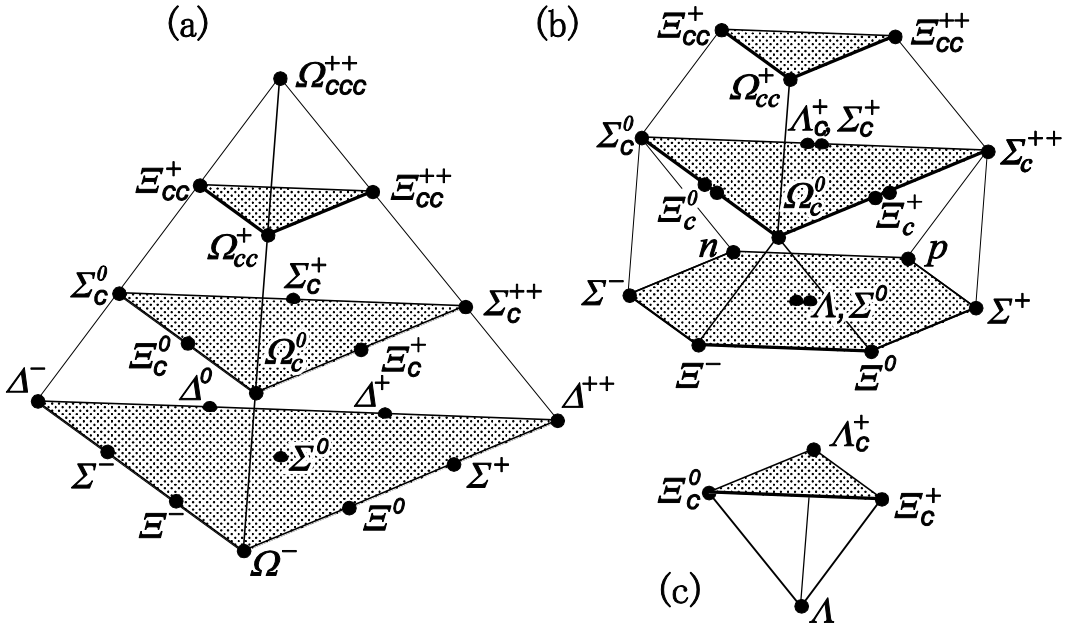
Charmed Baryon spectroscopy at Belle

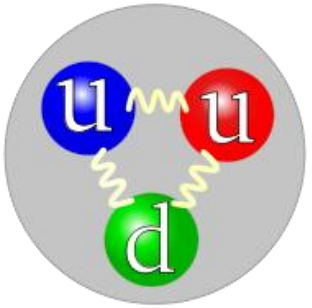
Y. Kato
KMI topics



Mainly based on the paper recently accepted by PRD
(arXiv:1312.1026)

Introduction

The mass of matter is almost made of nucleons.
But they are still not understood.



1. **Mass generation.**
   Mass of up, down quark is several MeV ⇔ Nucleon mass: ~1000 MeV.
   Nucleon mass is generated from dynamics of quarks and gluons.

2. **Quark confinement.**
   Single quark has been never observed.

These happens simultaneously!

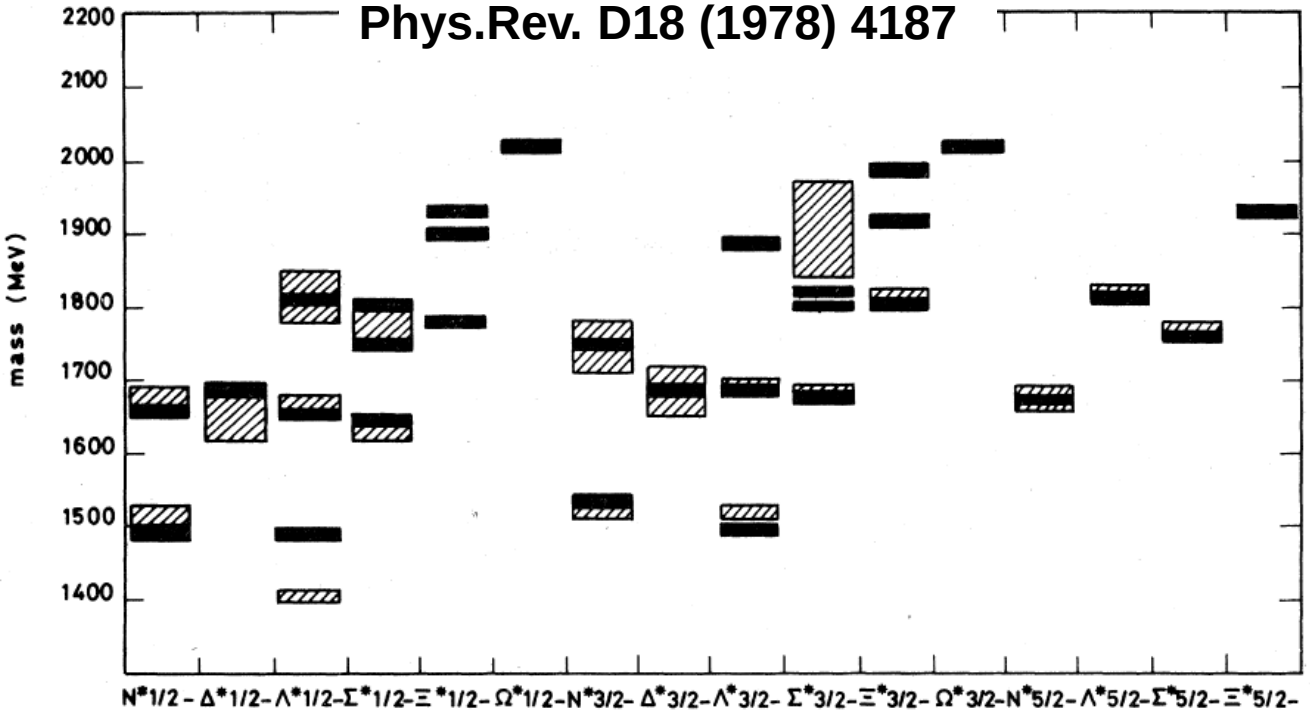
Bound state means it has negative potential like nuclei.
But quarks obtain masses inside nucleon.
To understand these two is (personal) goal of hadron physics.

QCD is non-perturbative in low energy. Hard to solve … but

Success of the constituent quark model

- Assume ~300 (~500) MeV/c^2 for u,d (s) quark mass (constituent quark).
- Harmonic oscillation and hyperfine interaction.

very simple!



- "Constituent quark" is a good apporoximation.
- Why it works so well? What is adaptive limit?
- What is the real degree of freedom to describe hadrons? Constituent quarks are enough?

Physics of charmed baryons (1)

Mass of the charm quark is ~1.5 GeV.

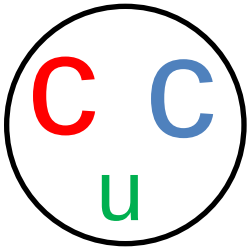
This is much heavier than….

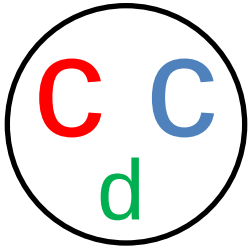
1. Momentum of quarks inside the baryon (~0.2 GeV/c)

Non-relativistic potential approach is a good approximation to describe interaction between heavy quarks

Charmonium spectroscopy→understanding of QQ^{bar} potential
Linear+Coulomb

doubly charmed baryon(Ξ_{cc}) spectroscopy→
understanding of QQ potential. Interaction of colored object





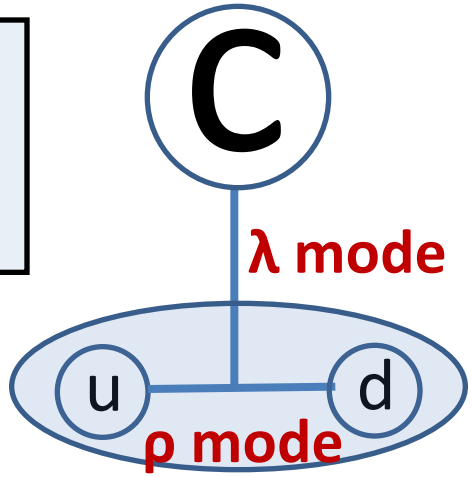
Physics of charmed baryons (2)

Mass of the charm quark is ~1.5 GeV/c^2.

This is much heavier than….

2.Mass of u,d,s quarks (0.3-0.5 GeV/c^2)

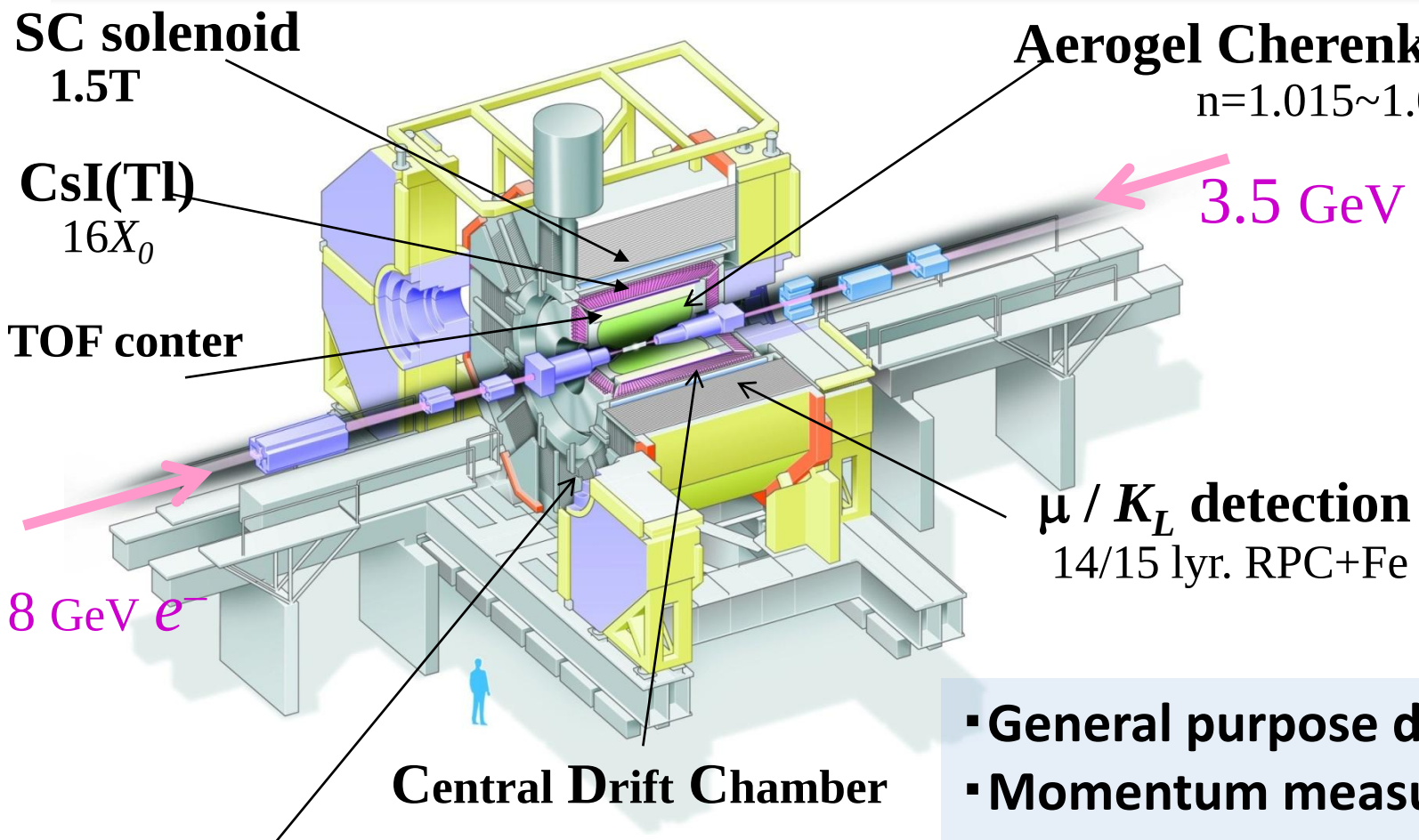
spin-spin interaction $\propto 1/m_1 m_2$.
In single charm baryon, strong spin-spin interaction among light quarks may form diquark



Two excitation modes in the baryon
Interaction among diquark: ρ mode
Interaction among diquark and c quark: λ mode

Diquark is a appropriate freedom to describe hadrons?
Study of ρ mode→diquark spectroscopy.
Clear information for interaction of two light quarks.

Experimental probe: Belle experiment



- General purpose detector
- Momentum measurement by SVD, CDC
- p/K/π ID by CDC (dE/dx), TOF, ACC → cover p<~3.5 GeV/c

Hadron physics at B-factories

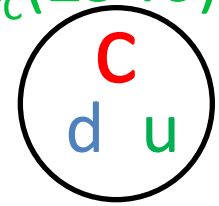
	Mesons	Baryons
2014	Z(3900)	
2012	$Z_b(10610)$ $Z_b(10650)$ $h_b(2P)$ $\eta_b(2S)$	
2010	$h_b(1P)$ Z(4430)	
2008	Z(4050) Z(4250) $\eta_b(1S)$ Y(3940) Y(4660)	$\Xi_c(3055)?$ $\Xi_c(3123)?$ $\Lambda_c(2940)$
2006	Y(4260)	$\Omega_c(2770)$ $\Xi_c(2980)$ $\Xi_c(3080)$ $\Sigma_c(2800)$
2004	Ds(2317) Ds(2460) X(3872)	
2002	$\eta_c(2S)$	

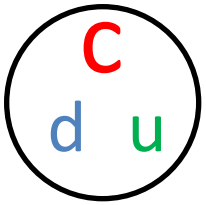
More than 20 “new hadrons” have been discovered by B-factories

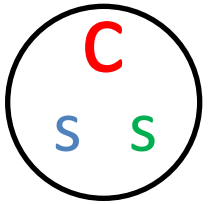
Among them, so called XYZ states are very famous.

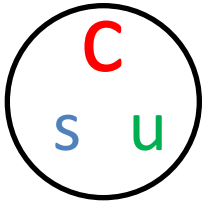
Observed charmed baryons

Λ_c^+	$1/2^+$	$\Sigma_c(2455)$	$1/2^+$	Ξ_c	$1/2^+$	Ω_c	$1/2^+$
$\Lambda_c(2595)^+$	$1/2^-$	$\Sigma_c(2520)$	$3/2^+$	Ξ'_c	$1/2^+$	$\Omega_c(2770)$	$3/2^+$
$\Lambda_c(2625)^+$	$3/2^-$	$\Sigma_c(2800)$	$?^?$	$\Xi_c(2645)$	$3/2^+$		
$[\Lambda_c(2765)^+$	$?^?]$			$\Xi_c(2790)$	$1/2^-$		
$\Lambda_c(2880)^+$	$5/2^+$			$\Xi_c(2815)$	$3/2^-$		
$\Lambda_c(2940)^+$	$?^?$			$[\Xi_c(2930)$	$?^?]$		
				$\Xi_c(2980)$	$?^?$		
				$[\Xi_c(3055)$	$?^?]$		
				$\Xi_c(3080)$	$?^?$		
				$[\Xi_c(3123)$	$?^?]$		





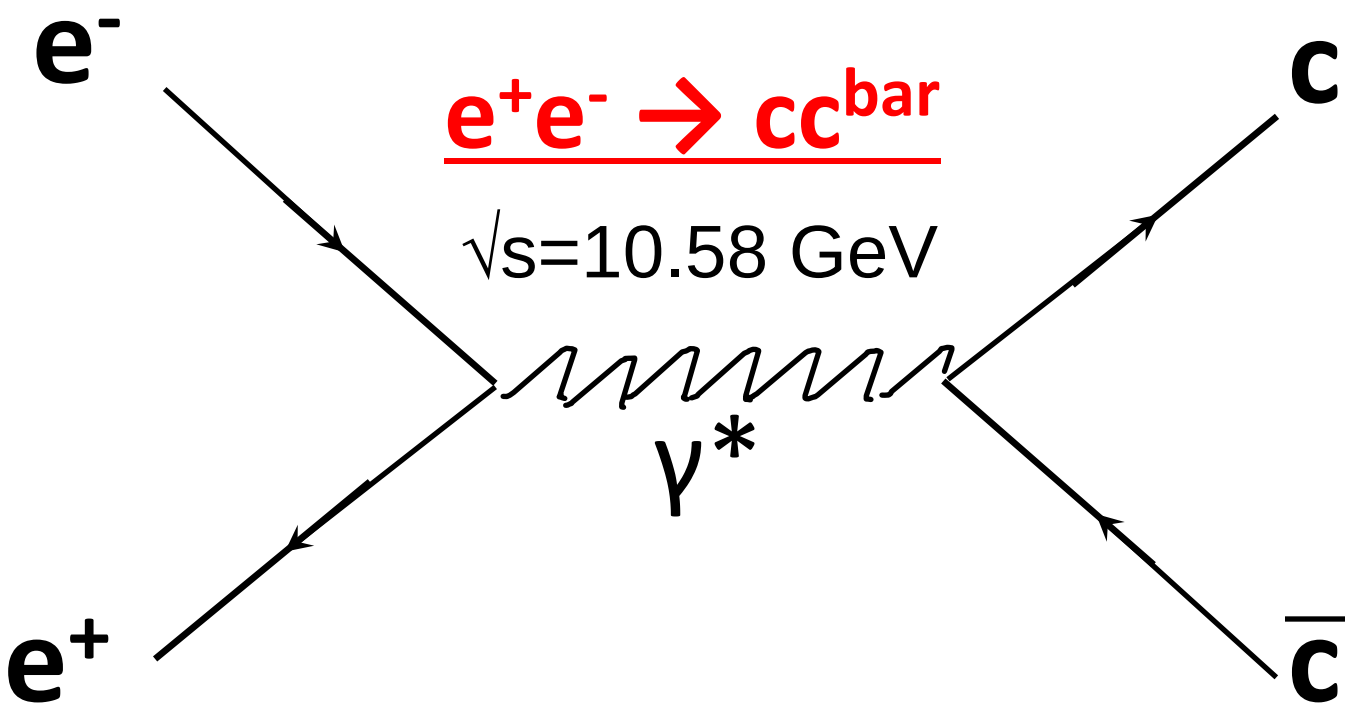




CLEO 8(7) (1995～2001)
BELLE 3 (2006～)
BABAR 5(2) (2007～)

- 16/21 (12/17) charmed baryons are observed in e^+e^- collider experiment.
- All the ground state of single charmed baryons are discovered.
- Except for $\Lambda_c(2595)^+$, $\Lambda_c(2880)^+$, $\Sigma_c(2455)$, spin/parity are not measured.

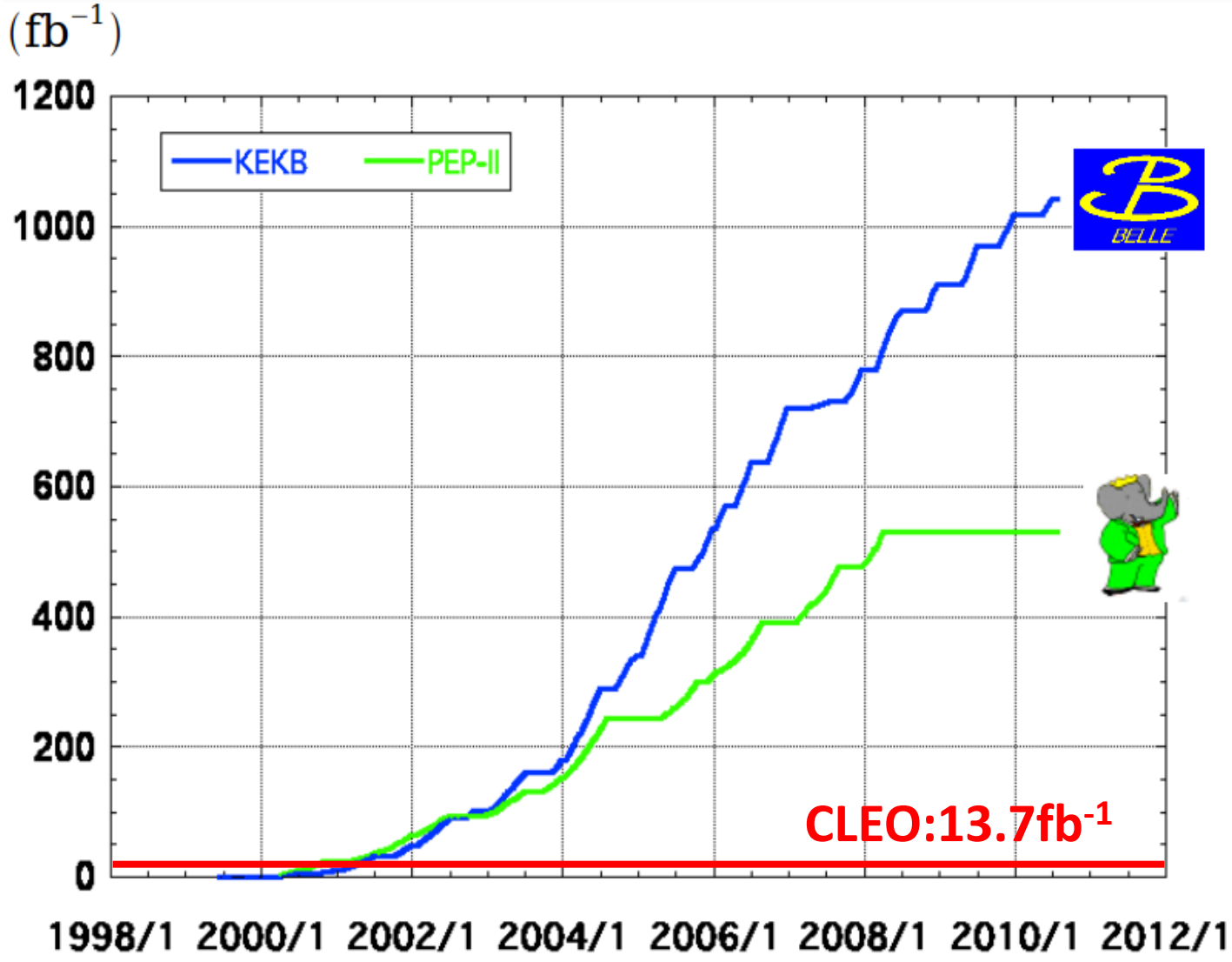
Charm production in e^+e^- collider



- Cross section for $e^+e^- \rightarrow q\bar{q}$ does not depend on the flavor of quarks. Depends only on the charge^2.
  $\rightarrow \sigma(e^+e^- \rightarrow c\bar{c}) = \sigma(e^+e^- \rightarrow u\bar{u}) = 4\sigma(e^+e^- \rightarrow s\bar{s}) = 4\sigma(e^+e^- \rightarrow d\bar{d})$

- Detect decay particles only (inclusive reaction) ⇔ $\pi(p,D^*)Y_c$@J-PARC.

Integrated luminosity of B-factories



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

~ 54 fb^{-1}

$\sigma(e^+e^- \rightarrow c\bar{c}^{bar}) \simeq 1nb \rightarrow 10^{\wedge 9}$ $c\bar{c}^{bar}$ events are produced!

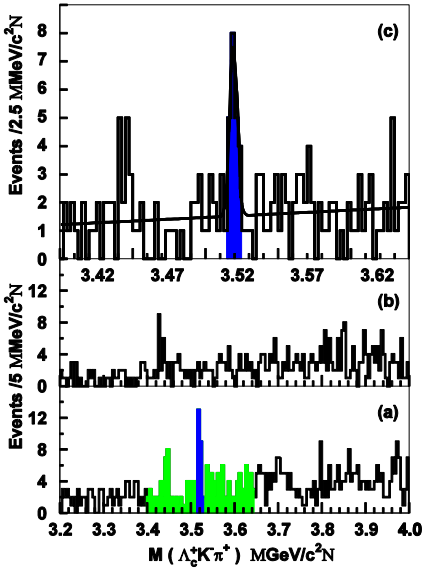
Outline of this talk

- Doubly charmed baryon(Ξ_{cc}) search.
- Excited charm-strange baryons (Ξ_c*).
- Work in progress.

Past experimental search for Ξ_{cc}

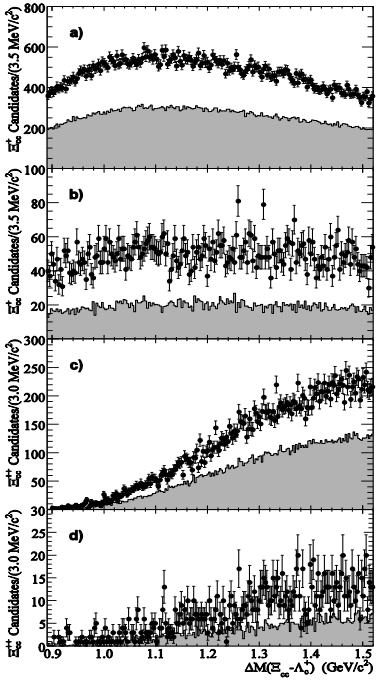
- Prediction of the mass: ~3.5-3.75 GeV by quark model, 3.6 GeV by LQCD
- Evidence by SELEX was not supported by FOCUS, B-factories.
- No established state even for ground state.

Evidence from SELEX in 2003
Mass:~3.52 GeV/c^2



$M(\Lambda_c^+K^-\pi^+)$
hep-ex/0208014

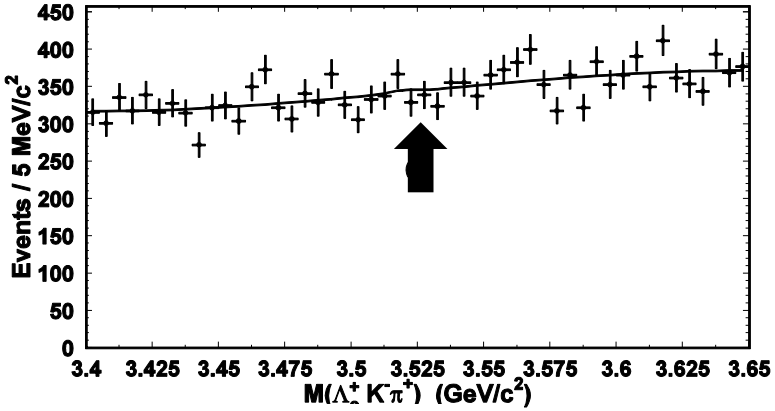
BaBar@232 fb^{-1}



hep-ex/0605075

B-factories

Belle@461.5fb^{-1}

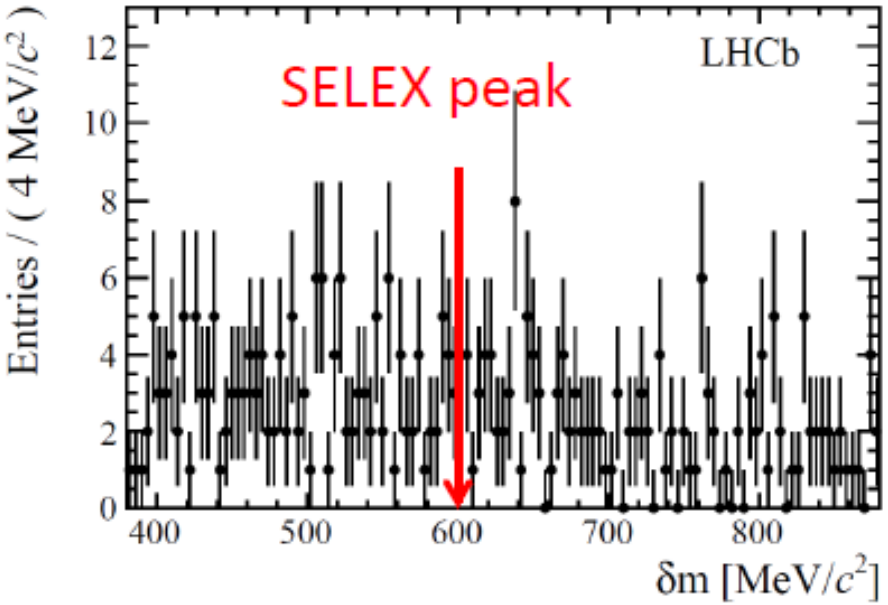


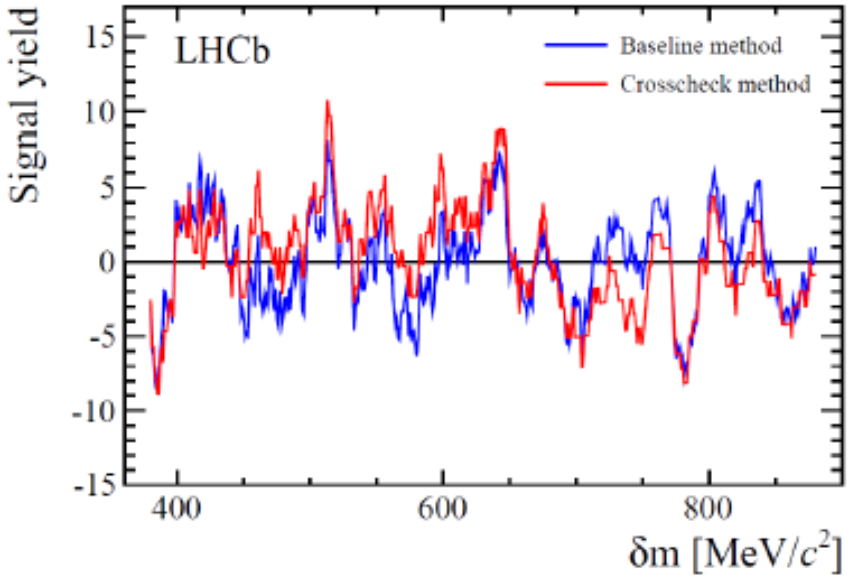
$M(\Lambda_c^+K^-\pi^+)$
hep-ex/0606051

Search for Ξ_{cc}^+ at LHCb

- Search for Ξ_{cc}^+ through $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+, \Lambda_c^+ \to p K^- \pi^+$ arXiv:1310.2538
  - Dataset: 0.65 fb^{-1} of 2011 data
- For signal yield construct δm quantity
  - $\delta m = m(\Lambda_c^+ K^- \pi^+) - m(\Lambda_c^+) - m(K^-) - m(\pi^+)$
- No significant signal observed

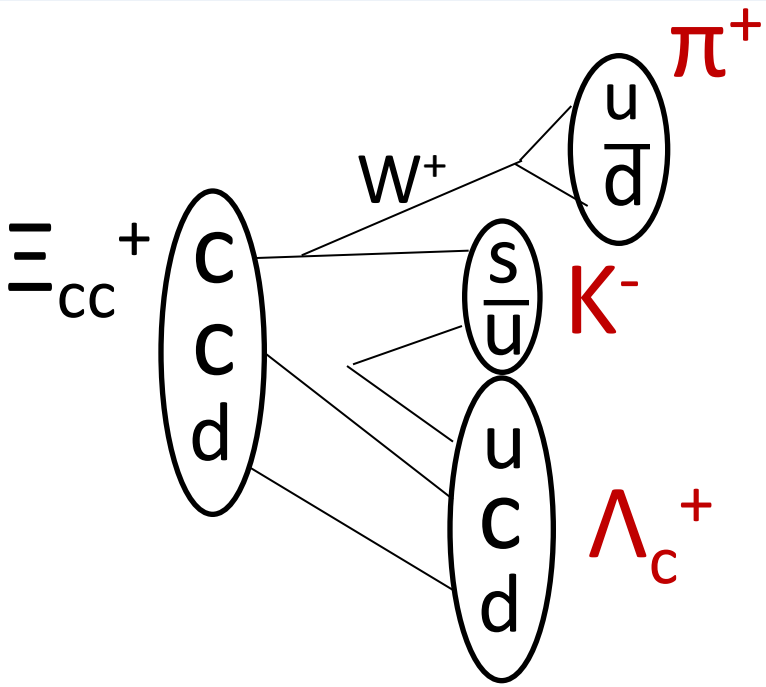
Λ_c^+ yield ~8×10^5
$\Leftrightarrow$ ~3×10^6 for Belle

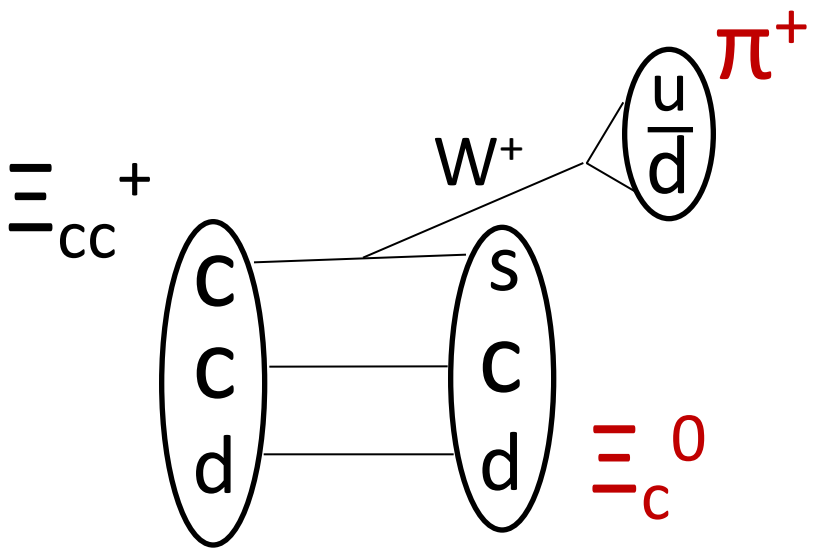




Ξ_{cc} decay modes

- Ground state baryon decays via weak interaction(c→s).
- Ξ_{cc}^{+} is expected to decay into $\Lambda_c K^- \pi^+$ and $\Xi_c^0 \pi^+$





- Background: inclusive Λ_c^+ or Ξ_c^0 production.
- $\sigma(e^+e^- \to \Lambda_c^+ X) \times Br(\Lambda_c^+ \to pK\pi)/\sigma(e^+e^- \to \Xi_c^0 X) \times Br(\Xi_c^0 \to \Xi^-\pi^+) \sim 10$.

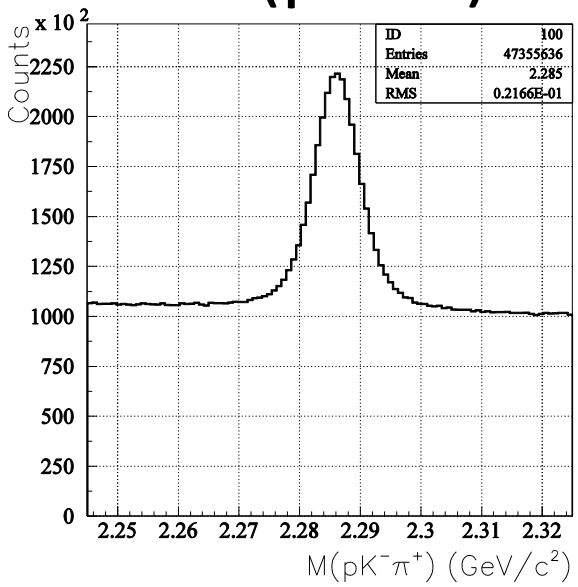
Improved search of Ξ_{cc}^{+} by Belle

	BaBar	Previous Belle	This study
Luminosity (fb^{-1})	232	462	980
Ξ_{cc}^{+} decay	$\Lambda_c^{+}K^{-}\pi+$ $\Xi_c^{0}\pi^{+}$	$\Lambda_c^{+}K^{-}\pi^{+}$	$\Lambda_c^{+}K^{-}\pi^{+}$ $\Xi_c^{0}\pi^{+}$
Λ_c^{+} decay	$pK^{-}\pi^{+}$	pK-π+	$pK^{-}\pi^{+}$, pK_S^{0}
Ξ_c^{0} decay	$\Xi^{-}\pi^{+}$	----------	$\Xi^{-}\pi^{+}$, $\Lambda K^{-}\pi^{+}$, $pK^{-}K^{-}\pi^{+}$

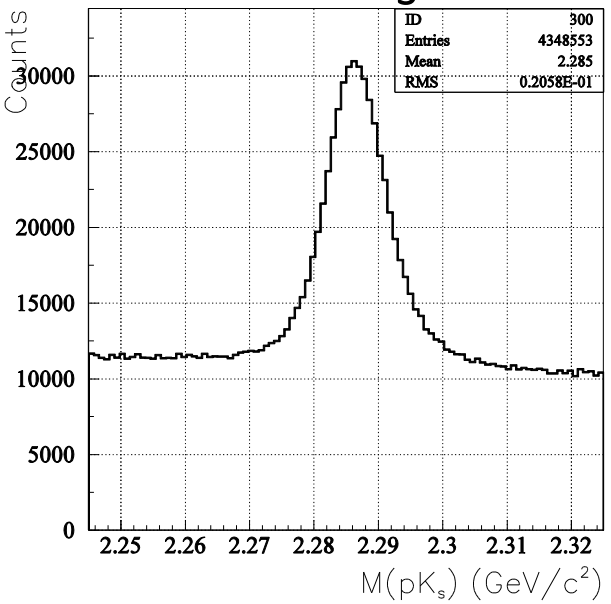
- Full statistics
- Two Ξ_{cc} decay modes.
- Several sub decay modes

Reconstruction of Λ_c^+

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



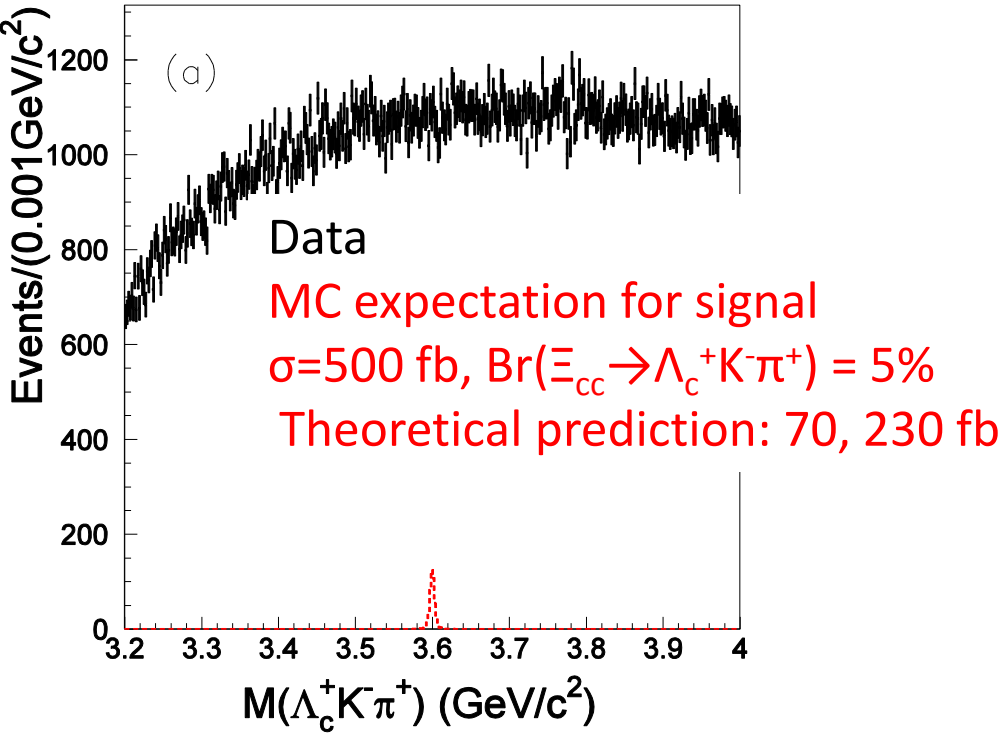
$M(pK_s)$



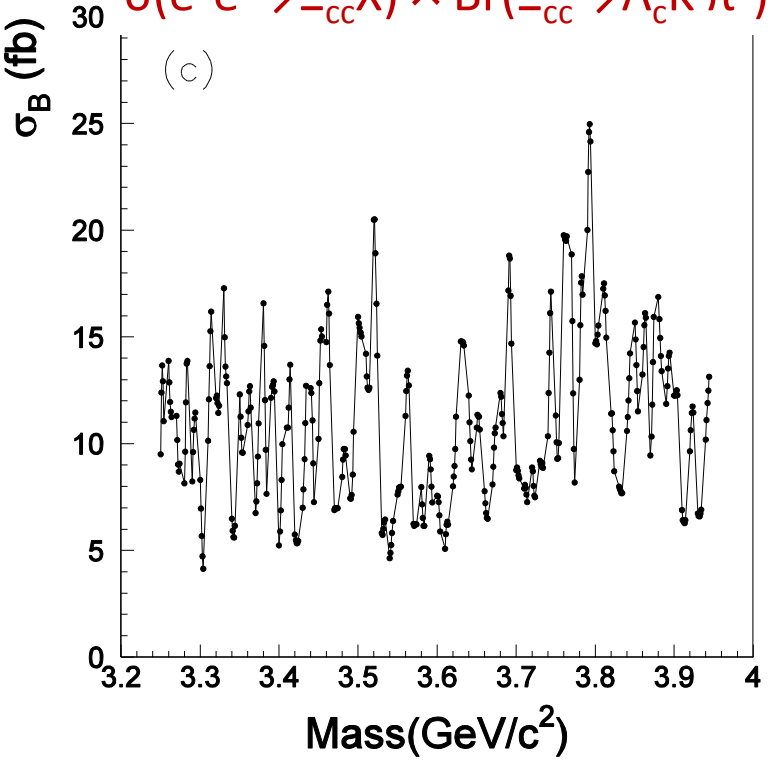
- Previous studies used $pK^-\pi^+$ only.
- Inclusion of pK_S mode increases statistics by ~20 %.
- S/N ratio is comparable.→Combine two decay modes.
- Total Λ_c^+ yield is around ~3×10^6⇔ ~1600 Λ_c^+ by SELEX.
- Apply mass constraint on Λ_c^+→Mass resolution for Ξ_{cc} is 2.5-3.5 MeV/c^2

Result for $\Lambda_c^+K^-\pi^+$ decay mode

$M(\Lambda_c^+K^-\pi^+)$



95% C.L Upper limit of
$\sigma(e^+e^-\to\Xi_{cc}X)\times Br(\Xi_{cc}\to\Lambda_cK^-\pi^+)$

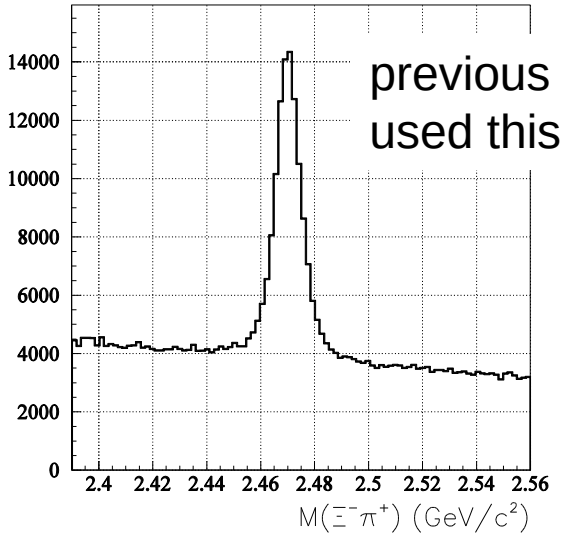


- Significance from -2ln(L/L(0))
- Significance is less than 3σ in all mass region...

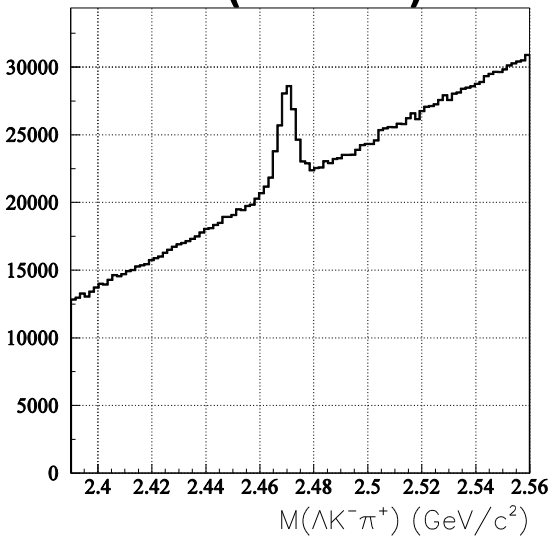
Belle	**4.1-25.0 fb**
Theory	3.5-11.5 fb (assuming Br=5%)

Reconstruction of Ξ_c^0

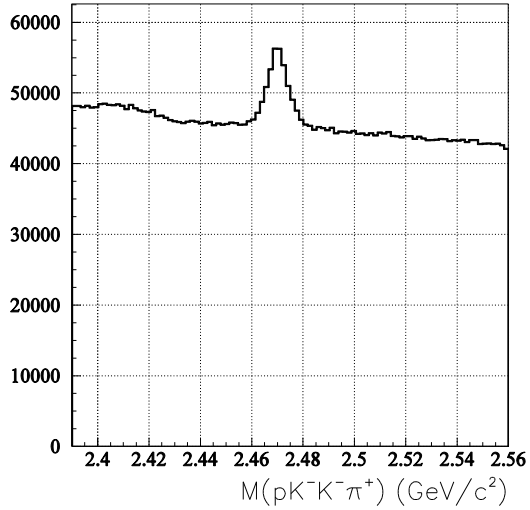
$M(\Xi^-\pi^+)$



$M(\Lambda K^-\pi^+)$



$M(pK^-K^-\pi^+)$



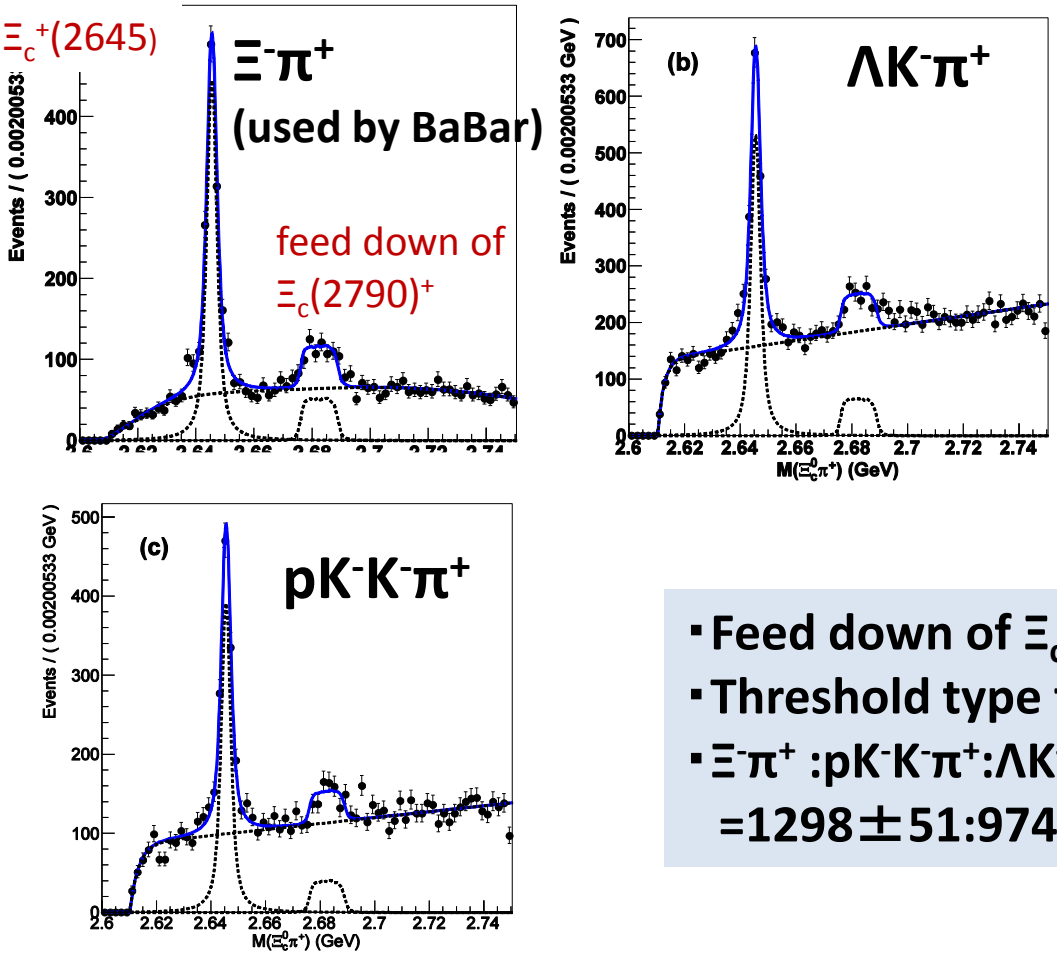
- Total yield of the Ξ_c^0 is 1.6×10^5
- Previous study by BaBar use $\Xi^-\pi^+$ only.
- S/N largely depends on the decay mode.

→Simultaneous fit with fixing
relative signal yield gives better sensitivity.

Calibration mode for $\Xi_{cc}^{+} \rightarrow \Xi_c^{0}\pi^{+}$: $\Xi_c^{+}(2645)$

Signal yield ratio for each decay mode of Ξ_c^{0} is determined from yield of $\Xi_c(2645)^{+}$, which decays strongly to $\Xi_c^{0}\pi^{+}$.

$M(\Xi_c^{0}\pi^{+})$ in low mass region



- Feed down of $\Xi_c(2790)^{+} \rightarrow \Xi_c^{0}\pi^{+}\gamma$ from MC
- Threshold type function for B.G
- $\Xi^{-}\pi^{+}$:$pK^{-}K^{-}\pi^{+}$:$\Lambda K^{-}\pi^{+}$:
  $=1298 \pm 51 : 974 \pm 47 : 1444 \pm 58$

Width of the $\Xi_c^+(2645)$

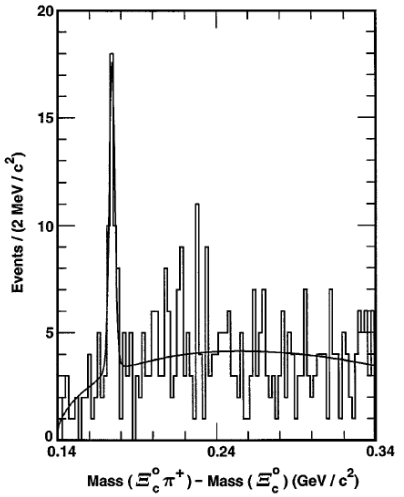
Only upper limit is given in PDG

$\Xi_c(2645)$ WIDTHS

$\Xi_c(2645)^+$ WIDTH

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
<3.1	90	GIBBONS	96	CLE2	$e^+e^- \approx \Upsilon(4S)$

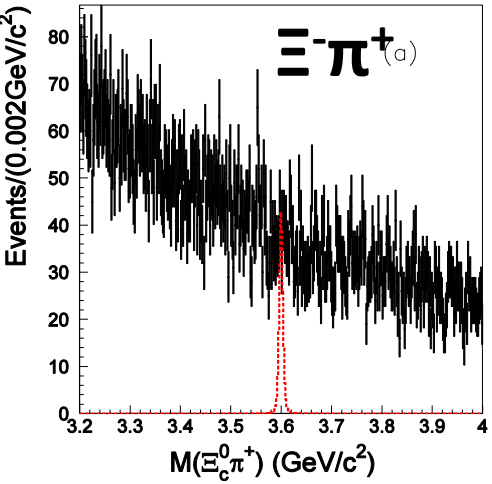
CLEO PRL. **77**, 810

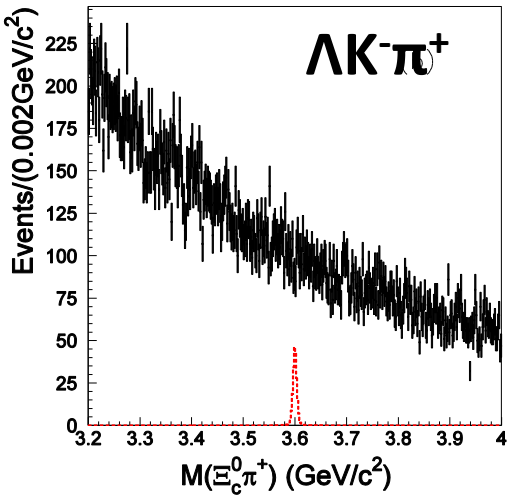


Mode	Width(MeV/c^2)	Peak(MeV/c^2)
$pK^-K^-\pi^+$	2.5±0.3	2645.5±0.1
$\Lambda K^-\pi^+$	2.6±0.3	2645.3±0.1
$\Xi^-\pi^+$	2.9±0.3	2645.4±0.1
Simultaneous	**2.6±0.2±0.4**	2645.4±0.1 (statistics only)

First significant measurement of the width of $\Xi_c^+(2645)$

Result of Ξ_{cc}^{+} search:$\Xi_c^0\pi^+$

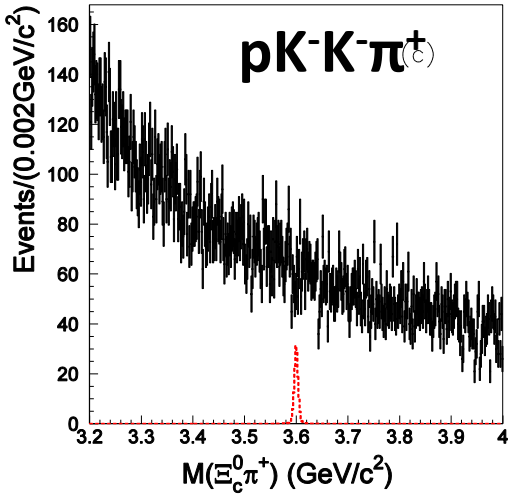




Data

Signal MC

(assuming 500 fb and 5% for branching farctions.)



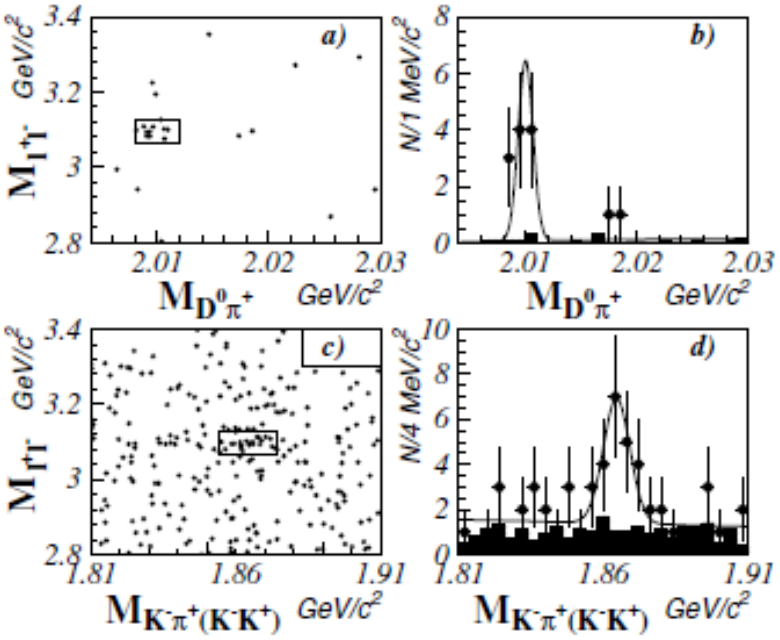
- Simultaneous fit with fixing signal yield ratio.
- 3.2σ for 3.553 GeV/c^2 but probability to observe a peak with significance>3.2 in this the mass range of 3.2-4.0 GeV is 26%.

95% UL of $\sigma(e^+e^-\to\Xi_{cc}X)\times Br(\Xi_{cc}^+\to\Xi_c^0\pi^+)\times Br(\Xi_c^+\to\Xi^-\pi^+)$

Belle	**0.076-0.35 fb**
Theory	0.18-0.5 fb (assuming Br=5%)

Study of double charm production

- **Production mechanism of double charm production is poorly known.**
  →predicted cross section is not reliable.
  - **e^+e^- → J/ψ+cc^{bar} by Belle**

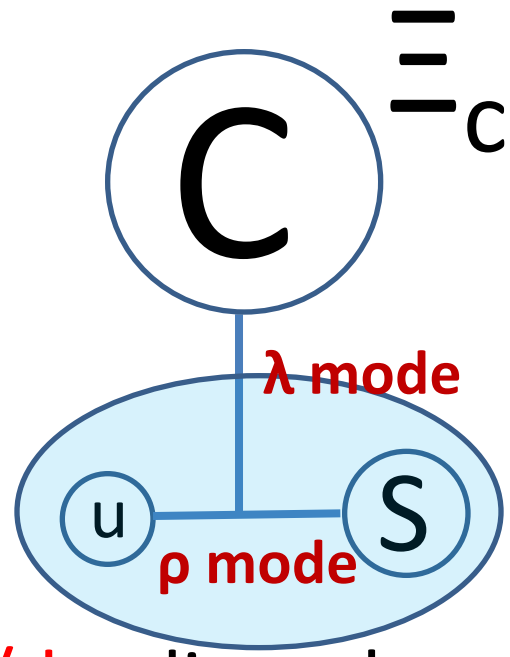


$$\sigma(J/\psi + c\bar{c}) = 0.87^{+0.21}_{-0.19} \pm 0.17\,pb \Leftrightarrow 0.006 - 0.012\,pb$$

No measurement on the double charm production without J/ψ so far.

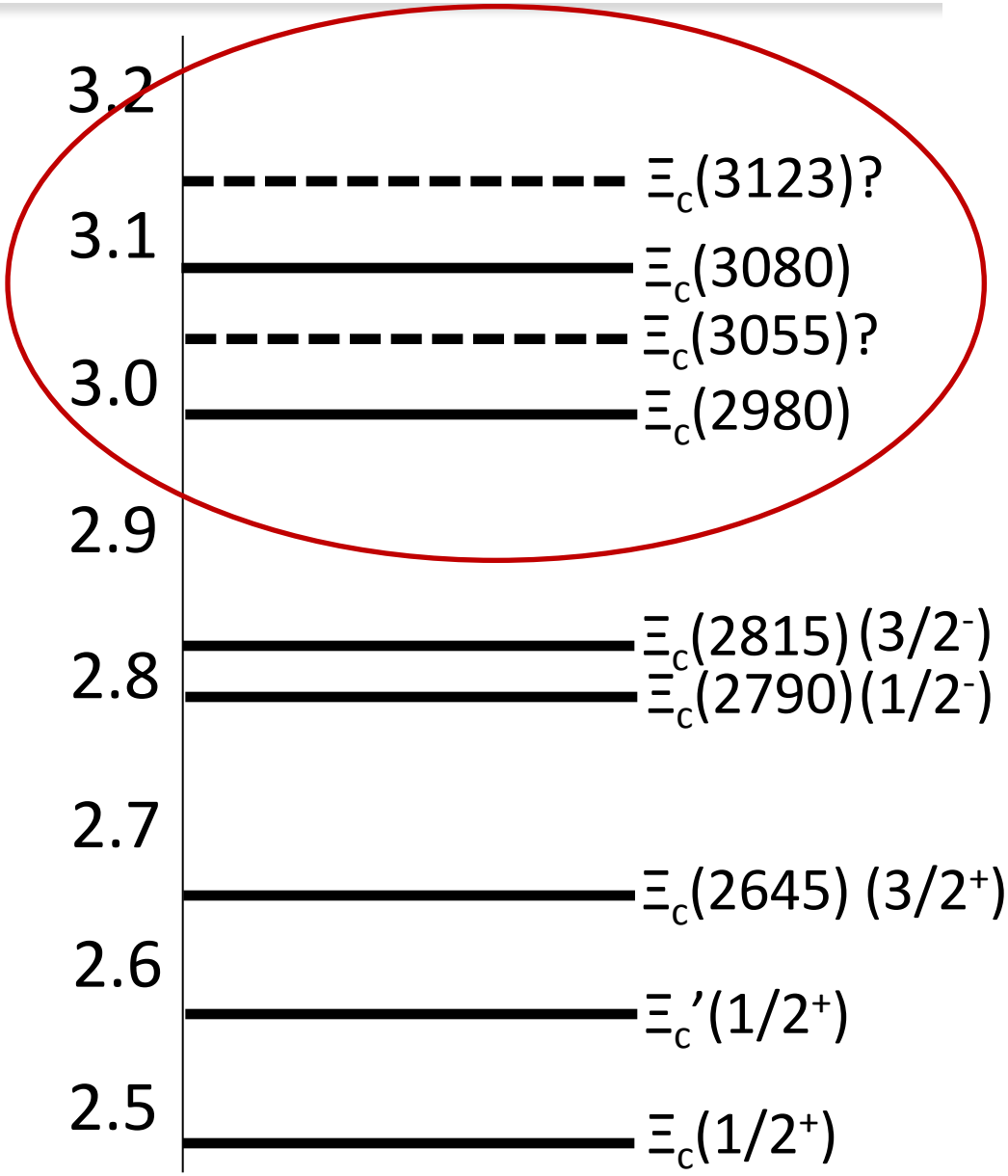
- O. Seon in Nagoya University is studying the elementary DD production using Belle data.

Charmed strange baryons (Ξ_c)



u/d-s diquark system!

Identification of ρ mode excitation is essential for di-quark spectroscopy. (only λ mode excitation is observed)

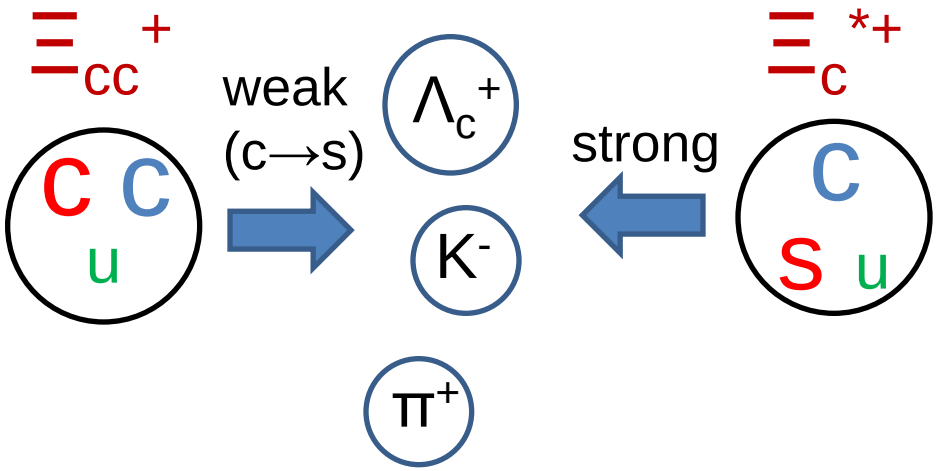


Ξ_{cc} and Ξ_c

Ground hadrons decays via the weak interaction.
This is also a strong decay of hadrons in light quark configuration.

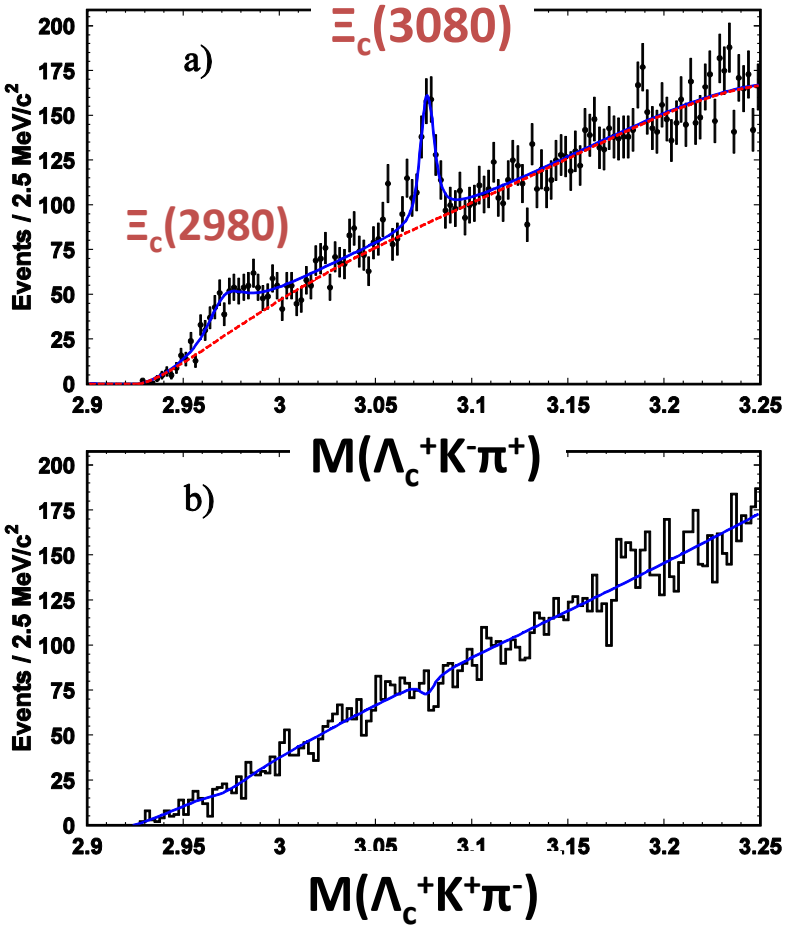
ex. pπ is a weak decay mode of Λ and strong decay mode of Δ
Kπ is a weak decay mode of D and strong decay mode of K*

Ξ_{cc} weak decay modes are Ξ_c* strong decay modes

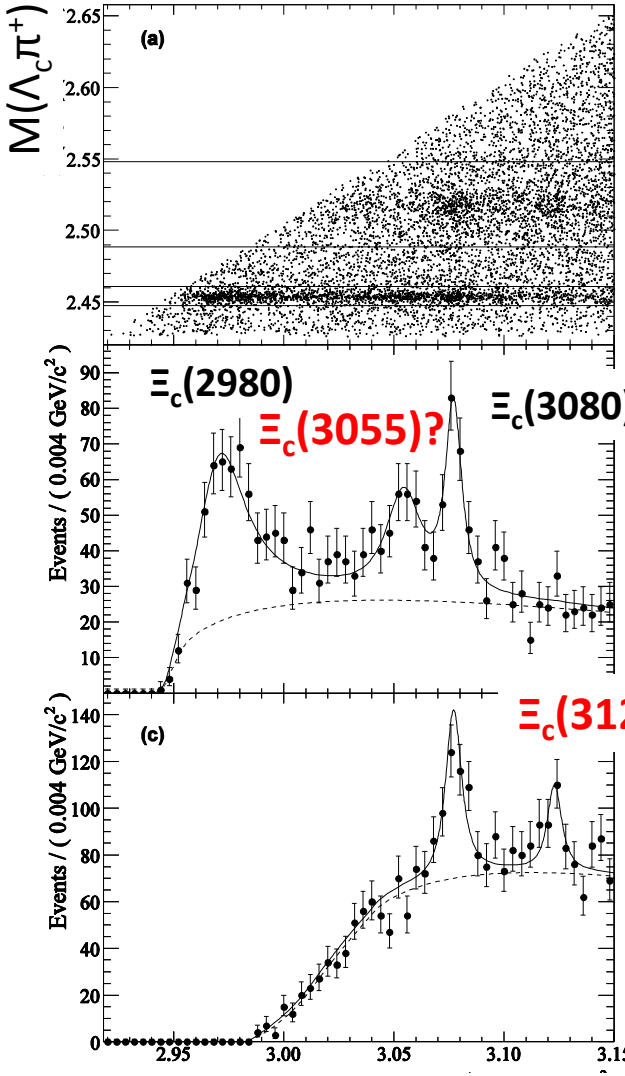


Excited Ξ_c^+ in $\Lambda_c^+K^-\pi^+$ by Belle and BaBar

hep-ex/0606051 **Belle@461.5fb^{-1}**

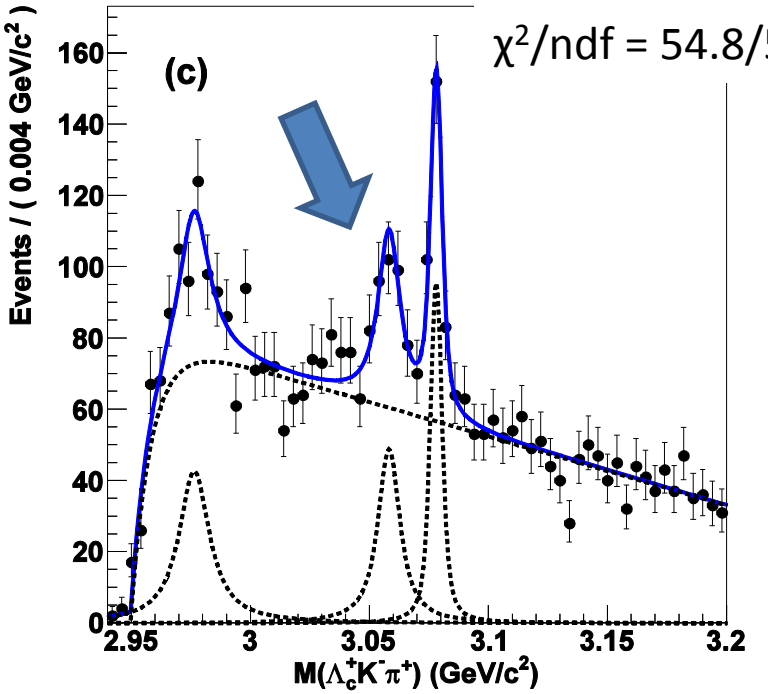


hep-ex :0710.5763 **Babar@384fb^{-1}**



- **Belle: First evidence of $\Xi_c(3080)$, $\Xi_c(2980)$**
- **BaBar: Confirmed them and reported two more states. $\Xi_c(3055)\rightarrow$2star, $\Xi_c(3123)\rightarrow$1star.**

$M(\Sigma_c(2455)^{++}K^-)$ by Belle



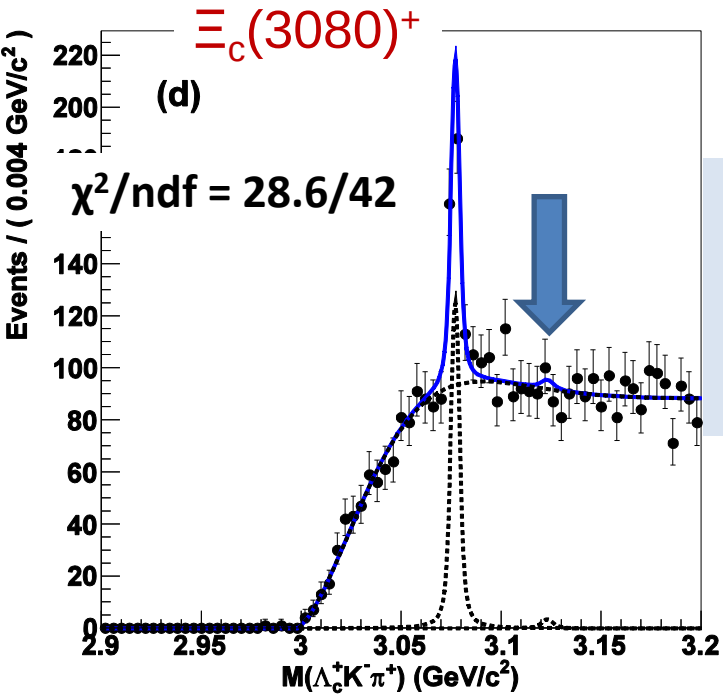
- Structure near 3055 MeV/c^2 is seen.
- Significance from -2log(L_{max}/L(0).
- Significance of 6.6 σ.

Mass/width of $\Xi_c^+(3055)$

	Belle	Babar
Mass	3058.1±1.0±2.1	3054.2±1.2±0.5
Width	9.7±3.4±3.3	17±6±1.1

Result of the Babar is confirmed with 6.8 σ.

$M(\Sigma_c^*(2520)^{++}K^-)$ by Belle



- Structure near 3123 MeV/c^2 is not seen
- Signal PDF:Gaussian convoluted Breit Wigner.
  Mean, width was fixed from measurement by BABAR.
- Yield = 8.2±22.0 → Measurement of upper limit

$\sigma \times Br(\Lambda_c^+ \to pK^-\pi^+)$ of $\Xi_c^+(3123)$

< 0.34 fb @95%C.L ⇔ 1.6±0.6±0.2 fb by BaBar

Result of the Babar was not reproduced...

Comparison of Λ_c^+ and Ξ_c or Σ_c and Ξ_c'

J^p	Λ_c^+(udc)	Ξ_c(usc)	$\Delta M(Mev/c^2)$
$1/2^+$	$\Lambda_c(2286)^+$	$\Xi_c(2470)$	181
$1/2^-$	$\Lambda_c(2595)^+$	$\Xi_c(2790)$	194
$3/2^-$	$\Lambda_c(2625)^+$	$\Xi_c(2815)$	188
??	$\Lambda_c(2765)^{+?}$	$\Xi_c(2980)$?	205
$5/2^+$	$\Lambda_c(2880)^+$	$\Xi_c(3080)$?	200

spin0 di-quark

J^p	Σ_c(udc)	Ξ_c' (usc)	$\Delta M(Mev/c^2)$
$1/2^+$	$\Sigma_c(2455)$	$\Xi_c(2575)$	120
$3/2^+$	$\Sigma_c(2520)$	$\Xi_c(2645)$	125
??	$\Sigma_c(2800)$	??	

spin1 di-quark

- The mass difference of Λ_c and Ξ_c is ~200 MeV/c^2, Σ_c and Ξ_c' is ~120 MeV

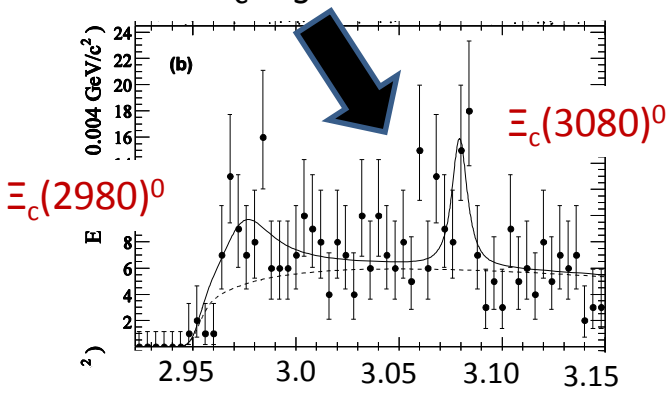
Λ_c^+ with 3055-200 = 2855? Σ_c with 3055-120 = 2935?

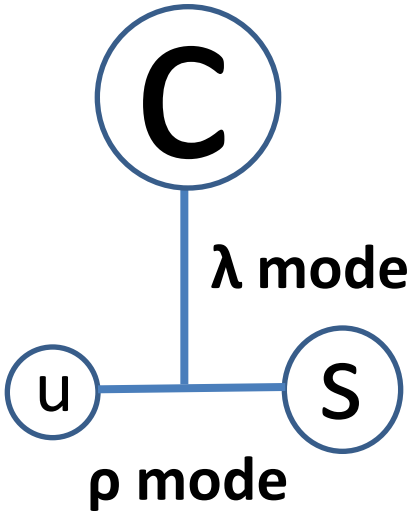
Further study for Ξ_c^*

- We confirmed $\Xi_c(3055)^+$ but its isospin partner $\Xi_c(3055)^0$ is not found.
- Spin-parity and excitation mode is not known for excited states.
- Relative branching fraction is sensitive to the excitation mode.
- More excited states?

arxiv:0710.5763

$M(\Lambda_c^+ K_S^0 \pi^-)$ by BaBar

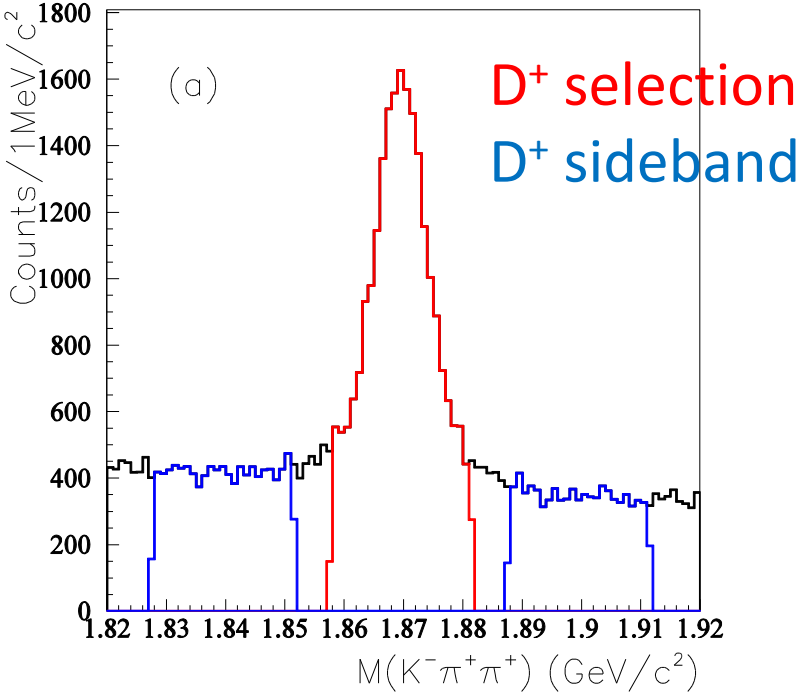




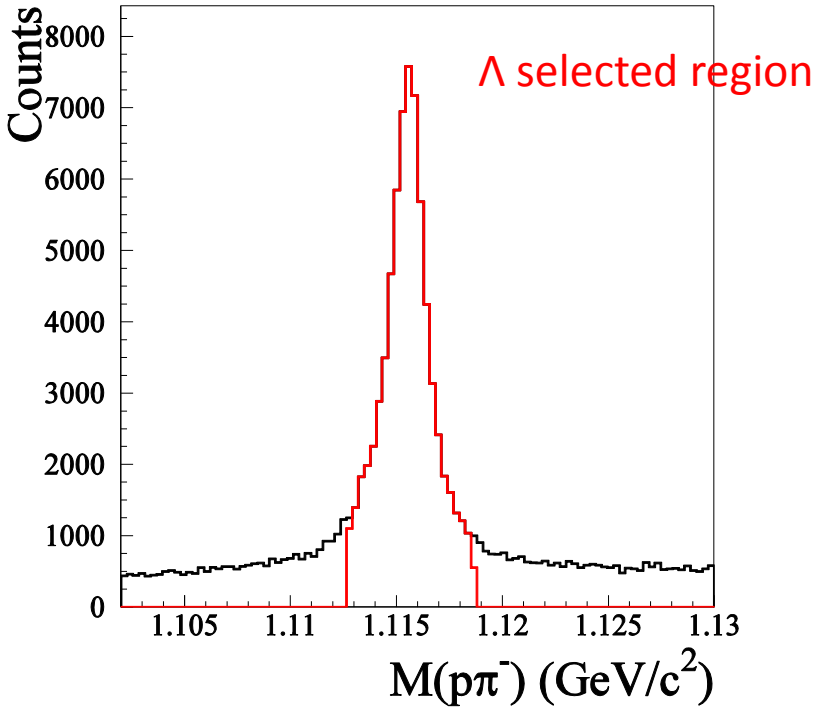
- All the Ξ_c^* are observed in (heavy baryon) + (light meson) final states.
  $\Lambda_c^+, \Sigma_c, \Xi_c, \Xi_c'$.. π, K
- How about the (light baryon) + (heavy meson) ? → study ΛD!

Analysis of ΛD^+

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

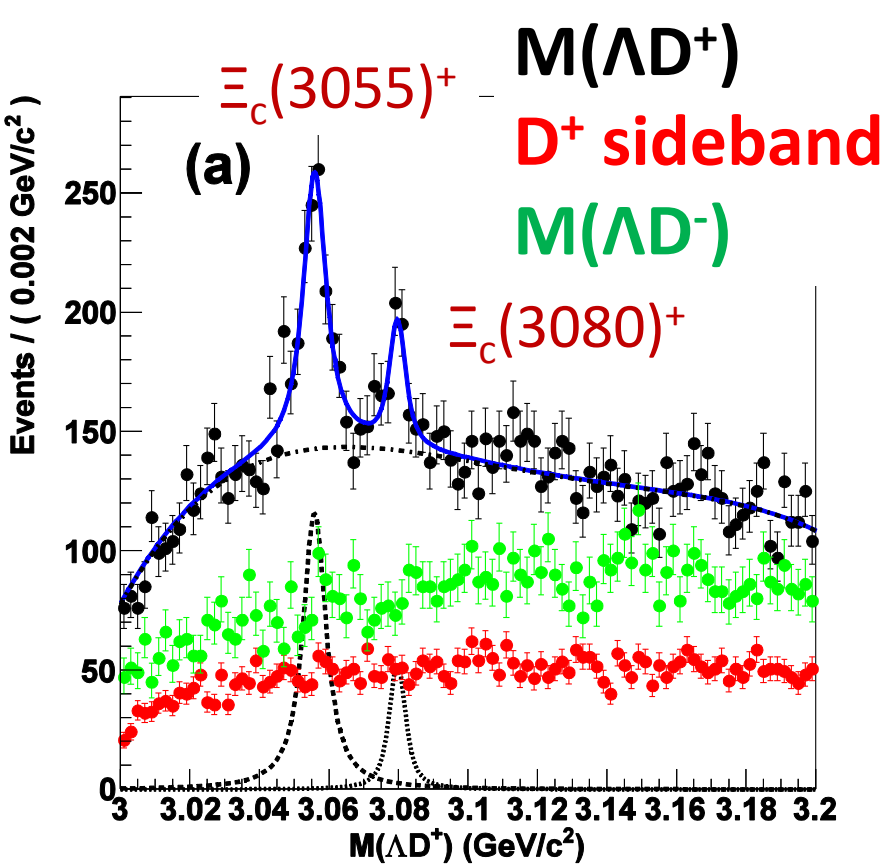


$M(p\pi^-)$



- D^+ from $K^-\pi^+\pi^+$, Λ from $p\pi^-$. Vertex information on Λ.

$M(\Lambda D^+)$ distribution

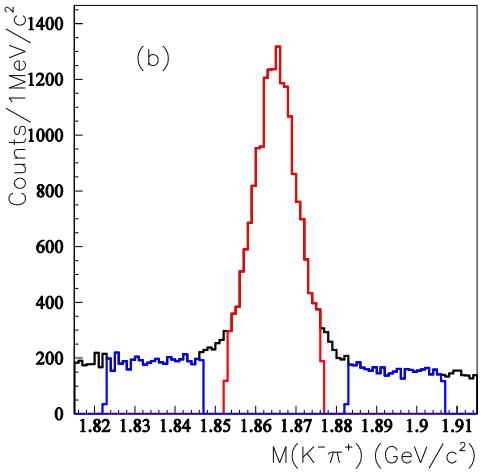


- Peaks corresponds to $\Xi_c(3055)^+$, $\Xi_c(3080)^+$.
- No peak structure in D^+ sideband region and wrong-sign ΛD^- combination.
- Significance of the peaks are: 11.7σ for $\Xi_c(3055)^+$ and 4.7σ for $\Xi_c(3080)^+$.
- Further confirmation for $\Xi_c(3055)^+$
- Most precise mass/width for $\Xi_c(3055)^+$ and consistent with previous measurements.

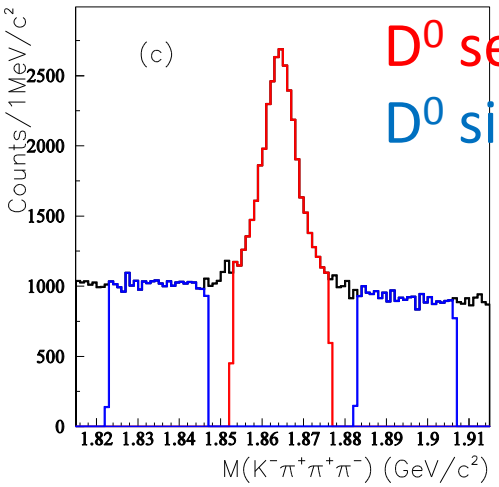
	$\Xi_c(3055)^+$	$\Xi_c(3080)^+$
Mass(MeV/c^2)	3055.7±0.4±0.4	3079.6±0.6±0.7
Width(MeV)	7.1±1.2±1.8	4.0±1.5±1.0

Analysis of ΛD^0

$D^0 \to K^-\pi^+$



$D^0 \to K^-\pi^+\pi^+\pi^-$

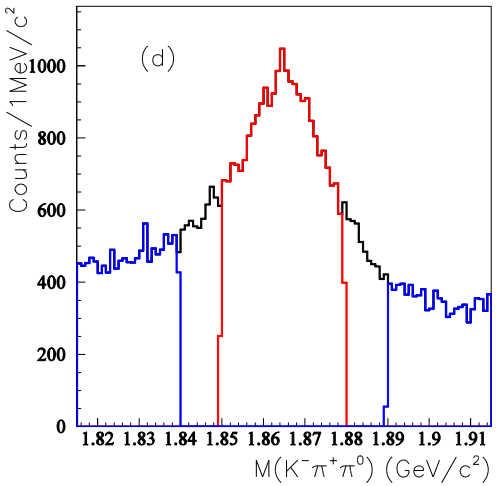


D^0 selection

D^0 sideband

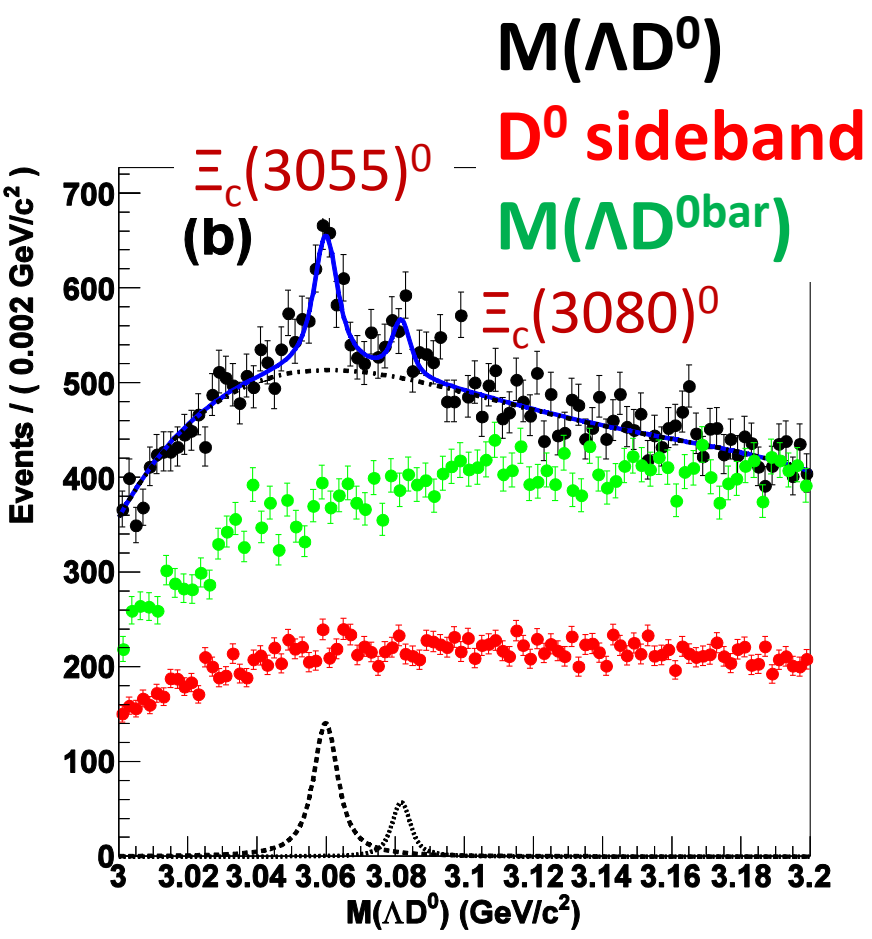
- D^0 from $K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$, $K^-\pi^+\pi^0$
- Relative yields are comparable.

$D^0 \to K^-\pi^+\pi^0$



	Branch(%)	Efficiency(%)	Product(%)
$D^+ \to K^-\pi^+\pi^+$	9.13	18.9	1.72
$D^0 \to K^-\pi^+$	3.88	23.5	0.912
$D^0 \to K^-\pi^+\pi^+\pi^-$	8.07	14.8	1.20
$D^0 \to K^-\pi^+\pi^0$	13.9	6.28	0.873

$M(\Lambda D^0)$ distribution



- Peaks corresponds to $\Xi_c(3055)^0$, $\Xi_c(3080)^0$.
- No peak structure in D^0 sideband region and wrong-sign $D^{0bar}\Lambda$ combination.
- Significance of the peaks are:
  7.6σ for $\Xi_c(3055)^0$ and 2.6σ for $\Xi_c(3080)^0$.
- **First observation of $\Xi_c(3055)^0$!**

	$\Xi_c(3055)^0$	$\Xi_c(3080)^0$
Mass(MeV/c^2)	3059.7±0.6±0.5	3079.6±0.6±0.7
Width(MeV)	7.4±1.9±3.4	4.4±1.8±1.9

Discussion from decay modes

- The Ξ_c^* with mass around 3.0 GeV/c^2 is likely to be in N=2 shell.

partial width

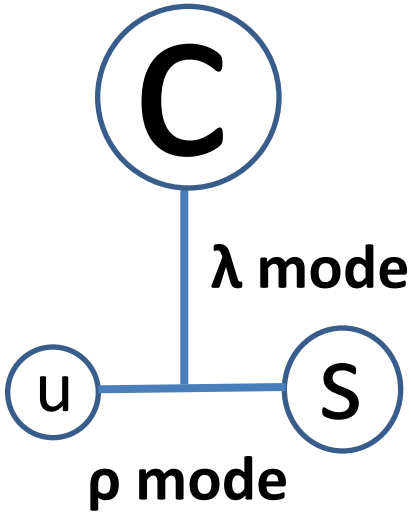
	$\Sigma_c K$	$\Xi_c^*(2645)\pi$	$\Xi_c'\pi$	$\Sigma_c^* K$	$D\Lambda$	total
$^2D_{\lambda\lambda}(3/2^+)$	2.3	0.5	1.0	0.1	0.1	4.0
$^2D_{\rho\rho}(3/2^+)$	5.6	0.8	3.3	0.3	–	10.0

Prediction by chiral quark model for partial width of $\Xi_c(3055)$ is inconsistent with this observation.

arXiv:1205.2943
Lei-Hua Liu et al

- $\Xi_c(3055)/(3080)$ can decay into both of
  (heavy baryon) + (light meson) and **(light baryon) + (heavy meson)**

Σ_c K^- Λ D



Naively thinking,
λ mode → **(light baryon) + (heavy meson)**
ρ mode → **(heavy baryon) + (light meson)**

Both ρ and λ mode excitation??

Help of the theorist is necessary!

Another interest: $\Lambda_c/\Sigma_c(2765)^+$

$\Lambda_c(2765)^+$ or $\Sigma_c(2765)$

$I(J^P) = ?(?^?)$ Status: *

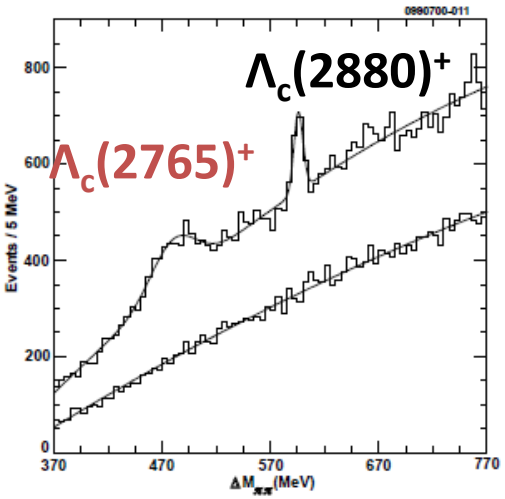
OMITTED FROM SUMMARY TABLE

A broad, statistically significant peak (997^{+141}_{-129} events) seen in $\Lambda_c^+\pi^+\pi^-$. However, nothing at all is known about its quantum numbers, including whether it is a Λ_c^+ or a Σ_c, or whether the width might be due to overlapping states.

Most poorly known Λ_c/Σ_c state

hep-ex/0010080

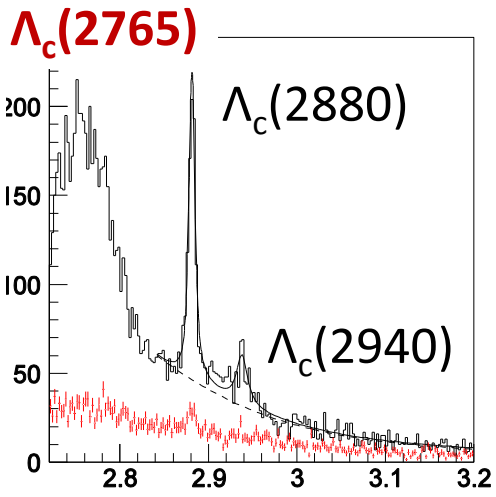
- **First evidence by CLEO**



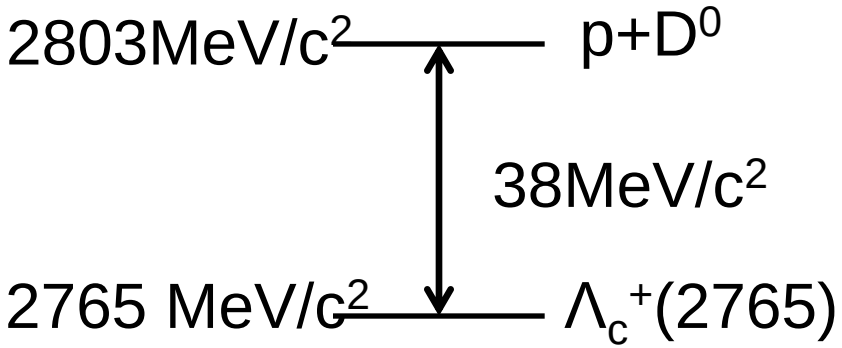
$M(\Lambda_c^+\pi^+\pi^-)$

hep-ex/0608043

- **By Belle**



$M(\Sigma_c\pi)$

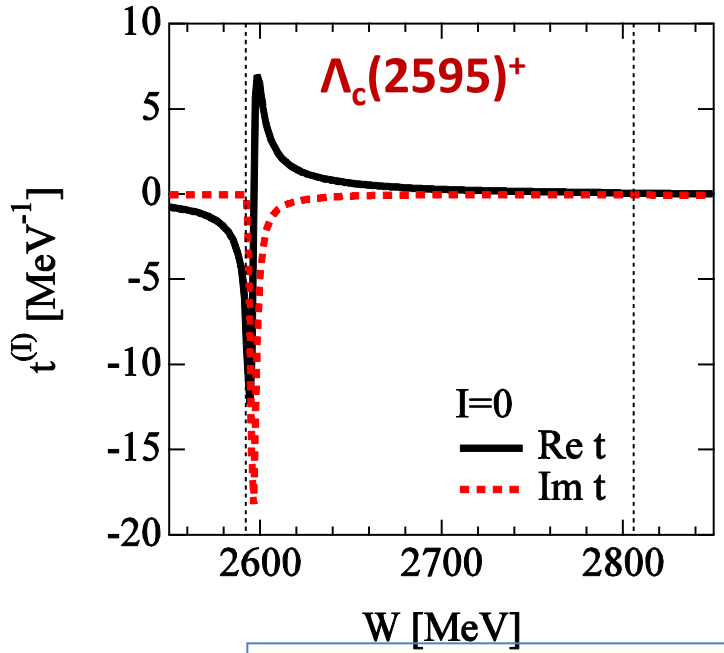


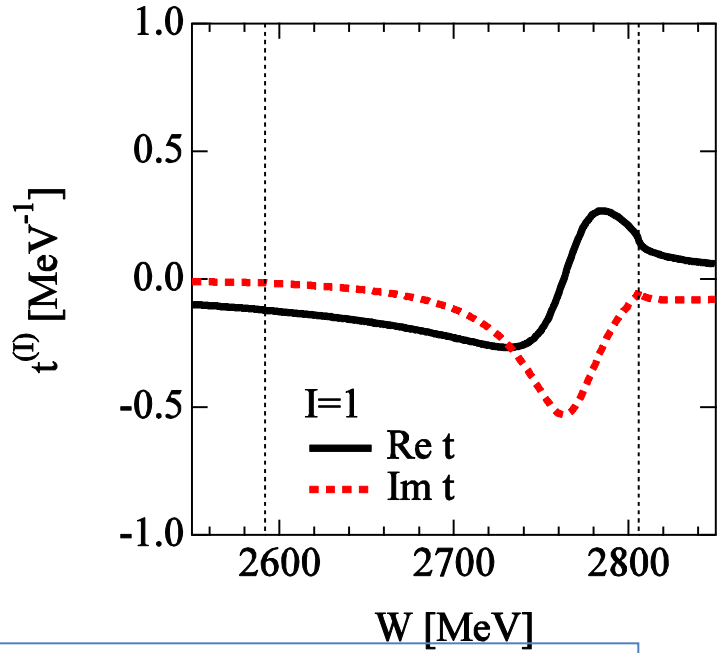
Prediction from coupled channel approach

hep-ph:1205.2275

Coupled channel calculation in I=0 channel. $\Lambda_c(2595)^+$ is clearly seen.

Calculate amplitude in I=1 channel





If the scenario is correct, it must be...

- **Isospin = 1 (Σ_c state)**
- **J^p= 1/2$^-$ (S-wave DN scattering)**

Summary

- Charmed baryon spectroscopy at Belle experiment.
- B-factory is a good laboratory for hadron physics.
- Ξ_{cc} is not discovered with full data of Belle.
  U.L is comparable with some of the predictions.
  Further study of double charm production is on going.
- First significant measurement on the width of $\Xi_c(2645)^+$
- Existence of $\Xi_c(3055)$ is confirmed but not for $\Xi_c(3123)$.
- First observation of $\Xi_c(3055)$ in ΛD final state.
  Both experiment/theory approach is necessary to clarify the structure.