Recent results on charmonium states and search for pentaquark at Belle

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Outline:

• Introduction

• Observation of $\chi_{c0}(2P)$ candidate in $e^+e^- \rightarrow J/\psi D\bar{D}$

• Measurement of the branching fractions of $B^+ \rightarrow X_{cc} K^+$ decays

• Search for hidden-strangeness pentaquark decay $P_s^+ \rightarrow \phi p$ in $\Lambda_c \rightarrow \phi p\pi^0$.

Summary
The Belle experiment
Observation of $\chi_{c0}(2P)$ in $e^+e^-\rightarrow J/\psi D\bar{D}$

$X(3915)$ was observed by the Belle in $B \rightarrow J/\psi \omega K$ decays. $J^{PC}$ is measured to be $0^{++}$. As a result, it was identified as the $\chi_{c0}(2P)$ in PDG 2014.

Doubts: expected main decay $\chi_{c0}(2P) \rightarrow D\bar{D}$ in an S-wave.

We search for $e^+e^- \rightarrow J/\psi \chi_{c0}(2P)$ with $\chi_{c0}(2P) \rightarrow D\bar{D}$

Only $J/\psi$ and one of the $D$ mesons are reconstructed; the other $\bar{D}$ meson is identified by the recoil mass of the $J/\psi D\bar{D}$ system.

Reconstructed channels:
- $D^+ \rightarrow K^0_S\pi^+, K^-\pi^+\pi^+, K^0_S\pi^+\pi^0, K^-\pi^+\pi^0$, and $K^0_S\pi^+\pi^+\pi^-$.  
- $D^0 \rightarrow K^-\pi^+, K^0_S\pi^+\pi^-, K^-\pi^+\pi^0$, and $K^-\pi^+\pi^+\pi^-$.  
- $J/\psi \rightarrow e^+e^-, \mu^+\mu^-$.  

Multivariable analysis to suppress background.

Observation of $\chi_{c0}(2P)$ in $e^+e^- \to J/\psi D\bar{D}$

Background contribution is estimated using $J/\psi$ and $D$ invariant masses:

1. pure combinatorial background
2. real $D$, combinatorial $J/\psi$
3. real $J/\psi$, combinatorial $D$
4. signal

Signal yield is extracted from the fit to the recoil mass to $J/\psi D$ combination

Observation of $\chi_{c0}(2P)$ in $e^+e^- \rightarrow J/\psi D\bar{D}$

Amplitude analysis: 6 dimensions, $M_{DD}$, $\theta_{\text{prod}}$, $\theta_{J/\psi}$, $\theta_{X^{**}}$, $\phi_L$, $\phi_D$.

Background is described by 2$^{\text{nd}}$ order polynomia.
Observation of $\chi_{c0}(2P)$ in $e^+e^- \rightarrow J/\psi D\bar{D}$

Fit to the data: Signal, non-resonant only, background
A new charmonium-like state, the $X^{*}(3860)$ is observed, with mass of $3862^{+26}_{-32}^{+40}_{-13}$ MeV/$c^2$, and width $201^{+154}_{-67}^{+88}_{-82}$ MeV.

The $J^{PC} 0^{++}$ is preferable, from $2^{++}$ at the level of $2.5\sigma$.

$X^{*}(3860)$ consistent with $\chi^{0}_{c}(2P)$ charmonium state hypotheses.

The measured mass is close to potential model expectations for the $\chi^{0}_{c}(2P)$.
\[ B^+ \rightarrow X_{cc} K^+ \]

X(3872) observed by Belle. J^{PC}=1^{++} is confirmed by LHCb. Most natural explanation S-wave D^0\overline{D}^{*0} molecular state. High cross section production in pp by CDF suggests admixture of molecular and \( \chi_{c1}(2P) \). Absolute branching measurement of \( B^+ \rightarrow X(3872) K^+ \) would help to measure X(3872) → F branching fractions and understand its nature.

Inclusive reconstruction of other B^- and K^+ from signal B^+. Fit to the K^+ recoil mass distribution. Cross check channel: \( B^+ \rightarrow \overline{D}^{(*)0} \pi^+ \).

<table>
<thead>
<tr>
<th>Mode</th>
<th>( N_{\text{sig}} )</th>
<th>( \mu_{\text{data}} - \mu_{\text{MC}} ) (MeV/c^2)</th>
<th>( \sigma_{\text{data}}/\sigma_{\text{MC}} )</th>
<th>( \epsilon \times 10^{-3} )</th>
<th>( B \times 10^{-3} )</th>
<th>World average for B ( \times 10^{-3} ) [10]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^+ \rightarrow \pi^+ D^0 )</td>
<td>8550 ± 190</td>
<td>-0.5 ± 0.8</td>
<td>0.994 ± 0.025</td>
<td>2.48±0.02</td>
<td>4.34 ± 0.10 ± 0.25</td>
<td>4.80 ± 0.15</td>
</tr>
<tr>
<td>( B^+ \rightarrow \pi^+ D^{*0} )</td>
<td>9980 ± 250</td>
<td>-0.8 ± 0.8</td>
<td>1.035 ± 0.029</td>
<td>2.61±0.02</td>
<td>4.82 ± 0.12 ± 0.35</td>
<td>5.18 ± 0.26</td>
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</tbody>
</table>
$B^+ \rightarrow X_{cc} K^+$
\[ B^+ \rightarrow X_{cc} K^+ \]

- \(B^+ \rightarrow X_{cc} K^+\) branching fractions have been measured.
- We significantly improve knowledge for \(\eta_c\) and \(\eta_c(2S)\) branchings.
- Results for \(J/\psi, \chi_{c0}, \chi_{c1}\) and \(\psi(2S)\) are consistent with world average.
- No significant signals are observed for \(\psi(3770), X(3872), X(3915)\). We set 90% CL ULs.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield</th>
<th>Significance ((\sigma))</th>
<th>(\epsilon(10^{-3}))</th>
<th>(B (10^{-4}))</th>
<th>World average for (B (10^{-4})) [10]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\eta_c)</td>
<td>2590 ± 180</td>
<td>14.2</td>
<td>2.73 ± 0.02</td>
<td>12.0 ± 0.8 ± 0.7</td>
<td>9.6 ± 1.1</td>
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<tr>
<td>(J/\psi)</td>
<td>1860 ± 140</td>
<td>13.7</td>
<td>2.65 ± 0.02</td>
<td>8.9 ± 0.6 ± 0.5</td>
<td>10.26 ± 0.031</td>
</tr>
<tr>
<td>(\chi_{c0})</td>
<td>430 ± 190</td>
<td>2.2</td>
<td>2.67 ± 0.02</td>
<td>2.0 ± 0.9 ± 0.1 (&lt; 3.3)</td>
<td>1.50 ± 0.15</td>
</tr>
<tr>
<td>(\chi_{c1})</td>
<td>1230 ± 180</td>
<td>6.8</td>
<td>2.68 ± 0.02</td>
<td>5.8 ± 0.9 ± 0.5</td>
<td>4.79 ± 0.23</td>
</tr>
<tr>
<td>(\eta_c(2S))</td>
<td>1050 ± 240</td>
<td>4.1</td>
<td>2.77 ± 0.02</td>
<td>4.8 ± 1.1 ± 0.3</td>
<td>3.4 ± 1.8</td>
</tr>
<tr>
<td>(\psi(2S))</td>
<td>1410 ± 210</td>
<td>6.6</td>
<td>2.79 ± 0.02</td>
<td>6.4 ± 1.0 ± 0.4</td>
<td>6.26 ± 0.24</td>
</tr>
<tr>
<td>(\psi(3770))</td>
<td>-40 ± 310</td>
<td>-</td>
<td>2.76 ± 0.02</td>
<td>-0.2 ± 1.4 ± 0.0 (&lt; 2.3)</td>
<td>4.9 ± 1.3</td>
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<td>(X(3872))</td>
<td>260 ± 230</td>
<td>1.1</td>
<td>2.79 ± 0.01</td>
<td>1.2 ± 1.1 ± 0.1 (&lt; 2.6)</td>
<td>(&lt; 3.2)</td>
</tr>
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<td>(X(3915))</td>
<td>80 ± 350</td>
<td>0.3</td>
<td>2.79 ± 0.01</td>
<td>0.4 ± 1.6 ± 0.0 (&lt; 2.8)</td>
<td>-</td>
</tr>
</tbody>
</table>
Search for pentaquark in $\Lambda_c \to P_s^+[\phi p]\pi^0$

Observation of two hidden-charm pentaquark states, $P_c^+(4380)$ and $P_c^+(4450)$, by LHCb motivate us to search for hidden-strange partner $P_s^+ \to \phi(1019)\, p$. We use decay $\Lambda_c \to \phi\, p\, \pi^0 \to K^+ K^-\, p\, \pi^0$. 

Search for pentaquark in $\Lambda_c \rightarrow P_s^+[\phi p]\pi^0$

Significance of $\Lambda_c \rightarrow \phi p \pi^0$ signal is below $3\sigma$. Therefore we set 90% CL UL.

$$\frac{B(\Lambda_c^+ \rightarrow \phi p \pi^0)}{B(\Lambda_c^+ \rightarrow pK^-\pi^+)} = (1.538 \pm 0.641^{+0.077}_{-0.100}) \times 10^{-3}$$

$$B(\Lambda_c^+ \rightarrow \phi p \pi^0) < 15.3 \times 10^{-5},$$
$$B(\Lambda_c^+ \rightarrow K^+K^-p\pi^0)_{NR} < 6.3 \times 10^{-5},$$

Fit gives $78 \pm 28$ events for $\Lambda_c \rightarrow P_s^+[\phi p]\pi^0$. Local significance is below $3\sigma$. 90% CL UL is set.

$$B(\Lambda_c \rightarrow P_s^+\pi^0) \cdot B(P_s^+ \rightarrow \phi p) < 8.3 \times 10^{-5}$$
Summary

- Observation of charmonium-like state $X^*(3860)$, consistent with $\chi_{c0}(2P)$.
  $X(3915)$ observed by the Belle is NOT $\chi_{c0}(2P)$.

- The branching fractions of $B^+ \to X_{cc} K^+$ decays have been measured.
  Statistics is not enough to measure branching fraction of $B^+ \to X(3872) K^+$.

- No hidden-strangeness pentaquark $P_{s^+} \to \phi p$ is found in decay $\Lambda_c \to \phi p \pi^0$.

- More exciting results are going to come from Belle II.

Stay tuned!