Observation of $B_s^0 \to J/\psi f_0(980)$ and Evidence for $B_s^0 \to J/\psi f_0(1370)$

J. Li,[42] H. Aihara,[49] K. Arinstein,[1,35] V. Aulchenko,[1,35] T. Aushev,[21,14] T. Aziz,[45] A. M. Bakich,[44] V. Balagura,[14]
E. Barberio,[25] K. Belous,[13] V. Bhardwaj,[37] B. Bhuyan,[11] A. Bozek,[31] M. Bračko,[23,15] O. Brovchenko,[17] T. E. Browder,[8]
P. Chang,[30] A. Chen,[28] P. Chen,[30] B. G. Cheon,[7] C.-C. Chiang,[30] R. Chistov,[14] I.-S. Cho,[55] K. Cho,[18] S.-K. Choi,[6]
Y. Choi,[43] J. Dalseno,[24,46] Z. Doležal,[2] A. Drutskoy,[3] S. Eidelman,[1,35] S. Esen,[3] M. Feindt,[17] V. Gaur,[45] N. Gabyshev,[1,35]
A. Garmash,[1,35] B. Golob,[22,15] H. Ha,[19] J. Haba,[9] T. Hara,[9] H. Hayashii,[27] Y. Horii,[48] Y. Hoshi,[47] W.-S. Hou,[30]
Y. B. Hsiung,[30] H. J. Hyun,[20] T. Iijima,[26] A. Ishikawa,[40] R. Itoh,[9] Y. Iwasaki,[9] T. Iwashita,[27] T. Julius,[25] J. H. Kang,[55]
P. Kapusta,[31] N. Katayama,[9] T. Kawasaki,[33] H. Kichimi,[9] C. Kiesling,[24] H. J. Kim,[20] H. O. Kim,[20] M. J. Kim,[20]
S. K. Kim,[42] Y. J. Kim,[18] K. Kinoshita,[3] B. R. Ko,[19] N. Kobayashi,[38,50] S. Korpar,[23,15] P. Križan,[22,15] T. Kuhr,[17]
R. Kumar,[37] T. Kumita,[51] A. Kuzmin,[1,35] Y.-J. Kwon,[55] J. S. Lange,[4] M. J. Lee,[42] S.-H. Lee,[19] C.-L. Lim,[55] C. Liu,[41]
D. Liventsev,[14] R. Louvot,[21] J. MacNaughton,[9] A. Matyja,[31] S. McOnie,[44] K. Miyabayashi,[27] H. Miyata,[33] Y. Miyazaki,[26]
G. B. Mohanty,[45] A. Moll,[24,46] E. Nakano,[36] M. Nakao,[9] H. Nakazawa,[28] Z. Natkaniec,[31] S. Neubauer,[17] S. Nishida,[9]
K. Nishimura,[8] O. Nitoh,[52] T. Nozaki,[9] T. Ohshima,[26] S. Okuno,[16] S. L. Olsen,[42,8] P. Pakhlov,[14] G. Pakhlova,[14]
C. W. Park,[43] H. Park,[20] H. K. Park,[20] R. Pestotnik,[15] M. Petrič,[15] L. E. Piilonen,[53] A. Poluektov,[1,35] M. Prim,[17]
K. Prothmann,[24,46] M. Röhrken,[17] M. Rozanska,[31] S. Ryu,[42] H. Sahoo,[8] Y. Sakai,[9] O. Schneider,[21] C. Schwanda,[12]
A. J. Schwartz,[3] R. Seidl,[39] K. Senyo,[26] M. E. Sevior,[25] M. Shapkin,[13] V. Shebalin,[1,35] C. P. Shen,[8] J.-G. Shiu,[30]
B. Shwartz,[1,35] F. Simon,[24,46] J. B. Singh,[37] P. Smerkol,[15] Y.-S. Sohn,[55] A. Sokolov,[13] E. Solovieva,[14] S. Stanič,[34]
M. Starič,[15] J. Stypula,[31] M. Sumihama,[38,5] T. Sumiyoshi,[51] S. Suzuki,[40] S. Tanaka,[9] Y. Teramoto,[36] K. Trabelsi,[9]
M. Uchida,[38,50] S. Uehara,[9] Y. Unno,[7] S. Uno,[9] Y. Ushiroda,[9] Y. Usov,[1,35] S. E. Vahsen,[8] G. Varner,[8] A. Vinokurova,[1,35]
A. Vossen,[10] C. H. Wang,[29] M.-Z. Wang,[30] M. Watanabe,[33] Y. Watanabe,[16] J. Wicht,[9] K. M. Williams,[53]
E. Won,[19] B. D. Yabsley,[44] Y. Yamashita,[32] D. Zander,[17] C. C. Zhang,[56] Z. P. Zhang,[41] V. Zhilich,[1,35] P. Zhou,[54]
V. Zhulanov,[1,35] and A. Zupanc[17]

(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]*Justus-Liebig-Universität Gießen, Gießen*
[5]*Gifu University, Gifu*
[6]*Gyeongsang National University, Chinju*
[7]*Hanyang University, Seoul*
[8]*University of Hawaii, Honolulu, Hawaii 96822*
[9]*High Energy Accelerator Research Organization (KEK), Tsukuba*
[10]*University of Illinois at Urbana-Champaign, Urbana, Illinois 61801*
[11]*Indian Institute of Technology Guwahati, Guwahati*
[12]*Institute of High Energy Physics, Vienna*
[13]*Institute of High Energy Physics, Protvino*
[14]*Institute for Theoretical and Experimental Physics, Moscow*
[15]*J. Stefan Institute, Ljubljana*
[16]*Kanagawa University, Yokohama*
[17]*Institut für Experimentelle Kernphysik, Karlsruher Institut für Technologie, Karlsruhe*
[18]*Korea Institute of Science and Technology Information, Daejeon*
[19]*Korea University, Seoul*
[20]*Kyungpook National University, Taegu*
[21]*École Polytechnique Fédérale de Lausanne (EPFL), Lausanne*
[22]*Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana*
[23]*University of Maribor, Maribor*
[24]*Max-Planck-Institut für Physik, München*
[25]*University of Melbourne, School of Physics, Victoria 3010*
[26]*Nagoya University, Nagoya*
[27]*Nara Women's University, Nara*
[28]*National Central University, Chung-li*
[29]*National United University, Miao Li*

^{30}Department of Physics, National Taiwan University, Taipei
^{31}H. Niewodniczanski Institute of Nuclear Physics, Krakow
^{32}Nippon Dental University, Niigata
^{33}Niigata University, Niigata
^{34}University of Nova Gorica, Nova Gorica
^{35}Novosibirsk State University, Novosibirsk
^{36}Osaka City University, Osaka
^{37}Panjab University, Chandigarh
^{38}Research Center for Nuclear Physics, Osaka
^{39}RIKEN BNL Research Center, Upton, New York 11973
^{40}Saga University, Saga
^{41}University of Science and Technology of China, Hefei
^{42}Seoul National University, Seoul
^{43}Sungkyunkwan University, Suwon
^{44}School of Physics, University of Sydney, New South Wales 2006
^{45}Tata Institute of Fundamental Research, Mumbai
^{46}Excellence Cluster Universe, Technische Universität München, Garching
^{47}Tohoku Gakuin University, Tagajo
^{48}Tohoku University, Sendai
^{49}Department of Physics, University of Tokyo, Tokyo
^{50}Tokyo Institute of Technology, Tokyo
^{51}Tokyo Metropolitan University, Tokyo
^{52}Tokyo University of Agriculture and Technology, Tokyo
^{53}CNP, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
^{54}Wayne State University, Detroit, Michigan 48202
^{55}Yonsei University, Seoul
^{56}Institute of High Energy Physics, Chinese Academy of Sciences, Beijing
(Received 14 February 2011; published 23 March 2011)

We report the observation of $B_s^0 \rightarrow J/\psi f_0(980)$ and evidence for $B_s^0 \rightarrow J/\psi f_0(1370)$, which are CP eigenstate decay modes. These results are obtained from 121.4 fb^{-1} of data collected at the $\Upsilon(5S)$ resonance with the Belle detector at the KEKB e^+e^- collider. We measure the branching fractions $\mathcal{B}(B_s^0 \rightarrow J/\psi f_0(980); f_0(980) \rightarrow \pi^+\pi^-) = (1.16^{+0.31}_{-0.19}(\mathrm{stat})^{+0.15}_{-0.17}(\mathrm{syst})^{+0.26}_{-0.18}(N_{B_s^{(*)}\bar{B}_s^{(*)}})) \times 10^{-4}$ with a significance of 8.4σ, and $\mathcal{B}(B_s^0 \rightarrow J/\psi f_0(1370); f_0(1370) \rightarrow \pi^+\pi^-) = (0.34^{+0.11}_{-0.14}(\mathrm{stat})^{+0.03}_{-0.02}(\mathrm{syst})^{+0.08}_{-0.05}(N_{B_s^{(*)}\bar{B}_s^{(*)}})) \times 10^{-4}$ with a significance of 4.2σ. The last error listed is due to uncertainty in the number of produced $B_s^{(*)}\bar{B}_s^{(*)}$ pairs.

The $b \rightarrow c\bar{c}s$ process $B_s^0 \rightarrow J/\psi\phi$, which has a relatively large branching fraction, has been used to extract the B_s^0 decay width difference $\Delta\Gamma$ and CP-violating phase β_s from time-dependent angular analyses [1]. The parameter β_s is expected to be small in the standard model and can be sensitive to new physics (NP). The same $b \rightarrow c\bar{c}s$ process can also produce the decay $B_s^0 \rightarrow J/\psi f_0(980)$ [2], which is another promising channel for accessing the CP violation parameter, with the clear advantage that no angular analysis is required because the $J^P = 0^+$ quantum numbers of the $f_0(980)$ restrict the J/ψ and $f_0(980)$ to be in a relative P wave in contrast to a vector-vector channel such as $B_s \rightarrow J/\psi\phi$ in which three partial waves are allowed.

A recent study [3] also shows that measurement of the branching fraction $\mathcal{B}(B_s^0 \rightarrow J/\psi f_0(980))$ can be used to estimate the background from $B_s^0 \rightarrow J/\psi f_0(980)$, $f_0 \rightarrow K^-K^+$ decays and the corresponding bias in the $B_s \rightarrow J/\psi\phi$, $\phi \rightarrow K^-K^+$ analysis of β_s, the CP violation parameter relevant to NP searches. Leading-order light-cone QCD predicts that $\mathcal{B}(B_s^0 \rightarrow J/\psi f_0(980)) = (3.1 \pm 2.4) \times 10^{-4}$ [4].

The ratio $\mathcal{R}_{f_0/\phi} = \frac{\Gamma(B_s^0 \rightarrow J/\psi f_0(980); f_0(980) \rightarrow \pi^+\pi^-)}{\Gamma(B_s^0 \rightarrow J/\psi\phi; \phi \rightarrow K^+K^-)}$ is expected to lie in the range $0.2 \lesssim \mathcal{R}_{f_0/\phi} \lesssim 0.5$, based on scaling from the measurements of D_s decays to f_0 and ϕ mesons [2,5]. Using the value $\mathcal{B}(B_s^0 \rightarrow J/\psi\phi) = (1.3 \pm 0.4 \pm 0.2) \times 10^{-3}$ [6], we obtain $1.3 \times 10^{-4} \lesssim \mathcal{B}(B_s^0 \rightarrow J/\psi f_0(980); f_0(980) \rightarrow \pi^+\pi^-) \lesssim 3.2 \times 10^{-4}$.

We study $B_s^0 \rightarrow J/\psi f_0(980)$ in fully reconstructed $B_s^0 \rightarrow J/\psi\pi^+\pi^-$ final states using a 121.4 fb^{-1} data sample collected at the $\Upsilon(5S)$ resonance with the Belle detector at the KEKB collider [7]. B_s^0 mesons can be produced in three $\Upsilon(5S)$ decays: $\Upsilon(5S) \rightarrow B_s^*\bar{B}_s^*$, $B_s^*\bar{B}_s^0$, and $B_s^0\bar{B}_s^0$ where the B_s^* mesons decay to $B_s^0\gamma$. The number of $B_s^{(*)}\bar{B}_s^{(*)}$ pairs in the sample is measured to be $N_{B_s^{(*)}\bar{B}_s^{(*)}} = (7.1 \pm 1.3) \times 10^6$ using inclusive D_s production methods described in [8,9]. Using fully reconstructed $B_s^0 \rightarrow D_s^-\pi^+$ decays as described in [10], we determine the fraction of $B_s^*\bar{B}_s^*$ pairs among all $B_s^{(*)}\bar{B}_s^{(*)}$ events to be $f_{B_s^*\bar{B}_s^*} = (87.0 \pm 1.7)\%$ in the sample. The number of B_s^0 mesons

in the dominant $B_s^* \bar{B}_s^*$ production mode is thus $N_{B_s^0} = 2N_{B_s^{(*)} \bar{B}_s^{(*)}} f_{B_s^* \bar{B}_s^*} = (1.24 \pm 0.23) \times 10^7$.

The Belle detector [11] 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 (ECL) 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 the coil is instrumented to detect K_L^0 mesons and identify muons (KLM).

Charged tracks are required to originate within 0.5 cm in the radial direction and within 5 cm along the beam direction with respect to the interaction point in the cylindrical geometry of the Belle detector. Electrons or charged pions are identified by combining information from the ECL or TOF, the CDC (dE/dx), and the ACC [11]. Muon candidates are identified through their track penetration depth and hit patterns in the KLM system. For both electrons and muons, the identification efficiency is nearly 100%. For a pion from $B_s^0 \to J/\psi f_0(980)$, the momentum-averaged identification efficiency is about 96% with a 22% kaon misidentification probability.

Two oppositely charged leptons $l^+ l^-$ ($l = e$ or μ) and any bremsstrahlung photons lying within 50 mrad of an e^+ or e^- track are combined to form a J/ψ candidate. The invariant mass is required to lie in the ranges $-0.150 \text{ GeV}/c^2 < M_{ee(\gamma)} - m_{J/\psi} < 0.036 \text{ GeV}/c^2$ or $-0.060 \text{ GeV}/c^2 < M_{\mu\mu} - m_{J/\psi} < 0.036 \text{ GeV}/c^2$, where $m_{J/\psi}$ denotes the J/ψ mass, and $M_{ee(\gamma)}$ or $M_{\mu\mu}$ is the reconstructed invariant mass for $e^+ e^-(\gamma)$ or $\mu^+ \mu^-$, respectively. We combine the J/ψ candidate and a $\pi^+ \pi^-$ pair to form a B_s^0 candidate. The $\pi^+ \pi^-$ and J/ψ vertex positions are required to be consistent.

Two kinematic variables are computed in the $e^+ e^-$ collision rest frame: the energy difference $\Delta E = E_B^* - E_{\text{beam}}$, and the beam-energy constrained mass $M_{\text{bc}} = \sqrt{(E_{\text{beam}})^2 - (p_B^*)^2}$, where E_B^* and p_B^* are the energy and momentum of the reconstructed B_s^0 candidates and E_{beam} is the beam energy. To improve the ΔE and M_{bc} resolutions, mass-constrained kinematic fits are applied to J/ψ candidates. After an initial loose selection, 66% of events have multiple candidates. From these we choose the candidate with the M_{bc} value closest to the nominal B_s^* mass. This requirement has an efficiency of 90% for the correctly reconstructed signal in the $\Upsilon(5S) \to B_s^* \bar{B}_s^*$ channel, according to Monte Carlo (MC) simulations. We then select events that lie inside a 3σ M_{bc} signal region for $B_s^* \bar{B}_s^*$ with the criterion $5.4041 \text{ GeV}/c^2 < M_{\text{bc}} < 5.4275 \text{ GeV}/c^2$, which completely rejects the small $\Upsilon(5S) \to B_s^{(*)} \bar{B}_s$ contribution and retains only candidates from the dominant $\Upsilon(5S) \to B_s^* \bar{B}_s^*$ production process. We use ΔE and the $\pi^+ \pi^-$ invariant mass $M_{\pi\pi}$ to extract the signal.

To suppress two-jet-like continuum background arising from $e^+ e^- \to q\bar{q}$ ($q = u, d, s, c$) processes, we require the ratio of the second to zeroth Fox-Wolfram moments [12] to be less than 0.4. This requirement is optimized by maximizing the figure of merit $N_S/\sqrt{N_S + N_B}$, where N_S is the expected number of signal events and N_B is the expected number of background events in the (ΔE, $M_{\pi\pi}$) signal box. Other significant background sources are from $B\bar{B}$ ($B \equiv B_s^0, B_d^0, B_u^\pm$) events with one B meson decaying to a final state with a J/ψ (denoted $J/\psi X$). We use a sample of simulated $\Upsilon(5S)$ decays, with the most recent B meson pair production rates [13] and all known $B \to J/\psi X$ processes, to estimate this background. The fit region is chosen to be $-0.1 \text{ GeV} < \Delta E < 0.2 \text{ GeV}$ and $M_{\pi\pi} < 2.0 \text{ GeV}/c^2$. Background from $B_d^0 \to J/\psi \pi^+ \pi^-$ peaks near $\Delta E = -0.14 \text{ GeV}$ and lies entirely outside the fit region.

A study of the $J/\psi X$ MC simulation is used to categorize these background components according to their origins and shapes. The expected yields in the fit region from each source are (a) $B_s^0 \to J/\psi \eta'$, 2.6 events, with $\eta' \to \rho^0 \gamma$ in which the photon is lost, (b) $B^+ \to J/\psi (K^+, \pi^+)$, 45.3 events, which enter the fit region after combining with a random pion, and (c) other $J/\psi X$ sources, 240.4 events, that do not peak in ΔE and $M_{\pi\pi}$. There are negligible correlations between ΔE and $M_{\pi\pi}$ for (b) and (c), which are parametrized by the product of a smooth ΔE function with a threshold $M_{\pi\pi}$ function for the two-dimensional probability density function (PDF). The $B^+ \to J/\psi K^+$ and $B^+ \to J/\psi \pi^+$ background shapes are treated separately. For (a), the shape and yield are obtained from a dedicated MC simulation and the measured branching fraction [14], where a MC-generated two-dimensional PDF is used, since there are correlations between ΔE and $M_{\pi\pi}$ that are difficult to parametrize analytically. The non-J/ψ background is studied with data from a J/ψ mass ($M_{ll(\gamma)}$) sideband defined as $2.5 \text{ GeV}/c^2 < M_{ll(\gamma)} < 3.4 \text{ GeV}/c^2$, with the regions $-0.200(-0.080) \text{ GeV}/c^2 < M_{ll(\gamma)} - m_{J/\psi} < 0.048 \text{ GeV}/c^2$ for $J/\psi \to e^+ e^- (\mu^+ \mu^-)$ excluded. MC-determined scale factors 0.226 (0.097) for the ratio of the non-J/ψ yield in the J/ψ selection window to the yield in the J/ψ sideband region are used in the ee ($\mu\mu$) channels. We fix the non-J/ψ background yield to 122.7 in the fit region. The non-J/ψ background shape is obtained by fitting the J/ψ sideband data with relaxed lepton identification requirements to enhance the statistics.

Figure 1 shows the data together with the fitting function. The $M_{\pi\pi}$ distribution in Fig. 1(a) includes a selection on the ΔE signal region, which has a width of 60 MeV; this is much narrower than the width of the ΔE fit region, 300 MeV. We find two peaks in the $M_{\pi\pi}$ spectrum of the events in the ΔE signal region: one for $f_0(980)$ and another around 1.4 GeV/c^2. We model the signal $M_{\pi\pi}$ PDF as a coherent sum of a Flatté function [15] for the $f_0(980)$ resonance and a relativistic Breit-Wigner function for a second f_X resonance with mass $m_0(f_X)$ and width $\Gamma_0(f_X)$:
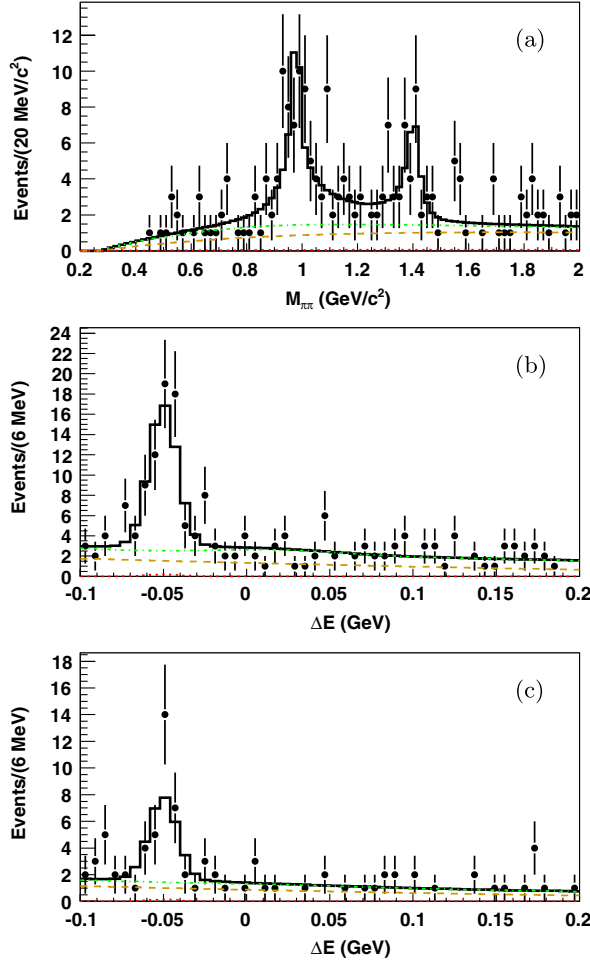
FIG. 1 (color online). Data fit projections to $M_{\pi\pi}$ for (a) -79.7 MeV $< \Delta E < -19.7$ MeV, and to ΔE for (b) 0.80 GeV/c^2 $< M_{\pi\pi} <$ 1.16 GeV/c^2 and (c) 1.3 GeV/$c^2 <$ $M_{\pi\pi} <$ 1.5 GeV/c^2. The total PDF is shown with a solid line. The dash-dotted curves represent the total background, and the dashed curves show other J/ψ background. The dotted curves are the nonresonant components, which are barely visible due to the smallness of their yields.

$$P(M_{\pi\pi}) = p_{J/\psi} \left| \frac{p_{J/\psi}\sqrt{M_{\pi\pi}\Gamma_1}}{m_0(f_0)^2 - M_{\pi\pi}^2 - i(g_1\rho_1 + g_2\rho_2)} \right.$$
$$\left. + ae^{i\theta}\frac{p_{J/\psi}\sqrt{M_{\pi\pi}\Gamma(f_X)}}{m_0(f_X)^2 - M_{\pi\pi}^2 - im_0(f_X)\Gamma(f_X)} \right|^2,$$
(1)

where the phase-space factors are $\rho_1 = 2q/M_{\pi\pi}$, $\rho_2 = 2q_K/M_{\pi\pi}$, and the mass-dependent widths are $\Gamma_1 = g_1\rho_1/m_0$ and $\Gamma(f_X) = \Gamma_0(f_X)(q/q_0)(m_0(f_X)/M_{\pi\pi})$. Here q (or q_0) is the pion momentum in the di-pion rest frame where the di-pion mass is $M_{\pi\pi}$ (m_0), while q_K is the momentum a kaon would have if the resonance decayed to a kaon pair. The J/ψ momentum in the B_s^0 rest frame $p_{J/\psi}$ is a phase-space factor outside the modulus, and a spin factor inside the modulus for $L = 1$. The Flatté function follows the BES parametrization [16], with the

parameters $m_0(f_0) = 965 \pm 10$ MeV/c^2, $g_1 = 0.165 \pm 0.018$ GeV$^2/c^4$, and $g_2/g_1 = 4.21 \pm 0.33$. The ΔE PDF for the signal is parametrized as a sum of two Gaussians with widths calibrated using a control sample of $\Upsilon(5S) \to B_d^{*0}\bar{B}_d^{*0}$, $B_d^0 \to J/\psi K^{*0}(K^+\pi^-)$ in data.

Contributions from the self-cross-feed (SCF) events in which one or two pion tracks from the signal are misreconstructed as well as nonresonant $B_s^0 \to J/\psi\pi^+\pi^-$ events are also considered. The SCF component is fixed to the MC value of 6.0% of the total signal yield in the fit region; the PDF shape is modeled with a nonparametric histogram. For the nonresonant component, the $M_{\pi\pi}$ shape is obtained from a phase-space model and the ΔE shape is the same as that of the $J/\psi f_0$ signal.

An unbinned extended maximum likelihood fit to the data is performed using the sum of all component PDFs. The parameters allowed to vary in the fit are the total resonant signal yield, which includes the SCF contribution, parameters a, θ, $m_0(f_X)$, $\Gamma_0(f_X)$, the yield of the nonresonant component, and the yield of other $J/\psi X$ background. The yield of the $J/\psi(K, \pi)$ background is fixed to the MC expectation.

We obtain 98 ± 15 resonant events corresponding to Eq. (1), where 63^{+16}_{-10} are from $B_s^0 \to J/\psi f_0(980)$ and 19^{+6}_{-8} are from $B_s^0 \to J/\psi f_X$, and the rest are from the interference. The yield for each signal component is calculated using the amplitude squared of that component divided by the coherent sum of all amplitudes squared, with statistical errors obtained from error propagation using the covariance matrix of relevant parameters. The amplitude and phase parameters are determined to be $a = 0.47 \pm 0.10$ and $\theta = 1.63 \pm 0.98$ rad. The fitted mass and width for the f_X component are $m_0 = 1.405 \pm 0.015^{+0.001}_{-0.007}$ GeV/c^2 and $\Gamma_0 = 0.054 \pm 0.033^{+0.014}_{-0.003}$ GeV, where the first error is statistical and the second is systematic. These results are consistent with the $f_0(1370)$ parameters listed in the Particle Data Group [17]. Henceforth, we refer to this contribution as $B_s^0 \to J/\psi f_0(1370)$, however, the possibility of other scalar resonance contributions in

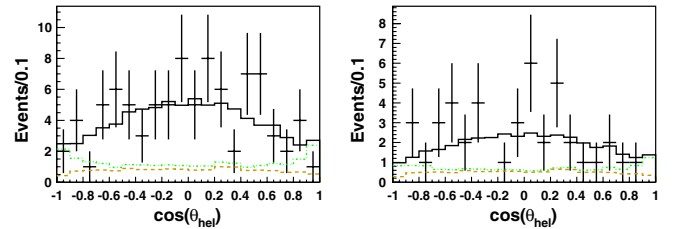FIG. 2 (color online). The cosine of the angle θ_{hel} between l^+ and the direction opposite to that of the B_s^0 in the J/ψ rest frame. $\cos(\theta_{\text{hel}})$ is projected in the ΔE signal region and $f_0(980)$ and $f_0(1370)$ signal regions as 0.80 GeV/c^2 $< M_{\pi\pi} <$ 1.16 GeV/c^2 (left) and 1.3 GeV/c^2 $< M_{\pi\pi} <$ 1.5 GeV/c^2 (right). The expected distributions from the fit assuming a longitudinally polarized J/ψ, which would result from a $B_s^0 \to J/\psi +$ scalar decay, are superimposed. The curves follow the convention in Fig. 1.

TABLE I. Summary of signal yields, significances, and product branching fractions $\mathcal{B}(B_s^0 \to J/\psi F; F \to \pi^+ \pi^-)$, where $F = f_0(980)$ or $f_0(1370)$.

Mode	Yield	Significance	$\mathcal{B}(B_s^0 \to J/\psi F; F \to \pi^+ \pi^-)$
$B_s^0 \to J/\psi f_0(980)$	63^{+16}_{-10}	8.4σ	$(1.16^{+0.31}_{-0.19}(\text{stat})^{+0.15}_{-0.17}(\text{syst})^{+0.26}_{-0.18}(N_{B_s^{(*)}\bar{B}_s^{(*)}})) \times 10^{-4}$
$B_s^0 \to J/\psi f_0(1370)$	19^{+6}_{-8}	4.2σ	$(0.34^{+0.11}_{-0.14}(\text{stat})^{+0.03}_{-0.02}(\text{syst})^{+0.08}_{-0.05}(N_{B_s^{(*)}\bar{B}_s^{(*)}})) \times 10^{-4}$

TABLE II. Relative systematic errors (in %) for $\mathcal{B}(B_s^0 \to J/\psi F; F \to \pi^+ \pi^-)$.

Source	$\mathcal{B}(F = f_0(980))$	$\mathcal{B}(F = f_0(1370))$
ΔE shape	1.0	$+0.8, -0.6$
$f_0(980)$ shape	$+12.4, -13.6$	$+8.9, -5.3$
Background parameters	$+1.9, -1.7$	$+1.0, -0.4$
Track reconstruction	1.3	
Lepton identification	2.6	
Pion identification	1.6	
$\mathcal{B}(J/\psi \to ll)$	0.7	
$f_{B_s^*\bar{B}_s^*}$	2.0	
$N_{B_s^{(*)}\bar{B}_s^{(*)}}$	$+22.4, -15.5$	
Total	$+26.0, -21.1$	$+24.5, -16.8$

this region cannot be excluded with the present statistics. The obtained nonresonant yield is 4 ± 12, consistent with zero. The yield of other J/ψ background 262 ± 23 is consistent with the MC estimate of 240 events. The J/ψ helicity distributions, shown in Fig. 2, are consistent with a longitudinally polarized J/ψ in both $f_0(980)$ and $f_0(1370)$ signal regions, as expected for scalar $\pi\pi$ resonances.

The signal yields, branching fractions, and significances including systematic uncertainties are listed in Table I. The significance is calculated from the log likelihood difference for two parameters in the $f_0(980)$ case and four parameters in the $f_0(1370)$ case, when the corresponding signal amplitude is set to zero.

Contributions to the systematic error are obtained by varying each fixed parameter by its error and are summarized in Table II. Apart from the $N_{B_s^*\bar{B}_s^*}$ normalization, the largest systematic effect arises from the uncertainties of the Flatté parameters for the $f_0(980)$ line shape, where the parameters are varied according to errors in [16]. For the signal ΔE shape, the error on the mean value is determined from the beam energy calibrated with $\Upsilon(5S) \to \Upsilon(1S)\pi\pi$ and $B_s^0 \to D_s\pi$, and the error on the width is determined from the control sample. The yields of the $B_s^0 \to J/\psi \eta'$ and $B^+ \to J/\psi(K^+, \pi^+)$ components are varied according to the experimental errors on their branching fractions. Finally, the non-J/ψ background parameters are varied according to the results of the J/ψ sideband study. Other background shape uncertainties are negligible.

In summary, we report the observation of $B_s^0 \to J/\psi f_0(980)$ and evidence for $B_s^0 \to J/\psi f_0(1370)$. The measured $B_s^0 \to J/\psi f_0(980)$ branching fraction is in agreement with the estimate $1.3 \times 10^{-4} \lesssim \mathcal{B}(B_s^0 \to J/\psi f_0(980); f_0(980) \to \pi^+ \pi^-) \lesssim 3.2 \times 10^{-4}$. The signal for $B_s^0 \to J/\psi f_0(1370)$ has a significance of 4.2σ.

This mode represents a new CP channel that can be used to study B_s^0 mixing properties.

Note added.—While preparing the final version of this manuscript, we became aware that the LHCb Collaboration reports similar results for $B_s^0 \to J/\psi f_0(980)$ [18].

[1] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **100,** 161802 (2008); V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **101,** 241801 (2008).
[2] S. Stone and L. Zhang, Phys. Rev. D **79,** 074024 (2009).
[3] O. Leitner, J. P. Dedonder, B. Loiseau, and B. El-Bennich, Phys. Rev. D **82,** 076006 (2010).
[4] P. Colangelo, F. De Fazio, and W. Wang, Phys. Rev. D **81,** 074001 (2010).
[5] K. M. Ecklund *et al.* (CLEO Collaboration), Phys. Rev. D **80,** 052009 (2009).
[6] F. Abe *et al.* (CDF Collaboration), Phys. Rev. D **54,** 6596 (1996).
[7] S. Kurokawa and E. Kikutani, Nucl. Instrum. Methods Phys. Res., Sect. A **499,** 1 (2003), and other papers included in this volume.
[8] M. Artuso *et al.* (CLEO Collaboration), Phys. Rev. Lett. **95,** 261801 (2005).
[9] A. Drutskoy *et al.* (Belle Collaboration), Phys. Rev. Lett. **98,** 052001 (2007).
[10] R. Louvot *et al.* (Belle Collaboration), Phys. Rev. Lett. **102,** 021801 (2009).
[11] A. Abashian *et al.* (Belle Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **479,** 117 (2002).
[12] G. C. Fox and S. Wolfram, Phys. Rev. Lett. **41,** 1581 (1978).
[13] A. Drutskoy *et al.* (Belle Collaboration), Phys. Rev. D **81,** 112003 (2010).
[14] I. Adachi *et al.* (Belle Collaboration), arXiv:0912.1434.
[15] S. M. Flatte, Phys. Lett. B **63,** 224 (1976).
[16] M. Ablikim *et al.* (BES Collaboration), Phys. Lett. B **607,** 243 (2005).
[17] K. Nakamura *et al.* (Particle Data Group), J. Phys. G **37,** 075021 (2010).
[18] R. Aaij *et al.* (LHCb Collaboration), arXiv:1102.0206.