Exotic and Conventional Quarkonium Physics Prospects at Belle II

QCD@LHC
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On behalf of the Belle II collaboration
QUARKONIA: legacy of 1st generation B-Factories

BELLE II: the next generation B-Factory

FUTURE PROSPECTS:

• Charmonium(-like) production
• Bottomonium(-like): above $Y(4S)$
• Bottomonium(-like): below $Y(4S)$
QUARKONIA: legacy of 1st generation B-Factories

BELLE II: the next generation B-Factory

FUTURE PROSPECTS:

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- Bottomonium(-like): above $Y(4S)$
- Bottomonium(-like): below $Y(4S)$
• The legacy of 1\textsuperscript{st} generation B-factories is a variety of quarkonium states
• Good agreement with predictions below open flavor threshold
• Many discoveries are difficult to explain with quarkonium model
• Several states have non-zero charge (cannot be q\bar{q} pairs)
• Exotic candidates, XYZ states

Challenge for the new generation B-factories
X(3872)  
\[ B^\pm \rightarrow K^\pm [\pi^+ \pi^- J/\psi] \]

Y(4260)  
\[ e^+ e^- \rightarrow \gamma [\pi^+ \pi^- J/\psi] \]

Z(4430)  
\[ B \rightarrow K [\pi^\pm \psi'] \]

B-Factory milestones

PRL 91, 262001 (2003)  
PRL 95, 142001 (2005)  
PRL 100, 142001 (2008)
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BELLE II: the next generation B-Factory

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Goal: x50 Belle integrated luminosity (50 ab\(^{-1}\))

Target luminosity:
\[ L = 8 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1} (x40 \text{ Belle}) \]

Nano-beam scheme
(P. Raimondi for SuperB)
- beam currents x2
- squeeze beam @ IP by 1/20
As expected, the effective bunch length is reduced from ~10 mm (KEKB) to ~0.5 mm (SuperKEKB)

- We measured it in two track events with early Belle II data
The Belle II detector

Electrons (7 GeV)

Positrons (4 GeV)

Vertex Detector
2 layers Si Pixels (DEPFET) + 4 layers Si double sided strip DSSD

Central Drift Chamber
Smaller cell size, long lever arm

EM Calorimeter
CsI(Tl), waveform sampling electronics

Particle Identification
Time-of-Propagation counter (barrel) Prox. focusing Aerogel RICH (forward)

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

Belle II TDR, arXiv:1011.0352
Belle II status and schedule

![Graph showing Belle II status and schedule]
Phase 1:
Accelerator commissioning (completed in 2016)
Detector roll-in (April 2017)
Phase 2 (ended in July 2018):
- Beam optimization and background minimization, ~1/10 vertex detector
- Detector calibration
- Understanding of the new machine, test of the nano beam scheme
- First collisions and first data collected
In Phase 2 luminosity tuning had priority over data taking.

\[ L_{\text{peak}} = 5.5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \]
First collisions (April 26th)
~0.5 fb\(^{-1}\) data collected until July
• Optimization of tracking algorithms and performance
• “Re-discovery” of most particles
• Calorimeter energy calibration
• Detector alignment
• Calibration of PID
• Background studies
Getting ready for physics

- Optimization of tracking algorithms and performance
- "Re-discovery" of most particles
- Calorimeter energy calibration
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1 week after the first collisions!
• Optimization of tracking algorithms and performance
• “Re-discovery” of most particles
• Calorimeter energy calibration
• Detector alignment
• Calibration of PID
• Background studies
• Phase3 (early 2019):
  Full Belle II detector (vertex detector), physics run
**Belle II status and schedule**

**Phase 3 (early 2019):** Full Belle II detector, physics run

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<thead>
<tr>
<th>Experiment</th>
<th>$\Upsilon(1S)$</th>
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<td>1.2 (21)</td>
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<td>$R_b$ scan</td>
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<td>BelleII</td>
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<td>100 + 400 (scan)</td>
<td>3.6%</td>
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5 ab$^{-1}$ by 2020
50 ab$^{-1}$ in 2024

"Exotic and conventional Quarkonium physics prospects at Belle II"
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BELLE II: the next generation B-Factory

FUTURE PROSPECTS:
- Charmonium(-like) production
- Bottomonium(-like): above $Y(4S)$
- Bottomonium(-like): below $Y(4S)$
• Competition from LHCb (B decays) and BESIII (scans for 1- - states)
• Exploit different production methods
Charmonia: B decay

• Competition from LHCb

*Phys. Rev. D* 95, 012002 (2017)

LHCb amplitude analysis of $B \to J/\psi \phi K$

• $e^+e^-$ B-factories only: ➔ Belle II

*PRD* 97, 012005 (2018)
Charmonia: B decay

• Competition from LHCb


LHCb amplitude analysis of $B \rightarrow J/\psi \phi K$

- hadronic transitions with $\pi^0, \eta, \omega$ in final state
- states decaying with large multiplicities

• $e^+e^-$ B-factories only: ➡ Belle II

PRD 97, 012005 (2018)

Competitive with LHCb exclusive reconstruction only for:

QCD@LHC 2018 - Bianca Scavino
• Competition from BESIII

• Recent BESIII scan data show a complex landscape: scan of all decay channels is needed!

- **Belle II**
  - Higher effective luminosity
  - Wider mass range
• Observed in combinations of $J=1$ and $J=0$
  $e^+e^- \rightarrow c\bar{c} \ (0+/-) \ c\bar{c} \ (1-/+)$

$\Rightarrow$ Belle II
  - angular distributions, production
  - probe for new states

*Belle, PRL 98, 082001 (2005)*
Bottomonia: motivation for non-$Y(4S)$ running

\[ \Rightarrow \text{above } Y(4S): \]
- conventional state search
- exotica discovery
- precision $Z_b$ mass measurement

- $1 \text{ ab}^{-1} @ Y(5S)$: also $B_s$ physics
- $100 \text{ fb}^{-1} @ Y(6S) + \sim 400 \text{ fb}^{-1}$ scan

**Current samples in fb$^{-1}$ (millions of events)**

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**Bottomonium: motivation for non-**$\Upsilon$(4S) running

→ **below $\Upsilon$(4S):**
  - bottomonium studies/searches
  - new physics in decays (DM / light Higgs)
  - anti nucleon production (possible DM application)
  - baryon physics

- 300 fb$^{-1}$ @$\Upsilon$(3S): order of magnitude increase

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QCD@LHC 2018 - Bianca Scavino
• open question: are $Z_b$ masses below or above $B^{(*)}B^*$ thresholds?
• fundamental question to understand their nature

\[ e_B(Z_b) = (0.60 \pm 0.40 \pm 0.02) \text{ MeV}, \]
\[ e_B(Z_{b'}) = (0.97 \pm 0.22) \text{ MeV}, \]

\[ e_B(Z_b) \equiv M(B\bar{B}^*) - M(Z_b), \]
\[ e_B(Z_{b'}) \equiv M(B^*\bar{B}^*) - M(Z_{b'}), \]

\( \text{Phys. Rev. D 93, 074031 (2016)} \)

\( \rightarrow \) Belle II
- 1 ab\(^{-1}\) @ Y(5S): determine if they are located above or below the open threshold
High energy scans: resolve new states ($Z_b^{\pm}$)

- Belle energy scan, search for $Y(6S) \rightarrow \pi^+ \pi^- h_b(1P, 2P)$ decay
- Observation of $Z_b(106XX)$ state, but unable to resolve them

**Belle II**

- Understand $Y(6S) \rightarrow Z_b$ decay
  - $Y(6S) \rightarrow \pi^+ \pi^- h_b(1P, 2P)$
  - $Y(6S) \rightarrow \pi^+ \pi^- Y(1S, 2S, 3S)$
Phys. Rev. D89 (2014) no.11, 111102

- \( \bar{d} \) in cosmic rays have long been considered a probe for supersymmetric relics in the galactic halo
- \( \bar{d} \) production described with coalescence models tuned on HEP data
- need to further constrain in the production model

⇒ CLEO and Babar measured the \( \bar{d} \) spectrum (no dedicated PID or tracking)

⇒ Belle II:
  - dedicated tracking and PID
  - collect \( \sim 3 \times 10^4 \bar{d} \) in 300 fb\(^{-1}\)
  - world’s best estimate of coalescence parameter
  - search for excited nucleons (\( d^* \))
  - \( d\bar{d} \) associated production
From Belle:
- No sign of weakly bound H dibaryon
- Near threshold enhancement in exclusive annihilations
  \( Y(1S,2S) \rightarrow \Lambda \bar{\Lambda} X \) (still not published)

Belle II
- Search for H dibaryon in missing mass (\( Y(3S) \rightarrow \Lambda \bar{\Lambda} H + \text{hadrons} \))
- High statistics study near threshold

Rough extrapolation to 300 fb\(^{-1}\) \( Y(3S) \)
- \( \sim 60 \text{ Million events with one } \Lambda \) or \( \bar{\Lambda} \)
- \( \sim 3 \text{ Million events with one } \Lambda \bar{\Lambda} \) pair
• We have entered the post B-factory era:
  • Variety of states in the quarkonium spectroscopy
  • Exotic states

• Belle II will collect 50 times more statistics than Belle II

• Belle II just ended Phase 2 commissioning run:
  • Effort to understand machine and the backgrounds, detector response, and test the software
  • First collision data

• Physics run will start at the beginning of 2019

• A variety of quarkonium studies will be possible
Summary

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Thanks for the attention and.. stay tuned!
BACKUP
### KEKB vs SuperKEKB

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<th>Parameters</th>
<th>KEKB</th>
<th>SuperKEKB</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>$E_b$</td>
<td></td>
<td>GeV</td>
</tr>
<tr>
<td>CM Boost</td>
<td>$\beta\gamma$</td>
<td>0.425</td>
<td>0.28</td>
</tr>
<tr>
<td>Half Crossing Angle</td>
<td>$\varphi$</td>
<td>11</td>
<td>41.5</td>
</tr>
<tr>
<td>Horizontal Emittance</td>
<td>$\varepsilon_x$</td>
<td>18</td>
<td>3.2</td>
</tr>
<tr>
<td>Emittance Ratio</td>
<td>$\kappa$</td>
<td>0.88</td>
<td>0.37</td>
</tr>
<tr>
<td>Beta-Function at IP</td>
<td>$\beta_x*/\beta_y*$</td>
<td>1200/5.9</td>
<td>32/0.27</td>
</tr>
<tr>
<td>Beam Currents</td>
<td>$I_b$</td>
<td>1.64</td>
<td>3.6</td>
</tr>
<tr>
<td>Beam-Beam Parameter</td>
<td>$\xi_y$</td>
<td>129</td>
<td>0.0881</td>
</tr>
<tr>
<td>Beam Size at IP</td>
<td>$\sigma_x*/\sigma_y*$</td>
<td>100/2</td>
<td>10/0.059</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$\mathcal{L}$</td>
<td>2.1x10$^{34}$</td>
<td></td>
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</table>
SVD 4 layers (DSSD) → 2 DEPFET + 4 DSS
CDC: small cell, long lever arm
ACC+TOF → TOP + ARICH
ECL: waveform sampling
KLM: RPC → Scintillator+SiPM
New challenges

- x40 luminosity:
  - x40 produced signal events
  - Higher background (detector occupancy, fake hits, radiation damage)
  - Higher event rate (trigger rate, DAQ, computing)

- Important to have a dedicated phase for background studies, detector response and alignment
Quarkonium production at B-factory

B decays

\[
\begin{align*}
&b \rightarrow W^+ c \bar{c} \\
&\bar{q} \rightarrow s \bar{q}
\end{align*}
\]

Initial State Radiation (ISR)

\[
\begin{align*}
&\Gamma \rightarrow e^- \gamma \gamma^* \\
&\Gamma \rightarrow e^+ \gamma^* \\
&\Gamma \rightarrow e^- \gamma^* \\
\end{align*}
\]

Two $\gamma$ interaction

\[
J^{PC} = 0^{--}, 0^{++}, 2^{++}
\]

Double charmonium production

\[
J^{PC} = 1^{--} \ (J/\Psi, \Psi(2S)) & \ J=0
\]

Quarkonium transitions
Anti-deuteron production is described by p-n coalescence models tuned on the HEP data.

Most recent data are from Alice:
- Large final state
- MC-driven correction

\[ \frac{dN_{\bar{d}}}{dT_{\bar{d}}} = \frac{p_0^3}{6k_{\bar{d}}} \frac{m_{\bar{d}}}{m_{\bar{p}}m_{\bar{n}}} \frac{dN}{dT_{\bar{p}}} \bigg|^{**} \frac{dN}{dT_{\bar{n}}} \bigg|^{**} \]

where \( T_i = E_i - m_i \) is the kinetic energy of \( i = \bar{d}, \bar{p}, \bar{n} \) and the \[^{**}\] notation recalls that the \( \bar{p} \) and \( \bar{n} \) spectra must be evaluated at \( T_{\bar{p}} = T_{\bar{d}}/2 \) and \( T_{\bar{n}} = T_{\bar{d}}/2 \), respectively (as dictated by Eq. (2.14)). In deriving Eq. (2.19), we have clearly assumed \( m_{\bar{p}} = m_{\bar{n}} = m_{\bar{d}}/2 \).