Quarkonium at Belle II

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On behalf of the Belle II collaboration

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The menu of this talk

1- An overview of the Belle II experiment

2- Status of the quarkonium physics program

3- Plans for the near and far future
# The B-factories legacy

![Graph showing integrated luminosity](image)

<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>?</td>
<td>$5 \times 10^4$ ($5.4 \times 10^4$)</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td></td>
</tr>
</tbody>
</table>
Belle II goal: collect 50 ab$^{-1}$ (~50x Belle data)
Super-KEKB goal: >30x KEKB luminosity
Super-KEKB and the nano-beam scheme

**Belle II goal:** collect 50 ab$^{-1}$ (~50x Belle data)

**Super-KEKB goal:** >30x KEKB luminosity

Beam aspect ratio (flat beam ~ 1-2%)

- **Brute force:** Current 2 x larger
- **Nanobeam scheme:**
  - $\beta_y$ * 20 x smaller
  - Vertical beam size ~ 50 nm

Beam currents

Vertical $\beta$ function at IP

Geometrical corrections
Super-KEKB: how is it going?

Operations started on March 19th 2018

Currently running at
- $L = 2.8 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- $\beta_y^* = 1 \text{ mm}$
- $L_{\text{int}} = 140 \text{ fb}^{-1}$ (As of May 12th 2021)
Belle II VS Belle, a matter of backgrounds

[P.Lewis et al, NIM A 914, 69-144 (2019)]

**Single beam backgrounds:**

- Touschek $\propto I^2 \sigma^{-1} n_b^{-1}$
- Beam Gas $\propto I$
- Synchrotron radiation $\propto I$

**Luminosity backgrounds:**

- Radiative Bhabha $\propto L$
- Two-photon $\propto L$
- Injection

Belle II is designed to perform as well as or better than Belle with much higher backgrounds!
Belle II

Electromagnetic calorimeter (ECL):
CsI(Tl) crystals, waveform sampling

K_{L} and muon detector (KLM):
- Resistive Plate Counters (RPC) (outer barrel)
- Scintillator + WLSF + MPPC (endcaps, inner barrel)

Magnet:
1.5 T superconducting

Trigger:
- Hardware: < 30 kHz
- Software: < 10 kHz

Vertex detectors (VXD):
- 2 layer DEPFET pixel detectors (PXD)
- 4 layer double-sided silicon strip detectors (SVD)

Central drift chamber (CDC):
- He(50%):C_{2}H_{6}(50%), small cells, fast electronics

Particle Identification (PID):
- Time-Of-Propagation counter (TOP) (barrel)
- Aerogel Ring-Imaging Cherenkov Counter (ARICH) (FWD)

DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fiber
MPPC: multi-pixel photon counter
Belle II performance VS Belle, in broad strokes

**Tracking** [Comp. Phys. Comm. 259 (2021) 107610 (Monte Carlo only), in preparation (data)]
- Better resolution at both low and high $p_t$
- Better efficiency at low $p_t$
- 2x better vertexing and decay time resolution

**Full event reconstruction** [Comput. Softw. Big Sci 3, 6 (2019)]
- Better purity and efficiency

**Neutrals** [paper in preparation]
- Better algorithms and electronics
- (Currently) only enough to compensate the increased backgrounds

**Particle identification** [paper in preparation]
- Better algorithms and new detectors (working on NN-based approaches)
- (Currently) only enough to compensate the increased backgrounds
Belle II road map

Summer 2022: match Belle data set at Y(4S)

2022-2023: Long shutdown: Detector HW replacement and upgrade (LS1)

2026-2027: Long shutdown: Accelerator HW upgrade (LS2)
What are we doing right now?

**Current data set:** 140 fb$^{-1}$ (increasing by 1-1.5 fb$^{-1}$/day)
- Understand the detector and the performance
- Check all the results at [https://docs.belle2.org/](https://docs.belle2.org/)!

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**Low-p PID in the SVD**  
[BELLE2-NOTE-PL-2020-028]

**Lepton-ID**  
[BELLE2-NOTE-PL-2020-027]

0.82 ≤ θ < 1.16 rad, muonID > 0.9

**Tracking efficiency**  
[BELLE2-NOTE-PL-2020-014]

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**Trigger efficiency**  
[BELLE2-NOTE-PL-2020-009]

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What are we doing right now?

**Current data set: 140 fb\(^{-1}\)** (increasing by 1-1.5 fb\(^{-1}\)/day)
- Understand the detector and the performance
- **Exploit new methods**
- **Take advantage of looser triggers for “low” luminosity**

\[ B^+ \rightarrow K^+ \bar{\nu} \bar{\nu} \text{ with a new tagging method} \]
[arXiv:2104.12624]

Search for Axion-Like Particles

Search for an Invisibly Decaying Z' Boson

+3 more papers already in internal review!
Quarkonia at Belle II
Quarkonia @ Belle II: how?

**Bottomonium**
- Hadronic transitions from $Y(4S)$
  - Best gateway to $h_b(1P)$ and $\eta_b(1S)$!
- ISR production
- Direct production
Quarkonia @ Belle II: how?

**Bottomonium**
- Hadronic transitions from Y(4S)
  - Best gateway to $h_b(1P)$ and $\eta_b(1S)$!
- ISR production
- Direct production

**Charmonium**
- $\gamma\gamma$ fusion running at Y(4S)
- B decays via $b \rightarrow c$
- ISR production
Non-4S runs are not scheduled yet.

Charmonia: 2 ab$^{-1}$

Narrow bottomonia: 0.2 ab$^{-1}$
(at CM energy below Y(4S))

Spin-singlet bottomonia from Y(4S): 1 ab$^{-1}$

Exotic bottomonia: 0.2 ab$^{-1}$
(at CM energy above Y(4S))

Right now: rediscovery time!
Reconstruct $B^\pm \rightarrow K^\pm \pi^+\pi^- J/\psi$
The X(3872) rediscovery

Reconstruct $B^\pm \rightarrow K^\pm \pi^+\pi^- J/\psi$

$\pi^+\pi^- J/\psi = \psi'$

$\pi^+\pi^- J/\psi = X(3872)$

Expected BF : $8.6 \pm 0.8 \times 10^{-6}$
Observed BF : $7.9 \pm 2.5 \times 10^{-6}$
Dipion transitions among bottomonia

Study $e^+e^- \rightarrow \pi^+\pi^- \mu^+\mu^- (+\gamma \text{ undetected})$
- $Y(4S) \rightarrow \pi^+\pi^- Y(nS)$
- $e^+e^- \rightarrow \gamma_{\text{ISR}} Y(mS), \ Y(mS) \rightarrow \pi^+\pi^- Y(nS)$
Dipion transitions among bottomonia

Study $e^+e^- \rightarrow \pi^+\pi^-\mu^+\mu^- (+\gamma \text{ undetected})$

- $Y(4S) \rightarrow \pi^+\pi^- Y(nS)$
- $e^+e^- \rightarrow \gamma_{\text{ISR}} Y(mS), \; Y(mS) \rightarrow \pi^+\pi^- Y(nS)$

Compare with Belle, 496 fb$^{-1}$ [PRD 96 (2017) 5, 052005]

- Improved low momentum tracking
Near-term plans and projects
By 2022 Belle II should have as much Y(4S) as Belle. Analysis results from 2023!

Many analysis already ongoing, just waiting for more data!

**Charmonium**
- $X(3872)$ lineshape combining Belle and Belle II dataset
- Full amplitude analysis of $B \rightarrow$ charmonium modes
- Inclusive $B \rightarrow K (c\bar{c})$

**Bottomonium sector**
- Dalitz analysis of $Y(4S) \rightarrow \pi^+\pi^- Y(nS)$
- $h_b(1P)$ and $\eta_b(1S)$ exclusive decays
A non-4S early run?

Outside Y(4S) even small data sets can make a difference

Currently available data sets in the bottomonium region
What’s special about 10.750 GeV?

JHEP10(2019)220 (Belle):
- “High-stat” scan points: 1 fb\(^{-1}\) each
- 1 point “on resonance”
- 2-3 points in the region of interest
- Significance: 5.2 \(\sigma\)

Parameters:

<table>
<thead>
<tr>
<th>(\Upsilon(10860))</th>
<th>(\Upsilon(11020))</th>
<th>New structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>(M) (MeV/c(^2))</td>
<td>10885.3 ± 1.5(^{+2.2}_{-0.9})</td>
<td>10752.7 ± 5.9(^{+0.7}_{-1.1})</td>
</tr>
<tr>
<td>(\Gamma) (MeV)</td>
<td>36.6(^{+4.5}<em>{-3.9})(^{+0.5}</em>{-1.1})</td>
<td>35.5(^{+17.6}<em>{-11.3})(^{+3.9}</em>{-3.3})</td>
</tr>
</tbody>
</table>
Why is the $Y(10750)$ important?

- Unlikely to be a molecule as it’s far from any S- threshold
- No direct matching to conventional states (but may be an S-D mixing?)

![Diagram showing the masses of Y(4S), B^+B^-, B^*B^*, B_s^+B_s^-, B_s^+B_s^-, and Y(5S) with the corresponding energies in GeV.]
The early $Y(10750)$ run

Proposal under discussion to take before the 2022 shutdown:
- **10.751 GeV**: 10 fb$^{-1}$ to study the $Y(10750)$ on-peak
- **10.657, 10.706, 10.810** (1+2+3 fb$^{-1}$) ancillary points for the BBbar decomposition
- **Total**: 10 + 6 fb$^{-1}$
Long-term plans and projects
**The wish:** 0.5 ab$^{-1}$ scan between Y(4S) and at least 11.02 GeV

[Bondar, Mizuk, Voloshin; Mod. Phys. A 32, 04, 1750025 (2017)]

**QCD goals:**
- Precise decomposition of the R-ratio
  and systematic exploration of the threshold region

**When?**
- Challenging for the accelerator operations
The wish: **collect 1 Billion Y(3S) or Y(2S)**

**NP goals:**

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

- **LFV:** push as much as possible
  the sensitivity on 
  \[ Y(nS) \rightarrow e\tau, \mu\tau \]
  - Best sensitivity to EFT Wilson coefficients
    [Hazard, Petrov; Phys. Rev. D 94, 074023]
The wish: collect 1 Billion Y(3S) or Y(2S)

(A personal favourite) QCD goals:
- \( Y(nS) \rightarrow \text{multi-quark system} + X \)
  - Exotic charmonia
  [Phys. Rev. D 93, 112013 (2016)]
The wish: collect 1 Billion $Y(3S)$ or $Y(2S)$

(A personal favourite) QCD goals:
- $Y(nS) \rightarrow$ multi-quark system + $X$
  - Exotic charmonia
    [Phys. Rev. D 93, 112013 (2016)]
  - Di-baryons
    - Loosely-bound
    - Deeply-bound
Belle II and SuperKEKB have fully entered the physics data taking phase

Detector performances are good
- First performance publications in fall 2021

Belle II is providing the first physics results
- Mostly low-multiplicity, NP channels

First quarkonium results from 2023!
- Bottomonium-related plans are under discussion
Backup
Y(10750): further evidences

Chin.Phys.C 44 8, 083001:
- Refit the BaBar $R_b$ scan
- Further evidence of $Y(10750)$ in interference

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$Y(10750)$</th>
<th>$Y(5S)$</th>
<th>$Y(6S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass/(MeV/$c^2$)</td>
<td>$10761 \pm 2$</td>
<td>$10882 \pm 1$</td>
<td>$11001 \pm 1$</td>
</tr>
<tr>
<td>Width/MeV</td>
<td>$48.5 \pm 3.0$</td>
<td>$49.5 \pm 1.5$</td>
<td>$35.1 \pm 1.2$</td>
</tr>
</tbody>
</table>
The (theoretical) golden modes at $Y(10750)$

1) $BB : BB^* : B^*B^*$ ratio is predicted by almost all models

2) $Y(10750) \rightarrow \omega \eta_b(1S)$ very large in one tetraquark-based model

<table>
<thead>
<tr>
<th>Mode</th>
<th>$B(4q)$ (%)</th>
<th>$B(bb)$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BB$</td>
<td>$39.3^{+38.7}_{-22.9}$</td>
<td>21.3</td>
</tr>
<tr>
<td>$BB^*$</td>
<td>$\sim0.2$</td>
<td>14.3</td>
</tr>
<tr>
<td>$B^<em>\overline{B}^</em>$</td>
<td>$52.3^{+54.9}_{-31.7}$</td>
<td>64.1</td>
</tr>
<tr>
<td>$B_s\overline{B}_s$</td>
<td>$-$</td>
<td>0.3</td>
</tr>
<tr>
<td>$\omega\eta_b$</td>
<td>$7.9^{+14.0}_{-5.0}$</td>
<td>$-$</td>
</tr>
<tr>
<td>$f_0(1370)\Upsilon$</td>
<td>$0.2^{+0.6}_{-0.2}$</td>
<td>$-$</td>
</tr>
<tr>
<td>$\omega\Upsilon$</td>
<td>$\sim0$</td>
<td>$-$</td>
</tr>
</tbody>
</table>

3) $M(\pi\pi)$ shape predicted by the tetraquark models
The (theoretical) golden modes at $Y(10750)$

Current energy limit: $E_{cm} = 11.02$ GeV
## ISR: Belle II VS Belle

<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>

At 4.26 GeV/c² for \(\pi^+\pi^- J/\psi\)

- \(\epsilon_{\text{BESIII}} = 46\%\)
- \(\epsilon_{\text{BelleII}} = 10\%\)

Same sensitivity as BESIII with \(~10\) ab\(^{-1}\)
Bottomonium spectrum

Mass [GeV/c^2]

Y(6S)
Y(5S)
Y(4S)
Y(3S)
Y(2S)  η_b(2S)
Y(1S)  η_b(1S)

\[ \begin{array}{c}
11.00 \\
10.75 \\
10.50 \\
10.25 \\
10.00 \\
9.75 \\
9.50 \\
\end{array} \]

\[ \begin{array}{cccc}
\chi_{b1}(3P) & \chi_{b2}(3P) & \chi_{b0}(2P) & \chi_{b1}(2P) \\
\chi_{b2}(2P) & h_b(2P) & \chi_{b0}(1P) & \chi_{b1}(1P) \\
\chi_{b2}(1P) & h_b(1P) & & \\
& & & \end{array} \]

\[ Y_2(1D) \]

1  2  3