PoS PROCEEDINGS OF SCIENCE

Recent Bottomonium Results From Belle II

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The Belle II experiment is a substantial upgrade of both the Belle detector and the KEKB e^+e^- accelerator currently operating at the KEK laboratory in Japan. It is uniquely capable to search for exotic multiquark bound states and probe the fundamentals of QCD. An unprecedented dataset was collected above the $\Upsilon(4S)$ energy to study the region around $\sqrt{s} = 10.75$ GeV, where enhanced transition rates to lighter bottomonia suggest the existence of a new exotic bound state.

10th International Conference on Quarks and Nuclear Physics (QNP2024)
8-12 July, 2024
Barcelona, Spain

*Speaker

1. Introduction

Quarkonia were investigated in particular by the first generation B factories and a great number of unexpected so-called XYZ states in the charmonium and bottomonium mass regions were discovered [1–3]. These states are not predicted by the quark model, such that different, more exotic compositions are considered. Configurations like tetraquarks, hybrids or mesonic molecules are a way of treating these XYZ states [4]. In that sense, the unique dataset collected above the $\Upsilon(4S)$ resonance by Belle II is an excellent probe of quantum chromodynamics (QCD). In the following, a look at the $\Upsilon(10753)$ and several of its decay channels will be given below. Additionally, the energy the dependence of the $e^+e^- \to B^{(*)}\bar{B}^{(*)}$ cross sections is discussed.

2. $\Upsilon(10753)$ state

The $\Upsilon(10753)$ state is a bottomonium-like vector state and was observed as an enhancement (a bump) in the cross-section of $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$ ($n = 1, 2, 3$) by Belle [5]. Its mass and width are $M = 10756.6 \pm 2.7 \pm 0.9$ MeV and $\Gamma = 29.0 \pm 8.8 \pm 1.2$ MeV, respectively. These values are not consistent with states predicted by the quark model, which makes it difficult assigning the $\Upsilon(10753)$ to a conventional bottomonium state [6–9]. The unidentified composition is accompanied by great interest on the theoretical side with interpretations ranging from a mixture of $\Upsilon(4S)$ and $\Upsilon(3D)$ states [10, 11], to a hybrid [12], a hadronic molecule with admixture of a bottomonium [13], or a tetraquark [14, 15], but there is no definite explanation yet.

2.1 $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS)$

Recently, the Belle collaboration observed an enhancement at 10.75 GeV by measuring the energy dependence of the $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$ ($n = 1, 2, 3$) cross section with a total of 21 fb^{-1} at evenly distributed points between 10.63 and 11.02 GeV [5]. To confirm and study the properties of this new structure, Belle II collected a total of 19.3 fb^{-1} of data at four energy points, namely $\sqrt{s}$ =10.653, 10.701, 10.745 and 10.806 GeV. With this data, we study the mentioned cross section, again as a function of $\sqrt{s}$, to further constrain the mass and the width of the new structure. Additionally we perform a study on the di-pion spectrum and look for intermediate states, which may provide a deeper understanding of the unconventional nature of the observation at 10.75 GeV.

Born cross sections for $\Upsilon(10753)$,$\Upsilon(5S)$ and $\Upsilon(6S)$, as well as the fit with three interfering Breit-Wigner functions to it can be seen in Figure 1. Signals are observed in $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(1S)$ and $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(2S)$ with 4.1 σ and 7.2 σ respectively. No significant enhancement is found for $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(3S)$. The cross section ratios $\sigma(\Upsilon(10753) \to \pi^+\pi^-\Upsilon(1S, 3S))$ / $\sigma(\Upsilon(10753) \to \pi^+\pi^-\Upsilon(2S))$ are $0.46^{+0.15}_{-0.12}$ and $0.10^{+0.05}_{-0.04}$ and were calculated for the first time [16]. The ratio for the transition to $\Upsilon(1S)$ is compatible with $\Upsilon(5S, 6S) \to \pi^+\pi^-\Upsilon(1S)$, but the transition to $\Upsilon(3S)$ is 3-4 times smaller for the $\Upsilon(10753)$ than for $\Upsilon(5S)$ and $\Upsilon(6S)$. When looking at the di-pion invariant mass in the $\pi^+\pi^-\Upsilon(1S)$ transition and the simulated phase-space distribution, agreement between the two is found. In contrast to that, the di-pion invariant mass in $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(2S)$ is similar to the distribution in $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ and can be described by the $\Upsilon(nS)$ transition amplitudes. Since Belle has

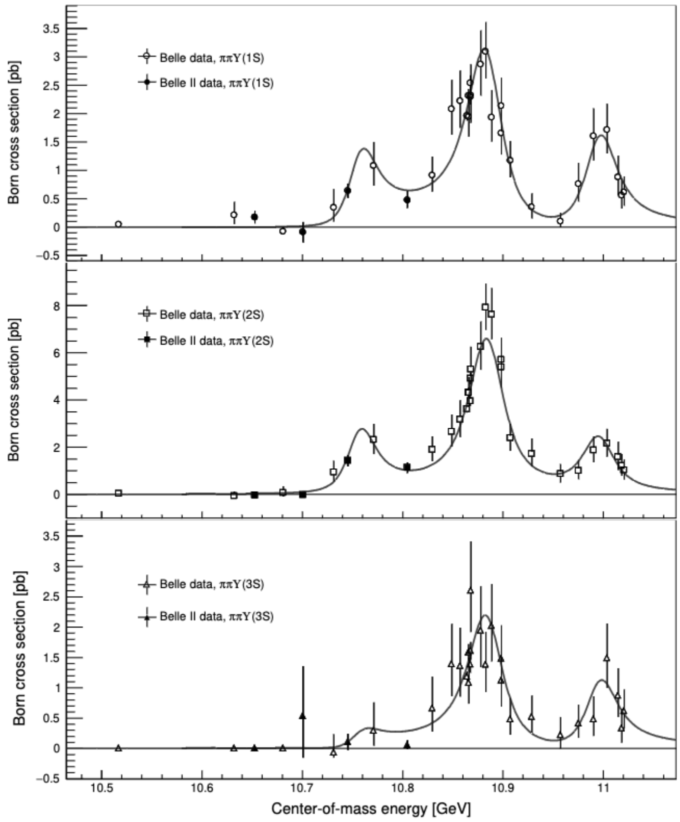

Figure 1: Measured cross section for $\Upsilon(10753)$ (left peak),$\Upsilon(5S)$ (central peak) and $\Upsilon(6S)$ (right peak) and their decay to $\pi^+\pi^-\Upsilon(1S)$ in the top plot, $\pi^+\pi^-\Upsilon(2S)$ in the middle plot and $\pi^+\pi^-\Upsilon(3S)$ on the bottom. The solid line represents the fit [16].

observed a $Z_b(10610/10650)^\pm \to \pi^\pm\Upsilon(nS)$ signal in $\Upsilon(5S) \to \pi^+\pi^-\Upsilon(nS)$ decays and the mass-threshold of $M(\pi^\mp Z_b(10610)^\pm)$ sits right at 10.75 GeV, we also search for intermediate decays in $\pi^+\pi^-\Upsilon(1S, 2S)$ transition at $\sqrt{s}$ = 10.745 GeV and 10.806 GeV. However, no signals are found for $Z_b(10610)^\pm$ or $Z_b(10650)^\pm$ in ΔM_π, but the data is consistent with the simulated phase-space distribution.

2.2 $\Upsilon(10753) \to \omega\chi_{bJ}(1P)$ and $\Upsilon(10753) \to \gamma X_b$

Inspired by the three decay modes of the $\psi(4230)$, hadronic decays into $J/\psi\pi^+\pi^-$ and $\omega\chi_{cJ}$ and a (radiative) decay to $\gamma X(3872)$, we now take a look at the bottomonium counterpart of the latter two transitions.

One interpretation of the $\Upsilon(10753)$ is an admixture between a $\Upsilon(4S)$ and a $\Upsilon(3D)$ state and within that interpretation, predictions of comparable branching fractions for $\Upsilon(10753) \to \omega\chi_{bJ}$ and $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS)$ are made. The ω is reconstructed via $\omega \to \pi^+\pi^-\pi^0$ and the $\chi_{bJ}(1P)$ via the decay $\chi_{bJ}(1P) \to \gamma\Upsilon(1S)$. Access to the $\Upsilon(1S)$ is given via the annihilation decay $\Upsilon(1S) \to \mu^+\mu^-/e^+e^-$. The same final states from above can be used to search for $e^+e^- \to \gamma X_b$ and then $X_b \to \omega\Upsilon(1S)$, where the X_b is the bottomonium analog of the $X(3872)$ state. This

is motivated by a transition in the charmonium sector, where $\psi(4230) \to \gamma X(3872)$ and then $X(3872) \to \omega J/\psi$ was observed by the BES III collaboration [17].
In Figure 2, we present the mass-distributions of $M(\gamma\Upsilon(1S))$ and $M(\pi^+\pi^-\pi^0)$. A significant signal for $\omega\chi_{b1}(1P)$ and evidence for the decay to $\omega\chi_{b2}(1P)$ at $\sqrt{s} = 10.745$ GeV is observed by performing a two-dimensional unbinned likelyhood fit [18]. The ratio $R_{12} = \sigma(e^+e^- \to \omega\chi_{b1}(1P))/\sigma(e^+e^- \to \omega\chi_{b2}(1P)) = 1.3 \pm 0.6$, which contradicts the prediction for a pure $\Upsilon(3D)$ state ($R_{12} = 15$), and is in tension (1.8 σ) with the prediction for a $\Upsilon(4S) - \Upsilon(3D)$ mixed state ($R_{12} = \frac{1}{5}$) [9].
In the search for X_b, no evidence of a signal in the invariant mass distribution of $\omega\Upsilon(1S)$ could be

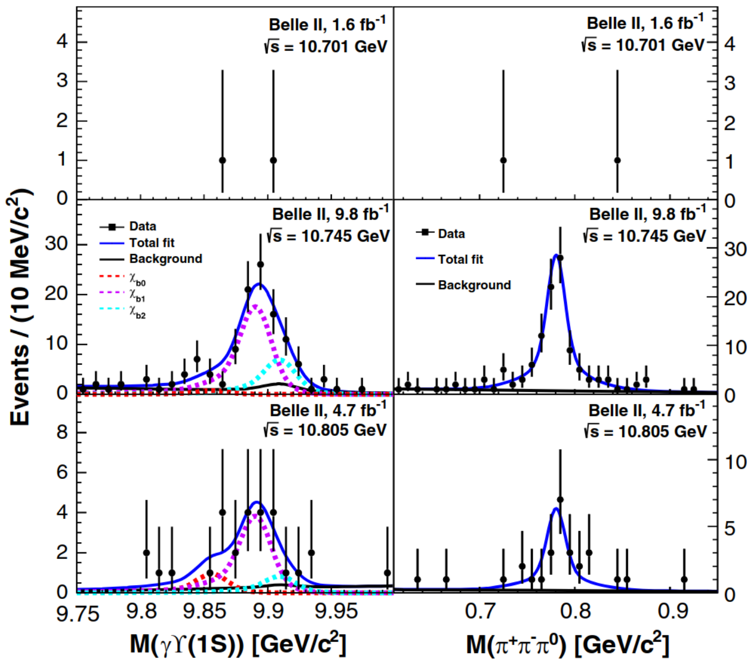

Figure 2: Mass distribution of $\gamma\Upsilon(1S)$ (left) and $\pi^+\pi^-\pi^0$ (right) for different center-of-mass energies $\sqrt{s}$. χ_{b1} and χ_{b2} signal contributions are clearly visible for $\sqrt{s} = 10.753$ GeV (middle), as well as χ_{b0}, χ_{b1} and χ_{b2} signals for $\sqrt{s} = 10.805$ (bottom) in the $M(\gamma\Upsilon(1S))$ distributions. Figure from [18].

obtained for X_b masses between 10.45 GeV and 10.65 GeV (see Figure 3). While a reflection of the $\omega\chi_{bJ}(1P)$ signal can be seen, no narrow structure from the X_b is found. However, for those masses and energies, we set upper limits at 90% CL on the products of Born cross section $e^+e^- \to \gamma X_b$ and branching fraction $X_b \to \omega\Upsilon(1S)$ [18].

3. Energy dependence of $e^+e^- \to B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$ cross section

Hadrons that contain a heavy $b\bar{b}$ quark pair and have masses above the open bottom threshold exhibit anomalous properties. $\pi\pi$ transitions to lower bottomonium levels are strongly enhanced and η transitions are not strongly suppressed, when compared to states below the open bottom threshold. In contrast to that, decays to open flavor mesons are expected to be the dominant decay channels and the main contribution to the total $b\bar{b}$ cross section.
We report the measurement of the exclusive cross section $e^+e^- \to B^{(*)}\bar{B}^{(*)}$, which provides

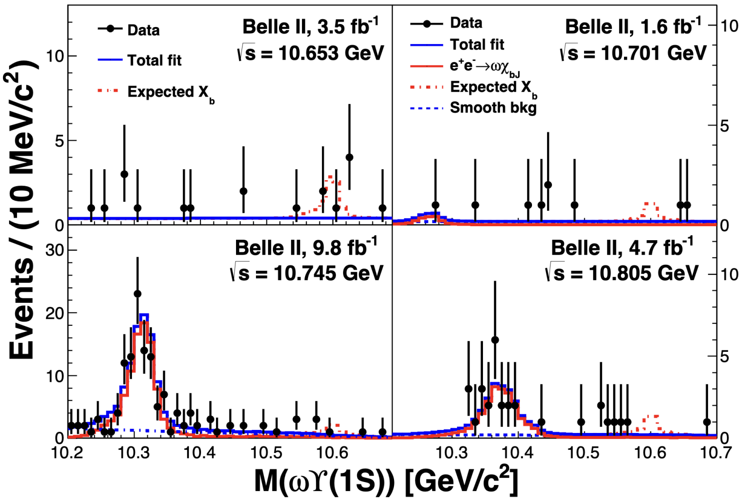

Figure 3: Invariant mass distribution of $\omega\Upsilon(1S)$. The dashed red line shows the expectation of X_b from simulation, whereas the other peaks in the lower mass regions are reflections of the $\omega\chi_{bJ}(1P)$ signal. No X_b structure was found. Figure from [18].

important information on the interactions in the open bottom energy region and the structure of the states above threshold [19].

We fully reconstruct one of the B-mesons in the hadronic channel and then use the beam-constrained mass M_{bc} to identify $B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$, where $M_{bc} = \sqrt{(E_{cm}/2)^2 - p_B^2}$. E_{cm} is the center-of-mass energy and p_B the momentum of the B-candidate measured in the center-of-mass frame. Essentially, the M_{bc} distribution peaks at the nominal B-meson mass m_B for $B\bar{B}$ events, whereas for $B\bar{B}^*$ and $B^*\bar{B}^*$ events, peaks at $m_B - \Delta m_{B*}/2$ and $m_B - \Delta m_{B*}$, respectively. Here, Δm_{B*} denotes the mass difference between a B- and a B^*-meson. The signal yields are estimated by fitting the M_{bc} distributions. The fit for signal and peaking background is performed identical to the previous measurement by Belle [20]. From the yield N of a specific decay mode, the corresponding dressed cross section is calculated as $\sigma_{dressed} = \frac{N}{(1+\delta_{ISR})\ L\ \epsilon}$, where $(1+\delta_{ISR})$ is the radiative correction factor, L is the integrated luminosity and ϵ is the reconstruction efficiency. A simultaneous fit of the energy dependence for each of the three cross sections mentioned above and of the total cross section $e^+e^- \longrightarrow b\bar{b}$ was done. The results and those of the previous Belle measurement are shown in Figure 4.

Figure 5 shows the sum of exclusive cross sections $B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$ measured with the Belle II data set collected above $\Upsilon(4S)$ and the Belle data set, both superimposed on the total cross section. At the energy points of the 2021 energy scan data, the sum of the three cross sections agrees well with the total cross section, however, we do not fully saturate it at those higher energies yet. The deviation at higher energies is assumed to stem from the contribution of B_s^0 mesons, $B^{(*)}\bar{B}^{(*)}\pi\pi$ multibody final states and the production of bottomonia in association with light hadrons.

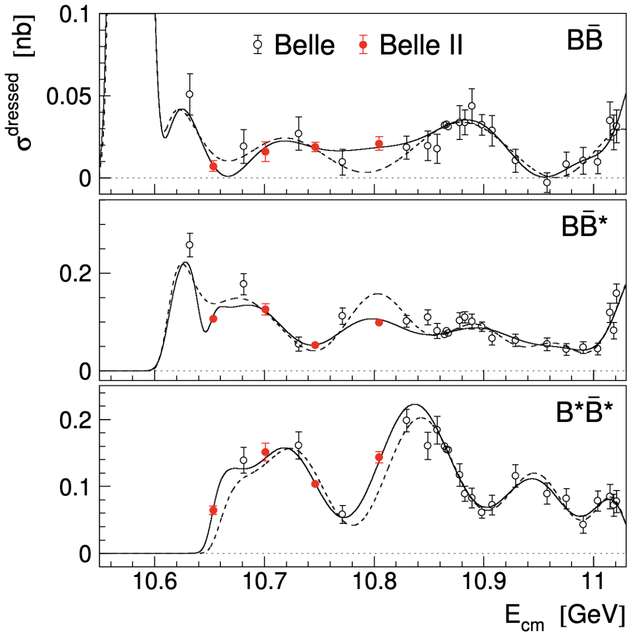

Figure 4: $e^+e^- \to B^{(*)}\bar{B}^{(*)}$ cross sections using Belle II energy scan data (red dots) combined with the results from the previous analysis at Belle (black dots) and fitted (solid black line). The dashed line represents the fit without the Belle II energy scan data. A sharp rise in the $B^*\bar{B}^*$ and a dip in the $B\bar{B}^*$ is observed. The first Belle II data point (red dot in bottom plot) is only 2 MeV above $B^{0^*}\bar{B}^{0^*}$. This could indicate a bound state. Figure from [19].

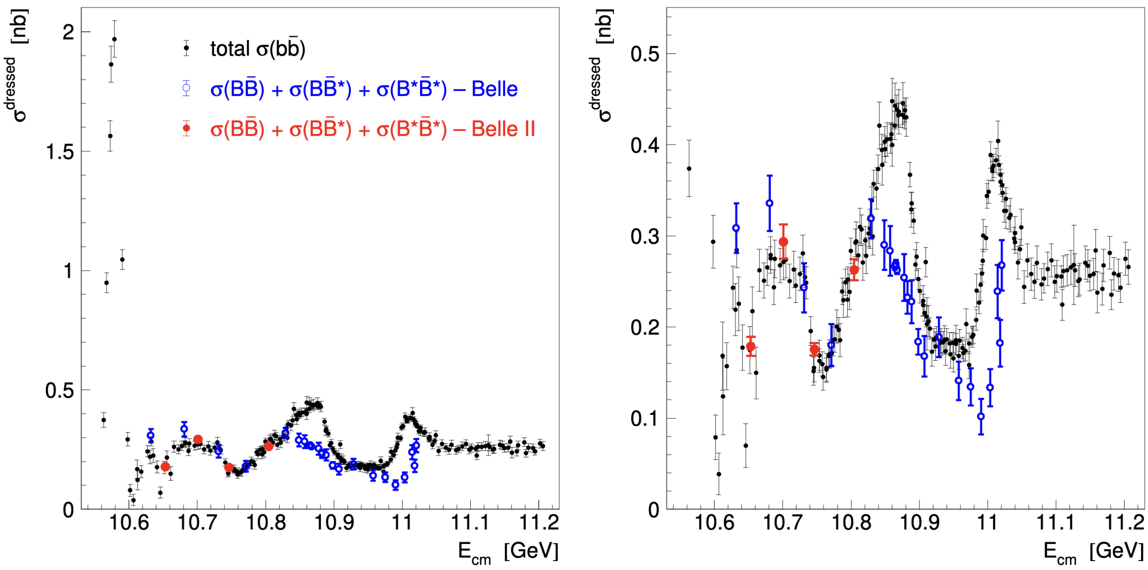

Figure 5: The sum of the exclusive cross sections, $B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$ of this work at Belle II and previously at Belle, superimposed on the total $b\bar{b}$ cross section, measured by Belle [21] and BaBar [22] (black dots). A close-up of the low cross-section region is displayed on the right. Figures from [19].

4. Summary

New production mechanisms, transitions and many unexpected XYZ states were observed in bottomonium by the first generation B factories, but their current understanding is still rather incomplete. The results presented here confirm the $\Upsilon(10753)$ state and further elucidate the knowledge of bottomonium-like states above the open flavor threshold. The unique data set collected at center-of-mass energies around 10.75 GeV will enable Belle II to provide further understanding in the bottomonium sector and more exciting results can be expected.

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