background using two variables: the beam-energy-constrained mass, $M_{\rm bc} = \sqrt{E^{*2}_{\rm beam} - p^{*2}_B}$, and the energy difference, $\Delta E = E^*_B - E^*_{\rm beam}$, where p^*_B and E^*_B are the momentum and energy of the reconstructed B^0_s meson in the c.m. frame, respectively. Candidates with -0.2 GeV $< \Delta E <$ 0.2 GeV and 5.35 GeV/c^2 $< M_{\rm bc} <$ 5.45 GeV/c^2 are selected. Since the dominant source of B^0_s mesons is $\Upsilon(5S) \to B^*_s\bar{B}^*_s$, we search for B^0_s mesons only in this decay channel and define the signal region to be -0.1 GeV $< \Delta E <$ 0.0 GeV and 5.40 GeV/c^2 $< M_{\rm bc} <$ 5.43 GeV/c^2.

The dominant background is due to continuum events, *i.e.*, $e^+e^- \to q\bar{q}$, where q stands for a u, d, s or c quark. The event topology difference between $q\bar{q}$ and $b\bar{b}$ events is exploited by computing a Fisher discriminant [23] based on a set of modified Fox-Wolfram moments [24]. Signal ($\mathcal{L}_{\rm s}$) and background ($\mathcal{L}_{q\bar{q}}$) likelihoods are formed using a GEANT-based [25] Monte Carlo (MC) simulation and data outside the signal region, respectively. They are combined into a likelihood ratio $\mathcal{R} = \mathcal{L}_{\rm s}/(\mathcal{L}_{\rm s} + \mathcal{L}_{q\bar{q}})$. The selection criterion, based on $\mathcal{R}$, is determined by maximizing $S/\sqrt{S+B}$, where S and B are the number expected in the signal region of signal or background events, respectively. The expected signals are determined by assuming the following branching fractions: $\mathcal{B}(B^0_s \to K^+K^-) = 2.6 \times 10^{-5}$, $\mathcal{B}(B^0_s \to K^+\pi^-) = 4.6 \times 10^{-6}$, $\mathcal{B}(B^0_s \to K^0\bar{K}^0) = 1.2 \times 10^{-5}$, $\mathcal{B}(B^0_s \to \pi^+\pi^-) = 1.0 \times 10^{-7}$. For the $B^0_s \to K^+K^-$ mode, we apply a looser criterion on $\mathcal{R}$ if the event contains an identified electron (muon) with momentum larger than 0.5 (0.8) GeV/c.

Backgrounds from B meson decays are studied using large MC samples, which include $\Upsilon(5S) \to B^{(*)}_s\bar{B}^{(*)}_s$, $\Upsilon(5S) \to B^*\bar{B}\pi$ and $\Upsilon(5S) \to B\bar{B}\pi\pi$ events. The contribution from $\Upsilon(5S) \to B\bar{B}, \Upsilon(5S) \to B^*\bar{B}$ and $\Upsilon(5S) \to B^*\bar{B}^*$ are negligible since the hh candidates from the corresponding B decays lie outside the required $M_{\rm bc}$-ΔE region. A non-negligible contribution from $\Upsilon(5S) \to B^{(*)}_s\bar{B}^{(*)}_s$ events is present in the $B^0_s \to K^-\pi^+$ mode when one of the kaons from $B^0_s \to K^+K^-$ is misidentified as a pion (cross-feed). With the branching fractions of $\Upsilon(5S) \to B^*\bar{B}\pi$ and $\Upsilon(5S) \to B\bar{B}\pi\pi$ assumed to be 6.8% and 9.2%, respectively [26], we expect to reconstruct about five $\bar{B}^0 \to K^-\pi^+$ events in the $B^0_s \to K^-\pi^+$ mode. This $\bar{B}^0 \to K^-\pi^+$ background is located outside the signal region and is treated as a systematic uncertainty.

We perform an unbinned extended maximum likelihood fit to $M_{\rm bc}$ and ΔE to extract signal yields. The likelihood function is defined as :

$$\mathcal{L} = \frac{e^{-\sum_j N_j}}{N!} \prod_{i=1}^{N} \sum_j N_j P_j, \qquad (1)$$

where N is the total number of events, i runs over the selected events and j over the signal and background components. N_j is the number of events for component j, and P_j is the corresponding probability density function (PDF). The continuum PDF is the product of a second-order polynomial function for ΔE and an empirical ARGUS function [27] for $M_{\rm bc}$. For each mode, the signal PDF is modeled from MC with a Gaussian function for $M_{\rm bc}$ and a double Gaussian for ΔE. The mean values of $M_{\rm bc}$ and ΔE are calibrated with $B^0_s \to D^+_s\pi^-$ decays, and the ΔE width is calibrated with $\bar{D}^0 \to K^+\pi^-$ decays. For the $B^0_s \to K^-\pi^+$ mode, the $B^0_s \to K^+K^-$ cross-feed and the $\bar{B}^0 \to K^-\pi^+$ background are modeled by two-dimensional smoothed histogram functions. Yields for signal and continuum candidates, and the parameters of the continuum PDF, are allowed to float in the fit while the parameters for other components are fixed. The branching fraction ($\mathcal{B}$) is computed as:

$$\mathcal{B} = \frac{N_s}{\epsilon \times 2N_{B^*_s\bar{B}^*_s}}, \qquad (2)$$

where N_s is the fitted signal yield and ϵ is the MC efficiency.

Two types of systematic uncertainties are considered: uncertainties associated with the fit and uncertainties on the signal reconstruction efficiency and number of B^0_s meson pairs. The fit systematic uncertainties are due to the modeling of the signal and continuum PDFs, and the statistical uncertainties in the background yields that were fixed in the fit. The uncertainties due to the signal PDFs are obtained by varying each PDF parameter successively by one standard deviation and repeating the fit. The systematic uncertainty is the quadratic sum of the changes in the signal yield. The uncertainty in modeling the continuum background is studied by changing the ΔE PDFs from second- to first-order polynomials. For the $B^0_s \to K^-\pi^+$ mode, the fit is repeated with the $B^0_s \to K^+K^-$ cross-feed yield varied by plus or minus

one standard deviation and with a $\bar{B}^0 \to K^-\pi^+$ component included in the fit. The signal yield variations are assigned as systematic uncertainties.

TABLE I: Systematic error (%).

Source	K^+K^-	$K^-\pi^+$	$\pi^+\pi^-$	K^0K^0
Signal PDF	2.3	10.6	10.3	6.8
Continuum PDF	0.7	1.5	3.9	6.3
Cross-feed background	–	5.5	–	–
$\bar{B}^0 \to K^-\pi^+$ background	–	7.1	–	–
$\mathcal{R}$ requirement	12.0	12.8	16.5	4.8
$\mathcal{R}(K/\pi)$ requirement	1.4	1.4	1.3	–
K_S^0 reconstruction	–	–	–	9.8
Track reconstruction	2.0	2.0	2.0	0.0
$\sigma_{b\bar{b}}^{\Upsilon(5S)}$	4.8	4.8	4.8	4.8
$L_{\rm int}$	1.3	1.3	1.3	1.3
f_s	13.3	13.3	13.3	13.3
$f_{B_s^*\bar{B}_s^*}$	4.8	4.8	4.8	4.8
Signal MC statistics	0.4	0.5	0.5	0.6
Total	19.5	24.3	25.0	20.7

The second type of systematic uncertainty is determined as follows. For the $\mathcal{R}$ requirement, we use the decay $B_s^0 \to D_s^-\pi^+$ to estimate the discrepancy between data and MC. The data-MC differences with various $\mathcal{R}$ requirements for the $B_s^0 \to hh$ modes are all less than $2/3\sigma$ and we conservatively assign the quadratic sum of the data-MC difference and the statistical uncertainty on the $D_s^-\pi^+$ sample as the systematic uncertainty. The identification of kaons and pions is calibrated using a control sample of $D^{*+} \to D^0(K^-\pi^+)\pi^+$ decays. For two-body $B_s^0 \to hh$ decays, this systematic uncertainty is 0.7% per kaon and 0.6% per pion. The K_S^0 reconstruction efficiency is verified using a sample of $D^+ \to K_S^0\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ decays. We compare the ratio of the yields of the two decay modes with the Monte Carlo expectation, which is obtained by generating a large Monte Carlo sample with the proper continuum and $B\bar{B}$ fractions. A systematic error of 4.9% per K_S^0 meson is obtained by adding, in quadrature, the deviation of the data and MC ratios and the uncertainties of the branching fractions of the two decay modes, where the latter is the dominant error. The systematic uncertainty due to the track reconstruction efficiency is estimated using partially reconstructed D^* events [28] and is 1% per track. Sources of uncertainty in the number of $B_s^*\bar{B}_s^*$ pairs include $L_{\rm int}$, $\sigma_{b\bar{b}}^{\Upsilon(5S)}$, f_s, and $f_{B_s^*\bar{B}_s^*}$. Systematic uncertainties are summarized in Table I.

The fit results are shown in Figure 1 and summarized in Table II. A significant signal is observed in the $B_s^0 \to K^+K^-$ mode, and the branching fraction is measured to be $\mathcal{B} = [3.8^{+1.0}_{-0.9}({\rm stat}) \pm 0.5({\rm syst}) \pm 0.5(f_s)] \times 10^{-5}$ with a significance of 5.8σ. The signal significance is defined by $\Sigma = \sqrt{2\ln(\mathcal{L}_{\rm max}/\mathcal{L}_0)}$, where $\mathcal{L}_{\rm max}(\mathcal{L}_0)$ is the likelihood value at its maximum (with zero signal yield)

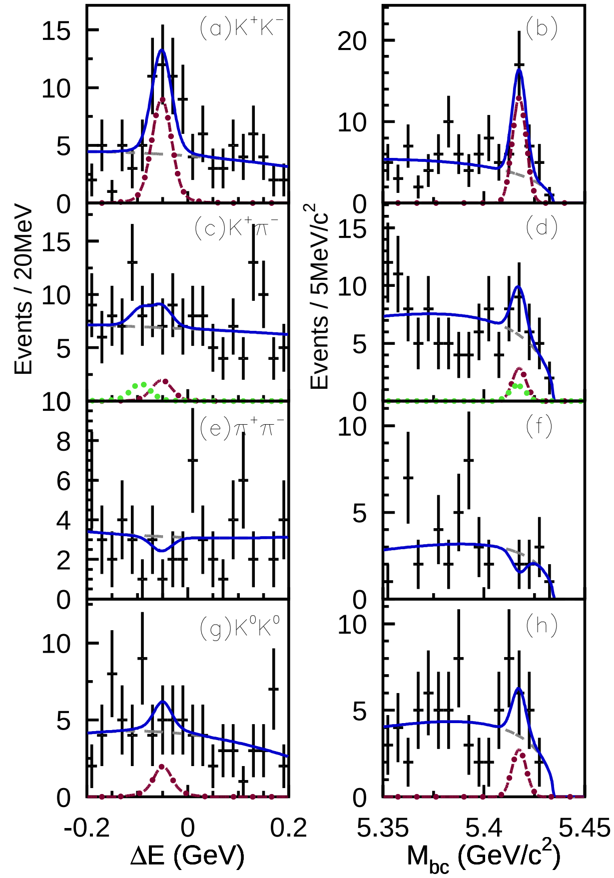

FIG. 1: Distributions of ΔE ($M_{\rm bc}$) with fit results superimposed for the K^+K^- (a,b), $K^+\pi^-$ (c,d), $\pi^+\pi^-$ (e,f), and $K^0\bar{K}^0$ (g,h) events in the $M_{\rm bc}$ (ΔE) signal region. The blue solid curves represent the fit results, in which the red dot-dashed (grey dashed) curves represent signal (continuum background). The green dotted curves in the $K^-\pi^+$ plot represent the K^+K^- cross-feed.

obtained after convolving the likelihood function with a Gaussian function having width equal to the fitting systematic uncertainty. For the other decay modes, the 90% upper limit ($\mathcal{B}_{90\%}$) is computed as

$$\frac{\int_0^{\mathcal{B}_{90\%}} \mathcal{L}(\mathcal{B})d\mathcal{B}}{\int_0^1 \mathcal{L}(\mathcal{B})d\mathcal{B}} = 0.9, \quad (3)$$

with the likelihood function after convolving with a Gaussian width equal to the total systematic uncertainty.

In conclusion, we observe $B_s^0 \to K^+K^-$ with

$$\begin{aligned} &\mathcal{B}(B_s^0 \to K^+K^-) \\ &= [3.8^{+1.0}_{-0.9}({\rm stat}) \pm 0.5({\rm syst}) \pm 0.5(f_s)] \times 10^{-5}. \quad (4) \end{aligned}$$

Our result is consistent with the Standard Model prediction [8] and the CDF measurement ($[2.44 \pm 0.14 \pm 0.46] \times$

TABLE II: Summary of the signal yields, significances (Σ), reconstruction efficiencies (ϵ), branching fractions ($\mathcal{B}$) and upper limits (U.L.) at the 90% confidence level.

Mode	Yield	Σ	ϵ(%)	$\mathcal{B}(10^{-5})$	U.L.(10^{-5})
K^+K^-	$23.4^{+5.5}_{-6.3}$	5.8	24.5	$3.8^{+1.0}_{-0.9} \pm 0.5 \pm 0.5$	–
$K^-\pi^+$	$5.4^{+5.1}_{-4.3}$	1.2	21.0	–	2.6
$\pi^+\pi^-$	$-2.0^{+2.3}_{-1.5}$	–	14.4	–	1.2
$K^0\bar{K}^0$	$5.2^{+5.0}_{-4.3}$	1.2	8.0	–	6.6

10^{-5}) [12]. No significant signals are observed in the other modes, and we set upper limits at 90% confidence level:

$$\begin{aligned} \mathcal{B}(B_s^0 \to K^-\pi^+) &< 2.6 \times 10^{-5}, \\ \mathcal{B}(B_s^0 \to \pi^+\pi^-) &< 1.2 \times 10^{-5}, \\ \mathcal{B}(B_s^0 \to K^0\bar{K}^0) &< 6.6 \times 10^{-5}. \end{aligned} \quad (5)$$

The first two limits are consistent with results from CDF [13], although with less sensitivity, and the third is a first report: this decay is very challenging to reconstruct at a hadron collider.

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