Charmonium studies at Belle

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Charmonium production:

- From $B$ decays - $711 \text{ fb}^{-1}$, $772 \times 10^6 \ B \bar{B}$ pairs.
- Double charmonium production (all energies): $980 \text{ fb}^{-1}$. 
Charmonium states

\[1S_0 \quad 3S_1 \quad 1P_1 \quad 3P_0 \quad 3P_1 \quad 3P_2 \quad 1D_2 \quad 3D_1 \quad 3D_2 \quad 3D_3 \quad J^P \quad \text{no} \quad J^P\ e^+e^-\]

Mass, GeV/c^2

\[\psi(4415)\]
\[\psi(4040)\]
\[\psi(2S)\]
\[\psi(4160)\]
\[\psi(3770)\]
\[\chi_{c1} \quad \chi_{c2}\]
\[\chi_{c0}\]
\[J/\psi\]
\[\eta_c\]

Discovered before 1980

DD threshold

charged
Charmonium states

Mass, GeV/c²

New conventional states

\( \psi(4415) \)

\( \psi(4040) \)

\( \psi(2S) \)

\( \eta_c(2S) \)

\( J/\psi \)

\( h_c \)

\( \chi_{c1} \)

\( \chi_{c2} \)

\( \chi_{c2}(2P) \)

\( \psi(3770) \)

\( \psi_2(1D) \)

\( \bar{D}D \) threshold

charged

\( 1S_0 \)

\( 3S_1 \)

\( 1P_1 \)

\( 3P_0 \)

\( 3P_1 \)

\( 3P_2 \)

\( 1D_2 \)

\( 3D_1 \)

\( 3D_2 \)

\( 3D_3 \)

\( J^P \)

\( \eta_c \)

Discovered before 1980

New conventional states

Some of them may be conventional charmonium states

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Charmonium states

\[
\begin{array}{cccccccc}
1S_0 & 3S_1 & 1P_1 & 3P_0 & 3P_1 & 3P_2 & 1D_2 & 3D_1 & 3D_2 & 3D_3 & J^P & no & J^P_{e^+e^-} \\
\end{array}
\]

Charmoniumlike states

\[
\begin{align*}
\psi(4415) & \quad \psi(4500) & \quad \psi(4040) & \quad \psi(4160) & \quad \psi(4100) \\
X(3940) & \quad X(4160) & \quad X(4140) & \quad X(4274) & \quad X(4260) \\
X^*(3860) & \quad X(3915) & \quad \chi_{c2}(2P) & \quad \psi(3770) & \quad \psi_2(1D) \\
\eta_c(2S) & \quad h_c & \quad \chi_{c1} & \quad \chi_{c2} & \quad \chi_{c0} \\
\end{align*}
\]

\[D\bar{D}\text{ threshold}\]

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Charmonium states

- Some of them may be conventional charmonium states
- Discovered before 1980
- New conventional states
- Charged charmoniumlike states

<table>
<thead>
<tr>
<th>Mass, GeV/c^2</th>
<th>States</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0-3.2</td>
<td>( \eta_c )</td>
</tr>
<tr>
<td>3.2-3.4</td>
<td>( \eta_c ), ( h_c ), ( \chi_{c0} ), ( \chi_{c1} ), ( \chi_{c2} )</td>
</tr>
<tr>
<td>3.4-3.6</td>
<td>( \psi(2S) ), ( \chi_{c2}(2P) ), ( \chi_{c0}(2P) ), ( \chi_{c1} ), ( \chi_{c2} )</td>
</tr>
<tr>
<td>3.6-3.8</td>
<td>( \chi_{c0} ), ( \chi_{c1} ), ( \chi_{c2} )</td>
</tr>
<tr>
<td>3.8-4.0</td>
<td>( \psi(4040) ), ( X(3940) ), ( X(3915) ), ( X(3872) ), ( \psi(3770) )</td>
</tr>
<tr>
<td>4.0-4.2</td>
<td>( \psi(4160) ), ( X(4140) ), ( X(4160) ), ( X(4274) ), ( Y(4260) )</td>
</tr>
<tr>
<td>4.2-4.4</td>
<td>( \psi(4415) ), ( X(4500) ), ( X(4700) ), ( Y(4660) )</td>
</tr>
<tr>
<td>4.4-4.6</td>
<td>( \psi(4160) )</td>
</tr>
<tr>
<td>4.6-5.0</td>
<td>( X(3840) ), ( X(3872) ), ( \psi(2S) ), ( Y(4360) ), ( Y(4660) )</td>
</tr>
</tbody>
</table>

D\( \bar{D} \) threshold
Charmonium states

Mass, GeV/c^2

$^1S_0$  $^3S_1$  $^1P_1$  $^3P_0$  $^3P_1$  $^3P_2$  $^1D_2$  $^3D_1$  $^3D_2$  $^3D_3$  $J^P$  no  $J^P_{e^+e^-}$

Charged charmoniumlike states

$X(4700)$  $Y(4660)$
$X(4500)$  $X(4274)$  $Y(4360)$  $Y(4260)$
$X(4160)$  $X(4140)$  $X(4100)$  $X(4040)$  $X(3940)$  $X(3915)$  $X(3872)$  $X(3840)$  $X(3820)$
$\psi(4415)$  $\psi(4040)$  $\psi(4030)$  $\psi(4020)$  $\psi(3770)$
$\chi_{c2}(2P)$  $\chi_{c2}(2P)$  $\psi_2(1D)$  $\chi_{c1}$  $\chi_{c2}$
$\eta_c(2S)$  $h_c$  $\chi_{c0}$
$\psi(2S)$

$\eta_c$

$J/\psi$

$D\bar{D}$ threshold

Discovered before 1980

New charmoniumlike states

Some of them may be conventional charmonium states

Charged charmoniumlike states

$X^+(4055)$  $Z_c^+(4430)$  $X^+(4050)$  $R_{c0}^+(4240)$  $X^+(4250)$  $Z_c^+(4200)$  $X^+(4020)$  $W_{c0}^+(4100)$  $X^+(4050)$  $Z_c^+(3900)$
1. Published results:
   - Observation of $\chi_{c0}(3860)$ (or $X^*(3860)$) in $e^+e^- \rightarrow J/\psi D\bar{D}$,
   - Measurement of the absolute branching fractions of $B^+ \rightarrow X_{c\bar{c}}K^+$,
   - Observation of $e^+e^- \rightarrow \chi_{c1}\gamma$.

2. New results:
   - Evidence for $B^+ \rightarrow h_cK^+$ and observation of $\eta_c(2S) \rightarrow p\bar{p}\pi^+\pi^-$.
Published results
**Alternative $\chi_{c0}(2P)$ in $e^+e^- \rightarrow J/\psi D\bar{D}$**

Full amplitude analysis of $e^+e^- \rightarrow J/\psi D\bar{D}$ (6 dimensions).

A new charmoniumlike state $X^*(3860)$ is observed ($6.5\sigma$ with systematic error); $M = 3862^{+26+40}_{-32-13}$ MeV/$c^2$, $\Gamma = 201^{+154+88}_{-67-82}$ MeV. The $J^{PC} = 0^{++}$ hypothesis is favored over the $2^{++}$ hypothesis at the level of $2.5\sigma$ (from MC pseudoexperiments).
Alternative $\chi_{c0}(2P)$ in $e^+e^- \rightarrow J/\psi D\bar{D}$

- Quantum numbers: $J^{PC} = 0^{++}$.
- Production: in $S$-wave. Same for $\chi_{c0}(1P)$, measured in PRD 70, 071102 (2004).
- Mass difference (potential models: $\sim 0.6 - 0.9$):
  \[ r_c = (m_{\chi_{c2}(2P)} - m_{\chi_{c0}(2P)})/(m_{\chi_{c2}(1P)} - m_{\chi_{c0}(1P)}) = 0.46^{+0.25}_{-0.34} \]
- Decay: $\chi_{c0}(2P)$ should primarily decay to $D\bar{D}$ (observation mode for the $X^*(3860)$) and not $J/\psi\omega$.
- The $X^*(3860)$ agrees with the peak in $\gamma\gamma$ data ($M = 3837.6 \pm 11.5$ MeV/$c^2$, $\Gamma = 221 \pm 19$ MeV).

The $X^*(3860)$ is a better $\chi_{c0}(2P)$ candidate than the $X(3915)$. 
Absolute $\mathcal{B}(B^+ \to X_{c\bar{c}}K^+)$

One of the $B$ mesons is fully reconstructed, the decay $B^+ \to X_{c\bar{c}}K^+$ is identified by the missing mass. Fit: background: $\exp(aM + bM^2)$, signal: binned PDF from MC.
Absolute $\mathcal{B}(B^+ \to X_{c\bar{c}} K^+)$

Results:

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield</th>
<th>Signif. ($\sigma$)</th>
<th>$\epsilon(10^{-3})$</th>
<th>$\mathcal{B} (10^{-4})$</th>
<th>World average for $\mathcal{B} (10^{-4})$</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>
</tr>
<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$^{+0.15}_{-0.14}$</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>
</tr>
<tr>
<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>
<tr>
<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>

- Improved limit for the $X(3872)$.
- The most precise measurements for the $\eta_c$ and $\eta_c(2S)$.
- First limit for $X(3915)$. Together with $\mathcal{B}(B^+ \to X(3915) K^+ \times \mathcal{B}(X(3915) \to J/\psi \omega) = (3.0^{+0.7+0.5}_{-0.6-0.3}) \times 10^{-5}$ (BaBar, PRD 82, 011101 (2010)) and the $X(3915)$ width value $(20 \pm 5 \text{ MeV})$ results in $\Gamma(X(3915) \to J/\psi \omega) \gtrsim 2.1 \text{ MeV}$, clearly suggesting that the $X(3915)$ is a non-$c\bar{c}$ candidate.
Observation of $e^+ e^- \rightarrow \chi_{c1}\gamma$

Search for $e^+ e^- \rightarrow \gamma \chi_{cJ} (\rightarrow J/\psi \gamma)$ and $e^+ e^- \rightarrow \eta_c \gamma$ ($\eta_c$ reconstructed in 5 channels: $K^+ K^0_S \pi^-$, $\pi^+ \pi^- K^+ K^-$, $\pi^+ \pi^- \pi^+ \pi^-$, $K^+ K^- K^+ K^-$, and $3(\pi^\pm \pi^\mp)$).

Significant $\chi_{c1}$ signal ($5.1\sigma$) is observed at $\sqrt{s} = 10.58$ GeV.
Observation of $e^+ e^- \rightarrow \chi_{c1} \gamma$

Born cross section at $\sqrt{s} = 10.58$ GeV: $17.3^{+4.2}_{-3.9} \pm 1.7$ fb.

Dependence of the cross section on energy (using also BESIII data, Chin. Phys. C 39, 041001 (2015)): $1/s^{2.1^{+0.3}_{-0.4} \pm 0.3}$
New results
Motivation and experimental status

The decays $B^+ \to h_c K^+$ and $B^0 \to h_c K_S^0$ are suppressed by factorization, they have never been observed. The theoretical predictions for the $B^+ \to h_c K^+$ branching fraction are slightly below the current experimental limit ($3.8 \times 10^{-5}$ at 90% C. L.):

- C. Meng, Y. J. Gao and K. T. Chao, hep-ph/0607221: $2.7 \times 10^{-5}$.
- X. Q. Li, X. Liu and Y. M. Wang, Phys. Rev. D 74, 114029: $3.6 \times 10^{-5}$
- M. Beneke and L. Vernazza, Nucl. Phys. B 811, 155: $(3.1 - 5.7) \times 10^{-5}$

Experimental limit: $\mathcal{B}(B^+ \to h_c K^+) < 3.8 \times 10^{-5}$ (90% C.L.) assuming $\mathcal{B}(h_c \to \eta_c \gamma) = 0.5$ (Belle: PRD 74, 012007):
Here we present an updated search for the decays $B^+ \to h_c K^+$, and also include a search for the decays $B^0 \to h_c K_S^0$.

- The $h_c$ candidates are reconstructed in 2 decay channels: $\eta_c \gamma$ and $p\bar{p}\pi^+\pi^-$. Only $\eta_c \gamma$ was used previously. The channel $p\bar{p}\pi^+\pi^-$ was recently observed by BESIII (arXiv:1810.12023). In addition, we study the decays of other charmonium states to $p\bar{p}\pi^+\pi^-$. 

- The $\eta_c$ candidates are reconstructed in 10 decay channels: $K^+ K_S^0 \pi^-$, $K^+ K^- \pi^0$, $K_S^0 K_S^0 \pi^0$, $K^+ K^- \eta$, $K^+ K^- K^+ K^-$, $\eta'(\to \eta \pi^+ \pi^-) \pi^+ \pi^-$, $p\bar{p}$, $p\bar{p}\pi^0$, $p\bar{p}\pi^+\pi^-$, and $\Lambda \bar{\Lambda}$. Only $K^+ K_S^0 \pi^-$ and $p\bar{p}$ were used previously.

- The discrimination of the signal and background events is improved by performing a multivariate analysis.

- The integrated luminosity is 2.8 times greater than the luminosity used in the previous analysis.
Resolution

The resolution is parameterized by the function

\[ S(\Delta E, M_{bc}) = N_{CB}F_{CB}(x_1)G_a^{(12)}(y_1) + N_{G1}G_a^{(21)}(x_2)G_a^{(22)}(y_2) + N_{G2}G_a^{(31)}(x_3)G_a^{(32)}(y_3), \]  

(1)

where \( F_{CB} \) is an asymmetric Crystal Ball function, \( G_a^{(ij)} \) are asymmetric Gaussian functions, \( N_{CB}, N_{G1} \) and \( N_{G2} \) are normalizations and \( x_i \) and \( y_i \) (i = 1, 2, 3) are rotated variables that are given by

\[
\begin{pmatrix}
  x_i \\
  y_i
\end{pmatrix} = \begin{pmatrix}
  \cos \alpha_i & \sin \alpha_i \\
  -\sin \alpha_i & \cos \alpha_i
\end{pmatrix} \begin{pmatrix}
  \Delta E - (\Delta E)_0 \\
  M_{bc} - (M_{bc})_0
\end{pmatrix}.
\]

(2)

Here, \((\Delta E)_0, (M_{bc})_0\) is the central point and \(\alpha_i\) are the rotation angles. Resolution for \(B^+ \to h_c K^+\) with \(\eta_c \to K^+ K^- \pi^0\):
Fit to the \((\Delta E, M_{bc})\) distribution

The \((\Delta E, M_{bc})\) distribution is fitted in order to estimate the expected number of the background events in the signal region. The distribution is fitted to the function

\[
N_S S(\Delta E, M_{bc}) + B(\Delta E, M_{bc}),
\]  

where \(N_S\) is the number of signal events and \(B\) is the background density function that is given by

\[
B(\Delta E, M_{bc}) = \sqrt{m_0 - M_{bc}} \exp[-a(m_0 - M_{bc})]P_3(\Delta E, M_{bc}),
\]

where \(m_0\) is the threshold mass, \(a\) is a rate parameter and \(P_3\) is a two-dimensional third-order polynomial. The region with \(\Delta E < -0.12\) GeV is excluded for the channel \(h_c \to p\bar{p}\pi^+\pi^-\) because of peaking backgrounds from partially reconstructed B decays with an additional \(\pi\) meson. Background for \(B^+ \to h_c K^+\) with \(\eta_c \to K^+ K^-\pi^0\) (with \(M_{bc} > 5.272\) GeV/c\(^2\) for the projection onto \(\Delta E\) and \(|\Delta E| < 20\) MeV for the projection onto \(M_{bc}\)).
A multivariate analysis is performed for each channel using the MLP from TMVA. Variables:

- All channels: thrust angles $B$ daughters - remaining particles in the event and all tracks - all photons, ratio of the Fox-Wolfram moments $F_2/F_0$, the $B$ production angle, vertex-fit quality.

- $h_c \rightarrow \eta_c \gamma$: the $h_c$ helicity angle, the $\eta_c$ mass, the numbers of $\pi^0$ candidates that have the $h_c$ daughter photon as one of their daughters.

- $\eta_c \rightarrow K^+K_S^0\pi^-, \eta_c \rightarrow K^+K^-\pi^0$ and $\eta_c \rightarrow K_S^0K_S^0\pi^0$: invariant masses of both ($K, \pi$) combinations.

- Channels with the corresponding particles in the final state: $K$ and $p$ particle-identification likelihoods.

- Channels with a $\pi^0$ or $\eta$: the $\pi^0$ ($\eta$) mass, the minimal energy of its daughter photons in the laboratory frame, the numbers of $\pi^0$ candidates that have the $\pi^0$ ($\eta$) daughter photon as one of their daughters.

- Channels with $\eta \rightarrow \pi^+\pi^-\pi^0$ or $\eta' \rightarrow \eta\pi^+\pi^-$: the $\eta$ ($\eta'$) mass.
Optimization of the selection requirements

An elliptical channel-dependent signal region is selected: \((\frac{\Delta E}{R_{\Delta E}^{(i)}})^2 + (\frac{M_{bc}^{(i)}}{R_{M_{bc}^{(i)}}})^2 < 1\). The following variables are optimized for each decay channel: half-axes \(R_{\Delta E}^{(i)}, R_{M_{bc}^{(i)}}\), and cutoff for MLP output \((v_0)\). The value being maximized is \(F_{\text{opt}} = \left(\sum_i N_{\text{sig}}^{(i)}\right)/\left(\frac{a}{2} + \sqrt{\sum_i N_{\text{bg}}^{(i)}}\right)\), where \(a = 3\) is the target significance. The optimization is performed separately for all \(\eta_c\gamma\) channels and \(p\bar{p}\pi^+\pi^-\). Results \((B^+ \to h_c K^+)\):

<table>
<thead>
<tr>
<th>Channel</th>
<th>Parameters</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\eta_c(\to K^+K_S^0\pi^-)\gamma)</td>
<td>(R_{\Delta E}^{(i)})</td>
<td>(R_{M_{bc}^{(i)}})</td>
</tr>
<tr>
<td>(\eta_c(\to K^+K^-\pi^0)\gamma)</td>
<td>32.7</td>
<td>4.82</td>
</tr>
<tr>
<td>(\eta_c(\to K^+K^-\eta_2\gamma)\gamma)</td>
<td>36.2</td>
<td>3.90</td>
</tr>
<tr>
<td>(\eta_c(\to K^+K^-\eta_3\pi)\gamma)</td>
<td>42.3</td>
<td>4.49</td>
</tr>
<tr>
<td>(\eta_c(\to K^+K^-\eta_2\gamma)\gamma)</td>
<td>34.4</td>
<td>4.16</td>
</tr>
<tr>
<td>(\eta_c(\to K^+K^-K^+K^-)\gamma)</td>
<td>24.9</td>
<td>3.59</td>
</tr>
<tr>
<td>(\eta_c(\to \eta'(\to \eta_2\gamma\pi^+\pi^-)\pi^+\pi^-)\gamma)</td>
<td>25.3</td>
<td>4.13</td>
</tr>
<tr>
<td>(\eta_c(\to \eta'(\to \eta_3\pi\pi^+\pi^-)\pi^+\pi^-)\gamma)</td>
<td>30.5</td>
<td>4.21</td>
</tr>
<tr>
<td>(\eta_c(\to p\bar{p}\gamma))</td>
<td>26.8</td>
<td>4.16</td>
</tr>
<tr>
<td>(\eta_c(\to p\bar{p}\pi^0\gamma))</td>
<td>38.9</td>
<td>5.48</td>
</tr>
<tr>
<td>(\eta_c(\to p\bar{p}\pi^+\pi^-)\gamma)</td>
<td>30.2</td>
<td>3.75</td>
</tr>
<tr>
<td>(\eta_c(\to \Lambda\bar{\Lambda})\gamma)</td>
<td>24.1</td>
<td>4.03</td>
</tr>
<tr>
<td>(p\bar{p}\pi^+\pi^-)</td>
<td>40.4</td>
<td>5.66</td>
</tr>
<tr>
<td>(p\bar{p}\pi^+\pi^-)</td>
<td>13.5</td>
<td>4.36</td>
</tr>
</tbody>
</table>

Efficiencies: \(\epsilon_{\text{SR}}^{(i)}\) - reconstruction and signal region selection; \(\epsilon_S^{(i)}(v_0^{(i)}), \epsilon_B^{(i)}(v_0^{(i)})\) - MLP for signal and background, respectively.
Data fitting procedure

We perform a simultaneous extended unbinned likelihood fit to the $h_c \rightarrow \eta_c \gamma$ signal, $h_c \rightarrow p\bar{p}\pi^+\pi^-$ background and $h_c \rightarrow p\bar{p}\pi^+\pi^-$ signal distributions. The signal PDF for the channel $h_c \rightarrow \eta_c \gamma$ is given by

$$S_{\eta_c \gamma}(M) = (N_{h_c} |A_{h_c}(M)|^2) \otimes R_{h_c}^{(\eta_c \gamma)}(\Delta M) + P_2(M),$$

where $N_{h_c}$ is the number of signal events, $R_{h_c}^{(\eta_c \gamma)}$ is the $h_c$ mass resolution, and $P_2$ is a second-order polynomial. The background PDF $B_{p\bar{p}\pi^+\pi^-}(M)$ for the channel $h_c \rightarrow p\bar{p}\pi^+\pi^-$ is a third-order polynomial. The signal PDF for the channel $h_c \rightarrow p\bar{p}\pi^+\pi^-$ is given by

$$S_{p\bar{p}\pi^+\pi^-}(M) = \left(|P_3(M) + \sum_{R=\eta_c, \chi_{c0}, \eta_c(2S)} \sqrt{N_R} e^{i\varphi_R} A_R(M)|^2 \right) \otimes R_{h_c}(\Delta M),$$

where $P_3$ is a third-order polynomial representing the noncharmonium signal. The wide states are added coherently to the signal PDF, while the states that are narrower than the resolution are added incoherently. The amplitudes are normalized in such a way that all the parameters $N$ represent the yields of the corresponding states. The signal distribution is fitted to the function $S_{p\bar{p}\pi^+\pi^-}(M) + wB_{p\bar{p}\pi^+\pi^-}(M)$, where $w$ is the weight of the background events in the signal region that is calculated as the ratio of integrals of the background distribution in $(\Delta E, M_{bc})$ over the signal and background regions.
Fit results (default model)

Fit to $h_c \rightarrow \eta_c \gamma$ signal

$B^+ \rightarrow h_c K^+$

$B^0 \rightarrow h_c K_S^0$

Significance of $B^+ \rightarrow h_c K^+$: 5.0$\sigma$.
No signal of $B^0 \rightarrow h_c K_S^0$ is seen: 0.8$\sigma$. 
Fit results \((B^+ \to h_c K^+, \text{ default model})\)

\[ p\bar{p}\pi^+\pi^- \text{ signal} \quad \chi_{cJ} \text{ region} \]

Significance of \(\eta_c(2S) \to p\bar{p}\pi^+\pi^-\): 12.3\(\sigma\).
The same decay is also seen in \(B^0 \to (c\bar{c})K^0_S\) (see backup slides).
Systematic uncertainty

Model dependence of the $h_c$ and $\eta_c(2S) \rightarrow p\bar{p}\pi^+\pi^-$ significance:

<table>
<thead>
<tr>
<th>Model</th>
<th>$h_c$ significance</th>
<th>$\eta_c(2S) \rightarrow p\bar{p}\pi^+\pi^-$ significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default</td>
<td>$5.0\sigma$</td>
<td>$12.3\sigma$</td>
</tr>
<tr>
<td>Free masses and widths</td>
<td>$5.0\sigma$</td>
<td>$12.3\sigma$</td>
</tr>
<tr>
<td>Polynomial order ($h_c \rightarrow \eta_c\gamma$)</td>
<td>$4.8\sigma$</td>
<td>$12.3\sigma$</td>
</tr>
<tr>
<td>Polynomial order ($h_c \rightarrow p\bar{p}\pi^+\pi^-$ background)</td>
<td>$5.0\sigma$</td>
<td>$12.2\sigma$</td>
</tr>
<tr>
<td>Polynomial order ($h_c \rightarrow p\bar{p}\pi^+\pi^-$ signal)</td>
<td>$5.0\sigma$</td>
<td>$12.2\sigma$</td>
</tr>
<tr>
<td>Fitting range variation ($h_c \rightarrow \eta_c\gamma$)</td>
<td>$5.0\sigma$</td>
<td>$12.3\sigma$</td>
</tr>
<tr>
<td>Fitting range variation ($h_c \rightarrow p\bar{p}\pi^+\pi^-$)</td>
<td>$5.0\sigma$</td>
<td>$12.1\sigma$</td>
</tr>
<tr>
<td>Scaled resolution</td>
<td>$5.0\sigma$</td>
<td>$12.3\sigma$</td>
</tr>
<tr>
<td>Fraction of $h_c \rightarrow \eta_c\gamma$ and $h_c \rightarrow p\bar{p}\pi^+\pi^-$</td>
<td>$4.9\sigma$</td>
<td>$12.2\sigma$</td>
</tr>
</tbody>
</table>

The significance with the systematic uncertainty taken into account is $4.8\sigma$ for $B^+ \rightarrow h_cK^+$ and $12.1\sigma$ for $\eta_c(2S) \rightarrow p\bar{p}\pi^+\pi^-$. 
### Branching fractions

<table>
<thead>
<tr>
<th>Branching fraction</th>
<th>Value or confidence interval (90 % C. L.)</th>
<th>World-average value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}(B^+ \rightarrow h_c K^+)$</td>
<td>$(3.7 \pm 1.0 \pm 0.8) \times 10^{-5}$</td>
<td>$&lt; 3.8 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\mathcal{B}(B^+ \rightarrow \eta_c K^+) \times \mathcal{B}(\eta_c \rightarrow p\bar{p}\pi^+\pi^-)$</td>
<td>$(39.4 \pm 4.1 \pm 2.2) \times 10^{-7}$</td>
<td>$(57.8 \pm 20.2) \times 10^{-7}$</td>
</tr>
<tr>
<td>$\mathcal{B}(B^+ \rightarrow J/\psi K^+) \times \mathcal{B}(J/\psi \rightarrow p\bar{p}\pi^+\pi^-)$</td>
<td>$(56.4 \pm 3.3 \pm 2.7) \times 10^{-7}$</td>
<td>$(60.6 \pm 5.3) \times 10^{-7}$</td>
</tr>
<tr>
<td>$\mathcal{B}(B^+ \rightarrow \chi_{c0} K^+) \times \mathcal{B}(\chi_{c0} \rightarrow p\bar{p}\pi^+\pi^-)$</td>
<td>$(3.7 \pm 1.2 \pm 0.2) \times 10^{-7}$</td>
<td>$(3.1 \pm 1.1) \times 10^{-7}$</td>
</tr>
<tr>
<td>$\mathcal{B}(B^+ \rightarrow \chi_{c1} K^+) \times \mathcal{B}(\chi_{c1} \rightarrow p\bar{p}\pi^+\pi^-)$</td>
<td>$(4.7 \pm 1.3 \pm 0.4) \times 10^{-7}$</td>
<td>$(2.4 \pm 0.9) \times 10^{-7}$</td>
</tr>
<tr>
<td>$\mathcal{B}(B^+ \rightarrow \chi_{c2} K^+) \times \mathcal{B}(\chi_{c2} \rightarrow p\bar{p}\pi^+\pi^-)$</td>
<td>$&lt; 1.9 \times 10^{-7}$</td>
<td>$(0.15 \pm 0.06) \times 10^{-7}$</td>
</tr>
<tr>
<td>$\mathcal{B}(B^+ \rightarrow \eta_c(2S) K^+) \times \mathcal{B}(\eta_c(2S) \rightarrow p\bar{p}\pi^+\pi^-)$</td>
<td>$(11.2 \pm 1.8 \pm 0.5) \times 10^{-7}$</td>
<td>not seen</td>
</tr>
<tr>
<td>$\mathcal{B}(B^+ \rightarrow \psi(2S) K^+) \times \mathcal{B}(\psi(2S) \rightarrow p\bar{p}\pi^+\pi^-)$</td>
<td>$(4.7 \pm 1.2 \pm 0.3) \times 10^{-7}$</td>
<td>$(3.7 \pm 0.3) \times 10^{-7}$</td>
</tr>
<tr>
<td>$\mathcal{B}(B^0 \rightarrow h_c K_S^0)$</td>
<td>$&lt; 1.4 \times 10^{-5}$</td>
<td>not seen</td>
</tr>
<tr>
<td>$\mathcal{B}(B^0 \rightarrow \eta_c K_S^0) \times \mathcal{B}(\eta_c \rightarrow p\bar{p}\pi^+\pi^-)$</td>
<td>$(19.0 \pm 3.2 \pm 1.3) \times 10^{-7}$</td>
<td>$(20.9 \pm 7.8) \times 10^{-7}$</td>
</tr>
<tr>
<td>$\mathcal{B}(B^0 \rightarrow J/\psi K_S^0) \times \mathcal{B}(J/\psi \rightarrow p\bar{p}\pi^+\pi^-)$</td>
<td>$(24.3 \pm 2.3 \pm 1.2) \times 10^{-7}$</td>
<td>$(26.2 \pm 2.4) \times 10^{-7}$</td>
</tr>
<tr>
<td>$\mathcal{B}(B^0 \rightarrow \chi_{c0} K_S^0) \times \mathcal{B}(\chi_{c0} \rightarrow p\bar{p}\pi^+\pi^-)$</td>
<td>$&lt; 1.3 \times 10^{-7}$</td>
<td>$(1.5 \pm 0.6) \times 10^{-7}$</td>
</tr>
<tr>
<td>$\mathcal{B}(B^0 \rightarrow \chi_{c1} K_S^0) \times \mathcal{B}(\chi_{c1} \rightarrow p\bar{p}\pi^+\pi^-)$</td>
<td>$(3.7 \pm 1.2 \pm 0.3) \times 10^{-7}$</td>
<td>$(1.0 \pm 0.4) \times 10^{-7}$</td>
</tr>
<tr>
<td>$\mathcal{B}(B^0 \rightarrow \chi_{c2} K_S^0) \times \mathcal{B}(\chi_{c2} \rightarrow p\bar{p}\pi^+\pi^-)$</td>
<td>$[0.7, 3.8] \times 10^{-7}$</td>
<td>not seen</td>
</tr>
<tr>
<td>$\mathcal{B}(B^0 \rightarrow \eta_c(2S) K_S^0) \times \mathcal{B}(\eta_c(2S) \rightarrow p\bar{p}\pi^+\pi^-)$</td>
<td>$(4.2 \pm 1.4 \pm 0.3) \times 10^{-7}$</td>
<td>not seen</td>
</tr>
<tr>
<td>$\mathcal{B}(B^0 \rightarrow \psi(2S) K_S^0) \times \mathcal{B}(\psi(2S) \rightarrow p\bar{p}\pi^+\pi^-)$</td>
<td>$[0.6, 3.9] \times 10^{-7}$</td>
<td>(1.7 $\pm$ 0.2) $\times 10^{-7}$</td>
</tr>
</tbody>
</table>

First direct measurement of the products in $B$ decays; world-average values are calculated by multiplying individual fractions. See backup slides for systematic error sources.
Conclusions

- A search for $B^+ \rightarrow h_c K^+$ and $B^0 \rightarrow h_c K_S^0$ has been performed.
- We find evidence for $B^+ \rightarrow h_c K^+ (4.8\sigma)$, but no evidence for $B^0 \rightarrow h_c K_S^0 (0.7\sigma)$.
- The branching fraction of $B^+ \rightarrow h_c K^+$ is measured to be $(3.7^{+1.0+0.8}_{-0.9-0.8}) \times 10^{-5}$; the upper limit for the $B^0 \rightarrow h_c K_S^0$ branching fraction is $1.4 \times 10^{-5}$ at 90% C. L. The measured value of $\mathcal{B}(B^+ \rightarrow h_c K^+)$ is consistent with the existing upper limit of $3.8 \times 10^{-5}$ (90% C. L.) obtained in the previous Belle analysis and supersedes it.
- In addition, we observe a new decay mode of the $\eta_c(2S)$: $\eta_c(2S) \rightarrow p\bar{p}\pi^+\pi^- (12.1\sigma)$. 
Thank you for attention!
BACKUP
Fit results (default model)

New: $B \rightarrow h_c K$

Fit to $h_c \rightarrow p\bar{p}\pi^+\pi^-$ background

$B^+ \rightarrow h_c K^+$

$B^0 \rightarrow h_c K_S^0$

K. Chilikin (LPI RAS) Charmonium studies at Belle 26 February 2019 27 / 30
Fit results ($B^0 \rightarrow h_c K^0_S$, default model)

$p\bar{p}\pi^+\pi^-$ signal

$\chi_{cJ}$ region

Significance of $\eta_c(2S) \rightarrow p\bar{p}\pi^+\pi^-$: $5.9\sigma$. 
Relative systematic uncertainties of the branching fractions for the channel $B^+ \to (c\bar{c})K^+$ ($B^+ \to h_cK^+$ for the $h_c$ and $B^+ \to (c\bar{c})(\to p\bar{p}\pi^+\pi^-)K^+$ for all other charmonium states):

<table>
<thead>
<tr>
<th>Error source</th>
<th>$h_c$</th>
<th>$\eta_c$</th>
<th>$J/\psi$</th>
<th>$\chi_0$</th>
<th>$\chi_1$</th>
<th>$\chi_2$</th>
<th>$\eta_c(2S)$</th>
<th>$\psi(2S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model dependence</td>
<td>(9.09%)</td>
<td>(3.45%)</td>
<td>(1.96%)</td>
<td>(4.59%)</td>
<td>(7.10%)</td>
<td>(21.13%)</td>
<td>(1.75%)</td>
<td>(3.40%)</td>
</tr>
<tr>
<td>PID</td>
<td>3.99%</td>
<td>3.64%</td>
<td>3.62%</td>
<td>3.50%</td>
<td>3.50%</td>
<td>3.52%</td>
<td>3.53%</td>
<td></td>
</tr>
<tr>
<td>Overtraining</td>
<td>0.41%</td>
<td>0.14%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Tracking</td>
<td>1.60%</td>
<td>1.75%</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>MLP efficiency</td>
<td>12.73%</td>
<td>0.25%</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Number of $\pi^0$ candidates</td>
<td>11.60%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>$\eta_c$ mass and width</td>
<td>0.99%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>$h_c$ branching fraction</td>
<td>10.22%</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B}(\Upsilon(4S) \to B^+B^-)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.17%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of $\Upsilon(4S)$ events</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.37%</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>(22.51%)</td>
<td>(5.62%)</td>
<td>(4.83%)</td>
<td>(6.30%)</td>
<td>(8.31%)</td>
<td>(21.57%)</td>
<td>(4.68%)</td>
<td>(5.52%)</td>
</tr>
</tbody>
</table>
Relative systematic uncertainties of the branching fractions for the channel $B^0 \to (c\bar{c})K_S^0$ ($B^0 \to h_c K_S^0$ for the $h_c$ and $B^0 \to (c\bar{c})(\to p\bar{p}\pi^+\pi^-)K_S^0$ for all other charmonium states):

<table>
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<tr>
<th>Error source</th>
<th>$h_c$</th>
<th>$\eta_c$</th>
<th>$J/\psi$</th>
<th>$\chi_{c0}$</th>
<th>$\chi_{c1}$</th>
<th>$\chi_{c2}$</th>
<th>$\eta_c(25)$</th>
<th>$\psi(25)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model dependence</td>
<td>($+30.94%$)</td>
<td>($+4.91%$)</td>
<td>($+1.45%$)</td>
<td>($+134.01%$)</td>
<td>($+6.79%$)</td>
<td>($+8.63%$)</td>
<td>($+4.51%$)</td>
<td>($+3.97%$)</td>
</tr>
<tr>
<td>PID</td>
<td>4.86%</td>
<td>3.93%</td>
<td>3.93%</td>
<td>3.87%</td>
<td>3.87%</td>
<td>3.86%</td>
<td>3.83%</td>
<td>3.81%</td>
</tr>
<tr>
<td>Overtraining</td>
<td>0.15%</td>
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<tr>
<td>Tracking</td>
<td>1.95%</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>MLP efficiency</td>
<td>12.79%</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Number of $\pi^0$ candidates</td>
<td>11.66%</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$\eta_c$ mass and width</td>
<td>0.96%</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$h_c$ branching fraction</td>
<td>10.27%</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$B(\Upsilon(4S) \to B^0 \bar{B}^0)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.23%</td>
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<tr>
<td>Number of $\Upsilon(4S)$ events</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>1.37%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>($+37.33%$)</td>
<td>($+6.89%$)</td>
<td>($+5.04%$)</td>
<td>($+134.10%$)</td>
<td>($+8.31%$)</td>
<td>($+9.87%$)</td>
<td>($+6.56%$)</td>
<td>($+6.18%$)</td>
</tr>
</tbody>
</table>