Recent quarkonium results at Belle II

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On behalf of the Belle II Collaboration

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Heavy quarkonium spectroscopy is an excellent laboratory to study non-perturbative QCD!

- **Below \( B\bar{B} \) threshold states** are well described by the potential models.
- **Above \( B\bar{B} \) threshold states** exhibit unexpected properties:
  - The transitions to lower bottomonium with the emission of light hadrons are not suppressed (violate OZI);
  - The \( \eta \) transitions are not suppressed compared to \( \pi^+\pi^- \) transitions (violate HQSS);
  - Two charged \( Z_b^+ \) states are observed.

- The states with other quantum numbers can be produced via hadronic or radiative transitions.

- Conventional bottomonium (pure \( b\bar{b} \) states)
- Bottomonium-like states (mix of \( b\bar{b} \) and \( B\bar{B} \))
- Purely exotic charged states (\( Z_b^+ \))
Discovery of $\Upsilon(10753)$

- The $\Upsilon(10753)$ was observed in the energy dependence of $e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^-$ ($n = 1,2,3$) cross sections by Belle.

<table>
<thead>
<tr>
<th>$\Upsilon(10860)$</th>
<th>$\Upsilon(11020)$</th>
<th>New structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$ (MeV/$c^2$)</td>
<td>$10885.3 \pm 1.5^{+2.2}_{-0.9}$</td>
<td>$11000.0^{+4.0}<em>{-4.5}^{+1.0}</em>{-1.3}$</td>
</tr>
<tr>
<td>$\Gamma$ (MeV)</td>
<td>$36.6^{+4.5}_{-3.9}^{+0.5}$</td>
<td>$23.8^{+8.0}<em>{-6.8}^{+0.7}</em>{-1.8}$</td>
</tr>
</tbody>
</table>

- Refit of Babar and Belle $\sigma(e^+e^- \rightarrow b\bar{b})$ [CPC 44 (2020) 8, 083001]:
  - Dip near 10.75 GeV likely caused by interference between BW and smooth component.

Possible interpretations:
- Conventional bottomonium?
- Hybrid state?
- Tetraquark state?
- Hadronic molecule with a small admixture of a bottomonium?
Belle II experiment

- Asymmetric $e^+e^-$ collider at KEK provides unique clean environment.
- Upgraded detector (better vertex and particle identification performances).
- World-record instantaneous luminosity: $4.7 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ ($\times 2$ of the Belle peak luminosity).
- Total integrated luminosity: $424\text{fb}^{-1}$.
In November 2021, Belle II collected 19 fb$^{-1}$ of scan data at four energy points near 10.75 GeV.

Physics goals: (1) understand the nature of the $\Upsilon(10753)$; (2) improve precision of exclusive cross-sections below $\Upsilon(5S)$. 
Observation of $e^+e^- \rightarrow \omega \chi_{bJ}(1P)$ and search for $X_b \rightarrow \omega \Upsilon(1S)$ at $\sqrt{s}$ near 10.75 GeV

[PRL 130 091902 (2023)]
Interpretations as an admixture of conventional 4S and 3D states predict comparable branching fractions of $10^{-3}$ for $\Upsilon(10753) \rightarrow \pi^+\pi^-\Upsilon(nS)$ and $\Upsilon(10753) \rightarrow \omega\chi_{bJ}(1P)$.

[PRD104, 034036 (2021), PRD 105, 074007 (2022)]

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>$N^{\text{sig}}$</th>
<th>$\Sigma(\sigma)$</th>
<th>$\sigma_B$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^- \rightarrow \omega\chi_{b0}$</td>
<td>10.701</td>
<td>$&lt; 3.0$</td>
<td>-</td>
<td>$&lt; 16.6$</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \omega\chi_{b1}$</td>
<td>$&lt; 3.9$</td>
<td>-</td>
<td>-</td>
<td>$&lt; 1.2$</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \omega\chi_{b2}$</td>
<td>$&lt; 4.0$</td>
<td>-</td>
<td>-</td>
<td>$&lt; 2.5$</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \omega\chi_{b0}$</td>
<td>10.745</td>
<td>$&lt; 12.0$</td>
<td>0.5</td>
<td>$&lt; 11.3$</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \omega\chi_{b1}$</td>
<td>$68.9_{-13.5}^{+13.7}$</td>
<td>5.9</td>
<td>$3.6_{-0.7}^{+0.7}$</td>
<td>± 0.5</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \omega\chi_{b2}$</td>
<td>$27.6_{-10.0}^{+11.6}$</td>
<td>3.1</td>
<td>$2.8_{-1.0}^{+1.2}$</td>
<td>± 0.4</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \omega\chi_{b0}$</td>
<td>10.805</td>
<td>$&lt; 9.9$</td>
<td>1.2</td>
<td>$&lt; 11.4$</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \omega\chi_{b1}$</td>
<td>$15.0_{-6.2}^{+6.8}$</td>
<td>2.7</td>
<td>-</td>
<td>$&lt; 1.7$</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \omega\chi_{b2}$</td>
<td>$3.3_{-3.8}^{+5.3}$</td>
<td>0.8</td>
<td>-</td>
<td>$&lt; 1.6$</td>
</tr>
</tbody>
</table>

We perform two dimensional un-binned maximum likelihood fits to the $M(\gamma\Upsilon(1S))$ and $M(\pi^+\pi^-\pi^0)$ distributions.

$\chi_{bJ}$ candidates

$\omega$ candidates

11$\sigma$

4.5$\sigma$
The $e^+e^- \rightarrow \omega \chi_{bJ}(1P)$ cross sections are enhanced at $\Upsilon(10753)$.

Combine Belle II measurements with Belle measurement [PRL 113, 142001(2014)] to fit cross sections:

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

The mass and width are fixed to the 10752.7 MeV/c^2 and 35.5 MeV. [JHEP 10, 220 (2019)]

$\sigma(e^+e^- \rightarrow \omega \chi_{bJ}(1P)) / \sigma(e^+e^- \rightarrow \pi^+\pi^- \Upsilon(nS)) \sim 1.5$ at $\sqrt{s} = 10.745$ GeV

$\sigma(e^+e^- \rightarrow \omega \chi_{bJ}(1P)) / \sigma(e^+e^- \rightarrow \pi^+\pi^- \Upsilon(nS)) \sim 0.15$ at $\sqrt{s} = 10.867$ GeV

It may indicate different internal structures for $\Upsilon(10753)$ and $\Upsilon(5S)$.

$\sigma(e^+e^- \rightarrow \omega \chi_{bJ}(1P)) / \sigma(e^+e^- \rightarrow \pi^+\pi^- \Upsilon(nS)) = 1.3 \pm 0.6$ at $\sqrt{s} = 10.745$ GeV

Contradicts the expectation for a pure D-wave bottomonium state of 15 [PLB 738, 172 (2014)].

A 1.8$\sigma$ difference with the prediction for a S-D-mixed state of 0.2 [PRD 104, 034036 (2021)].
Search for $X_b \rightarrow \omega \Upsilon(1S)$

- The $X_b$ is the posited bottomonium counterpart of the $X(3872)$;
- No evidence of $X_b$ signal;
- The peaks are the reflections of $e^+ e^- \rightarrow \omega \chi_b J$.
- Upper limits on cross sections are set for $M(X_b) \in [10.45, 10.65]$ GeV.

From simulated events with $m(X_b) = 10.6$ GeV/$c^2$ The yield is fixed at the upper limit at 90% C.L.

<table>
<thead>
<tr>
<th>Upper limits at 90% C.L. on $\sigma_B(e^+ e^- \rightarrow \gamma X_b) \times B(X_b \rightarrow \omega \Upsilon(1S))$</th>
<th>$\sqrt{s}$(GeV)</th>
<th>10.653</th>
<th>10.701</th>
<th>10.745</th>
<th>10.805</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m(X_b) = 10.6$ GeV</td>
<td>0.46</td>
<td>0.33</td>
<td>0.10</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>$m(X_b) = (10.45, 10.65)$ GeV</td>
<td>(0.14, 0.55)</td>
<td>(0.25, 0.84)</td>
<td>(0.06, 0.14)</td>
<td>(0.08, 0.37)</td>
<td></td>
</tr>
</tbody>
</table>
Search for $e^+e^- \to \omega \eta_b(1S)$ and $e^+e^- \to \omega \chi_{b0}(1P)$ at $\sqrt{s} = 10.745$ GeV with Belle II

[New for this conference]
Search for $e^+e^- \rightarrow \omega \eta_b(1S)/\chi_{b0}(1P)$

- Tetraquark interpretation of the $\Upsilon(10753)$ predicts enhancement of the $\Upsilon(10753) \rightarrow \omega \eta_b(1S)$ transition:
  \[
  \frac{\Gamma(\omega \eta_b)}{\Gamma(\pi^+\pi^-\Upsilon)} \sim 30
  \]  
  [CPC 43, 123102 (2019)]

- The $e^+e^- \rightarrow \omega \chi_{bJ}(1P)(J = 1,2)$ was found to be enhanced at $\sqrt{s} = 10.745$ GeV. The $e^+e^- \rightarrow \omega \chi_{b0}(1P)$ transition was not observed due to low branching fraction $\mathcal{B}(\chi_{b0}(1P) \rightarrow \Upsilon(1S)\gamma) = (1.94 \pm 0.27)\%$.
  [PRL 130 091902 (2023)]

- In this work, we reconstruct the $\omega$ meson via the $\pi^+\pi^-\pi^0$ mode, and then search for the $\eta_b(1S)$ and $\chi_{b0}(1P)$ states in the recoil mass spectrum of $\omega$ candidate.

\[
M_{\text{recoil}}(\pi^+\pi^-\pi^0) = \sqrt{\left(\frac{E_{\text{cm}} - E^*}{c^2}\right)^2 - \left(\frac{p^*}{c}\right)^2}
\]
The measured cross-section contradicts the prediction of tetraquark model in Ref. [CPC 43, 123102 (2019)].

No clear $\eta_b(1S)$ and $\chi_{b0}(1P)$ signals are observed.

Upper limits at the 90% C.L. on the Born cross sections are set.

This measurement and JHEP 10, 220 (2019):

$\sigma^B(e^+e^- \rightarrow \eta_b(1S)\omega) < 2.5 \text{pb at } 10.745 \text{ GeV}$

$\sigma^B(e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^-) \sim 5 \text{ pb at } 10.75 \text{ GeV}$
Measurement of the energy dependence of the $e^+e^- \rightarrow B^{(*)}\bar{B}^{(*)}$ cross sections at Belle II
The $B^{(*)}\bar{B}^{(*)}$ are expected to be dominant decay channels for excited bottomonium-like states.

The measured cross sections can be used in the coupled channel analysis of all available scan data to extract the parameter of $\Upsilon(10753)$.

Method:

- Fully reconstruct one $B$ in hadronic decays;
- Identify signals with $M_{bc}$:

\[ M_{bc} = \sqrt{(E_{cm}/2)^2 - p_B^2} \]

Contribution of $\Upsilon(4S) \rightarrow B\bar{B}$ production via ISR is visible, well described by the fit.
$e^+e^- \rightarrow B(\ast)\bar{B}(\ast)$ cross sections

- $\sigma(e^+e^- \rightarrow B^*\bar{B}^*)$ increases rapidly above $B^*\bar{B}^*$ threshold. The energy of the nearby point is only 5MeV above the threshold. High value of the cross section is surprising since the phase space of this reaction grows as the $3/2$ power of the difference between the beam energy and the threshold energy.

- **Possible interpretation:** resonance or bound state of $B^*\bar{B}^*$ (or $b\bar{b}$) near threshold [MPLA 21, 2779 (2006)].

- Also explains a narrow dip in $\sigma(e^+e^- \rightarrow B\bar{B}^*)$ near $B^*\bar{B}^*$ threshold by destructive interference between $e^+e^- \rightarrow B\bar{B}^*$ and $e^+e^- \rightarrow B^*\bar{B}^* \rightarrow B\bar{B}^*$.

- The $Y(nS)\pi^+\pi^-$ and $h_b(1P)\eta$ final states could also be enhanced [PRD 87, 094033 (2013)].
Summary

- **Observation of** $e^+ e^- \rightarrow \omega \chi_{bJ}(1P)$ **near** $\sqrt{s} = 10.75$ GeV:
  - $\sigma(e^+ e^- \rightarrow \omega \chi_{bJ}(1P))[J = 1,2]$ has a strong enhancement at 10.75 GeV;
  - Confirmation of $\Upsilon(10753)$ and observation of its new decay channel.

- **Search for** $e^+ e^- \rightarrow \omega \eta_b(1S)$ **and** $e^+ e^- \rightarrow \omega \chi_{b0}(1P)$:
  - No signals are observed, and upper limits on the Born cross sections are set;
  - The measured cross-section contradicts the prediction of tetraquark model.

- **Energy dependency of** $e^+ e^- \rightarrow \bar{B}B, \bar{B}B^*, \text{and } B^*\bar{B}^*$ **cross sections:**
  - Confirmation of “oscillatory” behavior, improvement of the accuracy;
  - Rapid rise of $\sigma(e^+ e^- \rightarrow B^*\bar{B}^*)$ above threshold—resonance or bound state of $B^*\bar{B}^*$?

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**Thanks for your attention!**
Uses the coupled-channel approach to perform a global fit to various cross section energy dependences.

Using data:
- Two-body exclusive cross sections
  \[ \sigma \left( e^+e^- \rightarrow B_s^{(*)} \bar{B}_s^{(*)} \right) \];
- Three-body exclusive cross sections
  \[ \sigma \left( e^+e^- \rightarrow \Upsilon(nS)/h_b(mP)\pi^+\pi^- \right) \] (n = 1,2,3; m = 1,2);
- Combined Belle and Babar \( R_b \) measurements.

Includes \( \Upsilon(4S), \Upsilon(10753), \Upsilon(5S), \) and \( \Upsilon(6S) \) poles.

Results:
- pole positions (masses and widths) and energy dependence of scattering amplitudes.

[PRD 106 (2022) 9, 094013]
Good agreement at low energy.

Deviation at higher energy is presumably due to $B_s^{(*)}$, multi-body $B^{(*)}\bar{B}^{(*)}\pi(\pi)$ and production of bottomonia with light hadrons.