

Search for doubly charmed baryon and studies of charmed strange baryons at Belle 1

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For the Belle collaboration

- Doubly charmed baryon(Ξ_{cc}^+).
- Excited Ξ_c^* states.
- Other charmed baryon results.



Phys. Rev. D 89, 052003
(arXiv:1312.1026)

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

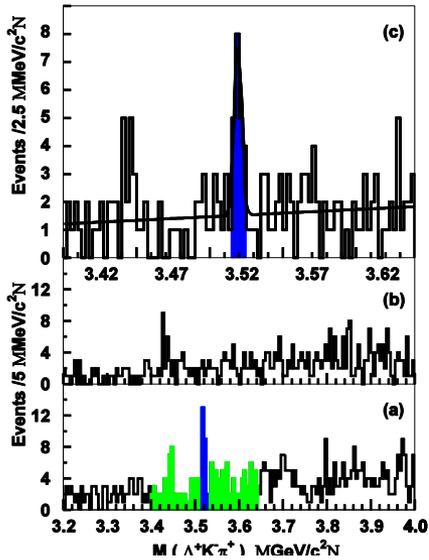
Introduction for Ξ_{cc}^+

2

- Ξ_{cc} is a good probe to study QQ potential (like charmonium)
- Prediction of the mass: $\sim 3.5-3.75$ GeV by quark model, 3.6 GeV by LQCD
- Evidence by SELEX was not supported by FOCUS, B-factories, and LHCb

Evidence from SELEX
in 2003

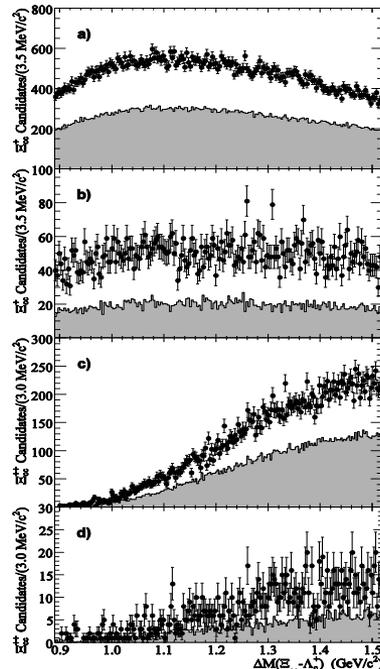
Mass: ~ 3.52 GeV/c²



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

PhysRevLett.89. 112001

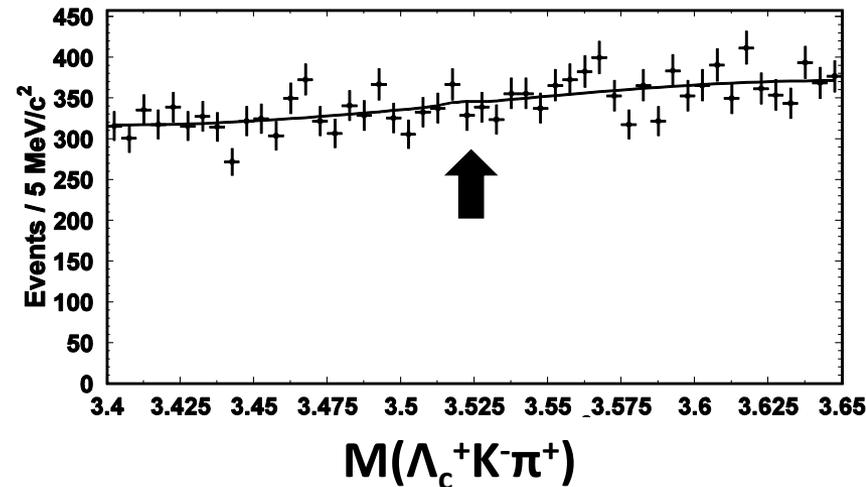
BaBar@232 fb⁻¹



Phys. Rev. D **74**, 011103

B-factories

Belle@461.5 fb⁻¹



PRL 97, 162001(2006)

Improved search of Ξ_{cc}^+ by Belle

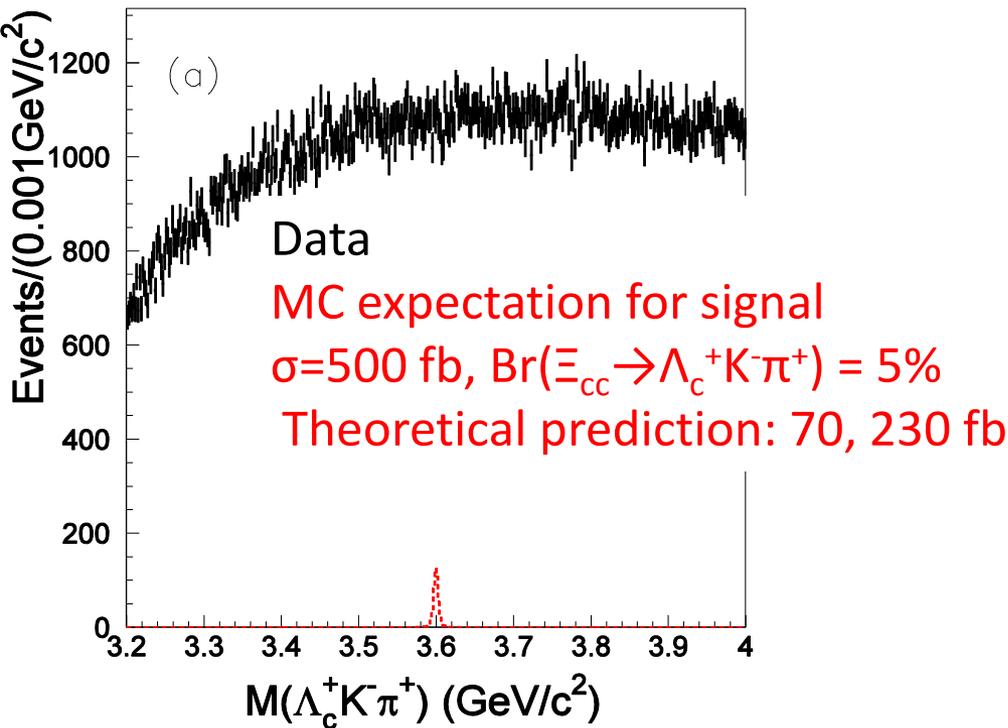
3

	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	$p K^- \pi^+$	$p K^- \pi^+$	$p K^- \pi^+$, $p K_S^0$ (+20%)
Ξ_c^0 decay	$\Xi^- \pi^+$	-----	$\Xi^- \pi^+$, $\Lambda K^- \pi^+$, $p K^- K^- \pi^+$ (+80%)

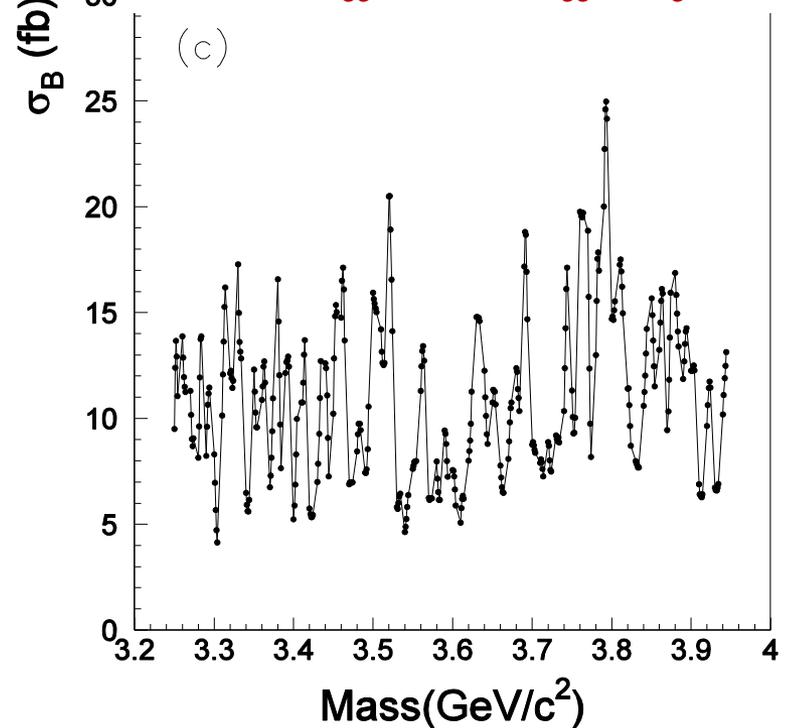
Result for $\Lambda_c^+ K^- \pi^+$ decay mode

4

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



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



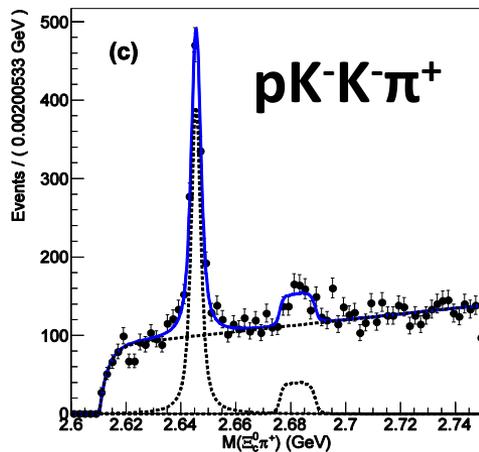
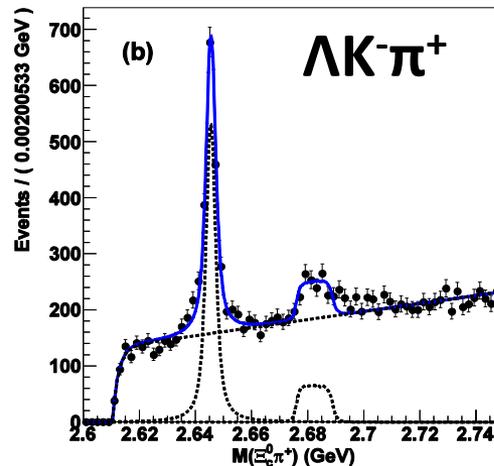
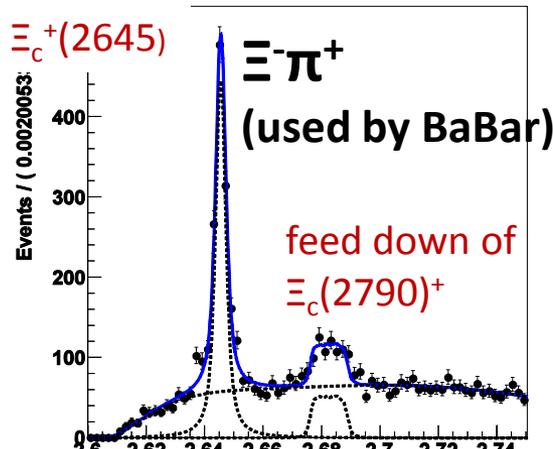
- Significance from $-2\ln(L/L(0))$
- Significance is less than 3σ in all mass region...

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

Calibration mode for $\Xi_{cc}^+ \rightarrow \Xi_c^0 \pi^+$: $\Xi_c^+(2645)$ 5

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
- $\Xi^- \pi^+$: $p K^- K^- \pi^+$: $\Lambda K^- \pi^+$:
= 1298 ± 51 : 974 ± 47 : 1444 ± 58

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

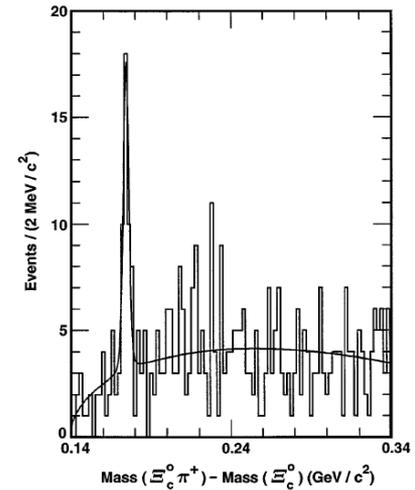
Only upper limit is given in PDG

$\Xi_c(2645)^+$ WIDTH	
VALUE (MeV)	CL%
<3.1	90

$\Xi_c(2645)$ WIDTHS

DOCUMENT ID	TECN	COMMENT
GIBBONS 96	CLE2	$e^+e^- \approx \Upsilon(4S)$

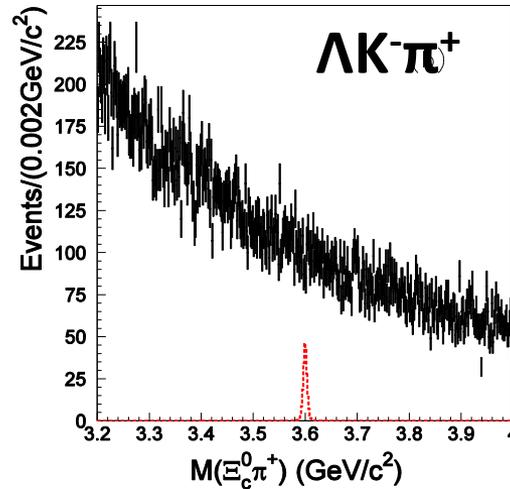
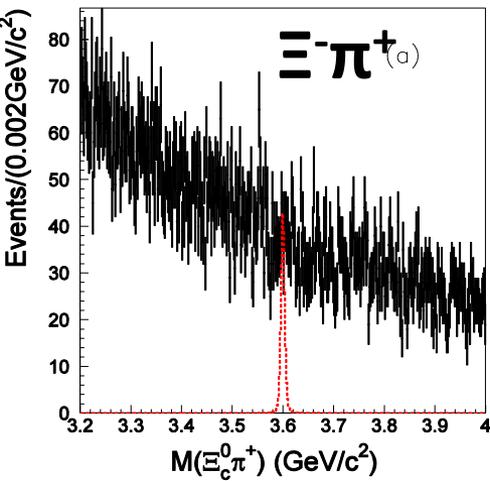
CLEO PRL. 77, 810



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	$2.6 \pm 0.2 \pm 0.4$	2645.4 ± 0.1 (statistics only)

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

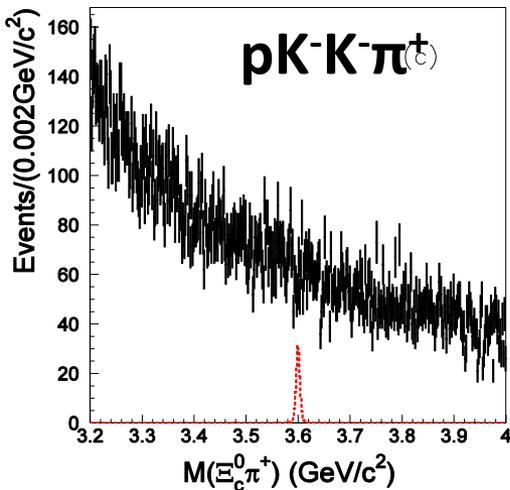
Result of Ξ_{cc}^+ search: $\Xi_c^0\pi^+$



Data

Signal MC

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



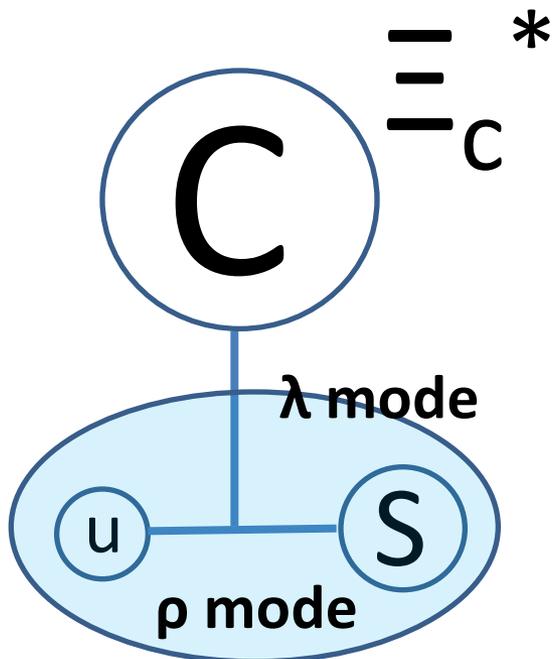
- Simultaneous fit with fixing signal yield ratio.
- 3.2σ for $3.553 \text{ GeV}/c^2$ but probability to observe a peak with significance >3.2 in this the mass range of $3.2\text{-}4.0 \text{ GeV}$ is 26%.

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

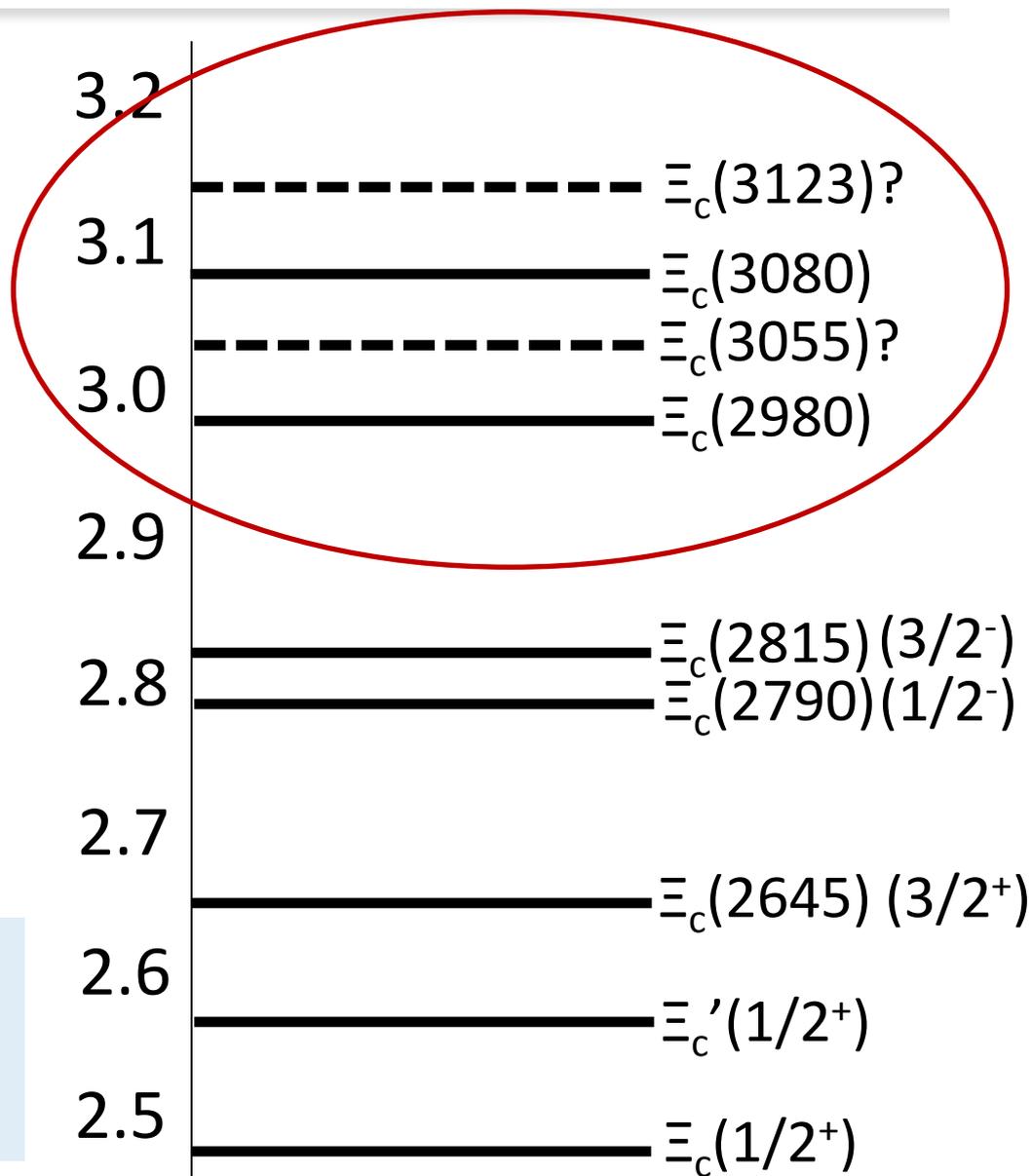
Belle	0.076-0.35 fb
Theory	0.18-0.5 fb (assuming Br=5%)

Excited Ξ_c states

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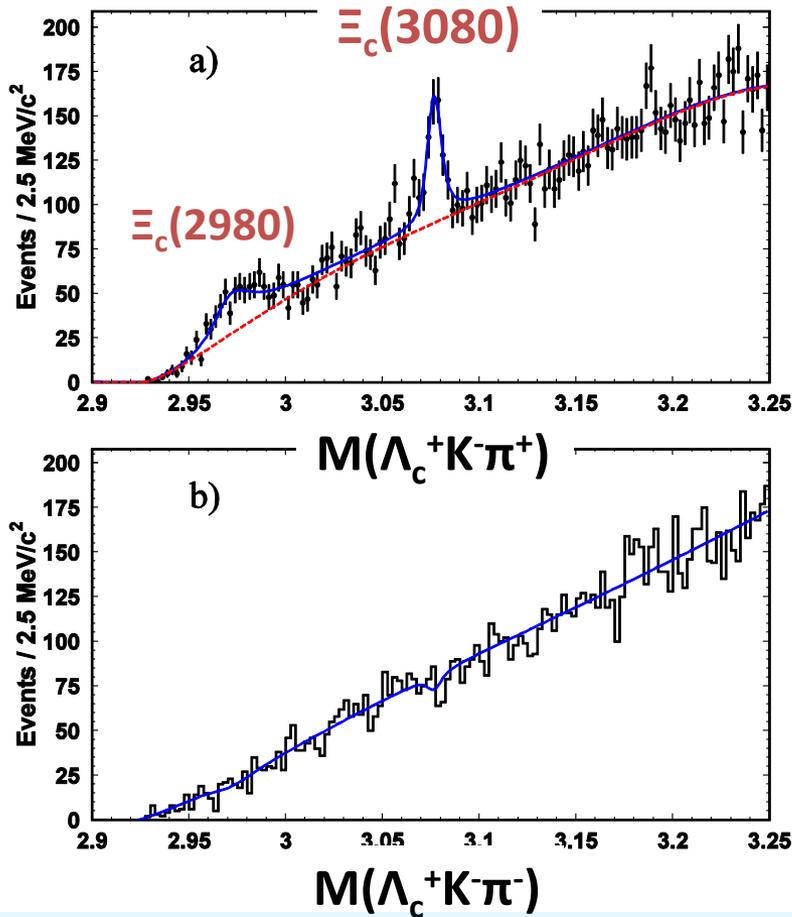
u/d-s diquark system!



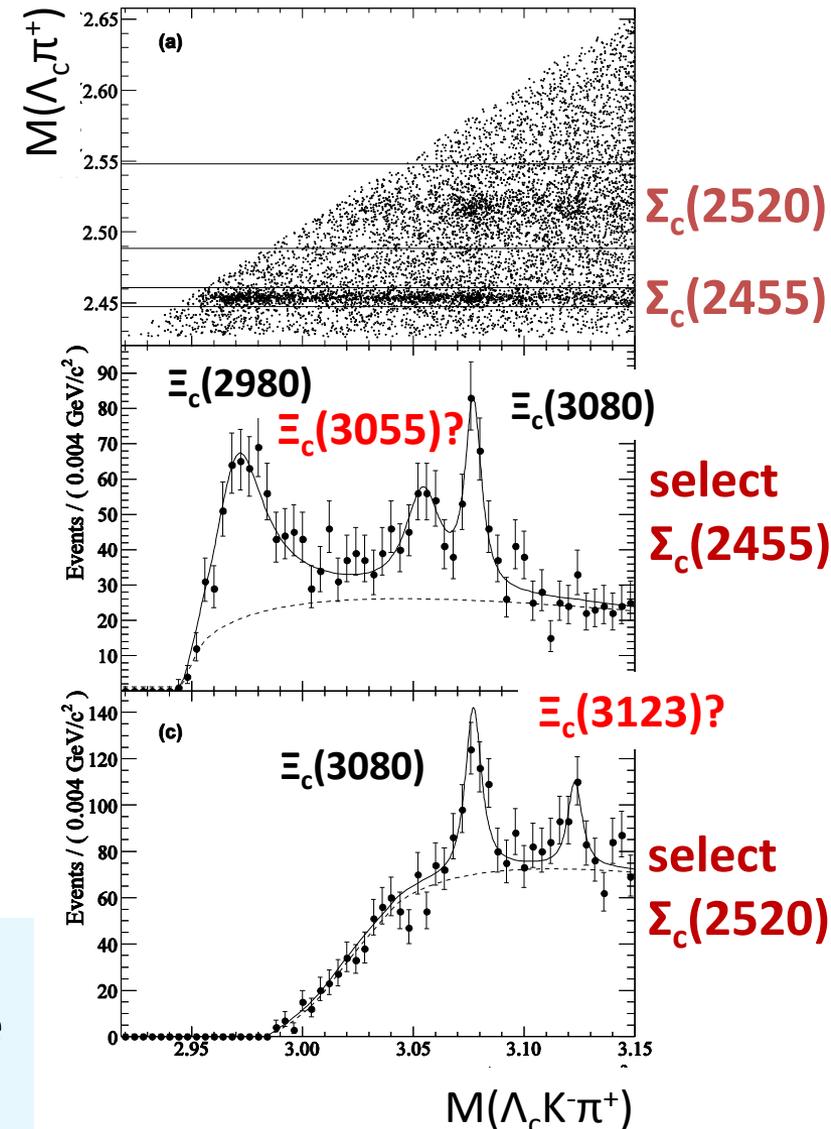
- Weak spin-spin interaction of c quarks
→ light quarks form a di-quark.
- ρ mode spectroscopy
→ di-quark spectroscopy

Excited Ξ_c^+ in $\Lambda_c^+ K^- \pi^+$ by Belle and BaBar 9

PRL 97, 162001(2006) Belle@461.5fb⁻¹

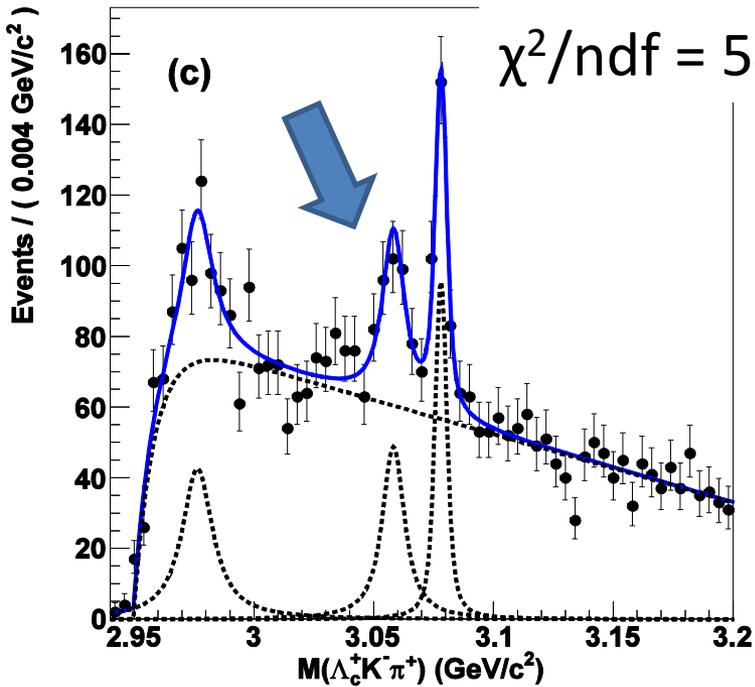


PRD 77 012002 BaBar@384fb⁻¹



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

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

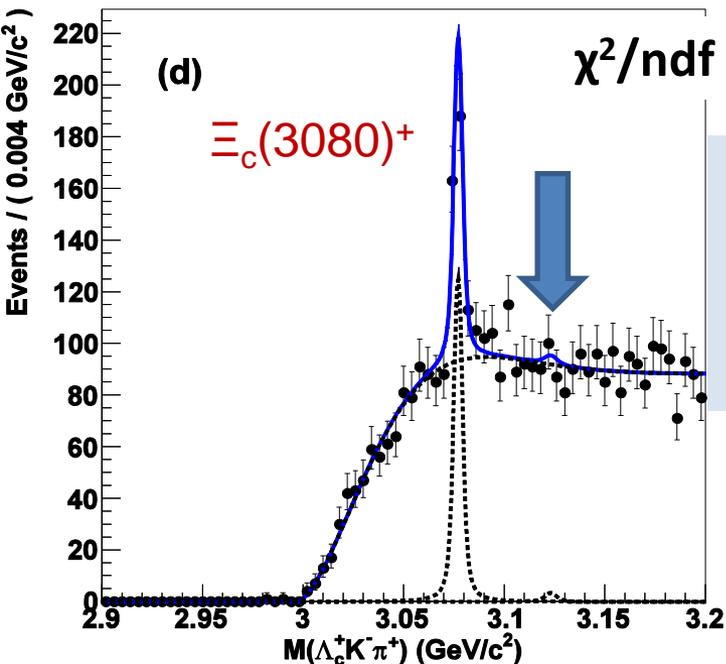


- Structure near 3055 MeV/c² is seen.
- Significance from $-2\log(L_{\max}/L(0))$.
- Signal pdf is Gaussian convoluted Breit-Wigner (σ from signal MC).
- BG shape $(1 - \exp((x - x_0)/dm_0)) * (x/x_0)^a + b * (x/x_0 - 1)$
- Significance of $\Xi_c(3055)^+$ is 6.6 σ .

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

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

Result of the Babar is confirmed with 6.6 σ .



- Structure near 3123 MeV/c² 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

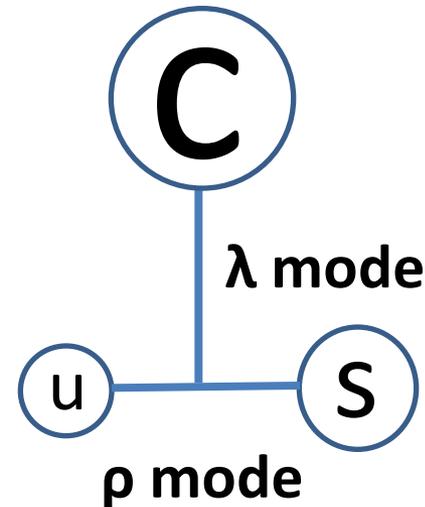
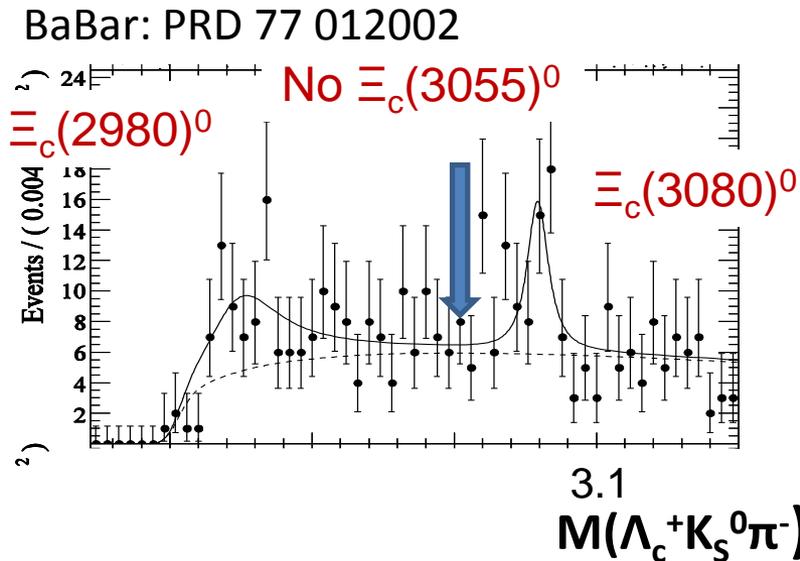
$\sigma \times \text{Br}(\Lambda_c^+ \rightarrow pK^- \pi^+)$ of $\Xi_c^+(3123)$

$< 0.34 \text{ fb @95\%C.L} \Leftrightarrow 1.6 \pm 0.6 \pm 0.2 \text{ fb by BaBar}$

Result of the Babar was not confirmed...

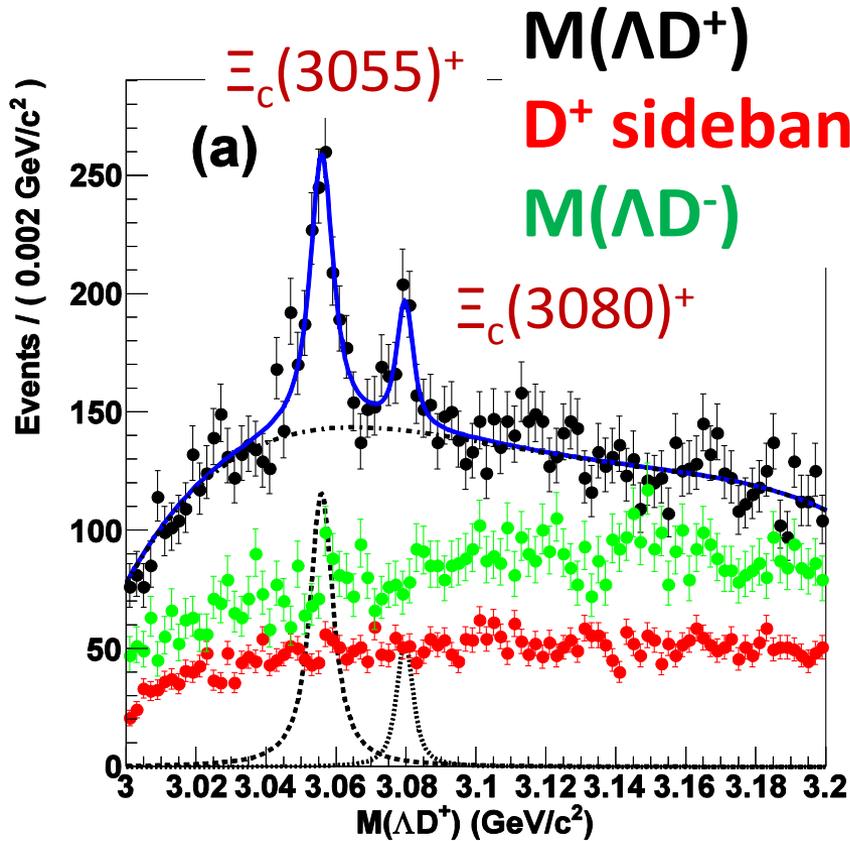
Further study for Ξ_c^*

- 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?



- 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) ? \rightarrow study $\Lambda D!$

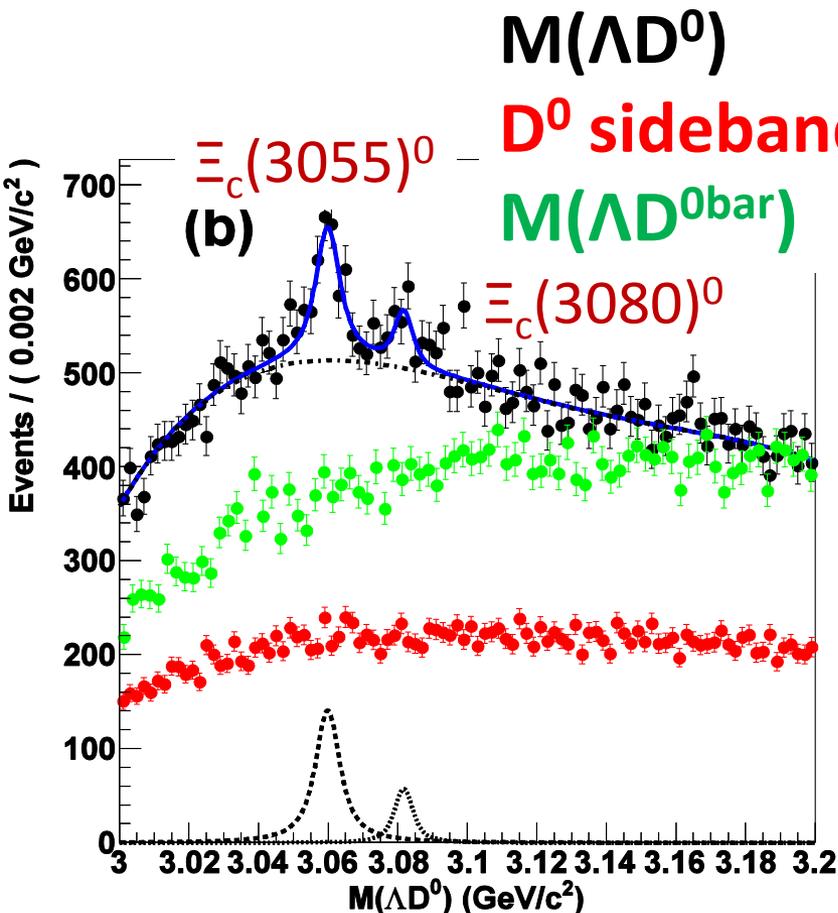
Preliminary



- 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:
11.7 σ for $\Xi_c(3055)^+$ and 4.7 σ for $\Xi_c(3080)^+$.
- Further confirmation for $\Xi_c(3055)^+$

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

Preliminary



- Sum of three D^0 decay modes ($K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-3\pi$)
- No peak structure in D^0 sideband region and wrong-sign $D^{0\text{bar}}\Lambda$ combination.
- Significance of the peaks are:
7.6 σ for $\Xi_c(3055)^0$ and 2.6 σ 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

1. Improved measurement of $\text{Br}(\Lambda_c^+ \rightarrow pK^-\pi^+)$: arXiv 1312.7826

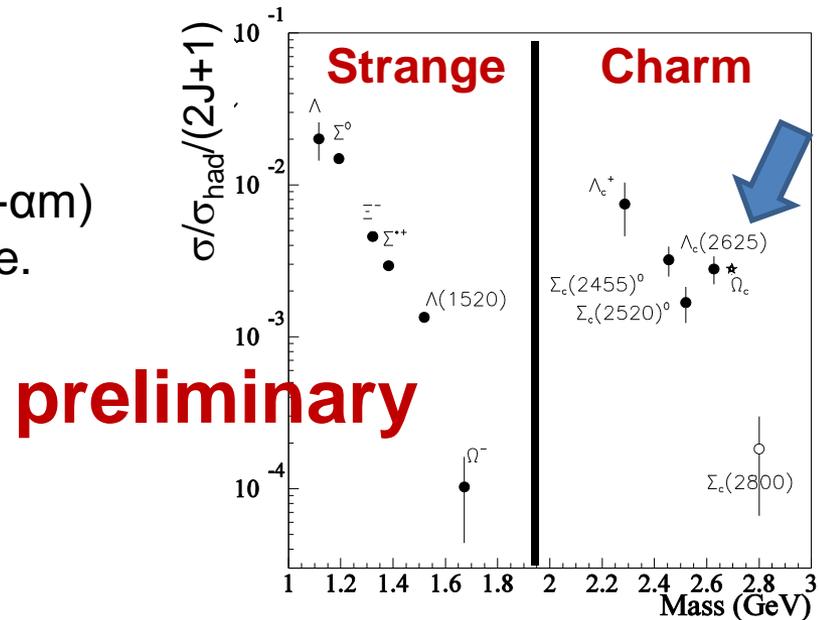
- Normalization mode for not only Λ_c^+ but all the charmed baryons.
- Identify Λ_c^+ by recoil mass of $D^{(*)}p\pi$ system.
- $5.0 \pm 1.3 \rightarrow 6.84 \pm 0.24$ (stat) $^{+0.21}_{-0.27}$ (sys)

2. Improved measurements of mass and width of $\Sigma_c^{(*)}$: arxiv 1404.5389

- $M(\Sigma_c(2455)^{++}) - M(\Sigma_c(2455)^0) = 0.22 \pm 0.01$ (stat) ± 0.01 (sys) MeV/c²
- Sign is opposite from the naïve expectation that d quark is heavier than u quark.

3. Production rate of various baryons

- Production rate of hadron is known to lie on $\exp(-\alpha m)$
- Deviation from this line may indicate exotic nature.
- First measurement in charm sector.
- **Large deviation in $\Lambda_c(2625)^+(3/2^-)$**

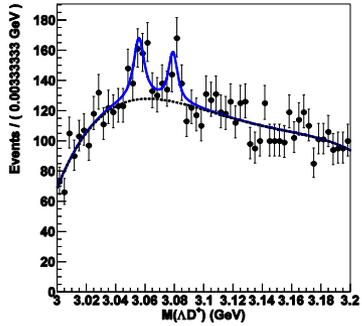


- Ξ_{cc}^+ is not discovered with full data of Belle.
U.L is comparable with some of the predictions.
- First significant measurement of $\Xi_c(2645)^+$ width.
- $\Xi_c(3055)^+$ is confirmed but not for $\Xi_c(3123)^+$.
- First observation of $\Xi_c(3055)^{+/0}$ in ΛD final state.
This is first observation of $\Xi_c(3055)^0$.
Need help of theorist to clarify the structure of $\Xi_c(3055)^{+/0}$.
- Many other interesting results will be published soon!

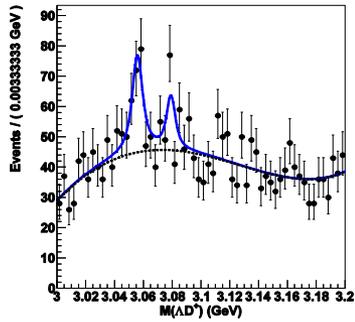
Backup

$M(\Lambda D^+)$ for each x_p

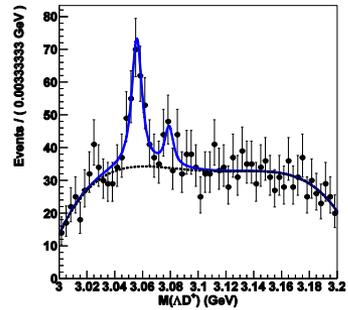
0.7-0.8



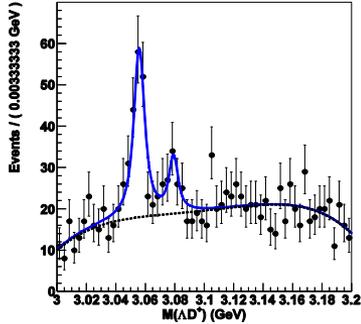
0.8-0.85



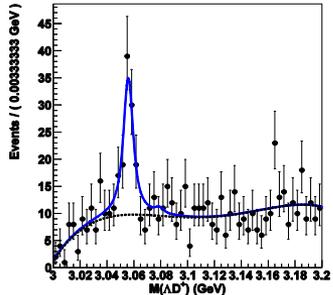
0.85-0.9



0.9-0.95

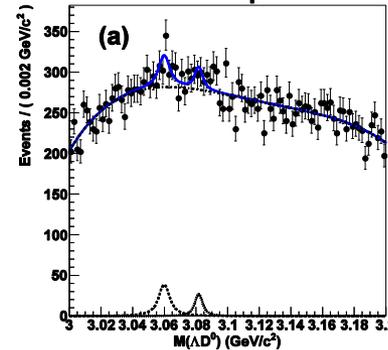


0.95-1.0

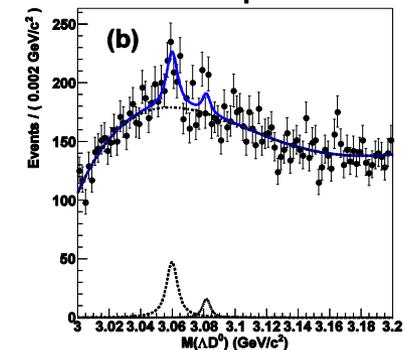


$M(\Lambda D^0)$ for each x_p

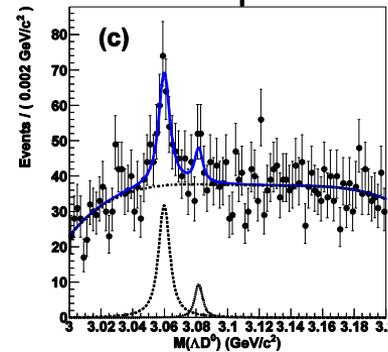
0.7 < x_p < 0.8



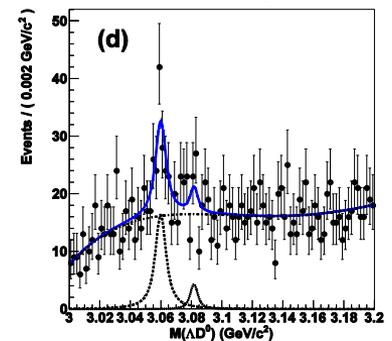
0.8 < x_p < 0.9



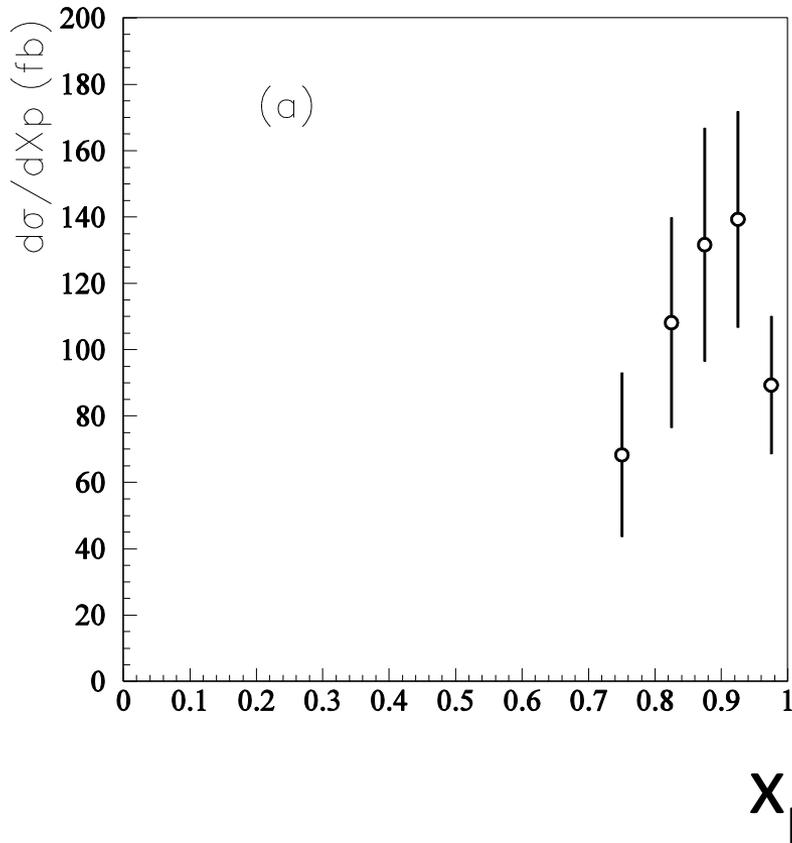
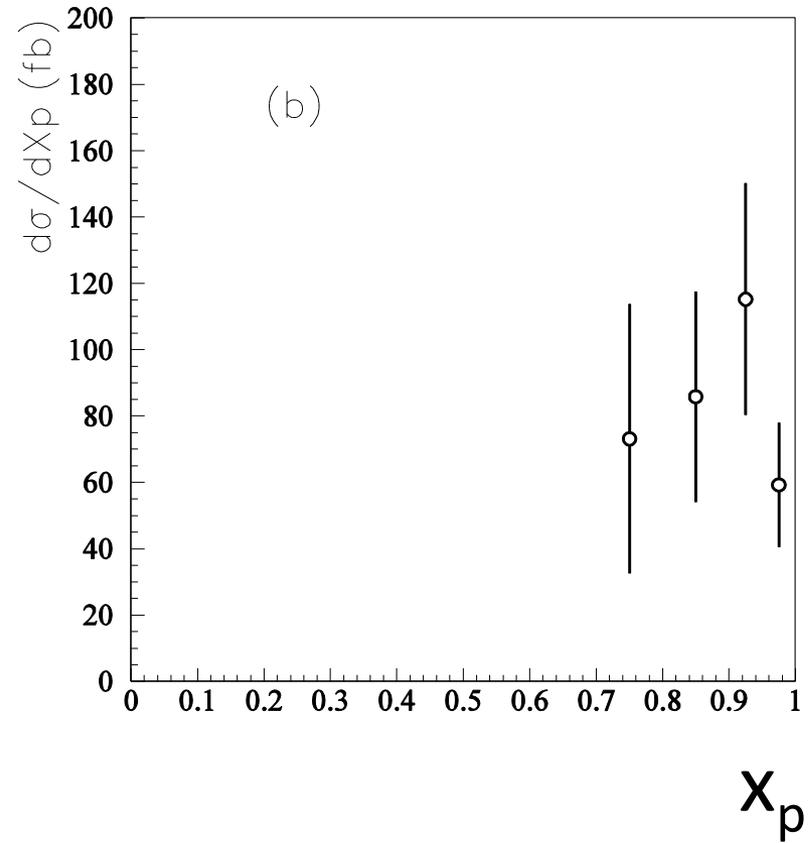
0.9 < x_p < 0.95



0.95 < x_p < 1.0

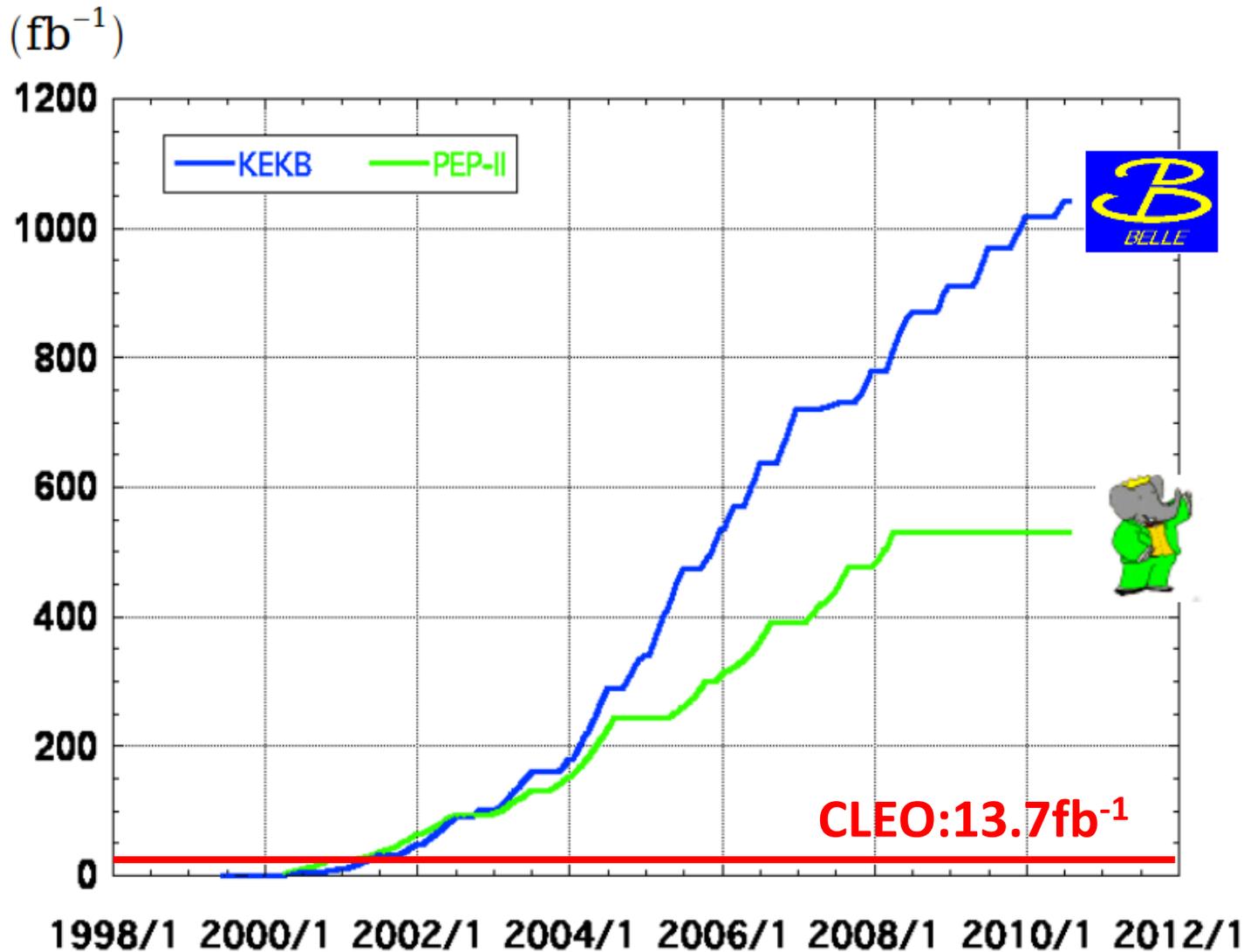


- Fix the mean and width from global fit.
(Systematic error on it is taken into account)
- S/N ratio improved as x_p becomes larger.

$\Xi_c(3055)^+$  $\Xi_c(3055)^0$ 

- Error bars are quadratic sum of stat and syst.
- In other charmed baryons, $d\sigma/dx_p$ show peaks in 0.7-0.8.

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:

$\sim 100 \text{ fb}^{-1}$

$\sim 550 \text{ fb}^{-1}$

On resonance:

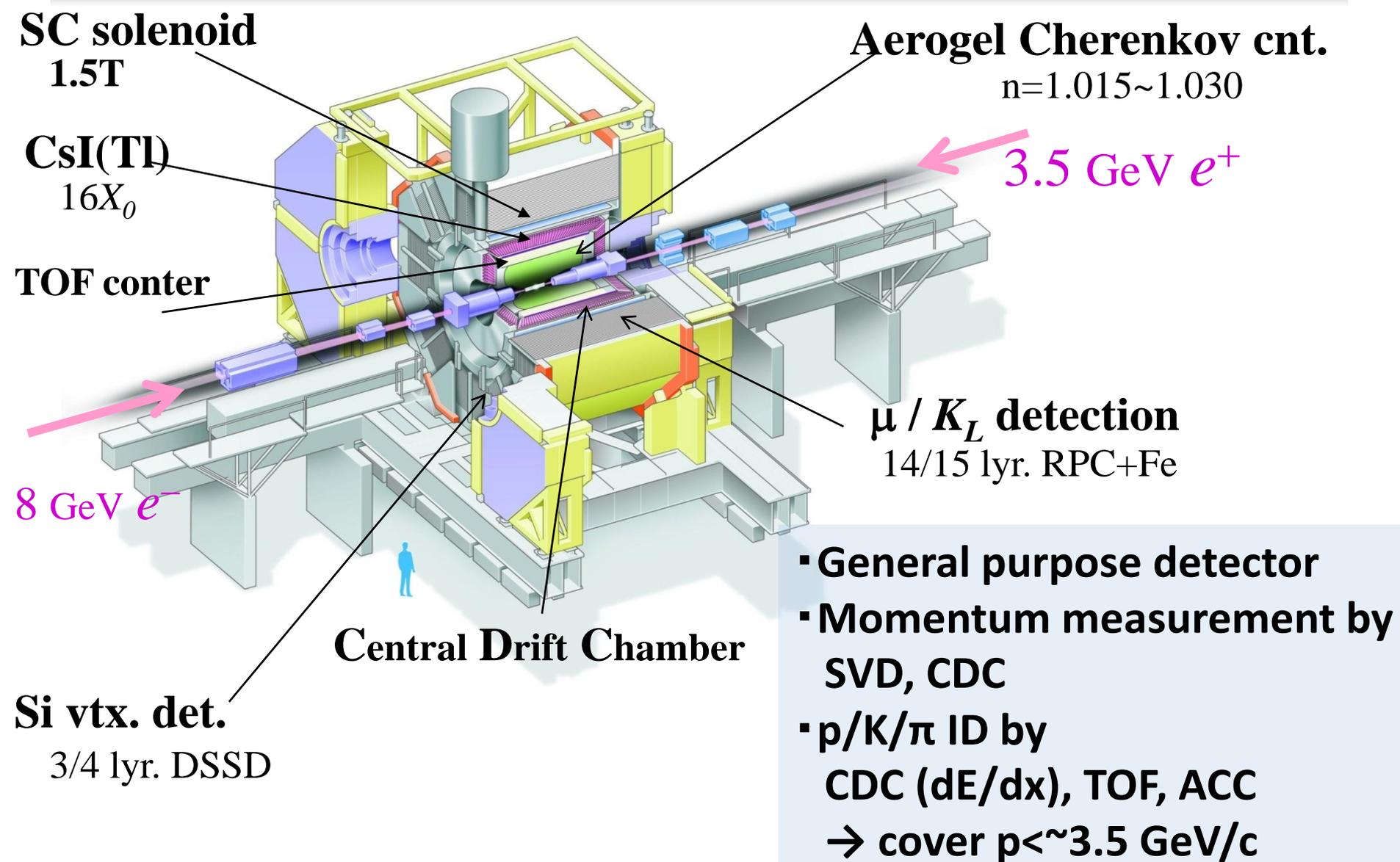
$\Upsilon(4S)$: 433 fb^{-1}

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

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

Off resonance:

$\sim 54 \text{ fb}^{-1}$



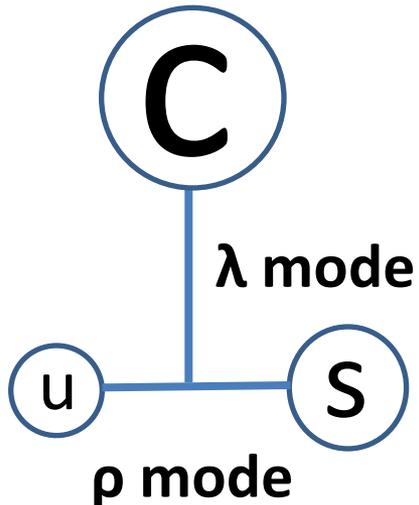
- The Ξ_c^* with mass around 3.0 GeV/c² is likely to be in **N=2 shell**.

	$\Sigma_c K$	$\Xi_c^*(2645)\pi$	$\Xi_c'\pi$	$\Sigma_c^* K$	$D\Lambda$	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 $\Xi_c(3055)$ 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)**



Naively thinking,

λ mode \rightarrow **(light baryon) + (heavy meson)**

ρ mode \rightarrow **(heavy baryon) + (light meson)**



Both ρ and λ mode excitation??

Help of the theorist is necessary!

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

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J^p	Λ_c^+	Ξ_c	$\Delta M(\text{MeV}/c^2)$	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	

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

spin0
di-quark

spin1
di-quark

• The mass difference of Λ_c and Ξ_c is $\sim 200 \text{ MeV}/c^2$, Σ_c and Ξ_c' is $\sim 120 \text{ MeV}$

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

- Gaussian convoluted Breit-Wigner ($\sigma=1.05$ MeV)
- Each modes gives consistent values. → Simultaneous fitting.
- Systematic error comes from..
 - BG shape, fitting region (0.3 MeV).
 - Result of Ensemble study (0.15 MeV)
 - 7% difference of resolution of Ξ_c^0 for data and MC (0.1 MeV)