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

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The recent observation of a significant difference between direct CP violation in $B^0 \to K^\pm \pi^\mp$ and $B^\pm \to K^\pm \pi^0$ [1,2] 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 $B^0$ 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 $B^0_s$ may discriminate among new physics models [6]: the angles $\phi_3(\beta)$ and $\phi_3(\alpha)$ of the unitarity triangle may be extracted using the time evolution of the decays $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$ [7]; the branching fractions and CP violating asymmetries of these two decays provide information on $U$-spin symmetry breaking [8]; and the decay $B^0_s \to K^-\pi^+$ can be used to determine $\phi_3(\gamma)$ [9].

The decay $B^0_s \to K^+K^-$ 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 $B^0_s - \bar{B}^0_s$ mixing phase ($\phi_s$) and the width difference of the two $B^0_s$ mass eigenstates ($\Delta \Gamma_s$); these two parameters provide a clean probe of new physics beyond the Standard Model. CDF and DØ have performed a time-dependent $CP$ analysis using $B^0_s \to J/\psi \phi$ events to measure $\phi_s$ 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 $B^0_s$ decay have been limited to just a few measurements from CDF [11] and Belle [12]. In this paper, we report on a search for $B^0_s$ decays to $K^+K^-$, $K^0\bar{K}^0$, $K^-\pi^+$ and $\pi^+\pi^-$ based on a (23.6±0.3) fb$^{-1}$ ($L_{\text{int}}$) data sample collected at the $\Upsilon(5S)$ resonance with the Belle detector operated at the KEKB asymmetric-energy (3.6 GeV on 8.2 GeV) $e^+e^-$ collider [13]. 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 [14]. At this energy, the total cross section for production of light quark pairs of the first two families is around 2.446 nb [15] while the cross section for $b\bar{b}$ events is $\sigma_{\Upsilon(5S)} = (0.302 \pm 0.014)$ nb, of which a fraction $f_s = (19.5\pm3.0)^%$ contains $B^0_s$ mesons [16]. Three production modes are kinematically allowed: $B_s^0\bar{B}_s^0$, $B^*_s\bar{B}_s^*$, and $B^0\bar{B}_s^*$, where the fraction of $B^*_s\bar{B}_s^*$ is $f_{B^*_s\bar{B}_s^*} = (90.1^{+3.8}_{-4.9} \pm 0.2\%)$ [17]. The number of $B^*_s\bar{B}_s^*$ pairs is thus computed as $N_{B^*_s\bar{B}_s^*} = L_{\text{int}} \times \sigma_{\Upsilon(5S)}^{b\bar{b}} \times f_s \times f_{B^*_s\bar{B}_s^*} = (1.25 \pm 0.19) \times 10^6$.

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 that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect $K^0_L$ mesons and to identify muons (KLM). The detector is described in detail elsewhere [18].

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 9.0 cm in the perpendicular direction. The charged tracks are required to be reasonably well matched to the event vertex, and the angles of the tracks are restricted to $|\theta| < 0.8 \pi$ where $\theta$ is the angle between the track and the IP. The kaon and pion identification is based on the comparison of the likelihood ratios for these two hypotheses [19]. The decay $K^0_L \to \pi^+\pi^-$ is not studied for the charged kaons and pions.

To detect $B^0_s \to K^-\pi^+$ events, at least one charged track and one neutral particle are required to pass through the central drift chamber (CDC). The neutral particle must be identified as a KLM or as a Čerenkov counter (ACC) or ECL or CsI(Tl) crystal. The $b\bar{b}$ events are defined as $D^0 \to \pi^+\pi^-$ events. The events with $D^0 \to \pi^+\pi^-$ are selected by requiring at least two charged tracks and one neutral particle to pass through the CDC. The neutral particle is identified as a KLM or as a Čerenkov counter (ACC) or ECL or CsI(Tl) crystal. The $b\bar{b}$ events are defined as $D^0 \to \pi^+\pi^-$ events. The events with $D^0 \to \pi^+\pi^-$ are selected by requiring at least two charged tracks and one neutral particle to pass through the CDC. The neutral particle is identified as a KLM or as a Čerenkov counter (ACC) or ECL or CsI(Tl) crystal.
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\[22\]. Furthermore, charged tracks positively identified as electrons or muons \[22\] 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 \(K_S^0 \rightarrow \pi^+\pi^-\) 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 \[23\].

\(B_s^0\) candidates are selected by combining kaons and pions in appropriate pairs and separated from background using two variables: the beam-energy-constrained mass, \(M_{bc} = \sqrt{E^2_{\text{beam}} - p^2_B}\), and the energy difference, \(\Delta E = E_B - E_{\text{beam}}\), where \(p_B\) and \(E_B\) are the momentum and energy of the reconstructed \(B_s^0\) meson in the c.m. frame, respectively. Figure 1 shows the GEANT-based \[24\] Monte Carlo \(\Delta E-M_{bc}\) distributions for the \(B_s^0 \rightarrow hh\) candidates from various \(\Upsilon(5S)\) decay modes with \(B\) mesons. Events in the circles are from \(\Upsilon(5S) \rightarrow B_s^{(*)}B_s^{(*)}\) decay modes; candidates in the parallelograms are generated with \(\Upsilon(5S) \rightarrow B_s^{(*)}B_s^{(*)}\); three-body \(B_s^{(*)}B^q\) and four-body \(B\bar{B}\pi\pi\) events are located at \(M_{bc} > 5.35\) GeV/c\(^2\) and \(\Delta E < -0.05\) GeV.

\(\mathcal{B}(B_s^0 \rightarrow \pi^+\pi^-) = 1.0 \times 10^{-7}\). For the \(B_s^0 \rightarrow K^+K^-\) 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. After the \(\mathcal{R}\) requirement, 300, 444, 188 and 345 candidates are retained for the \(K^+K^-\), \(K^\pi^\pi\), \(\pi^\pi\) and \(K^0\bar{K}^0\) modes, respectively.

Backgrounds from \(B\) meson decays are studied using large MC samples, which include \(\Upsilon(5S) \rightarrow B_s^{(*)}B_s^{(*)}\), \(\Upsilon(5S) \rightarrow B^*\bar{B}\pi\) and \(\Upsilon(5S) \rightarrow B\bar{B}\pi\pi\) events. The contributions from \(\Upsilon(5S) \rightarrow B\bar{B}\pi\pi\) and \(\Upsilon(5S) \rightarrow B^*\bar{B}\pi\) are negligible since the \(hh\) candidates from the corresponding \(B\) decays lie outside the required \(M_{bc}-\Delta E\) region as shown in Fig. 1. Out of the four \(B_s^0\) decays, \(B\) meson backgrounds only appear in the \(B_s^0 \rightarrow K^-\pi^+\) mode. A non-negligible contribution from \(\Upsilon(5S) \rightarrow B_s^{(*)}B_s^{(*)}\) events is present when one of the kaons from \(B_s^0 \rightarrow K^+K^-\) is misidentified as a pion (cross-feed). The second \(B\) meson background is the \(B_s^0 \rightarrow K^-\pi^+\) events from three-body \(\Upsilon(5S) \rightarrow B_s^*\bar{B}\pi\) and four-body \(\Upsilon(5S) \rightarrow B\bar{B}\pi\pi\) decays. With the branching fractions of \(\Upsilon(5S) \rightarrow B^*\bar{B}\pi\) and \(\Upsilon(5S) \rightarrow B\bar{B}\pi\pi\) assumed to be 6.8% and 9.2%, respectively \[28\], we expect to reconstruct about 5 \(B_s^0 \rightarrow K^-\pi^+\) events, located outside the signal region. These cross-feed- and \(B_s^0 \rightarrow K^-\pi^+\) backgrounds are considered when extracting the \(B_s^0 \rightarrow K^-\pi^+\) signals.

We perform an unbinned extended maximum likelihood fit to \(M_{bc}\) and \(\Delta E\) to extract signal yields. The
The likelihood function is defined as:

\[ \mathcal{L} = \frac{e^{-\sum_j N_j}}{N!} \prod_{i=1}^{N} N_j P_j, \]  

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 \( \Delta E \) and an empirical ARGUS function \([29]\) for \( M_{bc} \). For each mode, the signal PDF is modeled from MC with a Gaussian function for the 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 (B) is computed as:

\[ B = \frac{N_s}{\epsilon \times 2N_{B_s^0B_s^0}}, \]  

where \( N_s \) is the fitted signal yield and \( \epsilon \) 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 \( B_s^0 \) 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 \( \Delta E \) PDFs from second- to first-order polynomials. For the \( B_s^0 \to K^-\pi^+ \) mode, the fit is repeated with the \( B_s^0 \to K^+K^- \) cross-feed yield varied by plus or minus one standard deviation and the signal yield variations are assigned as systematic uncertainties. The systematic error that arises from the \( B_s^0 \to K^-\pi^+ \) background is obtained by taking the difference of the signal yield with and without including the \( B_s^0 \to K^-\pi^+ \) PDF in the fit.

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 same event selection except the continuum suppression used in Ref. \([20]\) is applied to reconstruct \( B_s^0 \to D_s^- \pi^+ \) candidates, where the \( D_s^- \) meson is identified via the \( D_s^- \to \phi\pi^-, D_s^- \to K_s^0K^- \) and \( D_s^- \to K_s^0K^- \) decays. When forming the variable \( \mathcal{R} \), the \( D_s^- \) mesons are treated as stable particles to mimic the \( B_s^0 \to hh \) events and the same sets of weighting factors used to combine the modified Fox-Wolfram moments in the \( hh \) analysis are adopted. We compare the reduction fractions in the \( D_s^- \pi^+ \) data and MC with the \( \mathcal{R} \) requirements for the four \( hh \) modes to obtain the systematic uncertainty. The data-MC differences with various \( \mathcal{R} \) requirements 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 \( D^{*-} \to D_s^0(K^-\pi^+)\pi^+ \) 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 \( D^+ \to K^-\pi^+\pi^0 \) 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 \( BB \) 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 and is 1% per track. Sources of uncertainty in the number of \( B_s^0 \to \bar{B}_s^0 \) pairs include \( L_{\text{int}}, \sigma_{\text{st}}^{\text{res}}, f_s, \) and \( f_{B_s^0\bar{B}_s^0} \). Systematic uncertainties are summarized in Table I.

The fit results are shown in Figure 2 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 \( B = (3.8_{-0.9}^{+1.0})_{\text{stat}} \pm 0.5_{\text{syst}} \pm 0.5(f_s) \times 10^{-5} \) with a significance of 5.8\( \sigma \). The signal significance is defined by \( \Sigma = \sqrt{2\ln(L_{\text{max}}/L_0)} \), where \( L_{\text{max}}(L_0) \) is the

| Source | \( K^-K^- \) | \( K^-\pi^+ \) | \( \pi^+\pi^- \) | \( K^0\bar{K}^0 \) |
|--------|------------|------------|-------------|-------------|
| 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 | – | – |
| \( B_s^0 \to K^-\pi^+ \) background | – | 7.1 | – | – |
| \( \mathcal{R}(K/\pi) \) requirement | 1.4 | 1.4 | 1.3 | – |
| \( K_s^0 \) reconstruction | – | – | – | 9.8 |
| Track reconstruction | 2.0 | 2.0 | 2.0 | 0.0 |
| \( L_{\text{int}} \) | 1.3 | 1.3 | 1.3 | 1.3 |
| \( f_s \) | 13.3 | 13.3 | 13.3 | 13.3 |
| \( f_{B_s^0\bar{B}_s^0} \) | 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 |

| Source | \( K^-K^- \) | \( K^-\pi^+ \) | \( \pi^+\pi^- \) | \( K^0\bar{K}^0 \) |
|--------|------------|------------|-------------|-------------|
| 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 | – | – |
| \( B_s^0 \to K^-\pi^+ \) background | – | 7.1 | – | – |
| \( \mathcal{R}(K/\pi) \) requirement | 1.4 | 1.4 | 1.3 | – |
| \( K_s^0 \) reconstruction | – | – | – | 9.8 |
| Track reconstruction | 2.0 | 2.0 | 2.0 | 0.0 |
| \( L_{\text{int}} \) | 1.3 | 1.3 | 1.3 | 1.3 |
| \( f_s \) | 13.3 | 13.3 | 13.3 | 13.3 |
| \( f_{B_s^0\bar{B}_s^0} \) | 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 |
Our result is consistent with the Standard Model prediction [8] and the CDF measurement \((2.44 \pm 0.14 \pm 0.46) \times 10^{-5}\) [12]. No significant signals are observed in the other modes, and we set upper limits at 90% confidence level:

\[
\begin{align*}
B(B_s^0 \to K^- \pi^+) &< 2.6 \times 10^{-5}, \\
B(B_s^0 \to \pi^+ \pi^-) &< 1.2 \times 10^{-5}, \\
B(B_s^0 \to K^0 \bar{K}^0) &< 6.6 \times 10^{-5}.
\end{align*}
\]

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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The cross section ($\sigma$) of light quark pair production, $e^+e^- \rightarrow q\bar{q}$, is estimated using the leading-order calculation, $\sigma = \frac{N_c \alpha^2 Q_f^2}{24\pi^2} \beta[1 + \frac{1}{3}\beta^2]$, where $N_c$ is the number of colors, $Q_f$ is the charge of the quark, $\alpha$ is the fine structure constant, $s$ is the total energy squared, and $\beta$ is velocity of the quark in the center of mass frame divided by the speed of light. The value of 2.446 nb is the cross section sum for the four light quark pairs.

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The inclusion of charge-conjugate modes is implied throughout this paper unless explicitly stated.

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