Hadron Spectroscopy Studies at Belle II
XLVII International Symposium on Multiparticle Dynamics, Tlaxcala, Mexico
Nils Braun for the Belle II Collaboration | 12.09.2017
Quarkonium and Quarkonium-like states

Quarkonium

- $c\bar{c}$
- $e^-e^+$
  - conventional quarkonium
  - positronium

Theory models for Quarkonium-like/Exotic States

- $q\bar{q}$-gluon “hybrid”
  - hadroquarkonium
- J/$\psi$
- diquark-diantiquark
- $D^0 - \bar{D}^{*0}$ “molecule”
Quarkonium and Quarkonium-like states

Starting from the discovery of $X(3872)$ in 2003, more than 20 exotic states have been reported!
Introduction to Belle II
Belle - A success story

- KEKB was an electron-positron collider at KEK in Tsukuba/Japan which studied the decay of B mesons at the $\Upsilon(4S)$ resonance
- It had a large physics program, including:
  - Measurements of CKM matrix elements and angles of the unitarity triangle
  - Observation of direct CP violation in B decays
  - Measurements of rare decay modes
  - Searches for rare $\tau$ decays
  - Discovery of exotic hadrons including charged charmonium- and bottomonium-like states
### From Belle to Belle II

<table>
<thead>
<tr>
<th></th>
<th>KEKB</th>
<th>Super KEKB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instantaneous Luminosity</td>
<td>$2 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>80</td>
</tr>
<tr>
<td>Integrated Luminosity</td>
<td>1 ab$^{-1}$</td>
<td>50</td>
</tr>
<tr>
<td>Runtime</td>
<td>1998 to 2010</td>
<td>start in 2018</td>
</tr>
<tr>
<td>Detector</td>
<td>Belle</td>
<td>Belle II</td>
</tr>
<tr>
<td>Raw Data</td>
<td>1 PB</td>
<td>100 PB (projected)</td>
</tr>
</tbody>
</table>

Higher precision – wider range of topologies – better spectroscopy

- Higher luminosity also leads to a higher background $\Rightarrow$ need for better detector, better trigger, better software reconstruction
- World-wide collaboration is working on the upgrade (681 scientists from 100 institutes in more than 20 countries)
Belle II Detector

EM Calorimeter:
- CsI(Tl), waveform sampling (barrel)
- CsI(Tl), waveform sampling (end-caps)

KL and muon detector:
- Resistive Plate Counter (barrel)
- Scintillator + WLSF + MPPC (end-caps)

Superconducting solenoid to provide 1.5T magnetic field

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

Electron (7 GeV)

Beryllium beam pipe
- 2 cm diameter

Vertex Detector
- 2 layers DEPFET + 4 layers DSSD

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

Positron (4 GeV)
First beam test for the innermost tracking detectors at DESY, Germany.
First cosmic events reconstructed with CDC
Belle II Commissioning and Early Physics Opportunities

- **BEAST Phase I** completed Feb-June 2016: SuperKEKB commissioning to characterize the beam environment

- **Phase II Early 2018:**
  - Belle II without the inner silicon-based VXD tracking system
  - Characterize background radiation the innermost tracking system is exposed to
  - Estimated duration $\sim 5$ month and recording of $20 - 40 \text{ fb}^{-1}$ at various energies
  - First months will be commissioning data to test the sub-detectors and to study the machine background

- **Phase III Beginning 2019:**
  - Start of data taking with the complete Belle II detector
  - Primary running at $\Upsilon(4S)$ for B-pair production

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Scans Off. Res.</th>
<th>$\Upsilon(6S)$ fb$^{-1}$</th>
<th>$\Upsilon(5S)$ fb$^{-1}$ 10$^6$</th>
<th>$\Upsilon(4S)$ fb$^{-1}$ 10$^6$</th>
<th>$\Upsilon(3S)$ fb$^{-1}$ 10$^6$</th>
<th>$\Upsilon(2S)$ fb$^{-1}$ 10$^6$</th>
<th>$\Upsilon(1S)$ fb$^{-1}$ 10$^6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO</td>
<td>17.1</td>
<td>-</td>
<td>0.1 0.4</td>
<td>16 17.1</td>
<td>1.2 5</td>
<td>1.2 10</td>
<td>1.2 21</td>
</tr>
<tr>
<td>BaBar</td>
<td>54</td>
<td>$R_b$ scan</td>
<td>433 471</td>
<td>30 122</td>
<td>14 99</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Belle</td>
<td>100</td>
<td>$\sim 5.5$</td>
<td>36 121</td>
<td>711 772</td>
<td>3 12</td>
<td>25 158</td>
<td>6 102</td>
</tr>
</tbody>
</table>
Quarkonium and Quarkonium-like states

bottomonium(like)
Hadron Spectroscopy at Belle II
The series of discoveries started with the observation of the $\eta'_c$ meson in $B \to K\eta'_c$ decays.

The first exotic state was $X(3872)$ – again found in $B \to KX(3872)$ decays.
Belle - Another success story continued

Coloured boxes: exotic candidates

X(3940), Y(3940)

Σc* baryon triplet

D0* & D1*

Ds (2317/2460)

Xcx (3090)

Y(3940)

Y(4008)

Y(4260)

Y(4660)

Y(4008)

Zc+ (3895)

Zb+ (10610)

Zb+ (10650)

Zc+ (4430)

h_b (1P, 2P)

DsJ (2317/2460)

DsJ (2860)

DsJ (2700)

Xcx (3090)

Σc* baryon triplet

D0* & D1*

Ds (2317/2460)

Xcx (3090)

χc2'

Σc* baryon triplet

D0* & D1*

Ds (2317/2460)

Xcx (3090)

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Σc* baryon triplet

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Σc* baryon triplet

D0* & D1*
Why Hadron Spectroscopy at Belle II?

Unique capabilities of B factories:

- Exactly two B mesons produced (at $\Upsilon(4S)$)
- Good reconstruction of $\gamma, \pi^0$
- Can reconstruct one resonance, look for the recoiling system (e.g. $e^+e^- \rightarrow J/\psi + X$)
- Variety of different production channels
- High resolution, large solid angle spectrometer with particle identification capability makes reconstruction of many decay modes possible.
Production of Quarkonium at $e^+e^-$ colliders

B decays

Initial state radiation

Double $c\bar{c}$

$\gamma\gamma$ collisions

Change CM energy

bb-exotic

Allowed/favored quantum numbers are different depending on production processes.
Analysis techniques for Quarkonium searches - selection

With X(3872) as an example

Event reconstruction and selection

\[ B^{\pm} \rightarrow K^{\pm} \pi^+ \pi^- J/\psi \]

- e.g. require two oppositely charged leptons with certain invariant mass

\[ 3.076 < M_{\ell^+ \ell^-} < 3.116 \text{ GeV} \]

- Reconstruct B mesons: Very helpful variables

\[ |\Delta E| = |E_{\text{B}}^{\text{cms}} - E_{\text{beam}}^{\text{cms}}| \]

\[ M_{bc} = \sqrt{(E_{\text{beam}}^{\text{cms}})^2 - (p_{B}^{\text{cms}})^2} \]

Similar without B mesons.

- Background sources: other decays, continuum, combinatorics, beam-induced background
Analysis techniques for Quarkonium studies

Extract information on state, e.g.
- Look at mass distributions:
  \[ M(\pi^+\pi^-\ell^+\ell^-) - M(\ell^+\ell^-) \]
- Recoil mass (e.g. of J/ψ)
- Extract mass, width, significance
- Dalitz analysis and fit
- Full angular analysis

Dalitz analysis of
\[ B \to K\pi^+\psi' \]
(looking for \( Z(4430)^+ \))
R. Mizuk et al.
(Belle collaboration),
PRD 80, 03114
Overview of the possible studies - Charmonium(-like)

Large amounts of data is needed (> 1 ab⁻¹) to be competitive to already performed studies ⇒ only for phase III.

- Effective luminosities at low energies by ISR in Belle and Belle II $\Upsilon(4S)$ runs.

- total amplitude analyses of the three-body decays of charged charmonium-like states ($Z^+$) in B-decays.

- new exotic vector states ($Y$), fit for resonance parameters in initial-state radiation.

- Understand "non-standard" decay properties above the open-charm threshold of standard charmonium ($\psi(4040), \psi(4160)$)

- $Y(4140)$ and $Y(4274)$
Overview of the possible studies

Interesting and promising examples for bottomonium:

- $\Upsilon(6S)$ beam energy:
  - Understand $\Upsilon(6S) \rightarrow Z_b$ states (molecular state? partners?)
  - bottomonium discovery ($h_b(3P), \Upsilon(2D)$)
  - sign of a $Y_b$ state?

- $\Upsilon(3S)$ beam energy:
  - conventional bottomonium physics: $\Upsilon(1^3D_J)$ triplet, $\eta_b(1S, 2S)$
  - Hindered radiative transitions
  - dipion transitions
  - invisible decays
Three out of many possible Analyses at Belle II
\( \eta \) transitions

\( \eta \) transitions are always violating the Heavy Quark Spin Symmetry

\[
\frac{B[\Upsilon(nS) \rightarrow \eta \Upsilon(mS)]}{B[\Upsilon(nS) \rightarrow \pi \pi \Upsilon(mS)]} \approx \frac{\Lambda_{\text{QCD}}^2}{m_b^2} \approx 10^{-3}
\]

\( \Upsilon(5S) \rightarrow \eta \Upsilon(mS) \)

(Belle, preliminary)

\( \Upsilon(5S) \rightarrow \pi \pi \Upsilon(mS) \)

(Belle, Phys. Rev. Lett. 108, 032001)
Selection algorithm:

1. Reconstruct event and photons, look for $\eta \rightarrow \gamma \gamma$ only  
   $\varepsilon = 58.0\%$

2. Cut on event topology (e.g. number of tracks $> 3$)  
   $\varepsilon = 52.4\%$

3. Veto on $\pi^0$  
   $\varepsilon = 33.1\%$

4. Kinematic fit on invariant mass
$\Upsilon(3S) \to \pi\pi h_b(1P)$

- Current limit on branching fraction of $< 1.2 \times 10^{-4}$ challenges most theoretical models.
- Search using the invariant mass recoiling against the $\pi^+\pi^-$ system (only possible at B-factories!)
- Great improvement possible because of better resolution of Belle II (compared to Belle and BaBar)
Search for partner states of $Z_b(10610)^0$

- $Z_b(10610)^0 \rightarrow \Upsilon(2S)\pi^0\pi^0$ was seen with $6.5\sigma$ significance (PhysRev D 88, 052016).
- Theory models may imply partners, which decay into $\chi_{bJ}$ (S. Ohkoda et al., PRD 86, 014004 (2012)).
- Higher statistics needed, because signal yield is much lower ($\gamma$ efficiency and $\text{Br}(\chi_{bJ} \rightarrow \Upsilon(1S, 2S, 3D)\gamma)$ are multiplied).

![Graph showing events with and without $Z_b$](image-url)
The large data sample of Belle II will have a large impact on (exotic) quarkonium physics.

Phase II with a partial detector will start soon.

Hopefully, a deeper understanding on the origin of exotic states will be possible soon.

Stay tuned!
Thank you for your attention
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- A new hadron spectroscopy, Stephen Lars Olsen, arXiv:1411.7738
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- Heavy flavored hadron spectroscopy at Belle and prospect, Kenkichi Miyabayashi, EINN 2015
Backup
### Tracking Detectors

**Beam pipe**
- **Type**: Beryllium double-wall
- **Configuration**: Cylindrical, inner radius 10 mm, 10 μm Au, 0.6 mm Be, 1 mm coolant (paraffin), 0.4 mm Be

**PXD**
- **Type**: Silicon pixel (DEPFET)
- **Configuration**: Sensor size: 15×100 (120) mm², pixel size: 50×50 (75) μm², 2 layers: 8 (12) sensors
- **Readout**: 10 M

**SVD**
- **Type**: Double sided Silicon strip
- **Configuration**: Sensors: rectangular and trapezoidal Strip pitch: 50(p)/160(n) - 75(p)/240(n) μm, 4 layers: 16/30/56/85 sensors
- **Readout**: 245 k

**CDC**
- **Type**: Small cell drift chamber
- **Configuration**: 56 layers, 32 axial, 24 stereo, r = 16 - 112 cm, - 83 ≤ z ≤ 159 cm
- **Readout**: 14 k

**Performance**
- Impact parameter resolution: $\sigma_{z_0} \sim 20 \text{ μm}$
  - (PXD and SVD)

\[ \sigma_{r\phi} = 100 \text{ μm}, \sigma_z = 2 \text{ mm} \]
\[ \frac{\sigma_{p_t}}{p_t} = \sqrt{(0.2\%p_t)^2 + (0.3\%/\beta)^2} \]
\[ \frac{\sigma_{p_t}}{p_t} = \sqrt{(0.1\%p_t)^2 + (0.3\%/\beta)^2} \text{ (with SVD)} \]
Cherenkov ring imaging with precision time measurement (better than 100 ps)

Kaon/Pion

$p = 2 \text{ GeV/c}$

Quartz Property  | Requirement
-----------------|-------------
Flatness         | <6.3 $\mu$m |
Perpendicularity | <20 arcsec  |
Parallelism      | <4 arcsec   |
Roughness        | < 0.5 nm (RMS) |
Bulk transmittance | > 98% / m |
Surface reflectance | > 99.9% / reflection |

Hadron Spectroscopy Studies at Belle II - Nils Braun
- Use two aerogel layers in focusing configuration to increase n. of photons without resolution degradation

\[ n_1 = 1.045, \quad n_2 = 1.055 \]
Why Hadron Spectroscopy?

- Large hierarchy of the physical scales makes heavy quarkonium very interesting
  - \( m > \Lambda_{\text{QCD}} \)
  - heavy-quark bound-state velocity \( v \ll 1 \)
  - mass \( m \), relative momentum \( p \sim mv \) and binding energy \( E \sim mv^2 \) all at different scales

- In perturbative calculations: different scales get entangled. In lattice calculations: requirements on lattice spacing and size are difficult to met

- Ideal test environment for interplay between perturbative and non-perturbative QCD

- Large mass of quarkonium makes it suitable for probing BSM models in decays
Some Theory Explanations

- **Meson Molecules:**
  Weakly bound state of two mesons

- **"Tetraquarks":**
  Color-singlet diquarks bound directly by strong force

- **Other exotica:**
  - Hybrids: quarkonium with bound excited gluon
  - Hadroquarkonium: qq-light hadron interaction

- **Nothing special:**
  Kinematic effects / standard quarkonium
Detector and Reconstruction
Performance Phase II

- Due to missing VXD system: lower tracking efficiency and resolution, especially for particles $< 500$ MeV
- The CDC tracking system will be fully installed and provide sufficient hits for high-pt tracks
- Particle identification systems and ECL are not affected by the missing VXD system

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