Quarkonium/QCD results at Belle II

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This proceeding summarizes recent discoveries and interprets exotic multiquark-bound states to probe the fundamentals of QCD at the Belle and Belle II experiments. The results are on a unique data set collected at energies higher than Υ (4S), including searches for the hidden bottom transition between $\Upsilon(10750)$ and χ_{bJ}.

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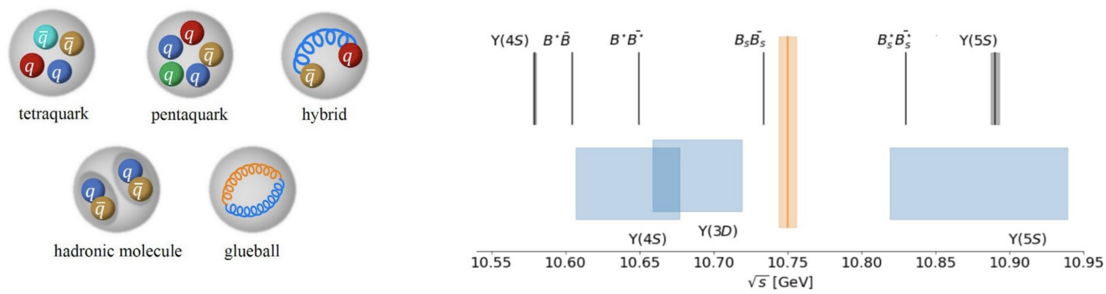
1. Introduction

Heavy quarkonium spectroscopy offers multiple opportunities to investigate the non-perturbative behavior of quantum chromodynamics. The $\Upsilon(10753)$[known as the Υ_b], bottomonium-like vector states observed in $e^+e^- \to \pi^+\pi^-\Upsilon(nS)(n=1,2,3)$ by Belle [1] and in fits to the $e^+e^- \to b\bar{b}$ cross sections at energies $\sqrt{s}$ from 10.6 to 11.2 GeV [2], is particularly interesting. The $\Upsilon(10753)$ has been interpreted as a conventional bottomonium [3–10], hybrid [11], hadronic molecule with a small admixture of a bottomonium [12] or tetraquark state [13, 14]. Interpretations as an admixture of the conventional 4S and 3D states predict comparable branching fractions of 10^{-3} for $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS)$ [8] and $\Upsilon(10753) \to \omega\chi_{bJ}$ [7], where χ_{bJ} denotes $\chi_{bJ}(1P)$ throughout. In this interpretation, the branching fraction for $\Upsilon(10753) \to \omega\chi_{b1}$ is expected to be about 1/5 of that for $\Upsilon(10753) \to \omega\chi_{b2}$ [7]. In addition, the process $e^+e^- \to \gamma X_b$, $X_b \to \omega\Upsilon(1S)$, which shares the same final states as $\Upsilon(10753) \to \omega\chi_{bJ}$, provides access to the X_b.

The X_b is the posited bottomonium counterpart of the $X(3872)$ [15]. Its existence has been predicted in molecular and tetraquark models, with masses close to the $B\bar{B}^*$ threshold or in the 10 to 11 GeV/c^2 range, respectively. Unlike in $X(3872)$ decays, due to negligible isospin breaking effects, the X_b may decay preferentially into $\pi^+\pi^-\pi^0\Upsilon(1S)$ instead of $\pi^+\pi^-\Upsilon(1S)$. Searches for an X_b state in $\pi^+\pi^-\Upsilon(1S)$ by CMS and ATLAS [16, 17], and in $e^+e^- \to \gamma X_b$, $X_b \to \pi^+\pi^-\pi^0\Upsilon(1S)$ near the $\Upsilon(10860)$ [known as the $\Upsilon(5S)$] energy by Belle [18], yielded null results.

The $e^+e^- \to b\bar{b}$ cross-section at various energies above the $B\bar{B}$ threshold show complicated spectra that are hard to describe with resonance shapes. Rescattering and opening of the various $B\bar{B}$ thresholds cause oscillatory behavior due to the coupled-channel effect. The coupled-channel approach is necessary to study the shape of the cross-section of $B^{(*)}\bar{B}^{(*)}$.



(a) The $\Upsilon(10753)$ has been interpreted as a conventional bottomonium, hybrid, hadronic molecule with a small admixture of a bottomonium or tetraquark state, etc.

(b) The $e^+e^- \to b\bar{b}$ cross-section at various energies above the $B\bar{B}$ threshold show complicated spectra that are hard to describe with resonance shapes.

Figure 1: To study the nature of $\Upsilon(10753)$ and improve the accuracy below $\Upsilon(5S)$, we use electron-positron collisions produced by the SuperKEKB collider at $\sqrt{s}$= 10.653, 10.701, 10.745, and 10.805 GeV. Data samples collected with the Belle II detector correspond to integrated luminosities of 3.5, 1.6, 9.8, and 4.7 fb^{-1}, respectively [19].

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

The Belle II observations of $e^+e^- \to \omega\chi_{bJ}(1P)$ [20] are presented in Figure 2 and Table 1. We find significant signals of χ_{b1} and χ_{b2} at $\sqrt{s}$ = 10.745 GeV. The significances of the χ_{b0}, χ_{b1} and χ_{b2} signals at 10.745 and 10.805 GeV are 11σ and 4.5σ, respectively.

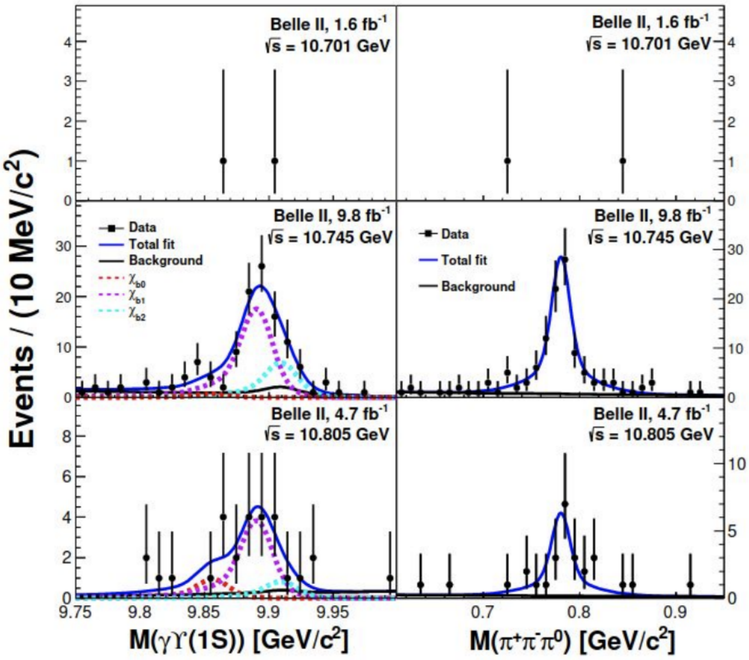


Figure 2: Distributions of (left) $\gamma\Upsilon(1S)$ and (right) $\pi^+\pi^-\pi^0$ masses in data at $\sqrt{s}$ = 10.701, 10.745, and 10.805 GeV with fit results overlaid.

Channel	$\sqrt{s}$(GeV)	N^{sig}	$\Sigma(\sigma)$	$\sigma_B(pb)$	$\Sigma_{all}(\sigma)$
$e^+e^- \to \omega\chi_{b0}$	10.701	<3.0	-	<16.6	-
$e^+e^- \to \omega\chi_{b1}$		<3.9	-	<1.2	
$e^+e^- \to \omega\chi_{b2}$		<4.0	-	<2.5	
$e^+e^- \to \omega\chi_{b0}$	10.745	<12.0	0.5	<11.3	11
$e^+e^- \to \omega\chi_{b1}$		$68.9^{+13.7}_{-13.5}$	5.9	$3.6^{+0.7}_{-0.7} \pm 0.5$	
$e^+e^- \to \omega\chi_{b2}$		$27.6^{+11.6}_{-10.0}$	3.1	$2.8^{+1.2}_{-1.0} \pm 0.4$	
$e^+e^- \to \omega\chi_{b0}$	10.805	<9.9	1.2	<11.4	4.5
$e^+e^- \to \omega\chi_{b1}$		$15.0^{+6.8}_{-6.2}$	2.7	<1.7	
$e^+e^- \to \omega\chi_{b2}$		$3.3^{+5.3}_{-3.8}$	0.8	<1.6	

Table 1: Measurements of $e^+e^- \to \omega\chi_{bJ}$ at $\sqrt{s}$ = 10.701, 10.745, and 10.805 GeV. Σ is the signal significance.

In addition, we search for the X_b in $e^+e^- \to \gamma X_b$ with $X_b \to \omega\Upsilon(1S)$ at $\sqrt{s}$ = 10.653, 10.701, 10.745, and 10.805 GeV. Distributions of $M[\omega\Upsilon(1S)]$ for events within $0.70 < M(\pi^+\pi^-\pi^0) < 0.86$

GeV/c^2 are shown in Figure 3. The results show no evidence of X_b, the partner of X(3872) in bottomonium. The upper limits on cross sections are set for $10.45 < M_{X_b} < 10.65$ GeV/c^2.

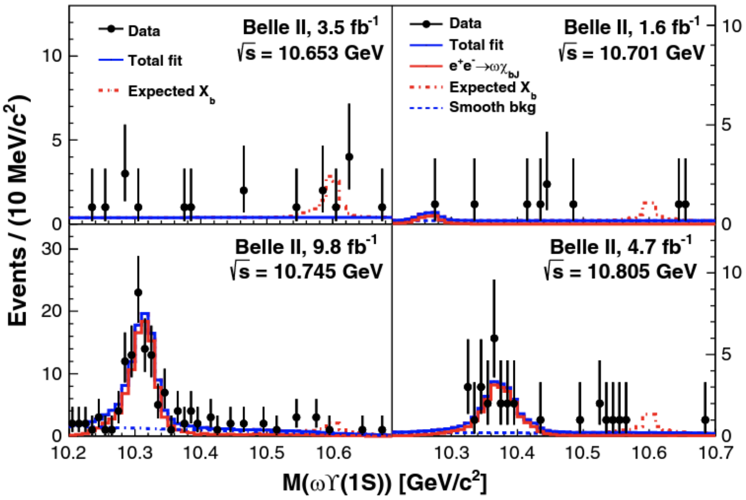


Figure 3: Distributions of $\omega\Upsilon(1S)$ mass from data at $\sqrt{s}$ = 10.653, 10.701, 10.745, and 10.805 GeV. The red dash-dotted histograms are from $e^+e^- \to \gamma X_b$ with $X_b \to \omega\Upsilon(1S)$ simulated events, and with the X_b mass fixed at 10.6 GeV/c^2 and yields fixed at the upper limit values.

3. Energy dependence of the $e^+e^- \to B^{(*)}\bar{B}^{(*)}$ cross section

The energy dependence of the $e^+e^- \to B^{(*)}\bar{B}^{(*)}$ cross-section study at Belle [21] is to perform a full reconstruction of one B meson in hadronic channels and then to identify the $B^{(*)}\bar{B}^{(*)}$ signals. Using the M_{bc} distribution, $M_{bc} = \sqrt{(E_{cm}/2)^2 - p_B^2}$, where E_{cm} is the center-of-mass (c.m.) energy and p_B is the B-candidate momentum measured in the c.m. frame. The M_{bc} distribution for $B\bar{B}$ events peaks at the nominal B-meson mass, m_B, while the distributions for $B\bar{B}^*$ and $B^*\bar{B}^*$ events peak approximately at $m_B - \frac{\Delta m_{B^*}}{2}$ and $m_B - \Delta m_{B^*}$, respectively, where Δm_{B^*} is the mass difference of the B^* and B mesons [22]. If the B meson originates from a $B^* \to B\gamma$ decay, the signal is expanded due to the photon recoil momentum. Therefore the energy variable $\Delta E = E_B - E_{cm}/2$ is replaced by $\Delta E' = \Delta E + M_{bc} - m_B$, where E_B is the energy of B candidate. The $|\Delta E'| < 18$ MeV and the signal is identified using M_{bc}, shown as in Figure 4.

The comparison of $\sigma_{b\bar{b}}$ and $\sigma_{B\bar{B}} + \sigma_{B\bar{B}^*} + \sigma_{B^*\bar{B}^*}$ is in Figure 5. It shows good agreement in the low energies. The difference at higher energy is due to $B_s^{(*)}\bar{B}_s^{(*)}$, multi-body $B^{(*)}\bar{B}^{(*)}\pi(\pi)$, etc.

4. Summary

The Belle and Belle II experiments have provided new results recently. Here shows the Belle II observations of $e^+e^- \to \omega\chi_{bJ}(1P)$ [20]. We find significant signals of χ_{b1} and χ_{b2} at $\sqrt{s}$ = 10.745 GeV. The significances of the χ_{b0}, χ_{b1} and χ_{b2} signals at 10.745 and 10.805 GeV are 11σ and 4.5σ, respectively. In addition, we search for the X_b in $e^+e^- \to \gamma X_b$ with $X_b \to \omega\Upsilon(1S)$ at

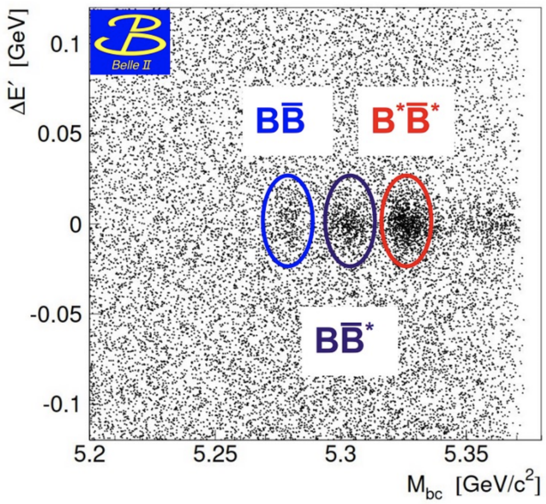


Figure 4: The $\Delta E'$ versus M_{bc} distribution for the $\Upsilon(5S)$ data, at E_{cm} = 10.746 GeV.

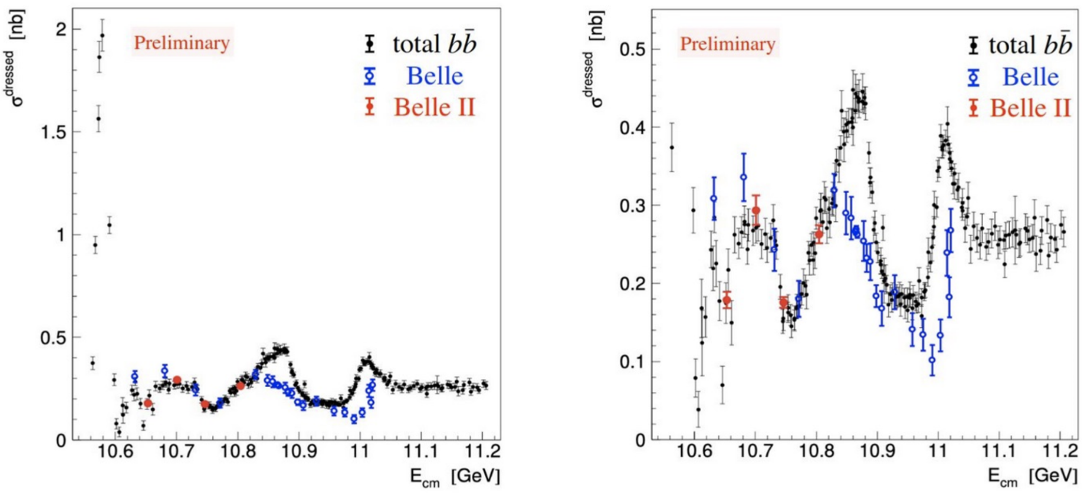


Figure 5: The comparison of $\sigma_{b\bar{b}}$ and $\sigma_{B\bar{B}} + \sigma_{B\bar{B}^*} + \sigma_{B^*\bar{B}^*}$. (Left) It shows good agreement in the low energies. (Right) The difference at higher energy is due to $B_s^{(*)}\bar{B}_s^{(*)}$, multi-body $B^{(*)}\bar{B}^{(*)}\pi(\pi)$, etc.

$\sqrt{s}$ = 10.653, 10.701, 10.745, and 10.805 GeV. The results show no evidence of X_b, the partner of X(3872) in bottomonium. The upper limits on cross sections are set for $10.45 < M_{X_b} < 10.65$ GeV/c^2. The energy dependence of the $e^+e^- \to B^{(*)}\bar{B}^{(*)}$ cross-section study at Belle [21] is to perform a full reconstruction of one B meson in hadronic channels and then to identify the $B^{(*)}\bar{B}^{(*)}$ signals. The comparison of $\sigma_{b\bar{b}}$ and $\sigma_{B\bar{B}} + \sigma_{B\bar{B}^*} + \sigma_{B^*\bar{B}^*}$ shows good agreement in the low energies, however the difference at higher energy is due to $B_s^{(*)}\bar{B}_s^{(*)}$, multi-body $B^{(*)}\bar{B}^{(*)}\pi(\pi)$, etc. Continuous efforts from experiment and theory are still needed. Beyond these important results, the accumulated knowledge on MC modeling, analysis techniques, etc. will be beneficial for future measurements by Belle II.

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