Measurement of the Decays $B_S^0 \to J/\psi f(1020)$, $B_S^0 \to J/\psi f_2^*(1525)$ and $B_S^0 \to J/\psi K^+ K^-$ at Belle

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We report a measurement of the branching fraction of the decay $B^0_s \to J/\psi \phi(1020)$, evidence and a branching fraction measurement for $B^0_s \to J/\psi f_2(1525)$, and the determination of the total $B^0_s \to J/\psi K^+K^-$ branching fraction, including the resonant and non-resonant contributions to the $K^+K^-$ channel. We also determine the $S$-wave contribution within the $\phi(1020)$ mass region. The absolute branching fractions are $\mathcal{B}[B^0_s \to J/\psi \phi(1020)] = (1.25 \pm 0.07 \text{(stat)} \pm 0.08 \text{(syst)} \pm 0.22(f_s)) \times 10^{-3}$, $\mathcal{B}[B^0_s \to J/\psi f_2(1525)] = (0.26 \pm 0.06 \text{(stat)} \pm 0.02 \text{(syst)} \pm 0.05(f_s)) \times 10^{-3}$ and $\mathcal{B}[B^0_s \to J/\psi K^+K^-] = (1.01 \pm 0.09 \text{(stat)} \pm 0.10 \text{(syst)} \pm 0.18(f_s)) \times 10^{-3}$, where the last systematic error is due to the branching fraction of $b \to B_s^{(*)}$. The branching fraction ratio is found to be $\mathcal{B}[B^0_s \to J/\psi f_2(1525)]/\mathcal{B}[B^0_s \to J/\psi \phi(1020)] = (21.5 \pm 4.9 \text{(stat)} \pm 2.6 \text{(syst)})\%$. All results are based on a 121.4 fb$^{-1}$ data sample collected at the $\Upsilon(5S)$ resonance by the Belle experiment at the KEKB asymmetric-energy $e^+e^-$ collider.

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I. INTRODUCTION

The study of $B^0_s \bar{B}^0_s$ mixing and $CP$ violation in $B^0_s$ decays \cite{1} helps advance our understanding of the Cabibbo-Kobayashi-Maskawa mechanism \cite{2,3}. The decay $B^0_s \to J/\psi \phi(1020)$ \cite{4} probes the $CP$-violating phase $\phi_s$ of $B^0_s \bar{B}^0_s$ oscillations \cite{5,6,7}, which is predicted to be small within the Standard Model (SM). However, contributions from physics beyond the SM can significantly enhance this parameter \cite{3}.

In this context, experiments have made significant progress to better understand contributions to the decay $B^0_s \to J/\psi K^+K^-$ beyond $B^0_s \to J/\psi \phi(1020)(\to K^+K^-)$. A recent discovery in this field is the decay $B^0_s \to J/\psi f_2(1525)$, whose branching fraction relative to $B^0_s \to J/\psi \phi(1020)$ is measured to be $(26.4 \pm 2.7 \text{(stat)} \pm 2.4 \text{(syst)})\%$ by LHCb \cite{10} and $(22 \pm 5 \text{(stat)} \pm 4 \text{(syst)})\%$ by DØ \cite{11}. A first measurement of the entire $B^0_s \to J/\psi K^+K^-$ decay rate (including resonant and non-resonant decays) was recently performed by LHCb with a measured branching fraction of $(7.70 \pm 0.08 \text{(stat)} \pm 0.39 \text{(syst)} \pm 0.60(f_s/f_d)) \times 10^{-4}$ \cite{12}.

In this analysis, we study the decay $B^0_s \to J/\psi K^+K^-$ using the Belle data and determine its absolute branching
fraction. We identify the resonant contributions 

$$B^0_s \rightarrow J/\psi \phi(1020) \rightarrow K^+ K^-$$

and 

$$B^0_s \rightarrow J/\psi f'_2(1525) \rightarrow K^+ K^-$$

determine the S-wave contribution in the 

$$\phi(1020)$$

mass region. In contrast to hadron collider experiments, we normalize to the absolute number of 

$$B^0_s B^0_s$$

pairs produced rather than to a reference decay channel. In addition, to determine the S-wave contribution in the 

$$\phi(1020)$$

mass region, we fit to the 

$$K^+ K^-$$

mass distribution rather than perform an angular analysis. Thus, our results are obtained using methods with systematic uncertainties that both differ from previous analyses.

II. EXPERIMENTAL PROCEDURE

A. Data Sample and Event Selection

The data used in this analysis were taken with the Belle detector \cite{13} at the KEKB asymmetric-energy \(e^+ e^-\) collider \cite{14}. Belle is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect \(K^0_L\) mesons and to identify muons (KLM).

The Belle data sample taken at the \(\Upsilon(5S)\) resonance has an integrated luminosity of 121.4 fb\(^{-1}\) and contains \((7.1 \pm 1.3) \times 10^9 \ B^0_s \bar{B}^0_s\) events with a cross section for the process \(e^+ e^- \rightarrow b \bar{b}\) of \(\sigma_{b\bar{b}} = (0.340 \pm 0.016) \text{nb}\) and a fraction of \(b\bar{b}\) states hadronizing into \(B^0_s (\bar{B}^0_s)\) of \(f_s = (17.2 \pm 3.0)\%\) \cite{13}.

Monte Carlo (MC) simulated events equivalent to at least six times the integrated luminosity of the data are used to evaluate the signal acceptance and perform background studies. MC events are generated with EvtGen \cite{16} and a full detector simulation based on GEANT3 \cite{17} is applied. QED bremsstrahlung is included using the PHOTOS package \cite{18}.

Hadronic events are selected based on the charged track multiplicity and the visible energy in the calorimeter. Charged tracks are required to originate from within 4 cm along the beam axis and 0.5 cm in the transverse plane with respect to the \(e^+ e^-\) interaction point. Electron candidates are identified using the ratio of the energy detected in the ECL to the track momentum, the ECL shower shape, position matching between track and ECL cluster, the energy loss in the CDC \((dE/dx)\), and the response of the ACC counters. Muons are identified based on their penetration range and transverse scattering in the KLM detector. Kaon candidates are distinguished from pion tracks by using combined information from the CDC, the ACC and the TOF scintillation counters.

To reconstruct \(J/\psi\) mesons, two identified leptons with the same flavor (\(e\) or \(\mu\)) and opposite charges are combined. The energy loss from bremsstrahlung is partially recovered by adding back the four-momentum of any photon within a 5° cone around the electron or positron direction. The invariant masses of the \(J/\psi \rightarrow e^+ e^- (\gamma)\) and \(J/\psi \rightarrow \mu^+ \mu^-\) candidates are required to lie within the range \(2.946 \text{ GeV} < M(e^+ e^- (\gamma)) < 3.133 \text{ GeV}\) and \(3.036 \text{ GeV} < M(\mu^+ \mu^-) < 3.133 \text{ GeV}\), respectively. The \(J/\psi\) mass resolution is approximately 11 MeV in the electron channel and about 10 MeV in the muon channel. Asymmetric mass windows are used to accommodate the residual bremsstrahlung tails.

The \(J/\psi\) candidate is combined with two oppositely charged kaon candidates to form a \(B^0_s\) candidate. We accept candidates in the entire \(K^+ K^-\) phase space. The resolution in \(M(K^+ K^-)\) is approximately 1 MeV. Due to the two-body kinematics in the process \(e^+ e^- \rightarrow \Upsilon(5S) \rightarrow B_s^{(*)} \bar{B}_s^{(*)}\), the \(B^0_s\) signal is extracted using the following two kinematic variables: the energy difference \(\Delta E = E_B - E_{\text{beam}}\) and the beam-energy constrained mass \(M_{bc} = \sqrt{E_{\text{beam}}^2 - (\vec{p}_B)^2}\), where \(E_{\text{beam}}\) is the beam energy in the center-of-mass (c.m.) frame of the colliding beams, and \(E_B\) and \(\vec{p}_B\) denote the energy and the momentum of the reconstructed \(B^0_s\) meson, respectively, in the c.m. system. As the photon from the decay \(B_s^* \rightarrow B_s^{0\gamma}\) is not reconstructed, there are three signal regions in the \((M_{bc}, \Delta E)\) plane, corresponding to the three initial states \(B_0 B^0_s, B_0^* B_s^0, B_s^* B_s^0\). We select the most abundant initial state \(B_0^* B_s^0\) (the \(B_0^* B_s^0\) fraction in the \(B_s^* B_s^0\) events being \(f_{B_0^* B_s^0} = (87.0 \pm 1.7)\%\) \cite{14}) by requiring \(-0.2 \text{ GeV} < \Delta E < 0.1 \text{ GeV}\) and \(M_{bc} > 5.4 \text{ GeV}\), as the signal peaks around \(\Delta E = M(B_s^*) - M(B_0^0) \approx 0.049 \text{ GeV}\) and \(M_{bc} = M(B_s^*) \approx 5.415 \text{ GeV}\) for the \(B_0^* B_s^0\) signal region.

B. Backgrounds and Signal Extraction

Background to the \(B_0^0 \rightarrow J/\psi K^+ K^-\) signal arises from random combinations in \(\Upsilon(5S)\) events and from so-called continuum, i.e., events originating from the process \(e^+ e^- \rightarrow q\bar{q}\) with \(q = u, d, s\) or \(c\). Contributions from the latter are suppressed by exploiting the difference in event shape between \(\Upsilon(5S)\) and continuum events (spherical vs. jet-like, respectively) and requiring the ratio of the second to zeroth Fox-Wolfram moment \(R_2 = H_2/H_0\) \cite{13} to be less than 0.4. This selection was optimized for this decay topology in the analysis of the decay \(B_s^0 \rightarrow J/\psi \pi^+ \pi^-\) \cite{20}.

Signal extraction is performed independently for the \(J/\psi \rightarrow e^+ e^-\) and \(J/\psi \rightarrow \mu^+ \mu^-\) subsamples by a two-dimensional unbinned maximum likelihood fit in \(\Delta E\) and \(M(K^+ K^-)\). The fit range is \(-0.2 \text{ GeV} < \Delta E < 0.1 \text{ GeV}\) and \(0.95 \text{ GeV} < M(K^+ K^-) < 2.4 \text{ GeV}\) and takes into account resolution effects at the lower end of the \(M(K^+ K^-)\) phase space. The probability density function (PDF) for signal \cite{21} in \(\Delta E\) is parameterized with
a sum of a Gaussian and a Crystal Ball function (a sum of two Gaussian functions) for the $J/\psi \rightarrow e^+e^- (J/\psi \rightarrow \mu^+\mu^-)$ data sample. The parameters of these PDFs are determined from data using a control sample of $B^0 \rightarrow J/\psi K^+(892)^0$ decays with $K^+(892)^0 \rightarrow K^+\pi^-$. The signal shapes of the $\phi(1020)$ and the $f_2^0(1525)$ resonances in $M(K^+K^-)$ are each described by a non-relativistic Breit-Wigner function whose width includes both the natural width and the detector resolution. The remaining $J/\psi(K^+K^-)_{\text{other}}$ component is modeled with an ARGUS function in $M(K^+K^-)$. When we perform the fit on the data, the shape parameters of all signal PDFs for the $\Delta E$ distribution are fixed using the control sample, while the parameters of the signal PDFs for the $M(K^+K^-)$ distribution are fixed using MC simulations.

The background, which includes contributions from combinatorial background in $\Upsilon(5S)$ events and continuum background, is parameterized by a first-order polynomial in $\Delta E$ and an ARGUS function in $M(K^+K^-)$. The parameters of the background PDFs are determined from a data sideband defined by $5.25 \text{ GeV} < M_{BC} < 5.35 \text{ GeV}$ and fixed in the fit on the real data.

The entire signal extraction procedure has been tested and validated on simulated events. Terms in the PDF due to interference among the $J/\psi \phi(1020)$, $J/\psi f_2^0(1525)$ and $J/\psi(K^+K^-)_{\text{other}}$ components cancel after integration over angular variables, since the $K^+K^-$ systems have distinct quantum numbers of 1, 2 and 0, respectively. As we find that the angular acceptance is approximately flat within our statistics, we do not consider interference effects among these components.

The yields obtained for the $J/\psi \rightarrow e^+e^-$ and $J/\psi \rightarrow \mu^+\mu^-$ samples are given in Table I. Figures 1 and 2 show the projections of the fit in $\Delta E$ and $M(K^+K^-)$, respectively.

### Table I: Extracted yields for signal components and background in the $J/\psi \rightarrow e^+e^-$ and $J/\psi \rightarrow \mu^+\mu^-$ samples.

| Channel                  | $e^+e^-$ | $\mu^+\mu^-$ |
|--------------------------|----------|--------------|
| $J/\psi \phi(1020)$      | 168 ± 13.5 | 158 ± 13     |
| $J/\psi f_2^0(1525)$     | 34 ± 10   | 26 ± 8       |
| $J/\psi(K^+K^-)_{\text{other}}$ | 83 ± 17 | 67 ± 14     |
| Background               | 232 ± 19  | 300 ± 20     |

The absolute branching fraction for the decay $B_s^0 \rightarrow J/\psi \phi(1020)$ is calculated from the fitted yields in Table I as

$$B[B_s^0 \rightarrow J/\psi \phi(1020)] = \frac{N_{J/\psi \phi(1020)}}{2\mathcal{L} \sigma_{b\bar{b}} f_{B_s^0} f_{B_s^0} \epsilon B[J/\psi \rightarrow \ell^+\ell^-] B[\phi(1020) \rightarrow K^+K^-]}$$

(1)

where $N_{J/\psi \phi(1020)}$ is the extracted yield, $\mathcal{L}$ is the luminosity of the Belle $\Upsilon(5S)$ sample, and $B[J/\psi \rightarrow \ell^+\ell^-]$ and $B[\phi(1020) \rightarrow K^+K^-]$ are the sub-decay branching fractions. The parameter $\epsilon$ denotes the reconstruction efficiency, whose values are given in Table I. Applying this formula to the electron and muon samples and averaging the results, we obtain

$$B[B_s^0 \rightarrow J/\psi \phi(1020)] = (1.25 \pm 0.07 \text{ (stat)} \pm 0.08 \text{ (syst)} \pm 0.22 (f_{\phi})) \times 10^{-3},$$

(2)
and fall into three categories: uncertainties in the input parameters in Eq. (3), uncertainties related to signal and detector response simulation, and the PDF model. The first class of uncertainties is dominant because of the large uncertainty in $f_s$, which we quote separately.

To estimate the error related to the $\phi(1020)$ polarization in the simulation of $B_s^0 \to J/\psi f_2^0(1525)$, we use the difference in efficiency between a simulation using the CDF $\phi(1020)$ polarization parameters determined by CDF and a different sample giving equal weights to each helicity amplitude.

The systematic error related to lepton ($\ell^\pm$) identification is determined using $\gamma\gamma \to \ell^+\ell^-$ events. The uncertainty arising from kaon identification is determined from a sample of $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ decays.

The error related to the PDF parameters is obtained by performing 1000 pseudo-experiments, sampling each parameter from a Gaussian distribution having a mean value and width equal to the parameter’s central value and uncertainty. The width of the distribution of signal yields is taken as the systematic uncertainty. As we do not find significant impact from the correlations among the parameters, we sample each parameter independently when performing this calculation.

The systematic error due to the PDF model is estimated by repeating the fit with alternative PDF functions, including a relativistic Breit-Wigner function and a non-relativistic Breit-Wigner function with a phase space correction for the $\phi(1020)$ and $f_2^0(1525)$ resonances, and a pure phase space description for the $J/\psi(K^+K^-)_{other}$ component. The maximum deviation between these fit
results and the results obtained with the default model is taken as a systematic uncertainty. Only for the $J/\psi(K^+K^-)_{other}$ component was a significant deviation found. For the $J/\psi\phi(1020)$ and the $J/\psi f_2'(1525)$ components the deviations were negligibly small.

### TABLE III: Contribution to the systematic uncertainty in the $B^0_s \to J/\psi K^+K^-$ branching fractions.

| Source                           | Uncertainty [%] |
|---------------------------------|-----------------|
| Luminosity                      | 0.7             |
| $\sigma_{bb}$ [15]              | 4.7             |
| $f_5$ [15]                      | 17.4            |
| $f_{B^+B^+_s}$ fraction in $B^{*_s}(s^*)$ | 2.0             |
| $B[J/\psi \to \ell^+\ell^-]$ [24] | 1.0             |
| $B[\phi(1020) \to K^+K^-]$ [24]   | 1.0             |
| $B[f_2'(1525) \to K^+K^-]$ [24]   | 2.5             |
| MC statistics                   | 0.3-0.8         |
| $\phi(1020)$ polarization       | 1.3             |
| Charged tracking                 | 1.4             |
| Electron identification          | 3.1             |
| Muon identification              | 3.0             |
| Kaon identification              | 1.9             |
| PDF parameters:                 |                 |
| $J/\psi_{e^+e^-} \phi(1020)$    | 1.1             |
| $J/\psi_{\mu^+\mu^-} \phi(1020)$ | 1.0             |
| $J/\psi_{e^+e^-}(K^+K^-)_{other}$ | 9.1             |
| $J/\psi_{\mu^+\mu^-}(K^+K^-)_{other}$ | 5.8             |
| $J/\psi_{e^+e^-} f_2'(1525)$    | 7.8             |
| $J/\psi_{\mu^+\mu^-} f_2'(1525)$ | 5.4             |
| PDF model:                      |                 |
| $J/\psi_{e^+e^-}(K^+K^-)_{other}$ | 2.4             |
| $J/\psi_{\mu^+\mu^-}(K^+K^-)_{other}$ | 3.0             |

The total systematic error is calculated separately for the electron and muon channels by adding all components in quadrature. For the calculation of the weighted mean value, the systematic errors are treated as fully correlated.

As an additional result, the S-wave contribution in the $\phi(1020)$ mass region is calculated using the signal yields presented in Table II. Here, we assume that the $K^+K^-$ system in $B^0_s \to J/\psi(K^+K^-)_{other}$ is a pure S-wave. This assumption is supported by the observed helicity angle distribution of $J/\psi(K^+K^-)_{other}$, where the helicity angle is defined as the angle between the $K^+$ meson and the $B^0_s$ meson in the $K^+K^-$ rest frame. Hence, the S-wave fraction ($S$) is the fitted yield of $J/\psi(K^+K^-)_{other}$ events relative to the yield of $J/\psi K^+K^-$ within a specific mass range,

$$S = \frac{\alpha N[J/\psi(K^+K^-)_{other}]}{\alpha N[J/\psi(K^+K^-)_{other}] + \beta N[J/\psi \phi(1020)]},$$

where $\alpha$ and $\beta$ denote the fractions of $J/\psi(K^+K^-)_{other}$ and $J/\psi \phi(1020)$, respectively, within the mass range considered. $N[J/\psi(K^+K^-)_{other}]$ and $N[J/\psi \phi(1020)]$ are the fitted yields from Table III. The results are shown in Table IV for the mass ranges used in hadron collider experiments. While the statistical uncertainty is propagated via the fitted yields, the systematic uncertainty in the S-wave contribution due to the PDF parameterization uncertainties and the PDF model are propagated through $\alpha$ and $\beta$.

To estimate the systematic uncertainty due to a possible $B^0 \to J/\psi f_0(980)$ contribution, as seen, e.g., by LHCb [21], we investigate the difference between the PDF model used in this analysis and the PDF model used by LHCb, which describes the $B^0_s \to J/\psi f_0(980)$ component with a Flatté function in $M(K^+K^-)$. From the S-wave contribution of 1.1% obtained by LHCb, we calculate the value of the parameter $\alpha$ in the LHCb PDF model. We find an increase in $\alpha$ from 0.8% (1.0%) to 5.0% for the CDF (LHCb) mass range in the electron channel, and from 0.9% (1.1%) to 5.0% in the muon channel. We assign this variation as an additional model uncertainty, which we quote separately in Table IV.

### TABLE IV: The $J/\psi K^+K^-$ S-wave contribution in different mass regions around the $\phi(1020)$ resonance. The first error is statistical, the second systematic and the third error is the uncertainty due to a possible $B^0_s \to J/\psi f_0(980)$ contribution.

| Mass range   | 1.009 GeV – 1.028 GeV |
|--------------|------------------------|
| CDF          | (0.8 $\pm$ 0.2)%       |
| This analysis | (0.47 $\pm$ 0.07 $\pm$ 0.22 $^{+0.2}_{-0.1}$)% |

| Mass range   | 1.007 GeV – 1.031 GeV |
|--------------|------------------------|
| LHCb         | (1.1 $\pm$ 0.1)^2%     |
| This analysis | (0.57 $\pm$ 0.09 $\pm$ 0.26 $^{+0.4}_{-0.0}$)% |

### IV. SUMMARY

In summary, we present a measurement of the absolute branching fraction for the decay $B^0_s \to J/\psi \phi(1020)$ (Eq. 2). This result is in good agreement with the CDF Run I result [24, 25] as well as their preliminary results based on the full data sample [24] and the current LHCb result [12]. We obtain evidence for the decay $B^0_s \to J/\psi f_2'(1525)$ (Eqs. 3 and 4), in good agreement with the measurements by LHCb [11, 12] and DØ [11]. We also present a measurement of the entire $B^0_s \to J/\psi K^+K^-$ component including resonant and non-resonant decays (Eq. 5). Finally, we determine the S-wave fraction of $B^0_s \to J/\psi K^+K^-$ in the $\phi(1020)$ mass region (Table IV). Our central value is somewhat lower than the LHCb and CDF values but in agreement with their results when including the systematic error due to a possible $B^0_s \to J/\psi f_0(980)$ component.

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[1] I. Dunietz, R. Fleischer and U. Nierste, 
Phys. Rev. D 63, 114015 (2001) [hep-ph/0012219].
[2] M. Cabibbo, Phys. Rev. Lett. 10, 531 (1963).
[3] Throughout this paper, the inclusion of the charge-
conjugate decay mode is implied.
[4] T. Aaltonen et al. [CDF Collaboration], Phys. Rev. Lett. 
109, 171802 (2012) arXiv:1208.2967 [hep-ex].
[5] V. M. Abazov et al. [D0 Collaboration], Phys. Rev. D 85, 
032006 (2012) arXiv:1109.3166 [hep-ex].
[6] R. Aaij et al. [LHCb Collaboration], Phys. Rev. D 87, 
112010 (2013) arXiv:1304.2600 [hep-ex].
[7] G. Aad et al. [ATLAS Collaboration], JHEP 1212, 072 
(2012) arXiv:1208.0572 [hep-ex].
[8] K. Anikeev et al., FERMILAB Report No. 01-197 (2001),
and references therein.
[9] R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. 
108, 151801 (2012) arXiv:1112.4695 [hep-ex].
[10] V. M. Abazov et al. [D0 Collaboration], Phys. Rev. D 86, 
092011 (2012) arXiv:1204.5723 [hep-ex].
[11] R. Aaij et al. [LHCb Collaboration], Phys. Rev. D 87, 
072004 (2013) arXiv:1302.1213 [hep-ex].
[12] A. Abashian et al. [Belle Collaboration], Nucl. Instr. and 
Meth. A 479, 117 (2002); also see detector section in J. Brodzicka et al., Prog. 
Theor. Exp. Phys. (2012) 04D001.
[13] S. Kurokawa and E. Kikutani, Nucl. Instr. and Meth. A 
499, 1 (2003), and other papers included in this volume. 
T. Abe et al., Prog. Theor. Exp. Phys. (2013) 03A001
and following articles up to 03A011.
[14] S. Esen et al. [Belle Collaboration], Phys. Rev. D 87, 
031101 (2013) arXiv:1208.0323 [hep-ex].
[15] D. J. Lange, Nucl. Instrum. Meth. A 462, 152 (2001).
[16] R. Brun, F. Bruyant, M. Maire, A. C. McPherson and 
P. Zanarini, CERN-DD/EE/84-1.
[17] E. Barberio and Z. Was, Comput. Phys. Commun. 79, 
291 (1994).
[18] G.C. Fox and S. Wolfram, Phys. Rev. Lett. 41, 1581 
(1978).
[19] J. Li et al. [Belle Collaboration], Phys. Rev. Lett. 106, 
121802 (2011).
[20] In this paper, “signal” refers to all of $B^0_d \to J/\psi \phi(1020)(\to K^+ K^-)$, $B^0_d \to J/\psi f_2(1525)(\to K^+ K^-)$ and $B^0_d \to J/\psi K^+ K^-$ other. The notation 
$J/\psi (K^+ K^-)$ other includes the non-resonant decay $B^0_d \to J/\psi K^+ K^-$ as well as decays via resonant intermediate 
states, except the $\phi(1020)$ and the $f_2(1525)$ resonance.
[21] T. Skwarnicki, Ph.D. Thesis, Institute for Nuclear
Physics, Krakow 1986; DESY Internal Report, DESY 
F31-86-02 (1986).
[22] H. Albrecht et al. [ARGUS Collaboration], Phys. Lett. 
B241, 278 (1990).
[23] J. Beringer et al. [Particle Data Group], Phys. Rev. D 
86, 010001 (2012) and 2013 partial update for the 2014
version.
[24] F. Abe et al. [CDF Collaboration], Phys. Rev. D 54, 6596 
(1996) hep-ex/9607003.
[25] CDF Collaboration, Public Note 10795, (2012).