Ξ_c Charmed Baryon Decays at Belle

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(with thanks to John Yelton)

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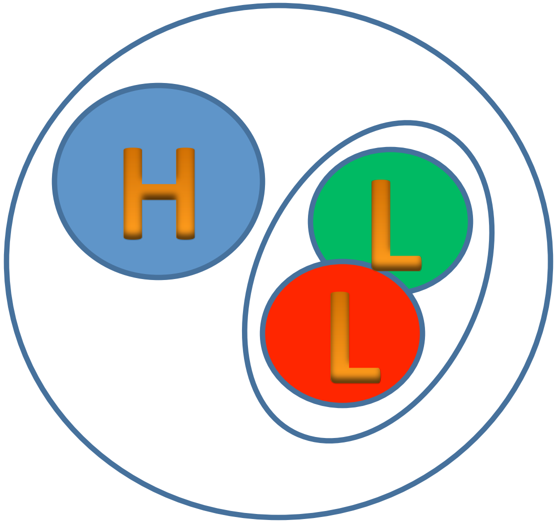
- *introduction*
- *the Belle experiment*
- $\Xi_c^{*(*)} \rightarrow \Xi_c X$ *decays*
- $\Xi_c^{*(*)} \rightarrow \Lambda D$ *decays*
- *summary*

Why Study Charmed Baryon Spectroscopy?



In the Heavy Quark Effective Theory, charmed baryons are considered to be a combination of a heavy c quark, rather loosely bound to a light di-quark.

All couplings and masses measured can be extrapolated using HQET, up to the B-baryons system (substitute c->b), and also (though not so precisely), the strange system (c->s) .

H is c quark for us, but can be b or s

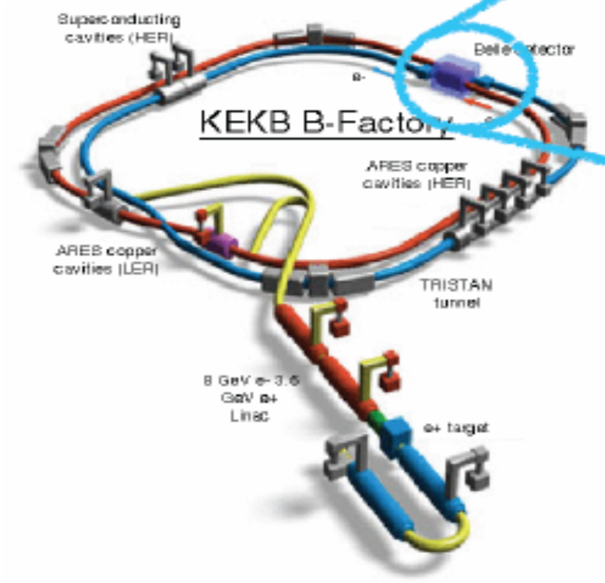
L is u, d, or s quark

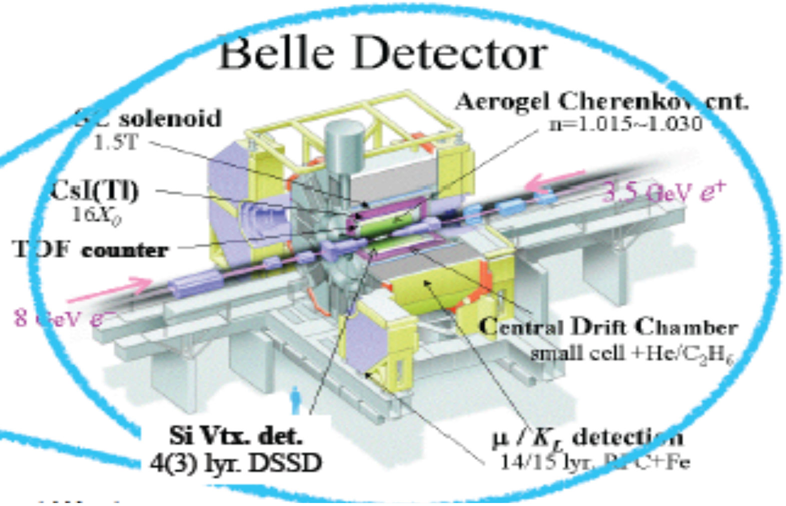
The charmed baryons offer more experimentally accessible states than those of the b-system; narrower and better defined states than the hyperon system; and more variety of possible states than for mesons.

Goal is to identify the states, and measure their widths and masses as accurately possible.

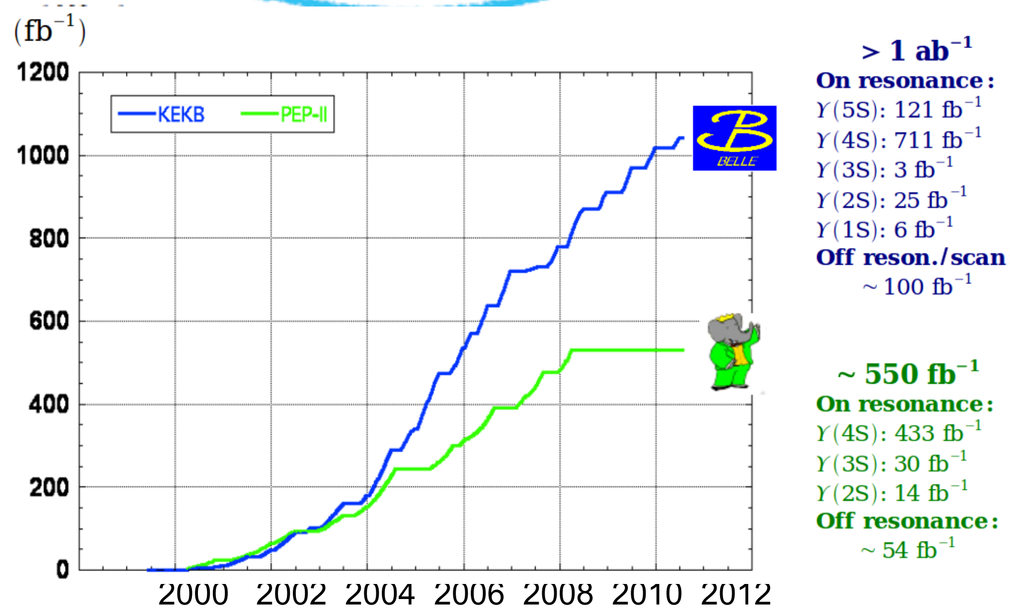
18 countries
84 institutes
~400 members

$$\mathcal{L}_{\text{peak}} = 21.1\ \text{nb}^{-1}\text{s}^{-1}$$





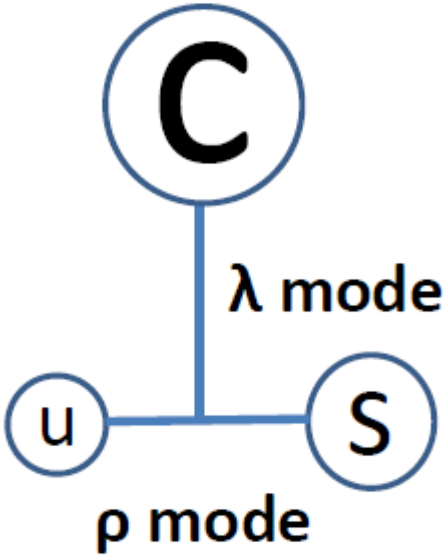
$$e^- \xrightarrow{8\ \text{GeV}} (\star) \xleftarrow{3.5\ \text{GeV}} e^+$$



Most of the data was taken at the Upsilon(4S) energy, but most charmed baryon studies are made using particles produced in the charm continuum. These charmed baryons are generally easier to detect, and have better signal:noise than those in B decays.

J. Yelton et al. (Belle), arXiv:1607.07123, to appear in PRD

New result: five different Ξ_c states are studied



Ξ_c	(J^p=1/2$^+$)
Ξ_c'	(J^p=1/2$^+$)
Ξ_c(2645)	(J^P=3/2$^+$)
Ξ_c(2790)	(J^P=1/2$^-$)
Ξ_c(2815)	(J^P=3/2$^-$)
Ξ_c(2980)	(J^P=?)

Use many Ξ_c decay modes to study decays of excited Ξ_c baryons

Ξ_c'	($J^P=1/2^+$)
$\Xi_c(2645)$	($J^P=3/2^+$)
$\Xi_c(2790)$	($J^P=1/2^-$)
$\Xi_c(2815)$	($J^P=3/2^-$)
$\Xi_c(2980)$	($J^P=?$)

} $\Xi_c X$

$\Sigma^0 \to \Lambda\gamma$ — $E_\gamma > 50$ MeV

$\Xi_c \to \Lambda X$ — Λ trajectory must come from IP

$\Xi^- \to \Lambda\pi^-$

$\Omega^- \to \Lambda K^-$

$\Sigma^+ \to p\pi^0$

} vertex between IP and Λ vertex, p impact param. w/r/t IP > 1 mm

$\Xi^0 \to p\pi^0$

Ξ_c reconstructed by vertex^constrained fit of daughters (IP not included in fit)

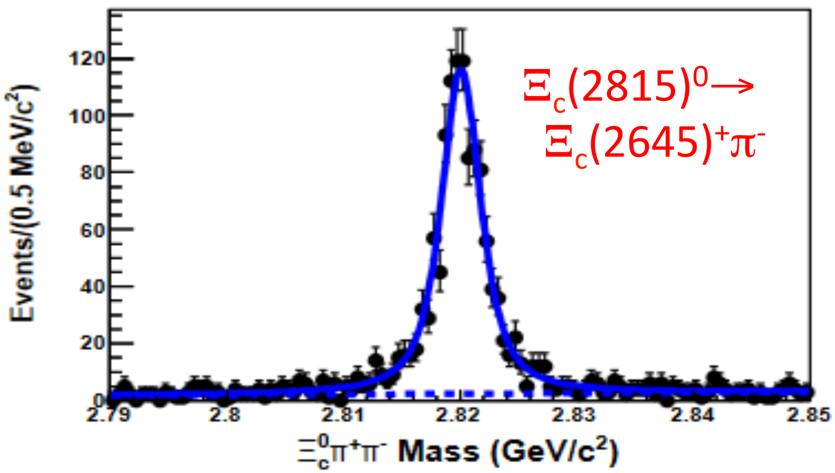
Mode	Signal yield (10^3)	Background yield (10^3)
$\Omega^- K^+$	4.3	0.4
$\Xi^- \pi^+$	24.3	6.5
$\Xi^- \pi^+ \pi^- \pi^+$	9.6	9.8
$\Lambda K^- \pi^+$	15.7	11.3
$p K^- K^- \pi^+$	9.5	6.5
$\Xi^- \pi^+ \pi^0$	15.8	13.2
$\Xi^0 \pi^+ \pi^+$	3.7	3.4
ΛK^0_S	4.8	5.0
$p K^- K^0_S$	6.4	10.6
$\Sigma^0 K^- \pi^+$	6.7	4.3
Sum of above Ξ_c^0 modes	100.8	71.0
$\Xi^- \pi^+ \pi^+$	33.6	8.8
$\Lambda K^- \pi^+ \pi^+$	5.0	3.4
$\Xi^0 \pi^+$	1.4	1.1
$\Xi^0 \pi^+ \pi^- \pi^+$	2.5	2.4
$\Sigma^+ K^- \pi^+$	6.0	3.5
$\Lambda K^0_S \pi^+$	6.5	7.4
$\Sigma^0 K^0_S \pi^+$	1.1	1.5
Sum of above Ξ_c^+ modes	56.1	28.1

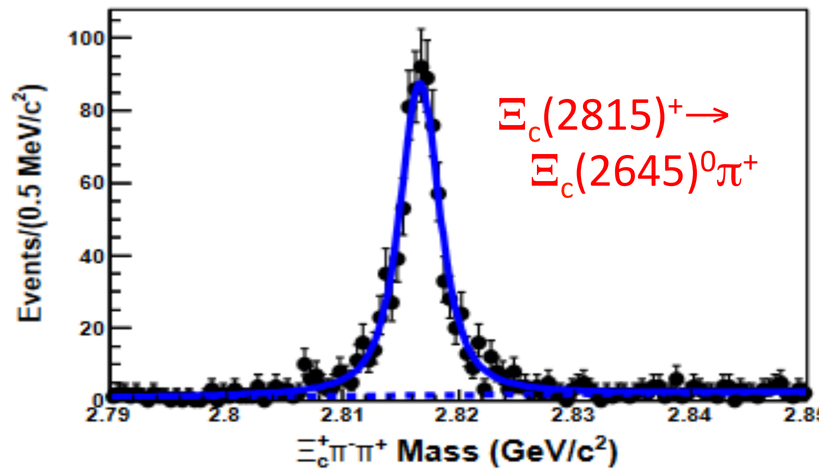
Use many Ξ_c decay modes to investigate the excited Ξ_c baryons

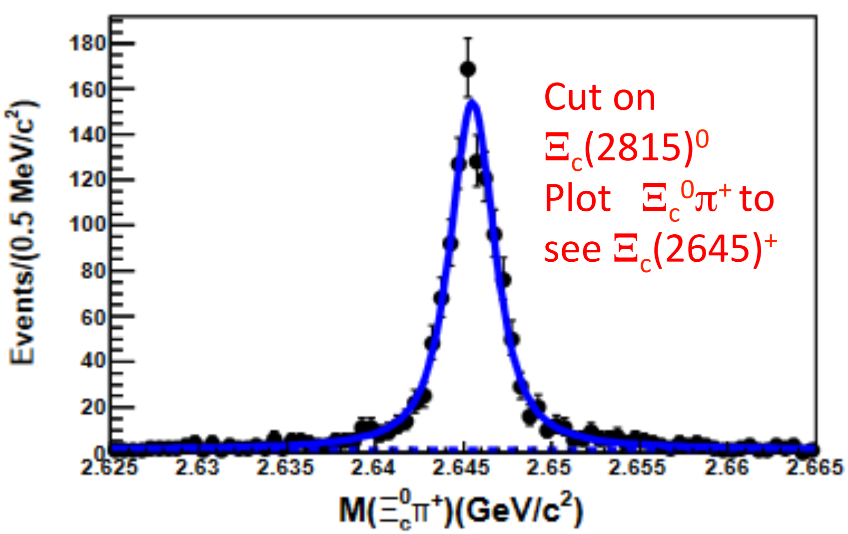
Ξ_c	$\Xi_c'(J^P=1/2^+)$	$\Xi_c(2645)(J^P=3/2^+)$	$\Xi_c(2790)(J^P=1/2^-)$	$\Xi_c(2815)(J^P=3/2^-)$	$\Xi_c(2980)$

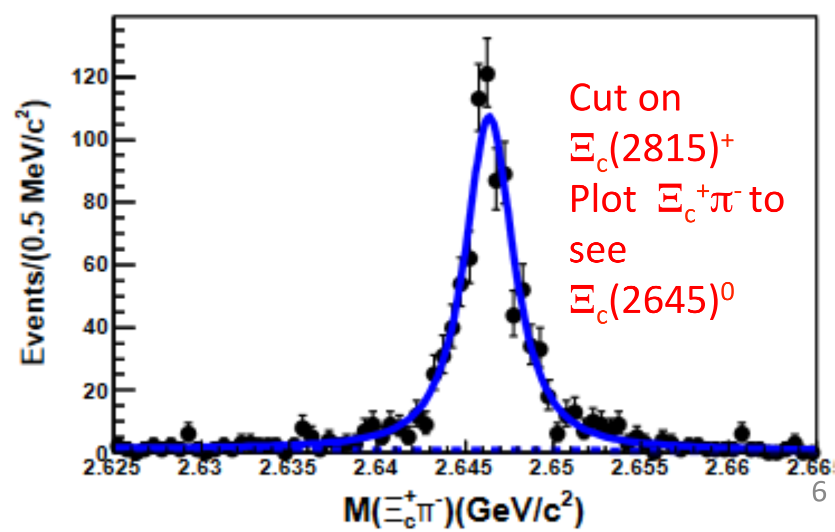
J. Yelton et al. (Belle), arXiv: 1607.07123, to appear in PRD

resolution function from MC; momentum scale calibrated from $D^{*+} \to D^0\pi^+$ decays









J. Yelton et al. (Belle), arXiv:1607.07123, to appear in PRD

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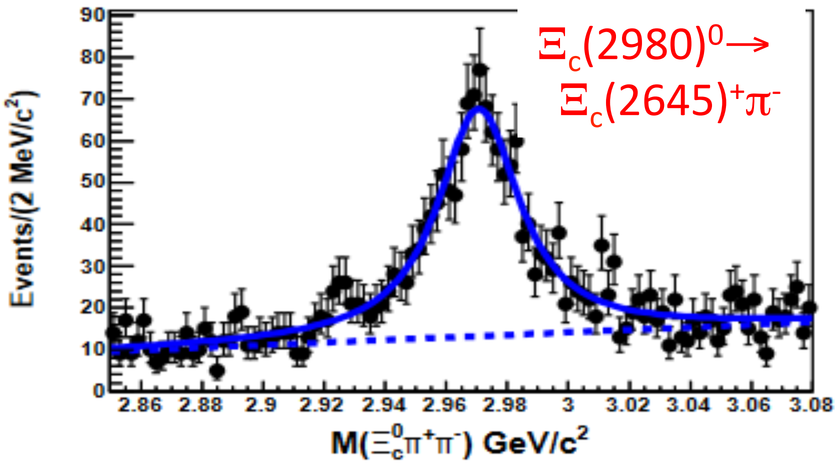

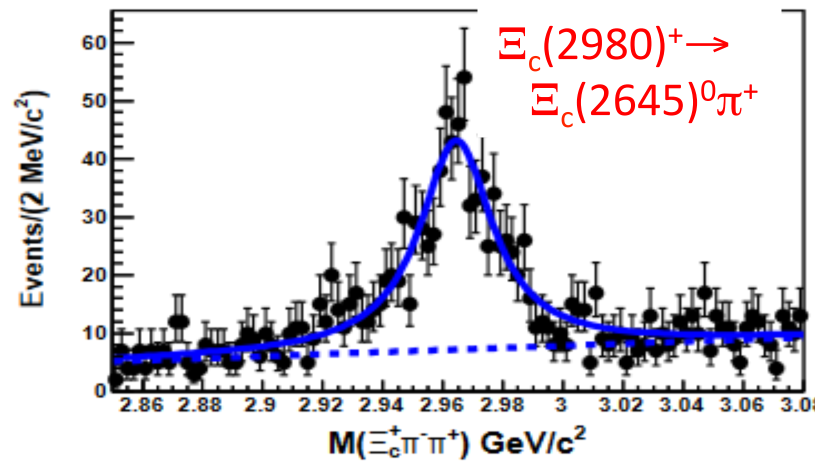

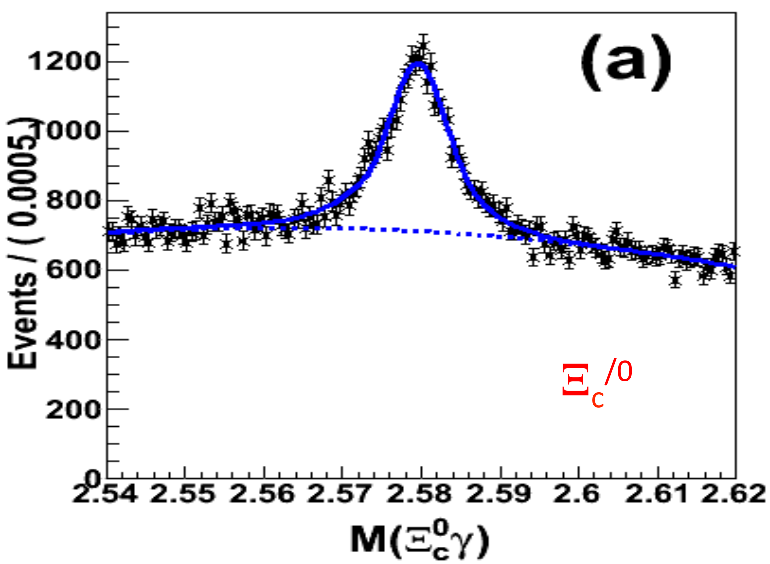

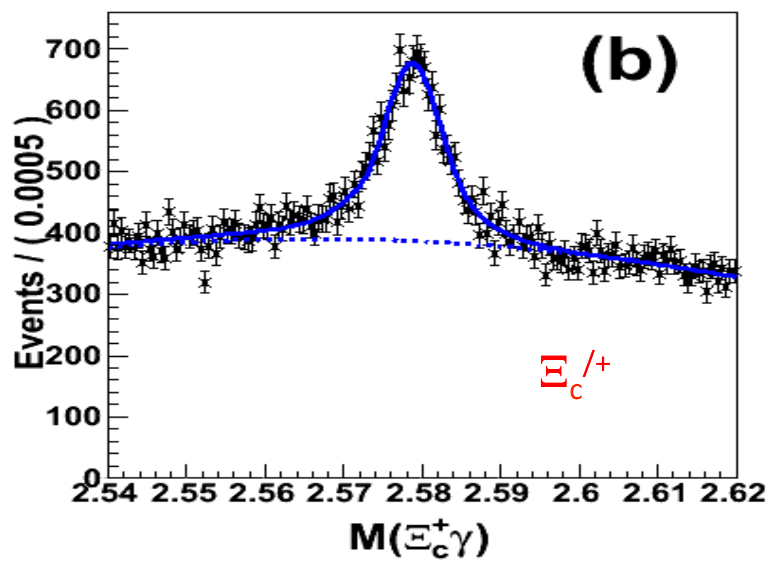

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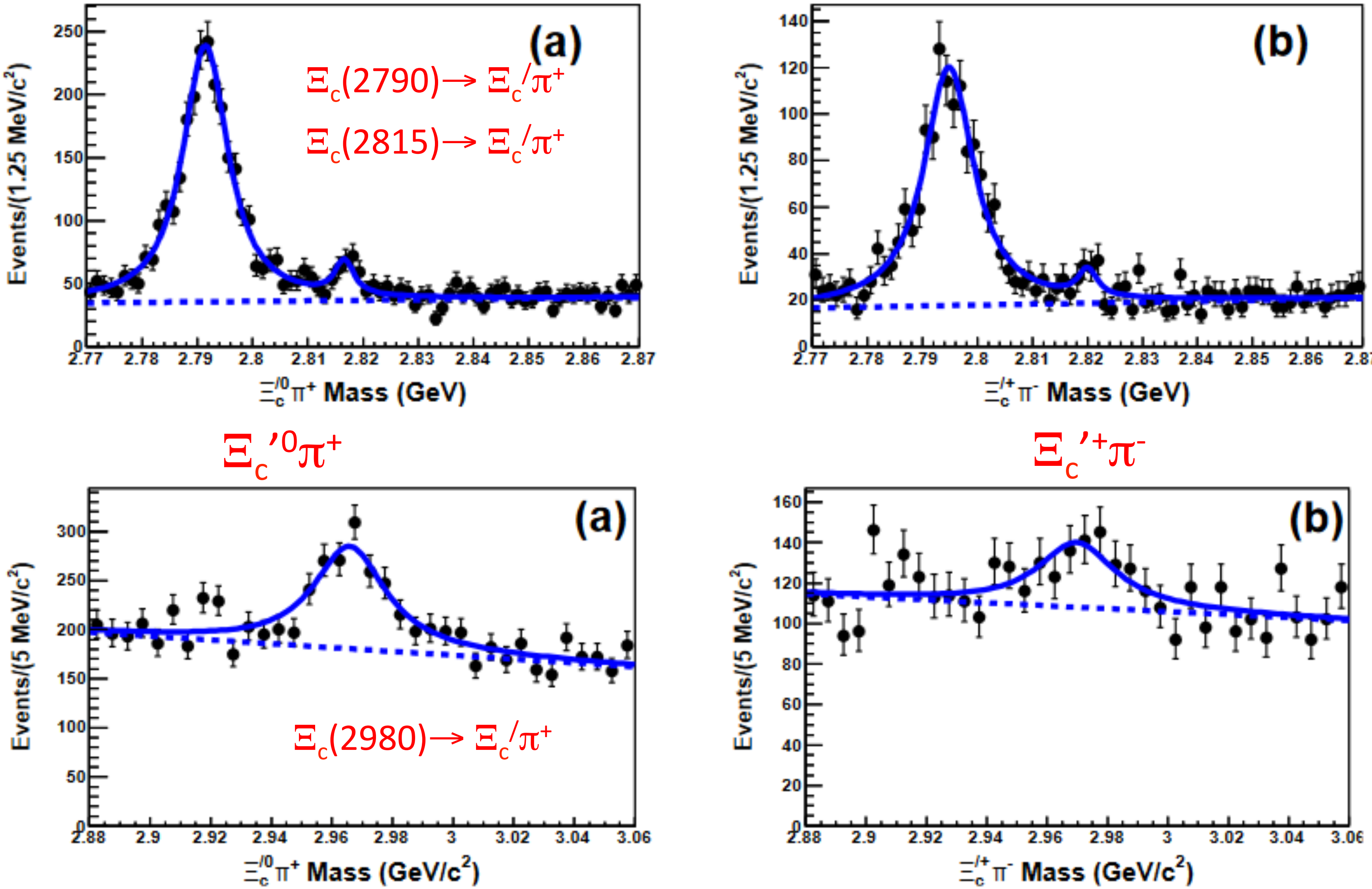


Fit Results

J. Yelton et al. (Belle), arXiv:1607.07123, to appear in PRD

es.

Particle	Yield	Mass	$M - M(\Xi_c)$	$M - M(\Xi_c')$	Width
$\Xi_c(2645)^+$	1260 ± 40	$2645.58 \pm 0.06 \pm 0.07^{+0.28}_{-0.40}$	$174.66 \pm 0.06 \pm 0.07$		$2.06 \pm 0.13 \pm 0.13$
PDG		2645.9 ± 0.5	175.0 ± 0.6		$2.6 \pm 0.2 \pm 0.4$
$\Xi_c(2645)^0$	975 ± 36	$2646.43 \pm 0.07 \pm 0.07^{+0.28}_{-0.40}$	$178.46 \pm 0.07 \pm 0.07$		$2.35 \pm 0.18 \pm 0.13$
PDG		2645.9 ± 0.5	178.0 ± 0.6		< 5.5
$\Xi_c(2815)^+$	941 ± 35	$2816.73 \pm 0.08 \pm 0.06^{+0.28}_{-0.40}$	$348.80 \pm 0.08 \pm 0.06$		$2.43 \pm 0.20 \pm 0.17$
PDG		2816.6 ± 0.9	348.7 ± 0.9		< 3.5
$\Xi_c(2815)^0$	1258 ± 40	$2820.20 \pm 0.08 \pm 0.07^{+0.28}_{-0.40}$	$349.35 \pm 0.08 \pm 0.07$		$2.54 \pm 0.18 \pm 0.17$
PDG		2819.6 ± 1.2	348.8 ± 1.2		< 6.5
$\Xi_c(2980)^+$	916 ± 55	$2966.0 \pm 0.8 \pm 0.2^{+0.3}_{-0.4}$	$498.1 \pm 0.8 \pm 0.2$		$28.1 \pm 2.4^{+1.0}_{-5.0}$
PDG		2970.7 ± 2.2			17.9 ± 3.5
$\Xi_c(2980)^0$	1443 ± 75	$2970.8 \pm 0.7 \pm 0.2^{+0.3}_{-0.4}$	$499.9 \pm 0.7 \pm 0.2$		$30.3 \pm 2.3^{+1.0}_{-1.8}$
PDG		$2968.0 \pm 2.6 \pm 0.5$			20 ± 7
$\Xi_c'^+$	7055 ± 211	$2578.4 \pm 0.1 \pm 0.4^{+0.3}_{-0.4}$	$110.5 \pm 0.1 \pm 0.4$		
PDG		2575.6 ± 3.0	107.8 ± 3.0		
$\Xi_c'^0$	11560 ± 276	$2579.2 \pm 0.1 \pm 0.4^{+0.3}_{-0.4}$	$108.3 \pm 0.1 \pm 0.4$		
PDG		2577.9 ± 2.9	107.0 ± 2.9		
$\Xi_c(2790)^+$	2231 ± 103	$2791.6 \pm 0.2 \pm 0.1 \pm 0.4^{+0.3}_{-0.4}$	$320.7 \pm 0.2 \pm 0.1 \pm 0.4$	$213.2 \pm 0.2 \pm 0.1$	$8.9 \pm 0.6 \pm 0.8$
PDG		2789.8 ± 3.2	318.2 ± 3.2		< 15
$\Xi_c(2790)^0$	1241 ± 72	$2794.9 \pm 0.3 \pm 0.1 \pm 0.4^{+0.3}_{-0.4}$	$323.8 \pm 0.2 \pm 0.1 \pm 0.4$	$215.7 \pm 0.2 \pm 0.1$	$10.0 \pm 0.7 \pm 0.8$
PDG		2791.9 ± 3.3	324.0 ± 3.3		< 12

All measured values significantly more precise than PDG values (~1 order of magnitude)

Isospin splitting

J. Yelton et al. (Belle), arXiv:1607.07123, to appear in PRD

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

Similar to -2 MeV/c^2 found in p-n isospin splitting

Note: *third uncertainty is due to mass uncertainties in ground state Ξ_c's*

Spectroscopy of Excited Ξ_c (csu and csd) States

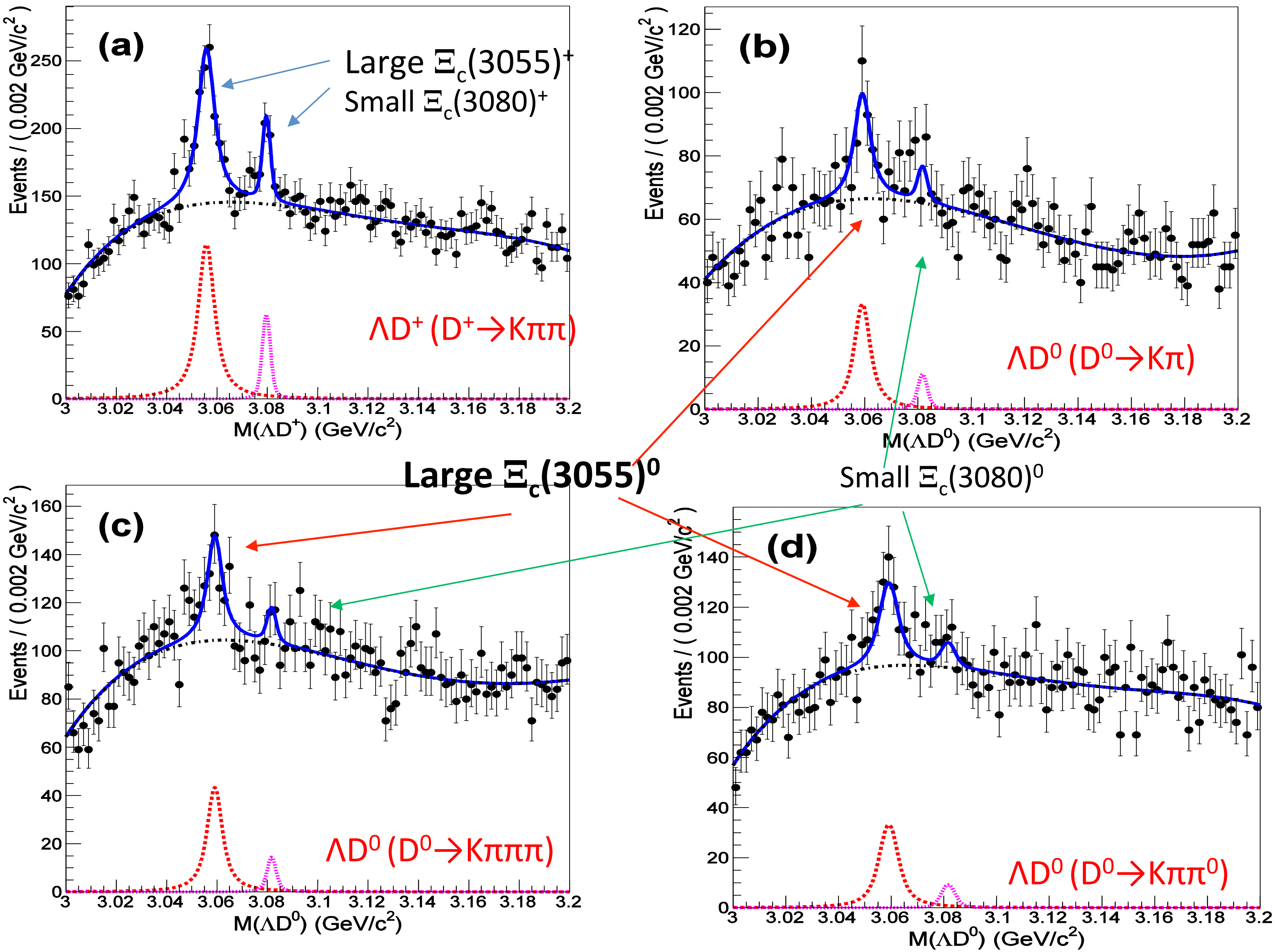
Lowest mass excited states seen in $\Xi_c\, n(\pi)$ (threshold = 2.61 GeV)

Higher mass resonances seen in $\Lambda_c^+ K^- \pi^+$ (threshold = 2.92 GeV)

why not also ΛD? (threshold = 2.97 GeV)

We can reconstruct Λ decays using their long lifetime, reconstruct D mesons (1 mode for D^+, 3 for D^0), cut at high momentum, and look for resonant peaks

Y. Kato et al. (Belle), PRD 94, 032002 (2016) [arXiv:1605.09103]



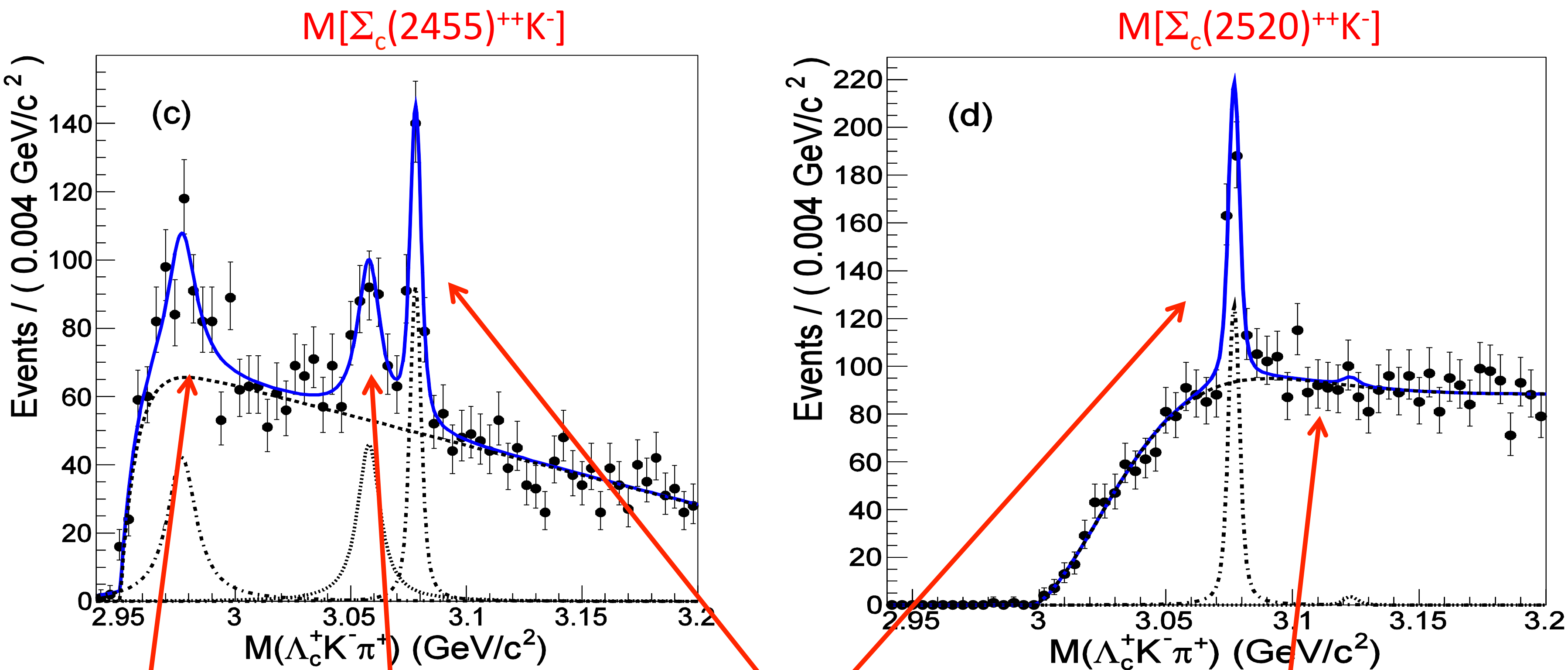
Y. Kato et al. (Belle), PRD 94, 032002 (2016) [arXiv:1605.09103]

Units are MeV	Mass (ΛD)	Width(ΛD)	Significance
$\Xi_c(3055)^0$ FIRST OBSERVATION	3059.0±0.5±0.6	6.4±2.1±1.1	8.6
$\Xi_c(3055)^+$	3055.8±0.4±0.2	7.0±1.2±1.5	11.7
$\Xi_c(3080)^+$	3079.6±0.4±0.1	<6.3	4.8

How does this compare to $\Xi_c \rightarrow \Sigma_c^{++}K^-$?

⇒ Combine the results to get more precise numbers for the masses and widths

Y. Kato et al. (Belle), PRD 89 052003 (2014) [arXiv:1312.1026]



$\Xi_c(2980)^+$
(well-known in $\Xi\pi\pi$)

$\Xi_c(3055)^+$

$\Xi_c(3080)^+$

NOTHING at 3123
Limit much tighter than observation reported by BaBar (Phys. Rev. D 77 012002)

Y. Kato et al. (Belle), PRD 89 052003 (2014) [arXiv:1312.1026]

$B(\Xi_c(3055)^+ \to \Lambda D^+)/B(\Xi_c(3055)^+ \to \Sigma_c^{++}K^-) = 5.09 \pm 1.01 \pm 0.76$

$B(\Xi_c(3080)^+ \to \Lambda D^+)/B(\Xi_c(3080)^+ \to \Sigma_c^{++}K^-) = 1.29 \pm 0.30 \pm 0.15$

$B(\Xi_c(3080)^+ \to \Sigma_c^{++}(2520)K^-/B(\Xi_c(3080)^+ \to \Sigma_c^{++}K^-) = 1.07 \pm 1.01 \pm 0.76$

⇒ the $\Xi_c(3055)$ *likes* to decay to ΛD; the $\Xi_c(3080)$ prefers to decay to $\Sigma_c^{(*)++}K^-$

This is a challenge to theory

Combining fit results of different decay modes:

Units are MeV	Mass (BELLE)	Mass(BaBar)	Width(BELLE)	Width(BaBar)
$\Xi_c(3055)^0$	3059.0±0.5±0.6		6.4±2.1±1.1	
$\Xi_c(3055)^+$	3055.9±0.4	3054.2±1.2±0.5	7.8±1.2±1.5	17±6±11
$\Xi_c(3080)^0$	3081.6±1.1±0.2		4.4±1.8±1.9	5.9±2.3±1.5
$\Xi_c(3080)^+$	3077.9±0.9	3077.0±0.4±0.2	3.0±0.7±0.4	5.5±1.3±0.6

Summary

- *The charmed baryon system remains a fertile ground of research, and Belle has substantial history of discoveries and measurements on the charmed baryon system*

- *Presented new results on masses and widths of excited Ξ_c states decaying into Ξ_c ground-states*

- *Presented recent observation of excited Ξ_c states decaying to ΛD. This includes the* ***first observation*** *of the $\Xi_c(3055)^0$*

- *All results should be significantly improved upon by Belle II, which should increase the statistics of Belle by a factor of* ***50*** *(see Belle II talk on Friday)*