Charmonium(-like) states at Belle

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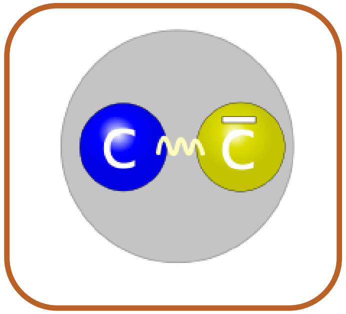
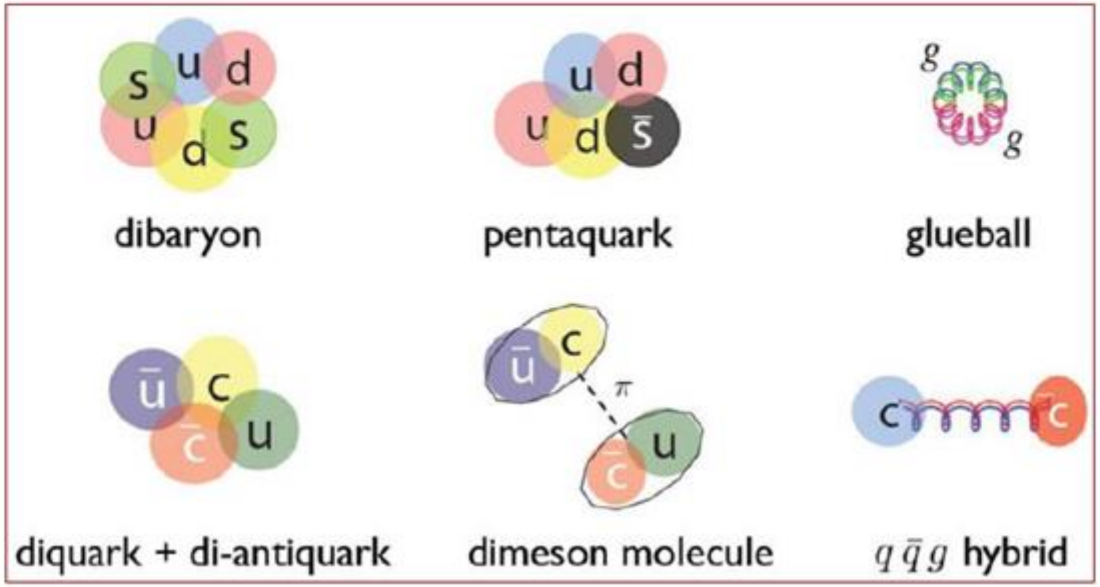
Introduction

- After 2002 six new conventional charmonium states + more than a dozen of exotic charmonium-like states were discovered.
- Charmonium consists of two heavy c quarks and allows to study strong interactions and to check different theoretical models of heavy quarkonia.
- Charmonium-like states are not predicted by potential models and seem to have a more complex structure than charmonia.
- Naming scheme: Y states (1^{--}), Z states (charged), X states (all the rest).

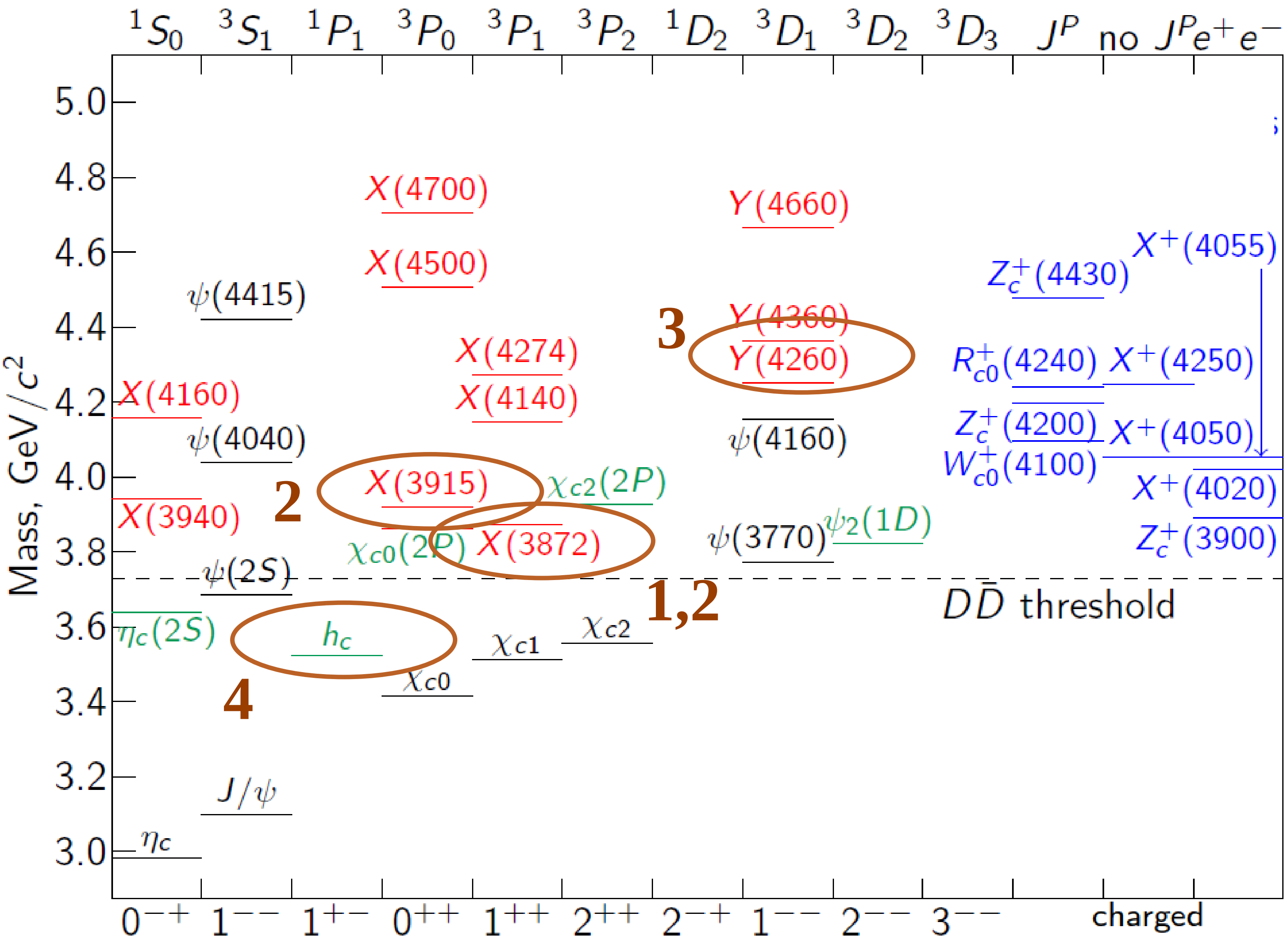
charmonium



charmonium-like



Plan of my talk

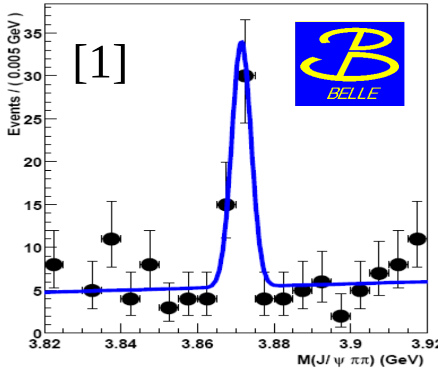


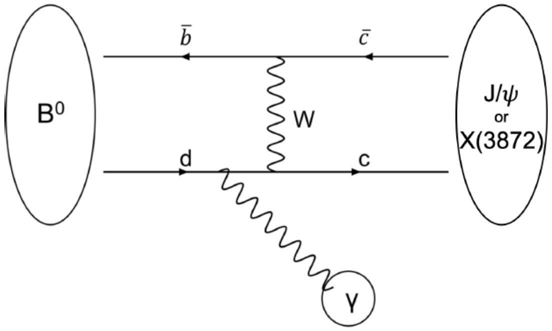
Full Belle *Y(4S)* data sample of 711 fb^{-1} is used for these analyses.

$B^0 \to X(3872)\gamma$ I

Motivation

- *X(3872)* is the first discovered and most famous exotic state:
  - observed by Belle in 2003 in $J/\psi\pi^+\pi^-$ mode [1],
  - mass near $D^0 D^{*0}$ threshold,
  - small width (< 1.2 MeV).
- Info on similar $\mathscr{B}(B^0 \to J/\psi\gamma)$:
  - 7.65×10^{-9} from QCD factorization [2],
  - 4.5×10^{-7} from pQCD [3],
  - $< 1.5 \times 10^{-6}$ from LHCb experiment [4].
- *X(3872)* probably contains other components than c and anti-c quarks $\Rightarrow$ $\mathscr{B}(B^0 \to X(3872)\gamma)$ $\Rightarrow$ should be smaller than $\mathscr{B}(B^0 \to J/\psi\gamma)$.
- New Physics contributions may enhance $B^0 \to X(3872)\gamma$!





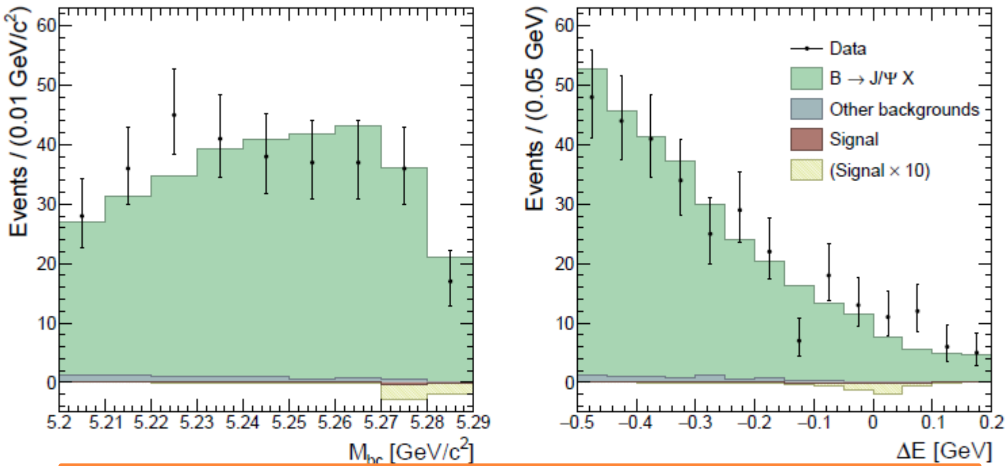
Analysis features

- $X(3872) \to J/\psi\pi^+\pi^-$, $J/\psi \to l^+l^-$ $(l=e,\mu)$;
- selections on $|M(ll\pi\pi) - M(ll)|$ to reduce combinatorial bkg and bkg from misidentified γ conversions;
- photon selections: $E_\gamma > 600$ MeV, E9/E25 > 0.87, π^0 veto;
- MVA to suppress main bg from $B \to J/\psi X$ (33 variables).

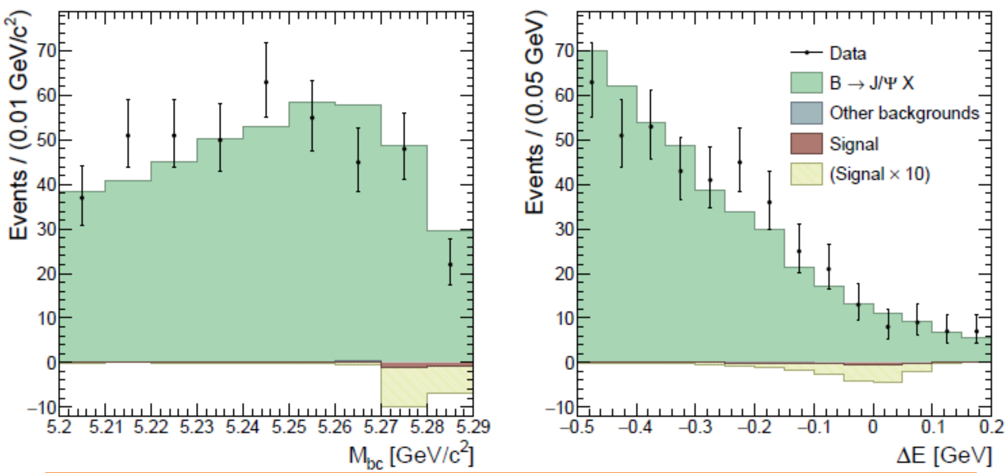
P.-C. Chou, P. Chang et al. (to be submitted to PRD)

[1] PRL 91 262001 (2003)
[2] EPJ C34 291 (2004)
[3] PRD 74 097502 (2006)
[4] PRD 98 030001 (2018)

$B^0 \to X(3872)\gamma$ II



$B^0 \to X(3872)\gamma$, $X(3872) \to J/\psi\pi^+\pi^-$, $J/\psi \to \mu^+\mu^-$



$B^0 \to X(3872)\gamma$, $X(3872) \to J/\psi\pi^+\pi^-$, $J/\psi \to e^+e^-$

Signal yields

- Feldman-Cousins counting method is used to get UL;
- fitting method for cross-check;
- to calibrate the efficiency in the signal region the $B^0 \to K_S^0\pi^+\pi^-\gamma$ control sample is used.

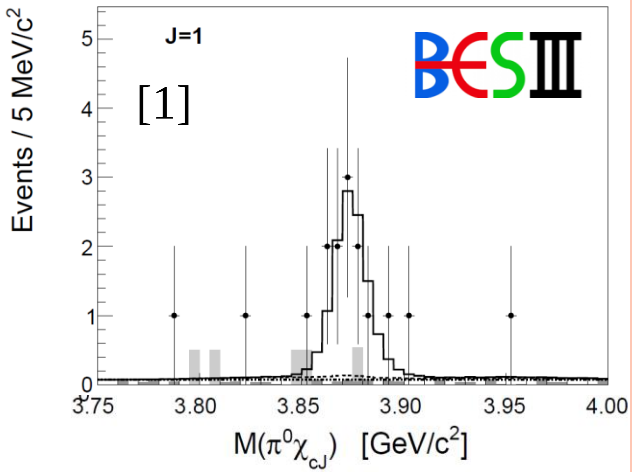
Preliminary result

$\mathcal{B}(B^0 \to X(3872)\gamma) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) < 5.1 \times 10^{-7}$ (90% C.L.)

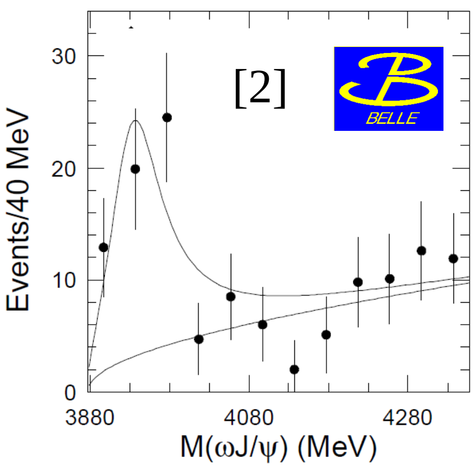
$B^+ \to X(3872,3915)K^+$ I

Motivation

- New decay of *X(3872)* was recently observed by BESIII in $e^+e^- \to X(3872)\gamma \to \chi_{c1}\pi^0\gamma$ [1].
- $\mathcal{B}(X(3872) \to \chi_{c1}\pi^0)$ / $\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = 0.88^{+0.33}_{-0.27} \pm 0.10$ is large compared to $\mathcal{B}(\psi(2S) \to J/\psi\pi^0)$ / $\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-) = 3.66\times10^{-3}$.
- This result disfavors $\chi_{c1}(2P)$ interpretation of *X(3872)* (isospin breaking otherwise).
- Worth checking this ratio from Belle data!



- *X(3915)* was first observed by Belle in $B \to X(3915)K \to J/\psi\omega K$ [2].
- $J^{PC} = 0^{++} \Rightarrow$ may be $\chi_{c0}(2P)$, but too narrow and decay to $J/\psi\omega$ is not suppressed.
- If *X(3915)* is a non-conventional state, single pion transitions may be enhanced.



Analysis features

- $X(3872) \to \chi_{c1}\pi^0$, $X(3915) \to \chi_{c1}\pi^0$;
- $\chi_{c1} \to J/\psi\gamma$, $J/\psi \to l^+l^-$ $(l=e,\mu)$;
- photon selections: $E_\gamma > 100$ MeV, E9/E25 > 0.85, π^0 veto.

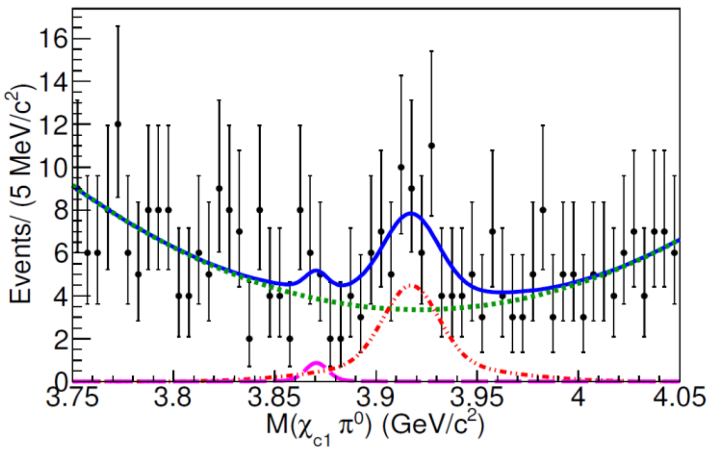
V. Bhardwaj, S. Jia et al. arXiv: 1904.0715 (submitted to PRD)

[1] arXiv: 1901.03992
[2] PRL 94 182002 (2005)
[3] PRL 99 142002 (2007)
[4] PRD 82 094008 (2010)

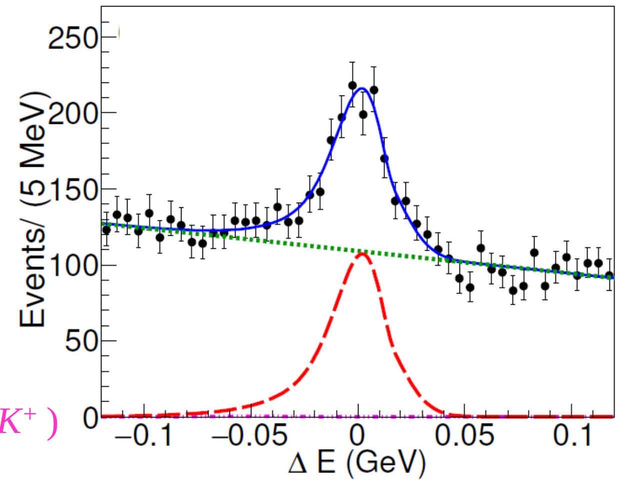
$B^+ \to X(3872,3915)K^+$ II

UML fit to ΔE gives (806 ± 69) signal events (consistent with similar previous Belle study of $B^+ \to \chi_{c1}\pi^+\pi^- K^+$ [5]).

Veto on $B^+ \to \chi_{c1}K^{*+}$: 791.8 MeV < $M(K^+\pi^0)$ < 991.8 MeV.



signal
combinatorial bg
peaking bg ($B^+ \to \chi_{c2}\pi^0 K^+$)
Total



Signal yields

X(3872): 2.7 ± 5.5 (0.3 σ)
X(3915): 42 ± 14 (2.3 σ)

Upper limits

$\mathscr{B}(B^+ \to X(3872)K^+) \times \mathscr{B}(X(3872) \to \chi_{c1}\pi^0) < 8.1 \times 10^{-6}$ (90% C.L.)

$\mathscr{B}(B^+ \to X(3915)K^+) \times \mathscr{B}(X(3915) \to \chi_{c1}\pi^0) < 3.8 \times 10^{-5}$ (90% C.L.)

$\mathscr{B}(X(3872) \to \chi_{c1}\pi^0) \,/\, \mathscr{B}(X(3872) \to J/\psi\pi^+\pi^-) < 0.97$ (90% C.L.)

No contradiction with BESIII result.

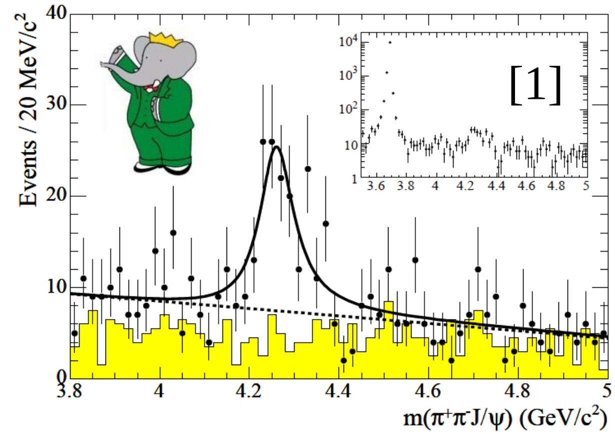
Compatible with the interpretation of *X(3872)* as an admixture of D^0D^{*0} molecule and $\chi_{c1}(2P)$ charmonium state.

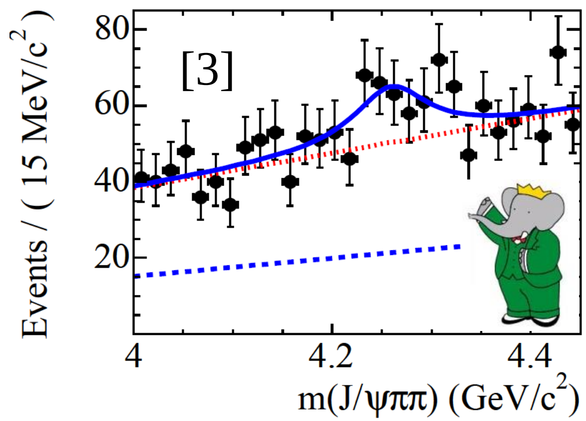
[5] PRD 93 052016 (2016)

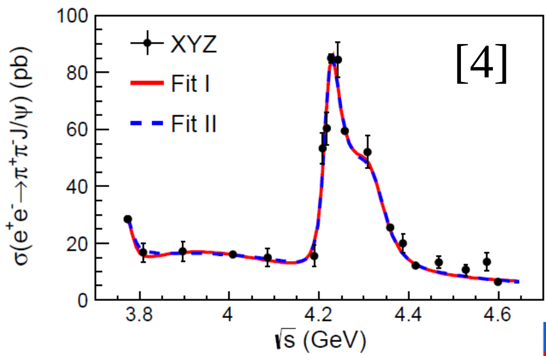
$B \to Y(4260)K$ I

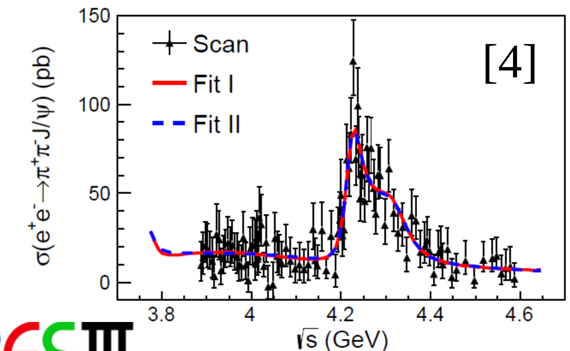
Motivation

- *Y(4260)* first seen by BaBar in $e^+e^- \to Y(4260)\gamma_{ISR} \to J/\psi\pi^+\pi^-\gamma_{ISR}$ [1].
- If *Y(4260)* is an admixture of charmonium and tetraquark state, from QCD sum rules $\mathscr{B}(B^+ \to Y(4260)K^+) \times \mathscr{B}(Y(4260) \to J/\psi\pi^+\pi^-)$ is in range $(3.0\times10^{-8} : 1.8\times10^{-6})$ [2].
- BaBar observed 128 ± 42 signal events ($3.1\ \sigma$) using 211 fb^{-1} and set a 95 % C.L. UL on $\mathscr{B}(B^+ \to Y(4260)K^+) \times \mathscr{B}(Y(4260) \to J/\psi\pi^+\pi^-) < 2.9\times10^{-5}$ [3].
- Two resonant structures observed by BESIII in $e^+e^- \to J/\psi\pi^+\pi^-$ are interpreted as *Y(4260)* and *Y(4360)* [4].
- Need to search for *Y(4260)* in B decays!









R. Garg, V. Bhardwaj, J.B. Singh et al. PRD 99 071102 (2019)

[1] PRL 95 142001 (2005)
[2] PLB 747 83 (2015)
[3] PRD 73 011101 (2006)
[4] PRL 118 092001 (2017)

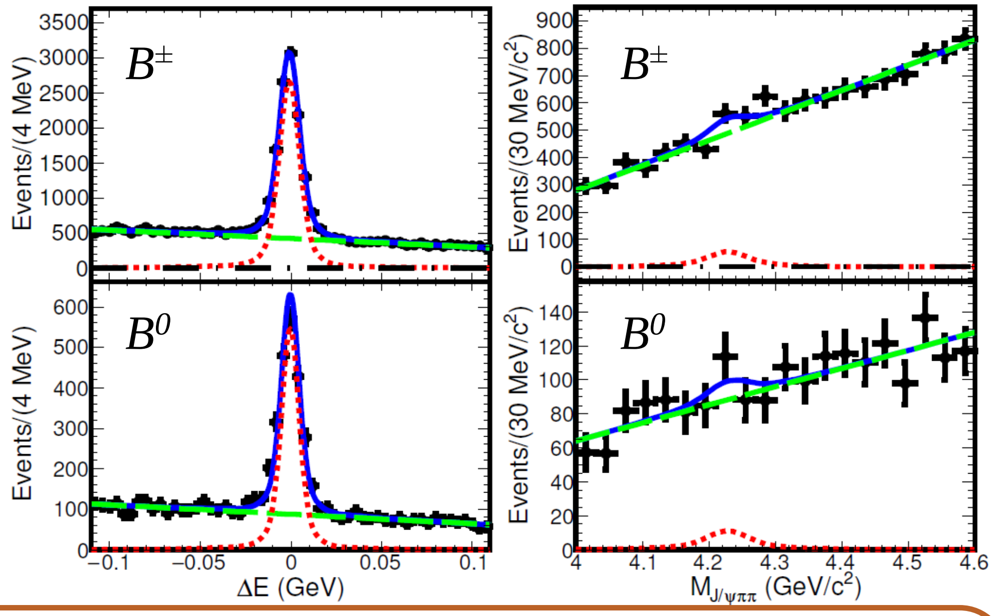
$B \rightarrow Y(4260)K$ II

Analysis features

- $B^{\pm}$ and B^0 are considered, $Y(4260) \rightarrow J/\psi\pi^+\pi^-$, $J/\psi \rightarrow l^+l^-$ ($l=e,\mu$);
- $B \rightarrow \psi(2S)K$ and $B \rightarrow X(3872)K$ are used as control samples;
- UML fit of ΔE, signal yield from weighted $M(J/\psi\pi^+\pi^-)$ by ${}_s\mathcal{P}lot$.

Consistent with BaBar but more stringent.

Given for the first time.



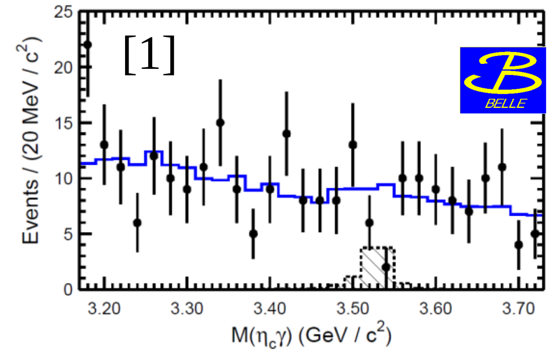
Upper limits

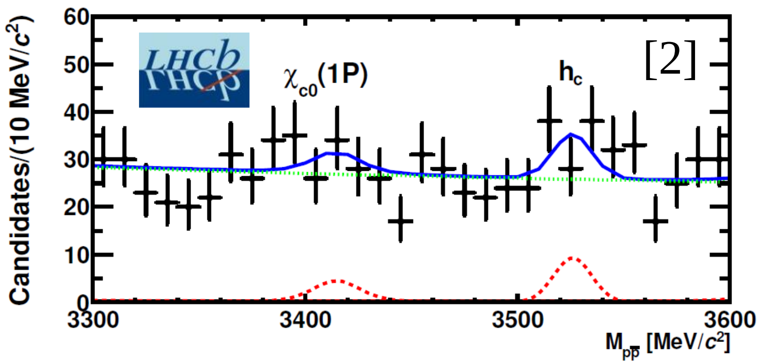
Decay	ϵ (%)	N_S	Σ (σ)	U.L.
$B^+ \rightarrow Y(4260)K^+$, $Y(4260) \rightarrow J/\psi\pi^+\pi^-$	19.8	$179 \pm 53^{+55}_{-41}$	2.1	1.4×10^{-5}
$B^0 \rightarrow Y(4260)K^0$, $Y(4260) \rightarrow J/\psi\pi^+\pi^-$	10.6	$39 \pm 28^{+7}_{-31}$	0.9	1.7×10^{-5}

$B\to h_c K$ I

Motivation

- Both $B^+\to h_c K^+$ and $B^+\to\chi_{c0}K^+$ are suppressed by factorization.
- Since $\mathscr{B}(B^+\to\chi_{c0}K^+) = (1.49\,^{+0.15}_{-0.14})\times10^{-4}$ (world average), $\mathscr{B}(B^+\to h_c K^+)$ should be of the same order. However has not been observed so far!
- Best upper limits:
  - Belle with $h_c\to\eta_c\gamma$, $\eta_c\to K_S K^\pm\pi^\pm$ and pp using 253 fb^{-1}
    $\mathscr{B}(B^+\to h_c K^+) < 3.8\times10^{-5}$ [1];
  - LHCb with $h_c\to pp$
    $\mathscr{B}(B^+\to h_c K^+)\times\mathscr{B}(h_c\to pp) < 6.4\times10^{-4}$ [2].
- Theoretical predictions:
  - 2.7×10^{-5} from QCD factorization [3];
  - 3.6×10^{-5} from pQCD [4];
  - $(3.1\times10^{-5} : 5.7\times10^{-5})$ from QCD factorization including the charmonium bound-state scales [5];
- Needs to be updated!





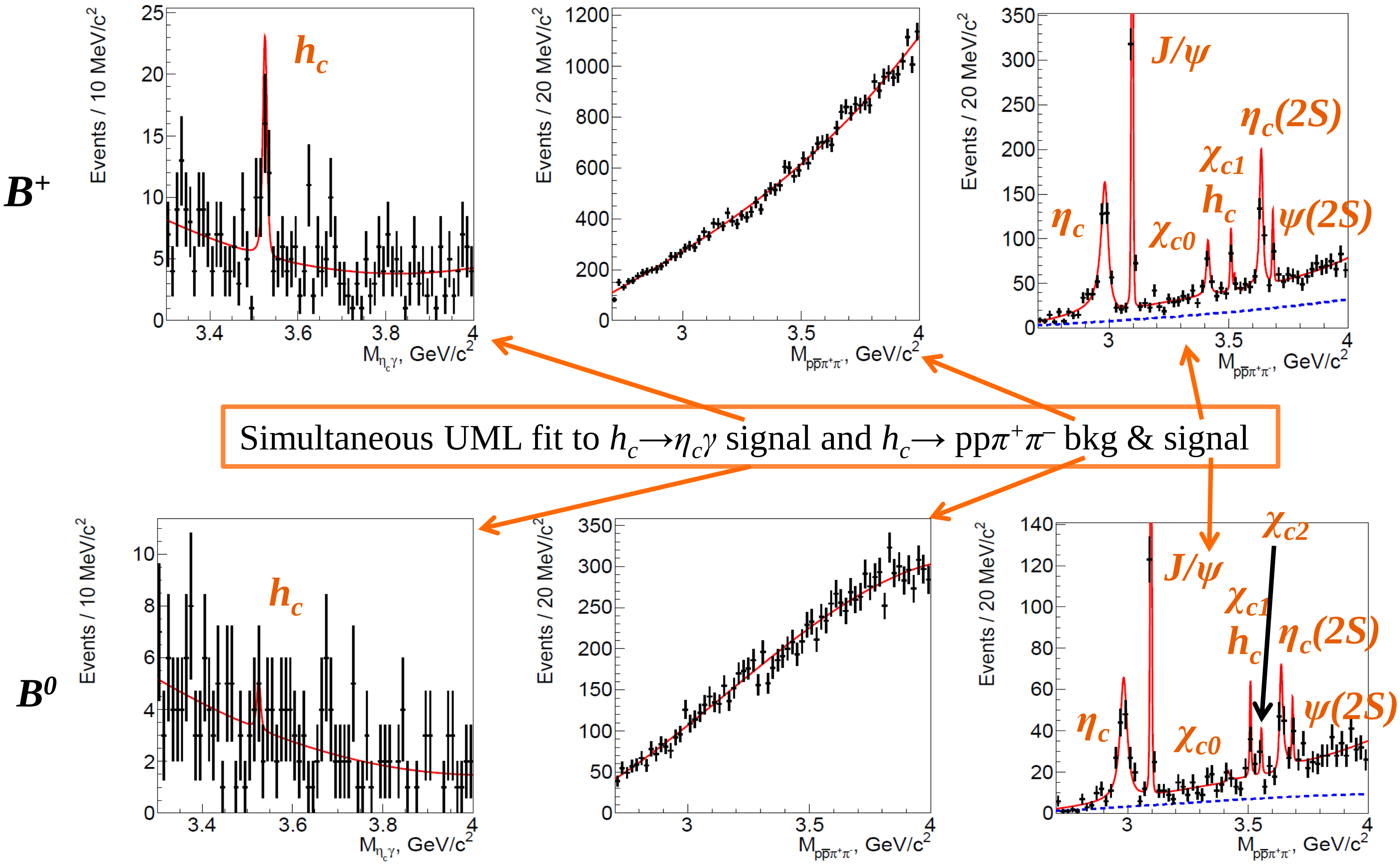
Analysis features

- $B^\pm$ and B^0 are considered, $h_c\to\eta_c\gamma$ and $pp\pi^+\pi^-$ (recently observed by BESIII [6]);
- η_c candidates are reconstructed in 10 decay channels ($K^+K_S^0\pi^-$, $K^+K^-\pi^0$, $K_S^0K_S^0\pi^0$, $K^+K^-\eta$, $K^+K^-K^+K^-$, $\eta'(\to\eta\pi^+\pi^-)\,\pi^+\pi^-$, pp, $pp\pi^0$, $pp\pi^+\pi^-$, and $\Lambda\Lambda$);
- MVA is used for each channel to separate signal from bkg;

K. Chilikin et al. arXiv: 1903.06414 (submitted to PRD)

[1] PRD 74 012007 (2006)
[2] EPJ C73 2462 (2013)
[3] hep-ph/06072201
[4] PRD 74 114029 (2006)
[5] NPB 811 155 (2009)
[6] arXiv:1810.12023

$B \to h_c K$ II

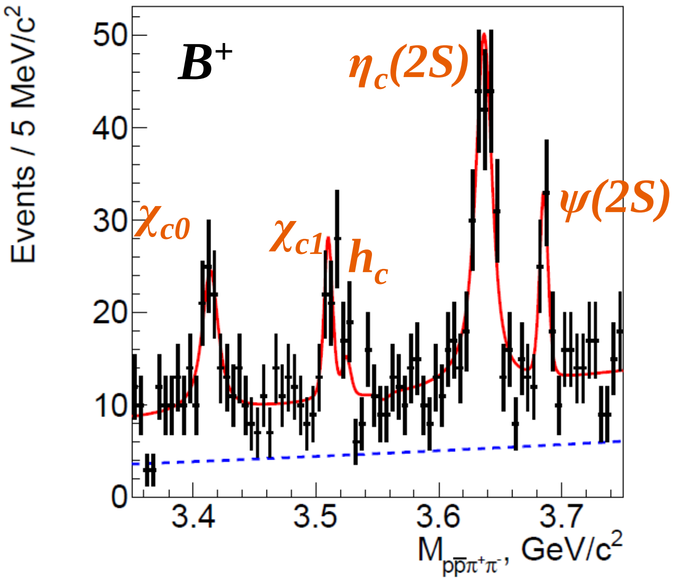


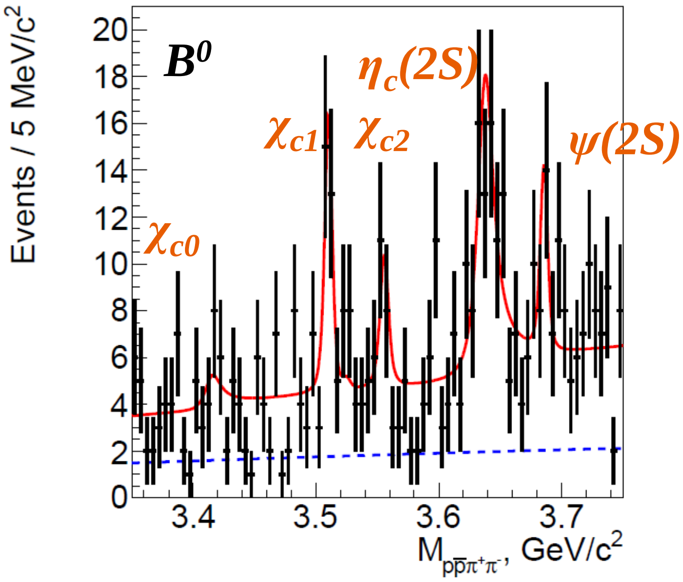
Signal yields

- $B^+ \to h_c K^+$: 32.6 ± 8.0 (4.8 σ taking into account systematics) → **evidence!**
- $B^0 \to h_c K_S^0$: 3.1 ± 3.7 (0.7 σ taking into account systematics)

$B \to h_c K$ III

A closer look at $h_c \to pp\pi^+\pi^-$ signal in χ_{cJ} region…





State	$B^+ \to (c\bar{c})K^+$	$B^0 \to (c\bar{c})K^0_S$
η_c	20.1σ	12.5σ
J/ψ	33.9σ	20.8σ
χ_{c0}	6.0σ	0.6σ
χ_{c1}	4.9σ	4.5σ
χ_{c2}	0.3σ	2.5σ
$\eta_c(2S)$	12.3σ	5.9σ
$\psi(2S)$	5.0σ	2.8σ

Observation of the new $\eta_c(2S)$ decay channel:
$\boldsymbol{\eta_c(2S) \to pp\pi^+\pi^-}$!

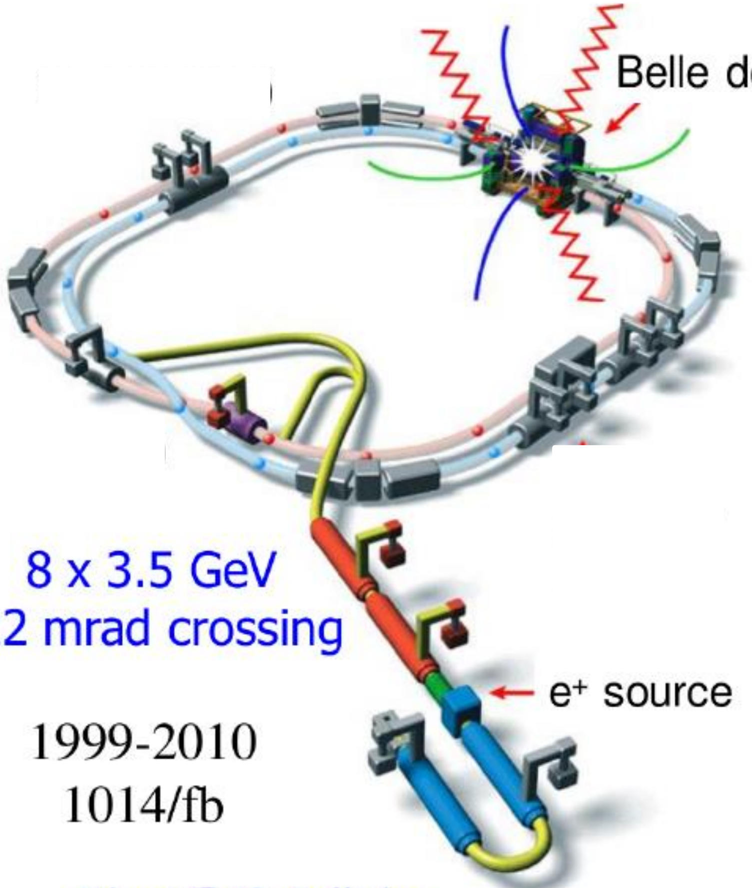
Other charmonium signals are consistent with PDG.

Summary

- ***$B^0 \to X(3872)\gamma$***
  - Upper limit is set on $\mathscr{B}(B^0 \to X(3872)\gamma) \times \mathscr{B}(X(3872) \to J/\psi\pi^+\pi^-)$.
- ***$B^+ \to X(3872,3915)K^+$***
  - Upper limits are set on the product branching fractions $\mathscr{B}(B^+ \to X(3872)K^+) \times \mathscr{B}(X(3872) \to \chi_{c1}\pi^0)$ and $\mathscr{B}(B^+ \to X(3915)K^+) \times \mathscr{B}(X(3915) \to \chi_{c1}\pi^0)$. Compatible with the interpretation of $X(3872)$ as an admixture of D^0D^{*0} molecule and $\chi_{c1}(2P)$ charmonium state.
  - Branching ratio $\mathscr{B}(X(3872) \to \chi_{c1}\pi^0) / \mathscr{B}(X(3872) \to J/\psi\pi^+\pi^-) < 0.97$ (90% C.L.). No contradiction with BESIII result.
- ***$B \to Y(4260)K$***
  - Upper limit on $\mathscr{B}(B^+ \to Y(4260)K^+) \times \mathscr{B}(Y(4260) \to J/\psi\pi^+\pi^-)$ is consistent with BaBar but more stringent.
  - Upper limit on $\mathscr{B}(B^0 \to Y(4260)K^0) \times \mathscr{B}(Y(4260) \to J/\psi\pi^+\pi^-)$ is given for the first time.
- ***$B \to h_cK$***
  - Evidence of the decay $B^+ \to h_cK^+$ is found, and $\mathscr{B}(B^+ \to h_cK^+) = (3.7\,^{+1.0}_{-0.9} \pm 0.8) \times 10^{-5}$ is consistent with the existing limit and theoretical predictions.
  - Upper limit is set on $\mathscr{B}(B^0 \to h_cK_S^0)$.
  - First observation of $\eta_c(2S) \to pp\pi^+\pi^-$ decay with 12.1σ significance.

Backup

Belle experiment



8 x 3.5 GeV
22 mrad crossing

1999-2010
1014/fb

The KEKB Collider

World record:

$L = 2.1 \times 10^{34}/cm^2/sec$

The new generation SuperKEKB has been launched, and Belle II recorded the first collisions on April 26, 2018, JST!

$B^0 \rightarrow X(3872)\gamma$

Source	Dimuon	Dielectron
$N_{B\bar{B}}$	1.4%	1.4%
Tracking (4 tracks)	1.4%	1.4%
$\mathcal{B}(J/\psi \to \ell^+\ell^-)$	0.6%	0.5%
γ detection	3.1%	3.1%
MC gen. model	1.1%	1.9%
$\pi^\pm$ identification	1.3%	1.3%
$\ell^\pm$ identification	2.1%	1.8%
Bkg. suppression	2.3%	2.5%
π^0 veto	0.8%	0.8%
Signal box eff.	3.5%	3.5%
Total	6.2%	6.4%

$B^+ \to X(3872,3915)K^+$

Source	$\mathcal{B}$ (%) $X(3915)$	$\mathcal{B}$ (%) $X(3872)$	$R^{X}_{\chi_{c1}/\psi}$ (%)
Lepton identification	2.3	2.2	-
Kaon identification	1.0	1.0	-
Efficiency	0.5	0.5	2.2
$B\bar{B}$ pairs	1.4	1.4	-
Tracking	1.1	1.1	0.7
γ identification	2.0	2.0	2.0
π^0 veto	1.2	1.2	1.2
π^0 reconstruction	2.2	2.2	2.2
Signal extraction	$^{+16.1}_{-19.5}$	$^{+37.0}_{-44.4}$	$^{+37.1}_{-44.5}$
Secondary $\mathcal{B}$	3.0	3.0	2.9
Total	$^{+17.0}_{-20.2}$	$^{+37.4}_{-44.7}$	$^{+37.4}_{-44.8}$

$B \to Y(4260)K$

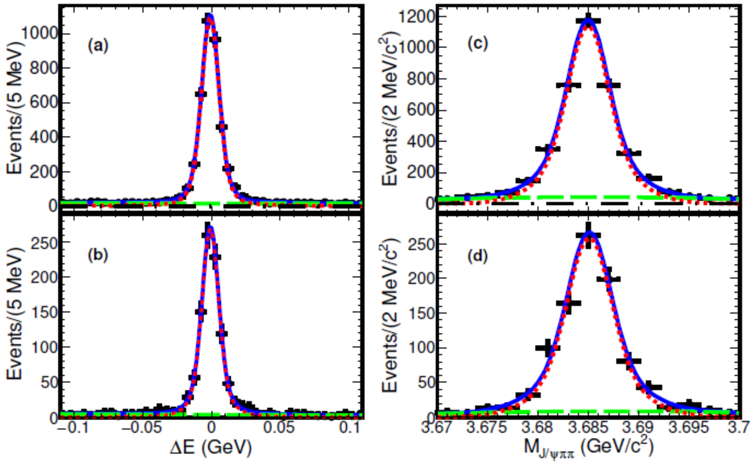


FIG. 1. Fit to the ΔE ((a) and (b)) and ${}_s\mathcal{P}lot$ of $M_{J/\psi\pi\pi}$ ((c) and (d)) distributions for $B^+ \to \psi(2S)(\to J/\psi\pi^+\pi^-)K^+$ decays (top) and $B^0 \to \psi(2S)(\to J/\psi\pi^+\pi^-)K^0_S$ decays (bottom), respectively. The curves show the fit functions for the signal (red dotted curve), background (green dashed curve) and their sum (blue solid line).

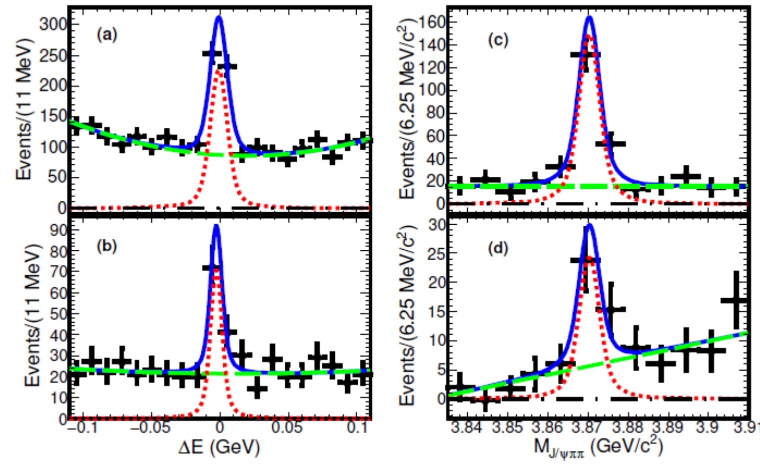


FIG. 2. Fit to the ΔE ((a) and (b)) and ${}_s\mathcal{P}lot$ of $M_{J/\psi\pi\pi}$ ((c) and (d)) distributions for $B^+ \to X(3872)(\to J/\psi\pi^+\pi^-)K^+$ decays (top) and $B^0 \to X(3872)(\to J/\psi\pi^+\pi^-)K^0_S$ decays (bottom), respectively. Fit follow the same convention as Fig. 1.

Decay	ϵ (%)	N_S	$\mathcal{B}$	$\mathcal{B}_{\mathrm{PDG}}$
$B^+ \to \psi(2S)K^+$	16.8	3481 ± 95	$(6.54 \pm 0.18) \times 10^{-4}$	$(6.21 \pm 0.23) \times 10^{-4}$
$B^0 \to \psi(2S)K^0$	10.3	856 ± 74	$(5.25 \pm 0.45) \times 10^{-4}$	$(5.8 \pm 0.5) \times 10^{-4}$
$B^+ \to X(3872)K^+,\ X(3872) \to J/\psi\pi^+\pi^-$	22.2	185 ± 13	$(9.07 \pm 0.64) \times 10^{-6}$	$(8.6 \pm 0.8) \times 10^{-6}$
$B^0 \to X(3872)K^0,\ X(3872) \to J/\psi\pi^+\pi^-$	13.1	29.9 ± 6.2	$(4.97 \pm 1.03) \times 10^{-6}$	$(4.3 \pm 1.3) \times 10^{-6}$

Source → Decay ↓	Tracking	Particle identification				PDF modeling	$Y(4260)$ parameters	Fit bias	$N_{B\bar{B}}$	$\mathcal{B}(J/\psi \to \ell^+\ell^-)$	Total
		K^0_S	Kaon	Pion	Lepton						
$B^+ \to Y(4260)K^+$	1.8	-	0.9	1.3	1.2	$^{+8.0}_{-11.1}$	$^{+29.0}_{-19.5}$	4.3	1.4	0.4	$^{+30.5}_{-23.0}$
$B^0 \to Y(4260)K^0_S$	2.1	0.7	-	1.3	1.2	$^{+7.7}_{-77.0}$	$^{+14.0}_{-17.3}$	6.5	1.4	0.4	$^{+17.5}_{-79.2}$
Simultaneous	1.9	0.2	0.7	1.3	1.2	$^{+5.3}_{-15.3}$	$^{+25.0}_{-18.0}$	4.8	1.4	0.4	$^{+26.2}_{-24.3}$

$B \to h_c K$

Resolution

New: $B \to h_c K$

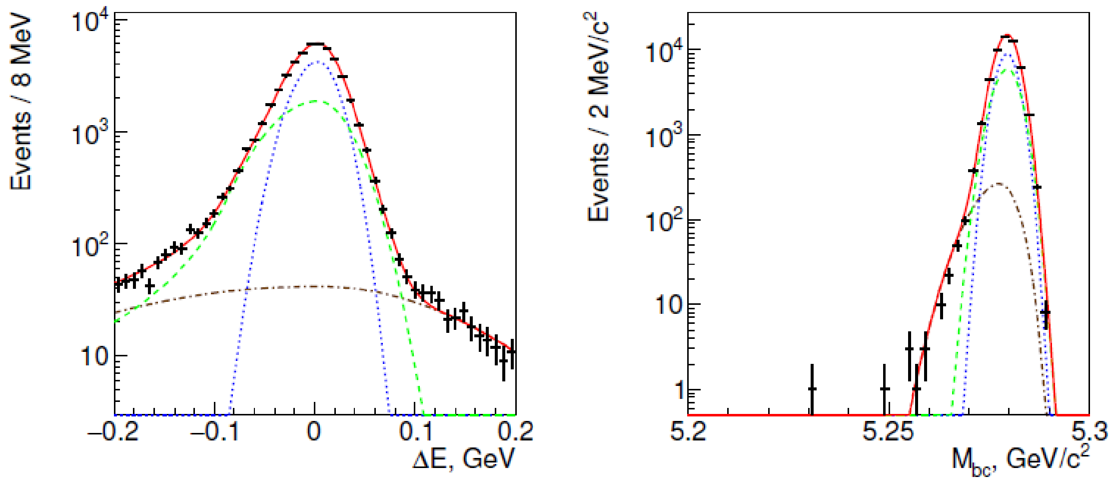
The resolution is parameterized by the function

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

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

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

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 $\eta_c \to K^+ K^- \pi^0$:



$B \to h_c K$

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

New: $B \to h_c K$

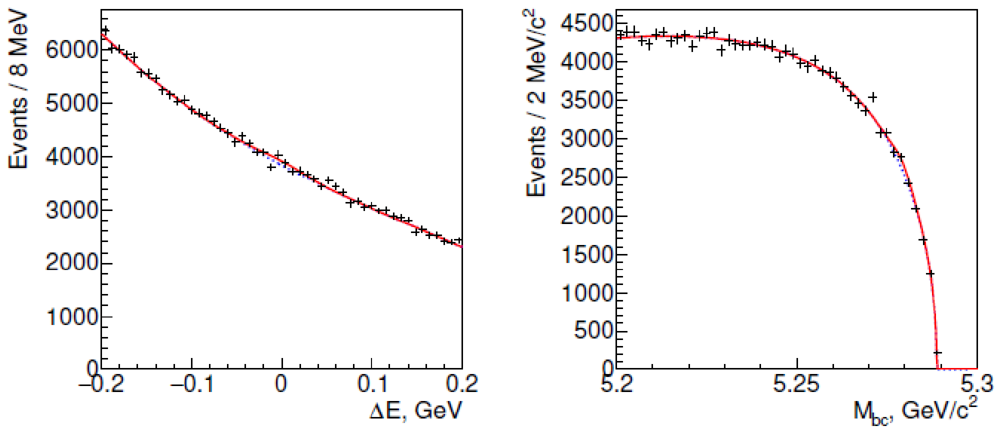
The $(\Delta E, M_{bc})$ distribution is fitted in order to estimate the expected number of the background events in the signal region. The distribution is fitted to the function

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

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

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

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 $M_{bc} > 5.272$ GeV$/c^2$ for the projection onto ΔE and $|\Delta E| < 20$ MeV for the projection onto M_{bc}):



$B \to h_c K$

Multivariate analysis

New: $B \to h_c K$

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.
- $\eta_c \to K^+ K_S^0 \pi^-$, $\eta_c \to K^+ K^- \pi^0$ and $\eta_c \to K_S^0 K_S^0 \pi^0$: 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.

$B \to h_c K$

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%
$\eta_c(\to K^0_SK^0_S\pi^0)\gamma$	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.

$B \to h_c K$

Data fitting procedure

New: $B \to h_c K$

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

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

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

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

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.

$B \to h_c K$

Model	h_c significance		$\eta_c(2S) \to p\bar{p}\pi^+\pi^-$ significance	
	$B^+ \to h_c K^+$	$B^0 \to h_c K^0_S$	$B^+ \to h_c K^+$	$B^0 \to h_c K^0_S$
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

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
$\mathcal{B}(B^0 \to \psi(2S) K^0_S) \times \mathcal{B}(\psi(2S) \to p\bar{p}\pi^+\pi^-)$	$[0.6, 3.9] \times 10^{-7}$	$(1.7 \pm 0.2) \times 10^{-7}$