Acta Physica Polonica B Proceedings Supplement **16**, 8-A19 (2023)

RECENT QUARKONIUM RESULTS AT BELLE II*

Dmytro Meleshko, Elisabetta Prencipe, Sören Lange

Justus-Liebig-Universität Gießen, Gießen, Germany

Received 15 February 2023, accepted 24 August 2023, published online 27 October 2023

The Belle experiment has given a substantial contribution into the field of heavy quarkonia. Several new states were announced by Belle for the first time, in both the charmonium and bottomonium spectrum, or the confirmation from Belle corroborated former observations. Belle II is a next-generation experiment, which aims further at continuing expanding the Belle physics program. In this document, we report on the current status of the experiment and early physics results. Particular attention is devoted to the results of the analyses of the data sets collected during the energy scan (Nov. 2021).

DOI:10.5506/APhysPolBSupp.16.8-A19

1. Introduction

The Belle and BaBar B-factories shed light on quarkonium physics. In fact, nowadays we count tens of new states, first observed at these e^+e^- asymmetric colliders. Not all observations showed good agreement with the predictions from theoretical quark models. Soon a plethora of new models arose, clearly showing the inadequacy of the former in classifying all observed states in a unique model. B-factories like BaBar and Belle offer several advantages in searching for new states and rare decays, for example, the setup of these electron–positron detectors allowed for full-event reconstruction and offered a clean environment for this kind of physics. They always represented a complementary tool for the search for exotic states, performed at proton–proton experiments.

B-factories can profit from running at the nominal center-of-mass (CM) energy of the $\Upsilon(4S)$ resonance: $B\bar{B}$ pairs are produced at rest, generating an enormous quantity of $b\bar{b}$, then $c\bar{c}$ pairs. This allows to perform quarkonium studies, both charmonium and bottomonium spectroscopy.

In Belle II, which is a major upgrade of the Belle experiment, the energy of 10.58 GeV (and potentially it is allowed up to 11 GeV) can be reached as a unique physics feature of this experiment. On the other hand, the unique

* Presented at *Excited QCD 2022*, Sicily, Italy, 23–29 October, 2022.

configuration of the Belle II detector gives a chance to study decay channels with soft (energy down to 30 MeV) neutral particles in the final state. This opens the possibility to study various production mechanisms, which, in combination with the large statistics to be collected in the upcoming years, makes the Belle II physics studies unique or complementary compared to the results from current running experiments.

One of the main features of the Belle II detector is the vertex detector (SVD) upgrade and the installation of the Pixel Detector (PXD). In particular, it includes the installation of a 2-layer PXD and a 4-layer SVD detectors for better vertexing performance. The electromagnetic calorimeter (ECAL) upgrade is going, and was made to ensure better background tolerance and readout electronics. The High-Level-Trigger (HLT) upgrade deals with a higher event rate ($\sim$ 30 kHz). Alongside with the detector upgrade, the KEKB accelerator was upgraded to its SuperKEKB version. Its main feature is the so-called "nano-beams" technique, which allows for a decreasing of the transverse dimension of the beam down to the nm scale. This technology in tandem with the factor 2 of the current increase will allow for an upgrade in integrated luminosity, which is planned to be by a factor 40 higher w.r.t. Belle. So far, Belle II has collected 430 fb^{-1} data in roughly 3 years of data taking. This is the same size as the whole dataset of the BaBar experiment and half of all Belle data, collected in less than half time.

The Belle II experiment is experiencing its first long shutdown, waiting for the major upgrade of the second PXD layer, which is supposed to happen in a few months. Before the shutdown, an accelerator and a partial detector upgrade took place. An important day for the collaboration is April 18, 2018, when the first collision took place, which started the first data-collection phase. The target integrated luminosity of the Belle II experiment by the end of its operation is 50 fb^{-1}.

2. Charmonium-like studies

At B-factories, we can search for new *quarkonia* in different production mechanisms. Without any doubt, the suppressed B decays are the most analysed for this purpose. The golden channel to be analysed in B decays is identified in the $B \to KX_{c\bar{c}}$ processes. They appear to be CKM favoured with relatively large branching fractions ($10^{-3} \sim 10^{-4}$). The absolute branching fractions of many of these decays are still unknown, though progresses has been made *e.g.* for $B \to X(3872)K$. The same applies to the *charmonium-charged* Z states, still not confirmed by Belle II due to the lack of statistics. We also state that Z_c neutral partners were not observed yet, which makes the puzzles of $X_{c\bar{c}}$ and Z_c worth revising, when more data is available.

We devote particular attention to the most cited resonance discovered by Belle, the $X(3872)$. Its early search with limited Belle II data (62 fb^{-1}) brought observation of 14.4 ± 4.6 events (4.5σ), which is considered to be the first $X(3872)$ observation in Belle II. At the same time, MC studies shown a 20% $\psi(2S)$ reconstruction efficiency gain w.r.t. Belle. However, the most intriguing side of the new $X(3872)$ study at Belle II refers to its width measurement in $D^0\bar{D}^0\pi^0$ decays. The Belle experiment was the first to observe the $X(3872)$ in this decay mode. The advantage of the $D^0\bar{D}^0\pi^0$ mode compared to $J/\psi\pi^+\pi^-$ is a significantly smaller Q value (7.05 ± 0.18 *vs.* 495.65 ± 0.17 MeV). This allows to push the boundaries down, when it comes to mass resolution (684 ± 8 keV *vs.* 1.93 ± 0.04 MeV), width the UL measurement (≈ 280 keV[1,2] *vs.* $0.96^{+0.19}_{-0.18} \pm 0.21$ [1]) and systematic uncertainties (110 keV [2]).

The study of the so-called Y family decays into c-baryon pairs (Λ_c^+, Σ_c^-, $\Sigma_c^+\Sigma_c^-$) and cs-meson pairs ($D_sD_{s2}(2573)$, $D_sD_{s0}^*(2317)$) via initial-state radiation (ISR) represents a unique physics case at Belle II. In particular, the well-known $Y(4260)$ state still needs to be rediscovered by Belle II. Our MC simulations, based on the Belle analyses, predict 60 $Y(4260)$ events over an integrated luminosity of 100 fb^{-1}, which may open the room for new line-shape-study analysis. The Belle II program includes the analysis of other ISR processes, such as the search for Z-charged states in decays such as $Z_{cs} \to K^\pm J/\psi$, $D_s^- D^{*0}$+c.c., which were not observed at Belle.

In addition, we underline that the J^{PC} measurement of the $X(3915)$ decaying into $\omega J/\psi$ draws particular attention in two-photon processes. This is another way to study *quarkonia* at B-factories, as well as the observation of $X(4350)$ decaying into $\phi J/\psi$. We also mention that $e^+e^- \to (c\bar{c})_{J=1}(c\bar{c})_{J=0}$ production rule puzzle, and J^{PC} of the $X(3940)$ measurement catches our eye on the double charmonium processes.

3. Bottomonium-like studies

The CM energy of B-factories grants *bottomonia* a pole position for studying various Υ, Y_b, and Z_b states. This was monetized in the discoveries of $h_b(1P, 2P)$ by BaBar [3] and $\eta_b(2S)$ [4], $h_b(1P, 2P)$ [4], $Z_b(10610, 10650)^\pm$ [5], and $Y(10753)$ [6] by Belle.

Aiming at complementing this legacy, the Belle II bottomonium program also includes: the study of the $\Upsilon(5S)$ and $\Upsilon(6S)$ discrepancy in $\pi\pi\Upsilon(nS)$ and $\eta\pi\pi$ decays, deeper study of the 10.750 GeV/c^2 energy region, and general $c\bar{c}$ and $b\bar{b}$ spectra discrepancy.

[1] With 50 fb^{-1} of collected data and at 90% C.L.

[2] The prediction of $X(3872)$ width provided by the Flaté fit is $220^{+70+11}_{-60-130}$ keV.

The first step taken in this direction has been the study of ISR events, and direct $\Upsilon(nS) \to \Upsilon(mS)$ transitions with early Belle II data (72 fb^{-1}). The result of this preliminary study brought to the confirmation of the transitions formerly seen in Belle, and to the first observation of the $\gamma_{\rm ISR}\Upsilon(3S) \to \pi^+\pi^-\Upsilon(2S)$ transition with Belle II data, which was not seen in Belle at all (see Fig. 1). A precise $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(nS)$ Dalitz analysis is ongoing to complement this picture.

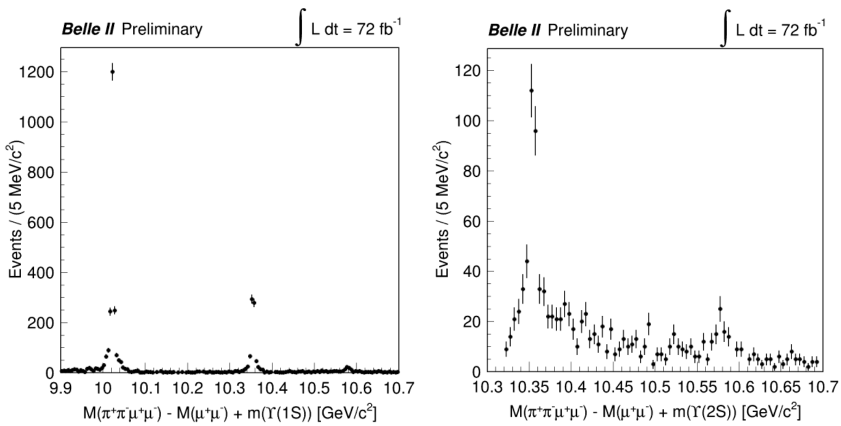

Fig. 1. Plots of $M(\pi^+\pi^-\mu^+\mu^-) - M(\mu^+\mu^-) + m(\Upsilon(nS))$ with a requirement of $|M(\mu\mu) - m(\Upsilon(nS))| < 75$ MeV$/c^2$, where $m(\Upsilon(nS))$ represents the nominal $\Upsilon(nS)$ mass ($n = 1, 2$).

Since the discovery of the $Y(10753)$ [6] in Belle energy scan data, its intrinsic nature remains still unclear. Its interpretation as a pure $\Upsilon(3S)$ state contradicts with theory [7], while its location on the mass scale makes unlikely its molecular interpretation. We do not even try to mention in this context its tetraquark and hybrid interpretations, for which a long debate has been ongoing. In addition to that, the similarity between $\pi\pi J/\psi$ and $\pi\pi\Upsilon$ cross sections [6, 8] might indicate a common deflating mechanism. In order to raise the curiosity and the attention of the reader, we mention that the $Y(4260)$ was observed by BESIII in $\gamma X(3872)$ and $\omega\chi_{c0}$ decays. Thus, the logical question arises, if we should also expect $Y_b(10753)$ decaying into γX_b, with $X_b \to \omega\Upsilon(1S)$.

The Belle energy scan produced valuable and successful data analyses, so the same we expect in Belle II. In November 2021, a sequence of 5 runs at different CM energies in the range from 10.579 to 10.810 GeV was performed at SuperKEKB. During these runs, a total dataset of 15 fb^{-1} has been accumulated (factor 4 larger w.r.t. Belle). The 10.750 GeV$/c^2$ energy region has been revised with the new data. In the new study [9], two processes with the identical final-state products have been studied: $e^+e^- \to \omega\chi_{cJ}$ and $e^+e^- \to \gamma X_b$. In the first decay mode, 3 different $E_{\rm CM}$ have been exploited ($\sqrt{s}$ = 10.701, 10.745, 10.805 GeV) in order to calculate cross sections and complement them with the cross section acquired by Belle (at $\sqrt{s} = 10.867$ GeV). These 4 values are eventually enough to study σ_b energy dependence. In the meantime, the second decay mode has been studied to search for the potential $X(3872)$ counterpart candidate, *e.g.* X_b, at 4 different energies.

The study of the $e^+e^- \to \omega\chi_{cJ}$ decay mode demonstrated significant signals (11σ and 5σ) at $\sqrt{s} = 10.745$ and 10.805 GeV (see Fig. 2). Based on the acquired cross-section values, one can calculate the values of $\mathcal{B}_f(Y_b(10753) \to \omega\chi_{b1})/\mathcal{B}_f(Y_b(10753) \to \pi^+\pi^-\Upsilon(1S))$ and $\mathcal{B}_f(\Upsilon(5S) \to \omega\chi_{b1})/\mathcal{B}_f(\Upsilon(5S) \to \pi^+\pi^-\Upsilon(1S))$ fractions, which appear to be one order of magnitude different. This may be considered an unambiguous sign of the differences in the intrinsic nature of $Y_b(10753)$ and $\Upsilon(5S)$. The acquired cross-section values were complemented with the one from Belle and fitted with two solutions, the constructive and the destructive interference (see Fig. 3). The total fit function clearly indicates an enhancement near 10.753 GeV and does not hint to any structure in the vicinity of $\Upsilon(5S)$. Another result to mention here is the $\Gamma_{ee}\mathcal{B}_f(\Upsilon(10753) \to \omega\chi_{b1})/\Gamma_{ee}\mathcal{B}_f(\Upsilon(10753) \to \omega\chi_{b2})$ fraction, which appears to be close to 1. The result agrees with the HQET predictions [10].

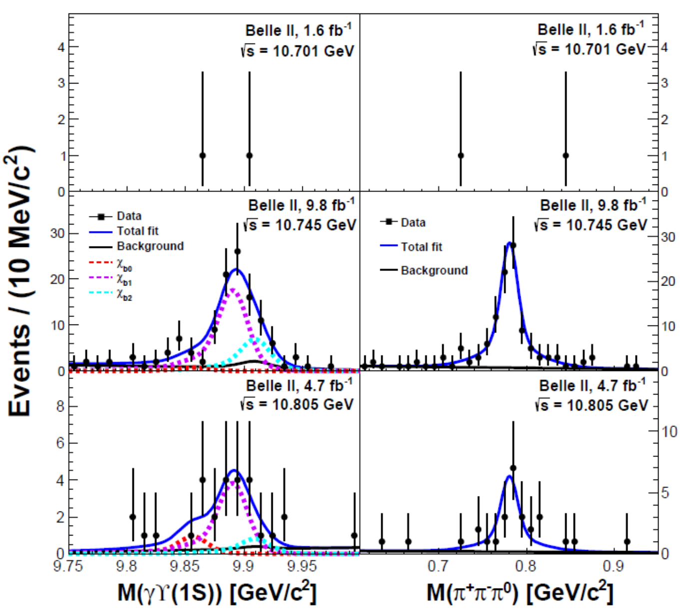

Fig. 2. Distribution of (left) $\gamma\Upsilon(1S)$ and (right) $\pi^+\pi^-\pi^0$ masses in data at $\sqrt{s}$ = 10.701, 10.745, and 10.805 GeV with fit results overlaid.

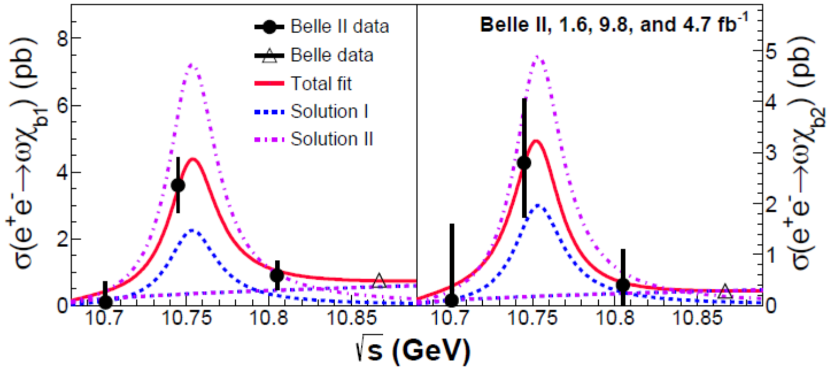

Fig. 3. Energy dependence of the Born cross sections for $e^+e^- \to \omega\chi_{bJ}$. Circles show the Belle II measurements [9], triangles represent Belle results [6].

Search for resonances in $\omega\Upsilon(1S)$ structure at different energies did not deliver X_b observation, but only a distinctive $\omega\chi_{bJ}$ reflection is observed. We evaluate in any case $\sigma^{\mathrm{UL}}_{X_b}$ upper limit, for each E_{CM} and $M(X_b)$ in the energy range from 10.45 to 10.65 GeV.

4. Summary

B-factories started the XYZ studies, now complemented and pushed by studies covered by other experiments. Belle II is performing well, and will deliver new results that will shed light on the most puzzling questions of heavy quarkonium. The long-term plan of the collaboration is to accumulate a data sample of 50 ab^{-1}. Early analyses at Belle II suggest possibilities for potential discoveries in the field of quarkonia.

REFERENCES

[1] LHCb Collaboration (R. Aaij *et al.*), *J. High Energy Phys.* **2020**, 123 (2020).

[2] Belle II Collaboration (F. Abudinén *et al.*), *Phys. Rev. Lett.* **127**, 211801 (2021).

[3] Belle Collaboration (I. Adachi *et al.*), *Phys. Rev. Lett.* **108**, 032001 (2012).

[4] Belle Collaboration (R. Mizuk *et al.*), *Phys. Rev. Lett.* **109**, 232002 (2012).

[5] Belle Collaboration (A. Bondar *et al.*), *Phys. Rev. Lett.* **108**, 122001 (2012).

[6] Belle Collaboration (R. Mizuk *et al.*), *J. High Energy Phys.* **2019**, 220 (2019).

[7] S. Godfrey, K. Moats, *Phys. Rev. D* **92**, 054034 (2015).

[8] BESIII Collaboration (M. Ablikim *et al.*), *Phys. Rev. Lett.* **118**, 092001 (2017).

[9] Belle II Collaboration (I. Adachi *et al.*), *Phys. Rev. Lett.* **130**, 091902 (2023), `arXiv:2208.13189 [hep-ex]`.

[10] A.G. Grozin, `arXiv:hep-ph/9908366`.