Belle II - Status and Prospects

Matthias Hoek
(Johannes Gutenberg-University Mainz)

On behalf of the
Belle II Collaboration
QCD – As You Like It

Pentaquark

Tetraquark

Glueball

Hybrid meson

diquark-diantiquark

H-dibaryon

D^0 – D^- \text{ “molecule”}

Normal baryon

Normal meson

M. Hoek

Bound states in QCD and beyond III | St. Goar, Germany | 9th - 12th April 2019
New Hadrons at 1st Generation B-Factories

Bound states in QCD and beyond III | St. Goar, Germany | 9th - 12th April 2019

M. Hoek

KEKB
PEP-II

\[ h_c(1P/2P), \eta_b(2S) \]

\[ Z_c^+(4430) \]

\[ Y(4660) \]
\[ Y(4008) \]

\[ \Xi_c^*(3055) \]

\[ \eta_b(1S) \]

\[ Z_c^+(3895) \]

\[ Z_b^+(10610) \]
\[ Z_b^+(10650) \]

\[ D_{sJ}(2860) \]
\[ D_{sJ}(2700) \]
\[ \Xi_c^*(2970/3080) \]

\[ X(3915), X(3940), Y(3940) \]

\[ D_0^{*0} \& D_1^{*0} \]

\[ \Sigma_c^* \text{ baryon triplet} \]

\[ Y(4260) \]

\[ X(3872) \]

\[ \eta_c \& e^+e^- \rightarrow c\bar{c}c\bar{c} \]

\[ \chi'_c, \Omega_c^* \]

\[ \Xi_c^* \]

\[ D_{sJ}(2317/2460) \]

Exotic candidates
Where the Future starts – KEK (Tsukuba, Ibaraki)
SuperKEKB - Overview

- Asymmetric $e^+e^-$ collider
  - 7 GeV $e^-$ (2.6A)
  - 4 GeV $e^+$ (3.6A)
- 40 times KEKB luminosity
  - $\mathcal{L} = 8 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$
SuperKEKB – Increasing Luminosity

SuperKEKB/Belle II
2018 (preliminary)

<table>
<thead>
<tr>
<th>Date</th>
<th>σ_0 (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>05/03</td>
<td>3.5</td>
</tr>
<tr>
<td>05/17</td>
<td>3.0</td>
</tr>
<tr>
<td>05/31</td>
<td>2.5</td>
</tr>
<tr>
<td>06/14</td>
<td>3.0</td>
</tr>
<tr>
<td>06/28</td>
<td>2.5</td>
</tr>
<tr>
<td>07/12</td>
<td>3.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>E (GeV)</th>
<th>β*_x (mm)</th>
<th>β* (cm)</th>
<th>φ (mrad)</th>
<th>I (A)</th>
<th>L (cm²s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LER/HER</td>
<td>LER/HER</td>
<td>LER/HER</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KEKB</td>
<td>3.5/8.0</td>
<td>5.9/5.9</td>
<td>120/120</td>
<td>11</td>
<td>1.6/1.2</td>
</tr>
<tr>
<td>SuperKEKB</td>
<td>4.0/7.0</td>
<td>0.27/0.30</td>
<td>3.2/2.5</td>
<td>41.5</td>
<td>3.6/2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>80 x 10³⁴</td>
</tr>
</tbody>
</table>
Belle II Detector - Overview

- Pixel Detector (PXD)
- Silicon Vertex Detector (SVD)
- Central Drift Chamber (CDC)
- TOP counter (TOP)
- Aerogel RICH counter (ARICH)
- Electromagnetic Calorimeter (ECL)
- $K_L^0$/Muon Detector (KLM)
Belle II Detector – New Developments

**VXD**
- PiXel Detector
  - Two layers DEPFET
  - \(75 \mu m\) thickness
  - ~0.19% \(X_0\)
- Silicon Vertex Detector
  - Four layers DSSD
  - ~0.7% \(X_0\)
- CO\(_2\) cooling
- Improve resolution by factor 2

**TOP**
- Time-of-Propagation Cherenkov counter
  - 2D + Time
  - Extreme timing precision
    - ~100ps single photon
- Fused Silica radiator
- MCP-PMT photo sensors
- Sampling readout + feature extraction
  - IRSX ASIC

**ARICH**
- Aerogel RICH with novel “focussing” radiator
  - Different Aerogel densities
- HAPD photo sensors for single-photon detection
- ~80k read-out channels
- Custom ASIC
Belle II Physics Plan

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)/\Upsilon(4S) )</th>
<th>%</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>Belle II</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>
Results from Phase II – Detector Performance

Belle II 2018 (Preliminary)

\[
\int L \, dt = 250 \, pb^{-1}
\]

Porosity of 0.997 ± 0.001

\[\sigma_Y < 1 \, \mu m\]

\[d_0 \]

Width of distribution is a measure of resolution

\[\sigma_z \sim 50 \, \mu m\]

Vertical beam spot size \(\sigma_Y \ll d_0\) resolution

\[\int L \, dt = 5 \, pb^{-1}\]

\[E_T > 0.15 \, GeV\]

Belle II 2018 (Preliminary)

\[\pi^0\]

\[\frac{1}{N} \frac{\Delta N}{10 \, \mu m}\]

\[\sigma_{68} = 12.1 \, \mu m\]

\[\sigma_{68} = 20.5 \, \mu m\]

Integral over \(22 \, pb^{-1}\)

\[d_0\) corrected for beam offset [\(\mu m\)]
Results from Phase II – PID Performance

The figure shows the results of decay channels in QCD, specifically:

1. $\phi \to K^+ K^-$
2. $\Lambda \to p\pi^-$

Graphs and plots illustrate the following:

- The distribution of events in the mass of $\phi$ for different decay modes.
- The PID performance in identifying $\phi$ and $\Lambda$ particles.

Event counts and integration over different datasets are highlighted, indicating the preliminary results from Belle II.
Results from Phase II – ‘Rediscoveries’

\[ \Lambda_c \]

\[ \int L = 472 \text{ pb}^{-1} \]

Belle II 2018 Preliminary

\[ J/\psi \rightarrow e^+ e^- \]

\[ \begin{align*}
\mu_s &= 3.0901 \pm 0.0012 \\
\text{nbkg} &= 893 \pm 32 \\
\text{nsig} &= 198 \pm 19
\end{align*} \]

\[ \int L \, dt = 472 \text{ pb}^{-1} \]

Belle II 2018 preliminary
Quarkonium Production at B-Factories

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

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

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

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

- **Quarkonium transitions**
  - Hadronic/radiative decays between states
Access to line shape of vector states

- Y(4230), Y(4260), Y(4360) could all be explored

- Unexpected Y(4260) line-shape measured at BESIII, inconsistent among different modes. Could explore w/ ISR

- Cross sections of exclusive $c\bar{c} +$ hadrons

- Search for strange partner of Z(3900) in $K^+K^-J/\psi$

Charmonium at Belle II – ISR

<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>$\pi^+\pi^-2S$</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>

BES III, PRL 118, 092001 (2017)

10ab$^{-1}$ (50ab$^{-1}$)
Charmonium at Belle II – Other Production Modes

- 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 $B \rightarrow \text{charmonium}$
Settle the nature of the $\Upsilon(5S)$!

- $\Upsilon(5S)$ line shapes
  - Apparent discrepancies in shape in $\pi\pi\Upsilon$ modes vs. $\pi\pi\phi$ modes
- Is $Z_b$ above/below $B^*(B^*)$ threshold?

- $\Upsilon(5S)$ and $\Upsilon(6S)$ provide windows to search for missing narrow states in the bottomonium spectrum
  - Understand $\Upsilon(6S) \rightarrow Z_b$ decay
  - Evidence $Z_b$ is a molecular state
  - Should have partners ("$W_b$")

These runs require dedicated scans and/or samples on specific resonances!
Could collect 10-fold BaBar data set at \( \Upsilon(3S) \) resonance

Focus on conventional \( b \bar{b} \) physics

- \( \Upsilon(1 \, ^3D_J) \) 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?

Even more Exotics

- Probing \( \Lambda \Lambda \) interaction
- Search for \( H \) dibaryon in missing mass from \( \Upsilon(3S) \to H \Lambda \Lambda + \) hadrons
- (Anti-)Deuteron production: Get the world best estimate of the coalescence parameter

BSM-Physics (Dark Sector)
Conclusions

- SuperKEKB and Belle II Detector status
  - Detector installation finished
  - Phase 3 just started

- Belle II promises to collect a huge data sample in $\Upsilon(4S)$ but also increase data on others areas

- 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

- BSM Searches in Dark Sector
Questions?
Quarkonium Spectroscopy today

Charmonium

Bottomonium