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Search for $B^+ \to J/\psi\eta' K^+$ and $B^0 \to J/\psi\eta' K^0_S$ decays

Q. L. Xie,[10] K. Abe,[8] I. Adachi,[8] H. Aihara,[46] D. Anipko,[1] K. Arinstein,[1] V. Aulchenko,[1] T. Aushev,[18,13] T. Aziz,[42] S. Bahinipati,[4] A. M. Bakich,[41] V. Balagura,[13] E. Barberio,[21] M. Barbero,[7] A. Bay,[18] I. Bedny,[1] K. Belous,[12] U. Bitenc,[14] I. Bizjak,[14] S. Blyth,[24] A. Bozek,[27] M. Bračko,[8,14,20] T. E. Browder,[7] M.-C. Chang,[5] Y. Chao,[26] A. Chen,[24] K.-F. Chen,[26] W. T. Chen,[24] B. G. Cheon,[3] R. Chistov,[13] Y. Choi,[40] Y. K. Choi,[40] S. Cole,[41] J. Dalseno,[21] M. Dash,[50] A. Drutskoy,[4] S. Eidelman,[1] D. Epifanov,[1] N. Gabyshev,[1] T. Gershon,[8] A. Go,[24] G. Gokhroo,[42] H. Ha,[16] J. Haba,[8] K. Hayasaka,[22] H. Hayashii,[23] M. Hazumi,[8] D. Heffernan,[32] T. Hokuue,[22] Y. Hoshi,[44] S. Hou,[24] W.-S. Hou,[26] T. Iijima,[22] K. Ikado,[22] A. Imoto,[23] K. Inami,[22] A. Ishikawa,[46] H. Ishino,[47] R. Itoh,[8] M. Iwasaki,[46] Y. Iwasaki,[8] J. H. Kang,[51] P. Kapusta,[27] N. Katayama,[8] H. Kawai,[2] T. Kawasaki,[29] H. Kichimi,[8] H. J. Kim,[17] Y. J. Kim,[6] S. Korpar,[14,20] P. Križan,[14,19] P. Krokovny,[8] R. Kulasiri,[4] R. Kumar,[33] C. C. Kuo,[24] A. Kuzmin,[1] Y.-J. Kwon,[51] S. E. Lee,[38] T. Lesiak,[27] S.-W. Lin,[26] Y. Liu,[6] G. Majumder,[42] F. Mandl,[11] T. Matsumoto,[48] S. McOnie,[41] W. Mitaroff,[11] K. Miyabayashi,[23] H. Miyake,[32] H. Miyata,[29] Y. Miyazaki,[22] R. Mizuk,[13] G. R. Moloney,[21] J. Mueller,[35] Y. Nagasaka,[9] E. Nakano,[31] M. Nakao,[8] Z. Natkaniec,[27] S. Nishida,[8] O. Nitoh,[49] T. Ohshima,[22] S. Okuno,[15] S. L. Olsen,[7] Y. Onuki,[36] H. Ozaki,[8] P. Pakhlov,[13] G. Pakhlova,[13] H. Park,[17] L. S. Peak,[41] R. Pestotnik,[14] L. E. Piilonen,[50] A. Poluektov,[1] H. Sahoo,[7] Y. Sakai,[8] N. Satoyama,[39] T. Schietinger,[18] O. Schneider,[18] J. Schümann,[25] K. Senyo,[22] M. Shapkin,[12] H. Shibuya,[43] B. Shwartz,[1] V. Sidorov,[1] A. Sokolov,[12] A. Somov,[4] S. Stanič,[30] M. Starič,[14] H. Stoeck,[41] K. Sumisawa,[8] T. Sumiyoshi,[48] S. Y. Suzuki,[8] F. Takasaki,[8] K. Tamai,[8] M. Tanaka,[8] G. N. Taylor,[21] Y. Teramoto,[31] X. C. Tian,[34] K. Trabelsi,[7] T. Tsuboyama,[8] T. Tsukamoto,[8] S. Uehara,[8] T. Uglov,[13] Y. Unno,[3] S. Uno,[8] P. Urquijo,[21] Y. Usov,[1] G. Varner,[7] C. H. Wang,[25] M.-Z. Wang,[26] Y. Watanabe,[47] R. Wedd,[21] E. Won,[16] A. Yamaguchi,[45] Y. Yamashita,[28] M. Yamauchi,[8] C. C. Zhang,[10] L. M. Zhang,[37] Z. P. Zhang,[37] V. Zhilich,[1] and A. Zupanc[14]

(Belle Collaboration)

[1]*Budker Institute of Nuclear Physics, Novosibirsk*
[2]*Chiba University, Chiba*
[3]*Chonnam National University, Kwangju*
[4]*University of Cincinnati, Cincinnati, Ohio 45221*
[5]*Department of Physics, Fu Jen Catholic University, Taipei*
[6]*The Graduate University for Advanced Studies, Hayama*
[7]*University of Hawaii, Honolulu, Hawaii 96822*
[8]*High Energy Accelerator Research Organization (KEK), Tsukuba*
[9]*Hiroshima Institute of Technology, Hiroshima*
[10]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing*
[11]*Institute of High Energy Physics, Vienna*
[12]*Institute of High Energy Physics, Protvino*
[13]*Institute for Theoretical and Experimental Physics, Moscow*
[14]*J. Stefan Institute, Ljubljana*
[15]*Kanagawa University, Yokohama*
[16]*Korea University, Seoul*
[17]*Kyungpook National University, Taegu*
[18]*Swiss Federal Institute of Technology of Lausanne, EPFL, Lausanne*
[19]*University of Ljubljana, Ljubljana*
[20]*University of Maribor, Maribor*
[21]*University of Melbourne, Victoria*
[22]*Nagoya University, Nagoya*
[23]*Nara Women's University, Nara*
[24]*National Central University, Chung-li*
[25]*National United University, Miao Li*
[26]*Department of Physics, National Taiwan University, Taipei*
[27]*H. Niewodniczanski Institute of Nuclear Physics, Krakow*
[28]*Nippon Dental University, Niigata*
[29]*Niigata University, Niigata*
[30]*University of Nova Gorica, Nova Gorica*
[31]*Osaka City University, Osaka*
[32]*Osaka University, Osaka*

[33]Panjab University, Chandigarh
[34]Peking University, Beijing
[35]University of Pittsburgh, Pittsburgh, Pennsylvania 15260
[36]RIKEN BNL Research Center, Upton, New York 11973
[37]University of Science and Technology of China, Hefei
[38]Seoul National University, Seoul
[39]Shinshu University, Nagano
[40]Sungkyunkwan University, Suwon
[41]University of Sydney, Sydney NSW
[42]Tata Institute of Fundamental Research, Bombay
[43]Toho University, Funabashi
[44]Tohoku Gakuin University, Tagajo
[45]Tohoku University, Sendai
[46]Department of Physics, University of Tokyo, Tokyo
[47]Tokyo Institute of Technology, Tokyo
[48]Tokyo Metropolitan University, Tokyo
[49]Tokyo University of Agriculture and Technology, Tokyo
[50]Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
[51]Yonsei University, Seoul

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We report the results of searches for $B^+ \to J/\psi\eta' K^+$ and $B^0 \to J/\psi\eta' K_S^0$ decays, using a sample of 388×10^6 $B\bar{B}$ pairs collected with the Belle detector at the $\Upsilon(4S)$ resonance. No statistically significant signal is found for either of the two decay modes and upper limits for the branching fractions are determined to be $\mathcal{B}(B^+ \to J/\psi\eta' K^+) < 8.8 \times 10^{-5}$ and $\mathcal{B}(B^0 \to J/\psi\eta' K_S^0) < 2.5 \times 10^{-5}$ at 90% confidence level.

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Studies of exclusive B meson decays to charmonium play an important role in exploring CP violation [1] and in observations of new resonant states that include a $(c\bar{c})$ pair [2,3]. The decay $B \to J/\psi\eta' K$ proceeds via a Cabibbo-allowed and color-suppressed transition ($b \to c\bar{c}s$) with $(s\bar{s})$ quark popping. A branching fraction comparable to that of the decay $B \to J/\psi\phi K$ [4] is therefore expected.

The $B \to J/\psi\eta' K$ decay modes are of particular interest in the search for hybrid charmonium states, ψ_g, which are excited gluonic $(c\bar{c}g)$ states, which may decay to $J/\psi + (\eta^{(\prime)}, \phi)$ [5]. These hybrid states are expected to be produced in B decays such as $B \to \psi_g K$. A near-threshold $\omega J/\psi$ enhancement in $B \to K\omega J/\psi$ decays observed by Belle [3] has some properties similar to those predicted for $c\bar{c}$-gluon hybrid states [5]. A state, $Y(4260)$, recently observed by *BABAR* in $e^+e^- \to Y(4260)\gamma_{(\mathrm{ISR})}$ transitions [6], is also a candidate for such a ψ_g state [7], where $\gamma_{(\mathrm{ISR})}$ denotes an initial state radiation photon. An enhanced decay rate to $J/\psi\eta^{(\prime)}$ modes would be a supporting evidence for this assignment.

In this paper, we report results on searches for the decay modes $B^+ \to J/\psi\eta' K^+$ and $B^0 \to J/\psi\eta' K_S^0$ [8] in a sample of 357 fb^{-1} containing 388×10^6 $B\bar{B}$ pairs accumulated at the $\Upsilon(4S)$ resonance with the Belle detector [9] at the KEKB energy asymmetric e^+e^- collider [10]. These are the first results ever presented for these decay modes.

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 Čerenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL). These detectors are 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.

Candidates for these two decay modes are reconstructed with the decay chains $J/\psi \to l^+l^-$ $(l = e, \mu)$, $\eta' \to \eta\pi^+\pi^-$, $\eta \to \gamma\gamma$, and $K_S^0 \to \pi^+\pi^-$.

Events are required to pass a basic hadronic event selection [11]. To suppress continuum background ($e^+e^- \to q\bar{q}$, where $q = u, d, s, c$), we require the ratio of the second to zeroth Fox-Wolfram moments [12] to be less than 0.5 and the absolute value of the cosine of the angle between the B meson and beam direction in the center-of-mass system to be less than 0.85.

The selection criteria for the J/ψ decaying to l^+l^- are identical to those used in our previous papers [11]. J/ψ candidates are pairs of oppositely charged tracks that originate from a region within 5 cm of the nominal interaction point (IP) along the beam direction and are positively identified as leptons. In order to reduce the effect of bremsstrahlung or final state radiation, photons detected in the ECL within 0.05 radians of the original e^- or e^+ direction are included in the calculation of the $e^+e^-(\gamma)$ invariant mass. Because of the radiative low-mass tail, the J/ψ candidates are required to be within an asymmetric invariant mass window: $-150(-60)\ \mathrm{MeV}/c^2 < M_{e^+e^-(\gamma)}(M_{\mu^+\mu^-}) - m_{J/\psi} < +36(+36)\ \mathrm{MeV}/c^2$, where $m_{J/\psi}$ is the nominal J/ψ mass [13]. In order to improve the momentum resolution of the J/ψ signal, a vertex and mass constrained fit to the reconstructed J/ψ candidates is then performed and a loose cut on the vertex fit quality is applied.

In order to identify hadrons, a likelihood L_i for each hadron type i ($i = \pi$, K and p) is formed using information from the ACC, TOF and CDC (dE/dx). Charged tracks that were previously identified as electrons or muons are rejected in the hadron identification procedure. The kaon from the B meson and the pions from η' are selected with the requirements of $L_K/(L_K + L_\pi) > 0.4$ and $L_\pi/(L_\pi + L_K) > 0.1$, which have efficiencies of 82.5% and 89.4%, respectively.

The η from η' decay is reconstructed by combining two photons that do not match to any charged track. The calorimeter cluster energy, E_γ, is required to exceed 50 MeV for both photons. To veto photons from π^0, we combine each photon candidate with another photon (with $E_\gamma > 50$ MeV) and reject it if the invariant mass is consistent with a π^0: $|M_{\gamma\gamma} - m_{\pi^0}| < 18\ \mathrm{MeV}/c^2$. For η candidates, $\cos\theta^\eta_{\mathrm{hel}}$ is used to suppress background, where $\theta^\eta_{\mathrm{hel}}$ is defined as the angle between the photon momentum in the η rest frame and the boost direction of η in the laboratory frame. Signal events have a uniform $\cos\theta^\eta_{\mathrm{hel}}$ distribution, whereas random photon pairs have a distribution that peaks near ±1. We require $|\cos\theta^\eta_{\mathrm{hel}}| < 0.94$ (0.97) for charged (neutral) B decay. The invariant mass of the η candidate is required to be within $0.496\ \mathrm{MeV}/c^2 < M_{\gamma\gamma} < 0.582\ \mathrm{MeV}/c^2$ (3σ of the nominal η mass). To improve the momentum resolution of the η, we apply a mass constrained fit to the reconstructed η.

We reconstruct η' candidates by combining the η and selected $\pi^+\pi^-$ candidates. We require the invariant mass to be $0.940\ \mathrm{MeV}/c^2 < M_{\eta\pi^+\pi^-} < 0.975\ \mathrm{MeV}/c^2$. To improve the momentum resolution, we apply a vertex and mass constrained fit on the η' [14].

For K^0_S candidates, we impose momentum-dependent requirements on the impact parameters from the IP for both K^0_S daughter tracks, the distance between the daughter tracks along the beam axis at the K^0_S vertex, the difference of azimuthal angles between the K^0_S momentum and the direction of the K^0_S vertex from the IP, and the flight length of the K^0_S. The invariant mass of the K^0_S candidate is required to be within $16\ \mathrm{MeV}/c^2$ (3σ) of the K^0_S mass. We apply vertex and mass constrained fits for the K^0_S candidates to improve the momentum resolution.

These criteria maximize $N_{\mathrm{sig}}/\sqrt{N_{\mathrm{sig}} + N_{\mathrm{bkg}}}$, where N_{sig} is the number of expected signal events from signal Monte Carlo (MC) samples with assumed branching fractions of 1.0×10^{-5} for both $B^+ \to J/\psi\eta' K^+$ and $B^0 \to J/\psi\eta' K^0_S$ modes, and N_{bkg} is the number of expected background events estimated from a MC sample of $B\bar{B}$-pairs with a J/ψ in the final state.

B mesons are reconstructed by combining a J/ψ, an η' and a K candidate. We identify B candidates using two widely used kinematic variables calculated in the center-of-mass system: the beam-energy constrained mass ($M_{\mathrm{bc}} \equiv \sqrt{E^2_{\mathrm{beam}} - P^2_B}$) and the energy difference ($\Delta E \equiv E_B - E_{\mathrm{beam}}$), where E_{beam} is the beam energy, P_B and E_B are the reconstructed momentum and energy of the B candidate. We select both B^+ and B^0 candidates within the range $|\Delta E| < 0.20$ GeV and $M_{\mathrm{bc}} > 5.20\ \mathrm{GeV}/c^2$ for the final analysis. The signal regions are defined to be $5.27\ \mathrm{GeV}/c^2 < M_{\mathrm{bc}} < 5.29\ \mathrm{GeV}/c^2$ and $|\Delta E| < 0.03$ GeV for both $B^+ \to J/\psi\eta' K^+$ and $B^0 \to J/\psi\eta' K^0_S$ modes, which corresponds to 3 standard deviations based on the MC simulation.

After all selection requirements, about 26.5% of the $B^+ \to J/\psi\eta' K^+$ candidates have more than one entry per event; this occurs for 30.0% of the $B^0 \to J/\psi\eta' K^0_S$ candidates. For these events, the B candidate with the best vertex fit quality is used. From a study of MC simulated events, we conclude that around 81.5% of multiple $B^+ \to J/\psi\eta' K^+$ candidates and 70.0% of multiple $B^0 \to J/\psi\eta' K^0_S$ candidates are selected correctly by this procedure.

The signal yields are extracted by maximizing the two dimensional extended likelihood function,

$$\mathcal{L} = \frac{e^{-\sum_k N_k}}{N!} \prod_{i=1}^{N} \left[\sum_k N_k \times P_k(M^i_{\mathrm{bc}}, \Delta E^i) \right],$$

where N is the total number of candidate events, i is the identifier of the i-th event, N_k and P_k are the yield and probability density function (PDF) of the component k, which corresponds to the signal and background.

The signal PDFs for the two decay modes are modeled using a sum of two Gaussians for M_{bc} and a sum of two Gaussians plus a bifurcated Gaussian that describes the tail of the distribution in ΔE. The PDF parameters are initially determined using signal MC and subsequently the primary Gaussian parameters are corrected using a control data sample of $B^+ \to J/\psi K^{*+}$ decays with $K^{*+} \to \pi^0 K^+$. The signal shape parameters are kept fixed in the fits to the data.

The dominant background comes from random combination of J/ψ, η', and K candidates in $B\bar{B}$ events. The background from continuum is found to be small (a few %). A threshold function [15] is used for the M_{bc} PDF. For ΔE, we use a first-order polynomial function. The MC

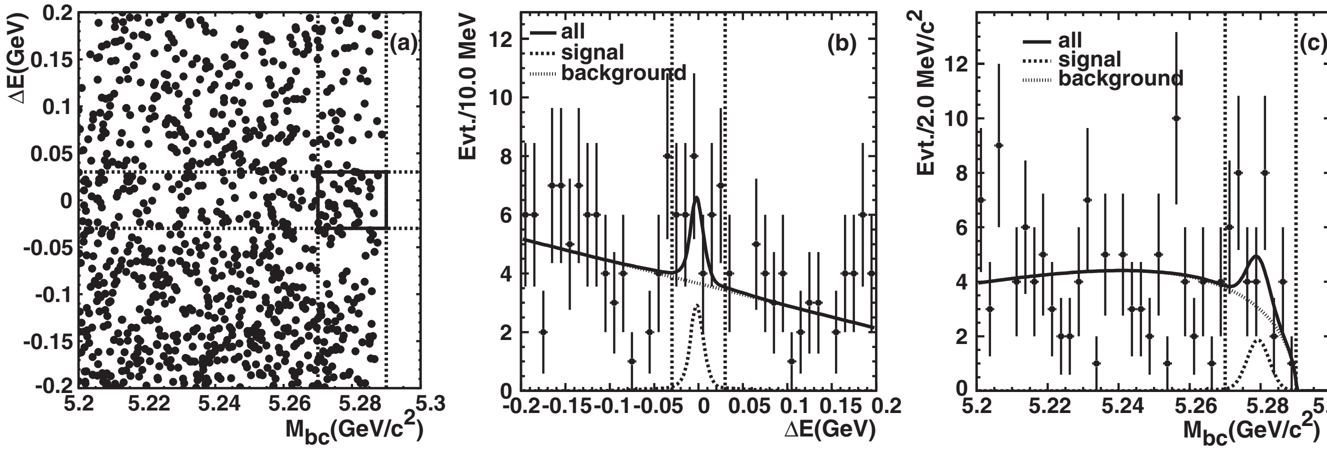

FIG. 1. (a) The $(M_{\rm bc}, \Delta E)$ scatterplot of $B^+ \to J/\psi\eta' K^+$ candidates and its projections onto (b) ΔE with $5.27\ {\rm GeV}/c^2 < M_{\rm bc} < 5.29\ {\rm GeV}/c^2$ and (c) $M_{\rm bc}$ with $|\Delta E| < 0.03$ GeV. The dashed lines and solid boxes indicate the signal regions. The curves are the result of the fit as described in the text.

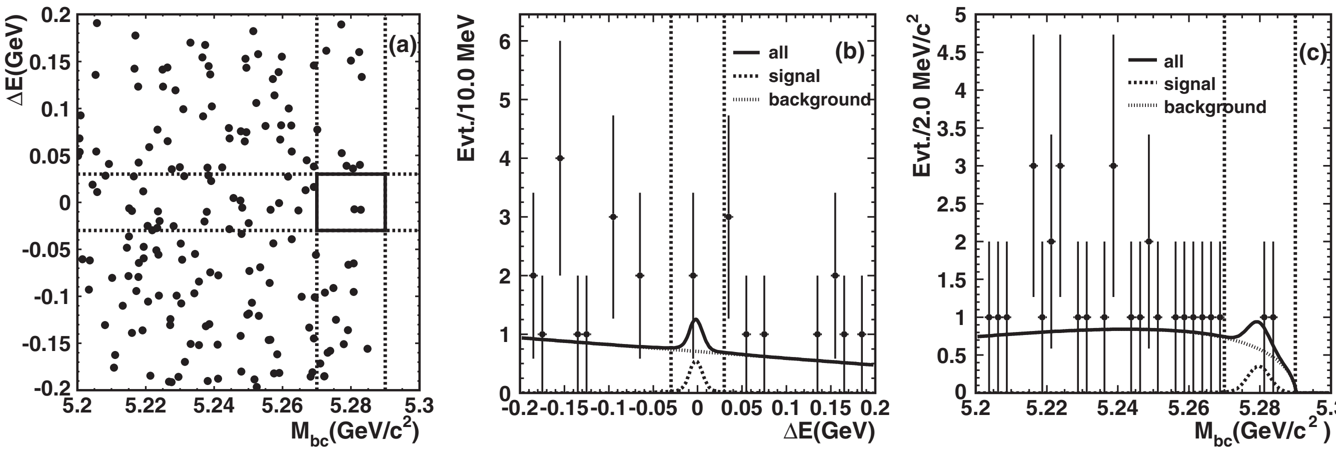

FIG. 2. (a) The $(M_{\rm bc}, \Delta E)$ scatterplot of $B^0 \to J/\psi\eta' K^0_S$ candidates and its projections onto (b) ΔE with $5.27\ {\rm GeV}/c^2 < M_{\rm bc} < 5.29\ {\rm GeV}/c^2$ and (c) $M_{\rm bc}$ with $|\Delta E| < 0.03$ GeV. The dashed lines and the solid box indicate the signal regions. The curves are the result of the fit.

study shows that the background from the decays with similar topology that would make a peak in $M_{\rm bc}$ or ΔE distributions is negligible.

In the fit, the value of N_k and the parameters for the combinatoric background are allowed to float. Figs. 1 and 2 show the $(M_{\rm bc}, \Delta E)$ scatterplots and their projections for candidates after all selections are applied. The fit results are superimposed on the projections. There are 37 candidate events in the signal region for $B^+ \to J/\psi\eta' K^+$ and two for $B^0 \to J/\psi\eta' K^0_S$.

Table I summarizes the maximum-likelihood fit results for the signal (Y) and signal-region background (b) yields and their statistical errors. The statistical significance is defined as $\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{\rm max})}$, where $\mathcal{L}_{\rm max}$ and $\mathcal{L}_0$ denote

TABLE I. Summary of the results. Y and b are the signal and expected total background yields in the signal region, Sig. is the statistical significance, n_0 is the observed number of candidate events in the signal region, Y_{90} is the upper limit on the signal yield at 90% confidence level, ϵ (error includes systematic error) is the detection efficiency and $\mathcal{B}$ is the branching fraction.

Mode	Y	b	Sig.	n_0	Y_{90}	ϵ (%)	$\mathcal{B}$
$B^+ \to J/\psi\eta' K^+$	$6.0^{+4.5}_{-3.9}$	22.0 ± 0.7	1.8σ	37	28.1	3.9 ± 0.6	$<8.8 \times 10^{-5}$
$B^0 \to J/\psi\eta' K^0_S$	$1.1^{+1.9}_{-1.2}$	4.2 ± 0.3	0.9σ	2	3.7	$2.7^{+0.6}_{-0.7}$	$<2.5 \times 10^{-5}$

TABLE II. Summary of systematic uncertainties (%) of the denominator in branching fraction calculation.

Source	$B^+ \to J/\psi\eta' K^+$	$B^0 \to J/\psi\eta' K_S^0$
Tracking error	± 7.4	± 8.9
PID (π and K)	± 2.7	± 1.4
Lepton ID	± 3.8	± 3.8
π^0 veto	± 3.0	± 3.0
η reconstruction	± 4.3	± 4.3
K_S^0 reconstruction	-	± 3.7
Branching fractions	± 3.3	± 3.3
MC statistics	± 0.2	± 0.3
3-body decay model	$+9.4/-11.3$	$+17.5/-22.8$
$N_{B\bar{B}}$	± 1.4	± 1.4
Total	$+14.3/-15.6$	$+21.4/-25.9$

the maximum likelihood with the fitted signal yield and with the yield fixed at zero, respectively.

No significant signal is found for either the $B^+ \to J/\psi\eta' K^+$ or $B^0 \to J/\psi\eta' K_S^0$ decay mode. We obtain upper limits on the yield at 90% confidence level (Y_{90}) from number of observed candidates in the signal region (n_0) and b using the Feldman-Cousins method [16]. We account for systematic uncertainty due to uncertainties in the signal reconstruction efficiency and background estimate using the method of Ref. [17].

The branching fraction is determined with $N_S/[\epsilon \times N_{B\bar{B}} \times \mathcal{B}(J/\psi \to l^+l^-) \times \mathcal{B}(\eta' \to \eta\pi^+\pi^-) \times \mathcal{B}(\eta \to \gamma\gamma)]$ for $B^+ \to J/\psi\eta' K^+$ and $N_S/[\epsilon \times N_{B\bar{B}} \times \mathcal{B}(J/\psi \to l^+l^-) \times \mathcal{B}(\eta' \to \eta\pi^+\pi^-) \times \mathcal{B}(\eta \to \gamma\gamma) \times \mathcal{B}(K_S^0 \to \pi^+\pi^-)]$ for $B^0 \to J/\psi\eta' K_S^0$. Here N_S is the signal yield, $N_{B\bar{B}}$ is the number of $B\bar{B}$ pairs. We use the world averages [13] for the branching fractions of $\mathcal{B}(J/\psi \to l^+l^-)$, $\mathcal{B}(\eta' \to \eta\pi^+\pi^-)$, $\mathcal{B}(\eta \to \gamma\gamma)$ and $\mathcal{B}(K_S^0 \to \pi^+\pi^-)$. The efficiencies ($\epsilon$) are determined from the signal MC sample with the same selection as used in the data. A three-body phase space model is employed for all three decay modes. The fractions of neutral and charged B mesons produced in $\Upsilon(4S)$ decays are assumed to be equal.

The sources and sizes of systematic uncertainties in branching fraction calculation are summarized in Table II. The dominant sources are uncertainties in the three-body decay model, tracking efficiency and particle identification. For the error due to uncertainty in decay modeling for $B^+ \to J/\psi\eta' K^+$ ($B^0 \to J/\psi\eta' K_S^0$), the distribution in phase space is unknown. We conservatively assign the maximum variation of efficiency among the slices of $M(J/\psi, \eta')$, $M(J/\psi, K^-)$ and $M(\eta', K^-)$ [$M(J/\psi, \eta')$, $M(J/\psi, K_S^0)$, and $M(\eta', K_S^0)$] as a systematic uncertainty. The uncertainties in the tracking efficiency are estimated by linearly adding the momentum-dependent single track systematic errors. We assign uncertainties of about 1.3% per kaon, about 0.7% per pion, and about 1.9% per lepton for the particle identification. The η reconstruction uncertainty is determined by measuring the efficiency ratio between data and MC sample in the inclusive η sample. The K_S^0 reconstruction is checked by comparing the ratio of $D^+ \to K_S^0\pi^+$ and $D^+ \to K^-\pi^+\pi^-$ yields.

The systematic errors for the background yield are evaluated by varying each of the PDF parameters by its statistical error from the fit.

In summary, we searched for $B^+ \to J/\psi\eta' K^+$ and $B^0 \to J/\psi\eta' K_S^0$ decays. No statistically significant signal was found for either of the two decay modes; upper limits for the branching fractions are determined to be $\mathcal{B}(B^+ \to J/\psi\eta' K^+) < 8.8 \times 10^{-5}$ and $\mathcal{B}(B^0 \to J/\psi\eta' K_S^0) < 2.5 \times 10^{-5}$ at 90% confidence level.

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