Exotic and Conventional Quarkonium Physics Prospects at Belle II

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Hadron Spectroscopy with Electron, Photon, and Hadron Beams II

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Introduction

- B Factories have played a pivotal role in discovery of exotic quarkonium states...
  - First observation of $X(3872)$ at Belle in 2003.
  - First observation of $Y(4260)$ at BaBar in 2005.
  - Charged exotic $Z_c^{±}(4430)$ observed at Belle in 2008.
  - ...and many other exotic candidates over years...

**X(3872)**
[PRL 91, 262001 (2003)]

**Y(4260)**
[PRL 95, 142001 (2005)]

**Zc(4430)**
[PRL 100, 142001 (2008)]
Many questions remain…

- What is the proper interpretation of the exotic states?
- Why are widths of exotics so narrow, despite being above threshold?

⇒ LHCb, BESIII, **now Belle II** will explore quarkonium sector over coming years!
Upgrade to SuperKEKB, Belle II

- “Nano-beam” scheme [P. Raimondi]
  - Squeeze beam at IP by ~1/20.
  - Reduce effective bunch length.
- Double beam currents.
  ➔ 40x increase in peak luminosity!

Operations Phases:
- Phase 1 (2016) – first turns, accelerator commissioning.
  - No QCS or Belle II.
- Phase 2 (2018) – first runs with QCS, Belle II, no vertexing.
- Phase 3 (2019) – first physics runs with full Belle II.
The Belle II detector

**Central Drift Chamber:**
He(50%):C₂H₆(50%), Small cells, long lever arm, fast electronics

**K₁ and muon detector:**
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

**EM Calorimeter:**
CsI(Tl), waveform sampling

**Beryllium beam pipe:**
2 cm diameter

**Vertex detector:**
2 layers DEPFET + 4 layers DSSD

**Particle Identification:**
Time-of-Propagation counter (barrel)
Prox. Focusing Aerogel RICH (fwd)

**Electron (7 GeV)**

**Positron (4 GeV)**

**Readout (TRG, DAQ):**
Max. 30kHz L1 trigger
~100% efficient for hadronic events.
1MB (PXD) + 100kB (others) per event
- over 30GB/sec to record

**Offline computing:**
Distributed computing over the world via the GRID

First new particle collider since the LHC
(intensity rather than energy frontier; e⁺e⁻ rather than pp)
Start of Data Taking @ Belle II

April 26, 2018: First Collisions!

Straight to work checking detector performances! Examples checking pion and kaon ID using the Time of Propagation (TOP) subdetector in $K_S \rightarrow \pi\pi$, $D^0 \rightarrow K\pi$. 

No PID 

w/o $\pi$ ID 

w/ $\pi$ ID 

w/o K ID 

w/ K ID
Phase 2 Running

- Phase 2 run concluded in July.
  - Machine tuning, verification of nano-beam scheme!
  - Peak luminosity reached $\sim 5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, $\sim 25\%$ of peak of Belle.
  - Total integrated luminosity $\sim 0.5 \text{ fb}^{-1}$ recorded at $\Upsilon(4S)$.
  - Beam background measurements and minimization (without vertex detectors).
  - Detector calibrations.
  - “Rediscovery” of many states, including $J/\psi \rightarrow \text{ee}, \mu\mu$.
Charmonium Physics at Belle II

- Many charmonium production mechanisms:
- B decays:
  - All quantum numbers.
- Initial state radiation (ISR):
  - $J^{PC} = 1--$
- Two-photon process:
  - $J^{PC} = 0^{-+}, 1^{++}, 2^{++}$
- Double charmonium:

Many production modes allows multiple pathways to observe same states.
Belle II charmonium program can be conducted in parallel with B physics!
Belle II Charmonium Program

- **ISR:**
  - Y(4230), Y(4260), Y(4360) could all be explored.
  - Unexpected Y(4260) line-shape measured at BESIII, inconsistent among different modes. Could explore with ISR. Cross sections of exclusive (c\bar{c}) + hadrons.
  - Search for strange partner of Z(3900) in K^+K^-J/\psi.

- **Double charmonium:**
  - Uniquely measurable at Belle II!
  - Absolute branching fractions.
  - Cross sections.
  - Spectroscopy.

- **Two photon:**
  - Also uniquely measurable at Belle II.
  - Could disentangle two of the four states seen by LHCb in \(\Phi J/\psi\).

- In addition, B physics program will provide \(~50x\) more data for expansion of studies in \(B \rightarrow\) charmonium.

<table>
<thead>
<tr>
<th>ISR Channels</th>
<th>(@10 \text{ ab}^{-1} ) (50 \text{ ab}^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Golden Channels</td>
<td>(E_{c.m.} ) (GeV)</td>
</tr>
<tr>
<td>(\pi^+\pi^- J/\psi)</td>
<td>4.23</td>
</tr>
<tr>
<td>(\pi^+\pi^- (2S))</td>
<td>4.36</td>
</tr>
<tr>
<td>(K^+K^- J/\psi)</td>
<td>4.53</td>
</tr>
<tr>
<td>(\pi^+\pi^- h_c)</td>
<td>4.23</td>
</tr>
<tr>
<td>(\omega_{\chi_c0})</td>
<td>4.23</td>
</tr>
</tbody>
</table>

BESIII Physics Book [arXiv:1808.10567]

PRL 118, 092001 (2017)

PRL 118, 092002 (2017)
Bottomonium Physics at Belle II

- Examples of open questions in $\Upsilon(5S, 6S)$...

- $\Upsilon(5S)$ line shapes:
  - Apparent discrepancies in shape in $\pi\pi\Upsilon$ modes vs. $\pi\pi h$ modes.
  - Hint of a new resonance around 10.75 GeV?
  - Is $Z_b$ above/below $B(B^{(*)})B^{(*)}$ threshold?
  - 5S and 6S provide windows to search for missing narrow states in the bottomonium spectrum.

  ➔ These runs require dedicated scans and/or samples on specific resonances!

**Many other 1S, 2S, 3S topics... see Belle II Physics Book!**
Proposals for Belle II Y(5S, 6S) Program

Current samples in fb\(^{-1}\) (millions of events), and the proposal for Belle II

<table>
<thead>
<tr>
<th>Experiment</th>
<th>(\Upsilon(1S))</th>
<th>(\Upsilon(2S))</th>
<th>(\Upsilon(3S))</th>
<th>(\Upsilon(4S))</th>
<th>(\Upsilon(5S))</th>
<th>(\Upsilon(6S))</th>
<th>(\Upsilon(nS))</th>
<th>(\Upsilon(4S))</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO</td>
<td>1.2 (21)</td>
<td>1.2 (10)</td>
<td>1.2 (5)</td>
<td>16 (17.1)</td>
<td>0.1 (0.4)</td>
<td>-</td>
<td>23%</td>
<td></td>
</tr>
<tr>
<td>BaBar</td>
<td>-</td>
<td>14 (99)</td>
<td>30 (122)</td>
<td>433 (471)</td>
<td>R(_b) scan</td>
<td>R(_b) scan</td>
<td>11%</td>
<td></td>
</tr>
<tr>
<td>Belle</td>
<td>6 (102)</td>
<td>25 (158)</td>
<td>3 (12)</td>
<td>711 (772)</td>
<td>121 (36)</td>
<td>5.5</td>
<td>23%</td>
<td></td>
</tr>
<tr>
<td>BelleII</td>
<td>-</td>
<td>-</td>
<td>300 (1200)</td>
<td>5 \times 10^4 (5.4 \times 10^4)</td>
<td>1000 (300)</td>
<td>100+400(scan)</td>
<td>3.6%</td>
<td></td>
</tr>
</tbody>
</table>

- Proposed runs at \(\sim 1\) ab\(^{-1}\) at \(\Upsilon(5S)\).
  - Complementary with \(B_s\) physics.
  - Determine if \(Z_b\) is above/below \(B^{(*)}B^*\) threshold.
- Scan \(\Upsilon(5S,6S)\) line shapes:
  - Proposed scans at \(\sim 10\) MeV steps, 10 fb\(^{-1}\) each.
  - Search in \(\pi\pi\Upsilon\) modes vs. \(\pi\pi\) modes.
- Settle the nature of the 5S!
- Complementary with the \(B_s\) physics program.
- Search for various exotics in hadronic channels of \(\Upsilon(6S)\) decay.
- SuperKEKB maximum \(E_{cm}\) \(\sim 11.02\) GeV, just above \(\Upsilon(6S)\).
- Would benefit from linac upgrade to get to max \(E_{cm}\) \(\sim 11.24\) GeV.
- Staged running at \(\Upsilon(6S)\):
  - Exploratory runs at low luminosity first, e.g., 10 fb\(^{-1}\) ... 30 fb\(^{-1}\) ... 100 fb\(^{-1}\).
Conclusion

• SuperKEKB has completed initial commissioning, has moved into first collisions as of April 26, 2018!

• Belle II has just completed Phase 2 running:
  o Calibrations, detector studies, and many rediscoveries!
  o Vertex detectors are being installed for Phase 3 physics run.

• Phase 3 begins early 2019, is the beginning of a new program of charmonium and bottomonium physics.
  o Charmonium program runs in parallel with B physics program.
  o Small samples of special runs at Y(6S, 5S, 3S) can provide a wide variety of new bottomonium results.
  o Much more detail available in Belle II Physics Book [arXiv:1808.10567]!

• Stay tuned for new results!