RAPID COMMUNICATIONS

PHYSICAL REVIEW D **78,** 011106(R) (2008)

Search for $B^0 \to J/\psi\phi$ decays

Y. Liu,[4] K. Trabelsi,[7] I. Adachi,[7] H. Aihara,[41] K. Arinstein,[1] V. Aulchenko,[1] T. Aushev,[12,17] T. Aziz,[37] A. M. Bakich,[36] A. Bay,[17] I. Bedny,[1] K. Belous,[11] V. Bhardwaj,[32] U. Bitenc,[13] A. Bondar,[1] A. Bozek,[26] M. Bračko,[13,19] T. E. Browder,[6] P. Chang,[25] Y. Chao,[25] A. Chen,[23] K.-F. Chen,[25] B. G. Cheon,[5] I.-S. Cho,[46] Y. Choi,[35] J. Dalseno,[7] M. Dash,[45] S. Eidelman,[1] N. Gabyshev,[1] B. Golob,[18,13] H. Ha,[15] J. Haba,[7] T. Hara,[31] K. Hayasaka,[21] H. Hayashii,[22] M. Hazumi,[7] D. Heffernan,[31] Y. Hoshi,[39] W.-S. Hou,[25] H. J. Hyun,[16] K. Inami,[21] H. Ishino,[42] R. Itoh,[7] M. Iwabuchi,[4] M. Iwasaki,[41] Y. Iwasaki,[7] D. H. Kah,[16] S. U. Kataoka,[22] N. Katayama,[7] T. Kawasaki,[28] H. Kichimi,[7] H. J. Kim,[16] H. O. Kim,[16] S. K. Kim,[34] Y. I. Kim,[16] Y. J. Kim,[4] K. Kinoshita,[2] S. Korpar,[13,19] P. Križan,[13,18] P. Krokovny,[7] R. Kumar,[32] Y.-J. Kwon,[46] S.-H. Kyeong,[46] J. S. Lange,[3] J. S. Lee,[35] M. J. Lee,[34] J. Li,[6] A. Limosani,[20] C. Liu,[33] D. Liventsev,[12] A. Matyja,[26] S. McOnie,[36] T. Medvedeva,[12] K. Miyabayashi,[22] H. Miyake,[31] H. Miyata,[28] Y. Miyazaki,[21] T. Nagamine,[40] Y. Nagasaka,[8] M. Nakao,[7] H. Nakazawa,[23] S. Nishida,[7] O. Nitoh,[44] T. Nozaki,[7] S. Ogawa,[38] T. Ohshima,[21] S. Okuno,[14] H. Ozaki,[7] P. Pakhlov,[12] G. Pakhlova,[12] C. W. Park,[35] H. Park,[16] H. K. Park,[16] L. S. Peak,[36] R. Pestotnik,[13] L. E. Piilonen,[45] H. Sahoo,[6] Y. Sakai,[7] O. Schneider,[17] J. Schümann,[7] C. Schwanda,[10] A. J. Schwartz,[2] A. Sekiya,[22] K. Senyo,[21] M. E. Sevior,[20] M. Shapkin,[11] C. P. Shen,[9] J.-G. Shiu,[25] J. B. Singh,[32] S. Stanič,[29] M. Starič,[13] T. Sumiyoshi,[43] F. Takasaki,[7] M. Tanaka,[7] G. N. Taylor,[20] Y. Teramoto,[30] I. Tikhomirov,[12] T. Tsuboyama,[7] S. Uehara,[7] T. Uglov,[12] Y. Unno,[5] S. Uno,[7] P. Urquijo,[20] G. Varner,[6] K. Vervink,[17] C. H. Wang,[24] P. Wang,[9] X. L. Wang,[9] Y. Watanabe,[14] R. Wedd,[20] E. Won,[15] H. Yamamoto,[40] Y. Yamashita,[27] C. C. Zhang,[9] Z. P. Zhang,[33] V. Zhilich,[1] V. Zhulanov,[1] T. Zivko,[13] A. Zupanc,[13] and O. Zyukova[1]

(Belle Collaboration)

[1]*Budker Institute of Nuclear Physics, Novosibirsk*
[2]*University of Cincinnati, Cincinnati, Ohio 45221*
[3]*Justus-Liebig-Universität Gießen, Gießen*
[4]*The Graduate University for Advanced Studies, Hayama*
[5]*Hanyang University, Seoul*
[6]*University of Hawaii, Honolulu, Hawaii 96822*
[7]*High Energy Accelerator Research Organization (KEK), Tsukuba*
[8]*Hiroshima Institute of Technology, Hiroshima*
[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]*Korea University, Seoul*
[16]*Kyungpook National University, Taegu*
[17]*École Polytechnique Fédérale de Lausanne (EPFL), Lausanne*
[18]*Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana*
[19]*University of Maribor, Maribor*
[20]*University of Melbourne, School of Physics, Victoria 3010*
[21]*Nagoya University, Nagoya*
[22]*Nara Women's University, Nara*
[23]*National Central University, Chung-li*
[24]*National United University, Miao Li*
[25]*Department of Physics, National Taiwan University, Taipei*
[26]*H. Niewodniczanski Institute of Nuclear Physics, Krakow*
[27]*Nippon Dental University, Niigata*
[28]*Niigata University, Niigata*
[29]*University of Nova Gorica, Nova Gorica*
[30]*Osaka City University, Osaka*
[31]*Osaka University, Osaka*
[32]*Panjab University, Chandigarh*
[33]*University of Science and Technology of China, Hefei*
[34]*Seoul National University, Seoul*
[35]*Sungkyunkwan University, Suwon*

1550-7998/2008/78(1)/011106(5)

[36]*University of Sydney, Sydney, New South Wales*
[37]*Tata Institute of Fundamental Research, Mumbai*
[38]*Toho University, Funabashi*
[39]*Tohoku Gakuin University, Tagajo*
[40]*Tohoku University, Sendai*
[41]*Department of Physics, University of Tokyo, Tokyo*
[42]*Tokyo Institute of Technology, Tokyo*
[43]*Tokyo Metropolitan University, Tokyo*
[44]*Tokyo University of Agriculture and Technology, Tokyo*
[45]*Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061*
[46]*Yonsei University, Seoul*

(Received 21 May 2008; published 24 July 2008)

We report a search for the decay $B^0 \to J/\psi\phi$, using a sample of 657×10^6 $B\bar{B}$ pairs collected with the Belle detector at the $\Upsilon(4S)$ resonance. No statistically significant signal is found and an upper limit for the branching fraction is determined to be $\mathcal{B}(B^0 \to J/\psi\phi) < 9.4 \times 10^{-7}$ at 90% confidence level.

DOI: 10.1103/PhysRevD.78.011106 PACS numbers: 13.25.Hw, 14.40.Gx, 14.40.Nd

Studies of exclusive B meson decays to charmonium play an important role in exploring CP violation [1] and establishing the Kobayashi-Maskawa anzatz [2] for CP violation in the standard model. Such studies have also resulted in observations of new resonant states that include a $(c\bar{c})$ pair [3–5]. The decay $B^0 \to J/\psi\phi$ is expected to proceed mainly via a Cabibbo-suppressed and color-suppressed transition $(b \to c\bar{c}d)$ with rescattering, as shown in Fig. 1. In B decays, effects presumably due to rescattering have been seen in various decay processes. For example, the large branching fractions observed for $B^0 \to D_s^- K^+$ [6] and $B^- \to \chi_{c0}K^-$ [7] decays can be attributed to rescattering processes [8,9]. An isospin analysis on $B \to DK^{(*)}$ decays indicates significant final-state rescattering effects [10]. Final-state rescattering may play an important role in understanding patterns of CP asymmetries in B decays to two charmless pseudoscalars [11]. Studies of B decays such as $B^0 \to J/\psi\phi$, which would proceed mainly via rescattering, provide useful information for understanding rescattering mechanisms. Previously, the *BABAR* collaboration reported a search for this decay mode and set an upper limit for the branching fraction $\mathcal{B} < 9.2 \times 10^{-6}$ at the 90% confidence level based on 56×10^6 $B\bar{B}$ pairs [12].

In this paper, we report the results of a search for the decay mode $B^0 \to J/\psi\phi$ using the Belle detector [13] at the KEKB energy-asymmetric e^+e^- collider [14] based on a 605 fb^{-1} data sample containing 657×10^6 $B\bar{B}$ pairs. This sample is more than an order of magnitude larger than that used previously.

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 (ECL) composed of CsI(Tl) crystals. 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.

Events are required to pass a basic hadronic event selection [15]. To suppress the 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 [16] to be less than 0.5.

Candidates for $B^0 \to J/\psi\phi$ decays are reconstructed from the decays $J/\psi \to \ell^+\ell^-$ ($\ell = e, \mu$), and $\phi \to K^+K^-$. The selection criteria for the J/ψ decaying to $\ell^+\ell^-$ are identical to those used in our previous papers [15]. 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: $-150(-60)\ \text{MeV}/c^2 < M_{e^+e^-(\gamma)}(M_{\mu^+\mu^-}) - m_{J/\psi} < +36(+36)\ \text{MeV}/c^2$, where $m_{J/\psi}$ is the nominal J/ψ mass [17]. In order to improve the J/ψ momentum resolution, a vertex and mass con-

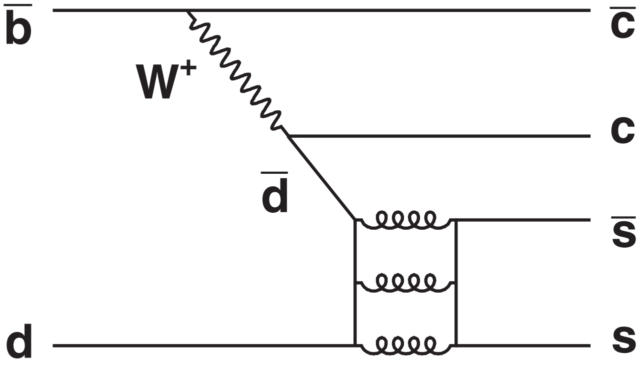

FIG. 1. Quark-level diagram for $B^0 \to J/\psi\phi$ decay.

strained 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, the TOF, and dE/dx measurements from the CDC. Kaons from the ϕ meson are selected with the requirement $L_K/(L_K + L_\pi) > 0.7$, which has an efficiency of 90.0% and a 5.9% probability to misidentify a pion as kaon. This requirement is chosen to minimize the upper limit expected in the absence of a real signal, based on studies of signal and background Monte Carlo (MC) events. We reconstruct ϕ candidates from pairs of K^+K^- candidates, where we require the invariant mass to be within ± 10 MeV$/c^2$ of the nominal ϕ mass [17].

B^0 mesons are reconstructed by combining a J/ψ with a ϕ candidate. We identify B^0 candidates using two kinematic variables calculated in the center-of-mass system: the beam-energy constrained mass ($M_{\rm bc} \equiv \sqrt{E_{\rm beam}^2 - P_B^2}$) and the energy difference ($\Delta E \equiv E_B - E_{\rm beam}$), where $E_{\rm beam}$ is the beam energy, and P_B and E_B are the reconstructed momentum and energy of the B^0 candidate. We select B candidates within the range -0.2 GeV $< \Delta E <$ 0.3 GeV and 5.27 GeV$/c^2 < M_{\rm bc} <$ 5.29 GeV$/c^2$ for the final analysis. After all selection requirements, about 4.9% of the events contain more than one B^0 candidate. For these events, we choose the B candidate whose daughter particle ϕ mass is closest to the nominal value. Finally, a total of 85 candidates are selected.

The dominant background comes from $B\bar{B}$ events with B decays to J/ψ. We use a MC sample corresponding to 3.86×10^{10} generic $B\bar{B}$ decays that includes all known $B \to J/\psi X$ processes to investigate these backgrounds. We find that the dominant backgrounds come from $B^0 \to J/\psi K^{*0}(892)[\to K^-\pi^+]$ and $B^{0/-} \to J/\psi K_1(1270)[\to K^-\pi^+\pi^{0/-}]$ [18]. In both cases, a pion is misidentified as a kaon, and in the latter case, the other pion is missed. The former has a peak at $\Delta E \sim 0.1$ GeV, while the latter has a broad peak in the negative ΔE region. The remaining background is due to random combinations of J/ψ and ϕ candidates and does not peak in the ΔE distribution (referred to as combinatorial background).

The signal yield is extracted by performing an unbinned extended maximum-likelihood fit to the ΔE distribution of candidate events. The likelihood function is given as

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

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, $J/\psi K_1$, $J/\psi K^{*0}$, and combinatorial backgrounds.

The signal PDF is modeled by a sum of two Gaussians. The background PDFs are two Gaussians for the $J/\psi K_1$ component, a bifurcated Gaussian for the $J/\psi K^{*0}$ component, and a second-order polynomial for the combinatorial background, respectively. The parameters of these PDFs are determined from MC simulations. We use $B^0 \to J/\psi K^{*0}$ decay with $K^{*0} \to K^-\pi^+$ as a control data sample to correct for small differences between data and MC in the mean and width of the signal PDF. The $J/\psi K_1$ component shape is verified by comparing data and MC events in the K^+K^- mass sideband region (1.04–1.10 GeV$/c^2$), while events in the 5.22 GeV$/c^2 < M_{\rm bc} <$ 5.26 GeV$/c^2$ and K^+K^- mass sideband region are used to check the combinatorial background shape. Possible differences between data and MC are included in the systematic errors.

In the fit, all N_k values are free parameters. Figure 2 shows the ΔE distribution of the $B^0 \to J/\psi\phi$ candidates together with the fit result. We obtain a signal yield of $4.6^{+3.1}_{-2.5}$ events with a statistical significance of 2.3σ. This 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 the maximum likelihood with the fitted signal yield and with the yield fixed to zero, respectively. The number of misidentified $B^0 \to J/\psi K^{*0}$ events obtained from the fit is $22.5^{+5.4}_{-4.8}$ and is consistent with the expectation obtained from MC simulation incorporating the misidentification probability and the world average branching fraction [17].

As no significant signal is found for the $B^0 \to J/\psi\phi$ decay mode, we obtain an upper limit on the yield at the 90% confidence level (Y_{90}) by a frequentist method using ensembles of pseudoexperiments. For a given signal yield, 10000 sets of signal and background events are generated according to the PDFs, and fits are performed. The con-

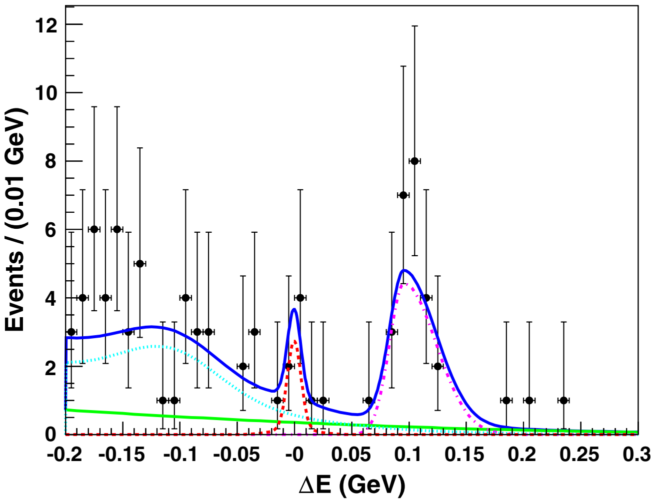

FIG. 2 (color online). ΔE distribution for $B^0 \to J/\psi\phi$ candidates. The curves show the signal (red dashed) and the background components (cyan dashed for $J/\psi K_1$, magenta dot-dashed for $J/\psi K^{*0}$ and green triple-dot-dashed for combinatorial) as well as the overall fit (blue solid curve).

fidence level is obtained as the fraction of samples that give a fit yield larger than that of data (4.6). We account for systematic error by smearing the fit yield by the total systematic error described below. We scan signal yields and obtain $Y_{90} = 9.5$.

The corresponding branching fraction upper limit is determined with

$$\mathcal{B} < \frac{Y_{90}}{\epsilon \times N_{B\bar{B}} \times \mathcal{B}(J/\psi \to \ell^+\ell^-) \times \mathcal{B}(\phi \to K^+K^-)}. \tag{2}$$

Here $N_{B\bar{B}}$ is the number of $B\bar{B}$ pairs, and we use the world averages [17] for the branching fractions of $\mathcal{B}(J/\psi \to \ell^+\ell^-)$ and $\mathcal{B}(\phi \to K^+K^-)$. The efficiency ($\epsilon = 26.2\%$) is determined from a signal MC sample with the same selection as used for the data, where a correction for muon identification efficiency due to differences between data and MC is included (described below). The fractions of neutral and charged B mesons produced in $\Upsilon(4S)$ decays are assumed to be equal. These results are summarized in Table I and an upper limit at the 90% confidence level is obtained

$$\mathcal{B}(B^0 \to J/\psi\phi) < 9.4 \times 10^{-7}. \tag{3}$$

The sources and sizes of systematic uncertainties are summarized in Tables II and III. The dominant sources of systematic error in the reconstruction efficiency are tracking efficiency and particle identification. Uncertainties in the tracking efficiency are estimated by linearly summing the momentum-dependent single track systematic errors ($\sim 1\%$ per track). We use control samples of $J/\psi \to \ell^+\ell^-$ and $e^+e^- \to e^+e^-\ell^+\ell^-$ events to estimate lepton identification efficiency corrections and uncertainties. For the $J/\psi \to \mu^+\mu^-$ mode, we find the efficiency for a muon track in the data to be $(4.3 \pm 3.1)\%$ lower than that of MC simulation. We correct the efficiency for this difference and assign a 3.1% uncertainty per muon track. For the $J/\psi \to e^+e^-$ mode, the difference between efficiencies in the data and in the MC simulation is small, and we assign a 2.7% uncertainty per electron track based on their difference and errors. We assign an uncertainty of 1.2% per kaon track, which is obtained using kinematically identified kaons in a $D^{*+} \to D^0\pi^+[D^0 \to K^-\pi^+]$ sample. Because of the small energy release in $\phi \to K^+K^-$ decay, the selection efficiency of $B^0 \to J/\psi\phi$ decays depends only weakly on the final-state polarization. We use an average of the efficiencies for fully longitudinally and transversely polarized cases and assign the difference as a systematic error ($\pm 2.6\%$ including MC statistical error). The systematic errors due to signal and background shapes are evaluated by varying each of the PDF parameters by its uncertainty. We find that the $J/\psi K_1$ component uncertainty is dominant and that the total systematic error on the signal yield is $+21.7\%/-26.1\%$ (Table III). Adding all sources in quadrature and conservatively taking the larger of the asymmetric errors, the total systematic error is estimated to be 27%. As a cross check of the MC efficiency and analysis procedure, we apply the same analysis procedure to the $B^0 \to J/\psi K^{*0}$ control sample and obtain $\mathcal{B} = (1.24 \pm 0.01) \times 10^{-3}$ (the error is statistical only). This is consistent with the world average [17] within its uncertainty and the estimated systematic error of the efficiency mentioned above.

TABLE I. Summary of the results: upper limits are at the 90% confidence level.

Signal yield	$4.6^{+3.1}_{-2.5}$
Significance	2.3σ
Upper limit of signal yield (Y_{90})	9.5
Detection efficiency (ϵ)	26.2%
Upper limit of branching fraction	$<9.4 \times 10^{-7}$

TABLE II. Summary of systematic uncertainties (%) other than signal yield extraction (denominator in Eq. (2)).

Uncertainty Source	Uncertainty (%)
Tracking efficiency	4.2
Lepton ID efficiency	4.2
Kaon ID efficiency	2.2
Polarization	2.6
J/ψ branching fractions	1.0
ϕ branching fraction	1.2
Number of $B\bar{B}$	1.4
Total	7.2

In summary, we have searched for $B^0 \to J/\psi\phi$ decays. No statistically significant signal is found and an upper limit for this decay is determined to be $\mathcal{B}(B^0 \to J/\psi\phi) < 9.4 \times 10^{-7}$ at the 90% confidence level. This result improves upon the previous result [12] by about a factor of 10 and imposes a more stringent constraint on rescattering effects in $B^0 \to J/\psi\phi$ decays.

We thank the KEKB group for their excellent operation of the accelerator, the KEK cryogenics group for their 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,

TABLE III. Summary of systematic uncertainties on signal yield (Δn) by source.

Uncertainty Source	$(+\sigma)\Delta$n	$(-\sigma)\Delta$n
$K_1(1270)$	1.0	1.2
K^{*0}	<0.1	<0.1
Combinatorial background	0.1	0.2
Signal	<0.1	0.1
Total	1.0	1.2

Science, and Technology of Japan and the Japan Society for the Promotion of Science; the Australian Research Council and the Australian Department of Education, Science and Training; the National Natural Science Foundation of China under Contract No. 10575109 and 10775142; the Department of Science and Technology of India; the BK21 program of the Ministry of Education of Korea, the CHEP SRC program and Basic Research program under Grant No. R01-2005-000-10089-0 of the Korea Science and Engineering Foundation, and the Pure Basic Research Group program of the Korea Research Foundation; the Polish State Committee for Scientific Research; 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.

[1] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **87**, 091801 (2001); K. Abe *et al.* (Belle Collaboration), Phys. Rev. Lett. **87**, 091802 (2001).
[2] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).
[3] S.-K. Choi *et al.* (Belle Collaboration), Phys. Rev. Lett. **91**, 262001 (2003).
[4] S.-K. Choi *et al.* (Belle Collaboration), Phys. Rev. Lett. **94**, 182002 (2005).
[5] S.-K. Choi *et al.* (Belle Collaboration), Phys. Rev. Lett. **100**, 142001 (2008).
[6] P. Krokovny *et al.* (Belle Collaboration), Phys. Rev. Lett. **89**, 231804 (2002); B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **98**, 081801 (2007).
[7] K. Abe *et al.* (Belle Collaboration), Phys. Rev. Lett. **88**, 031802 (2002); B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **69**, 071103 (2004).
[8] B. Block, M. Gronau, and J. Rosner, Phys. Rev. Lett. **78**, 3999 (1997).
[9] P. Colangelo, F. De Fazio, and T. N. Pham, Phys. Lett. B **542**, 71 (2002).
[10] Z.-Z. Xing, Eur. Phys. J. C **28**, 63 (2003).
[11] C. K. Chua, W. S. Hou, and K. C. Yang, Mod. Phys. Lett. A **18**, 1763 (2003).
[12] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **91**, 071801 (2003).
[13] A. Abashian *et al.* (Belle Collaboration), Nucl. Instr. and Meth. in Phys. Res. A **479**, 117 (2002).
[14] S. Kurokawa and E. Kikutani, Nucl. Instr. and Meth. in Phys. Res. A **499**, 1 (2003), and other papers included in this Volume.
[15] K. Abe *et al.* (Belle Collaboration), Phys. Rev. D **67**, 032003 (2003).
[16] G. C. Fox and S. Wolfram, Phys. Rev. Lett. **41**, 1581 (1978).
[17] W.-M. Yao *et al.* (Particle Data Group), J. Phys. G **33**, 1 (2006).
[18] Hereafter, we denote $K^{*0}(892)$ and $K_1(1270)$ as simply K^{*0} and K_1, respectively. Also, inclusion of the charge-conjugate states is implied throughout this paper.