Exotic quarkonium-like states and spectroscopy at

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Production of $b\bar{b}$ above $B\bar{B}$ threshold

New $\chi_{c0}(2P)$ candidate

Searches for $XYZ$ states in $\Upsilon$ decays

Searches for oddballs in $\Upsilon$ decays
The $\eta$ vs $\pi\pi$ transitions from $Y(nS)$: theory vs exp

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The figure shows the decay widths $\Gamma_{\pi\pi}$ and $\Gamma_\eta$ for transitions from $Y(2S)$ to $Y(1S)$ to $Y(1S)$ to $Y(2S)$, $Y(3S)$ to $Y(1S)$ to $Y(1S)$ to $Y(2S)$, $Y(4S)$ to $Y(1S)$ to $Y(2S)$ to $Y(3S)$, $Y(5S)$ to $Y(1S)$ to $Y(2S)$ to $Y(3S)$ to $Y(4S)$ to $Y(3S)$ to $Y(1P)$ to $Y(1D)$. The plots compare theoretical predictions with experimental data.

- $\eta$ transitions
- $\pi\pi$ transitions
Belle: $e^+e^- \rightarrow h_b(1,2P) \pi\pi$

The analysis of the 6 points (1 fb$^{-1}$ each) in the proximity of the Y(6S) show a clear evidence of dipion transitions to both the $h_b$ states. The small statistics does not allow to quantify the fractions decaying via $Z_b(10610)$ and $Z_b(10650)$.

Belle-II is planning to take more data at Y(6S) during the first or second year of data taking.
The energy dependence of the $b\bar{b}$ cross section in the resonance region exhibits a different behaviour, if compared with the cross sections for exclusive final states

$$e^+e^- \rightarrow \pi^+\pi^- \Upsilon(1,2,3S), \pi^+\pi^- h_b(1,2P)$$

We need to further study the exclusive two-body $B^{(*)}\bar{B}^{(*)}$ and three body $B^{(*)}\bar{B}^{(*)}\pi$ final states, to fully understand the $b\bar{b}$ hadronization and the nature of the $\Upsilon(4,5S)$ resonances.
\[ S(m) = |A_{Z_b(10610)} + A_{Z_b(10650)} + A_{nr}|^2. \]

Simultaneous fit to both the BB*π and B*B*π signals with different assumptions:
- Model-0: Z_b for BB*π and Z'_b for B*B*π
- Model-1: adding A_{nr} to both
- Model-2: allowing Zb+Zb' for BB*π
- Model-3: only A_{nr}

(*) WS: wrong sign  RS: right sign
\[ Z_b', Z_b \] Branching Ratios

<table>
<thead>
<tr>
<th>Channel</th>
<th>Fraction, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z_b(10610) )</td>
<td></td>
</tr>
<tr>
<td>( \Upsilon(1S)\pi^+ )</td>
<td>0.54_{-0.13}^{+0.16}+0.11 \quad 0.17_{-0.06}^{+0.07}+0.03 )</td>
</tr>
<tr>
<td>( \Upsilon(2S)\pi^+ )</td>
<td>3.62_{-0.59}^{+0.59}+0.59 \quad 1.39_{-0.38}^{+0.48}+0.34 )</td>
</tr>
<tr>
<td>( \Upsilon(3S)\pi^+ )</td>
<td>2.15_{-0.42}^{+0.55}+0.60 \quad 1.63_{-0.42}^{+0.53}+0.39 )</td>
</tr>
<tr>
<td>( h_b(1P)\pi^+ )</td>
<td>3.45_{-0.71}^{+0.87}+0.86 \quad 8.41_{-2.12}^{+2.43}+1.49 )</td>
</tr>
<tr>
<td>( h_b(2P)\pi^+ )</td>
<td>4.67_{-1.00}^{+1.24}+1.18 \quad 14.7_{-2.8}^{+3.2}+2.8 )</td>
</tr>
<tr>
<td>( B^+ \bar{B}^{*0} + \bar{B}^0 B^{**} )</td>
<td>85.6_{-2.0}^{+1.5}+1.5 \quad \ldots )</td>
</tr>
<tr>
<td>( B^{*+} \bar{B}^{*0} )</td>
<td>\ldots \quad 73.7_{-4.4}^{+3.4}+2.7 )</td>
</tr>
</tbody>
</table>
Study of $e^+e^- \rightarrow B_s^{(*)}\overline{B}_s^{(*)}$ from 10.77 to 11.02 GeV

Full reconstruction of these channels: $D_s^{(*)}\pi^+, \pi^+\pi^- J/\psi$, $K^+K^- J/\psi$, $K^+K^- \psi'$

$B_s^* \overline{B}_s^* : B_s^* \overline{B}_s^* +c.c. : B_s \overline{B}_s$ at 10.866 GeV

$7 : 0.853 \pm 0.106 \pm 0.053 : 0.638 \pm 0.094 \pm 0.033$

Strong tension with HQSS that predicts 7:4:1
More hadronic transitions

\[ \Upsilon(4S) \to \]
\[ \Upsilon(1S) \pi^+\pi^- \quad 1.7 \pm 0.2 \]
\[ \Upsilon(1S) \eta \quad 4.0 \pm 0.8 \]
\[ \Upsilon(2S) \pi^+\pi^- \quad 1.8 \pm 0.3 \]
\[ h_b(1P) \eta \quad 45 \pm 7 \]

Limited by available channels

Limited by available statistics

\[ \Upsilon(6S) \to \]
\[ \Upsilon(1S) \pi^+\pi^- \quad 137 \pm 32 \]
\[ \Upsilon(2S) \pi^+\pi^- \quad 183 \pm 43 \]
\[ \Upsilon(3S) \pi^+\pi^- \quad 77 \pm 28 \]
\[ Z_b(10610, 10650)^{\pm \pi^\mp} \quad 1300 - 6600 \]

A full scan (1 MeV steps, \( L_d t = 10 \text{ fb}^{-1} \)) from the \( B\bar{B} \) threshold to the maximum available energy will give Belle II a unique opportunity to shed light on the hadronization mechanism.

The $\eta$ and $\pi\pi$ transitions from $Y(4S)$

Data sample: 500 fb$^{-1}$ from $Y(4S)$, 58 from 10.52 GeV
Study of both dipion and eta transitions from the 4S
Search for the $Y(D) \to Y(1S)$ eta transition

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Result</th>
<th>PDG value $^{[17]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(Y(4S) \to \pi^+\pi^-Y(1S))$</td>
<td>$(8.2 \pm 0.5 \pm 0.4) \times 10^{-5}$</td>
<td>$(8.1 \pm 0.6) \times 10^{-5}$</td>
</tr>
<tr>
<td>$B(Y(4S) \to \pi^+\pi^-Y(2S))$</td>
<td>$(7.9 \pm 1.0 \pm 0.4) \times 10^{-5}$</td>
<td>$(8.6 \pm 1.3) \times 10^{-5}$</td>
</tr>
<tr>
<td>$B(Y(4S) \to \eta Y(1S))$</td>
<td>$(1.70 \pm 0.23 \pm 0.08) \times 10^{-4}$</td>
<td>$(1.96 \pm 0.28) \times 10^{-4}$</td>
</tr>
<tr>
<td>$\mathcal{R}$ as in Eq. 1</td>
<td>$2.07 \pm 0.30 \pm 0.11$</td>
<td>$2.41 \pm 0.42$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Result</th>
<th>Expected value $^{[12]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{ISR}(Y(2S))$</td>
<td>$(17.36 \pm 0.19 \pm 0.69)$ pb</td>
<td>$(17.1 \pm 0.3)$ pb</td>
</tr>
<tr>
<td>$\sigma_{ISR}(Y(3S))$</td>
<td>$(28.9 \pm 0.5 \pm 1.3)$ pb</td>
<td>$(28.6 \pm 0.5)$ pb</td>
</tr>
</tbody>
</table>
Similar to the one in charmonium(like):
\[ Y(4260) \rightarrow \pi\pi J/\psi \]

First evidence of the $f_0(980)$ peak also at $\Upsilon(4S)$. The difference in Dalitz Plot is in the band produced by the $Z_c(3900)$: we need to go up 185 MeV (at 10745 MeV) to start seeing the impact of $Z_b$ in $\Upsilon\pi\pi$. 

\[ \Upsilon(4S) \rightarrow \pi\pi \Upsilon(1S) \]

ArXiV 1707.04973

PRL 110, 252001 (2013)

\[ Y(4260) \rightarrow f_0(980)J/\psi \rightarrow \pi^+\pi^- \]

\[ f_0 \rightarrow \pi^+\pi^- \]

\[ \Upsilon_{4260} \]

J/\psi
The $f_0(980)$ peak was not visible in the previous Belle and Babar papers at $Y(4S)$, even if it appears quite clearly in the dipion mass distribution at the $Y(5S)$.

A theory paper (Chen et al. PRD 95 (2017) 034022) predicted the $f_0(980)$ peak in the dipion mass distribution: we need a theory model able to describe these features through the whole energy range.
**Progress on $\chi_c(2P)$ states**

![Diagram of $\chi_c(2P)$ states and other particle interactions]

- $\chi_c(2P)$ states
  - $\psi(4400)$
  - $X(4360)$
  - $X(4450)$
  - $\psi(4160)$
  - $\psi(4020)$
  - $\psi(3770)$
  - $\psi(3685)$
  - $\psi(4070)$
  - $\chi_c(2P)$
  - $\chi_c(1P)$
  - $\chi_c(1S)$
  - $\eta_c(2S)$
  - $\eta_c(1S)$
  - $\eta_b(2S)$
  - $\eta_b(1S)$
  - $\eta_b(1P)$
  - $\eta_b(2P)$
  - $\eta_b(3P)$
  - $\eta'(2S)$
  - $\eta'(1P)$
  - $\eta'(3P)$

- Baryonium (like)
  - $B_s^* B_s^*$
  - $B_s^* B_s^*$
  - $B_s^* B_s^*$
  - $B_s^* B_s^*$
  - $B_s^* B_s^*$
  - $B_s^* B_s^*$
  - $B_s^* B_s^*$
  - $B_s^* B_s^*$
  - $B_s^* B_s^*$

- Meson transitions
  - $\Delta M_A$ (MeV)$^2$
Observation of the 'real' $\chi_{c0}^{(2P)}$?

Phys. Rev. D95 (2017) 112003

Belle 2017: New analysis of $e^{+}e^{-} \rightarrow J/\psi \ D^{0}\bar{D}^{0}$: $X(3860)$

$\chi_{c0}^{(2P)}$ should have:

1) Dominant decay to $D^{0}\bar{D}^{0}$
   - $X(3915)$: $\times$
   - $X(3860)$: $\checkmark$

2) Be 80-120 MeV below $\chi_{c0,2}^{(2P)}$
   - $\times$
   - $\checkmark$

3) $B(\chi_{c0}^{'} \rightarrow \omega J/\psi) < 7.8\%$
   - $\times$
   - $\checkmark$
Belle 2017: New analysis of $e^+e^- \rightarrow J/\psi \ D^0\bar{D}^0$: $\chi_{c0}(2P)$

$\chi_{c0}(2P)$

Phys.Rev. D95 (2017) 112003

$M = 3862^{+26+40}_{-32-13}$ MeV/c$^2$, $\Gamma = 201^{+154+88}_{-67-84}$ MeV

$r_c = 0.46^{+0.25}_{-0.34}$, $r_b = 0.69 \pm 0.01$

$\chi_{c0}(2P)$
Phys. Rev. D95 (2017) 112003

Belle 2017: New analysis of $e^+e^- \to J/\psi D^0\bar{D}^0$: $X(3860)$

$\chi_{c0}^{2P}$

$M = 3862^{+26+40}_{-32-13}$ MeV/$c^2$ \hspace{1cm} $\Gamma = 201^{+154+88}_{-67-84}$ MeV

Open problems:
- what is the $X(3915)$, then?
- where is the $J=1$ state?
( $X_{3872}$ is NOT a simple $c\bar{c}$ )
Search for XYZ states in $\Upsilon$ decays

**BELLE, PRD93 (2016),112013**

Belle had already excluded XYZ production in two-body $\Upsilon$ decays, here we extended the measurement to inclusive production.

Best measurement of the spectrum of inclusive $J/\psi$ and $\psi^+$ production.

Belle searched for: $\pi^+\pi^- J/\psi$, $\pi^+\pi^- \psi'$, $K^+K^- J/\psi$, $\phi J/\psi$, $\pi^+ J/\psi$, $\pi^- J/\psi$, $K^\pm J/\psi$.
Search for XYZ states in $\Upsilon$ decays

**BELLE, PRD93 (2016),112013**

We set 90\% CL Upper Limits for charmonium-like states at O(10^{-6}) to O(10^{-4}) level

<table>
<thead>
<tr>
<th>$X$</th>
<th>$N_{fit}$</th>
<th>$N_{up}$</th>
<th>$\varepsilon$ (%)</th>
<th>$\sigma_{syst}$ (%)</th>
<th>$\Sigma(\sigma)$</th>
<th>$B_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X(3872) \rightarrow \pi^+\pi^- J/\psi$</td>
<td>8.8±6.5</td>
<td>18.6</td>
<td>0.89</td>
<td>7.1</td>
<td>1.6</td>
<td>&lt; 2.1 × 10^{-5}</td>
</tr>
<tr>
<td>$Y(4260) \rightarrow \pi^+\pi^- J/\psi$</td>
<td>-2.1±37.3</td>
<td>47.8</td>
<td>1.02</td>
<td>38.4</td>
<td>-</td>
<td>&lt; 4.6 × 10^{-5}</td>
</tr>
<tr>
<td>$Y(4260) \rightarrow \pi^+\pi^- \psi(2S)$</td>
<td>11.5±11.3</td>
<td>27.4</td>
<td>0.13</td>
<td>30.4</td>
<td>1.2</td>
<td>&lt; 2.1 × 10^{-4}</td>
</tr>
<tr>
<td>$Y(4360) \rightarrow \pi^+\pi^- \psi(2S)$</td>
<td>-4.8±10.4</td>
<td>14.7</td>
<td>0.16</td>
<td>39.7</td>
<td>-</td>
<td>&lt; 9.1 × 10^{-5}</td>
</tr>
<tr>
<td>$Y(4660) \rightarrow \pi^+\pi^- \psi(2S)$</td>
<td>-19.3±9.0</td>
<td>14.4</td>
<td>0.24</td>
<td>40.9</td>
<td>-</td>
<td>&lt; 5.9 × 10^{-5}</td>
</tr>
<tr>
<td>$Y(4260) \rightarrow K^+ K^- J/\psi$</td>
<td>-16.0±9.6</td>
<td>5.8</td>
<td>1.43</td>
<td>28.7</td>
<td>-</td>
<td>&lt; 4.0 × 10^{-6}</td>
</tr>
<tr>
<td>$Y(4140) \rightarrow \phi J/\psi$</td>
<td>0.2±1.2</td>
<td>3.6</td>
<td>0.49</td>
<td>20.1</td>
<td>0.2</td>
<td>&lt; 7.3 × 10^{-6}</td>
</tr>
<tr>
<td>$X(4350) \rightarrow \phi J/\psi$</td>
<td>1.2±2.3</td>
<td>6.1</td>
<td>0.70</td>
<td>33.0</td>
<td>0.6</td>
<td>&lt; 8.6 × 10^{-6}</td>
</tr>
<tr>
<td>$Z_c(3900)^{\pm} \rightarrow \pi^{\pm} J/\psi$</td>
<td>9.2±18.7</td>
<td>35.4</td>
<td>1.44</td>
<td>27.0</td>
<td>0.4</td>
<td>&lt; 2.5 × 10^{-5}</td>
</tr>
<tr>
<td>$Z_c(4200)^{\pm} \rightarrow \pi^{\pm} J/\psi$</td>
<td>67.1±73.8</td>
<td>125.3</td>
<td>1.29</td>
<td>43.3</td>
<td>2.0</td>
<td>&lt; 9.9 × 10^{-5}</td>
</tr>
<tr>
<td>$Z_c(4430)^{\pm} \rightarrow \pi^{\pm} J/\psi$</td>
<td>45.5±33.9</td>
<td>84.1</td>
<td>1.29</td>
<td>46.2</td>
<td>2.4</td>
<td>&lt; 6.6 × 10^{-5}</td>
</tr>
<tr>
<td>$Z_c(4050)^{\pm} \rightarrow \pi^{\pm} \psi(2S)$</td>
<td>-8.4±20.3</td>
<td>23.1</td>
<td>0.31</td>
<td>45.8</td>
<td>-</td>
<td>&lt; 7.4 × 10^{-5}</td>
</tr>
<tr>
<td>$Z_c(4430)^{\pm} \rightarrow \pi^{\pm} \psi(2S)$</td>
<td>11.7±18.5</td>
<td>36.6</td>
<td>0.40</td>
<td>67.9</td>
<td>0.6</td>
<td>&lt; 9.0 × 10^{-5}</td>
</tr>
<tr>
<td>$Z_c^{\pm} \rightarrow K^{\pm} J/\psi$</td>
<td>-31.3±13.7</td>
<td>30.5</td>
<td>2.95</td>
<td>68.7</td>
<td>-</td>
<td>&lt; 1.1 × 10^{-5}</td>
</tr>
</tbody>
</table>
Search for XYZ states in $\Upsilon$ decays

**BELLE, PRD93 (2016),112013**

Inclusive production of $J/\psi$ and $\psi'$ from $Y(1S)$ decays: measurements

\[ B(\ Upsilon(1S) \rightarrow J/\psi \ + \text{anything}) \]

Belle: \((5.25 \pm 0.13 \pm 0.25) \times 10^{-4}\)  
(PDG: \((6.5 \pm 0.7) \times 10^{-4}\))

\[ B(\ Upsilon(1S) \rightarrow \psi' + \text{anything}) \]

Belle: \((5.25 \pm 0.13 \pm 0.25) \times 10^{-4}\)  
(PDG: \((2.7 \pm 0.9) \times 10^{-4}\))
Search for XYZ states in $\Upsilon$ decays

We can compare these upper limits with our measured inclusive rates for production of known resonances, and link them to $\psi'$ production rate in CMS: more statistics is needed.
0− glueballs (oddballs) are predicted by theory (\textit{PRL113, 221601 (2014), JHEP 1510 (2015) 137})
Belle has searched for them inclusively:
- in Y(1,2S) decays, recoiling against $\chi_{c1}$ and $f_1(1285)$
- in $\chi_{bJ}(1P)$ decays, recoiling against $J/\psi$ and $\omega$
Search for Oddballs in Y(1,2S) decays

$\Upsilon(1S)$

$\Upsilon(2S)$

$f_1(1285) + G_0$ --

$J/\psi + G_0$ --

$\omega + G_0$ --

Upper Limits (90% C.L.)

Glueball Width (GeV)

$G(2800)$

$G(3810)$

$G(4330)$

PRD 95 (2017), 012001
Inclusive production of $\chi_{c1}$ in $Y(1,2S)$ decays

Best measurement

$$\mathcal{B}(Y(1S) \to \chi_{c1} + \text{anything}) = (1.90 \pm 0.43 \text{(stat.)} \pm 0.14 \text{(syst.)}) \times 10^{-4}$$

First measurement

$$\mathcal{B}(Y(2S) \to \chi_{c1} + \text{anything}) = (2.24 \pm 0.44 \text{(stat.)} \pm 0.20 \text{(syst.)}) \times 10^{-4}$$
B-Factories largely contributed to a revolution in our understanding of the mechanisms of $c\bar{c}$ and $b\bar{b}$ production in the proximity of the double meson thresholds. This has led to the discovery of a new class of mesonic states made of four quarks: the Zc's and Zb's.

In addition, violation of the heavy quark spin symmetry (HQSS) has given us unexpected pathways to access heavy paraquarkonia from the broad resonances above open flavor thresholds: $Y(4S)$ to $\eta h_b$ being the most striking case.

Belle has recently observed a significant HQSS violation at the $Y(5S)$ energy, mainly in the $B_{s}^{*}\bar{B}_{s}$ channel. Belle's unique datasets are still yielding many unexpected results.

The B-factories have also discovered a large number of exotic states, together with many missing parts of the charmonium and bottomonium spectra. Recently, Belle has probably found the J=0 member of the charmonium 2P multiplet, casting light in the very intriguing region in the proximity of the $X(3872)$ resonance, whose nature is still not understood. This opens though new questions on the nature of the $X(3915)$ charmonium like state.

Finally, Belle is continuously searching other processes to produce for the newly discovered $XYZ$ states. In narrow Upsilon decays, we set a large number of upper limits on inclusive production of $XYZ$ states and improved the BR's for inclusive production of conventional charmonia. Furthermore, Belle set limits on production of $0^-$ glueballs from $Y(1,2S)$.
Topical Seminar School on
Heavy Quarkonia at Accelerators: New Theoretical Tools and Experimental Techniques
October 8-11, 2004, ITP Beijing

3rd International Workshop on Heavy Quarkonia
Organized by the Quarkonium Working Group
October 12-15, 2004, IHEP Beijing

See you at ...

The 9th International Workshop on Heavy Quarkonium
April 22-26, 2013, IHEP, Beijing

Quarkonium 2017
The 12th International Workshop on Heavy Quarkonium
November 6-10, 2017, Peking University, Beijing, China