Study of charmonia and charmed baryons at Belle

Yuji Kato (KMI, Nagoya University)

Kobayashi-Maskawa Institute
for the Origin of Particles and the Universe

BELLE

Contents

Charmonia

- Search for $\chi_{c1}(2P)$ and X(3872) in $B^+ \rightarrow \chi_{c1}\pi^+\pi^- K^+$
- Search for XYZ in Y(1S) decay

Charmed baryons

- Preicise mass/width measurement of excited Ξ_c
- Excited Ξ_c in ΛD decay
- First observation of baryon DCS decay:$\Lambda_c^+ \rightarrow pK^+\pi^-$

Introduction: Charmonia

- The charmonium spectroscopy
  → $q\bar{q}$ potential = Linear + Coulomb.

  - Phenomenological explanation of the confinement.

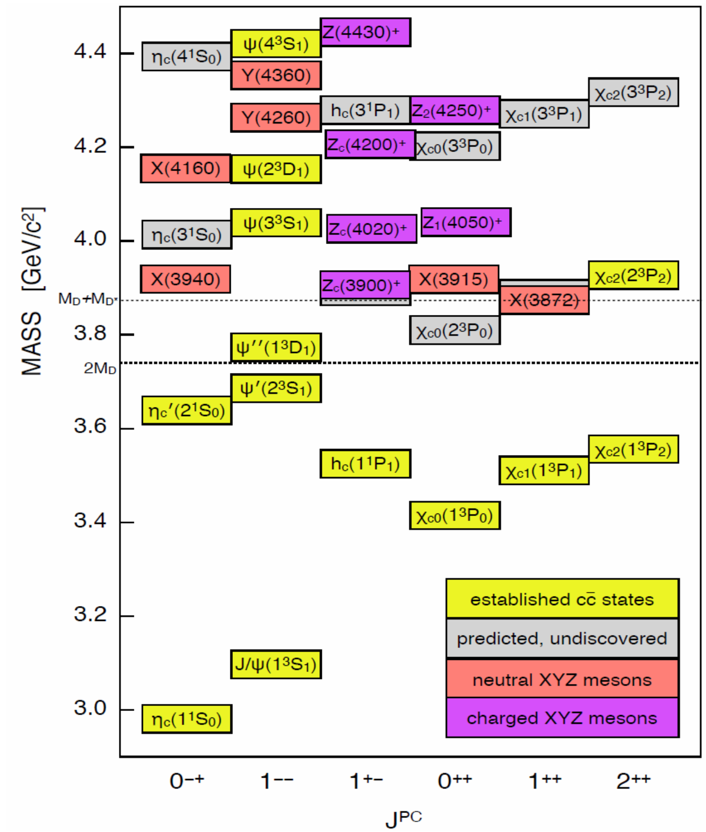
  - Prove the constituent quark model.

- The discovery of so-called XYZ opened new era.
  - Not fit to constituent quark model.

  - Even states with charge (Z_c).

  - Existence established and J^{PC} measured for many states.

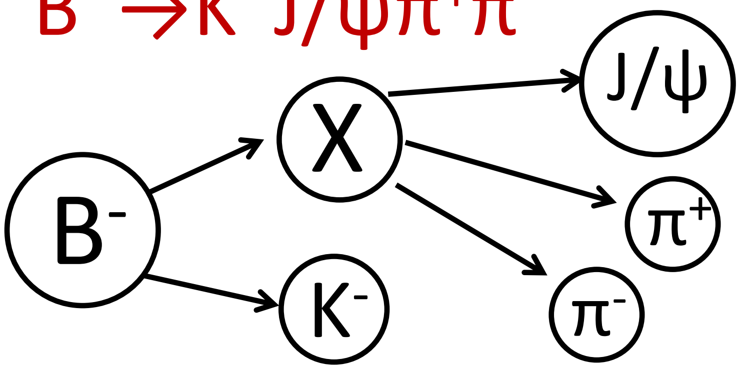
  - The nature not understood (molecule, tetra, hybrid??)



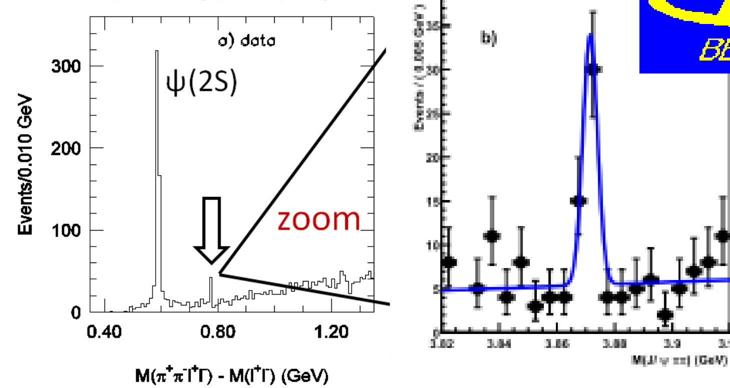
arXiv:1511.01589

X(3872): Mysterious charmonium

$B^- \to K^- J/\psi\pi^+\pi^-$

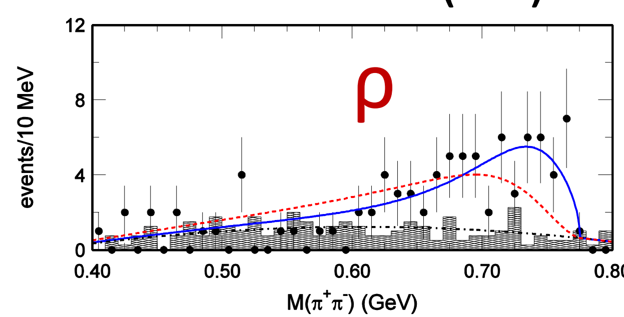


M(ππJ/ψ)-M(J/ψ)



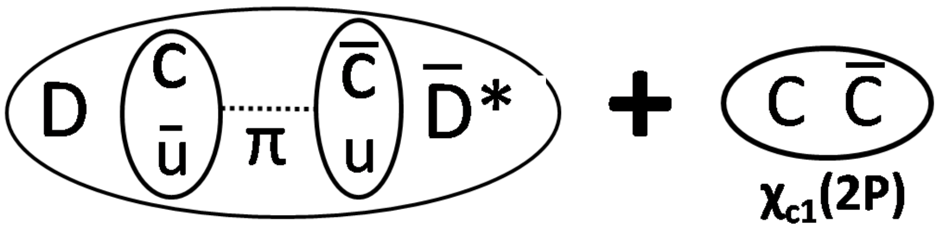
- First observed in $J/\psi\pi^+\pi^-$ at Belle (Phys. Rev. Lett. 91.262001) Most sited paper!.
- No prediction by quark model in this mass.
- Decay breaks isospin: ππ=ρ, I=1
- Mass just above the D^0D^{*0}
- $J^{pc} = 1^{++}$ by LHCb.
- What is the nature of X(3872)?

M(ππ)



$B^+ \to K^+ \chi_{c1} \pi^+ \pi^-$: Motivation

- One plausible interpretation of X(3872)
  = **Admixture of DD* molecule and χ_{c1}(2P).**



  - Molecular picture can explain isospin breaking.
  - Large prompt X(3872) cross section in $p\bar{p}$ require χ_{c1}(2P) component.
  - Non observation of χ_{c1}(2P).

    If χ_{c1}(2P) exists, it should decay into $\chi_{c1}\pi^+\pi^-$.

Phys.Rev.Lett.93:072001,2004

- Search for χ_{c1}(2P) and X(3872) in $B \to K^+ \chi_{c1} \pi^+ \pi^-$.
  - Include first observation of $B \to K \chi_{c1} \pi\pi$

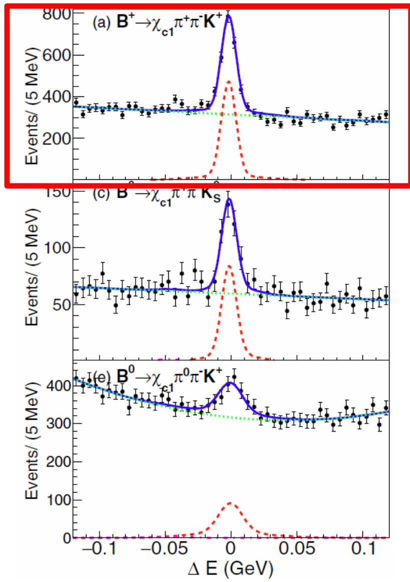
Search for X(3872) and $\chi_{c1}(2P)$ in $\chi_{c1}\pi^+\pi^-$

Phys. Rev. D 93, 052016

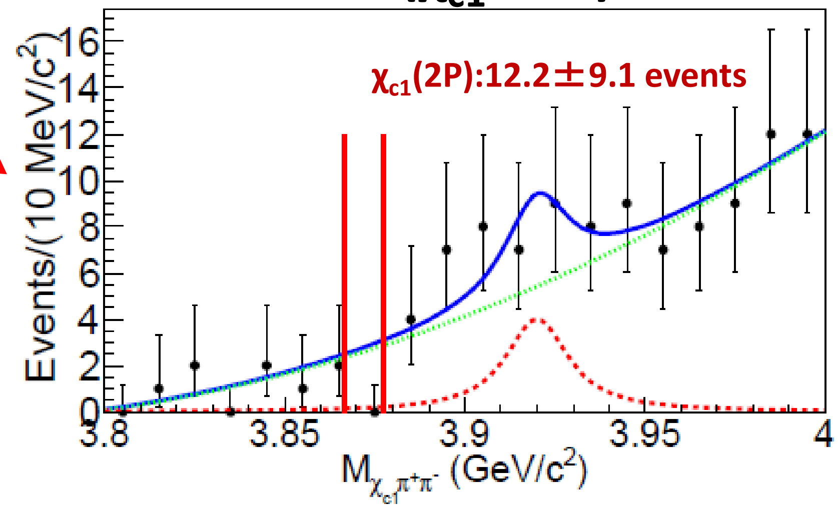
$B^+ \to K^+\chi_{c1}\pi^+\pi^-$

$B^0 \to K^0_S\chi_{c1}\pi^+\pi^-$

$B^0 \to K^+\chi_{c1}\pi^0\pi^-$



$M(\chi_{c1}\pi^+\pi^-)$



- First observation of three $B \to K\chi_{c1}\pi\pi$ decays.
  Use $B^+ \to \chi_{c1}\pi^+\pi^-$ for resonance searches.

- No events in the X(3872) region.
  $Br(B^+ \to X(3872)K^+) \times B(X(3872) \to \chi_{c1}\pi^+\pi^-) < 0.15 \times 10^{-6}$ (90% C.L.).

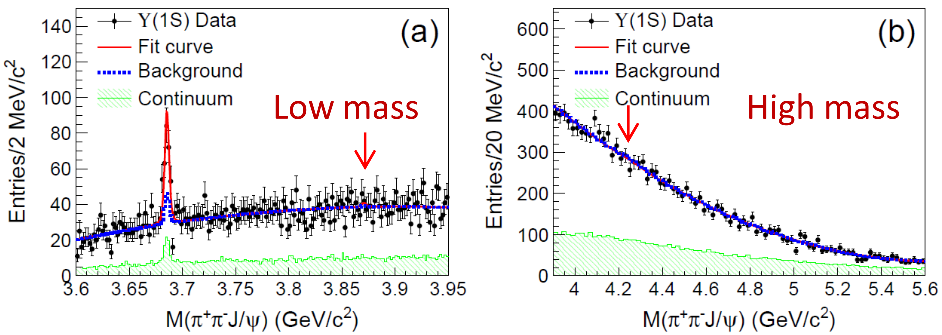
- $\chi_{c1}(2P)$ not significant.
  Assume $\chi_{c1}(2P)$ mass and width to be 3920 MeV/c^2 and 20 MeV
  $Br(B \to \chi_{c1}(2P)K^+) \times B(\chi_{c1}(2P) \to \chi_{c1}\pi^+\pi^-) < 1.10 \times 10^{-5}$ (90% C.L.)

- Not significant result is compatible with X(3872) as DD* and $\chi_{c1}(2P)$ admixture.

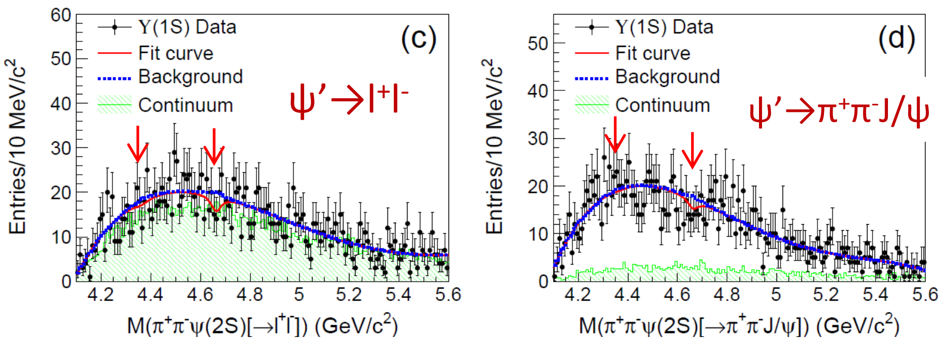
Search for XYZ in the Υ(1S) decay(1)

Submitted to PRD
arXiv:1605.00990

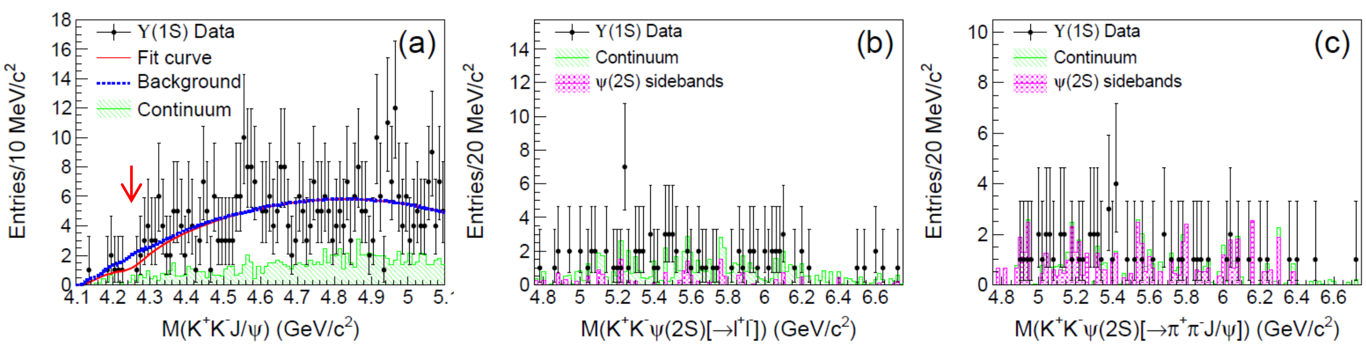
- Almost of the XYZ are observed in the B-decay and Initial State Radiation (ISR).
- Υ(1S) decays into 3 gluons ⇔ Different dynamics with B-decay or ISR.
- Comprehensive search of XYZ decaying to J/ψ or ψ' from the ~10^8 Υ(1S) decay.



M($\pi^+\pi^-$J/ψ)
No **X(3872)** and **Y(4260)**



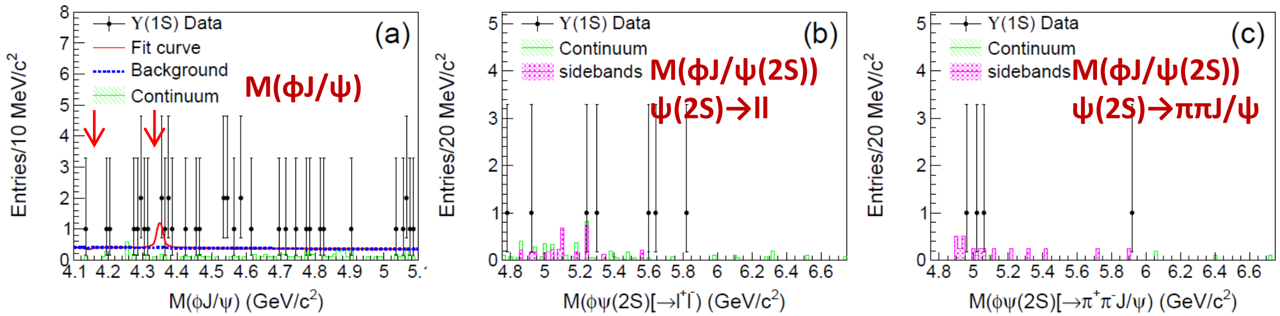
M($\pi^+\pi^-$ψ')
No **Y(4360)** and **Y(4660)**



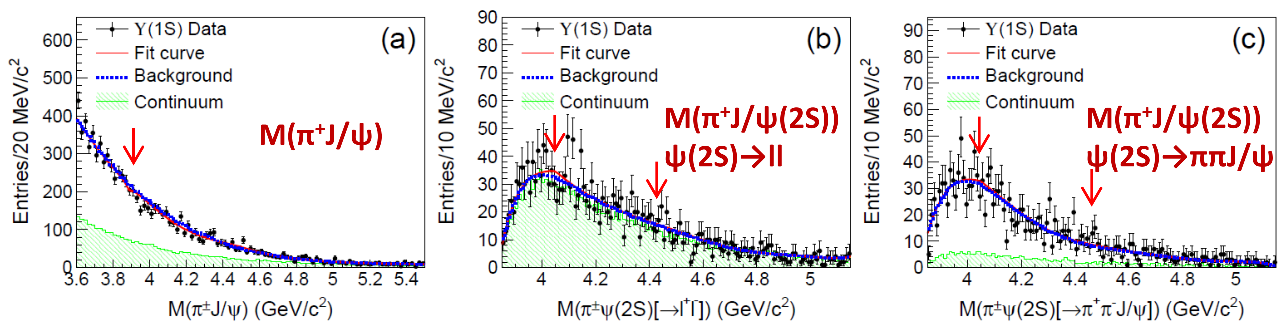
M(K^+K^-J/ψ)
M(K^+K^-ψ')
No **Y(4260)**
(~3σ evidence by CLEO)

Search for XYZ in the Υ(1S) decay(2)

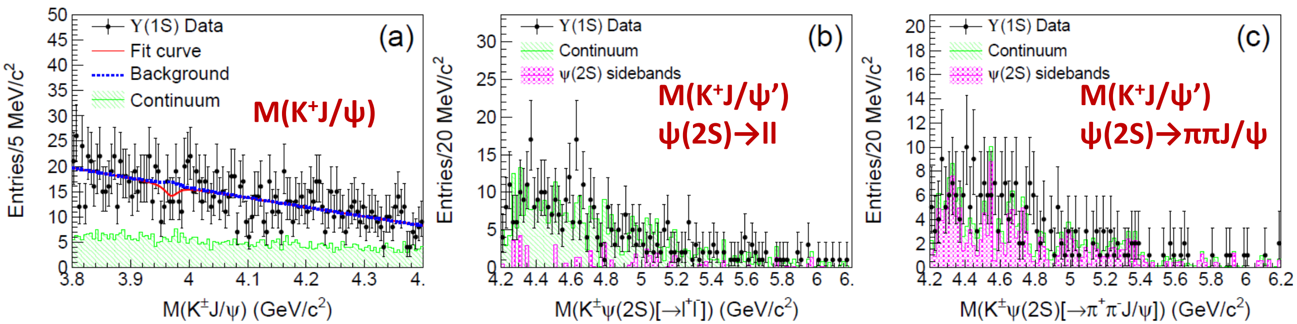
Submitted to PRD
arXiv:1605.00990



M(ϕJ/ψ)
M(ϕψ')
No X(4140) and X(4350)



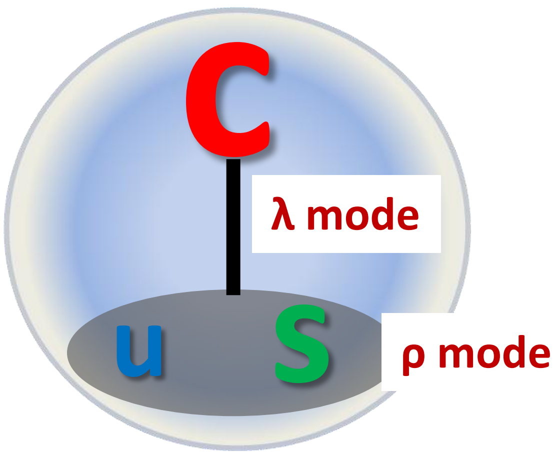
M(π⁺J/ψ)
M(π⁺ψ')
No Z(3900), Z(4050), and Z(4430

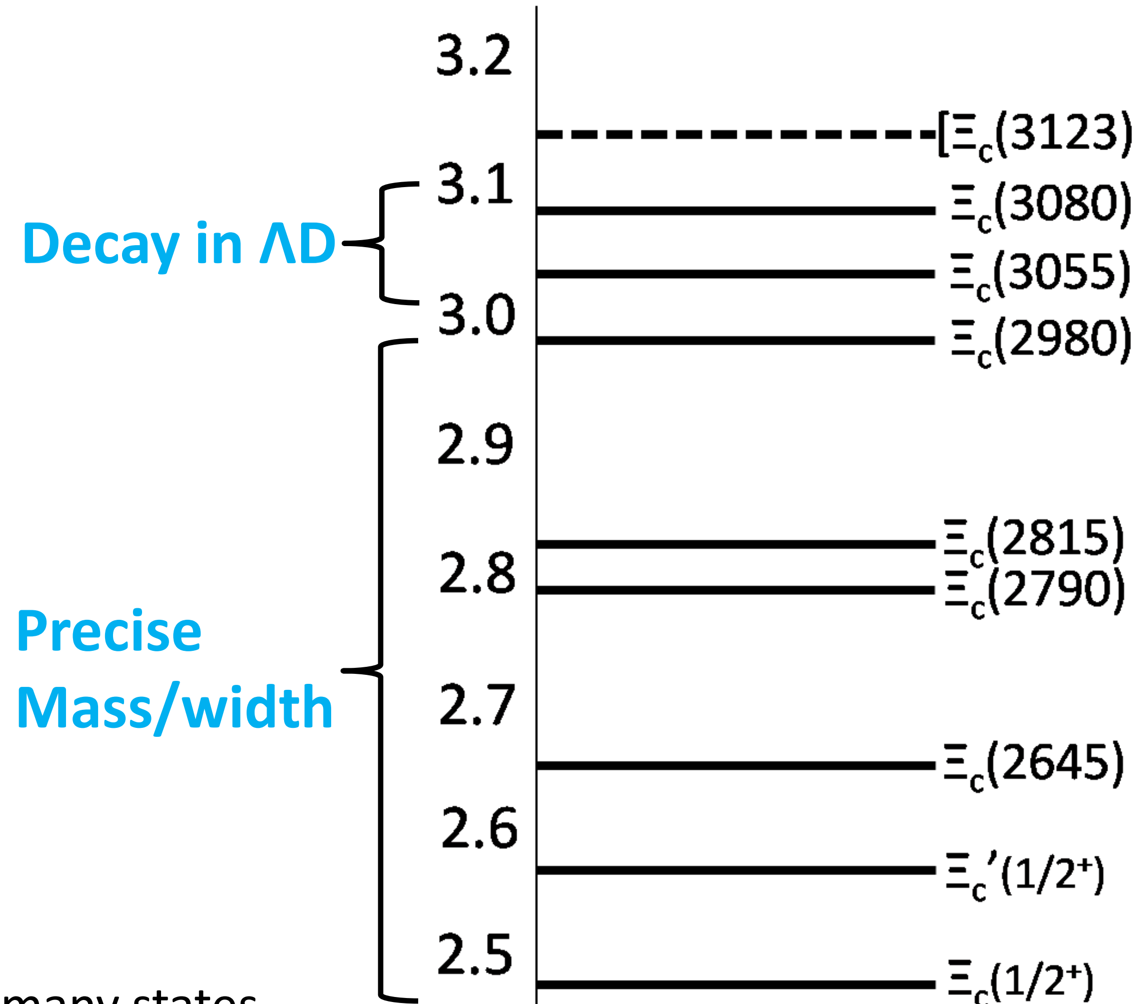


M(K⁺J/ψ)
M(K⁺ψ')
No new Z_{cs} states

No XYZ states observed from the decay of Υ(1S).
Input from theory is needed for interpretation.

Excited Ξ_c





- Small color spin interaction for charm ($\propto 1/m_1 m_2$).
  →u-s diquark + charm quark.

- Two excitations:
  -λ mode: c and di-quark
  -ρ mode: di-quark

- ~10 Ξ_c states observed.

Excitation mode not identified for many states.

Precise mass, width measurements

- Mass difference of isodoublet =
  u-d mass difference and EM interactions
  Important input to deduce the wave function.

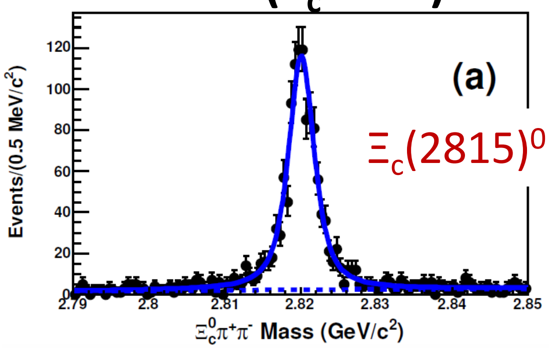
- Many of measurements are old and statistics not very high
  (errors are larger than splitting itself).
  For widths, many states have only upper limits.

- New measurements for 5 excited Ξ_c isodoublets
  decaying into final states with Ξ_c^+ or Ξ_c^0
  $\Xi_c' \to \Xi_c \gamma$
  $\Xi_c(2645) \to \Xi_c \pi$
  $\Xi_c(2790) \to \Xi_c' \pi$
  $\Xi_c(2815) \to \Xi_c \pi\pi$ and $\Xi_c' \pi$
  $\Xi_c(2980) \to \Xi_c \pi\pi$ and $\Xi_c' \pi$

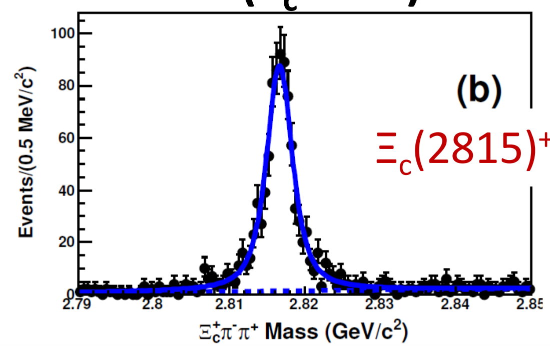
- Ξ_c^+ and Ξ_c^0 are reconstructed from 10 and 7 decay modes.
  Total yields are around 1×10^5 and 5×10^4.

$\Xi_c\pi(\pi)$ (Preliminary)

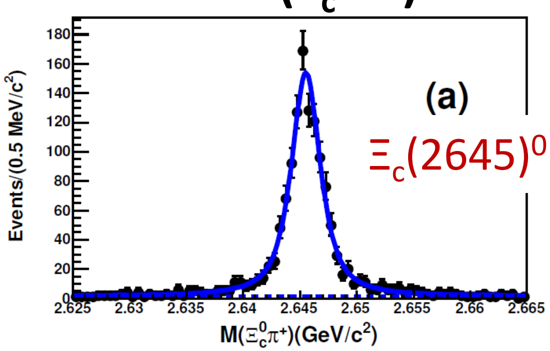
$M(\Xi_c^0\pi^+\pi^-)$



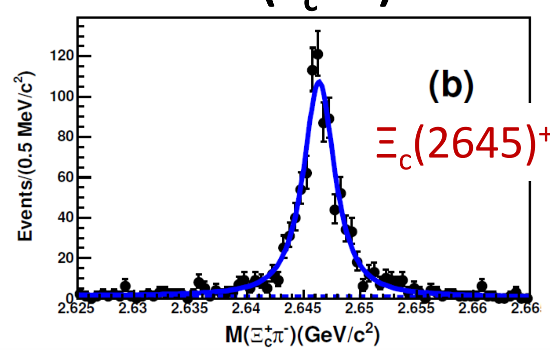
$M(\Xi_c^+\pi^+\pi^-)$



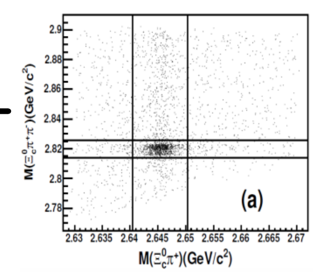
$M(\Xi_c^0\pi^+)$

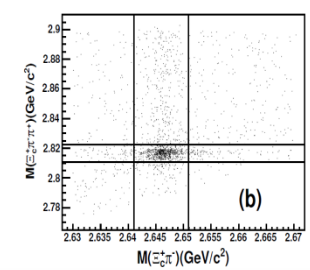


$M(\Xi_c^+\pi^-)$

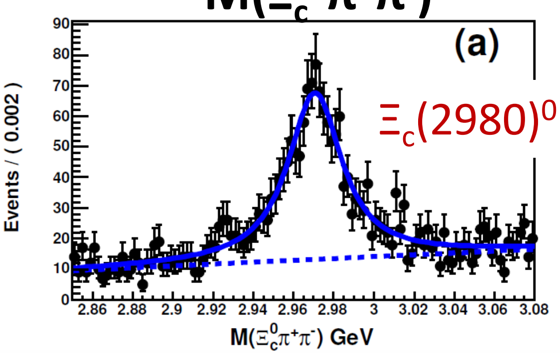


Reduce background using decay chain
$\Xi_c(2815) \rightarrow \Xi_c(2645)\pi \rightarrow \Xi_c\pi\pi$

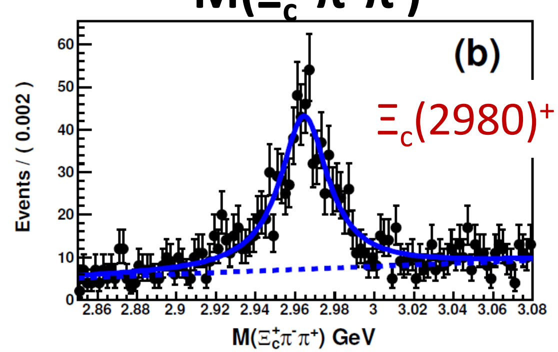




$M(\Xi_c^0\pi^+\pi^-)$

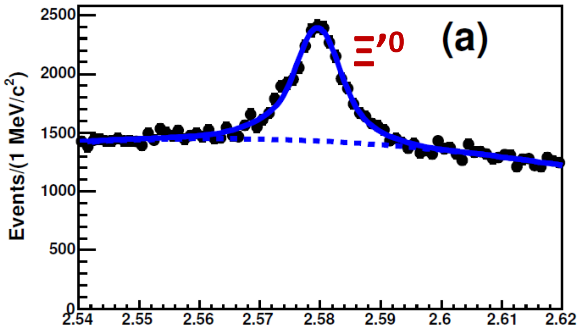


$M(\Xi_c^+\pi^+\pi^-)$

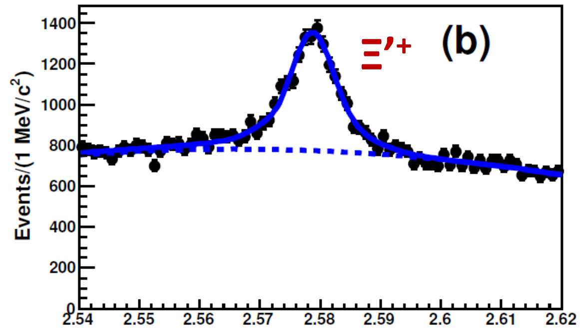


$\Xi_c'(\pi)$ (Preliminary)

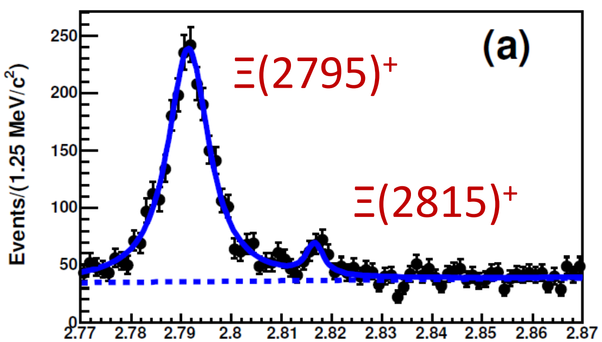
$M(\Xi_c^0\gamma)$



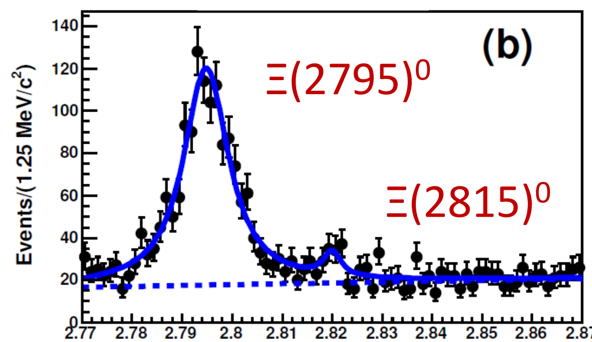
$M(\Xi_c^+\gamma)$

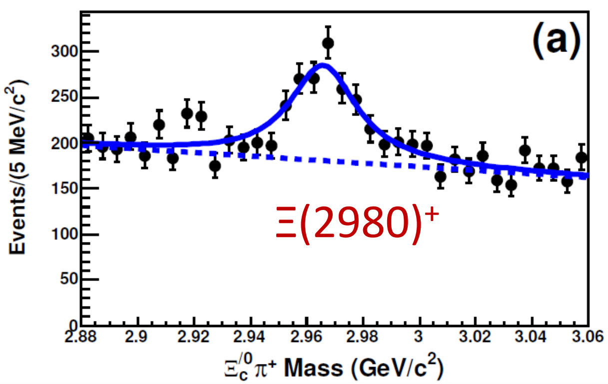


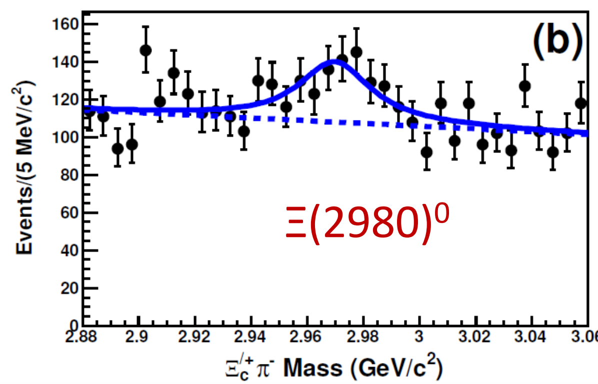
$M(\Xi_c'^0\pi^+)$



$M(\Xi_c'^+\pi^-)$







First observations for
$\Xi_c(2815) \rightarrow \Xi_c'\pi$
$\Xi_c(2980) \rightarrow \Xi_c'\pi$

Results (Preliminary)

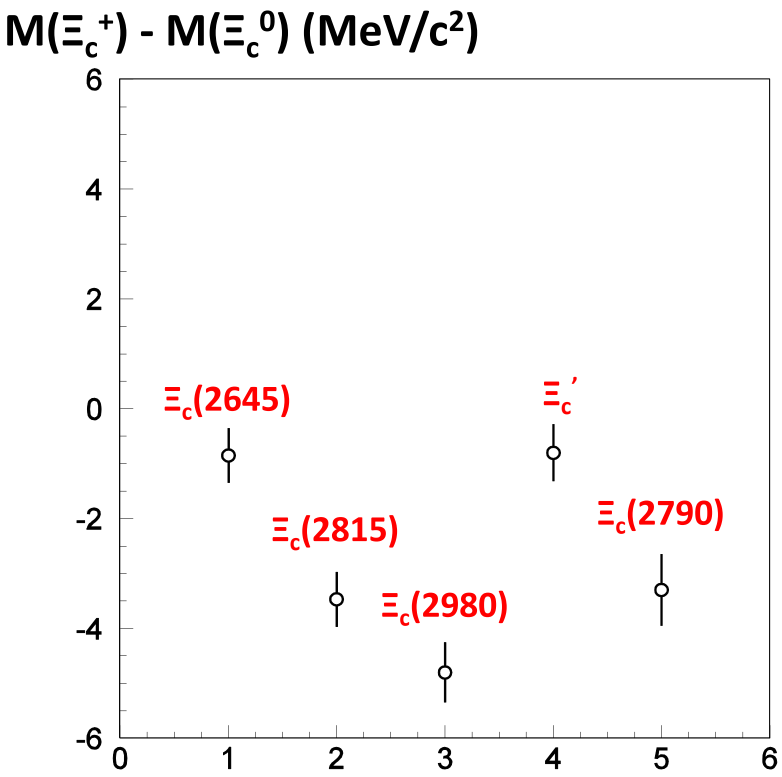
PDG values in ()

	Mass (MeV/c^2)	Width (MeV)
$\Xi_c(2645)^+$	$2645.58 \pm 0.06 \pm 0.07^{+0.28}_{-0.40}$ (2645.9 ± 0.5)	$2.06 \pm 0.13 \pm 0.13$ $(2.6 \pm 0.2 \pm 0.4)$
$\Xi_c(2815)^+$	$2816.73 \pm 0.08 \pm 0.06^{+0.28}_{-0.40}$ (2816.6 ± 0.9)	$2.43 \pm 0.20 \pm 0.17$ (<3.5)
$\Xi_c(2980)^+$	$2966.0 \pm 0.8 \pm 0.2^{+0.3}_{-0.4}$ (2970.7 ± 2.2)	$28.1 \pm 2.4^{+1.0}_{-5.0}$ (17.9 ± 3.5)
$\Xi_c'^+$	$2578.4 \pm 0.1 \pm 0.4^{+0.3}_{-0.4}$ (2575.6 ± 3.1)	-
$\Xi_c(2790)+$	$2791.6 \pm 0.2 \pm 0.1 \pm 0.4^{+0.3}_{-0.4}$ (2789.8 ± 3.2)	$8.9 \pm 0.6 \pm 0.8$ (<15)

- Significant improvement for the accuracy of masses.
  (third error is coming from ground state Ξ_c)

- First significant measurement for the widths for many states.

Isospin splitting (Preliminary)

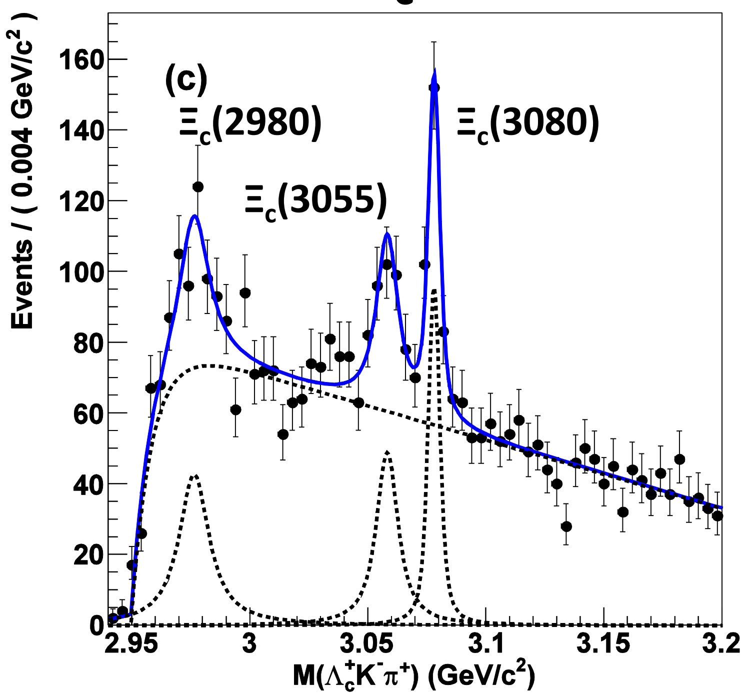


Particle	$M(\Xi_c^+) - M(\Xi_c^0)$ (MeV$/c^2$)
$\Xi_c(2645)$	$-0.85 \pm 0.09 \pm 0.08 \pm 0.48$
$\Xi_c(2815))$	$-3.47 \pm 0.12 \pm 0.05 \pm 0.48$
$\Xi_c(2980))$	$-4.8 \pm 0.1 \pm 0.2 \pm 0.5$
$\Xi_c'^+$	$-0.8 \pm 0.1 \pm 0.1 \pm 0.5$
$\Xi_c(2790))$	$-3.3 \pm 0.4 \pm 0.1 \pm 0.5$

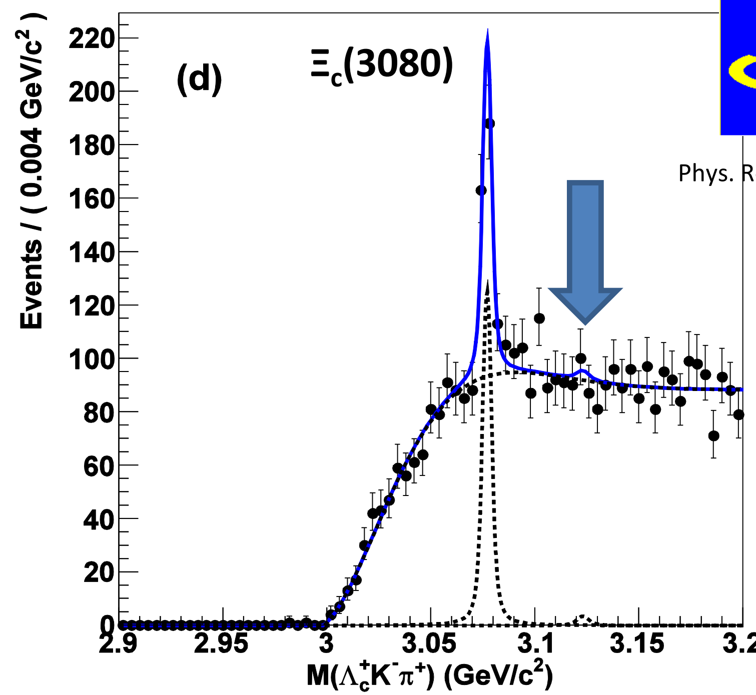
- Isospin splitting also quite accurate!
- Small splitting for $\Xi_c(2645)$ and Ξ_c' (spin 1 di-quark states) consistent with quark model (J. Phys. G 29, 2685 2003).

Higher excited states (past studies).

$M(\Sigma_c^{++}K^-)$



$M(\Sigma_c^{*++}K^-)$



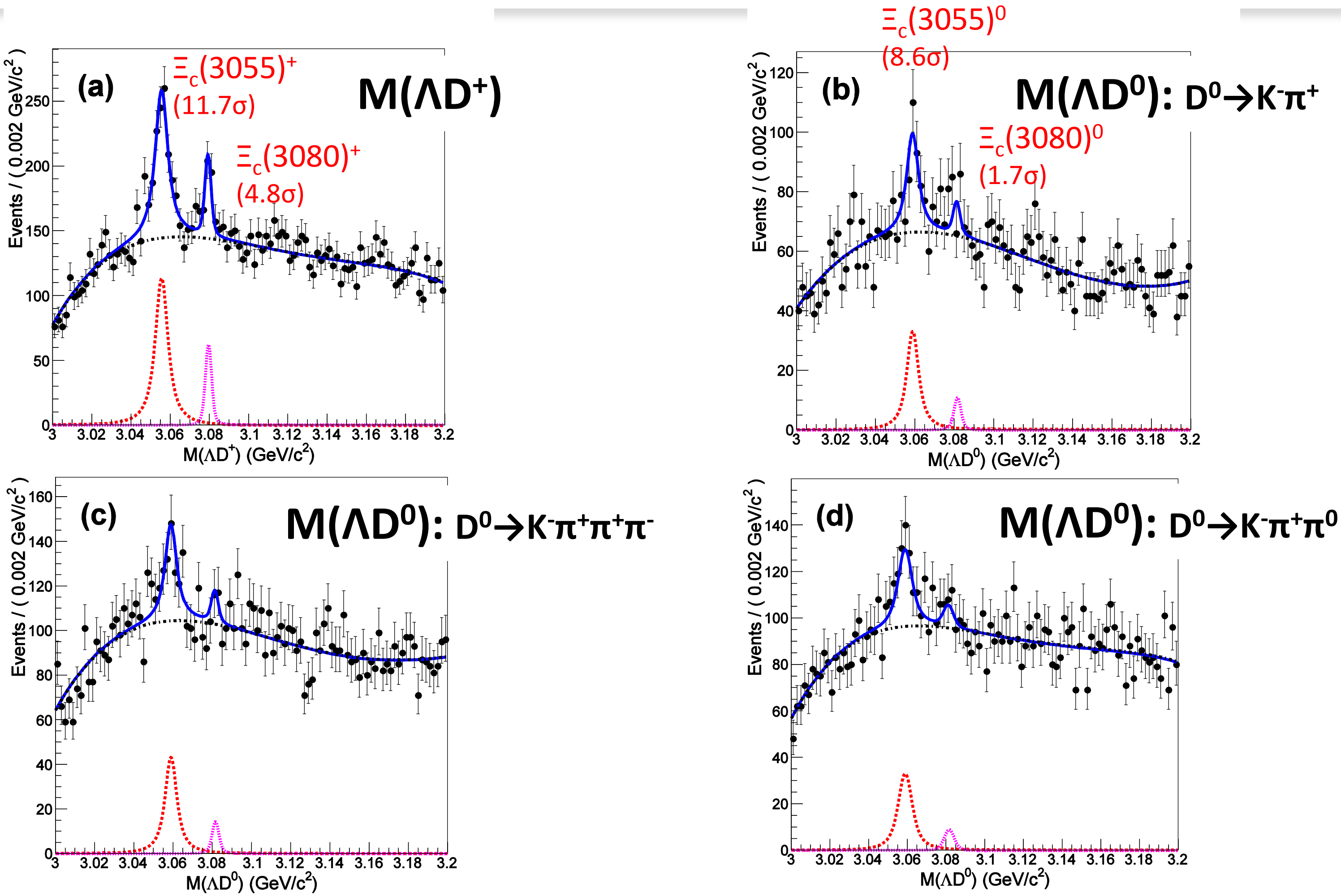
Phys. Rev. D 89, 052003

- Both Belle and BaBar observed
  $\Xi_c(2980)^+$, $\Xi_c(3055)^+$, and $\Xi_c(3080)^+$ in $\Sigma_c^{++}K^-$ final state.
  $\Xi_c(3080)^+$ in $\Sigma_c^{*++}K^-$ final state (only BaBar observed $\Xi_c(3123)^+$)

Phys. Rev. D 77, 012002
Phys. Rev. D 89, 052003

- All the excited Ξ_c are observed in (heavy baryon) + (light meson) final states.
  (Light baryon) + (heavy meson) decay provides complementary information → **ΛD!**

M(ΛD) spectra (Preliminary)



- First observation of $\Xi_c(3055),(3080) \rightarrow \Lambda D$
- First discovery of isospin partner, $\Xi_c(3055)^0$!
- Simultaneous fit for $M(\Lambda D^0)$ with common mass/width, fixed yield ratio.

$$M(\Xi_c(3055)^0) = 3059.0 \pm 0.5 \pm 0.6 \text{ MeV}/c^2$$
$$\Gamma(\Xi_c(3055)^0) = 6.4 \pm 2.1 \pm 1.1 \text{ MeV}$$

Combine with $\Sigma_c^{(*)}K^-$ modes (Preliminary)

- **Branching fraction ratios:**

- $\Xi_c(3055)^+$

Prefer ΛD

$Br(\Lambda D^+)/Br(\Sigma_c^{++}K^-) = 5.09 \pm 1.01 \pm 0.76$

- $\Xi_c(3080)^+$

Similar in 3 decays

$Br(\Lambda D^+)/Br(\Sigma_c^{++}K^-) = 1.29 \pm 0.30 \pm 0.15$

$Br(\Sigma_c^{*++}K^-)/Br(\Sigma_c^{++}K^-) = 1.07 \pm 0.27 \pm 0.01$

- In the chiral quark model, $\Xi_c(3055) = {}^2D_{\lambda\lambda}(3/2^+)$ and $\Xi_c(3080) = {}^2D_{\rho\rho}(3/2^+)$. (Phys. Rev. D 86, 034024)

They predicted ΛD decay is suppressed.
→Inconsistent with this measurement.

- **Mass (MeV/c^2) and width (MeV)**

	ΛD^+	$\Sigma_c K^-$	$\Sigma_c^* K^-$	Combined
$M(\Xi_c(3055)^+)$	$3055.8 \pm 0.4 \pm 0.2$	$3058.1 \pm 1.0 \pm 2.1$	-	3055.9 ± 0.4
$M(\Xi_c(3080)^+)$	$3079.6 \pm 0.4 \pm 0.2$	$3077.9 \pm 0.4 \pm 0.7$	$3076.9 \pm 0.3 \pm 0.2$	3077.9 ± 0.9
$\Gamma(\Xi_c(3055)^+)$	$7.0 \pm 1.2 \pm 1.5$	$9.7 \pm 3.4 \pm 3.3$	-	$7.8 \pm 1.2 \pm 1.5$
$\Gamma(\Xi_c(3080)^+)$	<6.3	$2.4 \pm 0.9 \pm 1.6$	$3.2 \pm 1.3 \pm 1.3$	$3.0 \pm 0.7 \pm 0.4$

DCS decay of the Λ_c^+

Accepted in PRL
arXiv:1512.07366

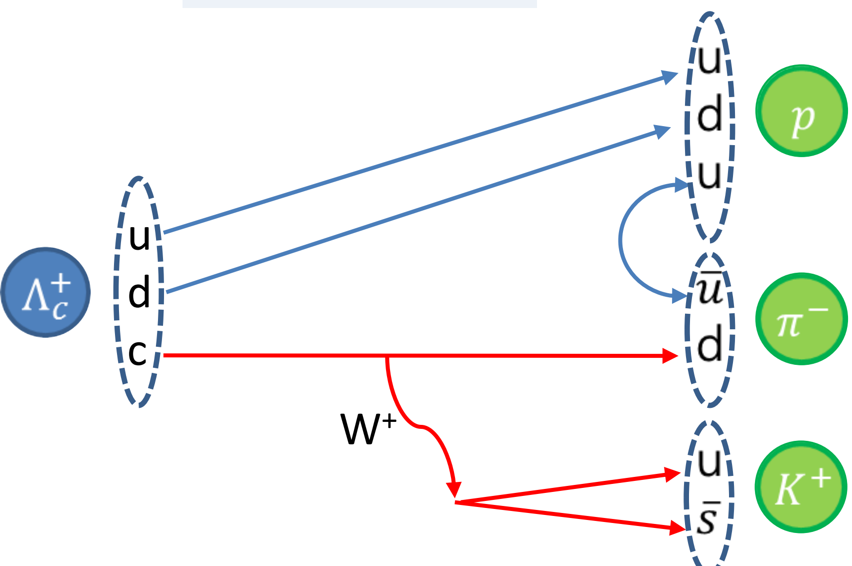
- In the baryon sector, Doubly Cabbibo Suppressed (DCS) decay has NEVER been observed. $\Lambda_c^+ \to pK^+\pi^-$ is expected to be sensitive.

- Naively, ratio to CF decay, $pK^-\pi^+$ is expected to be

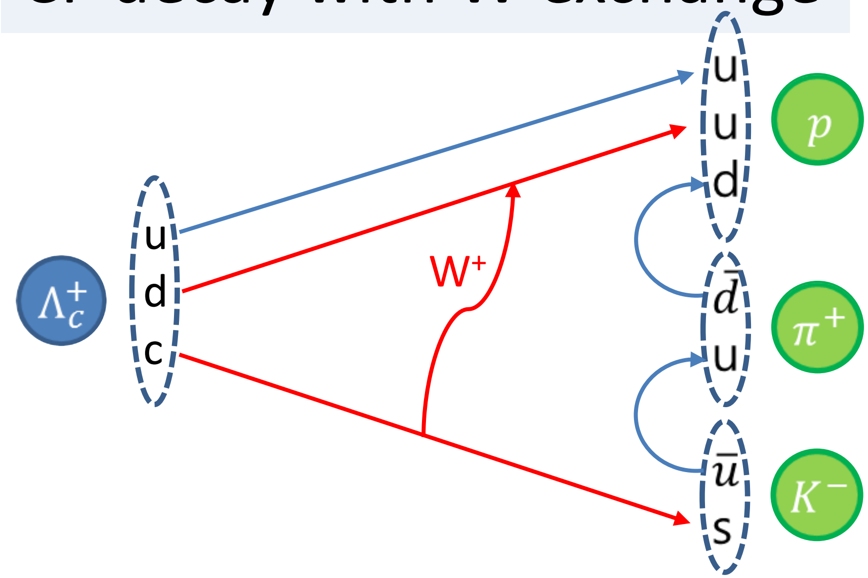
$$\frac{B(\Lambda_c^+ \to pK^+\pi^-)}{B(\Lambda_c^+ \to pK^-\pi^+)} \cong \tan^4 \theta_c$$

- In the CF decay, the W exchange diagram may contribute.

DCS decay

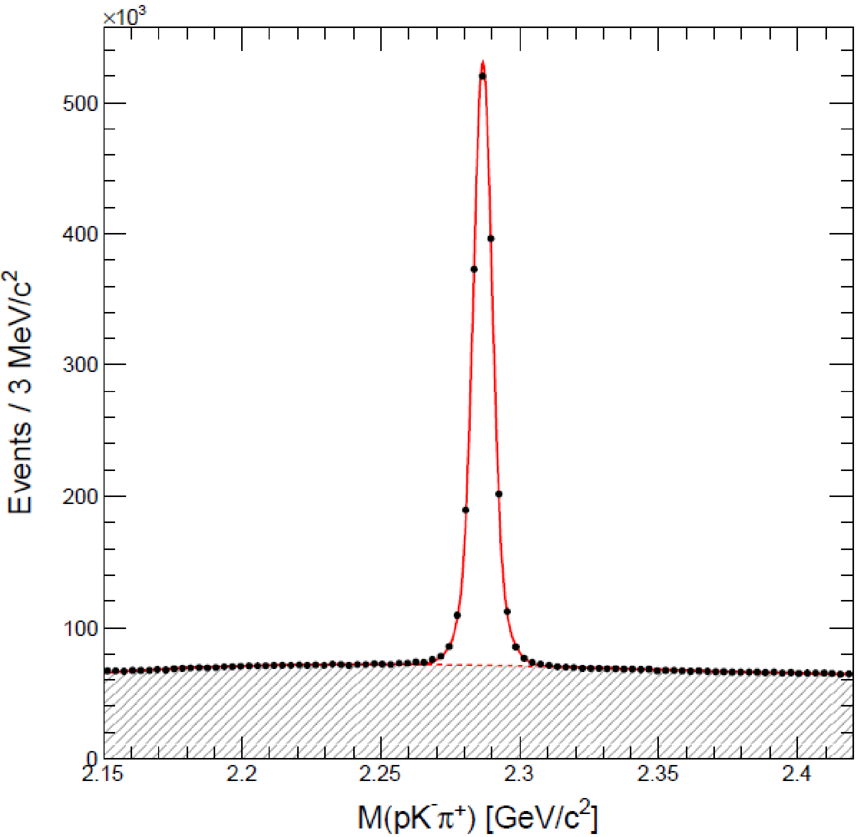


CF decay with W exchange



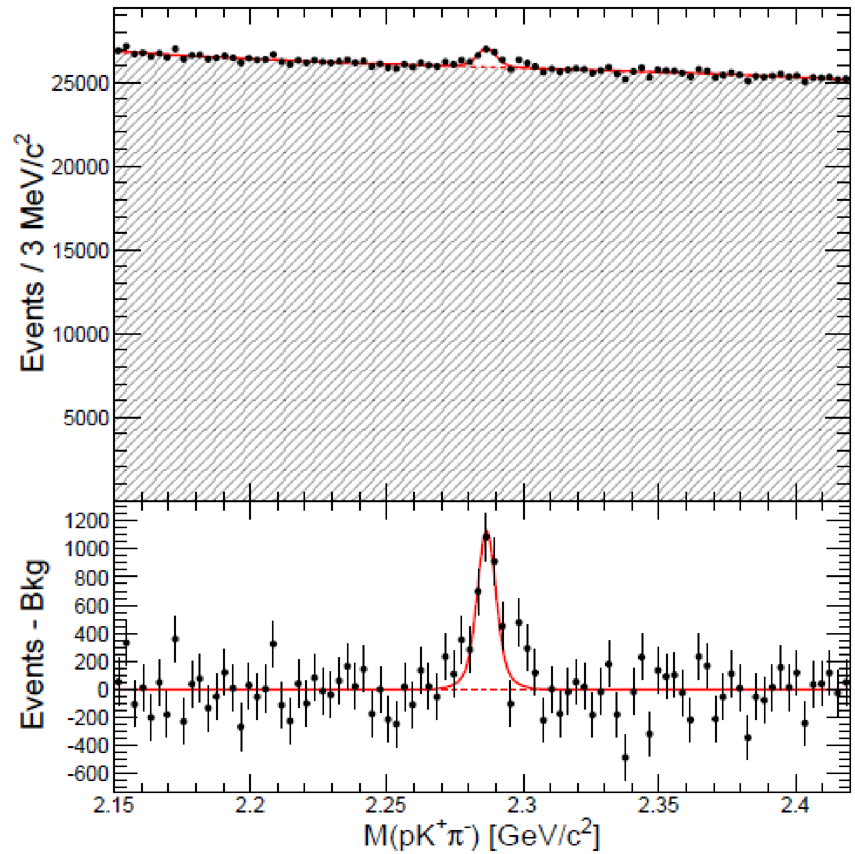
Observation of $\Lambda_c^+ \to pK^+\pi^-$

CF mode: $pK^-\pi^+$



$(1.452 \pm 0.0015) \times 10^6$ events

DCS mode: $pK^+\pi^-$



- 3587 ± 380 events
- ΛK^+ decay subtracted
- Significance: 9σ

Branching fraction ratio

- Branching fraction ratio = (2.35 ± 0.27(Stat) ± 0.21(Sys)) $\times 10^{-3}$
  = $(0.82 \pm 0.12) \times \tan^4\Theta$

- After subtracting contribution of $\Lambda(1520)$ or Δ intermediate, which contribute only on the CF decay, the ratio is
  $(1.10 \pm 0.17) \times \tan^4\Theta$

- Contribution from W exchange diagram is small.

Summary

- Belle is actively publishing on charmonia and charmed baryons!

- $\chi_{c1}(2P)$ not observed in $\chi_{c1}\pi\pi$:
  → Comparable with X(3872) as admixture picture.

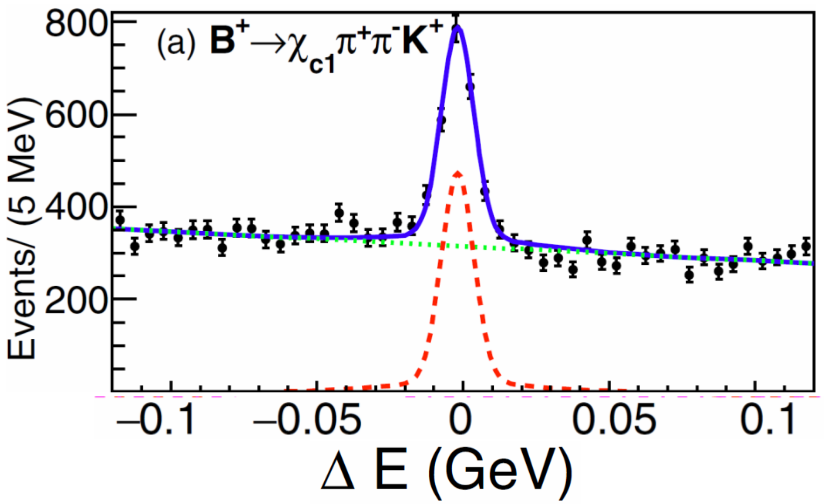
- No XYZ from Y(1S) decay. Theoretical input needed to understand.

- New results on excited Ξ_c baryons.
  - Precise mass/width for excited states decaying into Ξ_c
  - $\Xi_c(3055)$ and $\Xi_c(3080)$ into ΛD final state.
    Discovery of $\Xi_c(3055)^0$ and relative branching fraction measurements.

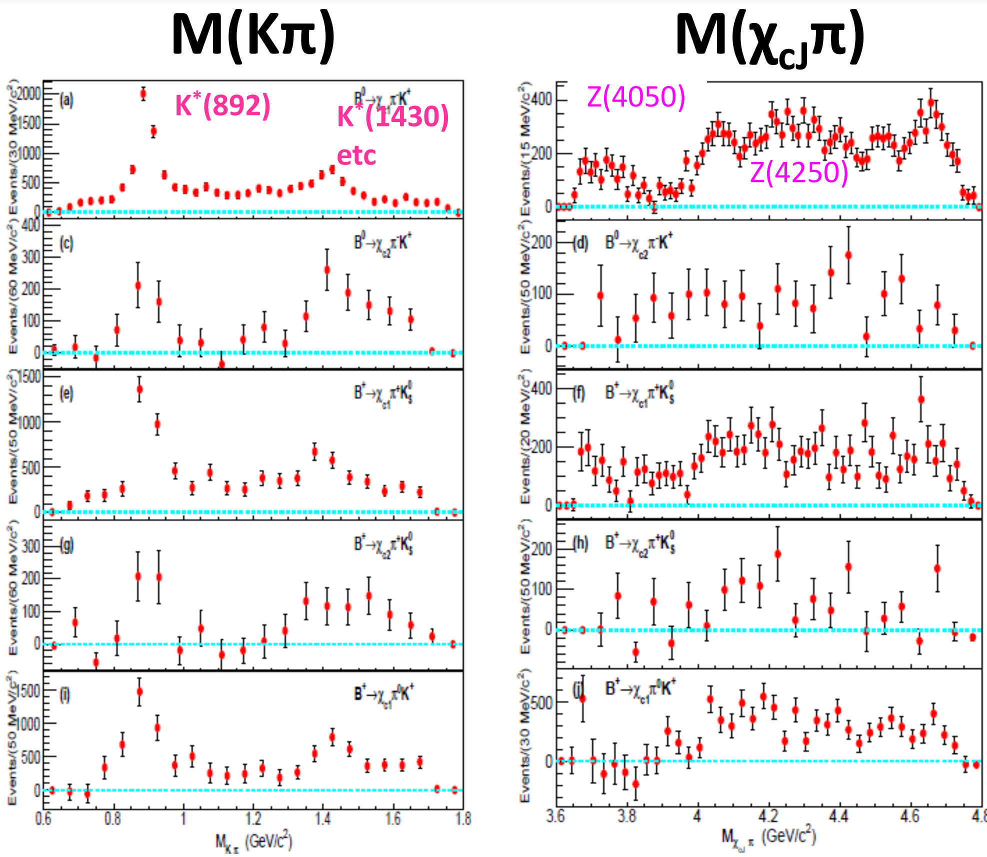
- First observation of DCS decay of baryon: $\Lambda_c^+ \to pK^+\pi^-$

- Stay tuned for more results from upcoming Belle II!

backup



Comparison of 3 body $B \to \chi_{c1}\pi K$ and $B \to \chi_{c2}\pi K$



$B^0 \to \chi_{c1}\pi^- K^+$

$B^0 \to \chi_{c2}\pi^- K^+$ (First observation)

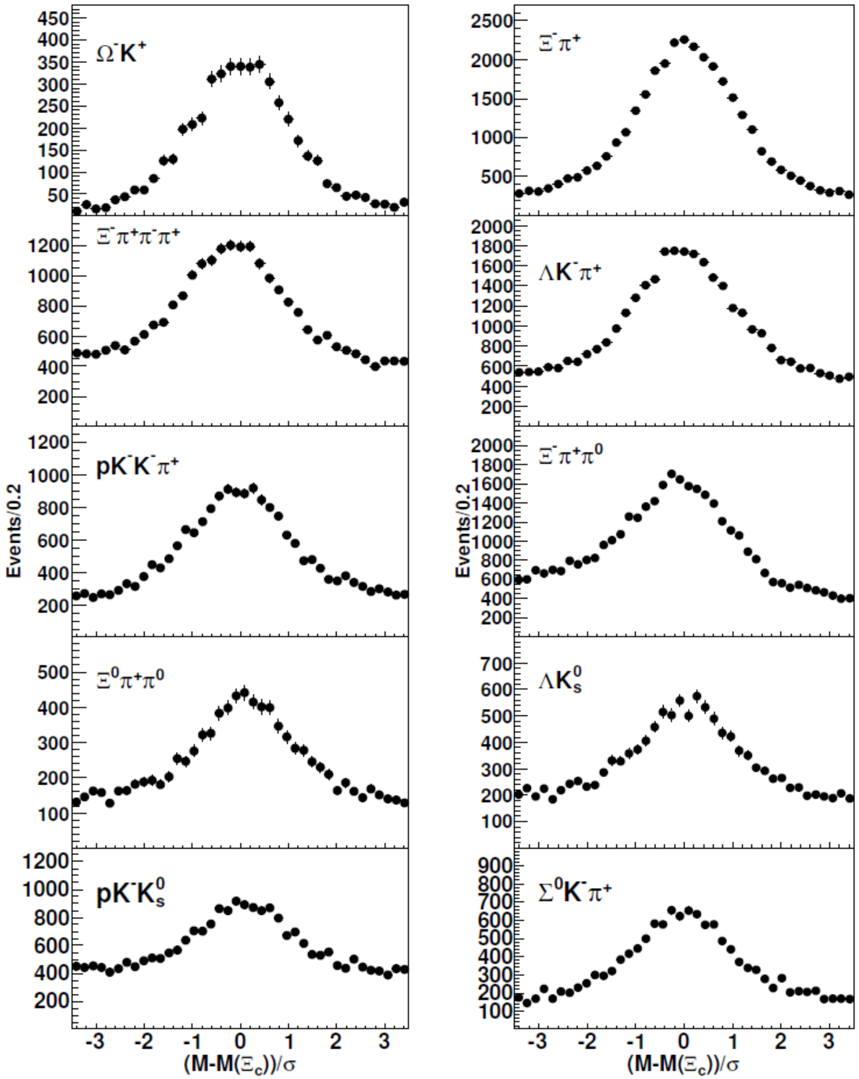
$B^+ \to \chi_{c1}\pi^- K_S$

$B^+ \to \chi_{c2}\pi^- K^0_S$ (First observation)

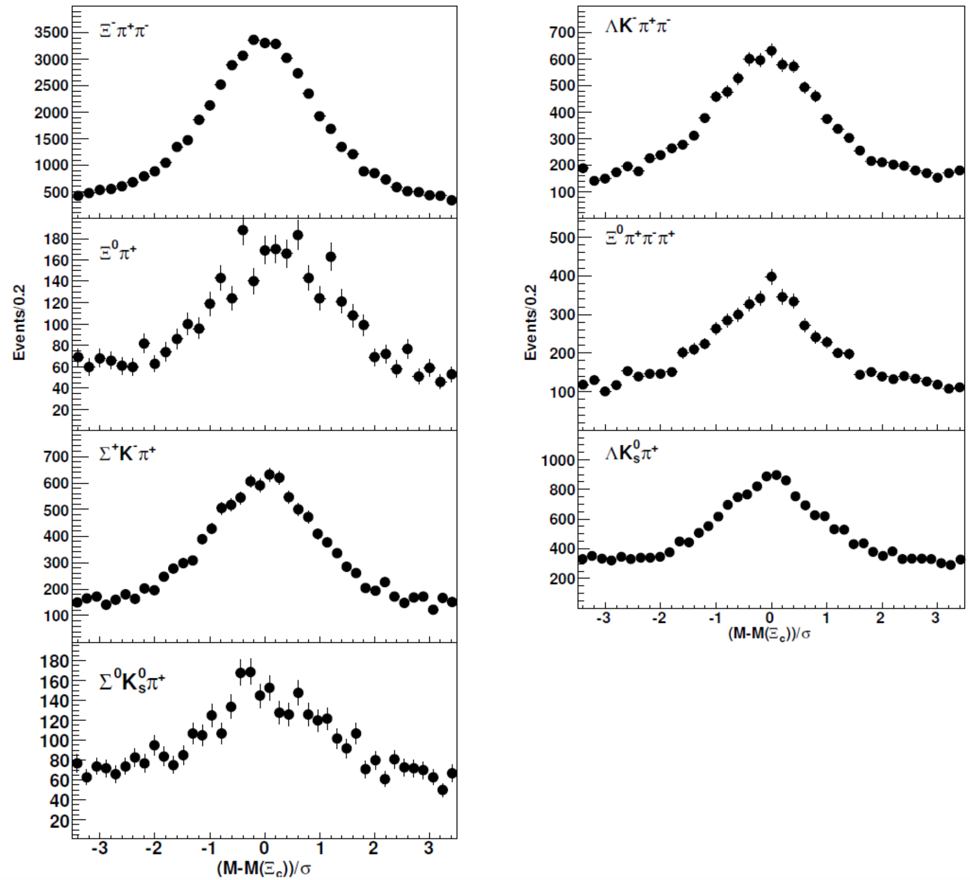
$B^+ \to \chi_{c1}\pi^0 K^+$

- First observation of two $B \to \chi_{c2}$ X exclusive decays.
- K*:K*(1430) etc is different for χ_{c1} and $\chi_{c2.}$ →Important input for decay dynamics.
- M($\chi_{c1}\pi$) consistent with previous Belle observation of two charged Z states. No narrow structure in M($\chi_{c2}\pi$).

Ξ_c^+ reconstruction



Ξ_c^0 reconstruction



B decays to χ_{c1} and χ_{c2}

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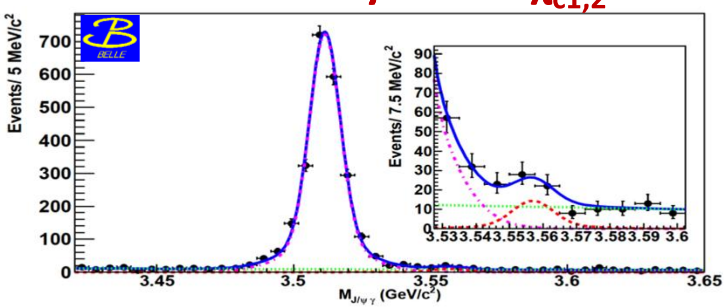
- The two body decay $B \to K^+ \chi_{c2}$ is suppressed relative to χ_{c1} (~2 %).
  - Due to the angular momentum conservation. Need FSI.

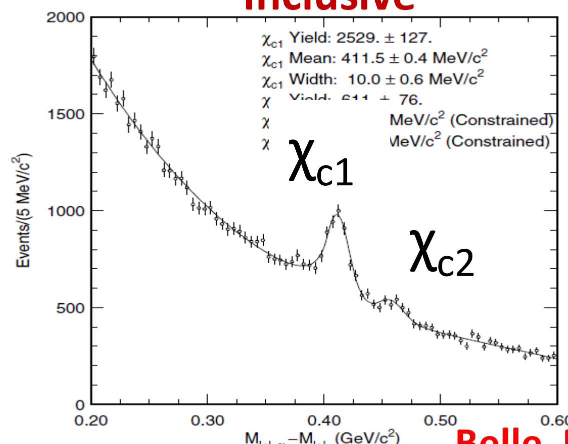
- In the inclusive measurement, the suppression is moderate (~25 %).
  → Multi body decays. Study of intermediate resonance clarifies decay dynamics.

Two body $B \to K^+ \chi_{c1,2}$



Belle, PRL 107, 091803 (2011)

Inclusive



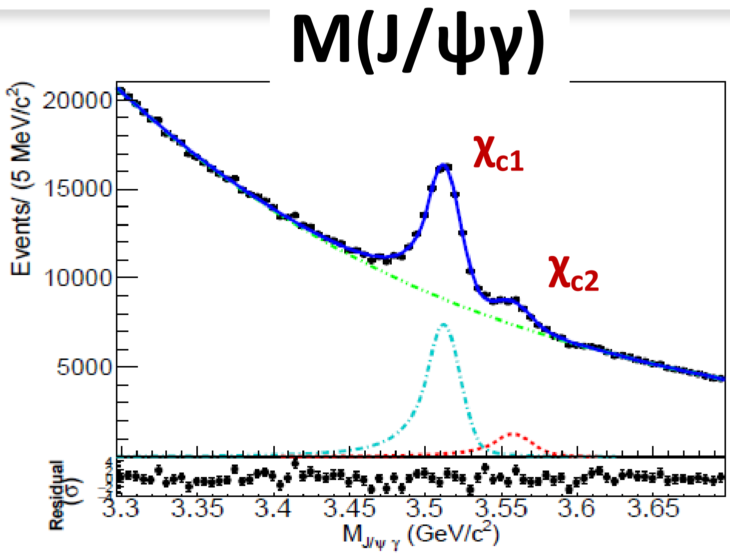
30 fb^{-1}

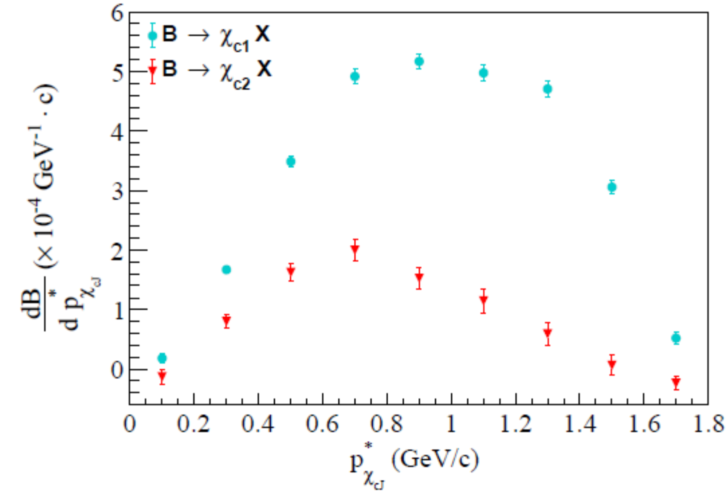
Belle, PRL 89, 011803(2002)

- Most plausible explanation of X(3872) is mixing of DD* molecule and $\chi_{c1}(2p)$, which Is not observed so far.
  → Search for X(3872) and $\chi_{c1}(2p)$ in $B \to K^+ \chi_{c1} \pi^+ \pi^-$.

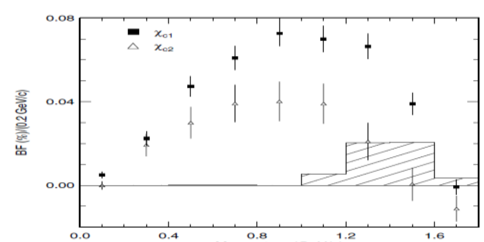
1. **Improvement measurement of inclusive χ_{c12} with full statistics**
2. **Several (new) exclusive decay modes and study of intermediate states.**

Inclusive measurements





	New (10^{-3})	Previous (10^{-3})
$B\rightarrow\chi_{c1}X$	$3.03\pm0.05\pm0.24$	$2.60\pm0.17\pm0.23$
$B\rightarrow\chi_{c2}X$	$0.70\pm0.06\pm0.10$	$0.97^{+0.16}_{-0.19}\pm0.13$



Old measurement

Belle, PRL 89, 011803(2002)

- Continuum, feed down are subtracted.
- Good agreement with previous measurements with improved accuracy.
- Differential measurement shows most of χ_{c2} decay are multi-body.

Exclusive measurements

Decay	Yield (Y)	$\mathcal{S}(\sigma)$	$\epsilon(\%)$	$\mathcal{B}$ (10^{-4})	$\mathcal{R}_{\mathcal{B}}$
$B^0 \to \chi_{cJ}\pi^- K^+$					0.14 ± 0.02
χ_{c1}	2774 ± 66	66.7	17.9	$4.97 \pm 0.12 \pm 0.28$	
χ_{c2}	206 ± 25	8.7	16.2	$0.72 \pm 0.09 \pm 0.05$	
$B^+ \to \chi_{cJ}\pi^+ K^0$					0.20 ± 0.04
χ_{c1}	770 ± 35	33.7	8.6	$5.75 \pm 0.26 \pm 0.32$	
χ_{c2}	76.4 ± 14.7	4.6	7.5	$1.16 \pm 0.22 \pm 0.12$	
$B^+ \to \chi_{cJ}\pi^0 K^+$					< 0.21
χ_{c1}	803 ± 70	15.6	7.8	$3.29 \pm 0.29 \pm 0.19$	
~~χ_{c2}~~	~~17.5 ± 28.4~~	~~0.4~~	~~7.0~~	~~< 0.62~~	
$B^+ \to \chi_{cJ}\pi^+\pi^- K^+$					0.36 ± 0.05
χ_{c1}	1502 ± 70	19.2	12.8	$3.74 \pm 0.18 \pm 0.24$	
χ_{c2}	269 ± 34	8.4	11.4	$1.34 \pm 0.17 \pm 0.09$	
$B^0 \to \chi_{cJ}\pi^+\pi^- K^0$					< 0.61
χ_{c1}	268 ± 30	7.1	5.4	$3.16 \pm 0.35 \pm 0.32$	
~~χ_{c2}~~	~~37.8 ± 14.2~~	~~1.8~~	~~4.8~~	~~< 1.70~~	
$B^0 \to \chi_{cJ}\pi^-\pi^0 K^+$					< 0.25
χ_{c1}	545 ± 81	6.5	5.0	$3.52 \pm 0.52 \pm 0.24$	
~~χ_{c2}~~	~~76.7 ± 42.0~~		~~4.3~~	~~< 0.74~~	

- **First observation of χ_{c2} exclusive decays**
- **First observation of χ_{c1} decays with 2π.**
- **Improved previous measurements.**
- **Cover 58 (32) % of inclusive BF for χ_{c1} (χ_{c2}).**

Upper limit on the branching fractions

State	$N_{\rm fit}$	$N_{\rm up}$	$\varepsilon(\%)$	$\sigma_{\rm syst}(\%)$	$\Sigma(\sigma)$	$\mathcal{B}_R^{\rm prod}$
$X(3872) \to \pi^+\pi^- J/\psi$	4.8±15.4	31.4	3.26	18.7	0.3	$< 9.5 \times 10^{-6}$
$Y(4260) \to \pi^+\pi^- J/\psi$	−31.1±88.9	134.6	3.50	35.6	–	$< 3.8 \times 10^{-5}$
$Y(4260) \to \pi^+\pi^- \psi(2S)$	6.7±29.4	56.9	0.71	35.0	0.2	$< 7.9 \times 10^{-5}$
$Y(4360) \to \pi^+\pi^- \psi(2S)$	−25.4±30.1	45.6	0.86	50.0	–	$< 5.2 \times 10^{-5}$
$Y(4660) \to \pi^+\pi^- \psi(2S)$	−55.0±26.2	23.1	1.06	40.7	–	$< 2.2 \times 10^{-5}$
$Y(4260) \to K^+K^- J/\psi$	−13.7±10.9	14.5	1.91	45.8	–	$< 7.5 \times 10^{-6}$
$Y(4140) \to \phi J/\psi$	−0.1±1.2	3.6	0.69	11.0	–	$< 5.2 \times 10^{-6}$
$X(4350) \to \phi J/\psi$	2.3±2.5	7.6	0.92	10.4	1.2	$< 8.1 \times 10^{-6}$
$Z_c(3900)^\pm \to \pi^\pm J/\psi$	−26.5±39.1	57.5	4.39	47.3	–	$< 1.3 \times 10^{-5}$
$Z_c(4200)^\pm \to \pi^\pm J/\psi$	−238.6±154.2	235.1	3.87	48.4	–	$< 6.0 \times 10^{-5}$
$Z_c(4430)^\pm \to \pi^\pm J/\psi$	94.2±71.4	195.8	3.97	34.4	1.2	$< 4.9 \times 10^{-5}$
$Z_c(4050)^\pm \to \pi^\pm \psi(2S)$	37.0±47.7	112.7	1.27	46.2	0.4	$< 8.8 \times 10^{-5}$
$Z_c(4430)^\pm \to \pi^\pm \psi(2S)$	23.2±42.4	92.0	1.35	47.1	0.1	$< 6.7 \times 10^{-5}$
$Z_{cs}^\pm \to K^\pm J/\psi$	−22.2±17.4	22.4	3.88	48.7	–	$< 5.7 \times 10^{-6}$