

2016 JAEA/ASRC Reimei Workshop : New exotic hadron matter at J-PARC  
24-26 Oct, 2016, Inha University, KOREA

# Structure of charmed baryons studied by pionic decays



Hideko Nagahiro (Nara Women's Univ. / RCNP)

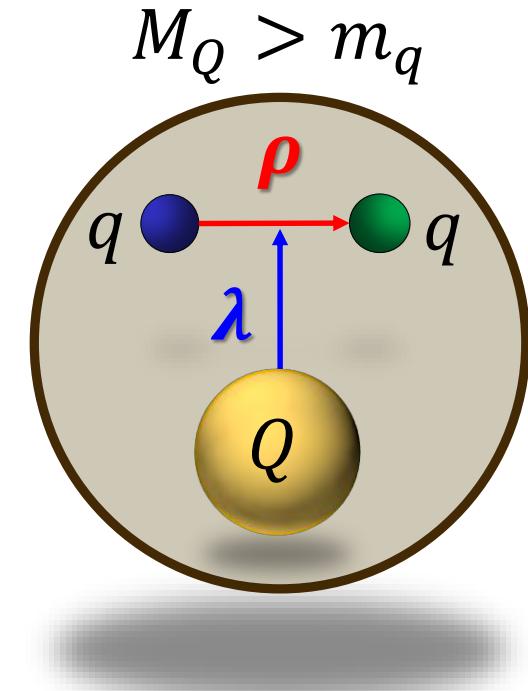
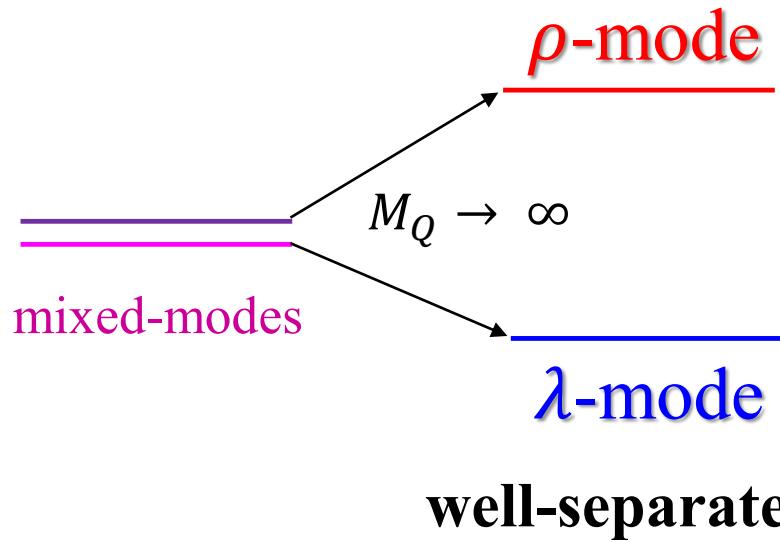
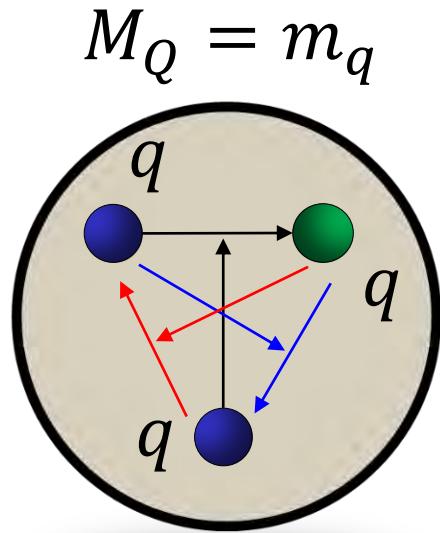
Shigehiro Yasui, Atsushi Hosaka, Makoto Oka, Hiroyuki Noumi

H. Nagahiro, S. Yasui, A. Hosaka, H. Noumi, M. Oka, arXiv:1609.01085

# Introduction : hadron structure $\Leftrightarrow$ hadron properties



- Charmed baryon  $\Lambda_C^*$ :  $Qqq$  system



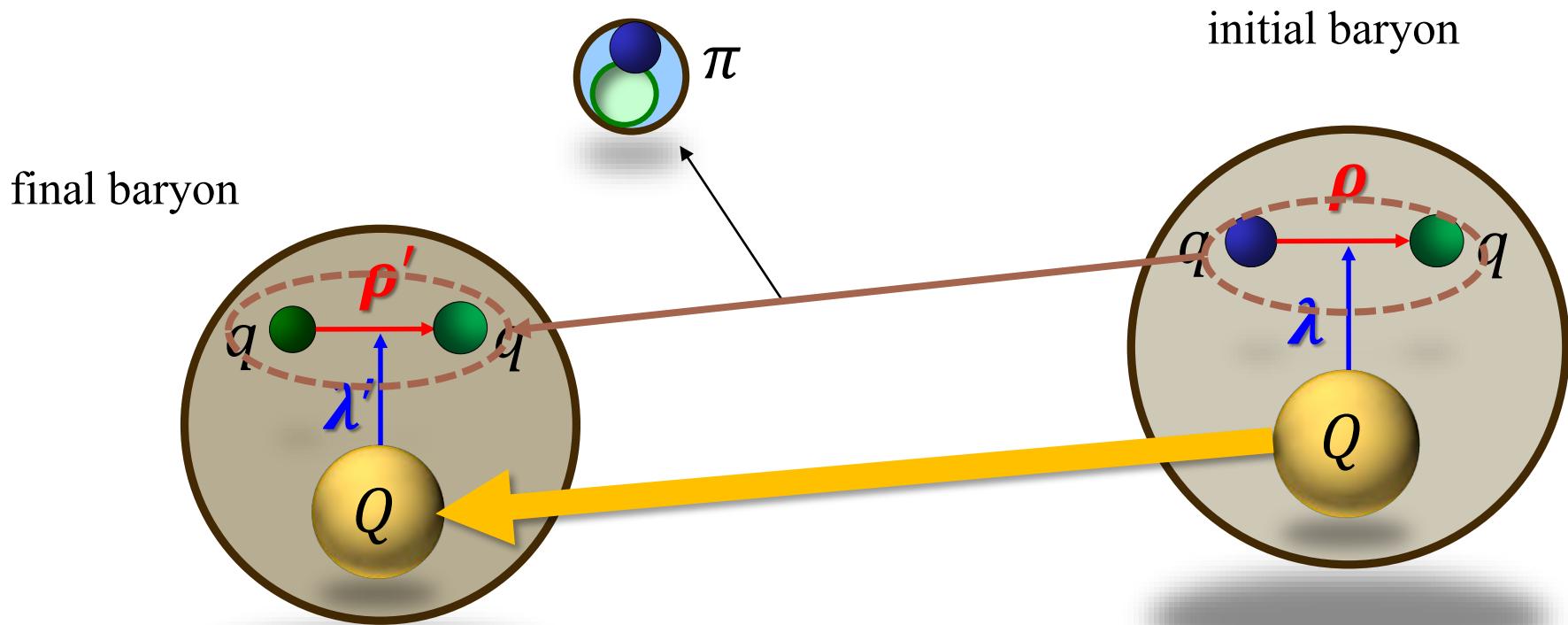
low-lying  $Y_c^*$  may have a *simple* configuration of quarks

T. Yoshida, E. Hiyama, A. Hosaka, M. Oka, K. Sadato, PRD92(2015)114029

**Extract clear information**

Structure  $\Leftrightarrow$  Spectrum, Production & Decay

# One pion emission decays



- ✓  $\pi$  couples dominantly with the light quarks  
→ charm quark behaves as a spectator
- ✓ Dynamics of light and heavy quarks are independent  
→ decay process can be simply described ?

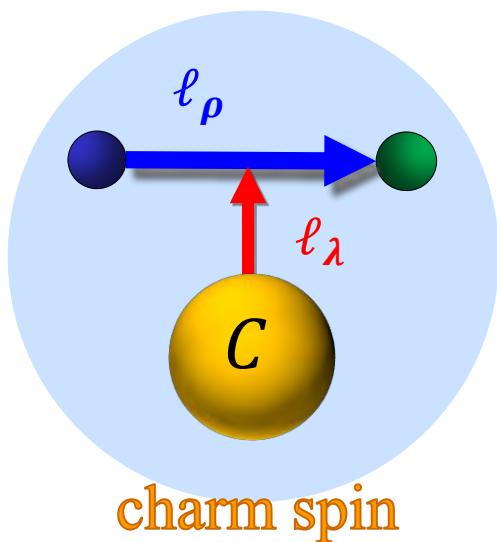
**Underlying structure  $\Leftrightarrow$  hadron dynamics (decay process)**

# Construction of the wave functions inspired by heavy Q spin sym.



## Charmed baryons with $J^P$

1. Combine the light components (*brown muck*)
2. Combine it with **charm quark spin**



$$J = \mathbf{s}_c + \mathbf{j}$$

total “spin” of remaining system  
(~ *brown muck* [Neubert, PR245])

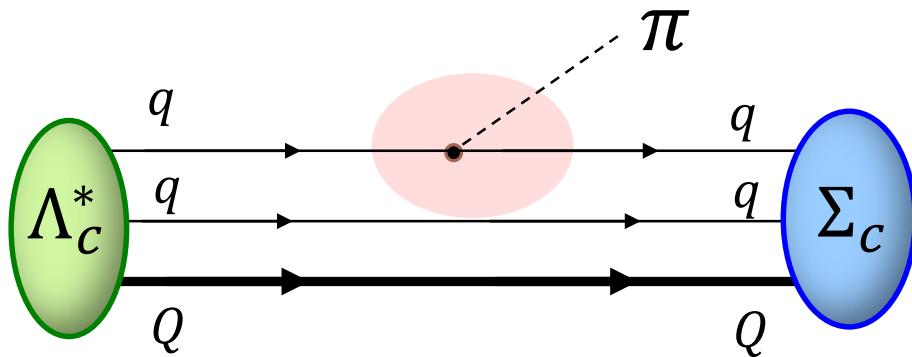
$$\Lambda_c = \left[ \left[ \psi_{\ell_\lambda}(\vec{\lambda}) \psi_{\ell_\rho}(\vec{\rho}), d \right]^j, s_c \right]^J D^0 c$$

orbital w.f.      charm spin  
Spin of two-light quarks

compatible with HQS

**heavy quark spin conservation  $\Leftrightarrow$  brown muck spin conservation**

# Formalism for decay with quark model



## $\pi qq$ interaction Lagrangian

axial-vector

$$\mathcal{L}_{\pi qq} = \frac{g_A^{(q)}}{2f_\pi} \bar{q} \gamma^\mu \gamma_5 \vec{\tau} q \cdot \partial_\mu \vec{\pi}$$

$$g_A^{(q)} = 1 \text{ [Weinberg '90]}$$

$$f_\pi = 93 \text{ MeV}$$

## H.O. parameters

$$m = 0.35 \pm 0.05 \text{ GeV}$$

$$M = 1.5 \pm 0.1 \text{ GeV}$$

$$k = 0.02 - 0.04 \text{ GeV}^3$$



$$\hbar\omega_\lambda \sim 0.3 - 0.4 \text{ GeV}$$

$$\sqrt{\langle R^2 \rangle} \sim 0.45 - 0.55 \text{ fm}$$

# Ambiguity of $\pi qq$ coupling constant $g_A^{(q)}$



$$\Sigma_c(2455) \ 1/2^+ \xrightarrow{100\%} \Lambda_c^{gs}(2286) 1/2^+ \ \pi$$

$$\Sigma_c(2520) \ 3/2^+ \xrightarrow{100\%} \Lambda_c^{gs}(2286) 1/2^+ \ \pi$$

$\Sigma_c(1/2^+(gs), 3/2^+) \rightarrow \Lambda_c^{gs}(2286, 1/2^+) \pi$  decay : p-wave decay

	$\Sigma_c(2455; 1/2^+)$	$\Sigma_c^*(2520; 3/2^+)$
PDG value $\Gamma_{\text{tot}}$ [MeV]	1.89	14.8
$\Gamma^{\text{theo}}$ [MeV]	1/2 <sup>+</sup> 4.27–4.33	-
	3/2 <sup>+</sup>	30.3–31.6

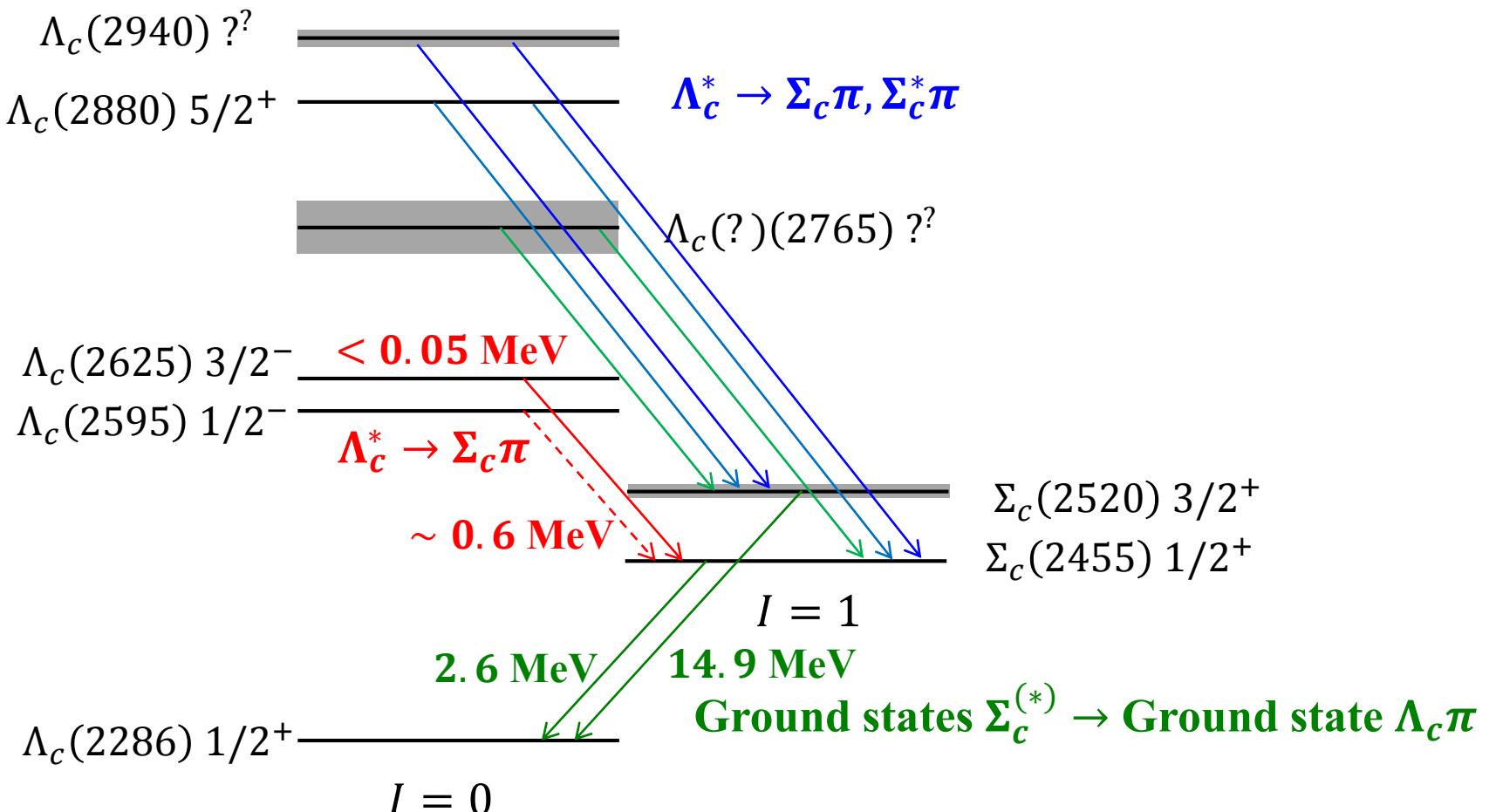
- stable for different parameters ( $m, M, k$ )
- factor 2 over-estimate**

→ consistent with *known* ambiguity of the axial-coupling of quark

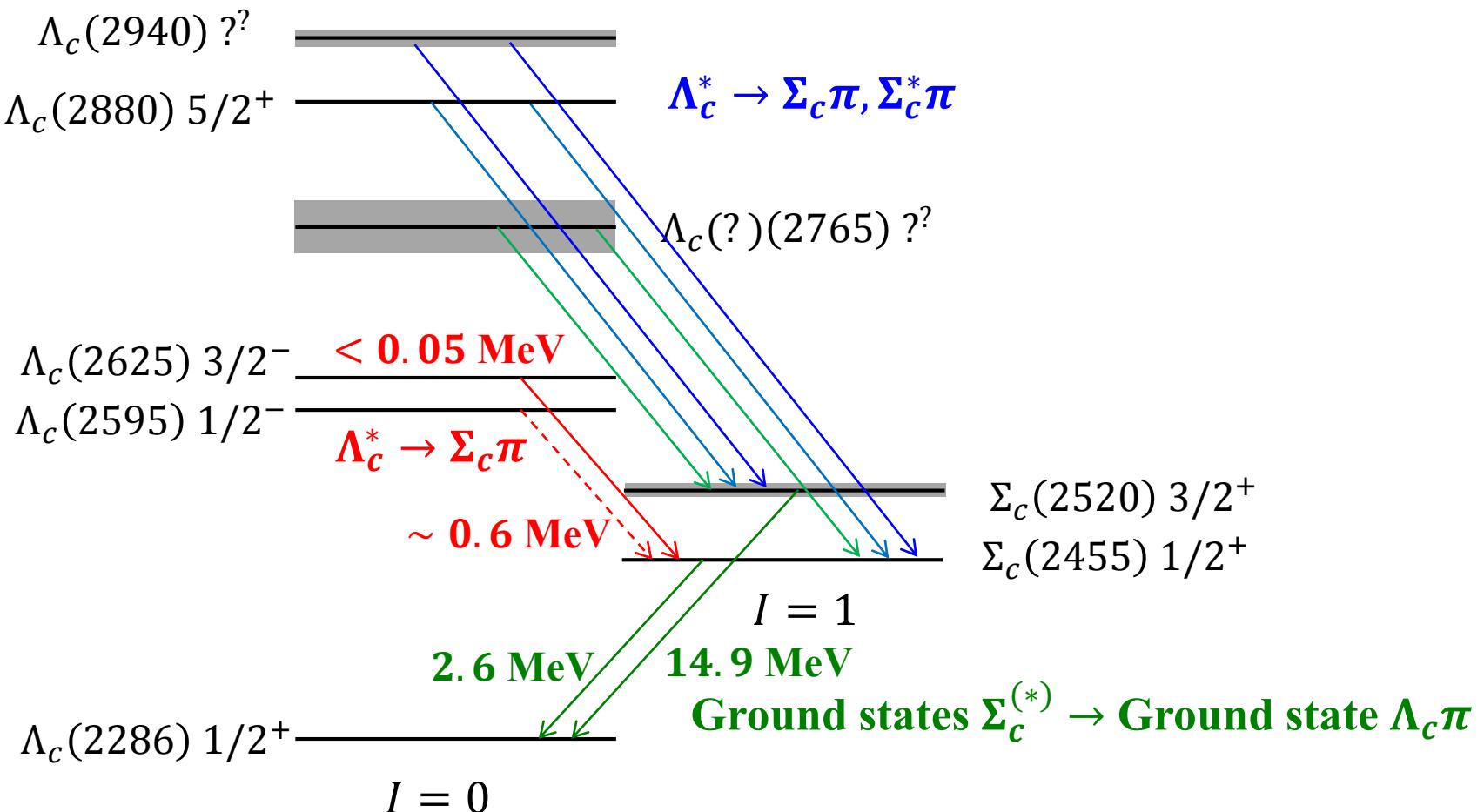
$$g_A^{(q)} = 1 \Leftrightarrow g_A^{(q)} \sim \frac{3}{4} \quad \text{to reproduce } g_A^N = 1.25$$

**we show our results with  $g_A^{(q)} = 1$  to see how our *simple & naïve* model works**

# Level structures $Y_c$ & possible one pion decays considered here



# Level structures $Y_c$ & possible one pion decays considered here



# Structure of first excited $\Lambda_c$ baryons



$\sqrt{s}$

$\rho$ -mode excitation ?



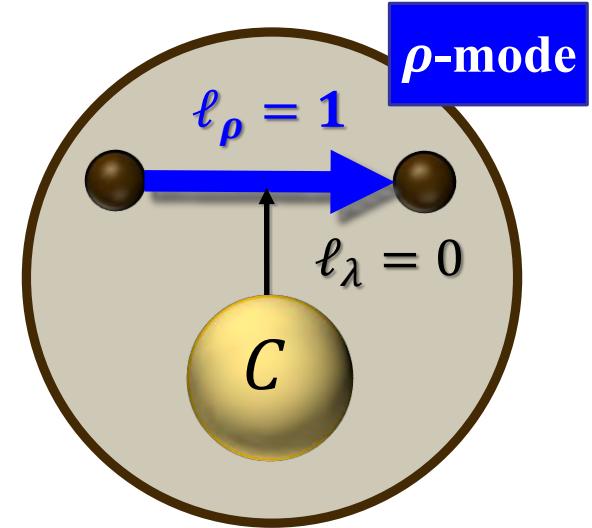
$\Lambda_c^*(2625) \frac{3}{2}^-$

2<sup>nd</sup> excited state

$\Lambda_c^*(2595) \frac{1}{2}^-$

1<sup>st</sup> excited state

Negative parity :  
 $\ell = 1$  p-wave excitation  
 with diquark spin-0

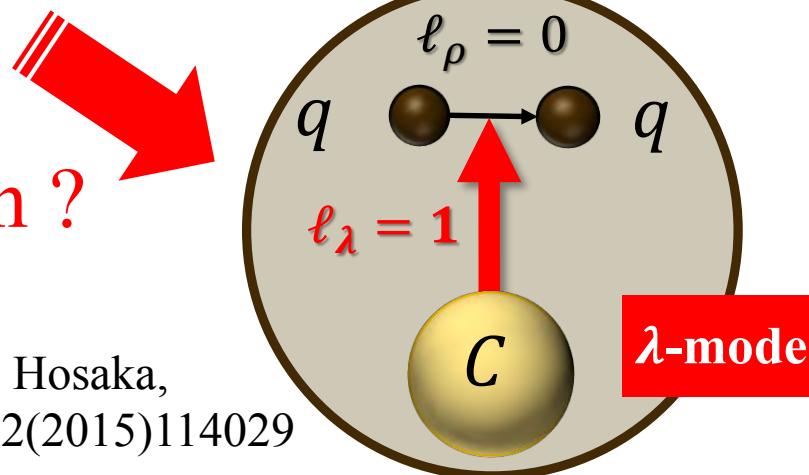


$\Lambda_c(2286) \frac{1}{2}^+$

ground state

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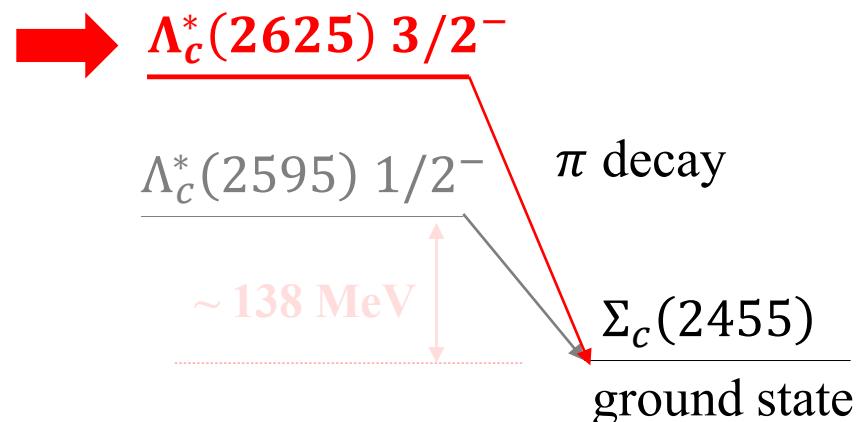
$\lambda$ -mode excitation ?



$\Lambda_c(2625; 3/2^-)^+ \rightarrow \Sigma_c^{gs}(2455)^{++} \pi^-$  decay

$\Lambda_c(2625; 3/2^-)$ partial decay			
PDG value $\Gamma_i^{\text{PDG}}$ [MeV]		$< 0.95 \times < 5\% = 0.05$	
$\Gamma_i^{\text{theo}}$ [MeV]	$\lambda$ -mode	$1/2^-$	s-wave decay
		$3/2^-$	0.024 – 0.039 d-wave decay

- the small width : well-reproduced by QM
- consistent with  $\lambda$ -mode  $J^P = 3/2^-$
- inconsistent with  $\lambda$ -mode  $J^P = 1/2^-$

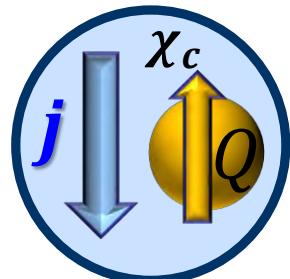


$\Lambda_c(2625; 3/2^-)^+ \rightarrow \Sigma_c^{gs}(2455)^{++} \pi^-$  decay



		$\Lambda_c(2625; 3/2^-)$ partial decay	
PDG value $\Gamma_i^{\text{PDG}}$ [MeV]		$< 0.95 \times < 5\% = 0.05$	
$\Gamma_i^{\text{theo}}$ [MeV]	$\lambda$ -mode	$1/2^-$	$= 5.4 - 10.7$
		$3/2^-$	$0.024 - 0.039$
$\Gamma_i^{\text{theo}}$ [MeV]	$\rho$ -mode	$1/2^- (j = 0)$	$= 0$
		$1/2^- (j = 1)$	$= 24 - 45$
		$3/2^- (j = 1)$	$0.013 - 0.019$
		$3/2^- (j = 2)$	$0.023 - 0.034$
		$5/2^- (j = 2)$	$0.010 - 0.015$

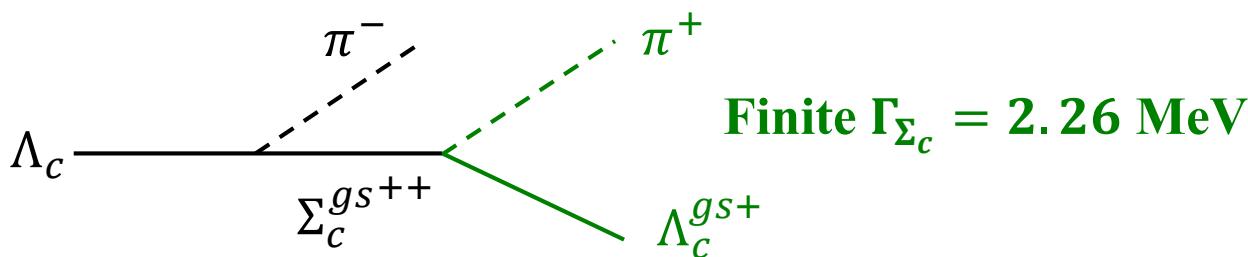
- We cannot exclude the possibilities of  $\rho$ -mode from view point of width



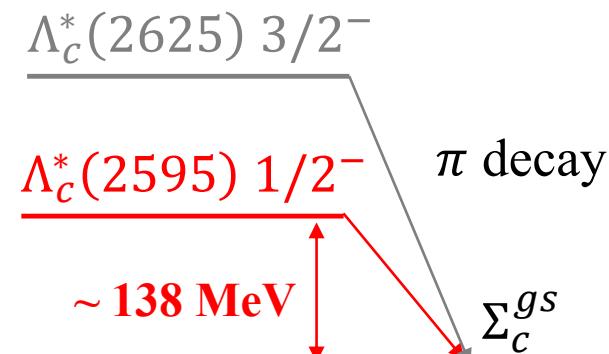
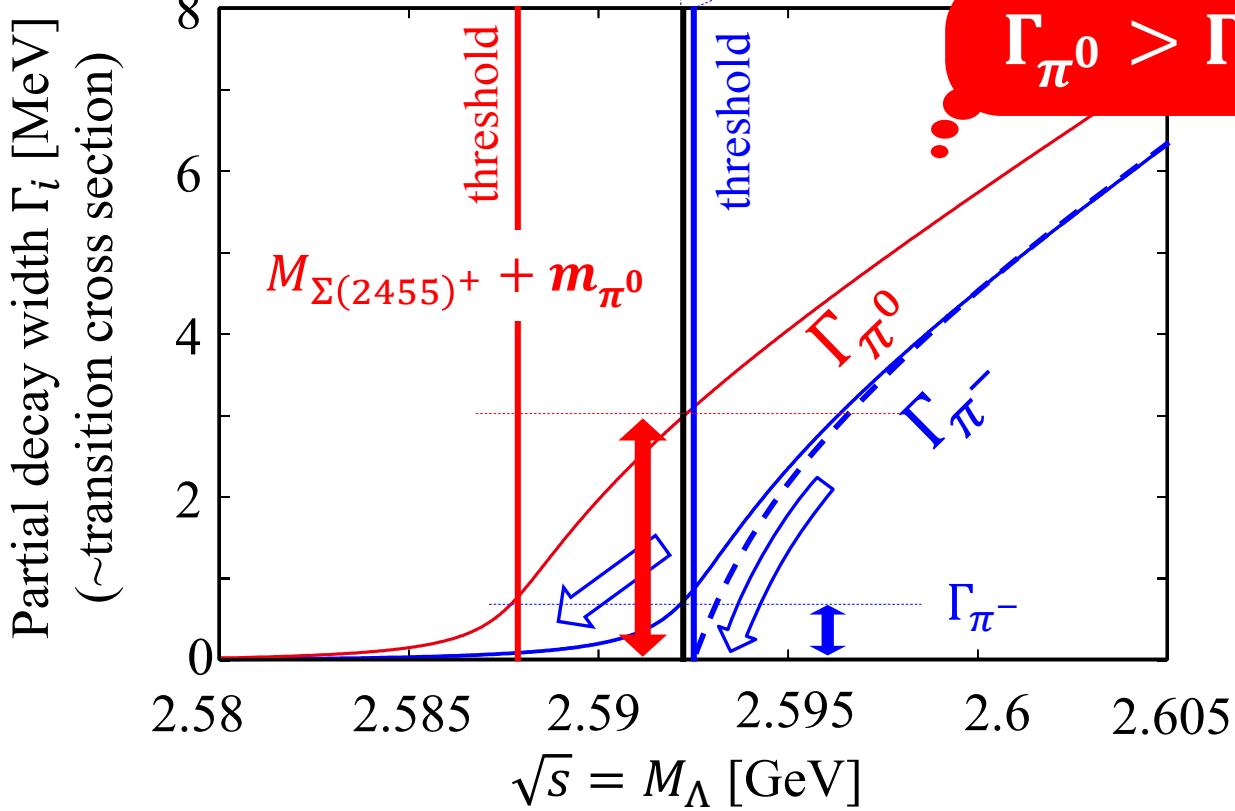
$$\Lambda_c(2595; 1/2^-)^+ \rightarrow \Sigma_c(2455)^{++} \pi^- :$$

$$\Gamma = 2.6 \text{ MeV} \times 24 \% = 0.6 \text{ MeV}$$

[PDG]



$$M_{\Lambda(2595)} < M_{\Sigma(2455)^{++}} + m_{\pi^-} \implies \Gamma_{\pi^-} = 0 ?$$

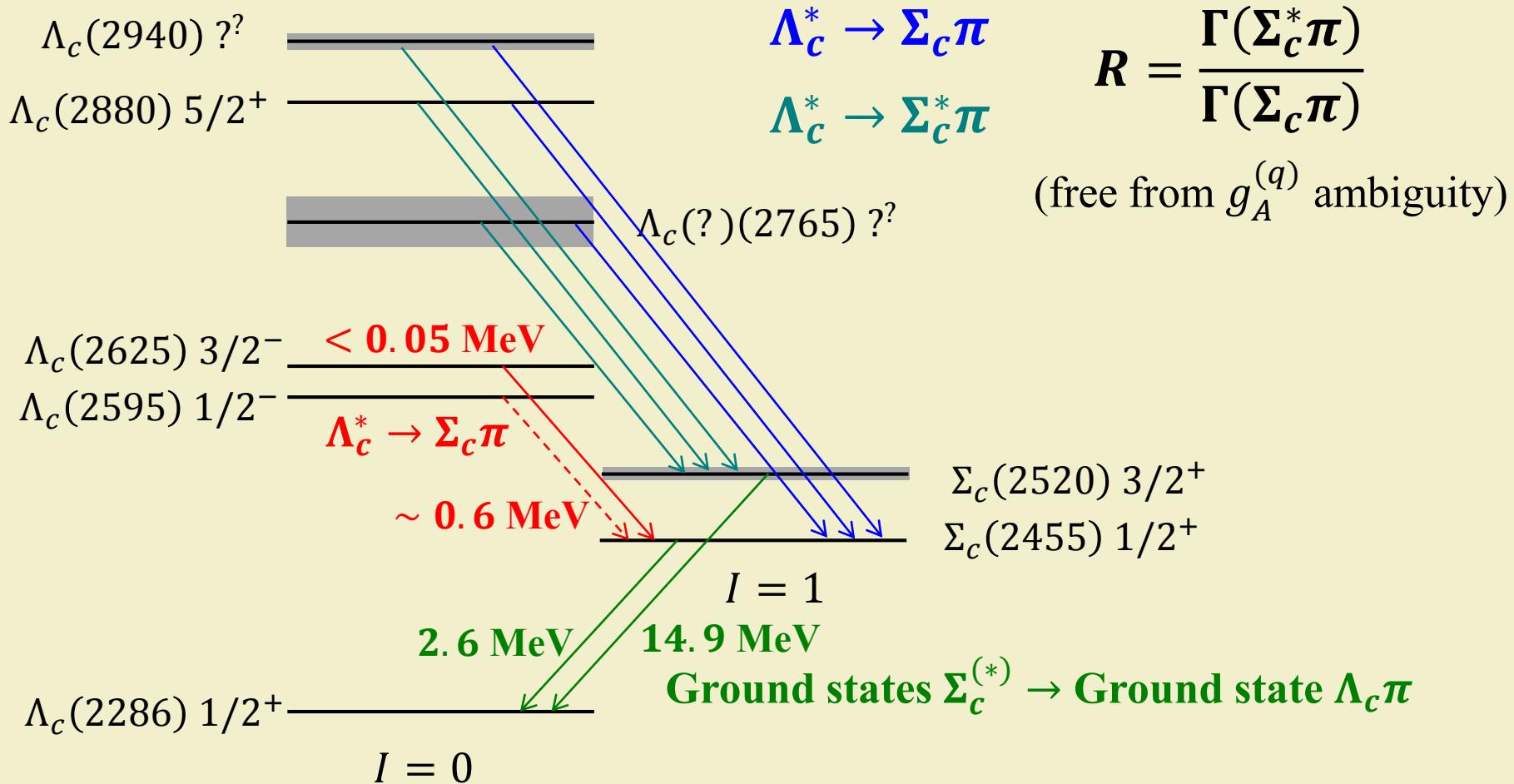


		$\Lambda_c(2592; 1/2^-)$	
PDG value $\Gamma_{\text{tot}}$ [MeV] (incl. 3body)		$2.6 \pm 0.26$	
$\Gamma^{\text{theo}} (\Sigma_c \pi)$ [MeV]	$\lambda$ -mode	$1/2^-$	$1.53 - 2.95$
	$\lambda$ -mode	$3/2^-$	-
	$\rho$ -mode	$1/2^- (j = 0)$	0
	$\rho$ -mode	$1/2^- (j = 1)$	$= 6.5 - 11.9$
	$\rho$ -mode	$3/2^- (j = 1)$	-
	$\rho$ -mode	$3/2^- (j = 2)$	-
	$\rho$ -mode	$5/2^- (j = 2)$	-

- **isospin breaking** effect is **considerably large**.
- compare the total width  $\Gamma_{PDG}$  (incl. 3-body decay) with our two body  $\Gamma_{\Sigma\pi}$ .
- the quark model description with  **$\lambda$ -mode assignment** works fairly well, even if we consider the model ambiguities
- $\lambda$ -mode is preferred rather than  $\rho$ -mode
- Pseudo-scalar coupling *cannot* reproduce the finite width.

$$\mathcal{L}'_{\pi qq} = g_{PS} \bar{q} \gamma_5 \vec{\tau} q \cdot \vec{\pi} \rightarrow \Gamma < 1 \text{ keV}$$

# Higher $\Lambda_c^*$

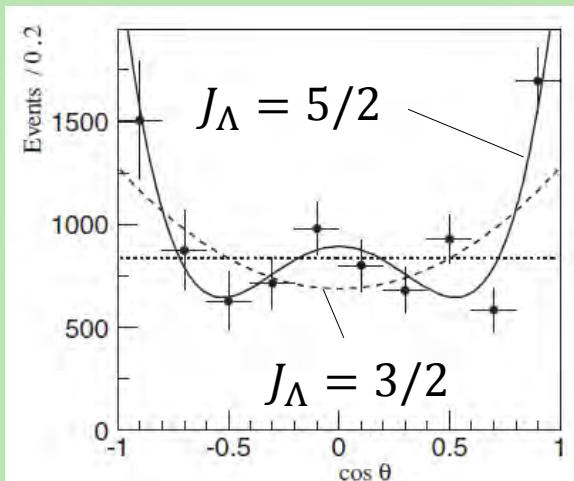


# Spin & parity $\Lambda_c(2880)$ in PDG

$$I(J^P) = 0(5/2)^+$$

Angular distribution

$\Sigma_c(2455)\pi$  angle dest. by Belle(07)



[Mizuk et al., (Belle), PRL98(07)262001, FIG. 3]

heavy quark symmetry  
for  $\Gamma(\Sigma_c^*\pi)/\Gamma(\Sigma_c\pi)$  ratio ???

$$R = \frac{\Gamma(\Sigma_c^*\pi)}{\Gamma(\Sigma_c\pi)} = 0.225 \pm 0.062 \pm 0.025$$

[Mizuk et al., (Belle), PRL98(07)262001]



theory : chiral perturbation + HQS

Isgur-Weise, PRL66(91)1130  
Cheng et al., PRD75(07)014006

$$R = 1.45 \quad \text{for } J_\Lambda^P = 5/2^-$$

$$R = 0.23, 0.36 \quad \text{for } J_\Lambda^P = 5/2^+$$

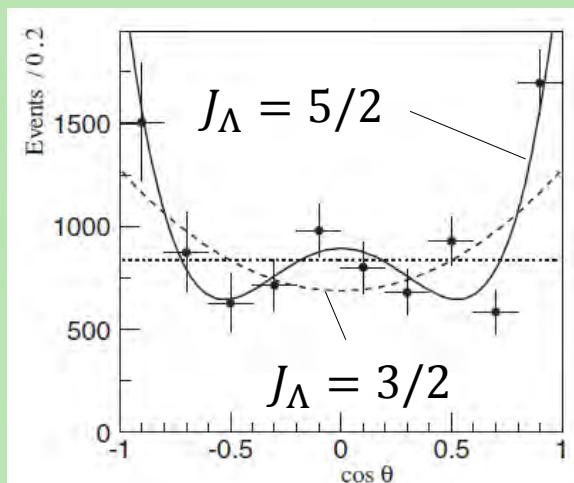
"The evidence for spin 5/2 comes from the  $\Sigma_c\pi$  decay ang. distribution, and the evidence for parity + comes from agreement branching ratio with a prediction of heavy quark symmetry." [in PDG live]

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$$R = 1.45 \quad \text{for } J_\Lambda^P = 5/2^-$$

$$\rightarrow R = 0.23, 0.36 \quad \text{for } J_\Lambda^P = 5/2^+$$

$$R = \frac{\Gamma([\Sigma_c^*\pi]_F + [\Sigma_c^*\pi]_R)}{\Gamma([\Sigma_c\pi]_F)}$$

They simply ignored.

**different q config.**

In general  $\Lambda_c^*(5/2^+) \rightarrow \Sigma_c^*(3/2^+)\pi \dots$  **P-wave** + F-wave

$j \dots$  Brown muck spin

			$\Lambda_c(2880)5/2^+$	
			$\Gamma$ (MeV)	$R = \Gamma(\Sigma_c^*\pi)/\Gamma(\Sigma_c\pi)$
Experimental values (Belle(07))			$5.8 \pm 1.1$	$0.225 \pm 0.062 \pm 0.025$
This work	$(\ell_\lambda, \ell_\rho)$	$J_\Lambda^P(j)$	$(\ell_\lambda + \ell_\rho)$	
	(0, 1)	$5/2^-$ (2)	1	<del>42 – 55</del> $= 1.6 – 1.7$
	(2, 0)	$5/2^+$ (2)	2	<del>11 – 26</del> $= 8.2 – 8.5$
	(0, 2)	$5/2^+$ (2)	2	<del>28 – 52</del> $= 19.0 – 19.1$
	(1, 1)	$5/2^+$ (2)	2	<del>52 – 110</del> $= 27.7 – 30.4$
			1	$0.63 – 1.7$ $= (\infty)$
			$5/2^+$ (3)	$2.8 – 5.7$ $= 0.41 – 0.43$

✓ Even though  $5/2^+$ ,  $\Gamma(\Sigma_c\pi) < \Gamma(\Sigma_c^*\pi)$

$$R = \frac{\Gamma([\Sigma_c^*\pi]_F + [\Sigma_c^*\pi]_P)}{\Gamma([\Sigma_c\pi]_F)} > 1$$

$$\frac{q \text{ (mom trans.)}}{a \text{ (\Lambda}_c \text{ size)}} \sim 0.56$$

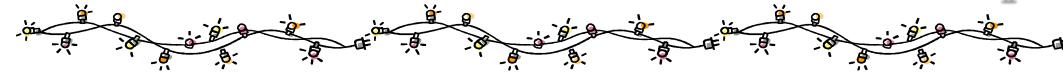
$$\Rightarrow \Gamma_P/\Gamma_F \sim 10$$

Only  $\rho\lambda$ -mode with  $j = 3$  case

$$\Lambda_c(5/2^+): \left[ [1,1]^2, d^1 \right]^3, \chi_c \right]^{5/2}$$

HQS does not necessarily  
lead to  $R < 1$

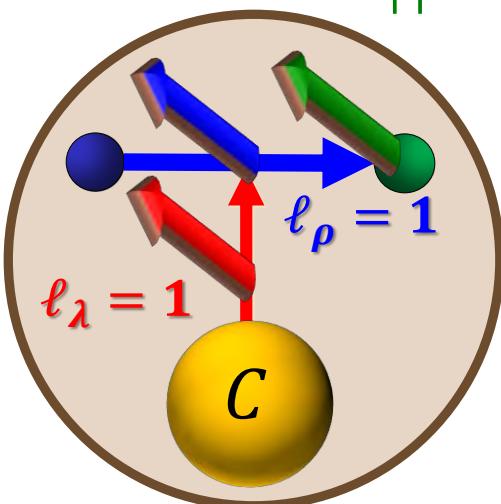
# Selection rule due to brown muck spin-parity conservation



$\Lambda_c(5/2^+(\rho\lambda))$

diquark spin = 1

↑↑



$\pi(0^-)$

$\Sigma_c(3/2^+)$

diquark spin = 1

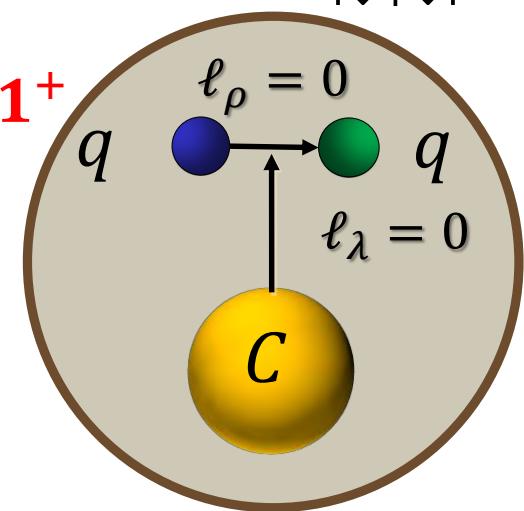
↑↓+↓↑

$L_\pi \geq 3$

$j^p = 3^+$

$j^p = 1^+$

P-wave



Among five  $5/2^+$ 's  
only  $\rho\lambda$ -mode with  $j=3$  consistent

Internal structure gives a *new selection rule*

which cannot be deduced by total spin-parity conservation

→ strongly affects the observables

$$\Lambda_c(5/2^+): \left[ [[1,1]^2, d^1]^3, \chi_c \right]^{5/2}$$

# $\Lambda_c(2765)$ or $\Sigma_c(2765)$ $I(J^P) =? (?^?)$



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

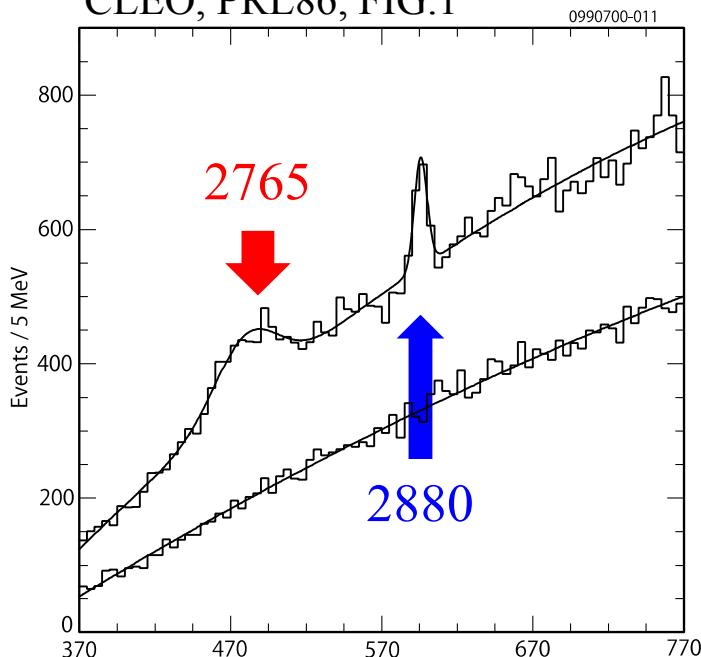
Mass  $2766.6 \pm 2.6$  MeV

Width 50 MeV (PRL86(01)4479, CLEO)

## Decay modes

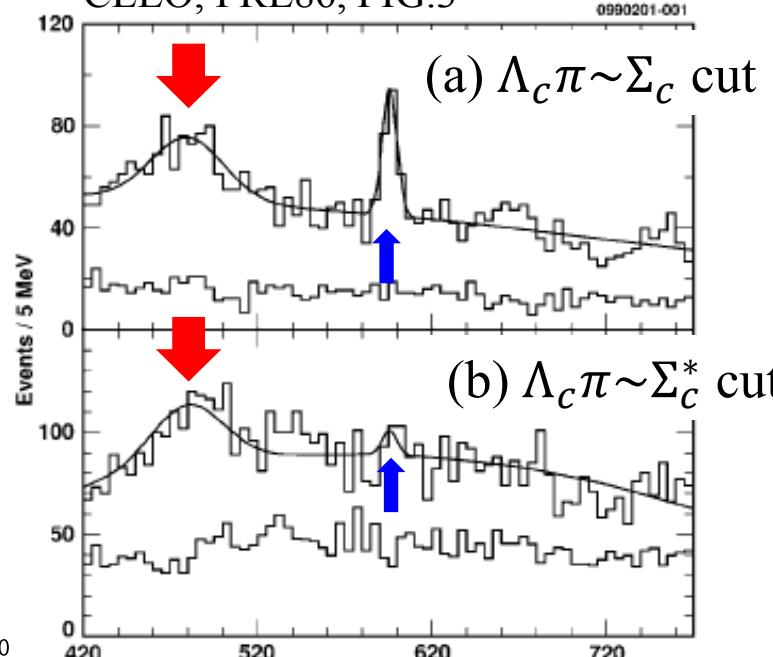
mode	Fraction seen
$\Lambda_c^+\pi^-\pi^+$	

CLEO, PRL86, FIG.1



$$\Delta M_{\pi\pi} = M(\Lambda_c^+\pi^+\pi^-) - M(\Lambda_c)$$

CLEO, PRL86, FIG.3



$$\Delta M_{\pi\pi} = M(\Lambda_c^+\pi^+\pi^-) - M(\Lambda_c)$$

→ 2765  
 $\Gamma(\Sigma_c\pi) \sim \Gamma(\Sigma_c^*\pi)$

→ 2880  
 $\Gamma(\Sigma_c\pi) > \Gamma(\Sigma_c^*\pi)$

# $\Lambda_c(2765)$ decay width : PDG total $\Gamma = 50$ MeV

	$J^P(j)$	$\Sigma_c\pi + \Sigma_c^*\pi$	$R = \Gamma(\Sigma_c^*\pi)/\Gamma(\Sigma_c\pi)$	
$\ell_\lambda = 1$	$\lambda$ -mode	$1/2^- (1)$	$65 - 146$	$0.04 - 0.06$
	$J^-$	$3/2^- (1)$	$52 - 104$	$5.6 - 7.8$
		$1/2^- (0)$	$0$	-
$\ell_\rho = 1$	$\rho$ -mode	$1/2^- (1)$	$326 - 675$	$0.004 - 0.006$
		$3/2^- (1)$	$211 - 414$	$49 - 70$
		$3/2^- (2)$	$9 - 13$	$0.25 - 0.26$
$n_\lambda = 1$ or $\ell_\lambda = 2$	$\lambda\lambda$ -mode	$5/2^- (2)$	$6 - 9$	$0.87 - 0.90$
		$1/2^+ (0)$	$1.6 - 4.5$	$0.79 - 0.91$
		$3/2^+ (2)$	$4.6 - 10.8$	$0.071 - 0.076$
$n_\rho = 1$ or $\ell_\rho = 2$	$\rho\rho$ -mode	$5/2^+ (2)$	$1.9 - 4.3$	$12.8 - 13.8$
		$1/2^+ (0)$	$5.2 - 10.8$	$0.71 - 0.77$
		$3/2^+ (2)$	$12 - 23$	$0.07$
$\ell_\lambda = 1$ $\&$ $\ell_\rho = 1$	$\lambda\rho$ -mode	$5/2^+ (2)$	$4.6 - 8.5$	$27 - 31$
		$1/2+(1)$	$5.5 - 13$	$0.19 - 0.21$
		$3/2+(1)$	$3.5 - 8.1$	$2.0 - 1.9$
	$J^+$	$1/2+(0)$	$0.7 - 1.8$	$0.6$
		$1/2+(1)$	$0.24 - 0.64$	$0.15$
		$3/2+(1)$	$0.13 - 0.35$	$1.5$
		$3/2+(2)$	$0.28 - 0.74$	$0.06$
		$5/2+(2)$	$0.09 - 0.25$	-
		$1/2+(1)$	$11 - 24$	$0.16$
		$3/2+(1)$	$6.5 - 13$	$1.6 - 1.7$
		$3/2+(2)$	$23 - 49$	$0.07$
		$5/2+(2)$	$8.9 - 18$	$45 - 46$
		$5/2+(3)$	$0.25 - 0.54$	$0.17 - 0.18$
		$7/2+(3)$	$0.17 - 0.37$	$0.41 - 0.43$

For example ...

three  $3/2^-$  states:

- $R > 1$  for  $j = 1$
- $R < 1$  for  $j = 2$

$j$  (light q com.)  
affects  
observables

for  $j=2$

$$R = \frac{\Gamma([\Sigma_c^*\pi]_S + [\Sigma_c^*\pi]_D)}{\Gamma([\Sigma_c\pi]_D)}$$

Brown muck spin  
conservation

# $\Lambda_c(2765)$ decay width : PDG total $\Gamma = 50$ MeV

	$J^P(j)$	$\Sigma_c\pi + \Sigma_c^*\pi$	$R = \Gamma(\Sigma_c^*\pi)/\Gamma(\Sigma_c\pi)$	
$\ell_\lambda = 1$	$\lambda$ -mode	$1/2^- (1)$	$65 - 146$	$0.04 - 0.06$
	$J^-$	$3/2^- (1)$	$52 - 104$	$5.6 - 7.8$
		$1/2^- (0)$	$0$	-
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		$3/2^- (1)$	$211 - 414$	$49 - 70$
		$3/2^- (2)$	$9 - 13$	$0.25 - 0.26$
		$5/2^- (2)$	$6 - 9$	$0.87 - 0.90$
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		$3/2^+ (2)$	$4.6 - 10.8$	$0.071 - 0.076$
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$n_\rho = 1$ or $\ell_\rho = 2$	$\rho\rho$ -mode	$1/2^+ (0)$	$5.2 - 10.8$	$0.71 - 0.77$
		$3/2^+ (2)$	$12 - 23$	$0.07$
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$\ell_\lambda = 1$ $\&$ $\ell_\rho = 1$	$\lambda\rho$ -mode	$1/2+(1)$	$5.5 - 13$	$0.19 - 0.21$
		$3/2+(1)$	$3.5 - 8.1$	$2.0 - 1.9$
		$1/2+(0)$	$0.7 - 1.8$	$0.6$
		$1/2+(1)$	$0.24 - 0.64$	$0.15$
		$3/2+(1)$	$0.13 - 0.35$	$1.5$
		$3/2+(2)$	$0.28 - 0.74$	$0.06$
		$5/2+(2)$	$0.09 - 0.25$	-
		$1/2+(1)$	$11 - 24$	$0.16$
		$3/2+(1)$	$6.5 - 13$	$1.6 - 1.7$
		$3/2+(2)$	$23 - 49$	$0.07$
		$5/2+(2)$	$8.9 - 18$	$45 - 46$
		$5/2+(3)$	$0.25 - 0.54$	$0.17 - 0.18$
		$7/2+(3)$	$0.17 - 0.37$	$0.41 - 0.43$

↔  $\Lambda_c(2595)$   
↔  $\Lambda_c(2625)$

PRL86(01)4479, CLEO

$\Gamma(\Sigma_c\pi) \sim \Gamma(\Sigma_c^*\pi)$

$\omega_\lambda \sim 0.35$  GeV  
 $\omega_\rho \sim 0.5$  GeV

↔  $\Lambda_c(2880)?$   
↔  $\Lambda_c(2940)?$

# $\Lambda_c(2765)$ decay width : PDG total $\Gamma = 50$ MeV



negative parity

$$\Gamma(\Sigma_c \pi) \sim \Gamma(\Sigma_c^* \pi)$$

$(n_\lambda, \ell_\lambda), (n_\rho, \ell_\rho)$	$J^P(j)$	$\Sigma_c \pi + \Sigma_c^* \pi$	$R = \Gamma(\Sigma_c^* \pi)/\Gamma(\Sigma_c \pi)$
(0,0), (0,1)	$5/2^- (2)$	6 – 9	0.87 – 0.90

positive parity

$(n_\lambda, \ell_\lambda), (n_\rho, \ell_\rho)$	$J^P(j)$	$\Sigma_c \pi + \Sigma_c^* \pi$	$R = \Gamma(\Sigma_c^* \pi)/\Gamma(\Sigma_c \pi)$
(1,0), (0,0)	$1/2^+(0)$	1.6 – 4.5	0.79 – 0.91
(0,0), (1,0)	$1/2^+(0)$	5.2 – 10.8	0.71 – 0.77
	$1/2^+(0)$	0.7 – 1.8	0.6
	$3/2^+(1)$	3.5 – 8.1	2.0 – 1.9
(0,1), (0,1)	$3/2^+(1)$	0.13 – 0.35	1.5
	$3/2^+(1)$	6.5 – 13	1.6 – 1.7
	$7/2^+(3)$	0.17 – 0.37	0.41 – 0.43

Our results come short of  $\Gamma = 50$  MeV

(some of these states are hard to be observed due to a small coupling ?)

→ non-resonant decay, interference, mixed states (exotic?)

# Is $\Lambda_c(2940)?^? J_\Lambda = 7/2^+$ doublet partner of $\Lambda_c(2880)??$



		$\Lambda_c(2940)?^?$	
experimental value [PDG]		$\Gamma$ [MeV]	$R = \Gamma(\Sigma_c^*\pi)/\Gamma(\Sigma_c\pi)$
This work $\Gamma_{\Sigma\pi} + \Gamma_{\Sigma^*\pi}$ [MeV]	$\lambda$ -mode	$1/2^-$	$17^{+8}_{-6}$ N/A
	$J^-$	$145 - 314$	$0.95 - 2.2$
	$\rho$ -mode	$182 - 332$	$1.8 - 2.8$
	$J^-$	$1/2^- (j = 0)$	0 -
		$1/2^- (j = 1)$	$558 - 1301$ 0.04 – 0.07
		$3/2^- (j = 1)$	$537 - 1155$ 14.7 – 26.5
		$3/2^- (j = 2)$	$96 - 119$ 0.55 – 0.58
		$5/2^- (j = 2)$	$80 - 101$ 1.9 – 2.0
	$\lambda$ -mode	$1/2^+ (j = 0)$	$3.8 - 17.5$ $> 1$
	$J^+$	$3/2^+ (j = 2)$	$24.8 - 61.4$ $< 1$
		$5/2^+ (j = 2)$	$19.8 - 46.5$ $> 1$
partner of $\Lambda_c(2880) ?$		$\rho\lambda$ -mode	$7/2^+ (j = 3)$ $5.8 - 11.0$ $1.2 - 1.3$ $\sim 1$

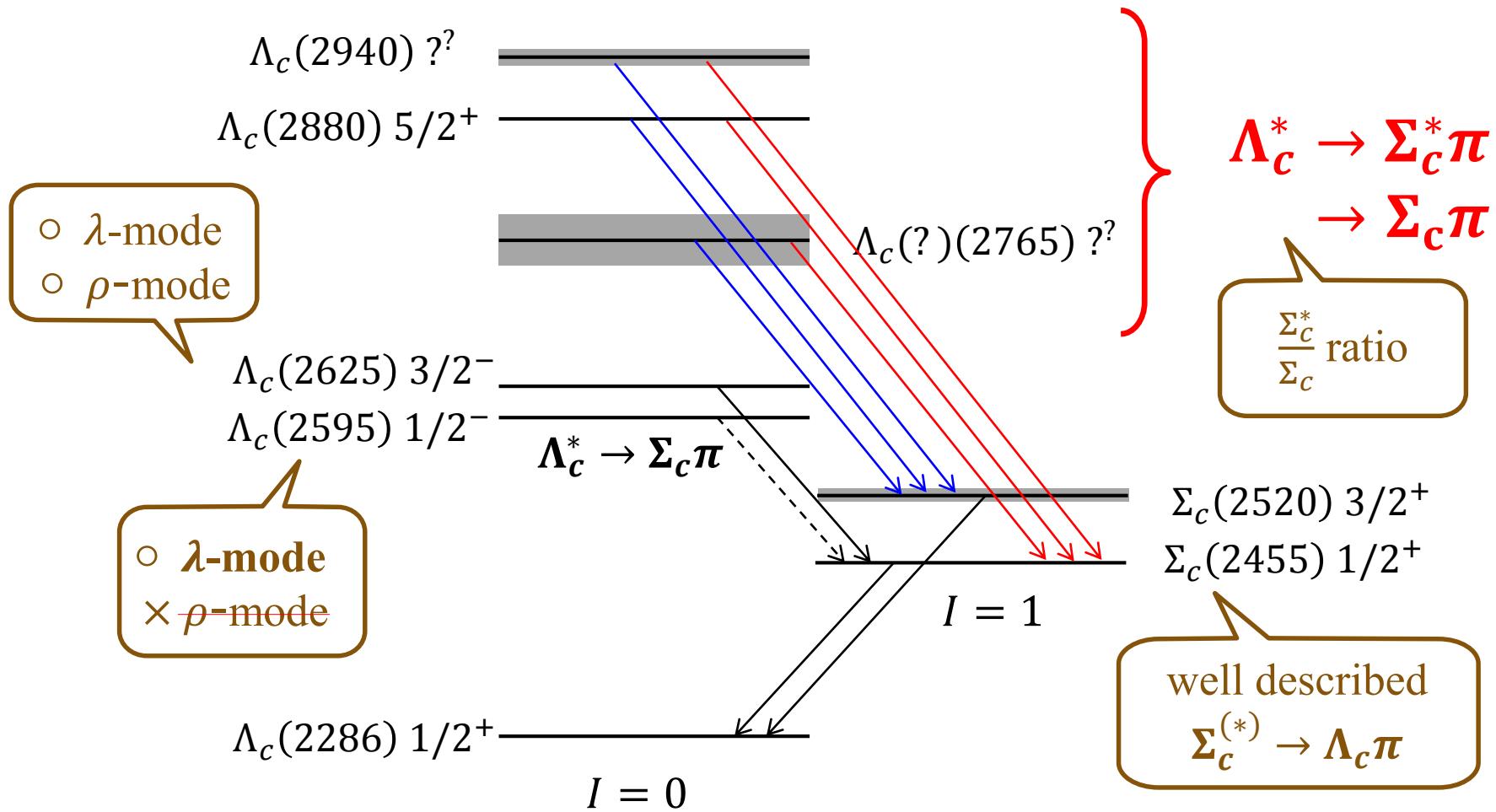
partner of  
 $\Lambda_c(2880) ?$

# Summary



Systematically evaluated pion emission decays based on NQM

- ✓ w/o any *fitting* parameter ( $m, M, k$  and  $g_A^{q\pi\pi}$ )
- ✓ Not only ratio but also their absolute values → **J-PARC Experiments**



# Summary



## $\Lambda_c^*(2765)? \Gamma = 50 \text{ MeV}$

- › We found significantly different decay widths for different  $J^P$  and different quark configuration
- › We can exclude some of possible configurations

## $\Lambda_c^*(2880) 5/2^+ \Gamma = 5.8 \text{ MeV}$

- › Only one quark configuration among possible  $5/2^+$  ones can lead to the consistent result with the experimental data, while all other configurations of  $5/2^+$  cannot if the p-wave decay is properly considered.
- › This fact calls an attention to the discussion based on the heavy quark symmetry, which requires decays in only one partial wave.
- › Only in  $5/2^+$  with  $j = 3$  :  
p-wave decay is forbidden due to brown muck spin conservation.

This is an interesting example in which :

A new selection rule appears and the decay ratio reflects the internal structure (*not* the total spin of baryons)

# Summary



$\Lambda_c^*(2940)?? \Gamma = 13 - 17 \text{ MeV : HOS doublet partner } 7/2^+ ??$

- › We found significantly different decay widths for different  $J^P$  and different quark configuration
- ›  $\Gamma$  &  $R = \Gamma(\Sigma_c^*\pi)/\Gamma(\Sigma_c\pi)$  helps to determine its spin and parity

Open issues : “where does  $\ell_\lambda = 2$  mode go ?”

- ›  $\Lambda_c(2880)$  : ratio R is inconsistent with  $\ell_\lambda = 2$   
if  $\Lambda_c(2880)$  is  $\rho\lambda$  mode,  $\lambda\lambda$ -mode should exist at lower energy around  $\hbar\omega_\rho - \hbar\omega_\lambda$  ... It is not observed.

## Future works

- ›  $pD^0$  decay width The heavy quark is contained by daughter meson not baryon which gives complementary information to the pion decay width
- › Mixing of multi-configuration states : higher order of  $O(1/M_Q)$

The model used here is **simple**, but the present systematic studies will help to know **where and how exotic (molecular or gluon excitation etc.) configurations** beyond the quark model **show up** : future J-PARC experiments.