Future of hadron exotics at Belle II

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Simons Center for Geometry and Physics
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Outline

Belle II: the next generation B Factory
- Detector / accelerator description
- Collaboration and plans
- Early Belle II status

Future prospects: quarkonium and exotics
- Charmonium(-like) production
- Bottomonium(-like): Above $\Upsilon(4S)$
- Bottomnoium(-like): Below $\Upsilon(4S)$
Search for New Physics via precision measurements

Belle II Advantages
- Sensitive to “New Physics” masses above direct production
- “Clean” experimental environment, full event reconstruction
- Tau decays and neutrals ($\gamma$, $\pi^0$, $K_L$, $\nu$) in final state
- Beam energy range and luminosity for exotics studies
- Complementary to LHC
The Belle II Collaboration

- 800+ members, 108 institutions, 25 countries
- Located at KEK in Tsukuba, Japan
SuperKEKB Accelerator Upgrade

- “Nano-beam” interaction point
- Increase in current
- Factor of 40x increase in luminosity
- Energy: $e^{-} (7 \text{ GeV}) e^{+} (4 \text{ GeV})$
Detector Upgrade

Order of magnitude luminosity increase means:

- Higher background
  - Radiation damage
  - Pile-up/ECAL hits
- Higher event rate
  - Trigger, DAQ, computing
- Boost change
  - Improve vertexing

Significant detector upgrades

- Calorimetry: electronics and readout
- Muon/$K_L$: plastic scintillator, electronics upgrade
- PID: TOP barrel, aerogel endcap
- Tracking: small-cell drift chamber
- Vertexing: 2 layer Si pixel + 4 layer Si strip

Exotics at Belle II – Bryan FULSOM (PNNL) – SCGP Workshop – 2018 05 29

Machine Capability

**Luminosity**
- **Belle**: $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- **Belle II**: $8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$

**Energy**
- **Nominal**: 10.58 GeV
- **Present Maximum**: 11.02 GeV
- **Potential Maximum**: 11.24 GeV
Belle II Schedule and Plans

- **Phase 1 (completed 2016)**
  - Accelerator commissioning

- **Detector roll-in: April 2017**

- **Phase 2 (2017/18)**
  - First collisions $(10\pm 10 \text{ fb}^{-1})$
  - Partial detector
  - Background study
  - Physics possible

- **Phase 3 (2018/19)**
  - Nominal Belle II start

- **Ultimate goal: 50 ab$^{-1}$**
First collisions: Apr. 26, 2018

Recent SuperKEKB status
First signs of physics

Beginning “rediscovery” of expected particles

\[ D^* \rightarrow \pi^\pm \, D^0(K^\mp \pi^\pm) \]

Also indications for \( \eta, \Lambda, K^*, \phi, \ldots \)
QUARKONIUM
AND EXOTICS
First discoveries of long-predicted conventional quarkonia

Many discoveries are difficult to explain by quarkonium model

Several states have non-zero charge, cannot be a $\bar{c}c/\bar{b}b$ pair
Quarkonium production at $e^+e^-$ colliders

- **B decays**
  - Charmonium only
  - All quantum numbers available

- **Direct production / Initial State Radiation (ISR)**
  - $E_{CM}$ or below
  - $J^{PC}=1^{--}$

- **Two-photon interaction**
  - $J^{PC} = 0^{-+}, 0^{++}, 2^{++}$

- **Double charmonium production**
  - Seen for $J^{PC}=1^{--}$ (J/$\psi$, $\psi(2S)$) plus $J=0$ states

- **Quarkonium transitions**
  - Hadronic/radiative decays between states
Charmonium(-like) Overview

- Charmonium system
  - Many states/overpopulation
  - Several in one process/mode
  - Limited statistics

- Belle II prospects
  - Competition from LHCb (B decays) and BESIII (scans for $1^-$ states)
  - Exploit unique production methods: ISR, double charmonium, two-photon
  - Require large statistics samples
  - Not necessarily restricted by $E_{CM}$
ISR Charmonium

- ISR gives access to: lineshape of vector states, decays of vector exotica
  - $Y(4220)$, $Y(4320)$, $Y(4360)$, $Y(4660)$: many nearby peaks and final states

- Belle II @ 50ab$^{-1}$
  - Wider range of energies
  - $Y(4260)$ lineshape
  - Strange partner of $Z_c$

- Modes of interest

<table>
<thead>
<tr>
<th>Golden Channels</th>
<th>$E_{c.m.}$ (GeV)</th>
<th>Statistical error (%)</th>
<th>Related $XYZ$ states</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+\pi^-J/\psi$</td>
<td>4.23</td>
<td>7.5 (3.0)</td>
<td>$Y(4008)$, $Y(4260)$, $Z_c(3900)$</td>
</tr>
<tr>
<td>$\pi^+\pi^-\psi(2S)$</td>
<td>4.36</td>
<td>12 (5.0)</td>
<td>$Y(4260)$, $Y(4360)$, $Y(4660)$, $Z_c(4050)$</td>
</tr>
<tr>
<td>$K^+K^-J/\psi$</td>
<td>4.53</td>
<td>15 (6.5)</td>
<td>$Z_{cs}$</td>
</tr>
<tr>
<td>$\pi^+\pi^-h_c$</td>
<td>4.23</td>
<td>15 (6.5)</td>
<td>$Y(4220)$, $Y(4390)$, $Z_c(4020)$, $Z_c(4025)$</td>
</tr>
<tr>
<td>$\omega_{\chi_{c0}}$</td>
<td>4.23</td>
<td>35 (15)</td>
<td>$Y(4220)$</td>
</tr>
</tbody>
</table>

BESIII, PRL 118, 092001 (2017)
Other Charmonium Production

- Measureable only at Belle II
- Double charmonium
  - $e^+e^- \rightarrow c\bar{c} (0^{+/-}) c\bar{c} (1^{-/+})$
- Belle II prospects
  - Angular distributions, production
  - Probe for new states
  - $\chi_c$ and $\eta_c$ recoil to study $1^{--}$

- Two-photon fusion
  - $e^+e^- \rightarrow c\bar{c} (0^{-+}, 2^+) e^+e^-$

- Belle II prospects
  - Disentangle $\phi J/\psi$ states
  - $\chi_{c0,2}(2P)$ properties
**Important past B-Factory contributions**

- Bottomonium spectroscopy: discovery of $\eta_b$, $h_b$
- Anomalous $\pi\pi$ and $\eta$ transitions
- Discovery of $Z_b$, exotic nature of above-threshold $\Upsilon$ states

**Most results from operation at non-$\Upsilon(4S)$ energies**

**Existing datasets in fb$^{-1}$ (M events)**

<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>
</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>
</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>
</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>
</tr>
</tbody>
</table>

**Expect additional samples to be collected at Belle II**

**Existing B-Factories $\sim$1.5 ab$^{-1}$ @ $\Upsilon(4S)$: opportunity for non-B physics results in early operation?**
Potential Belle II Bottomonium Scenarios

Above $\Upsilon(4S)$
- Study of exotic four-quark states
- $<6\text{fb}^{-1}$ accumulated by Belle at $E_{\text{CM}}=\Upsilon(6S)$
- $1\text{ ab}^{-1} @ \Upsilon(5S) =$ order of magnitude increase (also $B_s$ physics)
- $100\text{ fb}^{-1} @ \Upsilon(6S)$ plus $\sim400\text{ fb}^{-1}$ scan

Below $\Upsilon(4S)$
- Bottomonium search/study
- New Physics in decays
- Scan for direct production of $\Upsilon(n^3D_1)$
- $300\text{fb}^{-1} @ \Upsilon(3S) =$ order of magnitude increase

Dedicated operation $<5\%$ of total luminosity
**Z_b^± states in the bottomonium system**

- Anomalous dipion transition rate: γ(5S) → ππ b\bar{b}
- Discovery of h_b(1P, 2P), η_b(2S), **indication of charged Z_b^± states**
- γ(5S) → π^± Z_b^± → π^± γ(1S,2S,3S) and Z_b^± → π^± h_b(1P,2P)
- **Analogous to Y(4260) decays and Z_c^± in charmonium system!**

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**PRL 108, 122001 (2012)
Z_b^\pm states in the bottomonium system

- Decays to B^{(*)}B^* dominate

\[ Z_b(10610) \rightarrow B\bar{B}^* \]

\[ Z_b(10650) \rightarrow B^*\bar{B}^* \]

- Z_b masses \sim equal to B^{(*)}B^* thresholds?

PRL 116, 212001 (2016)
Z\(_{b}^{\pm}\) states from \(\Upsilon(6S)\) decays

- Belle energy scan up to \(\Upsilon(6S)\), search for \(\Upsilon(6S) \rightarrow \pi^{+}\pi^{-} h_{b}(1P,2P)\) decays
  
  ![Graph showing \(\Upsilon(5S)\) and \(\Upsilon(6S)\) transitions](image)

  - Enhanced transition rate, similar to \(\Upsilon(5S)\) scenario
  - Observation of \(Z_{b}(106XX)\) states, but unable to resolve them

PRL 117, 142001 (2016)
**γ(6S): Belle II Objectives**

**“New States”**

- Understand $\gamma(6S) \to Z_b$ decay
  - $\gamma(6S) \to \pi^+\pi^- h_b (1P,2P)$
  - $\gamma(6S) \to \pi^+\pi^- \gamma(1S,2S,3S) (+ \ell^+\ell^- \text{ exclusive})$
  - Also with $\pi^0\pi^0$?

- Evidence $Z_b$ is a molecular state
- Should have partners (“$W_b$”)
- Potential searches
  - $\gamma(5S, 6S) \to \gamma W_{b0}$
  - $\gamma(6S) \to \pi^+\pi^- (\rho) W_{b0}$ possible?
  - $W_{b0} \to \eta_b\pi, \chi_b\pi, \gamma\rho$

**Voloshin, PRD 84, 031502 (2011)**
γ(6S): Belle II Objectives

Quarkonia Transitions

► Analogies to γ(5S) evidence/observations at Belle
  - γ(6S) → π⁺π⁻ γ(n³D_J) (n=1 or 2)
  - γ(6S) → η γ(pS) and η γ(n³D_J) (n=1)
  - γ(6S) → ω χ_b(1P)
  - γ(6S) → K⁺K⁻ γ(1S)

► Inclusive and exclusive searches for all of the above

► Understand the nature of above-threshold γ(mS) states

Bottomonium Discovery

► γ(6S) phase space opens possibility for first discovery:
  - h_b(3P): γ(6S) → π⁺π⁻ h_b(3P)
  - Y(2D): γ(6S) → π⁺π⁻ Y(2D) or → η Y(2D)
  - 1F bottomonium multiplet via dipion transition?
Above $\Upsilon(4S)$ Scan

- Other $B^{(*)}\overline{B}^{(*)}$ thresholds show potential:
  - $R_b$ dip versus $\pi\pi\Upsilon$ rise
  - Similar features as charm thresholds?
  - Sign of “$Y_b$” state near $\sim 10.75$ GeV?

- Previous scans $<1$ fb$^{-1}$ per point

- 10MeV steps of 10 fb$^{-1}$ to understand entire region, measure final state $\sigma$

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PRL 117, 142001 (2016)

PRL 93, 011101 (2016)
**γ(3S) On-Resonance: Bottomonium physics**

- **300fb⁻¹ ~10xBaBar (Phase 3+)**
  - Focus on conventional $b\bar{b}$ physics
    - $γ(1^{3}D_{J})$ triplet: discover $J=1,3$
    - $\eta_{b}(1S,2S)$: confirm $m(\eta_{b}(1S,2S))$
    - Hadronic ($\pi^{0},\pi^{+}\pi^{-},\eta,\omega$) decays
    - Radiative transitions
  - $Z_{b}^{+}$ exotic contributions?

- **BSM physics**
  - $γ(1S,2S) \rightarrow$ invisible
  - $\chi_{b0} \rightarrow \tau\tau$ light Higgs search
  - Dark sector $γ\chi\bar{\chi}$ decays
Conclusions

► SuperKEKB / Belle II upgrade status
  ■ Accelerator commissioning ongoing, collisions are happening!
  ■ Nominal start early 2019

► Next generation flavor factory
  ■ At least 50 times more data and improved detector capabilities
  ■ Search for New Physics via high-statistics precision measurement

► Potential for understanding exotic hadrons and quarkonium
  ■ Unique production methods to probe charmonium(-like) system
  ■ Only experiment able to address nature of bottomonium(-like) states
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Thank you for your attention, and stay tuned!