Status and prospects for quarkonium at Belle II

IPA2022 conference, TU Wien
A. Boschetti
(on behalf of the Belle II collaboration)
Heavy quarkonia

A. Boschetti - Status and prospects for quarkonium at Belle II - IPA2022, TU Wien
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[Rev.Mod.Phys. 90, 015003 (2018)]
Spectroscopy = non-perturbative QCD
→ Can’t do direct calculation, rely on models approximating QCD
→ Quarkonium is a multi-scale system
  ⇒ energy scales can be separated in the models
→ Compare exp. results with models
  ⇒ improve understanding of QCD in NP regime

[Rev.Mod.Phys. 90, 015003 (2018)]
XYZ states

What are they? ⇔ Which partons, how is color arranged?

- **Glueball**: No quarks, "Excited" flux tube
- **Hybrid**: Compact object, gluon exchange
- **Tetraquark**: Bound mesons, \(\pi/\sigma/\omega\) exchange
- **Hadronic Molecule**: + threshold, cusp effects

[Rev.Mod.Phys. 90 (2018) 1, 015003]
Asymmetric $e^+e^-$ collider
$\Rightarrow J^{PC}=1^{--}$ states directly produced

$\sqrt{s} \sim 9 - 11 \ GeV \ \Rightarrow b\bar{b}$ energy region
Quarkonium production @SuperKEKB

**Bottomonium**
- Hadronic transitions from Y(4S)
- Initial state radiation (ISR)
- Direct production (tunable CM energy)

**Charmonium**
- γγ fusion at Y(4S)
- B decays via b→c
- ISR
Quarkonium production @SuperKEKB

**Bottomonium**
- Hadronic transitions from Y(4S)
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**Charmonium**
- γγ fusion at Y(4S)
- B decays via b→c
- ISR
Y(10750)

- Discovered in di-pion transitions to Y(nS)
- Far from S-wave threshold ⇒ unlikely hadronic molecule
- No direct matching to conventional states
- In this region we observe a drop in hadronic cross section!

May be 4S-3D mixing, predicted by [PRD 104, 034036 (2021)]

[Graph showing Y(4S), Y(3D), and Y(5S) with corresponding data plots]

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The Y(10750) state is generating a lot of theoretical interest

Conventional interpretations:

- Chen, Zhang & He, PRD 101, 014020 (2020)
- Li et al., EPJC 80, 59 (2020)
- Liang, Ikeno & Oset, PLB 803, 135340 (2020)

Less conventional interpretations:

- Wang, CPC 43, 123102 (2019)
- Ali, Maiani, Parkhomenko & Wang, PLB 802, 135217 (2020)
- Giron & Lebed, PRD 102, 014036 (2020)
- …
Belle II energy scan above $\Upsilon(4S)$

Nov. 2021 → Unique high stat. points between previous Belle energies

First time above $\Upsilon(4S)$ for SuperKEKB ⇒ important test!

$E_{CM}$ change w.r.t. $\Upsilon(4S)$

Belle II scan dataset is now bigger than Belle’s
Observation of $e^+e^- \rightarrow \omega[\pi^+\pi^-\pi^0]$ $X_{bJ}(1P)[\gamma Y(1S)]$ and search for $X_b \rightarrow \omega Y(1S)$  

Motivation:

- $BF[Y(10750) \rightarrow \omega X_{bJ}(1P)] \sim 10^{-3}$ predicted for 4S-3D mixing [PRD 104,034036 (2021)]
- BESIII: $e^+e^- \rightarrow Y(4220) \rightarrow \pi\pi J/\psi, \gamma X(3872), \omega X_{c0}(1P), \ldots \Rightarrow X_b$ analog of $X(3872)$?

Reconstruction:

- Events with 4 – 5 tracks
- Exclusive $\Rightarrow$ low background
- 4C kinematic fit
Belle II new result

Exclusive analysis ⇒ Very low background
Unbinned ML fits to invariant mass distributions
→ extract signal yield

[arXiv.2208.13189]
The Belle Collaboration published an analogous result at 10.867 GeV (triangle in plot). [PRL 113, 142001 (2014)]

Transition from Y(10860) resonance or tail of the Y(10750) structure?
No evidence for the $X_b$ state

Reflection of $e^+e^- \rightarrow \omega X_{bJ}(1P)$

Upper limits:
- $\sigma_B (e^+e^- \rightarrow \gamma X_b) < 10^{-1}$
- $B[X_b \rightarrow \omega Y(1S)] < 10^{-1}$
Ongoing analyses

Y(4S):
- $Y(4S) \rightarrow \eta b_{1P}(1P)$
- $Y(4S) \rightarrow \phi \eta_b(1S)$
- $e^+e^- \rightarrow Y(1S) + X$

Scan:
- $Y_b(10750) \rightarrow \pi^+\pi^-\eta_b(1P)$
- $B\bar{B}$ decomposition w.r.t. $\sqrt{s}$
- $Y_b(10750) \rightarrow \omega \eta_b(1S)$
- $e^+e^- \rightarrow \pi^+\pi^- Y_2(1D)$
- $e^+e^- \rightarrow J/\psi X$

Main goals:
- Improve knowledge on spectrum
- Search for more transitions
- Precise measurement of mass and width of $Y_b(10750)$
- Study of $\pi^+\pi^- / \omega / \eta / \phi$ transitions ⇒ test NRQCD and other models
Prospects: charmonium(-like) physics

Analysis of unexplored channels

\[ B \to J/\psi \eta K \]
\[ B \to J/\psi \eta' K \]

\[ e^+e^- \to J/\psi D^*\overline{D}^* \]
\[ e^+e^- \to J/\psi D^*\overline{D} \]
\[ e^+e^- \to \psi(2S)D(\ast)\overline{D}(\ast) \]

Improve meas. of cross section above 5 GeV

\[ e^+e^- \to \gamma_{ISR}(c\overline{c})X \]

\[ e^+e^- \to e^+e^- J/\psi \phi \]

Unique to Belle II!
Prospects: bottomonium(-like) physics

The program is much larger, waiting for more data!

QCD goals in the bottomonium region:

- Precise decomposition of the $R_b$ ratio
- Systematic exploration of threshold region

\[ R_b = \frac{\sigma(e^+e^- \rightarrow b\bar{b} \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} \]

[Chin.Phys.C 44 (2020) 8, 083001]
Narrow bottomonia: new physics

Target: collect 1 billion $Y(3S)$ or $Y(2S)$

NP goals:

- LFU: $< 0.5\%$ precision on $Y(nS) \to \tau^+\tau^-$, $Y(nS) \to \mu^+\mu^-$
  
  Connection with $R(D^*)$ [JHEP 06 (2017) 019]]

- LFV: maximize sensitivity on
  
  $Y(nS) \to e\tau, \mu\tau$

- $Y(nS) \to$ multi-quark system + $X$
  
  ○ exotic charmonia
Narrow bottomonia: baryogenesis

\[ e^+ e^- \rightarrow \Upsilon(nS') \rightarrow ggg \]

produces nuclei (N) and hyperons (Y)!

We can study N-N, Y-N, Y-Y prod. and interactions in small regions in an unique environment

Case studies:
- Y-Y interaction with \textbf{femtoscopy} ⇒ constraints on \textbf{neutron stars EoS} with hyperons (my PhD project)
- Limits on \textbf{H-dibaryon}/exaquark observation
- Scaling in N production

[Universe 2021, 7, 408]
Summary

We are at the beginning of a long program of quarkonium physics

- Belle II collected unique data at Y(10750)
  - Unique quarkonium production mechanisms at SuperKEKB
  - $Y(10750) \rightarrow \omega_{bJ}(1P)$ observed for the first time
  - No evidence for $X_b$ (bottomonium analog of $X(3872)$)
- Many analyses based on $\Upsilon(4S)$ and scan data
  - Study of baryon-baryon interactions

High luminosity: goal 50x Belle dataset
⇒ improvements on statistics-dominated analyses
The end
BACKUP
Observation of $e^+e^- \rightarrow \omega[\pi^+\pi^-\pi^0] \chi_{bJ}(1P)[\gamma\Upsilon(1S)]$ and search for $X_b \rightarrow \omega\Upsilon(1S)$

Motivation:
- $BF[Y(10750) \rightarrow \omega\chi_{bJ}(1P)] \sim 10^{-3}$ predicted for 4S-3D mixing [PRD 104,034036 (2021)]
- BESIII: $e^+e^- \rightarrow Y(4220) \rightarrow \pi\pi J/\psi$, $\gamma\Upsilon(3872)$, $\omega\chi_{c0}(1P)$, … $\Rightarrow X_b$ analog of X(3872)?

Selection criteria:
- 4 or 5 charged tracks
- standard Belle II PID $\rightarrow$ 90-95% eff, 1-5% misID
- $E_\gamma > 50$ MeV
- $105 < M(\gamma\gamma) < 150$ MeV $\rightarrow$ 90% eff.
- 4C kinematic fit
- Best candidate selected based on fit quality
- Data driven corrections and syst. (control samples)

Belle II results:
- Observation of $e^+e^- \rightarrow \omega\chi_{bJ}(1P)[\gamma\Upsilon(1S)]$
- No evidence for $\gamma X_b$

[arXiv.2208.13189]
**Belle II new result**

Two dimensional unbinned maximum likelihood fits to the $M(\gamma Y(1S))$ and $M(\pi^+\pi^-\pi^0)$ distributions.

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>$N_{\text{sig}}$</th>
<th>$\sigma_{\text{Born}}^{(UL)}$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega\chi_{b1}$</td>
<td>10.745</td>
<td>68.9$^{+13.7}_{-13.5}$</td>
<td>3.6$^{+0.7}_{-0.7}$ $\pm$ 0.4</td>
</tr>
<tr>
<td>$\omega\chi_{b2}$</td>
<td>10.745</td>
<td>27.6$^{+11.6}_{-10.0}$</td>
<td>2.8$^{+1.2}_{-1.0}$ $\pm$ 0.5</td>
</tr>
<tr>
<td>$\omega\chi_{b1}$</td>
<td>10.805</td>
<td>15.0$^{+6.8}_{-6.2}$</td>
<td>1.6 @90% C.L.</td>
</tr>
<tr>
<td>$\omega\chi_{b2}$</td>
<td>10.805</td>
<td>3.3$^{+5.3}_{-3.8}$</td>
<td>1.5 @90% C.L.</td>
</tr>
</tbody>
</table>

The total $\chi_{bJ}$ signal significances are 11.5$\sigma$ and 5.2$\sigma$ at $\sqrt{s} = 10.745$ and 10.805 GeV.

Note that the $\sigma_{\text{Born}}(e^+e^- \to \omega\chi_{b1}/\omega\chi_{b2})$ is only $(0.76\pm0.11\pm0.11)/(0.29\pm0.11\pm0.08)$ pb at $\sqrt{s} = 10.867$ GeV [PRL 113, 142001(2014)].
Belle II new result

- No significant $X_b$ signal is observed.
- The peaks are the reflections of $e^+e^- \rightarrow \omega X_b$.

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 $\sigma_B(e^+e^- \rightarrow \gamma X_b)$</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/$c^2$</td>
<td>0.45</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/$c^2$</td>
<td>(0.14, 0.54)</td>
<td>(0.25, 0.84)</td>
<td>(0.06, 0.14)</td>
<td>(0.08, 0.36)</td>
<td></td>
</tr>
</tbody>
</table>
Transitions and decays

Above threshold: $B\bar{B}$, $D\bar{D}$ dominate

Below threshold:

- transitions
  - hadronic
  - radiative
- decays to
  - hadrons
  - lepton pairs
  - photons
Y(5S) and Y(6S): new exotica

If $Z_b$'s are loosely bound molecules, then others must appear

\[ \text{[Mod. Phys. Lett. A 32, 1750025 (2017)]} \]

| $I^G(J^P)$ | Name   | Composition | Co-produced particles | $|\text{Threshold}, \text{GeV}/c^2|$ | Decay channels |
|-----------|--------|-------------|-----------------------|----------------------------------|----------------|
| $1^+(1^+)$ | $Z_b$  | $B\bar{B}^*$ | $\pi$ | $[10.75]$ | $\Upsilon(nS)\pi, h_0(nP)\pi, \eta_b(nS)r$ |
| $1^+(1^+)$ | $Z_b'$ | $B^*B^*$ | $\pi$ | $[10.79]$ | $\Upsilon(nS)\pi, h_0(nP)\pi, \eta_b(nS)r$ |
| $1^-(0^+)$ | $W_{b0}$ | $BB$ | $\rho$ | $[11.34]$ | $[10.56]$ | $\Upsilon(nS)r, \eta_b(nS)\pi$ |
| $1^-(0^+)$ | $W_{b0}'$ | $B^*B^*$ | $\rho$ | $[11.43]$ | $[10.65]$ | $\Upsilon(nS)r, \eta_b(nS)\pi$ |
| $1^-(1^+)$ | $W_{b1}$ | $B^*B^*$ | $\rho$ | $[11.38]$ | $[10.61]$ | $\Upsilon(nS)r, \eta_b(nS)\pi$ |
| $1^-(2^+)$ | $W_{b2}$ | $B^*B^*$ | $\rho$ | $[11.43]$ | $[10.65]$ | $\Upsilon(nS)r, \eta_b(nS)\pi$ |
| $0^+(1^+)$ | $X_{b1}$ | $B\bar{B}^*$ | $\eta$ | $[11.15]$ | $\Upsilon(nS)\eta, \eta_b(nS)\omega$ |
| $0^+(1^+)$ | $X_{b2}$ | $B^*B^*$ | $\eta$ | $[11.20]$ | $\Upsilon(nS)\eta, \eta_b(nS)\omega$ |
| $0^+(0^+)$ | $X_{b0}$ | $BB$ | $\omega$ | $[11.34]$ | $[10.56]$ | $\Upsilon(nS)\omega, \eta_b(nS)\eta$ |
| $0^+(0^+)$ | $X_{b0}'$ | $B^*B^*$ | $\omega$ | $[11.43]$ | $[10.65]$ | $\Upsilon(nS)\omega, \eta_b(nS)\eta$ |
| $0^+(1^+)$ | $X_{b1}$ | $B\bar{B}^*$ | $\omega$ | $[11.39]$ | $[10.61]$ | $\Upsilon(nS)\omega, \eta_b(nS)\eta$ |
| $0^+(2^+)$ | $X_{b2}$ | $B^*B^*$ | $\omega$ | $[11.43]$ | $[10.65]$ | $\Upsilon(nS)\omega, \eta_b(nS)\eta$ |
Tracking and vertexing $\rightarrow$ more precise

Calorimetry $\rightarrow$ Better reconstruction, more bkg
B-factories took also **non-4S data**

Some related discoveries:

- Belle @ Y(5S): h_b(1,2P), η_b(2S), Z_b(10610, 10650)
- Belle energy scan: Y_b(10750)

<table>
<thead>
<tr>
<th></th>
<th>Y(10860)</th>
<th>Y(11020)</th>
<th>New structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>M (MeV/c²)</td>
<td>10885.3 ± 1.5 +2.2 -0.9</td>
<td>11000.0 +1.0 -1.0 +4.5 -4.5</td>
<td>10752.7 ± 5.9 +0.7 -1.1</td>
</tr>
<tr>
<td>Γ (MeV)</td>
<td>36.6 ±3.5 +0.5 -0.5</td>
<td>23.8 ±8.0 +0.7 -0.8</td>
<td>35.5 ±17.6 +3.9 -1.1</td>
</tr>
</tbody>
</table>

[JHEP 06 (2021) 137]
Bottomonium(-like) physics

Belle II advantages

- Tunable beam energy
- Main possibility to study $\Upsilon$, $\Upsilon_b$ and $Z_b$ states
- Understanding relationship between c- and b-sector spectroscopy

Ability to run at non-4S energies:

- Revisit $\Upsilon(6S)$ with 10x+ statistics
- Higher statistics scan of entire region and $\Upsilon(5S)$
Particle identification → much more powerful

A key improvement is due to the TOP counter

The TOP is a “DIRC in the time domain”
- Cherenkov light trapped and propagated to the readout in bar of fused silica
- Cherenkov angle measured by the time of propagation
Two-particle **dynamic correlations** bring information about

- Interactions between them
- Geometry of the emitting source

E.g. is $X(3872)$ a $D \bar{D}$ molecule? (attractive interaction)

$\Rightarrow$ we could see correlations between reconstructed $D, \bar{D}$ momenta

- Method already used at ALICE (mixed event technique)
- We will develop analogous method, in cleaner exp. environment

$$C(k^*) \propto \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

[PLB 797, 134822 (2019)]
Femtoscopy in bottomonium decays

Two-particle **dynamic correlations** bring information about

- Interactions between them
- Geometry of the emitting source

Search for $\Lambda\Lambda$ interactions using **femtoscopy**

- Method already used at ALICE (mixed event technique)
- We will develop analogous method, in cleaner exp. environment

Applications: neutron star EoS, nuclear force, H-dybarion, …

\[
C(k^*) \propto \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}
\]

[PLB 797, 134822 (2019)]
XYZ states

And many more in charmonium sector: X(3915), Z_c(3900), Z_c(4430), …

What are they?
Many possible interpretations:

+ threshold, cusp effects

[Rev.Mod.Phys. 90 (2018) 1, 015003]
Heavy quarkonia

- Conventional states
- Neutral exotics
- Charged exotics
- Pentaquark candidates

Spectroscopy = non-perturbative QCD
→ Can’t do direct calculation, rely on models approximating QCD
→ Understand (solve?) QCD in NP regime

[Rev.Mod.Phys. 90, 015003 (2018)]
Charmonium(-like) physics

Improve stat. for observation of
\[ Z_c(3900)^+ \rightarrow J/\psi\pi^+ \]  
(PRL 110, 252002 (2013))

Improve meas. of cross section
\[ e^+e^- \rightarrow \gamma_{ISR}(c\bar{c})X \]  
Above 5 GeV

Amplitude analyses:
\[ B \rightarrow J/\psi\phi K \]
(PRL 118, 022003 (2017)
(confirm LHCb results)

Analysis of unexplored channels
\[ B \rightarrow J/\psi\eta K \quad B \rightarrow J/\psi\eta' K \]
Charmonium(-like) physics

Conventional states:
- $\chi_{c2}(2P)$
- search for states decaying to open charm

Exotic

$e^+e^- \rightarrow e^+e^- J/\psi \phi$
→ establish $X(4350)$?

Unique to Belle II!
Heavy quarkonia

Spectroscopy = non-perturbative QCD
→ Can’t do direct calculation, rely on models approximating QCD
→ Compare exp. results with models
⇒ improve understanding of QCD in NP regime

[Rev.Mod.Phys. 90, 015003 (2018)]