Belle & Belle II recent results

Junhao Yin on behalf of Belle&Belle II
Belle experiment at KEKB

- KEKB is an asymmetric-energy $e^+e^-$ collider operating near $\Upsilon(4S)$ mass peak ($\sim 10.58$ GeV/$c^2$, $>B\bar{B}$ threshold).
- Belle detector has good performances on momentum/vertex resolution; particle identification, etc.
- Accumulated data set of $\sim 1$ ab$^{-1}$: not only a large $B\bar{B}$ sample ($B$-factory); but also a large charm sample to study charm physics.

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**Integrated luminosity of B factories**

<table>
<thead>
<tr>
<th>Year</th>
<th>KEKB</th>
<th>PEP-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998/1</td>
<td>0 fb$^{-1}$</td>
<td>0 fb$^{-1}$</td>
</tr>
<tr>
<td>2000/1</td>
<td>200 fb$^{-1}$</td>
<td>200 fb$^{-1}$</td>
</tr>
<tr>
<td>2002/1</td>
<td>400 fb$^{-1}$</td>
<td>400 fb$^{-1}$</td>
</tr>
<tr>
<td>2004/1</td>
<td>600 fb$^{-1}$</td>
<td>600 fb$^{-1}$</td>
</tr>
<tr>
<td>2006/1</td>
<td>800 fb$^{-1}$</td>
<td>800 fb$^{-1}$</td>
</tr>
<tr>
<td>2008/1</td>
<td>1000 fb$^{-1}$</td>
<td>1000 fb$^{-1}$</td>
</tr>
<tr>
<td>2010/1</td>
<td>1200 fb$^{-1}$</td>
<td>1200 fb$^{-1}$</td>
</tr>
<tr>
<td>2012/1</td>
<td>1400 fb$^{-1}$</td>
<td>1400 fb$^{-1}$</td>
</tr>
</tbody>
</table>

**On resonance:**
- $\Upsilon(5S)$: 121 fb$^{-1}$
- $\Upsilon(4S)$: 711 fb$^{-1}$
- $\Upsilon(3S)$: 3 fb$^{-1}$
- $\Upsilon(2S)$: 25 fb$^{-1}$
- $\Upsilon(1S)$: 6 fb$^{-1}$

**Off resonance:**
- $\sim 100$ fb$^{-1}$

**Total luminosity:**
- $\sim 550$ fb$^{-1}$

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**Peak L = 2.1 \times 10^{34}$/cm$^2$/sec**
SuperKEKB and Belle II: The next generation B-factory

Upgraded detector and accelerator

- **SuperKEKB**
  - New beam pipe & bellows
  - Positron source
  - Low emittance positrons to inject

- **Belle II**
  - New IR
  - EM Calorimeter: CsI(Tl), waveform sampling
  - 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

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

- **Readout (TRG, DAQ)**
  - Max. 30kHz L1 trigger
  - ~100% efficient for hadronic events.
  - 1MB (PXD) + 100kB (others) per event
  - over 30GB/sec to record

- **Offline computing**
  - Distributed over the world via the GRID

**arXiv:1011.0352 [physics.ins-det]**
Belle II already achieve the world record instantaneous luminosity: \(4.7 \times 10^{34}/cm^2/s\)
Integrated luminosity: 427.79 fb\(^{-1}\)
hadron spectroscopy

- New knowledge feeds back to theory.
- Perfect ground to test theoretical models.
- New viewing angle towards QCD.
Baryon spectroscopy

Production:
- fragmentation
- B-decays

Focus:
- Searching for new states
- Properties measurement

Fruitful results recently

- Evidence of new excited charmed baryon decays to $\Sigma_c(2455)^{0,++}\pi^\pm$
- Observation of $\Omega(2012)^- \rightarrow \Xi(1530)\bar{K}$
- Measurement of $\Xi_c^0 \rightarrow \Lambda_c^+\pi^-$
- First measurement of the $\Lambda_c^+ \rightarrow p\eta'$ decay
- …
Evidence of new excited charmed baryon decays to $\Sigma_c(2455)^{0,++}\pi^\pm$

In $\bar{B}^0 \rightarrow \Sigma_c(2455)^{0,++}\pi^\pm\bar{p}$, resonant state is found on $M(\Sigma_c(2455)^{0,++}\pi^\pm)$. Significance: $4.2\sigma$ after considering possible $\Lambda_c(2880)^+$ or $\Lambda_c(2940)^+$ contribution.

<table>
<thead>
<tr>
<th>State</th>
<th>Mass ($MeV/c^2$)</th>
<th>Width ($MeV$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_c(2880)^+$</td>
<td>$2881.63 \pm 0.24$</td>
<td>$5.6^{+0.8}_{-0.6}$</td>
</tr>
<tr>
<td>$\Lambda_c(2940)^+$</td>
<td>$2939.6^{+1.3}_{-1.5}$</td>
<td>$20^{+6}_{-5}$</td>
</tr>
<tr>
<td>$\Lambda_c(2910)^+$</td>
<td>$2913.8 \pm 5.6 \pm 3.8$</td>
<td>$51.8 \pm 20.0 \pm 18.8$</td>
</tr>
</tbody>
</table>

Based on $772 \times 10^6 B\bar{B}$ events on Belle

arXiv: 2206.08822
Evidence of new excited charmed baryon decays to $\Sigma_c(2455)^{0,++} \pi^\pm$

 Joint BF: $\mathcal{B}(\bar{B}^0 \to \Lambda_c(2910)^+ \bar{p}) \mathcal{B}(\Lambda_c(2910)^+ \to \Sigma_c(2455)^{0} \pi^+) = (9.5 \pm 3.6 \pm 1.6) \times 10^{-6}$

 $\mathcal{B}(\bar{B}^0 \to \Lambda_c(2910)^+ \bar{p}) \mathcal{B}(\Lambda_c(2910)^+ \to \Sigma_c(2455)^{++} \pi^-) = (12.4 \pm 3.5 \pm 1.0) \times 10^{-6}$
Observation of $\Omega(2012)^- \rightarrow \Xi(1530)\bar{K}$

Early search found no signal [1]. Improve the selection criteria and signal parameterization.

- Optimized mass window: $M(\Xi^-\pi^+) < 1.517$ GeV/c$^2$ to remove $\Xi(1530)$ not from $\Omega(2012)$.

Clear $\Omega(2012)^-$ signal could be seen on $M(\Xi^-\pi^+K^-)$.

Significance: $5.2\sigma$ after considering systematic uncertainties

Simultaneous fit to $M(\Xi^−\pi^+K^−)$, $M(\Xi^0K^−)$, and $M(\Xi^-K_S^0)$, signal described with Flatté:

$$T_n(M) = \frac{g_n k_n(M)}{|M - m_{\Omega(2012)} + \frac{1}{2} \sum_{j=2,3} g_j [\kappa_j(M) + i k_j(M)]|^2},$$

$g_n$ is the effective coupling to the $n$-body final state, which are fitted to be:

$$g_3 = (41.1 \pm 35.8 \pm 6.0) \times 10^{-2} \text{ and}$$
$$g_2 = (1.7 \pm 0.3 \pm 0.3) \times 10^{-2}.$$
Quarkonium spectroscopy

Below $D\bar{D}/B\bar{B}$ threshold: Good agreement!

Above $D\bar{D}/B\bar{B}$ threshold: Exotic states!!

Parallel properties in $c\bar{c}$ and $b\bar{b}$.

Excellent experimental field!
Search for $X(3872) \rightarrow \pi^+\pi^-\pi^0$

Based on $772 \times 10^6 \bar{B}B$ events on Belle, in $B \rightarrow KX(3872)$

Signal is searched for in the assumption of $X(3872) \rightarrow \pi^+\pi^-\pi^0$ uniformly [named as: case I]

Upper limit is estimated at 90% C.L. < 1.3%.

Quote $\mathcal{B}(B \rightarrow KX(3872))$ from PRD 100, 094003 (2019).
BF is predicted at the level of $10^{-3} \sim 10^{-4}$

Mass of $\pi^+\pi^-$ accumulate around $M(D^0\bar{D}^0)$

Additional requirement [named as case II]:

$M(\pi^+\pi^-) \in [3.7, 3.75] \text{ GeV}/c^2$

Upper limit of the joint BF is also estimated:

<table>
<thead>
<tr>
<th>channel</th>
<th>case I</th>
<th>case II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^\pm \to K^\pm X(3872),\ X(3872)\to \pi^+\pi^-\pi^0$</td>
<td>$&lt; 1.9 \times 10^{-6}$</td>
<td>$&lt; 1.5 \times 10^{-7}$</td>
</tr>
<tr>
<td>$B^0 \to K^0 X(3872),\ X(3872)\to \pi^+\pi^-\pi^0$</td>
<td>$&lt; 1.5 \times 10^{-6}$</td>
<td>$&lt; 1.8 \times 10^{-7}$</td>
</tr>
<tr>
<td>$X(3872)\to \pi^+\pi^-\pi^0$</td>
<td>$&lt; 1.3%$</td>
<td>$&lt; 1.2 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Could be used to provide constraints on the triangle logarithmic singularity of $X(3872) \to D^0\bar{D}^{*0} \to D^0\bar{D}^0\pi^0$. 
In November 2021, Belle II collected 19 fb$^{-1}$ of unique data at energies above the Y(4S): four energy scan points around 10.75 GeV.

Physics goal: understand the nature of the Y(10753).

All points $\sim$1/fb except these ($\sim$20+/fb)
Observation of $Y(10750) \rightarrow \omega \chi_{bJ}$ in $e^+e^- \rightarrow \gamma \omega Y(1S)$

With the new scan data around $\sqrt{s} = 10.75$ GeV

Implying a $\omega \chi_b$ hadro-bottomonium interpretation of $Y(10750)$
Search for $X_b \rightarrow \omega \Upsilon(1S)$ in $e^+e^- \rightarrow \gamma \omega \Upsilon(1S)$

- No significant $X_b$ signal is observed.
- The peaks are the reflections of $e^+e^- \rightarrow \omega \chi_{bJ}$

From simulated events with $M(X_b) = 10.6 \text{ GeV}/c^2$

The yield is fixed at the upper limit on 90% C.L.

<table>
<thead>
<tr>
<th>Upper limits of</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>10.653</th>
<th>10.701</th>
<th>10.745</th>
<th>10.805</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_B(e^+e^- \rightarrow \gamma X_b)$ \cdot $M(X_b) = 10.6 \text{ GeV}/c^2$</td>
<td>0.45</td>
<td>0.33</td>
<td>0.10</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B}(X_b \rightarrow \omega \Upsilon(1S))$ (pb) at 90% C.L. \ ($M(X_b) = 10.45 \text{ GeV}/c^2$)</td>
<td>0.14</td>
<td>0.25</td>
<td>0.06</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>\ ($M(X_b) = 10.65 \text{ GeV}/c^2$)</td>
<td>0.54</td>
<td>0.84</td>
<td>0.14</td>
<td>0.36</td>
<td></td>
</tr>
</tbody>
</table>
Summary and outlook

- Belle and Belle II provide unique and fertile physics environment.
- Even a decade after data taking finished, the Belle experiment is producing interesting and important results.
- Belle II, the next generation B-factory, can make significant impacts in spectroscopy.
  - Precise measurement;
  - Spin-parities, transitions, and quantum numbers determination;
  - New decays searching;
  - Prediction/model/theory testing
  - …
- Belle II with $> 400 \text{ fb}^{-1}$ data, including unique $\Upsilon(10750)$ scan data, can already provide physics output on the level of its predecessors.
Back up
Measurement of $\Xi_c^0 \rightarrow \Lambda_c^+ \pi^-$

\[
\frac{B(\Xi_c^0 \rightarrow \Lambda_c^+ \pi^-)}{B(\Xi_c^0 \rightarrow \Xi^- \pi^+)} = \frac{N_{\Lambda_c \pi} \times \epsilon_{\Xi \pi}^{\text{ref}} \times B(\Xi^- \rightarrow \Lambda \pi^-) \times B(\Lambda \rightarrow p \pi^-)}{N_{\Xi \pi} \times \epsilon_{\Lambda_c \pi}^{\text{sig}} \times B(\Lambda_c^+ \rightarrow pK^- \pi^+)}
\]

\[
= 0.38 \pm 0.04(\text{stat.}) \pm 0.04(\text{syst.})
\]

arXiv: 2206.08527
Measurement of $\Lambda_c^+ \rightarrow p\eta'$

$$\frac{\mathcal{B}(\Lambda_c^+ \rightarrow p\eta')}{\mathcal{B}(\Lambda_c^+ \rightarrow pK^-\pi^+)} = (7.54 \pm 1.32 \pm 0.73) \times 10^{-3},$$

arXiv: 2112.14276