

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

C.-C. Peng,²⁸ P. Chang,²⁸ I. Adachi,⁸ H. Aihara,⁴⁴ T. Aushev,^{19,12} T. Aziz,³⁹ A. M. Bakich,³⁸ V. Balagura,¹² E. Barberio,²³ K. Belous,¹¹ V. Bhardwaj,³⁴ A. Bondar,^{1,32} A. Bozek,²⁹ M. Bračko,^{21,13} T. E. Browder,⁷ M.-C. Chang,⁴ Y. Chao,²⁸ A. Chen,²⁶ K.-F. Chen,²⁸ P. Chen,²⁸ B. G. Cheon,⁶ C.-C. Chiang,²⁸ R. Chistov,¹² I.-S. Cho,⁴⁸ Y. Choi,³⁷ J. Dalseno,^{22,40} M. Danilov,¹² A. Das,³⁹ M. Dash,⁴⁷ A. Drutskoy,³ W. Dungel,¹⁰ S. Eidelman,^{1,32} N. Gabyshev,^{1,32} P. Goldenzweig,³ B. Golob,^{20,13} H. Ha,¹⁷ J. Haba,⁸ H. Hayashii,²⁵ Y. Horii,⁴³ Y. Hoshi,⁴² W.-S. Hou,²⁸ H. J. Hyun,¹⁸ T. Iijima,²⁴ K. Inami,²⁴ R. Itoh,⁸ M. Iwabuchi,⁴⁸ M. Iwasaki,⁴⁴ Y. Iwasaki,⁸ N. J. Joshi,³⁹ T. Julius,²³ J. H. Kang,⁴⁸ T. Kawasaki,³¹ H. J. Kim,¹⁸ H. O. Kim,¹⁸ J. H. Kim,¹⁶ M. J. Kim,¹⁸ S. K. Kim,³⁶ Y. J. Kim,⁵ K. Kinoshita,³ B. R. Ko,¹⁷ P. Kodyš,² S. Korpar,^{21,13} P. Križan,^{20,13} P. Krokovny,⁸ T. Kuhr,¹⁵ Y.-J. Kwon,⁴⁸ S.-H. Kyeong,⁴⁸ M. J. Lee,³⁶ S.-H. Lee,¹⁷ J. Li,⁷ A. Limosani,²³ C. Liu,³⁵ D. Liventsev,¹² R. Louvot,¹⁹ A. Matyja,²⁹ S. McOnie,³⁸ K. Miyabayashi,²⁵ H. Miyata,³¹ R. Mizuk,¹² G. B. Mohanty,³⁹ M. Nakao,⁸ H. Nakazawa,²⁶ Z. Natkaniec,²⁹ S. Neubauer,¹⁵ S. Nishida,⁸ K. Nishimura,⁷ O. Nitoh,⁴⁶ S. Ogawa,⁴¹ T. Ohshima,²⁴ S. Okuno,¹⁴ S. L. Olsen,^{36,7} G. Pakhlova,¹² C. W. Park,³⁷ H. Park,¹⁸ H. K. Park,¹⁸ R. Pestotnik,¹³ M. Petrič,¹³ L. E. Piilonen,⁴⁷ M. Röhrken,¹⁵ S. Ryu,³⁶ Y. Sakai,⁸ O. Schneider,¹⁹ C. Schwanda,¹⁰ A. J. Schwartz,³ K. Senyo,²⁴ M. E. Sevier,²³ M. Shapkin,¹¹ C. P. Shen,⁷ J.-G. Shiu,²⁸ B. Shwartz,^{1,32} P. Smerkol,¹³ A. Sokolov,¹¹ M. Starič,¹³ K. Sumisawa,⁸ T. Sumiyoshi,⁴⁵ M. Tanaka,⁸ G. N. Taylor,²³ Y. Teramoto,³³ K. Trabelsi,⁸ S. Uehara,⁸ Y. Unno,⁶ S. Uno,⁸ G. Varner,⁷ K. E. Varvell,³⁸ K. Vervink,¹⁹ C. H. Wang,²⁷ P. Wang,⁹ M. Watanabe,³¹ Y. Watanabe,¹⁴ R. Wedd,²³ J. Wicht,⁸ E. Won,¹⁷ B. D. Yabsley,³⁸ Y. Yamashita,³⁰ C. Z. Yuan,⁹ C. C. Zhang,⁹ Z. P. Zhang,³⁵ V. Zhilich,^{1,32} V. Zhulanov,^{1,32} T. Zivko,¹³ and O. Zykova^{1,32}

(The Belle Collaboration)

¹*Budker Institute of Nuclear Physics, Novosibirsk*²*Faculty of Mathematics and Physics, Charles University, Prague*³*University of Cincinnati, Cincinnati, Ohio 45221*⁴*Department of Physics, Fu Jen Catholic University, Taipei*⁵*The Graduate University for Advanced Studies, Hayama*⁶*Hanyang University, Seoul*⁷*University of Hawaii, Honolulu, Hawaii 96822*⁸*High Energy Accelerator Research Organization (KEK), Tsukuba*⁹*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing*¹⁰*Institute of High Energy Physics, Vienna*¹¹*Institute of High Energy Physics, Protvino*¹²*Institute for Theoretical and Experimental Physics, Moscow*¹³*J. Stefan Institute, Ljubljana*¹⁴*Kanagawa University, Yokohama*¹⁵*Institut für Experimentelle Kernphysik, Karlsruher Institut für Technologie, Karlsruhe*¹⁶*Korea Institute of Science and Technology Information, Daejeon*¹⁷*Korea University, Seoul*¹⁸*Kyungpook National University, Taegu*¹⁹*École Polytechnique Fédérale de Lausanne (EPFL), Lausanne*²⁰*Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana*²¹*University of Maribor, Maribor*²²*Max-Planck-Institut für Physik, München*²³*University of Melbourne, School of Physics, Victoria 3010*²⁴*Nagoya University, Nagoya*²⁵*Nara Women's University, Nara*²⁶*National Central University, Chung-li*²⁷*National United University, Miao Li*²⁸*Department of Physics, National Taiwan University, Taipei*²⁹*H. Niewodniczanski Institute of Nuclear Physics, Krakow*³⁰*Nippon Dental University, Niigata*³¹*Niigata University, Niigata*³²*Novosibirsk State University, Novosibirsk*³³*Osaka City University, Osaka*³⁴*Panjab University, Chandigarh*³⁵*University of Science and Technology of China, Hefei*

³⁶*Seoul National University, Seoul*³⁷*Sungkyunkwan University, Suwon*³⁸*School of Physics, University of Sydney, NSW 2006*³⁹*Tata Institute of Fundamental Research, Mumbai*⁴⁰*Excellence Cluster Universe, Technische Universität München, Garching*⁴¹*Toho University, Funabashi*⁴²*Tohoku Gakuin University, Tagajo*⁴³*Tohoku University, Sendai*⁴⁴*Department of Physics, University of Tokyo, Tokyo*⁴⁵*Tokyo Metropolitan University, Tokyo*⁴⁶*Tokyo University of Agriculture and Technology, Tokyo*⁴⁷*IPNAS, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061*⁴⁸*Yonsei University, Seoul*

(Received 26 June 2010; published 15 October 2010)

We have searched for $B_s^0 \rightarrow hh$ 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 $1.25 \times 10^6 B_s^{(*)} \bar{B}_s^{(*)}$ events. We observe the decay $B_s^0 \rightarrow K^+K^-$ and measure its branching fraction, $\mathcal{B}(B_s^0 \rightarrow K^+K^-) = [3.8_{-0.9}^{+1.0}(\text{stat}) \pm 0.5(\text{syst}) \pm 0.5(f_s)] \times 10^{-5}$. 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 $e^+e^- \rightarrow b\bar{b}$ events. No significant signals are seen in other decay modes, and we set upper limits at the 90% confidence level: $\mathcal{B}(B_s^0 \rightarrow K^- \pi^+) < 1.2 \times 10^{-5}$, $\mathcal{B}(B_s^0 \rightarrow \pi^+ \pi^-) < 2.6 \times 10^{-5}$, and $\mathcal{B}(B_s^0 \rightarrow K^0 \bar{K}^0) < 6.6 \times 10^{-5}$.

DOI: 10.1103/PhysRevD.82.072007

PACS numbers: 13.25.Hw, 14.40.Nd

The recent observation of a significant difference between direct CP violation in $B^0 \rightarrow K^\pm \pi^\mp$ and $B^\pm \rightarrow K^\pm \pi^0$ [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_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 $B^0 \rightarrow \pi^+ \pi^-$ and $B_s^0 \rightarrow K^+ K^-$ [7]; the branching fractions and CP violating asymmetries of these two decays provide information on U -spin symmetry breaking [8]; and the decay $B_s^0 \rightarrow K^- \pi^+$ can be used to determine $\phi_3(\gamma)$ [9].

The decay $B_s^0 \rightarrow K^+ K^-$ is of particular interest because its branching fraction is expected to be large, in analogy to that of $B^0 \rightarrow K^+ \pi^-$, 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 of new physics beyond the standard model (SM). CDF and D0 have performed a time-dependent CP analysis using $B_s^0 \rightarrow J/\psi \phi$ 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 a $(23.6 \pm 0.3) \text{ fb}^{-1}$ (L_{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 [15]. In an earlier study, half of the center-of-mass (c.m.) energy was measured to be $E_{\text{beam}}^* = (5433.5 \pm 0.5) \text{ MeV}$ [16]. At this energy, the total cross section for production of light quark pairs of the first two families is around 2.446 nb [17], while the cross section for $b\bar{b}$ events is $\sigma_{b\bar{b}}^{\Upsilon(5S)} = (0.302 \pm 0.014) \text{ nb}$, of which a fraction $f_s = (19.5_{-2.3}^{+3.0})\%$ 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 $f_{B_s^* \bar{B}_s^*} = (90.1_{-4.0}^{+3.8} \pm 0.2)\%$ [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, 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 composed 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 detect K_L^0 mesons and to identify muons. 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 [21]. 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 $K_S^0 \rightarrow \pi^+\pi^-$ decay channel and are required to have an invariant mass in the range $490 \text{ MeV}/c^2 < M_{\pi^+\pi^-} < 510 \text{ MeV}/c^2$. The intersection point of the $\pi^+\pi^-$ pair must be displaced from the IP [22].

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, $M_{bc} = \sqrt{E_{\text{beam}}^{*2} - p_B^{*2}}$, 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 [23] Monte Carlo ΔE - M_{bc} distributions for the $B_{(s)}^0 \rightarrow hh$ candidates from various two-body, three-body, and four-body

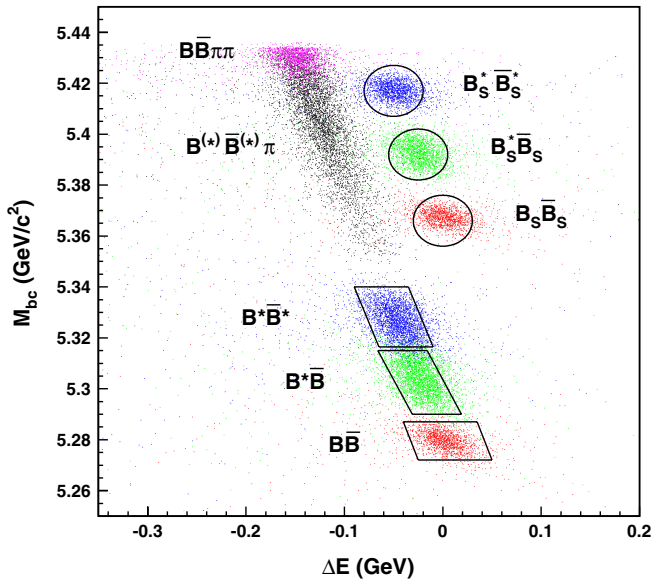


FIG. 1 (color online). Monte Carlo distributions of ΔE - M_{bc} for $B_{(s)}^0 \rightarrow hh$ candidates from various $Y(5S)$ decay modes with B mesons. Events in the circles are from $Y(5S) \rightarrow B_s^{0(*)}\bar{B}_s^{0(*)}$; candidates in the parallelograms are generated with $Y(5S) \rightarrow B^{0(*)}\bar{B}^{0(*)}$; three-body $B^{(*)}\bar{B}^{(*)}\pi$ and four-body $B\bar{B}\pi\pi$ events are located at $M_{bc} > 5.35 \text{ GeV}/c^2$ and $\Delta E < -0.05 \text{ GeV}$.

$Y(5S)$ decays generated with a B meson decaying into an hh pair. Although only one B meson per event is fully reconstructed, we can identify the $Y(5S)$ decay from which it originates based on its location in the ΔE - M_{bc} plane. Candidates with $-0.2 \text{ GeV} < \Delta E < 0.2 \text{ GeV}$ and $5.35 \text{ GeV}/c^2 < M_{bc} < 5.45 \text{ GeV}/c^2$ are selected. Since the dominant source of B_s^0 mesons is $Y(5S) \rightarrow B_s^*\bar{B}_s^*$, we search for B_s^0 mesons only in this decay channel and define the signal region to be $-0.1 \text{ GeV} < \Delta E < 0.0 \text{ GeV}$ and $5.40 \text{ GeV}/c^2 < M_{bc} < 5.43 \text{ GeV}/c^2$.

After applying the M_{bc} - ΔE selection, there are 14 528, 30 613, 27 454, and 444 candidates for the K^+K^- , $K^-\pi^+$, $\pi^+\pi^-$, and $K^0\bar{K}^0$ modes, respectively. These candidates are predominantly from continuum events, i.e., $e^+e^- \rightarrow q\bar{q}$, 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 [24] based on a set of modified Fox-Wolfram moments [25]. Signal (\mathcal{L}_s) and background ($\mathcal{L}_{q\bar{q}}$) likelihoods are formed using a Monte Carlo (MC) simulation and data outside the signal region, respectively. They are combined into a likelihood ratio $\mathcal{R} = \mathcal{L}_s/(\mathcal{L}_s + \mathcal{L}_{q\bar{q}})$. The selection criterion, based on \mathcal{R} , is determined by maximizing $S/\sqrt{S+B}$, where S and B are the numbers expected in the signal region of signal or background events, respectively. The expected signals are determined by assuming the following branching fractions [26]: $\mathcal{B}(B_s^0 \rightarrow K^+K^-) = 2.6 \times 10^{-5}$, $\mathcal{B}(B_s^0 \rightarrow K^-\pi^+) = 4.6 \times 10^{-6}$, $\mathcal{B}(B_s^0 \rightarrow K^0\bar{K}^0) = 1.2 \times 10^{-5}$, $\mathcal{B}(B_s^0 \rightarrow \pi^+\pi^-) = 1.0 \times 10^{-7}$. 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^- , $K^-\pi^+$, $\pi^+\pi^-$, and $K^0\bar{K}^0$ modes, respectively.

Backgrounds from B meson decays are studied using large MC samples, which include $Y(5S) \rightarrow B_s^{(*)}\bar{B}_s^{(*)}$, $Y(5S) \rightarrow B^*\bar{B}\pi$, and $Y(5S) \rightarrow B\bar{B}\pi\pi$ events. The contributions from $Y(5S) \rightarrow B\bar{B}$, $Y(5S) \rightarrow B^*\bar{B}$, and $Y(5S) \rightarrow B^*\bar{B}^*$ are negligible since the hh candidates from the corresponding B decays lie outside the required M_{bc} - ΔE 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 $Y(5S) \rightarrow B_s^{(*)}\bar{B}_s^{(*)}$ 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 $\bar{B}^0 \rightarrow K^-\pi^+$ events from three-body $Y(5S) \rightarrow B^*\bar{B}\pi$ and four-body $Y(5S) \rightarrow B\bar{B}\pi\pi$ decays. With the branching fractions of $Y(5S) \rightarrow B^*\bar{B}\pi$ and $Y(5S) \rightarrow B\bar{B}\pi\pi$ assumed to be 6.8% and 9.2%, respectively [27], we expect to reconstruct about five $\bar{B}^0 \rightarrow K^-\pi^+$ events, located outside the signal region. These cross-feed and $\bar{B}^0 \rightarrow K^-\pi^+$ 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 ΔE to extract signal yields. The likelihood function is defined as follows:

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

where N is the total number of events, i runs over the selected events, and j sums 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 [28] for M_{bc} . For each mode, the signal PDF is modeled from MC with a Gaussian function for M_{bc} and a double Gaussian for ΔE . The mean values of M_{bc} and ΔE are calibrated with $B_s^0 \rightarrow D_s^+ \pi^-$ decays, and the ΔE width is calibrated with $\bar{D}^0 \rightarrow K^+ \pi^-$ decays. For the $B_s^0 \rightarrow K^- \pi^+$ mode, the $B_s^0 \rightarrow K^+ K^-$ cross feed and the $\bar{B}^0 \rightarrow K^- \pi^+$ 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 follows:

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

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_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 1 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 $B_s^0 \rightarrow K^- \pi^+$ mode, the fit is repeated with the $B_s^0 \rightarrow K^+ K^-$ cross-feed yield varied by plus or minus 1 standard deviation and the signal yield variations are assigned as systematic uncertainties. The systematic error that arises from the $\bar{B}^0 \rightarrow K^- \pi^+$ background is obtained by taking the difference of the signal yield with and without including the $\bar{B}^0 \rightarrow K^- \pi^+$ PDF in the fit.

The second type of systematic uncertainty is determined as follows. For the \mathcal{R} requirement, we use the decay $B_s^0 \rightarrow D_s^- \pi^+$ to estimate the discrepancy between data and MC. The same event selection except the continuum suppression used in Ref. [19] is applied to reconstruct

$B_s^0 \rightarrow D_s^- \pi^+$ candidates, where the D_s^- meson is identified via the $D_s^- \rightarrow \phi \pi^-$, $D_s^- \rightarrow K_S^0 K^-$, and $D_s^- \rightarrow K_S^{*0} K^-$ decays. When forming the variable \mathcal{R} , the D_s^- mesons are treated as stable particles to mimic the $B_s^0 \rightarrow hh$ 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 $D^{*+} \rightarrow D^0(K^- \pi^+) \pi^+$ decays. For two-body $B_s^0 \rightarrow hh$ 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 $D^+ \rightarrow K_S^0 \pi^+$ and $D^+ \rightarrow K^- \pi^+ \pi^+$ 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 [29] and is 1% per track. Sources of uncertainty in the number of $B_s^* \bar{B}_s^*$ pairs include L_{int} , $\sigma_{b\bar{b}}^{Y(SS)}$, f_s , and $f_{B_s^* \bar{B}_s^*}$. Systematic uncertainties are summarized in Table I.

The fit results are shown in Fig. 2 and summarized in Table II. A significant signal is observed in the $B_s^0 \rightarrow K^+ K^-$ mode, and the branching fraction is measured to be $\mathcal{B} = [3.8_{-0.9}^{+1.0}(\text{stat}) \pm 0.5(\text{syst}) \pm 0.5(f_s)] \times 10^{-5}$ with

TABLE I. Contributions to the systematic error (%).

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	...	...
$\bar{B}^0 \rightarrow K^- \pi^+$ 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
$\sigma_{b\bar{b}}^{Y(SS)}$	4.8	4.8	4.8	4.8
L_{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

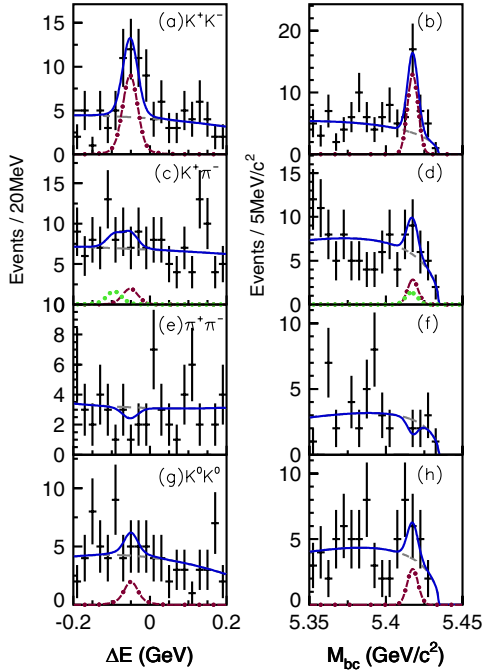


FIG. 2 (color online). Distributions of $\Delta E (M_{bc})$ with fit results superimposed for the K^+K^- (a), (b); $K^+\pi^-$ (c), (d); $\pi^+\pi^-$ (e), (f); and $K^0\bar{K}^0$ (g), (h) events in the $M_{bc} (\Delta E)$ signal region. The blue solid curves represent the fit results, in which the red dot-dashed (grey dashed) curves represent signal (continuum background). The green dotted curves in the $K^-\pi^+$ plot represent the K^+K^- cross feed.

a significance of 5.8σ . The signal significance is defined by $\Sigma = \sqrt{2 \ln(\mathcal{L}_{\max}/\mathcal{L}_0)}$, where $\mathcal{L}_{\max}(\mathcal{L}_0)$ is the likelihood value at its maximum (with zero signal yield) 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.

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	$\epsilon(\%)$	$\mathcal{B}(10^{-5})$	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

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

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

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:

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

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.

We thank the KEKB group for the excellent operation of the accelerator, the KEK cryogenics group for the efficient operation of the solenoid, and the KEK computer group and the National Institute of Informatics for valuable computing and SINET3 network support. We acknowledge support from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan, the Japan Society for the Promotion of Science (JSPS), and the Tau-Lepton Physics Research Center of Nagoya University; the Australian Research Council and the Australian Department of Industry, Innovation, Science and Research; the National Natural Science Foundation of China under Contracts No. 10575109, No. 10775142, No. 10875115, and No. 10825524; the Department of Science and Technology of India; the BK21 and WCU program of the Ministry Education Science and Technology, the CHEP SRC program, and Basic Research program (Grant No. R01-2008-000-10477-0) of the Korea Science and Engineering Foundation, Korea Research Foundation (KRF-2008-313-C00177), and the Korea Institute of Science and Technology Information; the Polish Ministry of Science and Higher Education; the Ministry of Education and Science of the Russian Federation and the Russian Federal Agency for Atomic Energy; the Slovenian Research Agency; the Swiss National Science Foundation; the National Science Council and the Ministry of Education of Taiwan; and the U.S. Department of Energy. This work is supported by a Grant-in-Aid from MEXT for Science Research in a Priority Area (“New Development of Flavor Physics”), and from JSPS for Creative Scientific Research (“Evolution of Tau-lepton Physics”).

- [1] S.-W. Lin *et al.* (Belle Collaboration), *Nature (London)* **452**, 332 (2008).
- [2] The inclusion of charge-conjugate modes is implied throughout this paper unless explicitly stated.
- [3] C.-W. Chiang, M. Gronau, J. L. Rosner, and D. A. Suprun, *Phys. Rev. D* **70**, 034020 (2004); Y.-Y. Charng and H.-N. Li, *Phys. Rev. D* **71**, 014036 (2005).
- [4] W.-S. Hou, M. Nagashima, and A. Soddu, *Phys. Rev. Lett.* **95**, 141601 (2005).
- [5] S. Baek, P. Hamel, D. London, A. Datta, and D. A. Suprun, *Phys. Rev. D* **71**, 057502 (2005).
- [6] D. London, J. Matias, and J. Virto, *Phys. Rev. D* **71**, 014024 (2005); H.J. Lipkin, *Phys. Lett. B* **621**, 126 (2005).
- [7] R. Fleischer, *Phys. Lett. B* **459**, 306 (1999).
- [8] S. Descotes-Genon, J. Matias, and J. Virto, *Phys. Rev. Lett.* **97**, 061801 (2006).
- [9] M. Gronau and J. L. Rosner, *Phys. Lett. B* **482**, 71 (2000).
- [10] CDF public note in http://www-cdf.fnal.gov/physics/new/bottom/080724.blessed-tagged_BsJpsiPhi_update_prelim_public_note.pdf; V.M. Abazov *et al.* (D0 Collaboration), *Phys. Rev. Lett.* **101**, 241801 (2008). The combined CDF and D0 results are documented in http://www-cdf.fnal.gov/physics/new/bottom/090721.blessed-betas_combination2.8/D0Note5928_CDFNote9787.pdf.
- [11] A. Abulencia *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **97**, 211802 (2006).
- [12] M. Morello *et al.* (CDF Collaboration), *Nucl. Phys. B, Proc. Suppl.* **170**, 39 (2007).
- [13] T. Aaltonen *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **103**, 031801 (2009).
- [14] A. Drutskoy *et al.* (Belle Collaboration), *Phys. Rev. D* **76**, 012002 (2007).
- [15] S. Kurokawa and E. Kikutani, *Nucl. Instrum. Methods Phys. Res., Sect. A* **499**, 1 (2003).
- [16] K.-F. Chen *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **100**, 112001 (2008). We obtain $\sqrt{s} = m_{Y(1S)} + \Delta M$, where $m_{Y(1S)}$ is the nominal $Y(1S)$ mass [30] and ΔM is the measured $M_{\mu^+\mu^-\pi^+\pi^-} - M_{\mu^+\mu^-}$.
- [17] The cross section (σ) of light quark pair production, $e^+e^- \rightarrow q\bar{q}$, is estimated using the leading-order calculation, $\sigma = [(N_c Q_f^2 4\pi\alpha^2)/(3s)]\beta[1 + \frac{1-\beta^2}{2}]$, where N_c is the number of colors, Q_f is the charge of the quark, α is the fine structure constant, s is the total energy squared, and β is the 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.
- [18] A. Drutskoy *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **98**, 052001 (2007); G.S. Huang *et al.* (CLEO Collaboration) *Phys. Rev. D* **75**, 012002 (2007). These two published values of $\sigma_{b\bar{b}}^{Y(5S)}$ are averaged. Experimental f_s values are also given by both of them; the average is given in Ref. [30].
- [19] R. Louvot *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **102**, 021801 (2009).
- [20] A. Abashian *et al.* (Belle Collaboration), *Nucl. Instrum. Methods Phys. Res., Sect. A* **479**, 117 (2002).
- [21] E. Nakano, *Nucl. Instrum. Methods Phys. Res., Sect. A* **494**, 402 (2002).
- [22] The K_s^0 selection is described in K.-F. Chen *et al.* (Belle Collaboration), *Phys. Rev. D* **72**, 012004 (2005).
- [23] R. Brun *et al.*, GEANT 3.21, CERN Report No. DD/EE/84-1, 1987.
- [24] R. A. Fisher, *Ann. Eugenics* **7**, 179 (1936).
- [25] The Fox-Wolfram moments were introduced in G. C. Fox and S. Wolfram, *Phys. Rev. Lett.* **41**, 1581 (1978). The modified moments used in this paper are described in S. H. Lee *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **91**, 261801 (2003).
- [26] For the \mathcal{R} selection, we use a value close to the CDF measurement [12] for $\mathcal{B}(B_s^0 \rightarrow K^+ K^-)$. For $B_s^0 \rightarrow K^- \pi^+$ and $B_s^0 \rightarrow K^0 \bar{K}^0$, we naively assume that by replacing a spectator s quark with a d quark we should obtain branching fractions similar to those of $B_d^0 \rightarrow \pi^+ \pi^-$ and $B_d^0 \rightarrow K^0 \pi^0$, respectively. The decay $B_s^0 \rightarrow \pi^+ \pi^-$ is Okubo-Zweig-Iizuka suppressed and the branching fraction should be 1 to 2 orders of magnitude smaller than that of the other three modes. We also compared our assumed values for the four decay modes with theoretical predictions, given in H.-Y. Cheng and C.-K. Chua, *Phys. Rev. D* **80**, 114026 (2009). No significant deviations were observed.
- [27] A. Drutskoy *et al.* (Belle Collaboration), *Phys. Rev. D* **81**, 112003 (2010). Although a majority of the remaining 9.2% are estimated to be due to initial-state-radiation events, $Y(5S) \rightarrow B\bar{B}\pi\pi$ decays give kinematic distributions of $B\bar{B}$ that are similar and sufficient for the purposes of background estimation.
- [28] H. Albrecht *et al.* (ARGUS Collaboration), *Phys. Lett. B* **241**, 278 (1990).
- [29] Y.-T. Tsai *et al.* (Belle Collaboration), *Phys. Rev. D* **75**, 111101(R) (2007).
- [30] C. Amsler *et al.* (Particle Data Group), *Phys. Lett. B* **667**, 1 (2008).