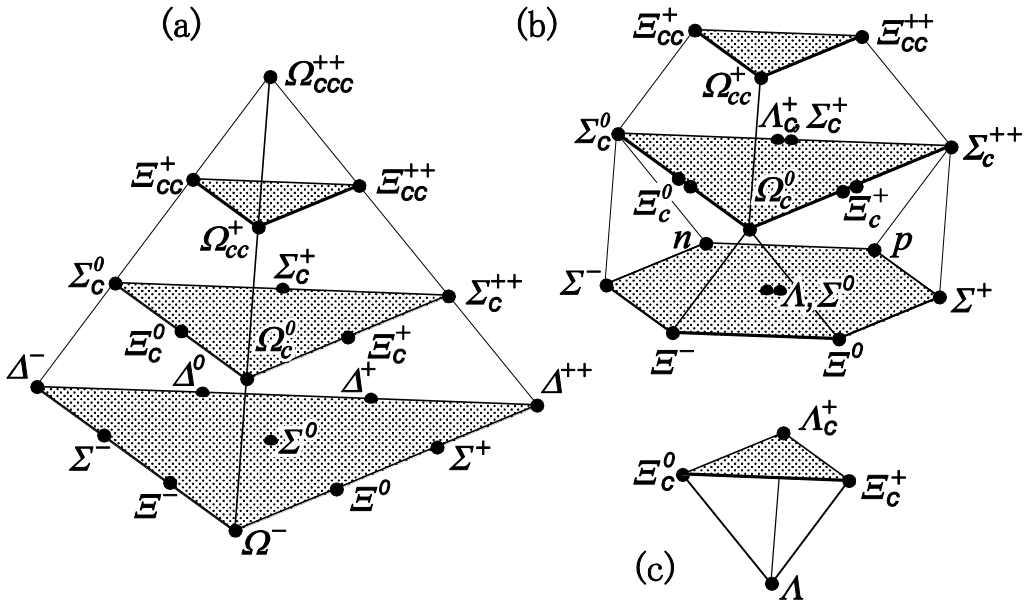
Study of charmed baryons at Belle (2)

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

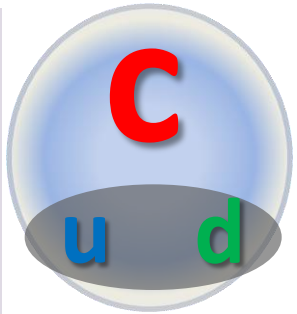
Y. Kato
KMI, Nagoya University



Physics of charmed baryons

Mass of the charm quark is ~1.5 GeV.
This is much heavier than…

1. Mass of the u,d,s quarks (300-500 MeV)
   spin-spin interaction $\propto 1/m_1 m_2$
   Di-quark correlation in from single charmed baryons.
   Is the di-quark really good degree of freedom?

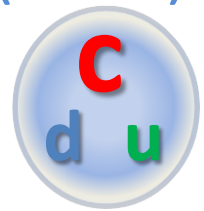


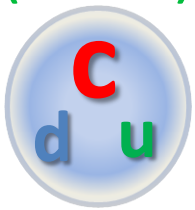
di-quark

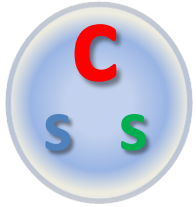
2. Momentum of quarks inside the baryon
   radius ~1 fm → 200MeV/c.
   →Non-relativistic quark model is a good approximation.
   QQ potential from doubly charmed baryon.
   (Similar to QQ^{bar} potential by charmonium spectroscopy)

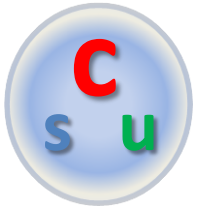
Observed charmed baryons

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～)

- More than 20 charmed baryons has been observed.
- How to extract physics from these states?
- What is missing from experimental side?

What is still missing? = Contents of this talk

- **Spin/parity not known for almost of excited states.**
  - Belle has capability to measure spin/parity of some of them.

- **Still many 1, 2 star states.**
  - Especially in many Ξ_c.
    Reported only by BaBar. Confirmation by Belle is necessary.

- **Decay modes, relative branching ratio.**
  - There may exists unknown decay modes.

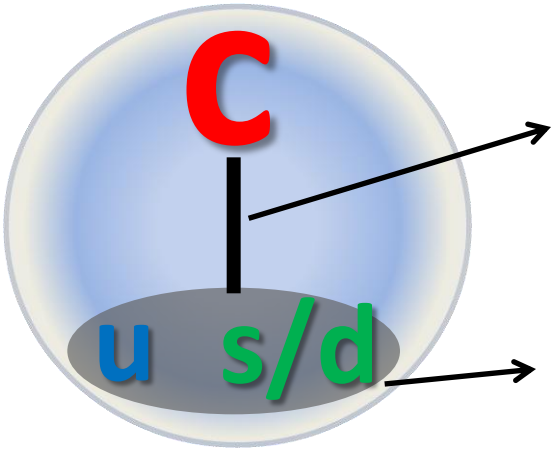
- **No doubly charmed baryons found so far.**
  - Belle? LHCb? any other experiment?

I review recent works related to these things.

Spin/parity measurement

Importance of the spin/parity measurement

Two excitation modes



λ mode:
Excitation between
di-quark and c-quark

ρ mode:
Excitation of di-quark

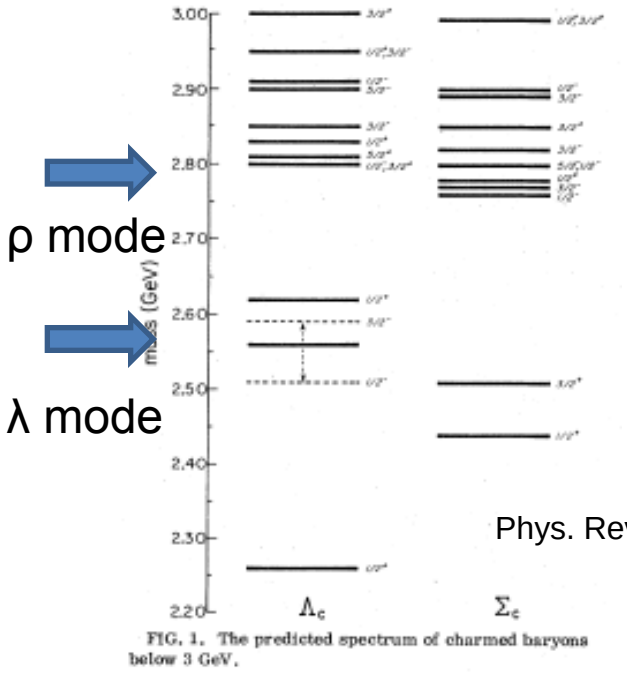


FIG. 1. The predicted spectrum of charmed baryons below 3 GeV.

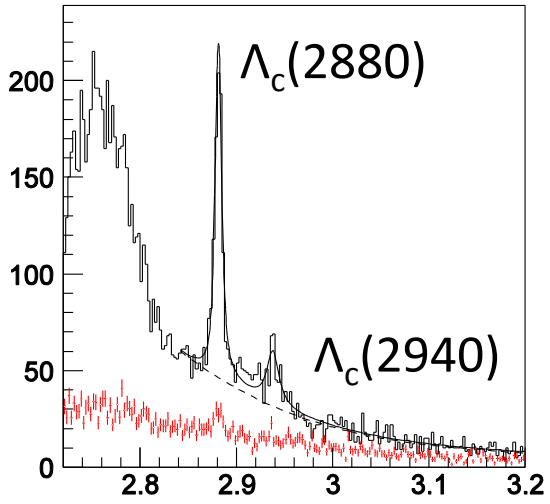
Phys. Rev. D **20**, 768

- In the first excitation, both ρ and λ mode should be $J^P=1/2^-$ and M(ρ)>M(λ)
- $\Lambda_c(2595)^+$ $\Xi_c(2790)^+$ are candidates of λ mode excitation.
- To identify ρ mode excitation and see the mass difference from λ mode is a good test of di-quark picture.

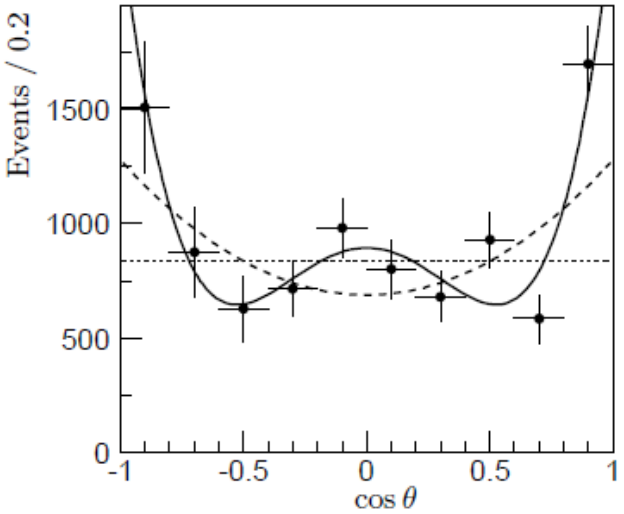
Spin-parity measurement of $\Lambda_c(2880)^+$

hep-ex/0608043

$M(\Sigma_c\pi)$

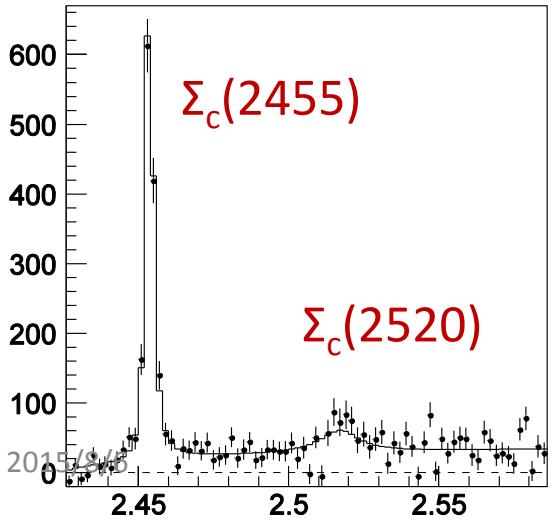


$\Sigma_c\pi$ decay angular distribution



~5σ exclusion for spin 1/2, 3/2

$M(\Lambda_c^+\pi^\pm)$ for $\Lambda_c(2880)^+$ events



$$R = \frac{Br(\Lambda_c(2880) \to \Sigma_c(2520)\pi)}{Br(\Lambda_c(2880) \to \Sigma_c(2455)\pi)} = 0.225 \pm 0.062 \pm 0.025$$

Prediction with **Heavy Quark Spin Symmetry**

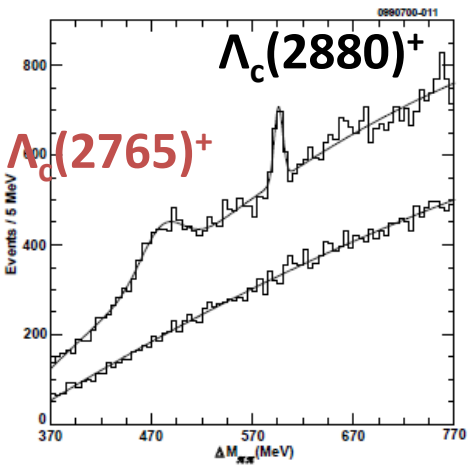
R=0.23 for $5/2^+$ (but neglect p-wave in $\Sigma_c^*\,\pi$ decay…)

R=1.45 for $5/2^-$

On going analysis: $\Lambda_c/\Sigma_c(2765)^+$

hep-ex/0010080

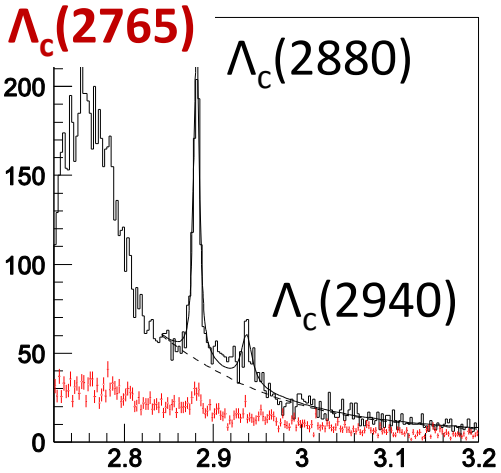
- **First evidence by CLEO**



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

hep-ex/0608043

- **By Belle**



$M(\Sigma_c\pi)$

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

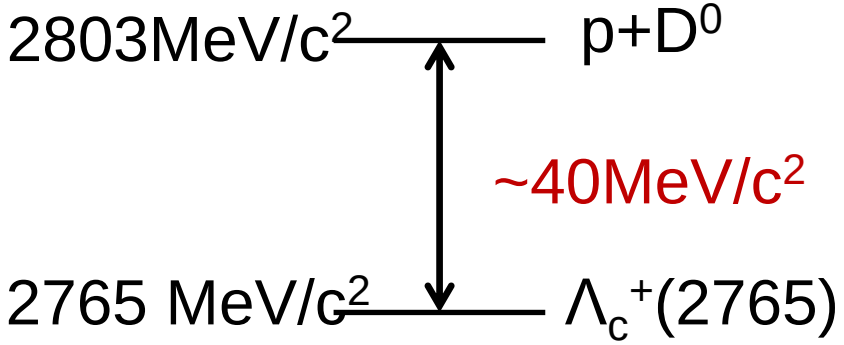
$I(J^P) = ?(?^?)$ Status: *

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.

Even isospin is not known…

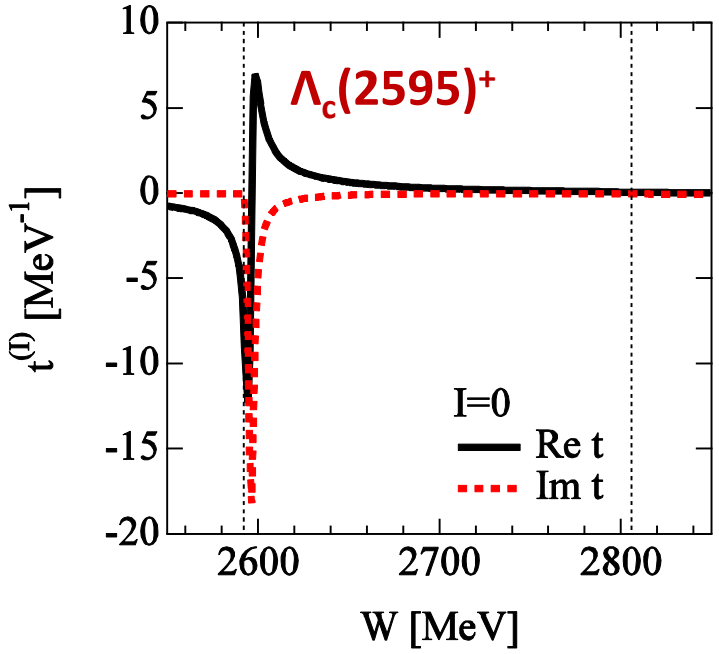
- ρ mode excitation($1/2^-$)?
- Roper like ($1/2^+$) state?
- pD bound state?



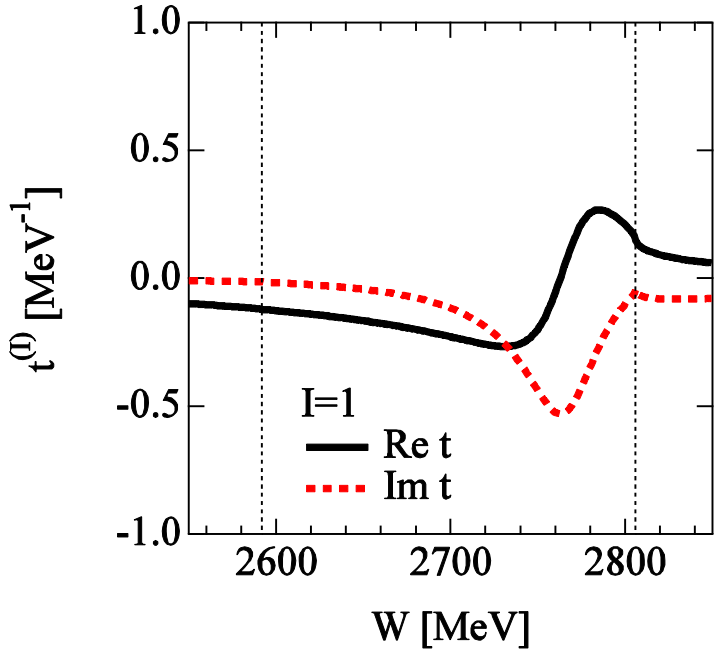
Prediction from coupled channel approach

hep-ph:1205.2275

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



Amplitude in I=1 channel

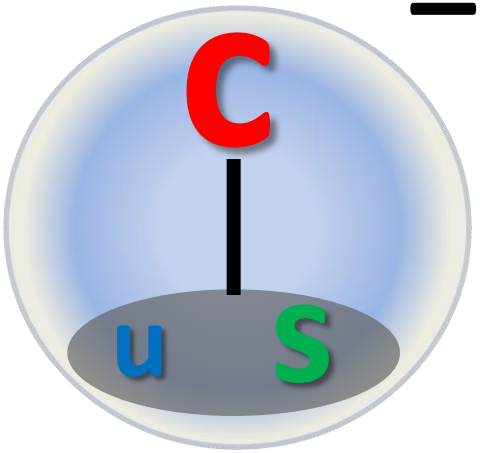


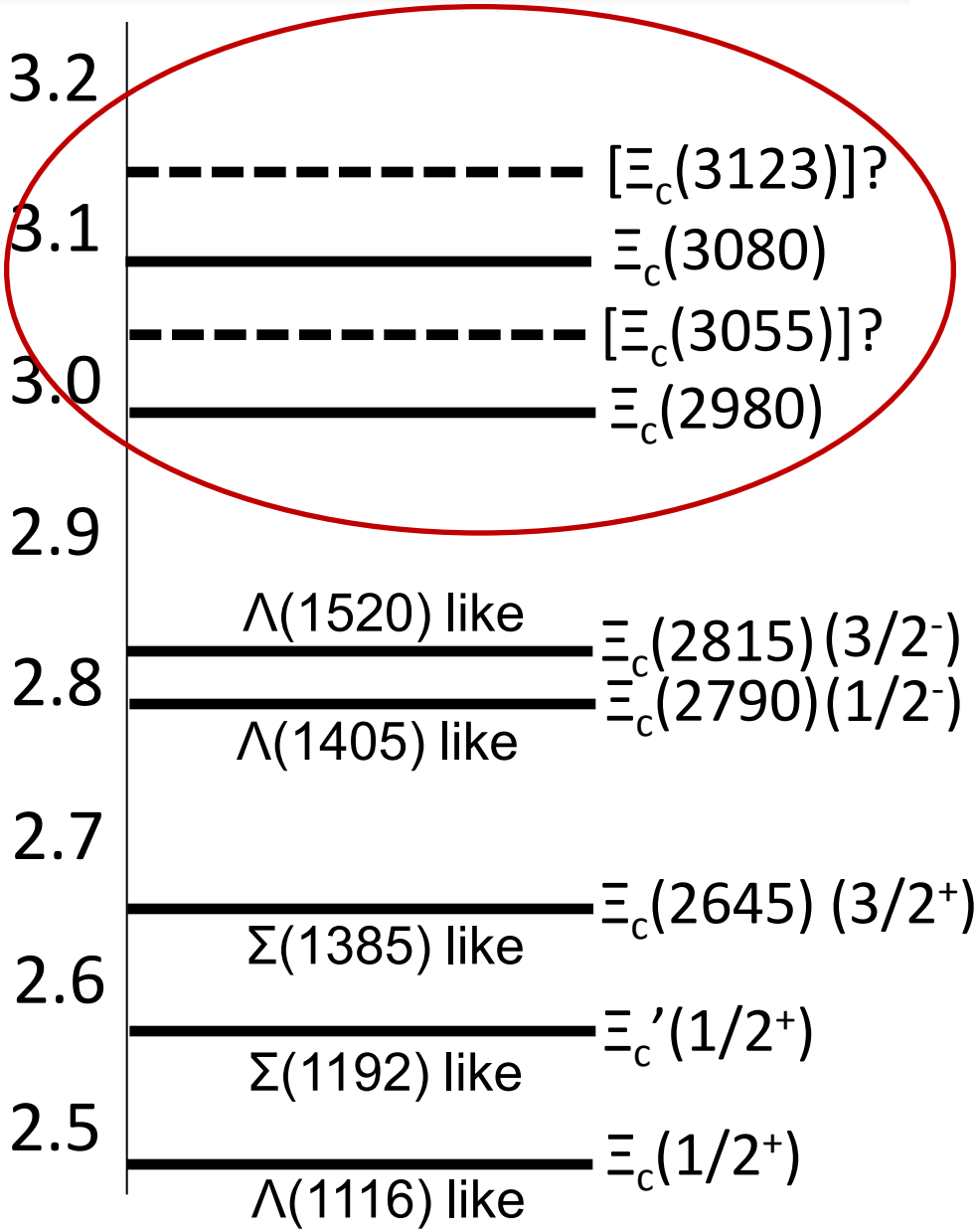
If the scenario is correct, it must be...

- **Isospin = 1 (By searching for isospin triplet)**
- **$J^p = 1/2^-$ (The same analysis as $\Lambda_c(2880)$)**

Confirmation of 1 star, 2 star states

Charmed strange baryons (Ξ_c)



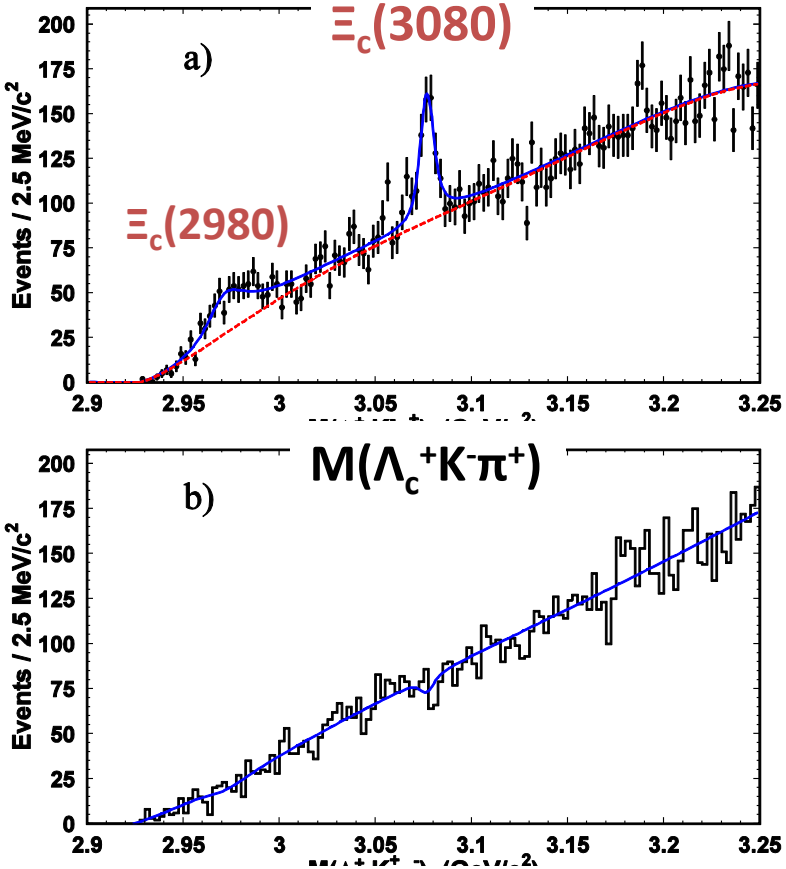


u/d-s diquark system!

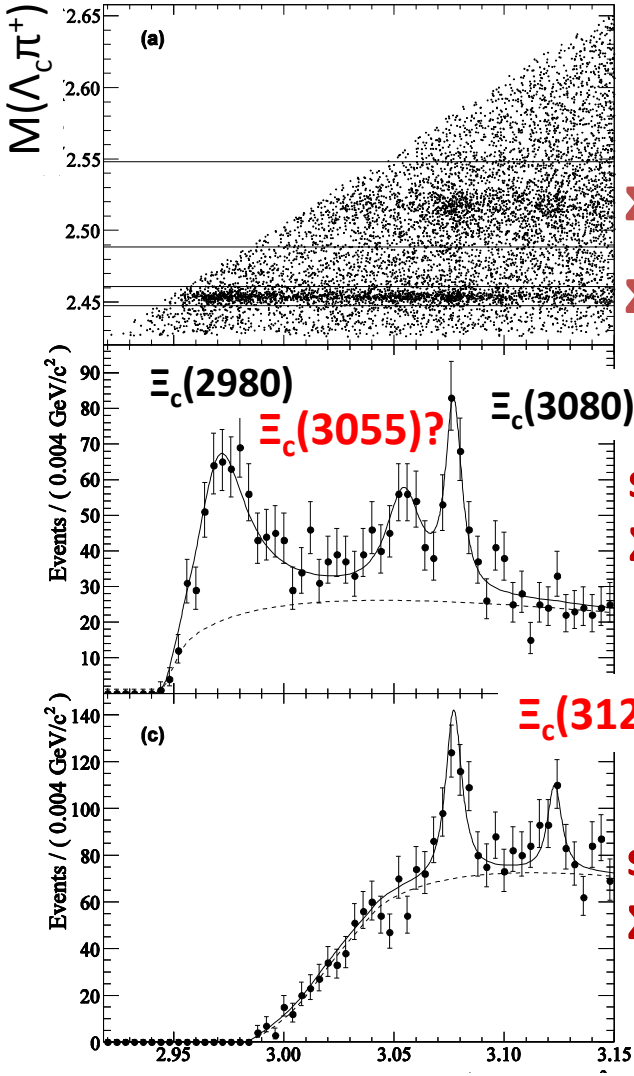
By searching for ρ mode excitation,
we can perform "di-quark spectroscopy"
Interaction of u/d-s quark can be studied.

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

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

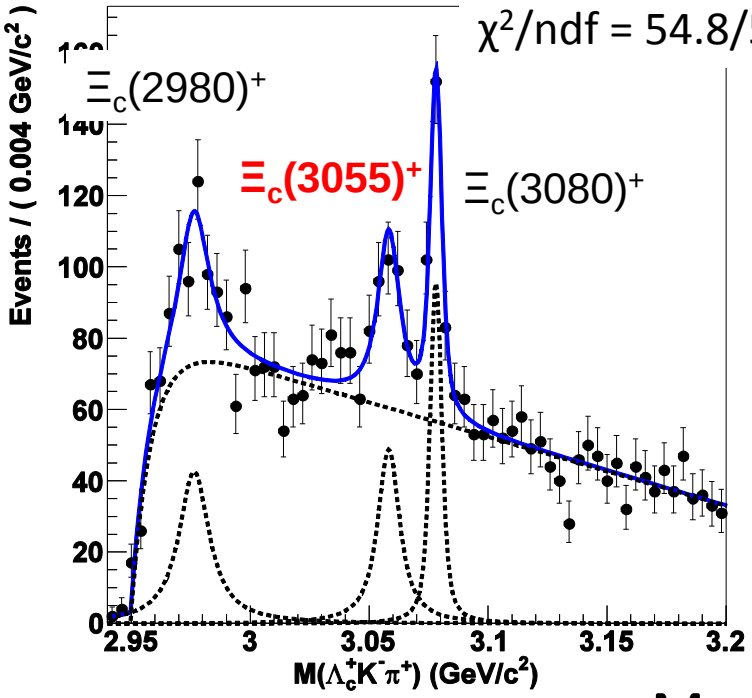


hep-ex :0710.5763 **Babar@384fb^{-1}**



- **Belle: Evidence of $\Xi_c(3080)$, $\Xi_c(2980)$**
- **BaBar: Confirmed them and reported another two states. $\Xi_c(3055)$→2star, $\Xi_c(3123)$→1star.**

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



Phys. Rev. D **89**, 052003

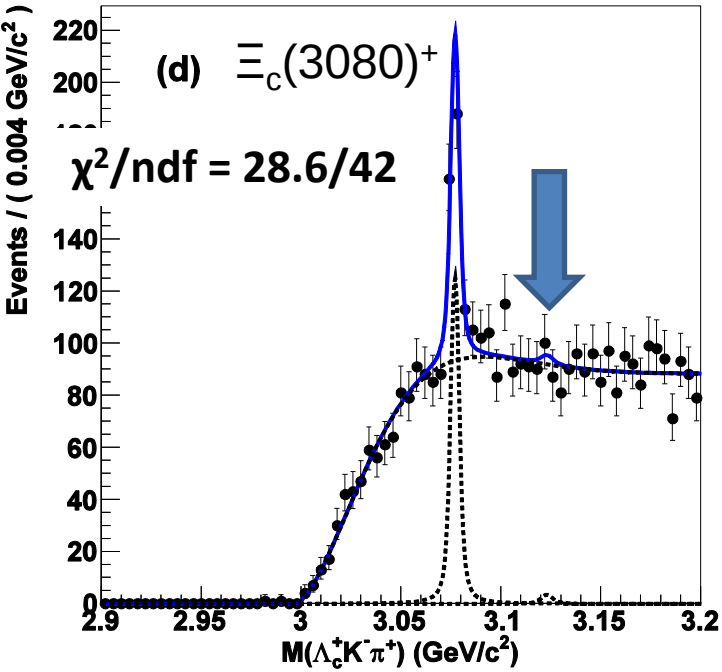
- Structure near 3055 MeV/c^2 is seen in addition to $\Xi_c(2980)$, $\Xi_c(3080)$.
- Significance of 6.6 σ.

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

	Belle	Babar
Mass (MeV/c^2)	3058.1±1.0±2.1	3054.2±1.2±0.5
Width (MeV)	9.7±3.4±3.3	17±6±1.1

Consistent result with BaBar with 6.8 σ

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



Phys. Rev. D **89**, 052003

- Structure near 3123 MeV/c^2 is not seen
- Signal PDF:Gaussian convoluted Breit Wigner.
  Mean, width was fixed from BABAR's result
- 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 confirmed...

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

J^p	Λ_c^+	Ξ_c	$\Delta M(Mev/c^2)$	Note
$1/2^+$	$\Lambda_c(2286)^+$	$\Xi_c(2470)$	181	ground state
$1/2^-$	$\Lambda_c(2595)^+$	$\Xi_c(2790)$	194	$\Lambda(1405)$ like
$3/2^-$	$\Lambda_c(2625)^+$	$\Xi_c(2815)$	188	$\Lambda(1520)$ like
??	$\Lambda_c(2765)^{+?}$	$\Xi_c(2980)$?	205	Isospin not determined
$5/2^+$	$\Lambda_c(2880)^+$	$\Xi_c(3080)$?	200	

spin0 di-quark

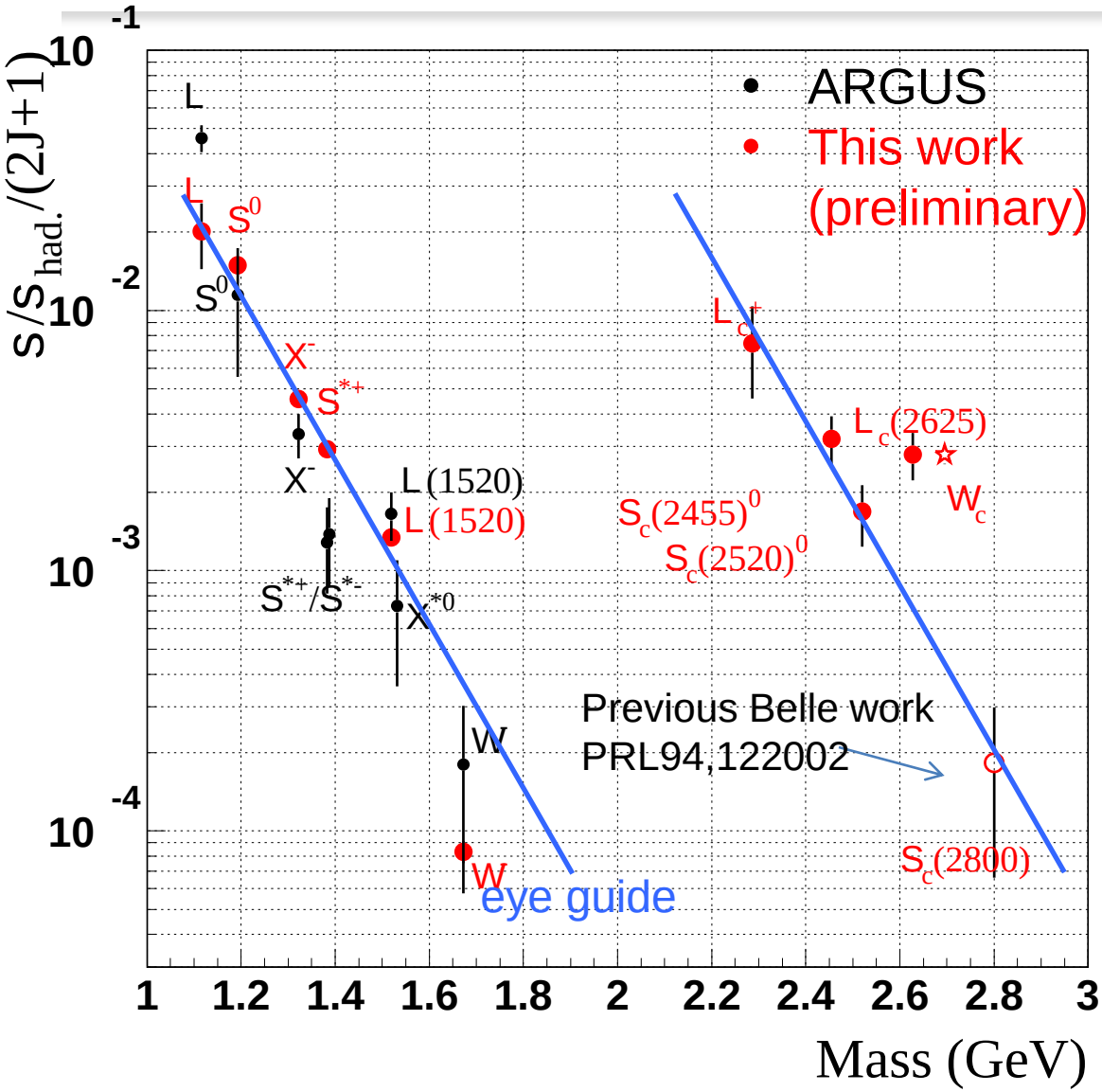
J^p	Σ_c	Ξ_c'	$\Delta M(Mev/c^2)$	Note
$1/2^+$	$\Sigma_c(2455)$	$\Xi_c(2575)$	120	ground state
$3/2^+$	$\Sigma_c(2520)$	$\Xi_c(2645)$	125	$\Sigma(1385)$ like
??	$\Sigma_c(2800)$	??		

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

$\Xi_c(3055)$ has no corresponding states in Λ_c/Σ_c

Corresponding state just not found?



Production rate of hadrons in e^+e^- collision is known to lie on the exponential curve.
If corresponding state in Λ_c or Σ_c exists, experimentally much easier to find.

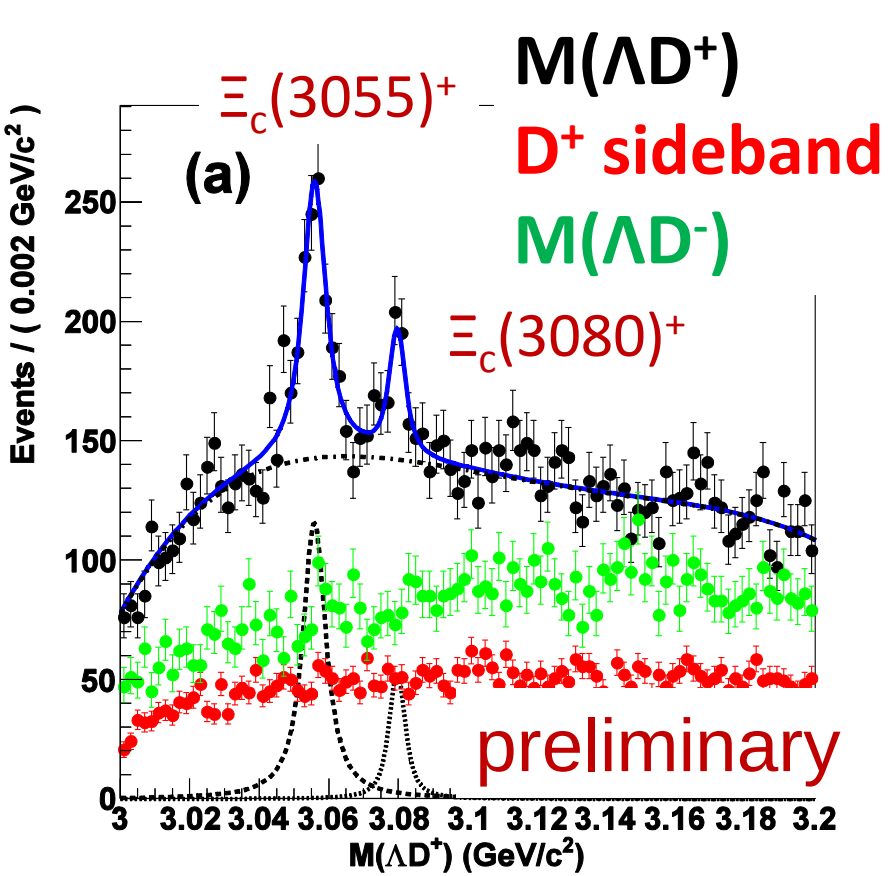
Further study for Ξ_c^*

- Unfortunately, statistics of $\Xi_c(3055)$ is not enough to measure spin.
- Relative branching fraction is useful to distinguish λ/ρ modes.
- All the Ξ_c^* are observed in (charm baryon) + (light meson) final states.

  Λ_c^+ Σ_c Ξ_c Ξ_c'.. π, K
- How about the (light baryon) + (charm meson) ?

$\longrightarrow$ study ΛD!

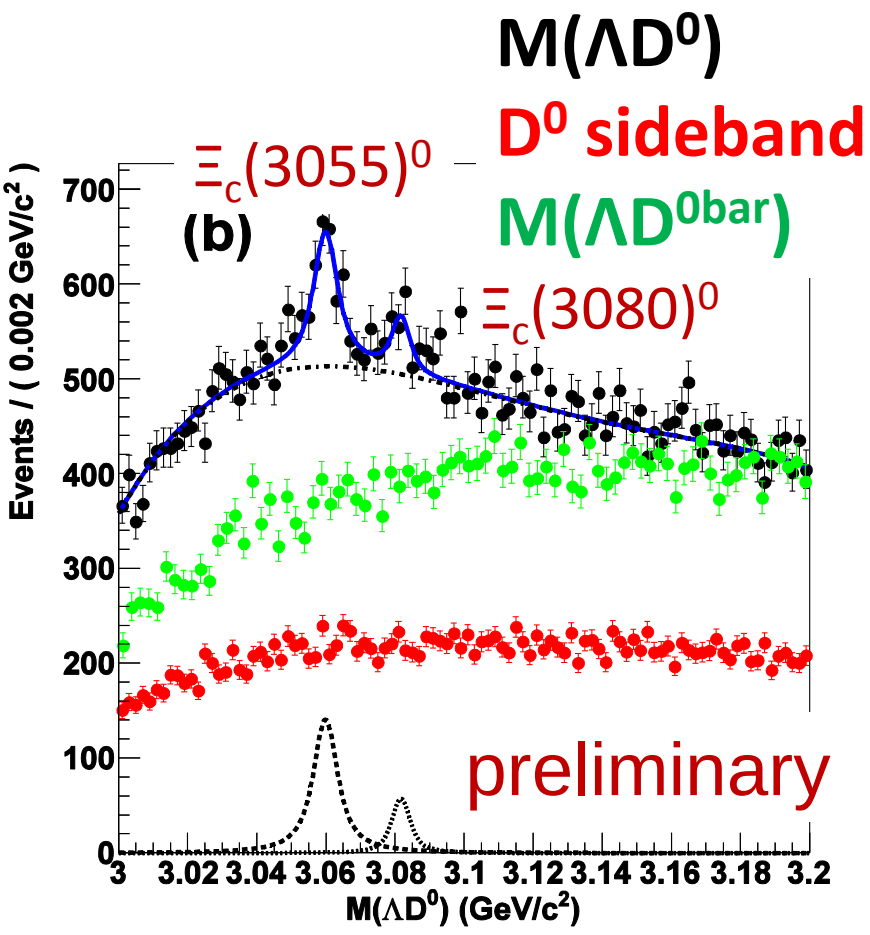
$M(\Lambda D^+)$ distribution



- 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)	$3055.7 \pm 0.4 \pm 0.4$	$3079.6 \pm 0.6 \pm 0.7$
Width(MeV)	$7.1 \pm 1.2 \pm 1.8$	$4.0 \pm 1.5 \pm 1.0$

$M(\Lambda D^0)$ distribution



- Sum of three D^0 decay modes.
- 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

- Comparison with prediction by chiral quark model is inconsistent.

Partial decay width

	$\Sigma_c \bar{K}$	$\Xi_c^*(2645)\pi$	$\Xi_c'\pi$	$\Sigma_c^* \bar{K}$	$D\Lambda$	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

arXiv:1205.2943
Lei-Hua Liu et al

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

Σ_c K^- Λ D

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

Both ρ and λ mode excitation??

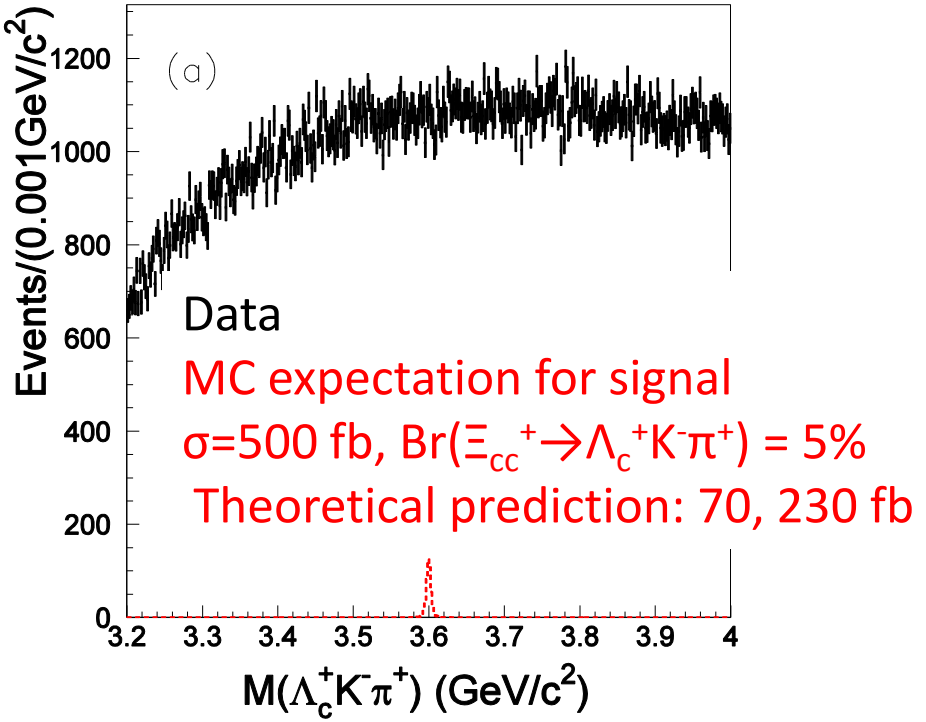
Doubly charmed baryons

Doubly charmed baryons

- Ground state still not established.
- Predicted mass: ~3.6 GeV/c^2
- $\Lambda_c^+K^-\pi^+$ and $\Xi_c^0\pi^+$ are candidate of decay modes
- Selex reported in $\Lambda_c^+K^-\pi^+$ but not supported by other experiments
- Study with Belle full statistics.

Phys. Rev. D **89**, 052003

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

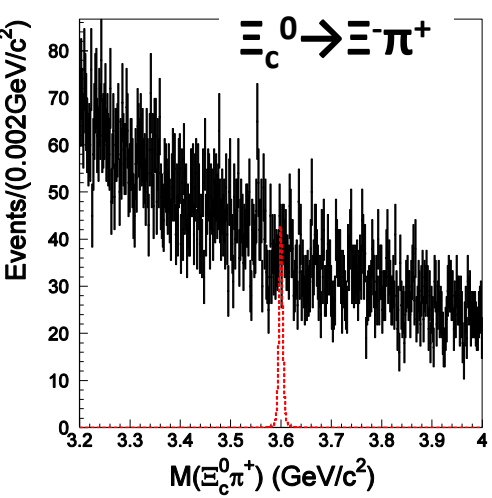


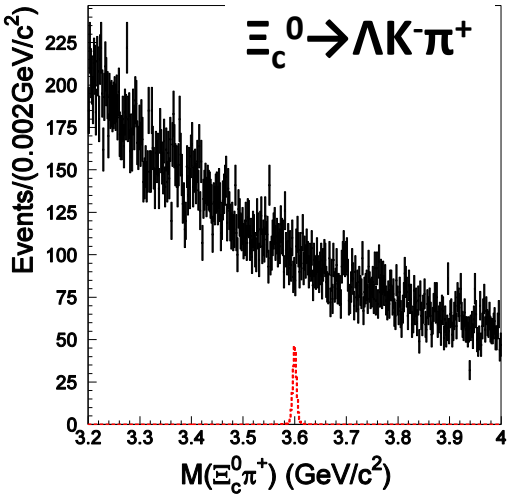
- Significance from -2ln(L/L(0))
  Fit the spectrum with/without signal
- Less than 3σ in 3.2-4.0 GeV/c^2.
- Upper limit on
  $\sigma(e^+e^-\to\Xi_{cc}^+ X) \times Br(\Xi_{cc}^+\to\Lambda_c^+K^-\pi^+)$

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

Comparable with some of the predictions

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

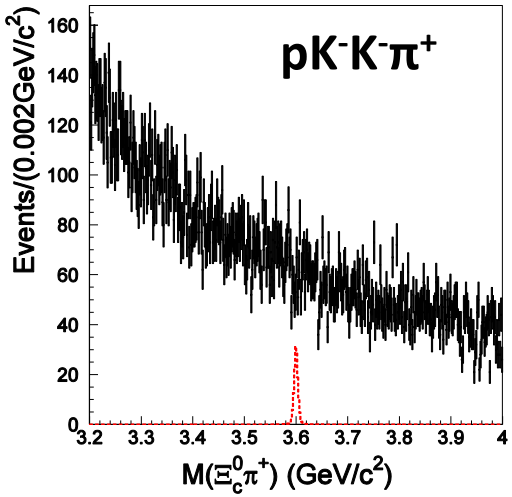




Data

Signal MC

(assuming 500 fb^{-1} and 5% for branching fractions.)



- 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 (depends on mass)
Theory	0.18 fb, 0.5 fb (assuming Br=5%)

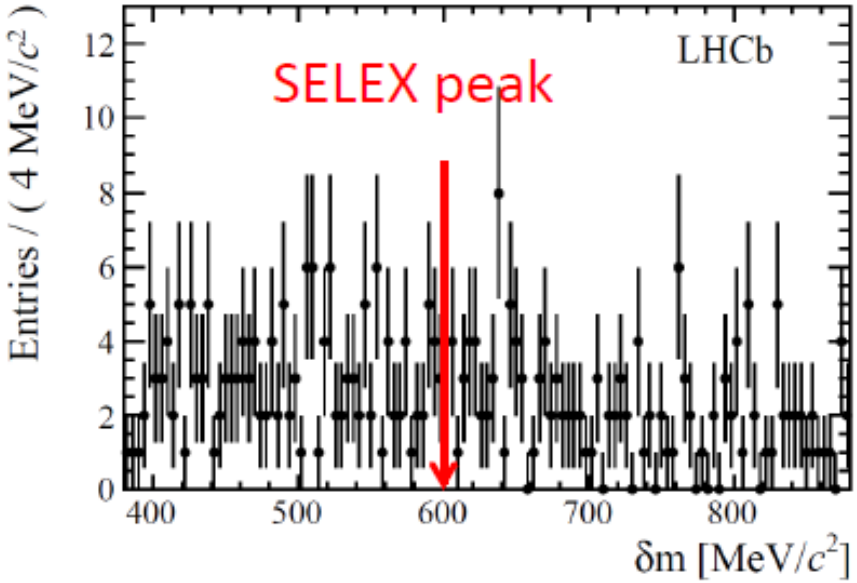
Comparable with some of the predictions

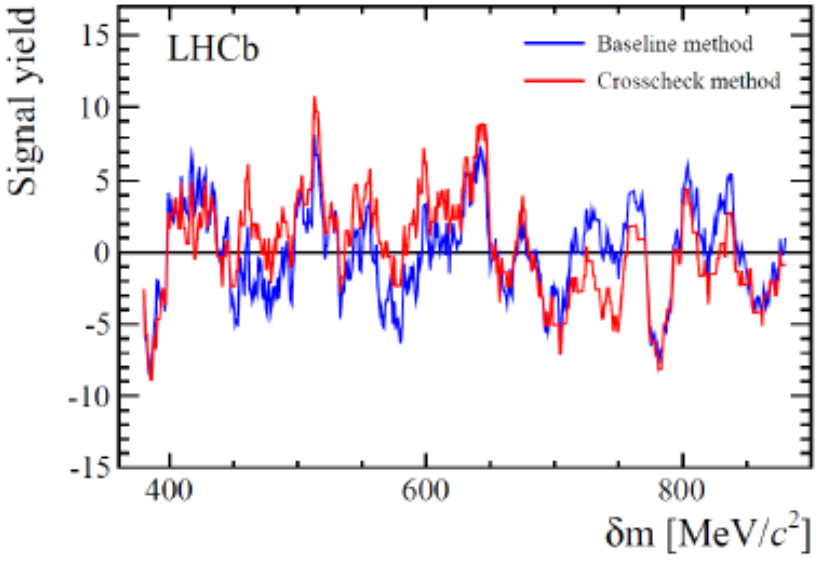
Phys. Rev. D **89**, 052003

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

Slide at Hadron2013





- Cross section of double charm in pp is much higher than e^+e^-.
- Require Ξ_{cc} fly in order to reduce background → Loss large signal, too. (lifetimes of charm hadrons are shorter than bottom hadrons).

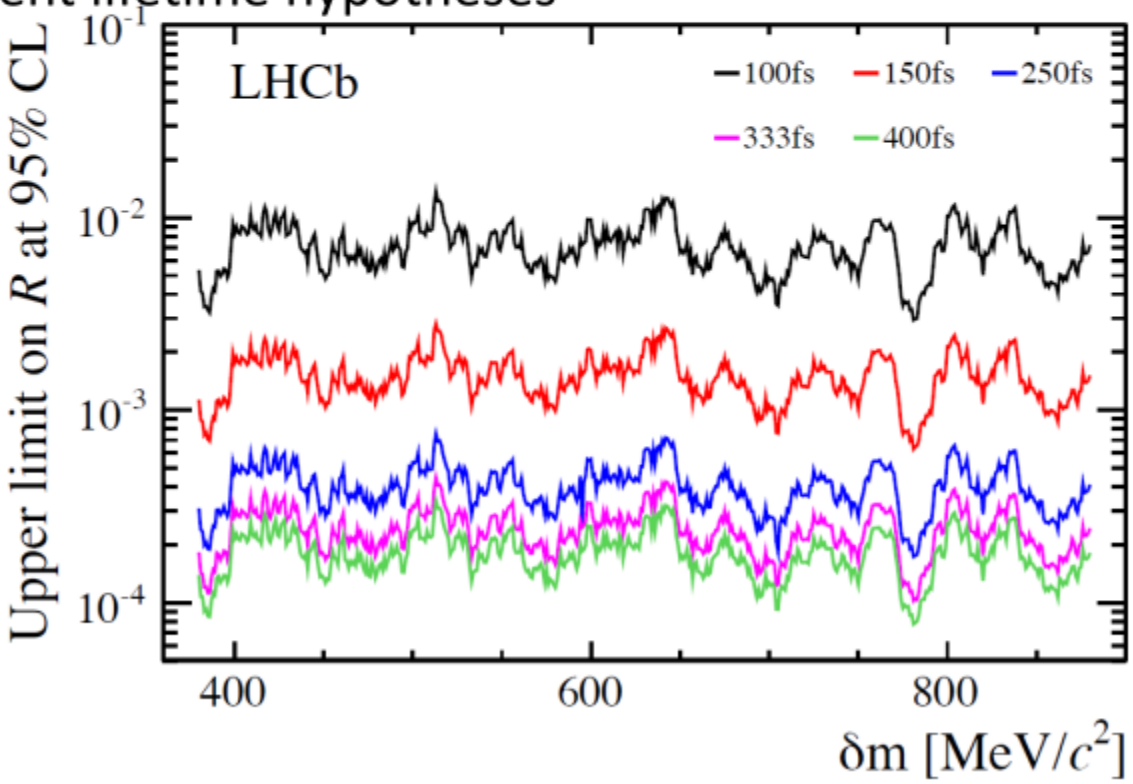
Upper limits for R

- Set upper limits for the production cross-section ratio R relative to Λ_c^+

$$R = \frac{\sigma(\Xi_{cc}^+)\,\mathcal{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)}$$

arXiv:1310.2538

- Mass and lifetime unknown: upper limits given as a function of δm, for 5 different lifetime hypotheses

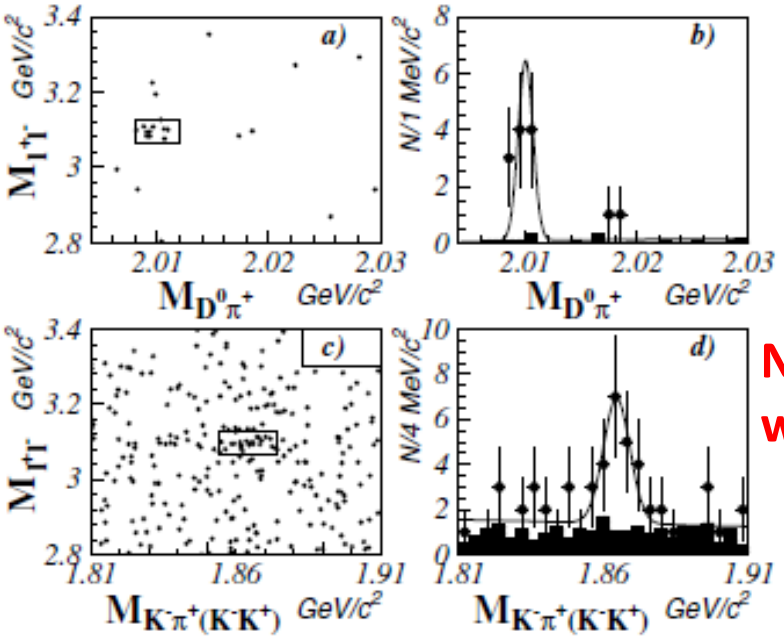


Prediction: ~200 fs
arXiv:hep-ph/9901323

Study of double charm production in progress

- **Production mechanism of double charm is poorly known.**
  →predicted cross section for Ξ_{cc} is not reliable.

- **$e^+e^- \rightarrow J/\psi + c\bar{c}^{bar}$ 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 working on the elementary DD (D^0D^0, D^0D^+, D^+D^+ etc) production at Belle.
  → Baseline for the double charm production in e^+e^- collision

Summary

- Spin/parity, isospin measurement
  - $\Lambda_c(2880)$ is a good example. $\Lambda_c/\Sigma_c(2765)$ on going.

- Confirmation of 1 star, 2 star states
  - $\Xi_c(3055)$ confirmed but not for $\Xi_c(3123)$. No corresponding states in Λ_c, Σ_c

- Relative branching ratio
  - $\Sigma_c\pi$ and ΛD for $\Xi_c(3055)$. Input from theorist is necessary.

- Double charm
  - Still no doubly charmed baryons
  - LHCb also fails..

- Prospect for Belle II
  - 50 times higher integrated luminosity compared with Belle.
  - Physics run starts from 2017 (without vertex detector), 2018 (with full Belle II).
  - New charmed baryons, new decay modes, spin/parity measurements, and doubly charmed baryons. **Stay tuned!**