Charmonium-like studies at Belle II

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(On behalf of the Belle II Collaboration)

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Outline of the talk:

- Introduction to quarkonium and the exotics
- Overview of the Belle II experiment
- X(3872) rediscovery at Belle II
- ISR preliminary results at Belle II
- Summary
Introduction:

- Quarkonium: $q\bar{q}$ meson with a heavy quark (i.e. $q = c$ or $b$).
- Is a best playground for constituent quark model.
  - Simple two body system.
  - Large mass
    - Non-relativistic, perturbative.
- Also a good playground for exotics
  - Quark model predictions are robust.
- Exotics?
  - Tetraquarks, molecular states, hybrids, glueballs.
Charmonium-like above threshold:

Observed States:
- Conventional Charmonium
- Unconventional neutral states
- Unconventional charged states
- Pentaquark candidates

Expected States
- Below threshold: Mostly mesons/baryons bound states.
- Above threshold: Zoo of more complex states so called XYZ states which have not yet been understood.

[Rev. Mod. Phys. 90 (2018) 15003]
Charmonium Production at B-factories:

- B decay \((B \rightarrow KX_{cc})\)
  - \(J^{PC} = 0^{-+}, 1^{-}, 1^{++}\)

- Initial-state Radiation (ISR)
  - \(J^{PC} = 1^{-}\)

- Two-photon Process
  - \(J^{PC} = 0^{-+}, 0^{++}, 2^{++}, 2^{-+}\)

- Double charmonium
  - e.g. \(e^+e^- \rightarrow J/\psi X\)
    [PRL 98, 082001 (2007)]
The B-factories Legacy:

- B-factories already provided excited results such as CKM matrix elements, CPV in B Decays and so on.
- It has also made rich contribution to quarkonium spectroscopy.
- First exotic state - $X(3872)$ observed at Belle in 2003.
SuperKEKB & Belle II:

- SuperKEKB: Asymmetric $e^-$ (7 GeV) - $e^+$ (4 GeV) collider at KEKB, Japan. $\sqrt{s} = 10.58$ GeV = $m(\Upsilon(4S))$.  
- SuperKEKB goal: $>30 \times$ KEKB luminosity.  
- Belle II is placed at an interaction point of SuperKEKB.
Belle II Dataset:

- Increasing by: 1-1.5 fb\(^{-1}\) per day.
- Luminosity record: \(3.1 \times 10^{34}\) cm\(^{-2}\)s\(^{-1}\).
- Belle II goal: 50 ab\(^{-1}\) (~50x Belle data).
X(3872):

- First discovered at Belle in 2003 in $B \to K(J/\psi \pi^+ \pi^-)$
  - 14.4±4.6 events ($4.6\sigma$) PRL 91, 262001 (2003)

- Upper limit from Belle: $\Gamma < 1.2$ MeV.
  Measured BW width from LHCb: $\Gamma = 1.19 \pm 0.19$ MeV.

- It has been widely studied in various decay modes.

<table>
<thead>
<tr>
<th>Productions in</th>
<th>B→KX, pâ--, pp, e+e- → γX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well established decay modes</td>
<td>$J/\psi \pi^+ \pi^-$, $J/\psi \pi^+ \pi^- \pi^0$, $J/\psi \gamma$, $\psi(2S)\gamma$, $D\bar{D}\pi$, $D\bar{D}\gamma$, $\pi^0\chi_{c1}$</td>
</tr>
</tbody>
</table>

- Yet the complete nature of this state is unknown.
  - Tetraquark/Molecule..?
  - Needs more experimental results to clarify its nature.
Search for $X(3872)$ at Belle II:

- Data Sample: 62.8 fb$^{-1}$.  
- Reconstruction of final states:
  - $B^\pm \rightarrow \pi^+ \pi^- J/\psi(l^+l^-)K^\pm$
  - $B^0 \rightarrow \pi^+ \pi^- J/\psi(l^+l^-)K_s$
- Standard Selection criteria:
  - Particle identification.
  - Continuum suppression.
  - Kinematics criteria: $M_{\pi^+\pi^-}$, $M_{bc}$ & $|\Delta E|$.  
  \[
  M_{bc} = \sqrt{(E_{beam}^{*2} - p_B^{*2})} \\
  |\Delta E| = E_B^{*} - E_{beam}^{*}
  \]
Rediscovery at Belle II:

- Calibration: $B \rightarrow \psi(2S)K$.
- First X(3872) at Belle II:
  - $14.4 \pm 4.6$ events ($4.6 \sigma$)
  - Consistent with Belle.

$\frac{B^0 \rightarrow X(3872)K^0}{B^+ \rightarrow X(3872)K^+} = 0.5$ [assumed]  
Belle, PRD 84, 052004 (2011)
Belle II Potential: XYZ

- Full width measurement at Belle II with $B \to KX(3872)$: $X(3872) \to DD\pi$!
- Due to low Q-value, the mass resolution is extremely good → expected improvement on width with 50 ab$^{-1}$

<table>
<thead>
<tr>
<th>mode</th>
<th>Q value [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi\pi^+\pi^-$</td>
<td>$495.65\pm0.17$</td>
</tr>
<tr>
<td>$D^0D^{0\pi_0}$</td>
<td>$7.05\pm0.18$</td>
</tr>
<tr>
<td>$D^0D^{0\pi^*}$</td>
<td>$0.01\pm0.18$</td>
</tr>
</tbody>
</table>

- Search for other exotics such as $Z_c(3900)$ at DD* threshold (better slow pion reconstruction efficiency at Belle II $> 60\%$).

- Projection with 50 ab$^{-1}$
  (extrapolated from belle):

<table>
<thead>
<tr>
<th>State</th>
<th>Production and Decay</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X(3872)$</td>
<td>$B \to KX(3872)$, $X(3872) \to J/\psi\pi^+\pi^-$</td>
<td>$~14400$</td>
</tr>
<tr>
<td>$Y(4230)$</td>
<td>$ISR, Y(4230) \to J/\psi\pi^+\pi^-$</td>
<td>$~29600$</td>
</tr>
<tr>
<td>$Z(4430)$</td>
<td>$B \to K\pm Z(4430), Z(4430) \to J/\psi\pi^\pm$</td>
<td>$~10200$</td>
</tr>
</tbody>
</table>

Belle II TDR: arXiv1011.0352
Charmonium (-like) ISR studies at B-factories

- At Belle, many exotic states have been observed in ISR processes, including Y(4260), Y(4630/4660), etc.
- The process $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ via ISR at C.M. energies upto 5 GeV was first studied by BaBar, where, an unexpected structure at about 4.26 GeV was observed clearly.
  - Which is referred to as Y(4260) state.
  - Subsequently, confirmed by Belle & BESIII in the same process.
- Besides Y(4260), Belle & BESIII also observed a broad excess near 4 GeV, called Y(4008).
- However, the nature of the events at around 4 GeV/c$^2$ is still ambiguous.
- Therefore, it is necessary to identify the existences of Y(4008) and Y(4320) in $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ at Belle II with a large number of data samples.
ISR Preliminary results at Belle II

- Reconstruction: $e^+e^- \gamma_{\text{ISR}} \rightarrow \pi^+\pi^- J/\psi (l^+l^-)$ final states
  - Nominal PID requirements.
  - $|M(J/\psi) - m_{J/\psi}| < 75$ MeV/c$^2$.
  - $|M^2_{\text{recoil}}(\pi^+\pi^- J/\psi)| < 2$ GeV/c$^2$.

- Clear observation of ISR $\psi(2S)$ signals.

- Next step: $Y(4260)$ rediscovery.
  Expect ~60 total events per 100 fb$^{-1}$.  

BELLE2-NOTE-PH-2020-060
**Belle II Potential: ISR**

- ISR is a useful tool to study $J^{PC}=1^{-}$ states below the center-of-mass energy.
- Fine structures can be investigated with ISR.
- Line shape of the Y(4260).
- Search for strange partner of $Z_c(3900)^{\pm}$ called the, $Z_{cs}$ in KKJ/$\psi$.
- Cross-sections of exclusive $c\bar{c} +$ hadrons.

<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>$\omega X_{c0}$</td>
<td>4.23</td>
<td>35 (15)</td>
<td>$Y(4220)$</td>
</tr>
</tbody>
</table>

- ISR analysis process is a unique case at $e^+ - e^-$ machines.

*Belle II TDR: arXiv1011.0352*
Summary:

- Current Recorded Luminosity: ~ 213 fb\(^{-1}\).

- Quarkonium/XYZ is the one of the main component of the physics program.

- With the significant increase of statistics compared to Belle, Belle II can measure
  - more precisely the line shapes of the states,
  - determine their spin-parities,
  - search for new decay channels.

- Statistics soon compared to BaBar/Belle.

Stay Tuned!
Thank You!
Back Up
Quarkonium Summary:

- Quarkonium: $q\bar{q}$: the simplest system of hadron
- Good agreement below open flavor threshold.
- Exotic candidates, so called XYZ states discovered.
Possible types of Exotic states?

The exotic color-neutral combinations allowed in SM - proposed by Gell-Mann and Zweig, includes tetra-quarks \((qqqq)\), penta-quarks \((qqqqq)\), glue-balls \((gg)\), and so on.

[Nature Reviews Physics 1, 480 (2019)]
$X(3872)$: