Charmonium studies at Belle

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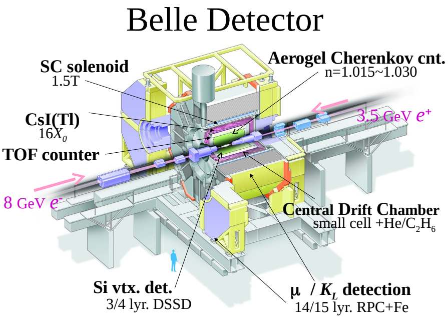
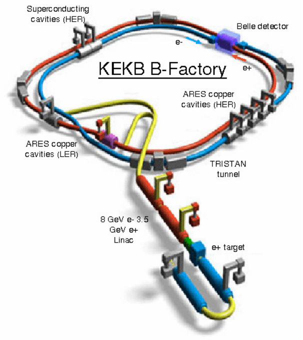
The Belle experiment

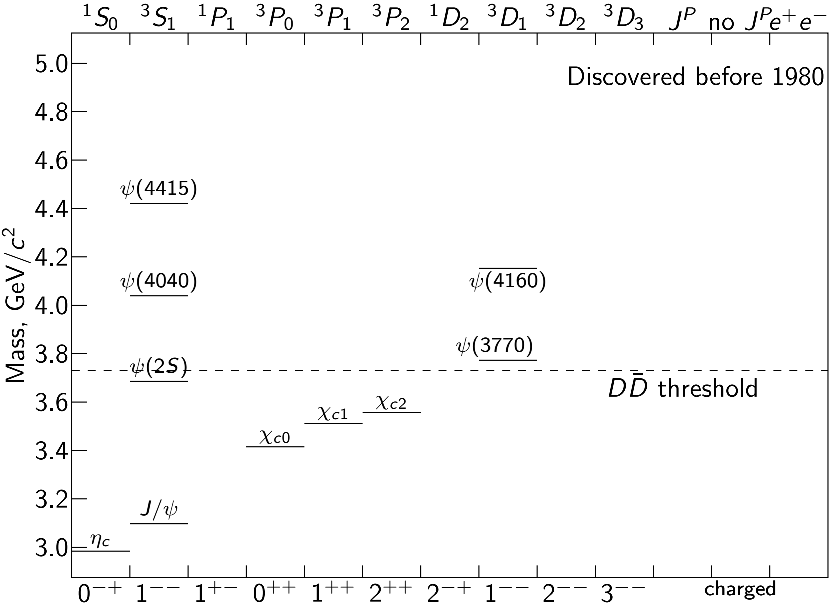




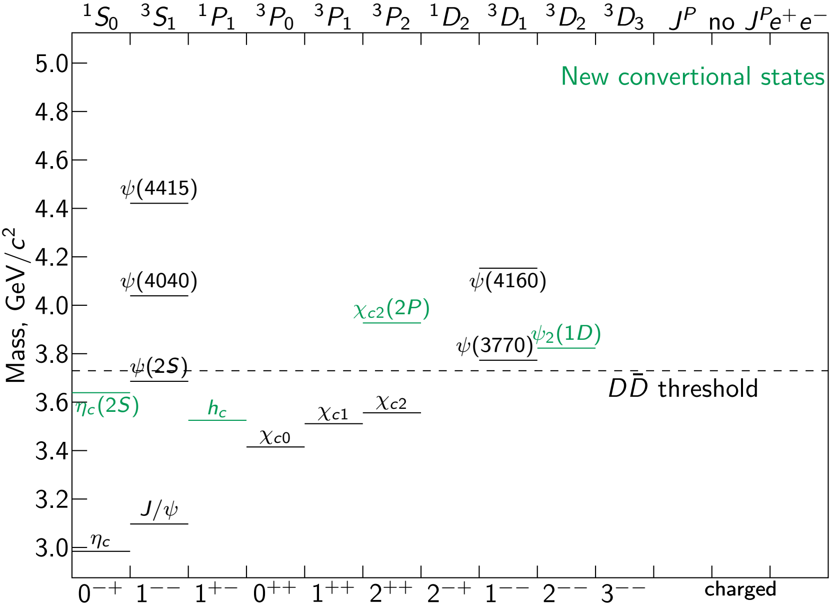
Charmonium production:

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

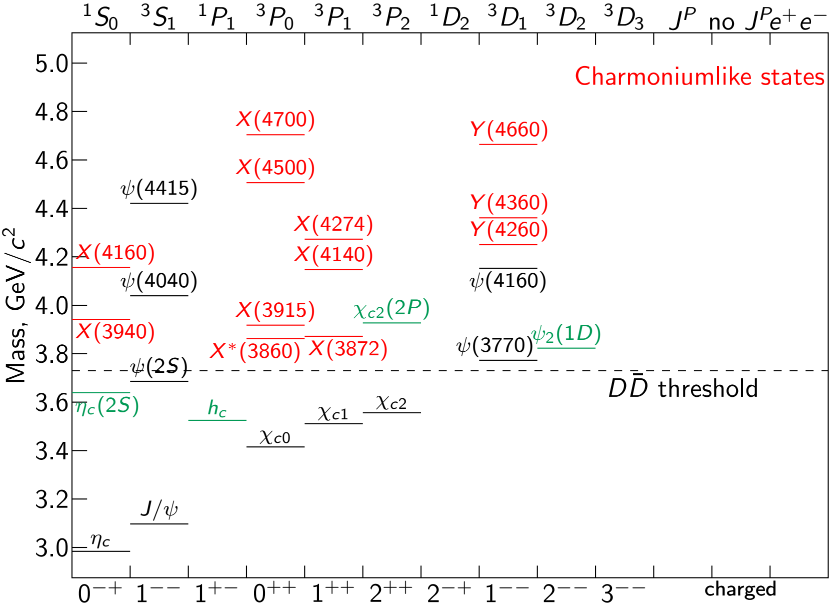
Charmonium states



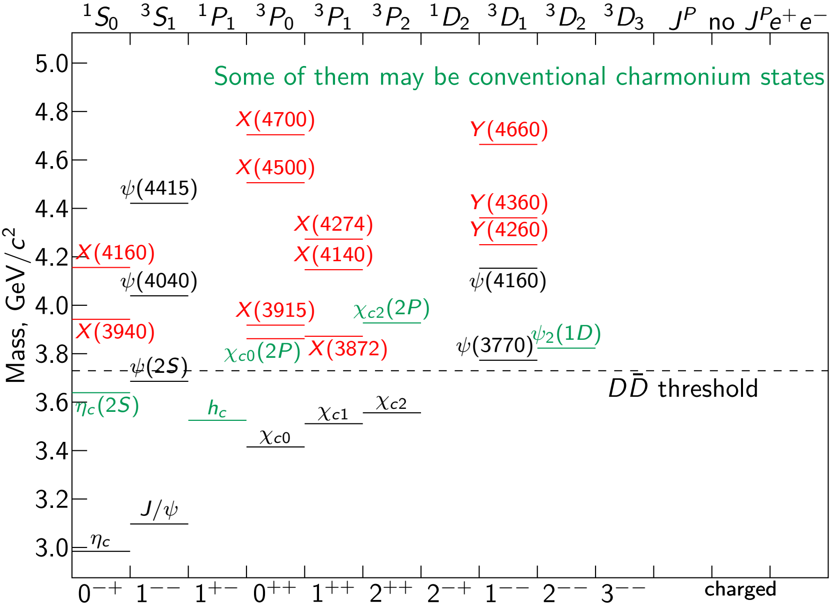
Charmonium states



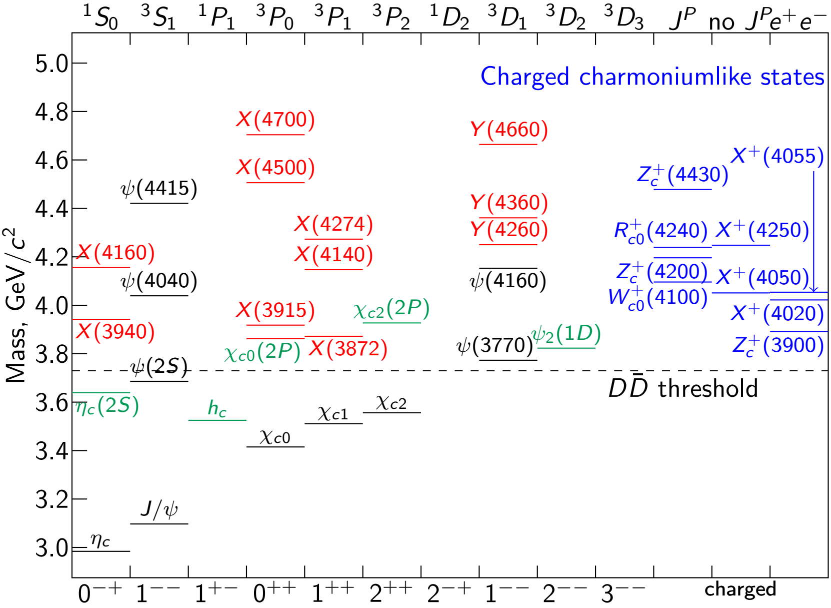
Charmonium states



Charmonium states



Charmonium states



Charmonuim studies at Belle

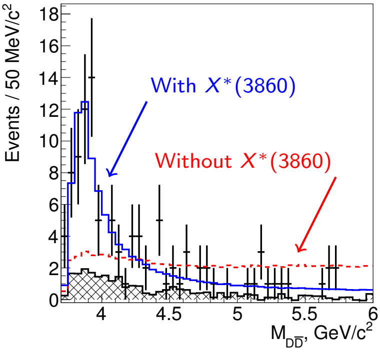
1. Published results:
   - Observation of $\chi_{c0}(3860)$ (or $X^*(3860)$) in $e^+e^- \to J/\psi D\bar{D}$,
   - Measurement of the absolute branching fractions of $B^+ \to X_{c\bar{c}}K^+$,
   - Observation of $e^+e^- \to \chi_{c1}\gamma$.
2. New results:
   - Evidence for $B^+ \to h_c K^+$ and observation of $\eta_c(2S) \to p\bar{p}\pi^+\pi^-$.

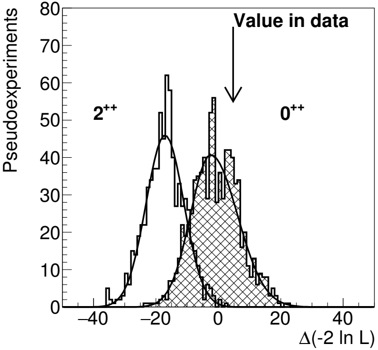
Published results

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

PRD **95**, 112003

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





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

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

PRD **95**, 112003

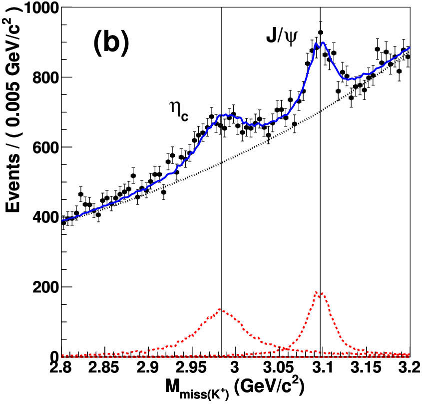
- Quantum numbers: $J^{PC} = 0^{++}$.
- Production: in S-wave. Same for $\chi_{c0}(1P)$, measured in PRD **70**, 071102 (2004).
- The $\chi_{c0}(2P)$ mass in Ebert-Faustov-Galkin model [PRD **67**, 014027 (2003)]: 3854 MeV$/c^2$, in Godfrey-Isgur model [PRD **32**, 189 (1985)]: 3916 MeV$/c^2$.
- Mass 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).

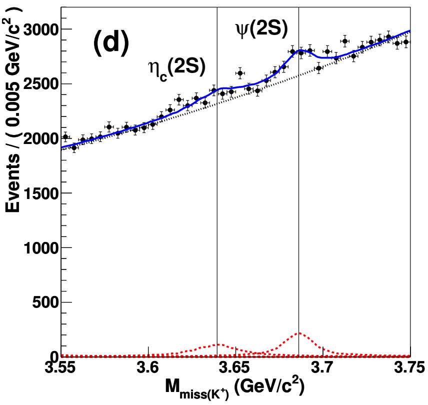
The $X^*(3860)$ is a better $\chi_{c0}(2P)$ candidate than the $X(3915)$.

Absolute $\mathcal{B}(B^+ \to X_{c\bar{c}} K^+)$

PRD **97**, 072005

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 $\mathcal{B}(B^+ \to X_{c\bar{c}} K^+)$

PRD **97**, 072005

Results:

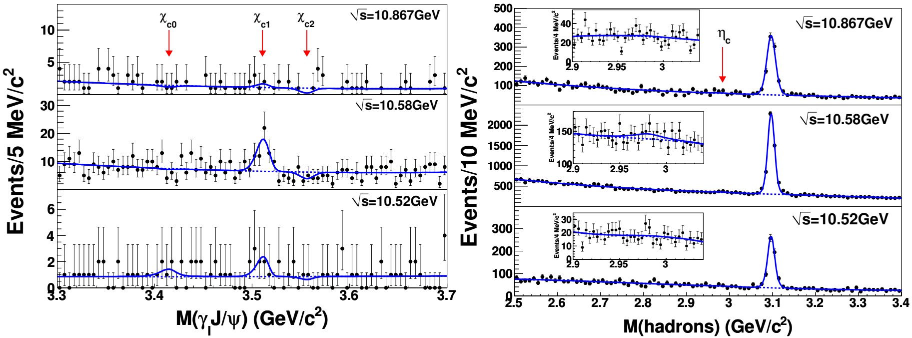
Mode	Yield	Signif. (σ)	$\epsilon (10^{-3})$	$\mathcal{B}$ (10^{-4})	World average for $\mathcal{B}$ (10^{-4})
η_c	2590 ± 180	14.2	2.73 ± 0.02	$12.0 \pm 0.8 \pm 0.7$	9.6 ± 1.1
J/ψ	1860 ± 140	13.7	2.65 ± 0.02	$8.9 \pm 0.6 \pm 0.5$	10.26 ± 0.031
χ_{c0}	430 ± 190	2.2	2.67 ± 0.02	$2.0 \pm 0.9 \pm 0.1$ (< 3.3)	$1.50^{+0.15}_{-0.14}$
χ_{c1}	1230 ± 180	6.8	2.68 ± 0.02	$5.8 \pm 0.9 \pm 0.5$	4.79 ± 0.23
$\eta_c(2S)$	1050 ± 240	4.1	2.77 ± 0.02	$4.8 \pm 1.1 \pm 0.3$	3.4 ± 1.8
$\psi(2S)$	1410 ± 210	6.6	2.79 ± 0.02	$6.4 \pm 1.0 \pm 0.4$	6.26 ± 0.24
$\psi(3770)$	-40 ± 310	-	2.76 ± 0.02	$-0.2 \pm 1.4 \pm 0.0$ (< 2.3)	4.9 ± 1.3
$X(3872)$	260 ± 230	1.1	2.79 ± 0.01	$1.2 \pm 1.1 \pm 0.1$ (< 2.6)	(< 3.2)
$X(3915)$	80 ± 350	0.3	2.79 ± 0.01	$0.4 \pm 1.6 \pm 0.0$ (< 2.8)	-

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

Observation of $e^+e^- \to \chi_{c1}\gamma$

PRD **98**, 092015

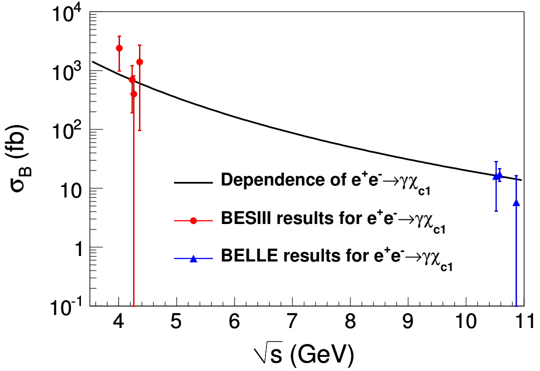
Search for $e^+e^- \to \gamma\chi_{cJ}(\to J/\psi\gamma)$ and $e^+e^- \to \eta_c\gamma$ (η_c resonstructed in 5 channels: $K^+K^0_S\pi^-$, $\pi^+\pi^-K^+K^-$, $\pi^+\pi^-\pi^+\pi^-$, $K^+K^-K^+K^-$, and $3(\pi^+\pi^-)$).



Significant χ_{c1} signal (5.1σ) is observed at $\sqrt{s} = 10.58$ GeV.

Observation of $e^+e^- \to \chi_{c1}\gamma$

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

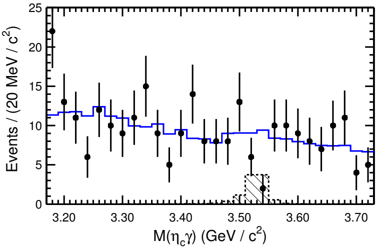
Motivation and experimental status

New: $B \to h_c K$

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 (3.8×10^{-5} at 90% C. L.):

- C. Meng, Y. J. Gao and K. T. Chao, hep-ph/0607221: 2.7×10^{-5}.
- X. Q. Li, X. Liu and Y. M. Wang, Phys. Rev. D **74**, 114029: 3.6×10^{-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):



Analysis and its improvements

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 η_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

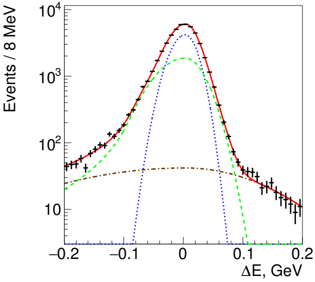
The resolution is parameterized by the function

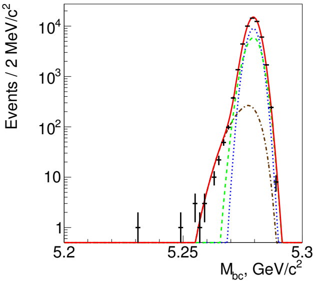
$$S(\Delta E, M_{\rm bc}) = N_{\rm CB} F_{\rm CB}(x_1) G_a^{(12)}(y_1) + N_{\rm G1} G_a^{(21)}(x_2) G_a^{(22)}(y_2) + N_{\rm G2} G_a^{(31)}(x_3) G_a^{(32)}(y_3), \quad (1)$$

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

$$\begin{pmatrix} x_i \\ y_i \end{pmatrix} = \begin{pmatrix} \cos\alpha_i & \sin\alpha_i \\ -\sin\alpha_i & \cos\alpha_i \end{pmatrix} \begin{pmatrix} \Delta E - (\Delta E)_0 \\ M_{\rm bc} - (M_{\rm bc})_0 \end{pmatrix}. \quad (2)$$

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





Fit to the $(\Delta E, M_{\text{bc}})$ distribution

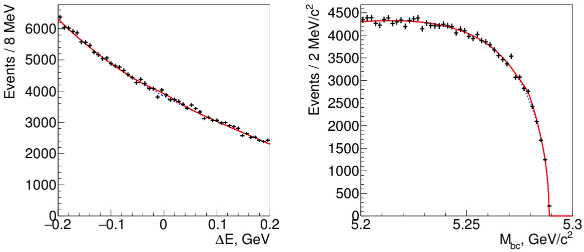
The $(\Delta E, M_{\text{bc}})$ distribution is fitted in order to estimate the expected number of the background events in the signal region. The distribution is fitted to the function

$$N_S S(\Delta E, M_{\text{bc}}) + B(\Delta E, M_{\text{bc}}), \quad (3)$$

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

$$B(\Delta E, M_{\text{bc}}) = \sqrt{m_0 - M_{\text{bc}}} \exp[-a(m_0 - M_{\text{bc}})] P_3(\Delta E, M_{\text{bc}}), \quad (4)$$

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 π meson. Background for $B^+ \to h_c K^+$ with $\eta_c \to K^+K^-\pi^0$ (with $M_{\text{bc}} > 5.272$ GeV$/c^2$ for the projection onto ΔE and $|\Delta E| < 20$ MeV for the projection onto M_{bc}):



Multivariate analysis

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.
- $h_c \to \eta_c \gamma$: the h_c helicity angle, the η_c mass, the numbers of π^0 candidates that have the h_c daughter photon as one of their daughters.
- $\eta_c \to K^+ K^0_S \pi^-$, $\eta_c \to K^+ K^- \pi^0$ and $\eta_c \to K^0_S K^0_S \pi^0$: invariant masses of both (K, π) combinations.
- Channels with the corresponding particles in the final state: K and p particle-identification likelihoods.
- Channels with a π^0 or η: the π^0 (η) mass, the minimal energy of its daughter photons in the laboratory frame, the numbers of π^0 candidates that have the π^0 (η) daughter photon as one of their daughters.
- Channels with $\eta \to \pi^+ \pi^- \pi^0$ or $\eta' \to \eta \pi^+ \pi^-$: the η (η') mass.

Optimization of the selection requirements

New: $B \to h_c K$

An elliptical channel-dependent signal region is selected: $\left(\frac{\Delta E}{R^{(i)}_{\Delta E}}\right)^2 + \left(\frac{M_{\rm bc}}{R^{(i)}_{M_{\rm bc}}}\right)^2 < 1$. The following variables are optimized for each decay channel: half-axes $R^{(i)}_{\Delta E}$, $R^{(i)}_{M_{\rm bc}}$, and cutoff for MLP output (v_0). The value being maximized is $F_{\rm opt} = (\sum_i N^{(i)}_{\rm sig})/(\frac{a}{2} + \sqrt{\sum_i N^{(i)}_{\rm bg}})$, 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 ($B^+ \to h_c K^+$):

Channel	Parameters			Efficiency		
	$R^{(i)}_{\Delta E}$	$R^{(i)}_{M_{\rm bc}}$	$v^{(i)}_0$	$\epsilon^{(i)}_{\rm SR}$	$\epsilon^{(i)}_S(v^{(i)}_0)$	$\epsilon^{(i)}_B(v^{(i)}_0)$
$\eta_c(\to K^+ K^0_S \pi^-)\gamma$	32.7	4.82	0.804	6.27%	59.5%	5.08%
$\eta_c(\to K^+ K^- \pi^0)\gamma$	36.2	3.90	0.958	4.27%	31.7%	0.56%
$\eta_c(\to K^0_S K^0_S \pi^0)\gamma$	42.3	4.49	0.976	1.79%	17.8%	0.18%
$\eta_c(\to K^+ K^- \eta_{2\gamma})\gamma$	34.4	4.16	0.977	4.21%	20.2%	0.22%
$\eta_c(\to K^+ K^- \eta_{3\pi})\gamma$	24.9	3.59	0.978	1.75%	29.7%	0.23%
$\eta_c(\to K^+ K^- K^+ K^-)\gamma$	25.3	4.13	0.770	4.89%	53.2%	6.69%
$\eta_c(\to \eta'(\to \eta_{2\gamma}\pi^+\pi^-)\pi^+\pi^-)\gamma$	30.5	4.21	0.958	2.69%	40.5%	0.63%
$\eta_c(\to \eta'(\to \eta_{3\pi}\pi^+\pi^-)\pi^+\pi^-)\gamma$	26.8	4.16	0.990	1.01%	29.2%	0.13%
$\eta_c(\to p\bar{p})\gamma$	38.9	5.48	0.654	17.70%	75.7%	10.66%
$\eta_c(\to p\bar{p}\pi^0)\gamma$	30.2	3.75	0.954	4.65%	30.3%	0.50%
$\eta_c(\to p\bar{p}\pi^+\pi^-)\gamma$	24.1	4.03	0.912	6.31%	30.0%	1.53%
$\eta_c(\to \Lambda\bar{\Lambda})\gamma$	40.4	5.66	0.727	4.04%	70.6%	6.79%
$p\bar{p}\pi^+\pi^-$	13.5	4.36	0.598	14.81%	64.6%	18.40%

Efficiencies: $\epsilon^{(i)}_{\rm SR}$ - reconstruction an signal region selection; $\epsilon^{(i)}_S(v^{(i)}_0)$, $\epsilon^{(i)}_B(v^{(i)}_0)$ - MLP for signal and background, respectively.

Data fitting procedure

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

$$S_{\eta_c\gamma}(M) = \left(N_{h_c}|A_{h_c}(M)|^2\right) \otimes R_{h_c}^{(\eta_c\gamma)}(\Delta M) + P_2(M), \tag{5}$$

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 $h_c \to p\bar{p}\pi^+\pi^-$ is a third-order polynomial. The signal PDF for the channel $h_c \to p\bar{p}\pi^+\pi^-$ is given by

$$\begin{aligned} S_{p\bar{p}\pi^+\pi^-}(M) = \Bigg(& |P_3(M) + \sum_{R=\eta_c,\chi_{c0},\eta_c(2S)} \sqrt{N_R} e^{i\varphi_R} A_R(M)|^2 \\ & + \sum_{R=J/\psi,\chi_{c1},h_c,\chi_{c2},\psi(2S)} N_R |A_R(M)|^2 \Bigg) \otimes R_{h_c}(\Delta M), \end{aligned} \tag{6}$$

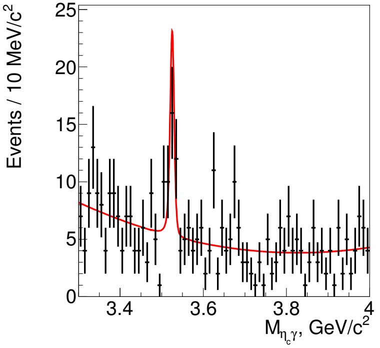
where P_3 is a third-order polynomial representing the noncharmonium signal. The wide states are added coherently to the signal PDF, while the states that are narrower than the resolution are added incoherently. The amplitudes are normalized in such a way that all the parameters N represent the yields 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 $(\Delta E, M_{\rm bc})$ over the signal and background regions.

Fit results (default model)

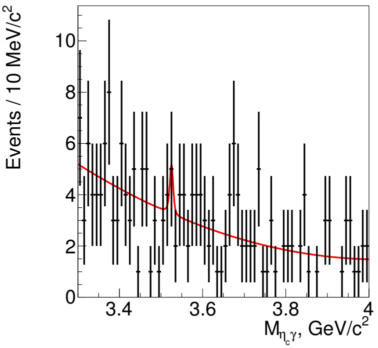
New: $B \to h_c K$

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

$B^+ \to h_c K^+$



$B^0 \to h_c K_S^0$

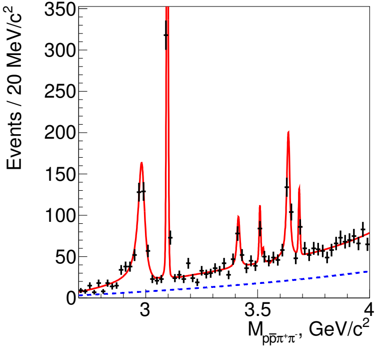


Significance of $B^+ \to h_c K^+$: 5.0σ.
No signal of $B^0 \to h_c K_S^0$ is seen: 0.8σ.

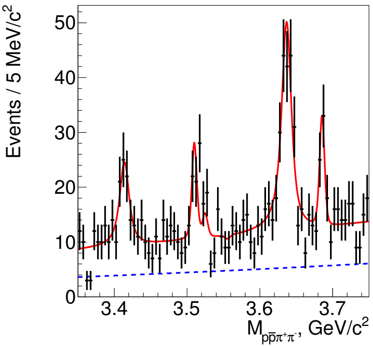
Fit results ($B^+ \to h_c K^+$, default model)

New: $B \to h_c K$

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



χ_{cJ} region



Significance of $\eta_c(2S) \to p\bar{p}\pi^+\pi^-$: 12.3σ.
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 $\eta_c(2S) \to p\bar{p}\pi^+\pi^-$ significance:

Model	h_c significance		$\eta_c(2S) \to p\bar{p}\pi^+\pi^-$ significance	
	$B^+ \to h_c K^+$	$B^0 \to h_c K_S^0$	$B^+ \to h_c K^+$	$B^0 \to h_c K_S^0$
Default	5.0σ	0.8σ	12.3σ	5.9σ
Free masses and widths	5.0σ	0.8σ	12.3σ	6.0σ
Polynomial order ($h_c \to \eta_c\gamma$)	4.8σ	0.8σ	12.3σ	5.9σ
Polynomial order ($h_c \to p\bar{p}\pi^+\pi^-$ background)	5.0σ	0.8σ	12.2σ	5.9σ
Polynomial order ($h_c \to p\bar{p}\pi^+\pi^-$ signal)	5.0σ	0.9σ	12.2σ	5.9σ
Fitting range variation ($h_c \to \eta_c\gamma$)	5.0σ	0.9σ	12.3σ	5.9σ
Fitting range variation ($h_c \to p\bar{p}\pi^+\pi^-$)	5.0σ	0.8σ	12.1σ	5.8σ
Scaled resolution	5.0σ	0.8σ	12.3σ	6.0σ
Fraction of $h_c \to \eta_c\gamma$ and $h_c \to p\bar{p}\pi^+\pi^-$	4.9σ	0.7σ	12.2σ	5.9σ

The significance with the systematic uncertainty taken into account is 4.8σ for $B^+ \to h_c K^+$ and 12.1σ for $\eta_c(2S) \to p\bar{p}\pi^+\pi^-$.

Branching fractions

New: $B \to h_c K$

Branching fraction	Value or confidence interval (90 % C. L.)	World-average value
$\mathcal{B}(B^+ \to h_c K^+)$	$(3.7\,^{+1.0}_{-0.9}\,^{+0.8}_{-0.8}) \times 10^{-5}$	$< 3.8 \times 10^{-5}$
$\mathcal{B}(B^+ \to \eta_c K^+) \times \mathcal{B}(\eta_c \to p\bar{p}\pi^+\pi^-)$	$(39.4\,^{+4.1}_{-3.9}\,^{+2.2}_{-1.8}) \times 10^{-7}$	$(57.8 \pm 20.2) \times 10^{-7}$
$\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to p\bar{p}\pi^+\pi^-)$	$(56.4\,^{+3.3}_{-3.2}\,^{+2.7}_{-2.5}) \times 10^{-7}$	$(60.6 \pm 5.3) \times 10^{-7}$
$\mathcal{B}(B^+ \to \chi_{c0} K^+) \times \mathcal{B}(\chi_{c0} \to p\bar{p}\pi^+\pi^-)$	$(3.7\,^{+1.2}_{-1.0}\,^{+0.2}_{-0.3}) \times 10^{-7}$	$(3.1 \pm 1.1) \times 10^{-7}$
$\mathcal{B}(B^+ \to \chi_{c1} K^+) \times \mathcal{B}(\chi_{c1} \to p\bar{p}\pi^+\pi^-)$	$(4.7\,^{+1.3}_{-1.2}\,^{+0.4}_{-0.2}) \times 10^{-7}$	$(2.4 \pm 0.9) \times 10^{-7}$
$\mathcal{B}(B^+ \to \chi_{c2} K^+) \times \mathcal{B}(\chi_{c2} \to p\bar{p}\pi^+\pi^-)$	$< 1.9 \times 10^{-7}$	$(0.15 \pm 0.06) \times 10^{-7}$
$\mathcal{B}(B^+ \to \eta_c(2S) K^+) \times \mathcal{B}(\eta_c(2S) \to p\bar{p}\pi^+\pi^-)$	$(11.2\,^{+1.8}_{-1.6}\,^{+0.5}_{-0.7}) \times 10^{-7}$	not seen
$\mathcal{B}(B^+ \to \psi(2S) K^+) \times \mathcal{B}(\psi(2S) \to p\bar{p}\pi^+\pi^-)$	$(4.7\,^{+1.2}_{-1.1}\,^{+0.3}_{-0.3}) \times 10^{-7}$	$(3.7 \pm 0.3) \times 10^{-7}$
$\mathcal{B}(B^0 \to h_c K^0_S)$	$< 1.4 \times 10^{-5}$	not seen
$\mathcal{B}(B^0 \to \eta_c K^0_S) \times \mathcal{B}(\eta_c \to p\bar{p}\pi^+\pi^-)$	$(19.0\,^{+3.2}_{-2.9}\,^{+1.3}_{-4.7}) \times 10^{-7}$	$(20.9 \pm 7.8) \times 10^{-7}$
$\mathcal{B}(B^0 \to J/\psi K^0_S) \times \mathcal{B}(J/\psi \to p\bar{p}\pi^+\pi^-)$	$(24.3\,^{+2.3}_{-2.2}\,^{+1.2}_{-1.3}) \times 10^{-7}$	$(26.2 \pm 2.4) \times 10^{-7}$
$\mathcal{B}(B^0 \to \chi_{c0} K^0_S) \times \mathcal{B}(\chi_{c0} \to p\bar{p}\pi^+\pi^-)$	$< 1.3 \times 10^{-7}$	$(1.5 \pm 0.6) \times 10^{-7}$
$\mathcal{B}(B^0 \to \chi_{c1} K^0_S) \times \mathcal{B}(\chi_{c1} \to p\bar{p}\pi^+\pi^-)$	$(3.7\,^{+1.2}_{-1.0}\,^{+0.3}_{-0.2}) \times 10^{-7}$	$(1.0 \pm 0.4) \times 10^{-7}$
$\mathcal{B}(B^0 \to \chi_{c2} K^0_S) \times \mathcal{B}(\chi_{c2} \to p\bar{p}\pi^+\pi^-)$	$[0.7, 3.8] \times 10^{-7}$	not seen
$\mathcal{B}(B^0 \to \eta_c(2S) K^0_S) \times \mathcal{B}(\eta_c(2S) \to p\bar{p}\pi^+\pi^-)$	$(4.2\,^{+1.4}_{-1.2}\,^{+0.3}_{-0.3}) \times 10^{-7}$	not seen
$\mathcal{B}(B^0 \to \psi(2S) K^0_S) \times \mathcal{B}(\psi(2S) \to p\bar{p}\pi^+\pi^-)$	$[0.6, 3.9] \times 10^{-7}$	$(1.7 \pm 0.2) \times 10^{-7}$

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

Thank you for attention!

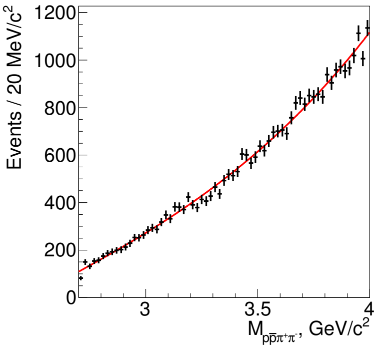
BACKUP

Fit results (default model)

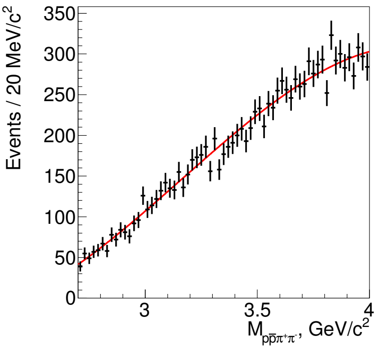
New: $B \to h_c K$

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

$B^+ \to h_c K^+$

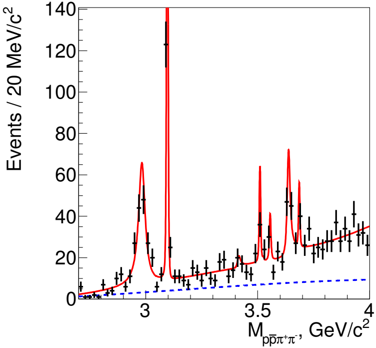


$B^0 \to h_c K_S^0$

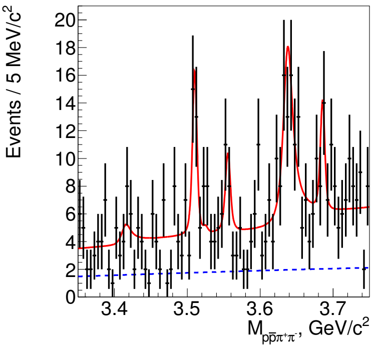


Fit results ($B^0 \to h_c K_S^0$, default model)

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



χ_{cJ} region



Significance of $\eta_c(2S) \to p\bar{p}\pi^+\pi^-$: 5.9σ.

Branching fraction uncertainty

Relative systematic uncertainties of the branching fractions for the channel $B^+ \to (c\bar{c})K^+$ ($B^+ \to h_c K^+$ for the h_c and $B^+ \to (c\bar{c})(\to p\bar{p}\pi^+\pi^-)K^+$ for all other charmonium states):

Error source	h_c	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	$\eta_c(2S)$	$\psi(2S)$
Model dependence	$(^{+9.09}_{-9.16})\%$	$(^{+3.45}_{-1.47})\%$	$(^{+1.96}_{-0.04})\%$	$(^{+4.59}_{-5.32})\%$	$(^{+7.10}_{-2.98})\%$	$(^{+-21.13}_{--65.93})\%$	$(^{+1.75}_{-4.62})\%$	$(^{+3.40}_{-3.07})\%$
PID	3.99%	3.64%	3.62%	3.50%	3.50%	3.51%	3.52%	3.53%
Overtraining	0.41%	0.14%						
Tracking	1.60%	1.75%						
MLP efficiency	12.73%	0.25%						
Number of π^0 candidates	11.60%	—						
η_c mass and width	0.99%	—						
h_c branching fraction	10.22%	—						
$\mathcal{B}(\Upsilon(4S) \to B^+B^-)$	1.17%							
Number of $\Upsilon(4S)$ events	1.37%							
Total	$(^{+22.51}_{-22.54})\%$	$(^{+5.62}_{-4.67})\%$	$(^{+4.83}_{-4.41})\%$	$(^{+6.30}_{-6.86})\%$	$(^{+8.31}_{-5.25})\%$	$(^{+21.57}_{-66.07})\%$	$(^{+4.68}_{-6.34})\%$	$(^{+5.52}_{-5.32})\%$

Branching fraction uncertainty

New: $B \to h_c K$

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):

Error source	h_c	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	$\eta_c(2S)$	$\psi(2S)$
Model dependence	$(^{+30.94}_{-24.05})\%$	$(^{+4.91}_{-24.37})\%$	$(^{+1.45}_{-1.80})\%$	$(^{+134.01}_{-24.56})\%$	$(^{+6.79}_{-2.28})\%$	$(^{+8.63}_{-4.78})\%$	$(^{+4.51}_{-5.36})\%$	$(^{+3.97}_{-3.91})\%$
PID	4.86%	3.93%	3.93%	3.87%	3.87%	3.86%	3.83%	3.81%
Overtraining	0.15%	0.19%						
Tracking	1.95%	2.10%						
MLP efficiency	12.79%	0.25%						
Number of π^0 candidates	11.66%	—						
η_c mass and width	0.96%	—						
h_c branching fraction	10.27%	—						
$\mathcal{B}(\Upsilon(4S) \to B^0\bar{B}^0)$	1.23%							
Number of $\Upsilon(4S)$ events	1.37%							
Total	$(^{+37.33}_{-31.86})\%$	$(^{+6.89}_{-24.85})\%$	$(^{+5.04}_{-5.16})\%$	$(^{+134.10}_{-25.02})\%$	$(^{+8.31}_{-5.30})\%$	$(^{+9.87}_{-6.76})\%$	$(^{+6.56}_{-7.17})\%$	$(^{+6.18}_{-6.14})\%$