PROCEEDINGS OF SCIENCE

Recent quarkonium results at Belle II

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Belle II offers unique possibilities for discovering and interpreting exotic multiquark bound states to probe the fundamentals of QCD. We present recent results obtained on a unique data set collected at energies above the $\Upsilon(4S)$, including searches for the hidden bottom transition between $Y(10750)$ and $\chi_{bJ}(1P)$ and the measurement of the energy dependence of the $e^+e^- \to b\bar{b}$ cross section.

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1. Introduction

Quarkonium spectroscopy is an excellent probe for the study of QCD in the nonperturbative regime [1]. In recent years various collaborations, in particular experiments at e^+e^- colliders, discovered a number of unexpected quarkonium-like states labeled as X, Y, and Z states in both the charmonium and bottomonium mass regions. Since the properties of these exotic hadrons are not predicted by the quark model, different partonic arrangements are being considered, such as compact tetraquarks, mesonic molecules and hybrids [2]. More experimental results are needed in this sector for a better understanding of the phenomenology of quarkonium(-like) states and transitions.

The new asymmetric-energy e^+e^- collider SuperKEKB, located at the KEK research facility in Tsukuba, Japan, operates at center-of-mass energy close to the mass of the $\Upsilon(4S)$ resonance in order to study CP violation in the B sector. However, the beam energies can be tuned to perform energy scans that are useful for quarkonium studies. The SuperKEKB collider detains the world record peak instantaneous luminosity $\mathcal{L} = 4.7 \times 10^{34}$ cm^{-2}s^{-1} [3] which has allowed Belle II to collect a data set of 428 fb^{-1} in a few years of operation. The target instantaneous luminosity of 6×10^{35} cm^{-2}s^{-1} will enable Belle II to collect a projected total data set of 50 fb^{-1} over the next decade.

The Belle II detector is a general purpose, nearly 4π magnetic spectrometer incorporating state of the art technology for tracking, calorimetry and particle identification. It consists of several sub-detector components. Two layers of pixelated silicon detectors (PXD) and four layers of double-sided silicon strip sensor (SVD) measure the decay vertex position. The central drift chamber (CDC) allows to measure the trajectories, momenta and dE/dx of charged particles. The barrel-shaped Time-Of-Propagation (TOP) detector and the ring-imaging aerogel Cherenkov radiator (ARICH) measure the Cherenkov radiation for particle identification in the barrel and forward end-cap regions respectively. The K-Long and Muon (KLM) detector located outside of the superconducting coil is used to detect K_L^0 mesons and identify muons. The details of the Belle II detector are described elsewhere [4].

2. Observation of $e^+e^- \to \omega\chi_{bJ}(1P)$ and search for $X_b \to \omega\Upsilon(1S)$ at $\sqrt{s}$ near 10.75 GeV

Recently, the Belle collaboration observed a new structure, Υ(10753), by measuring the energy dependence of the $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$, $(n = 1, 2, 3)$ cross sections at center-of-mass energies ranging from 10.52 to 11.02 GeV [6]. To confirm the existence of this new state and study its properties, Belle II performed an energy scan in the proximity of Υ(10753) collecting 19.3 fb^{-1} at the four center-of-mass energy points $\sqrt{s} = 10.653,\ 10.701,\ 10.745,\ 10.805$ GeV.

The unknown nature of the $Y(10753)$ state is generating a wide interest on the theoretical side. As the newly observed state does not correspond to any pure $b\bar{b}$ resonance, the most conventional interpretations describe $Y(10753)$ as a mixture of the $\Upsilon(4S)$ and $\Upsilon(3D)$ states [7, 8]. Other interpretations consider the state as a hybrid [9] or tetraquark [10, 11] candidate. Models that describe the $Y(10753)$ state as an admixture of the conventional 4S and 3D states predict comparable

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branching fractions for the $Y(10753) \to \pi^+\pi^-\Upsilon(nS)$ and $Y(10753) \to \omega\chi_{bJ}(1P)$ processes [12]. Moreover, the ratio $\frac{\mathcal{B}[Y(10753)\to\omega\chi_{b1}(1P)]}{\mathcal{B}[Y(10753)\to\omega\chi_{b2}(1P)]}$ is expected to be about 1/5 [13].

We present the measurement of the energy dependence of the cross sections $\sigma(e^+e^- \to \omega\chi_{bJ}(1P))$ [14], and the comparison with the analogous measurement by Belle at a higher center-of-mass energy [15]. The reconstruction of the $\omega\chi_{bJ}(1P)$ final state is fully exclusive. The ω meson is tagged via the $\omega \to \pi^+\pi^-\pi^0$ decay and $\chi_{bJ}(1P)$ is reconstructed via the radiative transition $\chi_{bJ}(1P) \to \gamma\Upsilon(1S)$. Finally, $\Upsilon(1S)$ is reconstructed via the di-leptonic decays $\Upsilon(1S) \to l^+l^-$, where $l = \mu,\ e$. In addition, the same final state is used to search for the bottomonium analog of the $X(3872)$ state, denoted as X_b, via the process $e^+e^- \to \gamma X_b \to \gamma\omega\Upsilon(1S)$. This is motivated by the observation of the analogous cascade decay in the charmonium sector $Y(4240) \to \gamma X(3872) \to \gamma\omega J/\psi$ by the BES III collaboration [16].

The online event selection is performed with a trigger [17] that uses the central drift chamber and electromagnetic calorimeter information. The offline event selection is equal for the two investigated channels. We require the events to contain 4 or 5 charged particles to reduce background. The particle identification is based on likelihood information obtained from subdetectors. Pions are identified with 90% efficiency, and at least one of the leptons is identified with 95% efficiency for electrons and 90% efficiency for muons. To reduce the effects of bremsstrahlung and final-state radiation, photons within a 50 mrad cone of the initial electron or positron direction are included in the calculation of the particle four-momentum. The $\Upsilon(1S)$ signal regions are selected by requiring $9.25 < M(e^+e^-) < 9.58$ GeV/c^2 and $9.34 < M(\mu^+\mu^-) < 9.58$ GeV/c^2. We apply a four-constraint (4C) kinematic fit that constrains the total four-momentum of the $\pi^+\pi^-\pi^0\Upsilon(1S)$ combination to the beam four-momentum. In events where more than one candidate is found, we keep only the one with the lowest χ^2.

The signal yields for the processes $e^+e^- \to \omega\chi_{bJ}(1P)$ are measured by performing a 2D unbinned maximum likelihood fit to $M(\pi^+\pi^-\pi^0)$ vs. $M(\gamma\Upsilon(1S)))$. The measurement is done at the three energy points $\sqrt{s} = 10.701,\ 10.745,\ 10.805$ GeV. The signal yields N_J^{sig} at the various scan points are used to measure the energy dependence of the $\sigma(e^+e^- \to \omega\chi_{bJ})$ Born cross sections, which are calculated using

$$\sigma_B(e^+e^- \to \omega\chi_{bJ}) = \frac{N_J^{sig}|1-\Pi|^2}{L\varepsilon\mathcal{B}_{int}(1+\delta_{ISR})} \tag{1}$$

where L is the integrated luminosity, ε is the reconstruction efficiency, $\mathcal{B}_{int}$ is the product of the intermediate branching fractions, $|1-\Pi|^2$ is the vacuum polarization factor and $(1+\delta_{ISR})$ is the radiative correction factor.

The measurements are combined with the results from Belle $\sigma_B(e^+e^- \to \omega\chi_{b1}) = (0.76 \pm 0.16)$ pb and $\sigma_B(e^+e^- \to \omega\chi_{b2}) = (0.29 \pm 0.14)$ pb at $\sqrt{s} = 10.867$ GeV, as shown in figure 1. We observe a strong enhancement of the cross sections near 10.75 GeV, while no obvious peak is observed at $\sqrt{s} = 10.867$ GeV. We fit the energy dependence of the cross section with a coherent sum of a two-body phase space and a Breit-Wigner function

$$\left|\sqrt{\Phi_2(\sqrt{s})} + \frac{12\pi\Gamma_{ee}\mathcal{B}_f\Gamma}{s - M^2 - iM\Gamma}\sqrt{\frac{\Phi_2(\sqrt{s})}{\Phi_2(M)}}e^{i\phi}\right|^2 \tag{2}$$

where Φ_2 is the two-body phase space factor, ϕ is the relative phase between the amplitudes, $\mathcal{B}_f$ is the branching ratio for $Y(10753) \to \omega\chi_{b1}$ or $\omega\chi_{b2}$, M is the mass of $Y(10753)$ and Γ (Γ_{ee}) is its total (electron) width. We keep M and Γ fixed to 10752.7 MeV/c^2 and 35.5 MeV [6] respectively. There are two solutions for both $\Gamma_{ee}\mathcal{B}[Y(10753) \to \omega\chi_{b1}]$ and $\Gamma_{ee}\mathcal{B}[Y(10753) \to \omega\chi_{b2}]$. The first solution (solution I) corresponds to constructive interference and yields $[0.63 \pm 0.39(\text{stat}) \pm 0.20(\text{syst})]$ and $[0.53 \pm 0.46(\text{stat}) \pm 0.15(\text{syst})]$ eV respectively. Solution II corresponds to destructive interference, yielding $[2.01 \pm 0.38(\text{stat}) \pm 0.76(\text{syst})]$ and $[1.32 \pm 0.44(\text{stat}) \pm 0.55(\text{syst})]$ eV. The details concerning systematic uncertainties are reported in ref. [14].

In summary, we observe a significant signal for $e^+e^- \to \omega\chi_{b1}(1P)$ and evidence for $e^+e^- \to \omega\chi_{b2}(1P)$. At $\sqrt{s} = 10.745$ GeV, we measure the ratio $\sigma(e^+e^- \to \omega\chi_{b1})/\sigma(e^+e^- \to \omega\chi_{b2}) = 1.3 \pm 0.6$, which is inconsistent with the prediction for a pure D-wave bottomonium state [18] and in 1.8σ tension with the prediction for a S-D mixed state [13].

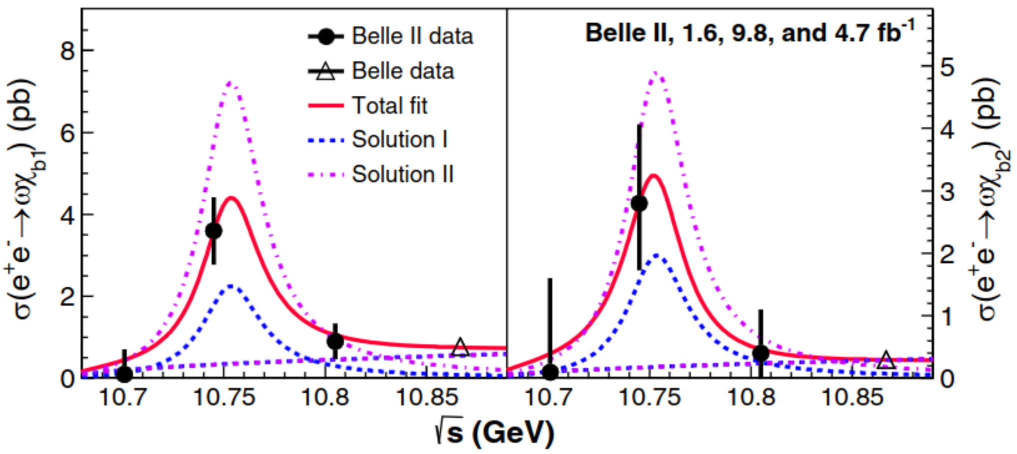

Figure 1: Energy dependence of the $e^+e^- \to \omega\chi_{b1}$ (left) and $e^+e^- \to \omega\chi_{b1}$ (right) cross sections. Circles are the results obtained with the Belle II data and triangles are the result of the Belle analysis. The error bars represent the combined statistical and systematic uncertainties. The red curve show the fit result and the dashed curves the components of the fit function.

We exploit the selected final state to search for the $e^+e^- \to \gamma X_b \to \gamma\omega\Upsilon(1S)$ process by measuring the $\omega\Upsilon(1S)$ invariant mass distribution, shown in figure 2. While a reflection of the $e^+e^- \to \omega\chi_{bJ}$ signal is observed, no narrow structure as expected from a X_b signal is found. We set upper limits at 90% Bayesian credibility on the product of the Born cross section $\sigma(e^+e^- \to \gamma X_b)$ and of the branching ratio $\mathcal{B}[X_b \to \omega\Upsilon(1S)]$. The results at all center-of-mass energies are reported in table 1.

3. Energy dependence of the $e^+e^- \to B\overline{B}$, $B\overline{B}^*$, $B^*\overline{B}^*$ cross sections

The cross section of the e^+e^- annihilation into hadrons is often reported by means of the R ratio

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma^B(e^+e^- \to \mu^+\mu^-)} \tag{3}$$

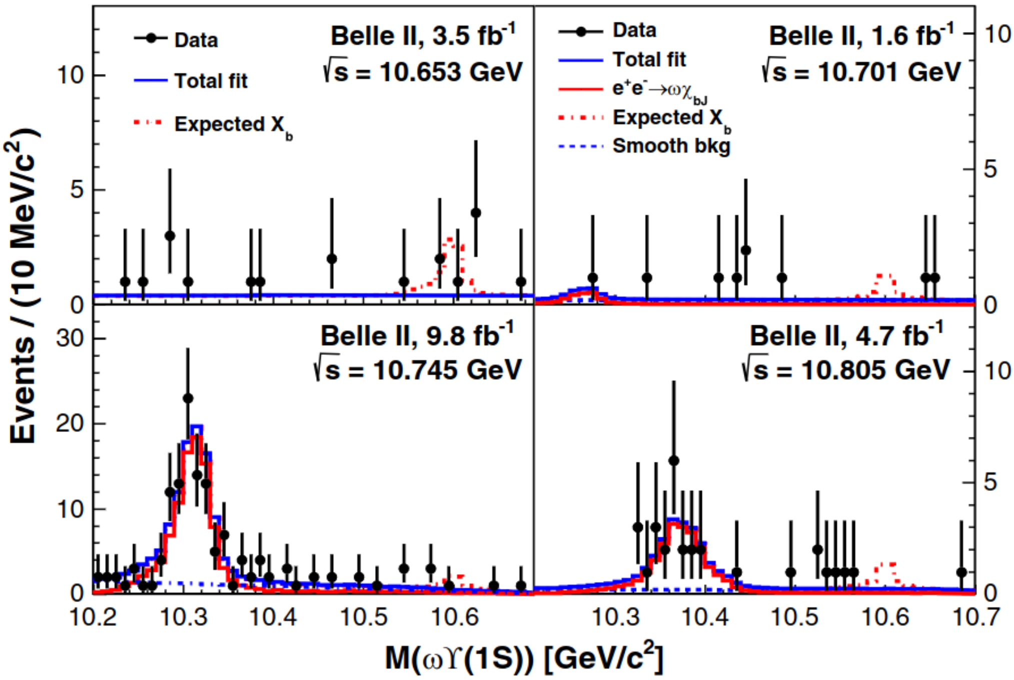

Figure 2: Distributions of the $\omega\Upsilon(1S)$ invariant mass at $\sqrt{s}$ = 10.653, 10.701, 10.745, and 10.805 GeV. The red dash-dotted histograms are obtained from MC with the X_b mass fixed to 10.6 GeV/c^2 and yields fixed to the upper limit values.

Table 1: Upper limits at 90% Bayesian credibility level at different center-of-mass energies for $\sigma^{UL}_{X_b} = \sigma(e^+e^- \to \gamma X_b) \times \mathcal{B}[X_b \to \omega\Upsilon(1S)]$.

$\sqrt{s}$ (GeV)	M_{X_b} (GeV/c^2)	$\sigma^{UL}_{X_b}$(pb)
10.653	10.59	0.55
10.701	10.45	0.84
10.745	10.45	0.14
10.805	10.53	0.47

where $\sigma^B(e^+e^- \to \mu^+\mu^-)$ is the Born cross section for $e^+e^- \to \mu^+\mu^-$. While many precise measurements of R at low energies are available, those at higher energies, such as the bottomonium region, are sparser and less precise. This is mainly due to the fact that the $b\overline{b}$ region has been accessible to fewer experiments. The BaBar and Belle collaborations measured the cross section of $e^+e^- \to b\overline{b}$ at center-of-mass energies ranging from 10.5 to 11.2 GeV [19, 20] by defining the ratio

$$R_b = \frac{\sigma(e^+e^- \to b\overline{b})}{\sigma^B(e^+e^- \to \mu^+\mu^-)}. \tag{4}$$

Belle II has the capability to improve the measurement of R_b by including new energy points. The predominant decay modes of bottomonium states above $B\overline{B}$ threshold are expected to be the open flavor channels $B\overline{B}$, $B\overline{B}^*$, $B^*\overline{B}^*$. The sum of the corresponding cross sections is expected

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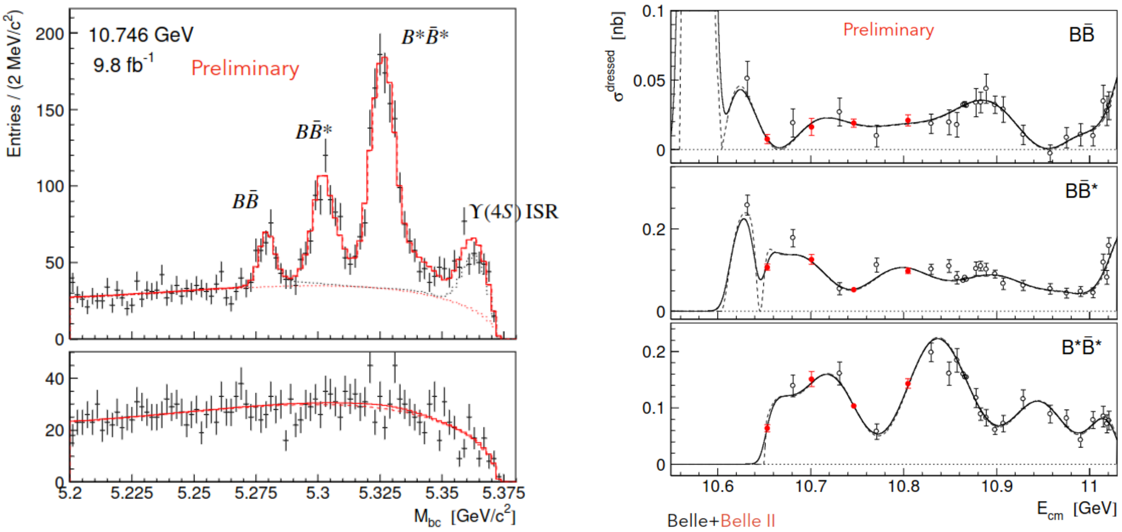
to saturate the $e^+e^- \to b\bar{b}$ cross section . Thus, measuring the exclusive $e^+e^- \to B^{(*)}\overline{B}^{(*)}$ cross sections provides important information on the interactions in this energy region and in particular about the structure of bottomonium(-like) resonances. This topic is of special interest since all the states above threshold exhibit anomalies, especially in transitions to lower bottomonia, which currently are not well understood [21]. The analysis follows the analogous measurement performed at Belle [22].

The method we follow consists in fully reconstructing one B meson in hadronic decay modes using the FEI algorithm [23], and identifying the $B\overline{B}$, $B\overline{B}^*$, and $B^*\overline{B}^*$ signals in the distribution of the beam-constrained mass $M_{bc} = \sqrt{(E_{cm}/2)^2 - p_B^2}$, where E_{cm} is the center-of-mass energy and p_B is the momentum of the reconstructed B candidate. For $B\overline{B}$ pairs, the M_{bc} distribution peaks at the nominal B mass m_B, while for $B\overline{B}^*$ and $B^*\overline{B}^*$ pairs it peaks approximately at $m_B + \frac{\Delta m_{B^*}}{2}$ and $m_B + \Delta m_{B^*}$ respectively, where Δm_{B^*} is the mass difference between the B^* and B mesons. The M_{bc} distribution obtained at $\sqrt{s} = 10.746$ GeV is shown in figure 3a. All the four scan points are used in this analysis.



(a) (b)

Figure 3: Preliminary results of the measurement of the $e^+e^- \to B\overline{B}$, $B\overline{B}^*$, $B^*\overline{B}^*$ cross sections using the Belle II scan data. The signal yields are obtained by fitting the M_{bc} distributions (a) at each value of $\sqrt{s}$. Figure (b) shows the energy dependence of the Born cross section, combined with the measurement from Belle.

The signal yields are estimated by fitting the M_{bc} distributions. The fit function for the signal and peaking background components is constructed in the same way as in ref. [22]. From the yield N of a specific decay mode, the corresponding dressed cross section is calculated as

$$\sigma^{\text{dressed}} = \frac{N}{(1+\delta_{ISR})L\varepsilon} \tag{5}$$

where $(1 + \delta_{ISR})$ is the radiative correction factor, L is the integrated luminosity and ε is the reconstruction efficiency. We fit simultaneously the energy dependence of the $e^+e^- \to$

$B\overline{B}$, $B\overline{B}^*$, $B^*\overline{B}^*$ cross sections and of the total $e^+e^- \to b\overline{b}$ cross section. The results are shown in fig. 3b, where the previous measurement from Belle is included.

4. Summary

We have shown recent measurements performed by the Belle II collaboration using the data set collected in an energy scan above the $\Upsilon(4S)$ resonance. These results are of great importance in understanding the nature of the new $Y(10753)$ state and, more generally, of the bottomonium(-like) states above the open flavor threshold. The uniqueness of the data set collected at center-of-mass energies around 10.75 GeV will enable Belle II to provide unprecedented results in the quarkonium sector in the near future.

References

[1] N. Brambilla *et al.* [Quarkonium Working Group], doi:10.5170/CERN-2005-005 [arXiv:hep-ph/0412158 [hep-ph]].

[2] N. Brambilla, S. Eidelman, C. Hanhart, A. Nefediev, C. P. Shen, C. E. Thomas, A. Vairo and C. Z. Yuan, Phys. Rept. **873** (2020), 1-154 doi:10.1016/j.physrep.2020.05.001 [arXiv:1907.07583 [hep-ex]].

[3] T. Abe, K. Akai, N. Akasaka, M. Akemoto, A. Akiyama, M. Arinaga, Y. Cai, K. Ebihara, K. Egawa and A. Enomoto, *et al.* PTEP **2013** (2013), 03A001 doi:10.1093/ptep/pts102

[4] T. Abe *et al.* [Belle-II], [arXiv:1011.0352 [physics.ins-det]].

[5] T. Kuhr *et al.* [Belle-II Framework Software Group], Comput. Softw. Big Sci. **3** (2019) no.1, 1 doi:10.1007/s41781-018-0017-9 [arXiv:1809.04299 [physics.comp-ph]].

[6] R. Mizuk *et al.* [Belle], JHEP **10** (2019), 220 doi:10.1007/JHEP10(2019)220 [arXiv:1905.05521 [hep-ex]].

[7] B. Chen, A. Zhang and J. He, Phys. Rev. D **101** (2020) no.1, 014020 doi:10.1103/PhysRevD.101.014020 [arXiv:1910.06065 [hep-ph]].

[8] J. F. Giron and R. F. Lebed, Phys. Rev. D **102** (2020) no.1, 014036 doi:10.1103/PhysRevD.102.014036 [arXiv:2005.07100 [hep-ph]].

[9] P. Bicudo, N. Cardoso, L. Mueller and M. Wagner, Phys. Rev. D **103** (2021) no.7, 074507 doi:10.1103/PhysRevD.103.074507 [arXiv:2008.05605 [hep-lat]].

[10] Z. G. Wang, Chin. Phys. C **43** (2019) no.12, 123102 doi:10.1088/1674-1137/43/12/123102 [arXiv:1905.06610 [hep-ph]].

[11] A. Ali, L. Maiani, A. Y. Parkhomenko and W. Wang, Phys. Lett. B **802** (2020), 135217 doi:10.1016/j.physletb.2020.135217 [arXiv:1910.07671 [hep-ph]].

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[12] Z. Y. Bai, Y. S. Li, Q. Huang, X. Liu and T. Matsuki, Phys. Rev. D **105** (2022) no.7, 074007 doi:10.1103/PhysRevD.105.074007 [arXiv:2201.12715 [hep-ph]].

[13] Y. S. Li, Z. Y. Bai, Q. Huang and X. Liu, Phys. Rev. D **104** (2021) no.3, 034036 doi:10.1103/PhysRevD.104.034036 [arXiv:2106.14123 [hep-ph]].

[14] I. Adachi *et al.* [Belle-II], Phys. Rev. Lett. **130** (2023) no.9, 091902 doi:10.1103/PhysRevLett.130.091902 [arXiv:2208.13189 [hep-ex]].

[15] X. H. He *et al.* [Belle], Phys. Rev. Lett. **113** (2014) no.14, 142001 doi:10.1103/PhysRevLett.113.142001 [arXiv:1408.0504 [hep-ex]].

[16] M. Ablikim *et al.* [BESIII], Phys. Rev. Lett. **122** (2019) no.23, 232002 doi:10.1103/PhysRevLett.122.232002 [arXiv:1903.04695 [hep-ex]].

[17] Y. Iwasaki, B. Cheon, E. Won, X. Gao, L. Macchiarulo, K. Nishimura and G. Varner, IEEE Trans. Nucl. Sci. **58** (2011), 1807-1815 doi:10.1109/TNS.2011.2119329

[18] F. K. Guo, U. G. Meißner and C. P. Shen, Phys. Lett. B **738** (2014), 172-177 doi:10.1016/j.physletb.2014.09.043 [arXiv:1406.6543 [hep-ph]].

[19] B. Aubert *et al.* [BaBar], Phys. Rev. Lett. **102** (2009), 012001 doi:10.1103/PhysRevLett.102.012001 [arXiv:0809.4120 [hep-ex]].

[20] D. Santel *et al.* [Belle], Phys. Rev. D **93** (2016) no.1, 011101 doi:10.1103/PhysRevD.93.011101 [arXiv:1501.01137 [hep-ex]].

[21] A. E. Bondar, R. V. Mizuk and M. B. Voloshin, Mod. Phys. Lett. A **32** (2017) no.04, 1750025 doi:10.1142/S0217732317500250 [arXiv:1610.01102 [hep-ph]].

[22] R. Mizuk *et al.* [Belle], JHEP **06** (2021), 137 doi:10.1007/JHEP06(2021)137 [arXiv:2104.08371 [hep-ex]].

[23] T. Keck, F. Abudinén, F. U. Bernlochner, R. Cheaib, S. Cunliffe, M. Feindt, T. Ferber, M. Gelb, J. Gemmler and P. Goldenzweig, *et al.* Comput. Softw. Big Sci. **3** (2019) no.1, 6 doi:10.1007/s41781-019-0021-8 [arXiv:1807.08680 [hep-ex]].