First evidence of $B \to h_c K$ and Recent Results on X and Y from Belle

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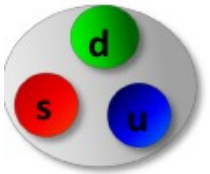
On the behalf of Belle collaboration
HADRON 2019

Introduction

Quark model: M. Gell-Mann, Phys.Lett. 8, 214 (1964)

Classification scheme for hadrons in terms of valance quarks.

Hadrons are composed of mesons ($q\bar{q}$, $qq\bar{q}\bar{q}$, ...) and baryons (qqq, $qqqq\bar{q}$, ...).



Baryons (qqq)

Mesons ($q\bar{q}$)

- Charmonium consists of two heavy c quarks and allows to study strong interactions.
- Charmonium-like states are not predicted by potential models.

X(3872), Y(4260), $Z_c(3900)$, $Z^+(4430)$, X(3915)... were found in last decade. Still their properties are not well understood.

Pentaquark:

S=+1 Baryon

Glueball

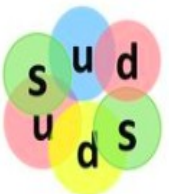
Color-singlet multi-gluon bound state

Tetraquark mesons

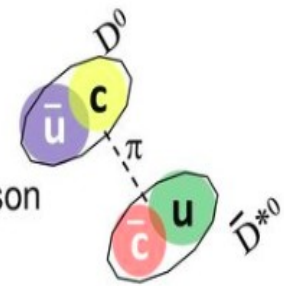
tightly bound diquark-diantiquark

H-diBaryon

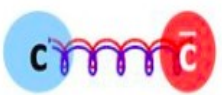
tightly bound 6-quark state



loosely bound meson-antimeson "molecule"

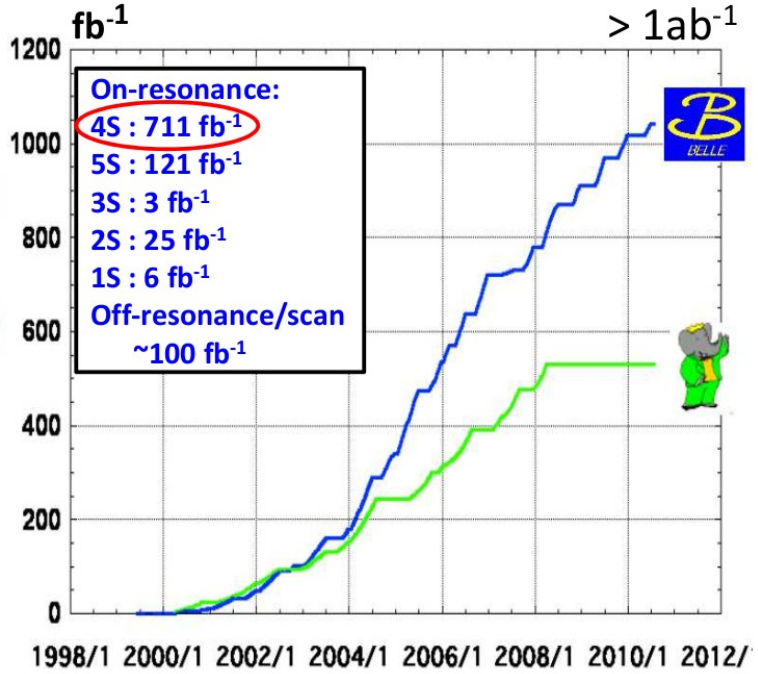


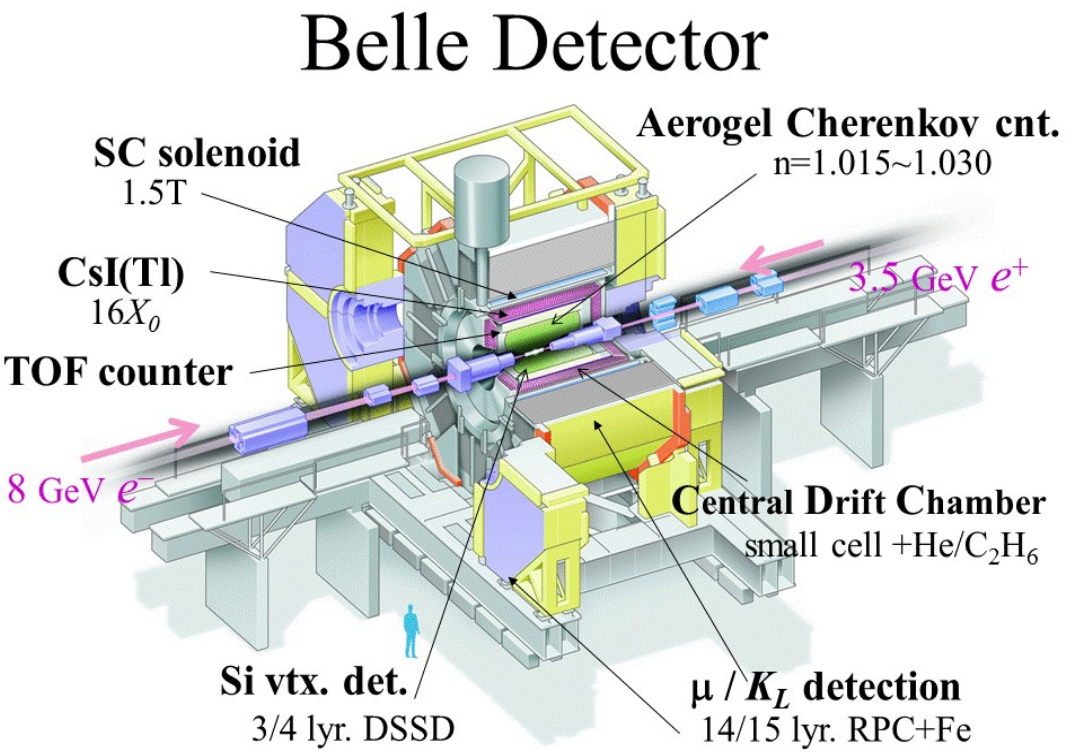
$q\bar{q}$-gluon hybrid mesons



Not observed in conventional matter. However, they should be allowed.

$c\bar{c}$ like states at Belle experiment



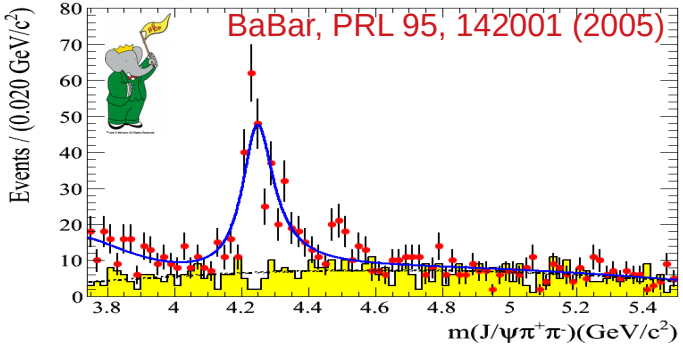


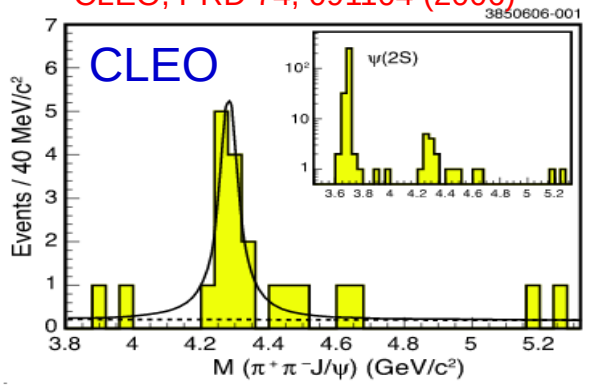
Contribution to charmonium like states:
X(3823), X(3872), $Z(3895)^+$, X(3915), Z(3930), X(3940), Y(4260),
X(4350), X(4630), Y(4660), $Z(4430)^+$, $Z_1(4050)^+$, $Z_2(4250)^+$...

The second generation of B-factories has been launched, and Belle II recorded the first collision on April, 2018

B→Y(4260)K

Y(4260) was firstly discovered in ISR by BaBar in 2005.





Confirmed by Belle and CLEO.

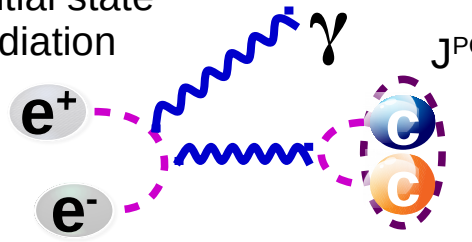
	BaBar	CLEO	Belle
Mass (MeV/c^2)	4244±5	4284^{+17}_{-16}	4295±10
Width (MeV)	114^{+16}_{-15}	73^{+39}_{-25}	133±26

- BESIII suggest that there are two peaks at Y(4260) [Y(4260) and Y(4360)].
- Measured by BESIII:
  - Mass: (4222.0±3.1) MeV/c^2 , Width: (44.1±4.3) MeV

Theory predicts Y(4260) to be charmonium-hybrid, tetraquark and admixture state. S. L. Zhu PLB 625 (2005)

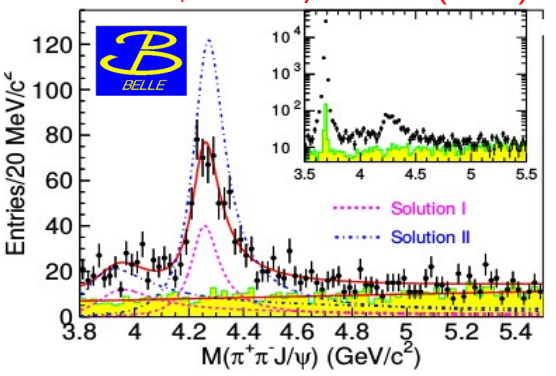
Belle, PRD 99, 071102(R) (2019)

Initial state radiation

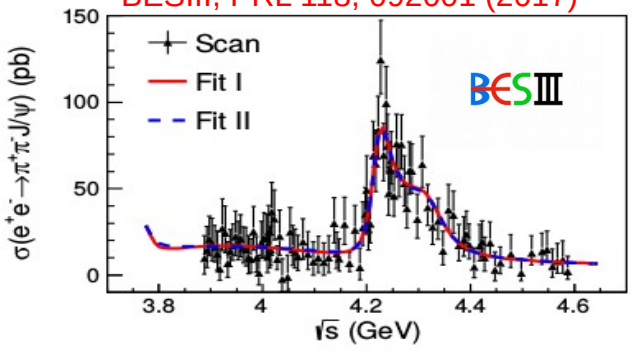


J^{PC}: 1^{--}

Belle, PRL 99, 182004 (2007)



BESIII, PRL 118, 092001 (2017)



B→Y(4260)K

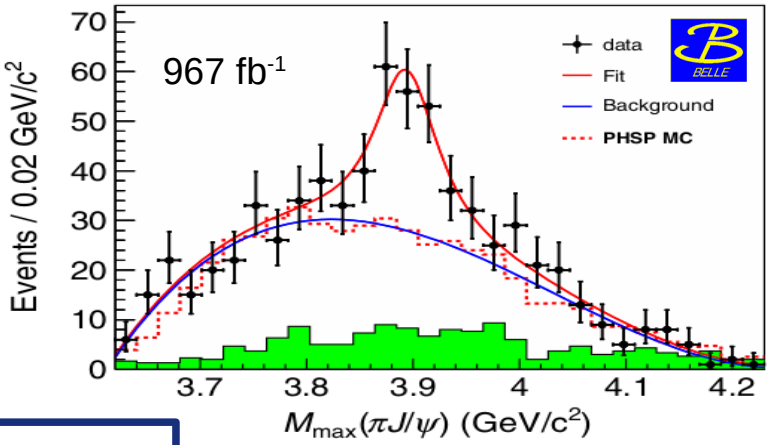
Measured by Belle: Belle, PRL 110, 252002 (2013)

$$\frac{B(Y(4260)\to Z_c(3900)^{\pm}\pi^{\mp})}{B(Y(4260)\to J/\psi\pi\pi)}=(29.0\pm8.9)\%$$

Measured by BESIII: BESIII, PRL 110, 252001 (2013)

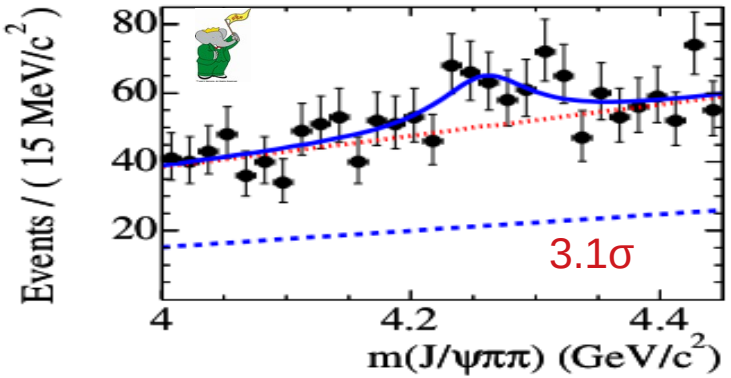
$$\frac{B(Y(4260)\to Z_c(3900)^{\pm}\pi^{\mp})}{B(Y(4260)\to J/\psi\pi\pi)}=(21.5\pm3.3)\%$$

Invariant mass of $Z_c(3900)^{\pm}$



- Theoretical prediction (B→Y(4260) K): R.M. Albuquerque et al. PLB 747 83 (2015)
  - $3.0 \times 10^{-8} < \mathcal{B}(B^- \to K^- Y(4260), Y(4260)\to J/\psi\pi\pi) < 1.8 \times 10^{-6}$
- Suggest Y(4260) is not pure charmonium state. It is an admixture state(?)

BaBar, PRD 73, 011101 (R) (2006)



Measured by BaBar:
$\mathcal{B}(B^- \to K^- Y(4260), Y(4260)\to J/\psi\pi\pi) < 2.9 \times 10^{-5}$

Updated results using Belle data.

B→Y(4260)K

Selection criteria:

- Y(4260) reconstructed in $J/\psi\pi\pi$ mode
- |dz|< 3.5cm& |dr| < 1.0 cm
- J/ψ reconstruction: 3.07 (3.05)<$M_{\mu\mu}$ ($M_{ee\gamma}$)< 3.13 GeV/c^2

  γs added within 0.5 mrad to $J/\psi\to e^+e^-$ mode Mass-constrained fit to J/ψ candidates to improve resolution.

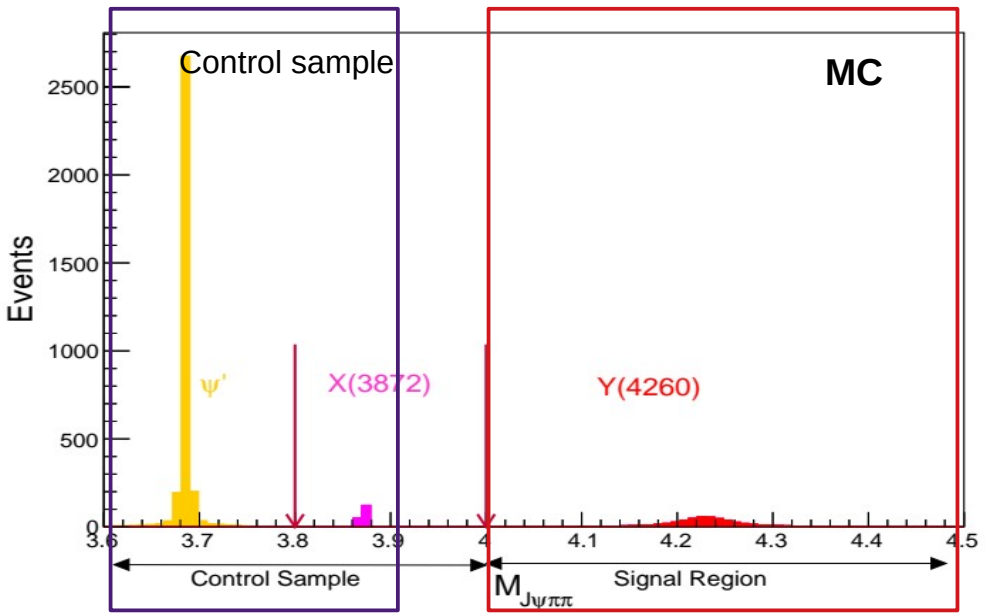
To identify signal:

$$\Delta E = E^*_B - E^*_{beam}$$

$$M_{bc} = \sqrt{(E^{*2}_{beam} - p^{*2}_B)}$$

- $B\to\psi'$ K and $B\to X(3872)$ K are good control sample.
- Have same final state: $J/\psi\pi\pi$.

Signal is extracted from fit to the ${}_s\mathcal{P}$lot distribution of $M_{J/\psi\pi\pi}$.



Control sample results:

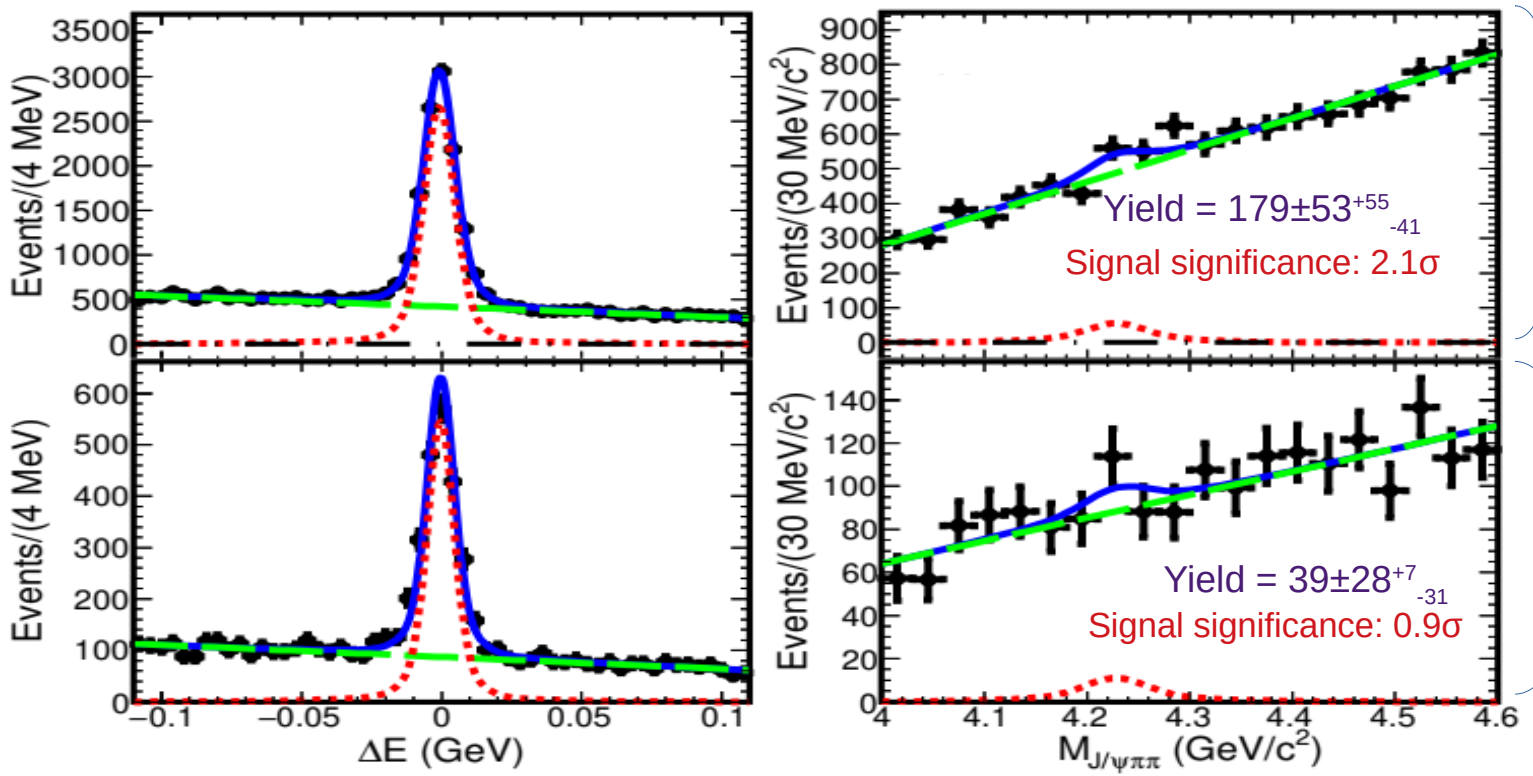
$\mathcal{B}(B^+\to\psi(2S)\,K^+) = [6.54\pm0.18(stat.)] \times 10^{-4}$
$\mathcal{B}(B^0\to\psi(2S)\,K^0) = [5.25\pm0.45(stat.)] \times 10^{-4}$

$\mathcal{B}(B^+\to X(3872)\,K^+, X(3872)\to J/\psi\pi\pi) = [9.07\pm0.64\,(stat.)] \times 10^{-6}$

$\mathcal{B}(B^0\to X(3872)\,K^0, X(3872)\to J/\psi\pi\pi) = [4.97\pm1.03\,(stat.)] \times 10^{-6}$

Agreement with Belle previous measurement.

B→Y(4260)K



Consistent with BaBar limit but more precise

Given for the first time

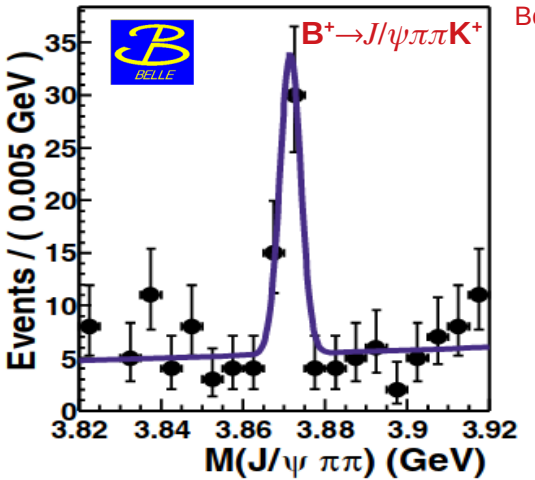
No significant signal with current dataset

$\mathcal{B}(B^+ \to Y(4260)\, K^+, Y(4260) \to J/\psi\pi\pi) < 1.4 \times 10^{-5}$ (90% C.L.)
$\mathcal{B}(B^0 \to Y(4260)\, K^0, Y(4260) \to J/\psi\pi\pi) < 1.7 \times 10^{-5}$ (90% C.L.)

$B \to X(3872,3915)(\to \chi_{c1}\pi^0)K$

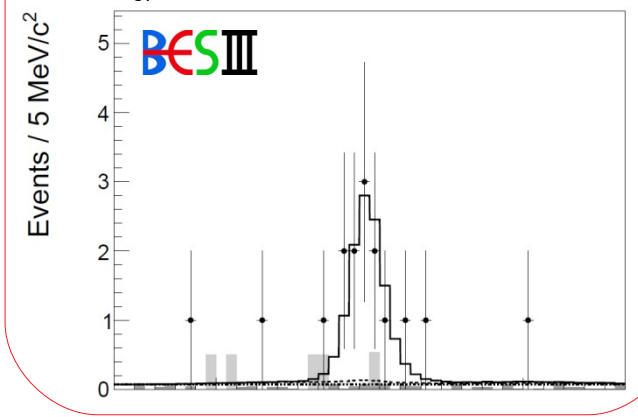
Belle, PRD 99, 111101(R) (2019)

X(3872) was first observed by the Belle Collaboration in 2003.



Belle, PRL 91, 262001 (2003)

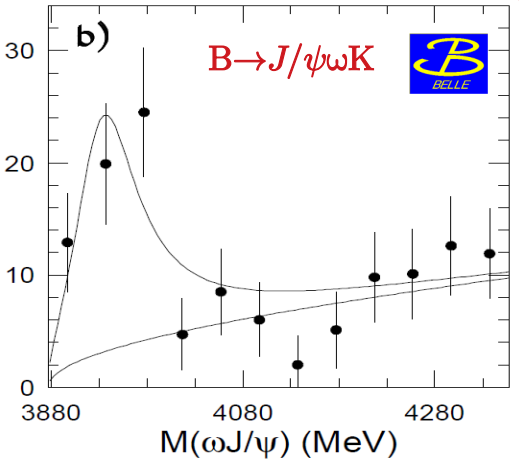
Recently, new decay of X(3872) was observed by BESIII in $e^+e^- \to X(3872)(\to \chi_{c1}\pi^0)\gamma$. BESIII, PRL 122, 202001 (2019)



- $J^{PC} = 1^{++} \Rightarrow$ may be $\chi_{c1}(2P)$, single pionic transistion is suppressed due to isospin breaking.
- $\mathcal{B}(X(3872)\to\chi_{c1}\pi^0)/\mathcal{B}(X(3872)\to J/\psi\pi^+\pi^-)=0.88^{+0.33}_{-0.27}\pm0.10$ is larger than $\mathcal{B}(\psi(2S)\to J/\psi\pi^0)/\mathcal{B}(\psi(2S)\to J/\psi\pi^+\pi^-) = 3.66 \times 10^{-3}$
- Disfavors the $\chi_{c1}(2P)$ interpretation of $X(3872)$.

$X(3915)$ was first observed by Belle collaboration in 2005.

Belle, PRL 94, 182002 (2005)



- $J^{PC} = 0^{++} \Rightarrow$ 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.

Worth checking this ratio using Belle data!

$B \to X(3872,3915)(\to \chi_{c1}\pi^0)K$

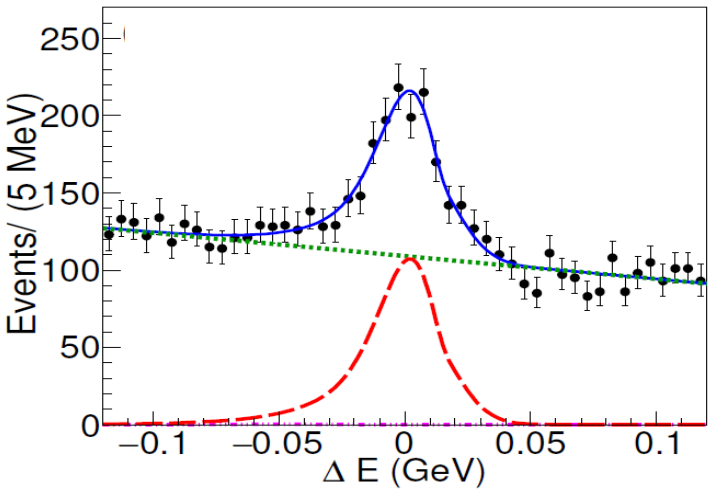
Selection:

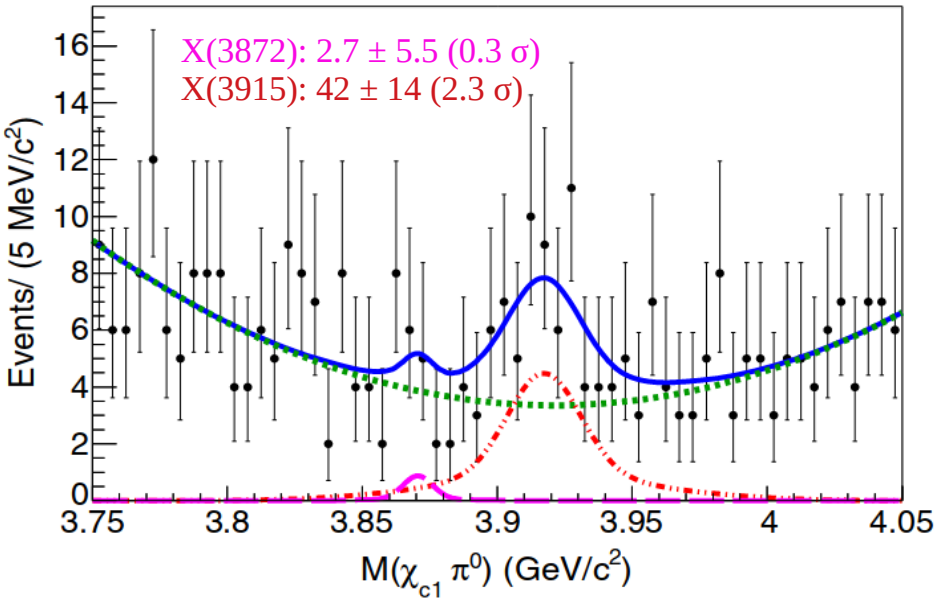
- χ_{c1} reconstructed in $J/\psi\gamma$ mode
- Photon selection: $E_\gamma > 100$ MeV, π^0 veto to reject γ from π^0

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

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

Belle, PRD 93, 052016 (2016)





$\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to \chi_{c1}\pi^0) < 8.1 \times 10^{-6}$ (90% C.L.)
$\mathcal{B}(B^+ \to X(3915)K^+) \times \mathcal{B}(X(3915) \to \chi_{c1}\pi^0) < 3.8 \times 10^{-5}$ (90% C.L.)
$\mathcal{B}(X(3872) \to \chi_{c1}\pi^0) / \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) < 0.97$ (90% C.L.)

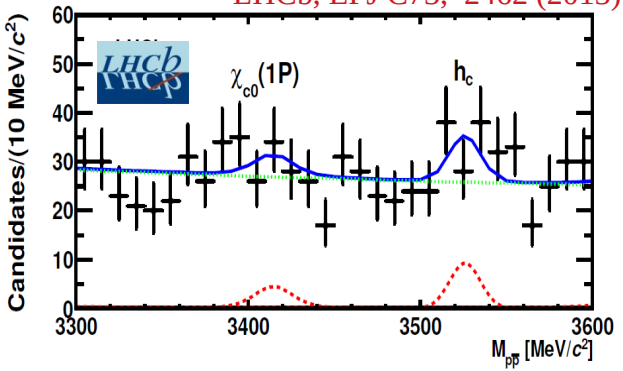
Results are consistent with BESIII result.

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

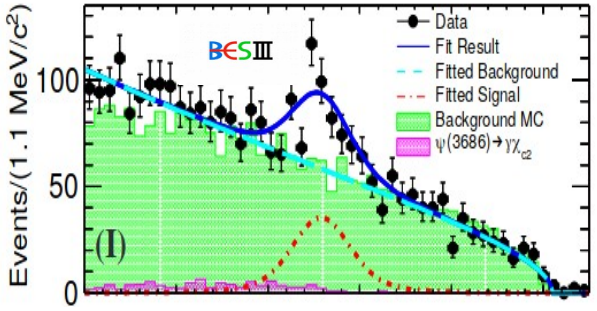
B→h_c K

- Charmonium state, mass=(3525±0.11) MeV and width=(0.7±0.4) MeV.
- $B^+ \to \chi_{c0} K^+$, $B^+ \to \chi_{c2} K^+$ and $B^+ \to h_c K^+$ are suppressed by factorization.
- $\mathcal{B}(B \to h_c K^+)$ is expected to be of same order as of $\mathcal{B}(B^+ \to \chi_{c0} K^+)$. However, not observed so far!

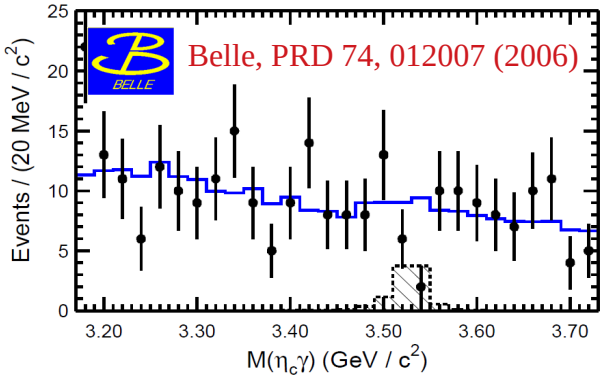
LHCb, EPJ C73, 2462 (2013)



LHCb also provided the upper limit $\mathcal{B}(B \to h_c K^+) \times \mathcal{B}(h_c \to p\bar{p}) < 6.4 \times 10^{-8}$ @ 95% C.L.



Belle, PRD 100, 012001 (2019)



Belle set the upper limit on $\mathcal{B}(B \to h_c K^+) < 3.8 \times 10^{-5}$ using 253 fb^{-1} [$h_c \to \eta_c(\eta_c \to K_S^0 K^\pm\pi^\mp, p\bar{p})\gamma$].

- Theoretical predictions:
  - 2.7×10^{-5} from QCD factorization C. Meng, et al. hep-ph/06072201
  - 3.6×10^{-5} from pQCD X. Q. Li, et al. PRD 74 114029 (2006)
  - (3.1×10^{-5} - 5.7×10^{-5}) from QCD factorization including the charmonium bound-state scales. M. Beneke, et al. NPB 811 155 (2009)
- Theoretical predictions are slightly below the current experimental limits.

New $h_c \to pp\pi^+\pi^-$ is recently observed by BESIII.

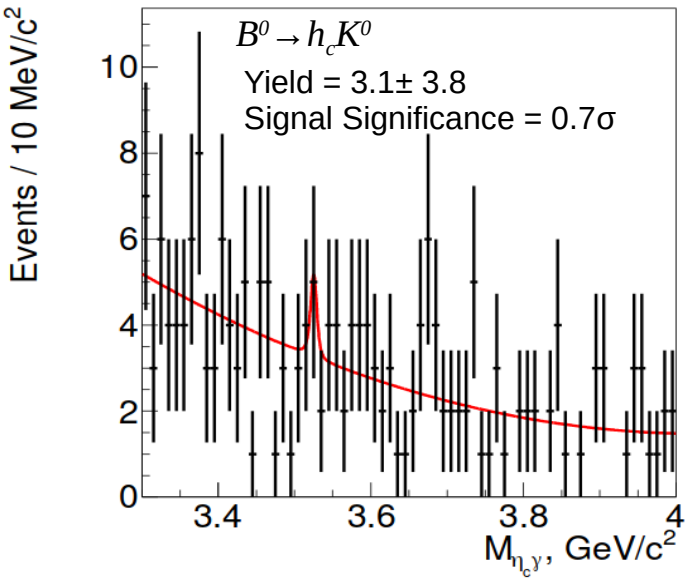
BESIII, PRD 99, 072008 (2019)

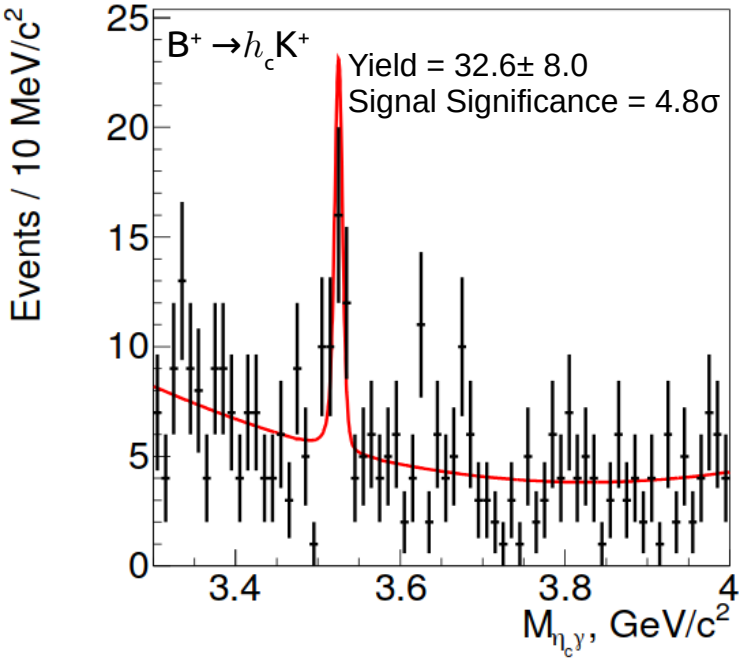
Updated results using Belle full data.

B→h_c K

Analysis feature:

- $h_c \to \eta_c \gamma$ and $pp\pi^+\pi^-$ are used.
- 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 $\Lambda\Lambda$).
- η candidates are reconstructed in $\gamma\gamma$ and $\pi^+\pi^-\pi^0$.
- MVA is used for each channel to separate signal from bkg.
- Simultaneous UML fit to $h_c \to \eta_c\gamma$ signal and $h_c \to pp\pi^+\pi^-$ bkg and signal.





Evidence for $B^+ \to h_c K^+$

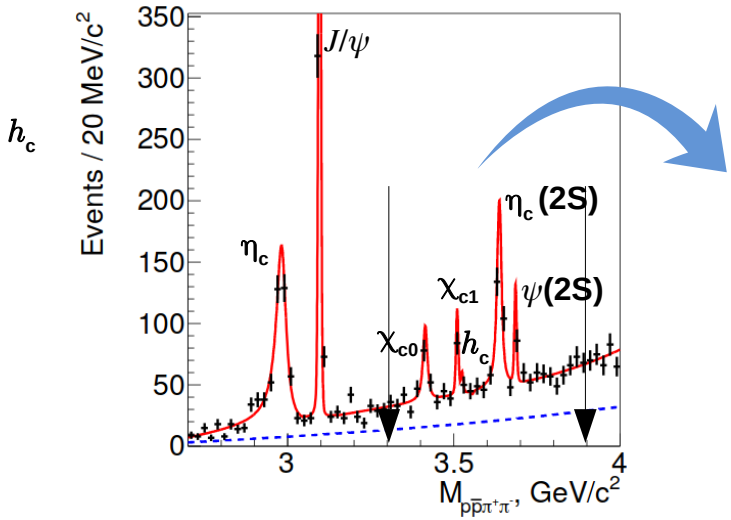
$\mathcal{B}(B^+ \to h_c K^+) = (3.7^{+1.0}_{-0.9} \pm 0.8) \times 10^{-5}$

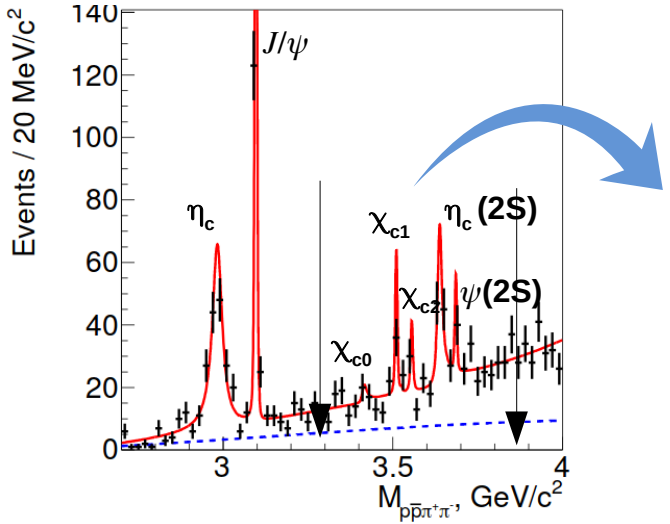
No evidence is observed for $B^0 \to h_c K^0$

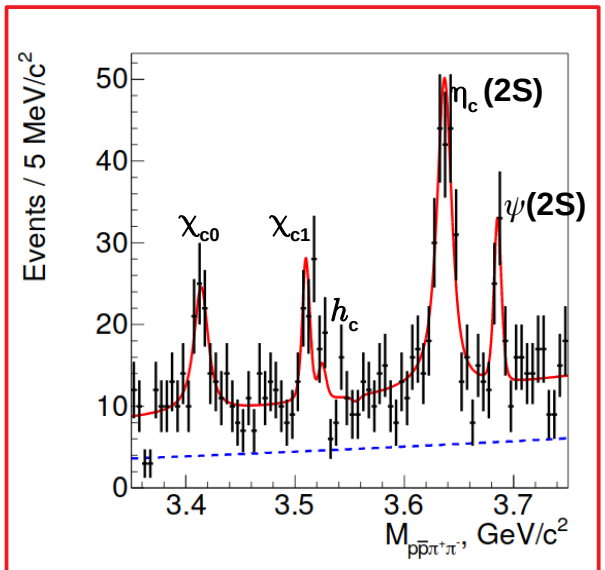
$\mathcal{B}(B^0 \to h_c K^0) < 1.4 \times 10^{-5}$ at 90% C.L.

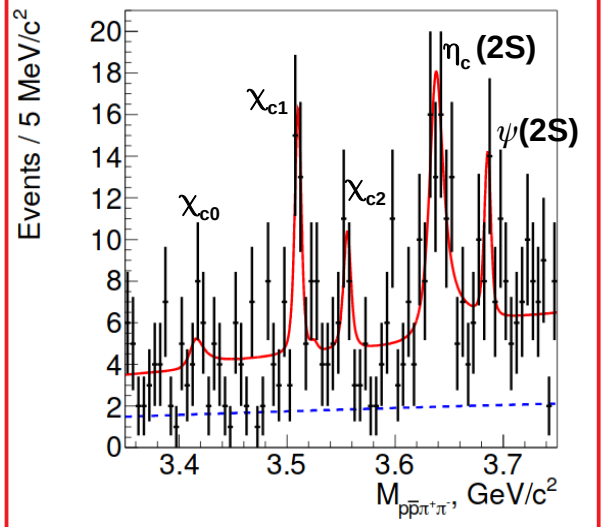
$B \to h_c K$

$h_c \to p\bar{p}\pi^+\pi^-$ 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: $\eta_c(2S) \to p\bar{p}\pi^+\pi^-$!

Other charmonium signals are consistent with PDG.

Summary

$B \to Y(4260)K$: Belle, PRD 99, 071102 (R) (2019)

- Upper limit on $\mathcal{B}(B^+ \to Y(4260)K^+) \times \mathcal{B}(Y(4260) \to J/\psi\pi^+\pi^-) < 1.4 \times 10^{-5}$ is consistent with BaBar but more precise.
- Upper limit on $\mathcal{B}(B^0 \to Y(4260)K^0) \times \mathcal{B}(Y(4260) \to J/\psi\pi^+\pi^-) < 1.7 \times 10^{-5}$ is given for the first time.

$B \to X(3872,3915)K$: Belle, PRD 99, 111101 (R) (2019)

- Upper limits are set on the product branching fractions $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to \chi_{c1}\pi^0) < 8.1 \times 10^{-6}$ and $\mathcal{B}(B^+ \to X(3915)K^+) \times \mathcal{B}(X(3915) \to \chi_{c1}\pi^0) < 3.8 \times 10^{-5}$.
- Compatible with the interpretation of X(3872) as an admixture of D^0D^{*0} molecule and $\chi_{c1}(2P)$ charmonium state.
- Ratio $\mathcal{B}(X(3872) \to \chi_{c1}\pi^0) / \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) < 0.97$ (90% C.L.) consistent with BESIII result.

$B \to h_c K$: Belle, PRD 100, 012001 (2019)

- Evidence of the decay $B^+ \to h_c K^+$ is found, and $\mathcal{B}(B^+ \to h_c K^+) = (3.7^{+1.0}_{-0.9} \pm 0.8) \times 10^{-5}$ is consistent with the existing limit and theoretical predictions.
- Upper limit is set on $\mathcal{B}(B^0 \to h_c K_S^0) < 1.4 \times 10^{-5}$ at 90% C.L.
- First observation of $\eta_c(2S) \to pp\pi^+\pi^-$ decay with 12.1σ significance.

Belle II is active and results can be measured more precisely.

Backup

B→h_c K

A multivariate analysis is performed for each channel using the MLP from TMVA library.

- All channels: thrust angle of B daughters and remaining particles in the events, thrust angle of all tracks and photons, ratio of Fox-wolfram moment F_2/F_0, the B production angle, vertex fit quality.
- $h_c \to \eta_c \gamma$: h_c helicity angle, η_c mass, number of π^0 candidates that include the h_c daughter photon as one of their daughters.
- $\eta_c \to K^+ K_S^0 \pi^-$, $\eta_c \to K^+ K^- \pi^0$, $\eta_c \to K_S^0 K_S^0 \pi^0$: invariant masses of (K, π) combinations.
- Channels with the corresponding particles in the final state: K and p particle identification likelihoods.
- Channels with π^0 and η: the π^0 (η) mass, the minimal energy of the π^0 (η) daughter photons in the lab frame, the number of π^0 candidates that includes π^0 (η) daughter photons as one of their daughters.
- Channels with $\eta \to \pi^+ \pi^- \pi^0$ or $\eta' \to \eta \pi^+ \pi^-$: the η (η') mass.