Decays of heavy baryons

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November 27nd (Mon), 2016

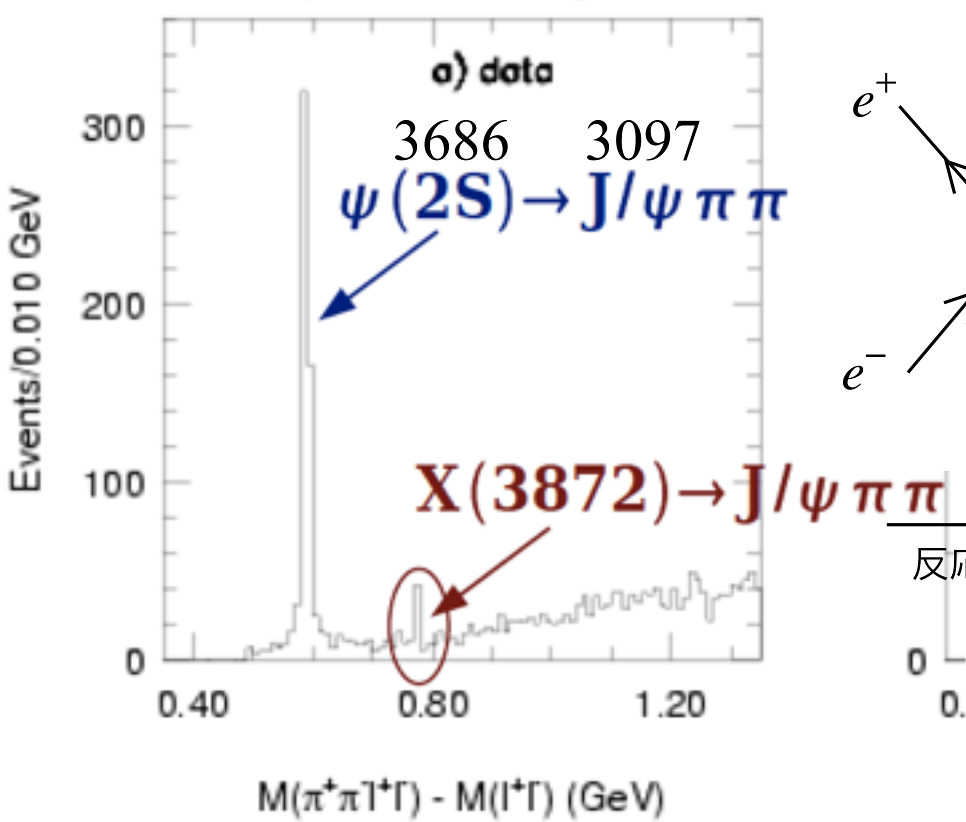
1. Exotic hadrons
2. Charmed baryons
   Structure and Decays
3. Summary

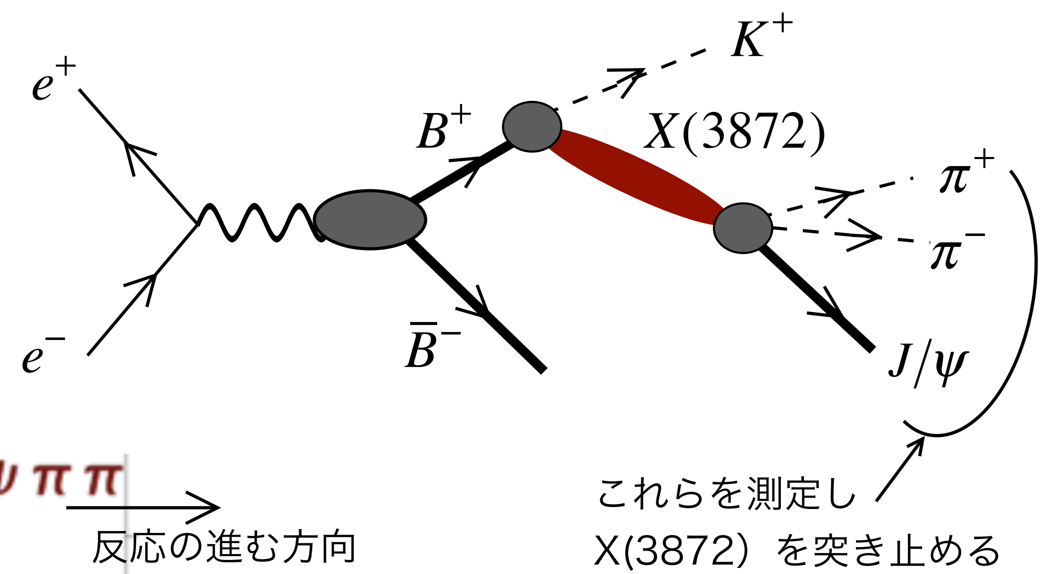
1. Exotic hadrons

X(3872) first observation PRL91,262001(2003)

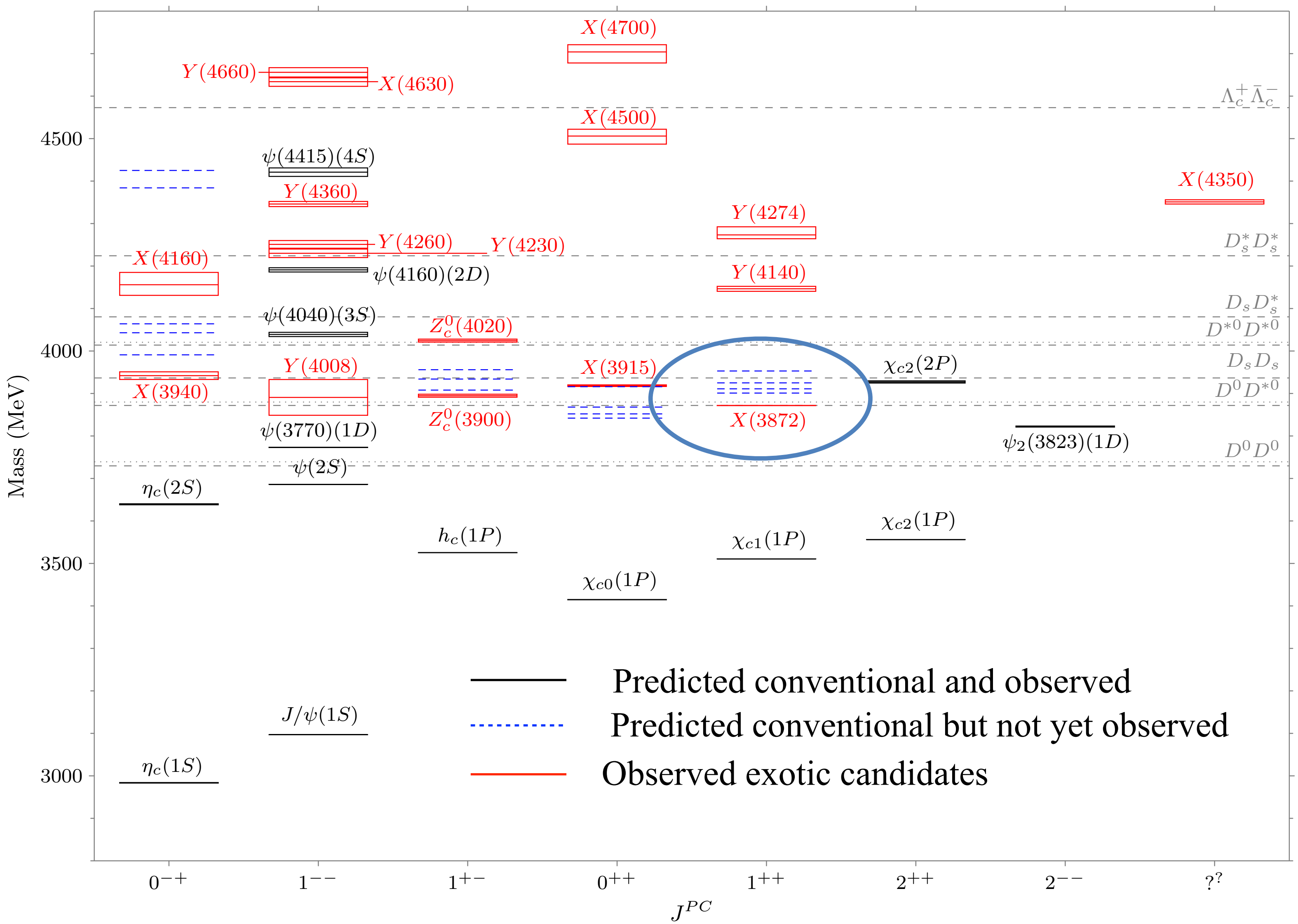
S. K. Choi et al. [Belle Collaboration], Phys. Rev. Lett. 91, 262001 (2003)

$B \to K\pi^+\pi^- J/\psi$ using $140\,\mathrm{fb}^{-1}$

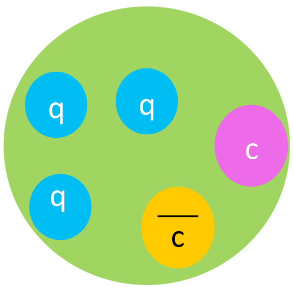




Neutral X, Y, Z_0 states



LHCb found Pentaquarks



Selected for a Viewpoint in *Physics*
PRL **115,** 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

R. Aaij *et al.**
(LHCb Collaboration)
(Received 13 July 2015; published 12 August 2015)

Observations of exotic structures in the $J/\psi p$ channel, which we refer to as charmonium-pentaquark states, in $\Lambda_b^0 \to J/\psi K^- p$ decays are presented. The data sample corresponds to an integrated luminosity of 3 fb^{-1} acquired with the LHCb detector from 7 and 8 TeV pp collisions. An amplitude analysis of the three-body final state reproduces the two-body mass and angular distributions. To obtain a satisfactory fit of the structures seen in the $J/\psi p$ mass spectrum, it is necessary to include two Breit-Wigner amplitudes that each describe a resonant state. The significance of each of these resonances is more than 9 standard deviations. One has a mass of $4380 \pm 8 \pm 29$ MeV and a width of $205 \pm 18 \pm 86$ MeV, while the second is narrower, with a mass of $4449.8 \pm 1.7 \pm 2.5$ MeV and a width of $39 \pm 5 \pm 19$ MeV. The preferred J^P assignments are of opposite parity, with one state having spin 3/2 and the other 5/2.

DOI: 10.1103/PhysRevLett.115.072001 PACS numbers: 14.40.Pq, 13.25.Gv

State	Mass (MeV)	Width (MeV)	Fit fraction (%)	Significance
$P_c(4380)^+$		205±18±86	8.4±0.7±4.2	9σ
$P_c(4450)^+$	4449.8±1.7±2.5	39± 5±19	4.1±0.5±1.1	12σ

- Best fit has J^P=(3/2$^-$, 5/2$^+$), also (3/2$^+$, 5/2$^-$) & (5/2$^+$, 3/2$^-$) are preferred

From exotics to conventional

- Exotic phenomena appear *exotic* mostly because we do not know much about the QCD dynamics for hadrons.
- There are many un-described phenomena especially in resonance region.

- Perhaps we need to come back to the most conventional questions,
  what are the essential mechanism (dynamics) for hadronic excitations
- Also better understanding for hadron structure is important for their interactions

- Charmed baryons may provide a basic features of three quark systems, λ and ρ motions.
- Their identifications is useful to know the behavior of quarks

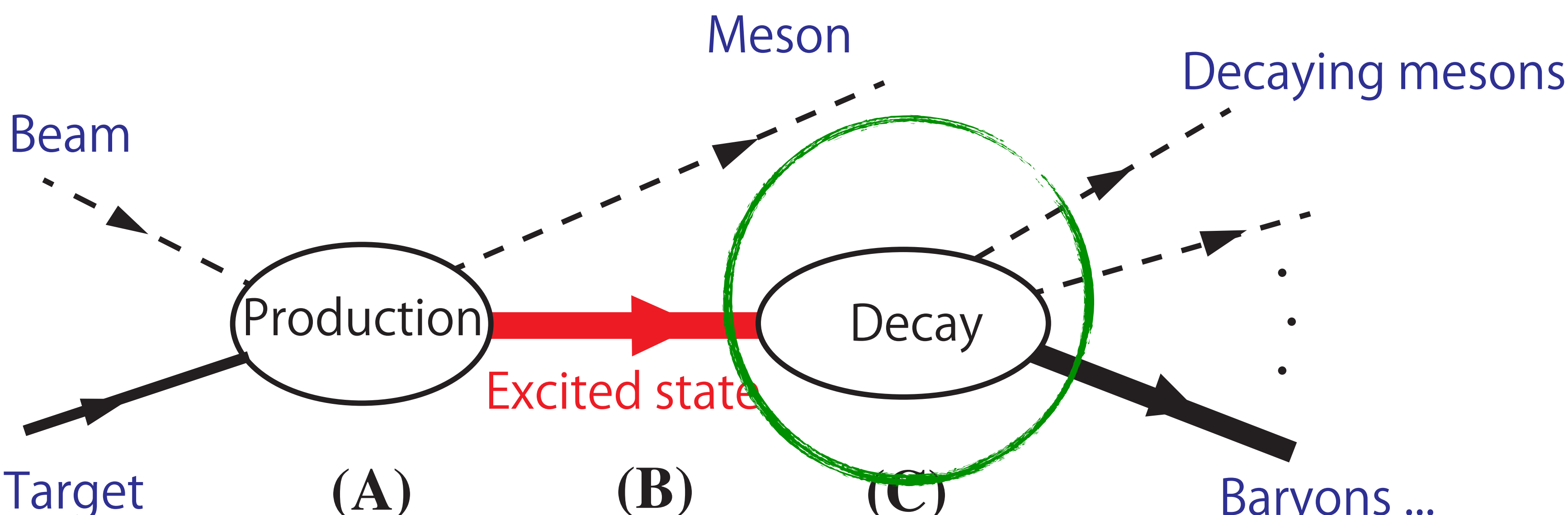
2. Charmed baryons

We have to produce

Production and decays

Fixed target experiment at J-PARC

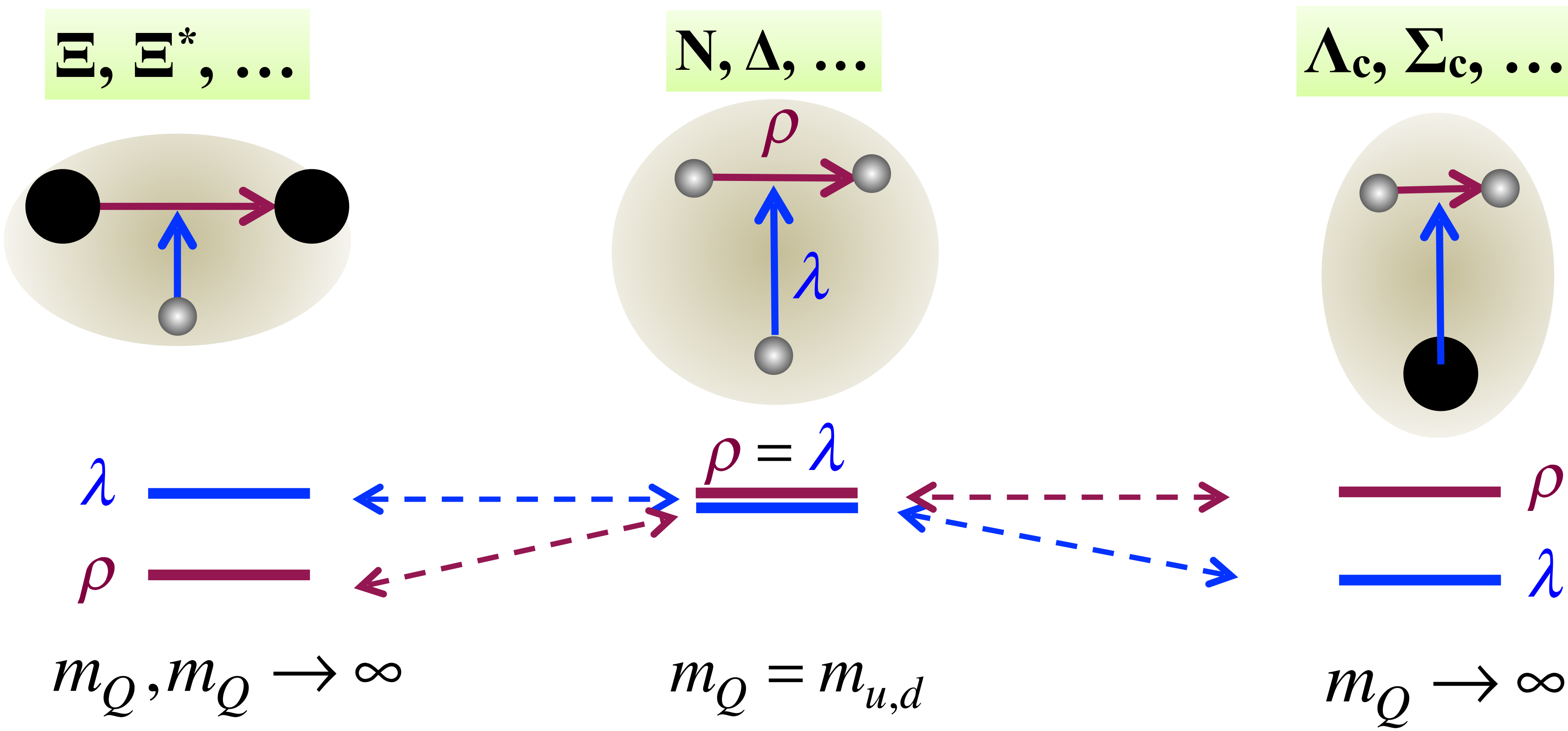
(A) Production
(B) Formation of resonances
(C) Decay of resonances



Exclusive reactions of this part

Heavy quarks distinguish the internal modes λ and ρ

Isotope-shift: Copley-Isgur-Karl, PRD20, 768 (1979)



These structures should be sensitive to reactions

Wave functions ~ Harmonic oscillator

$$H = \frac{p_1^2}{2m_q} + \frac{p_2^2}{2m_q} + \frac{p_3^2}{2M_Q} - \frac{P^2}{2M_{tot}}$$

$$+ V_{conf}(HO) + V_{spin-spin}(Color - magnetic) + \ldots$$

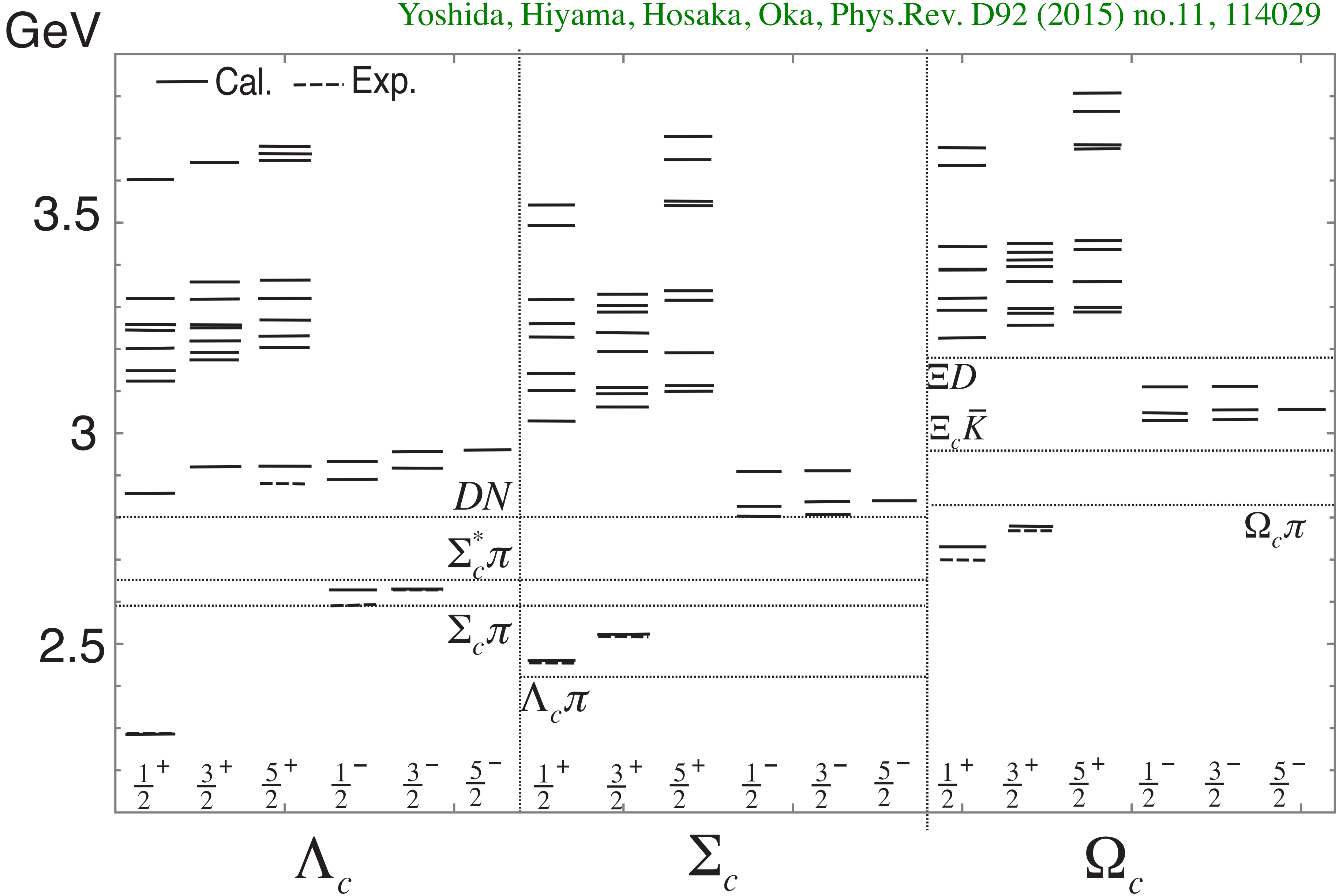
Λ^*_c, Σ_c, …

$$\Lambda_c(J^-;\lambda) = \left[\left[\psi_1(\vec{\lambda})\psi_0(\vec{\rho}), d^0 \right]^1, \chi_c \right]^{J=\frac{1}{2},\frac{3}{2}} D^0 c$$

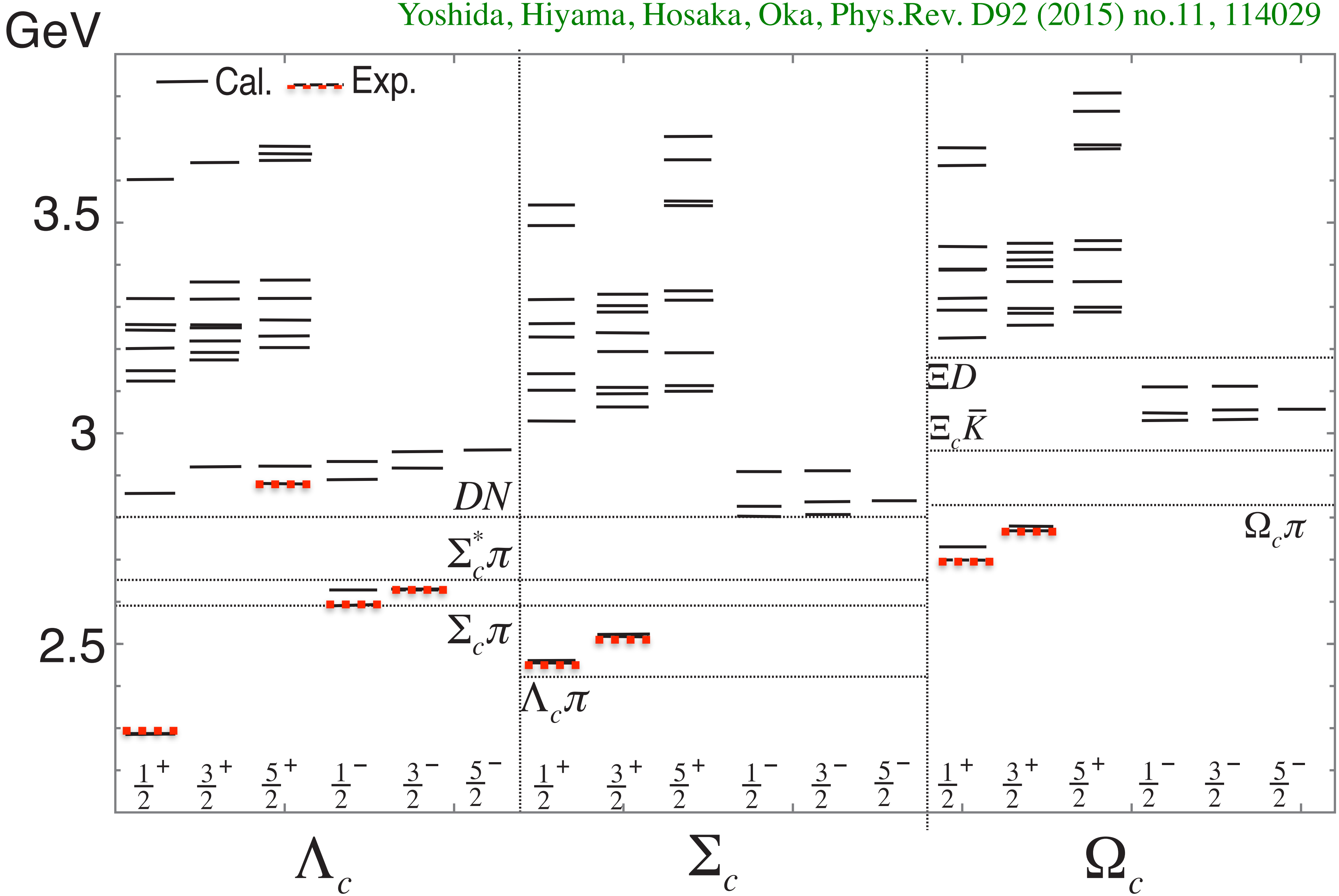
Brown muck + Charm quark

$$j + 1/2 = J$$

Yoshida, Hiyama, Hosaka, Oka, Phys.Rev. D92 (2015) no.11, 114029



Yoshida, Hiyama, Hosaka, Oka, Phys.Rev. D92 (2015) no.11, 114029



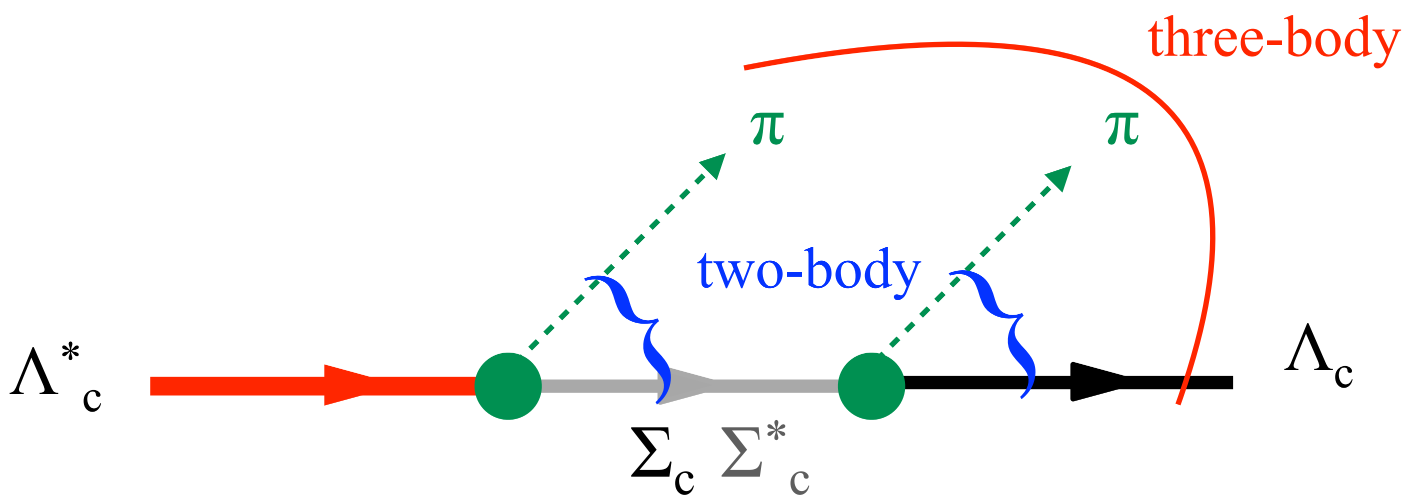
Strategy

- Decays (transitions) are sensitive to the structure
- Calculate decay rates of various states
- Compare with experimental data and identify the structure

Decays —Pion emission—

On going, Nagahiro, Yasui, …, Arifi

Nagahiro et al, arXiv:1609.01085



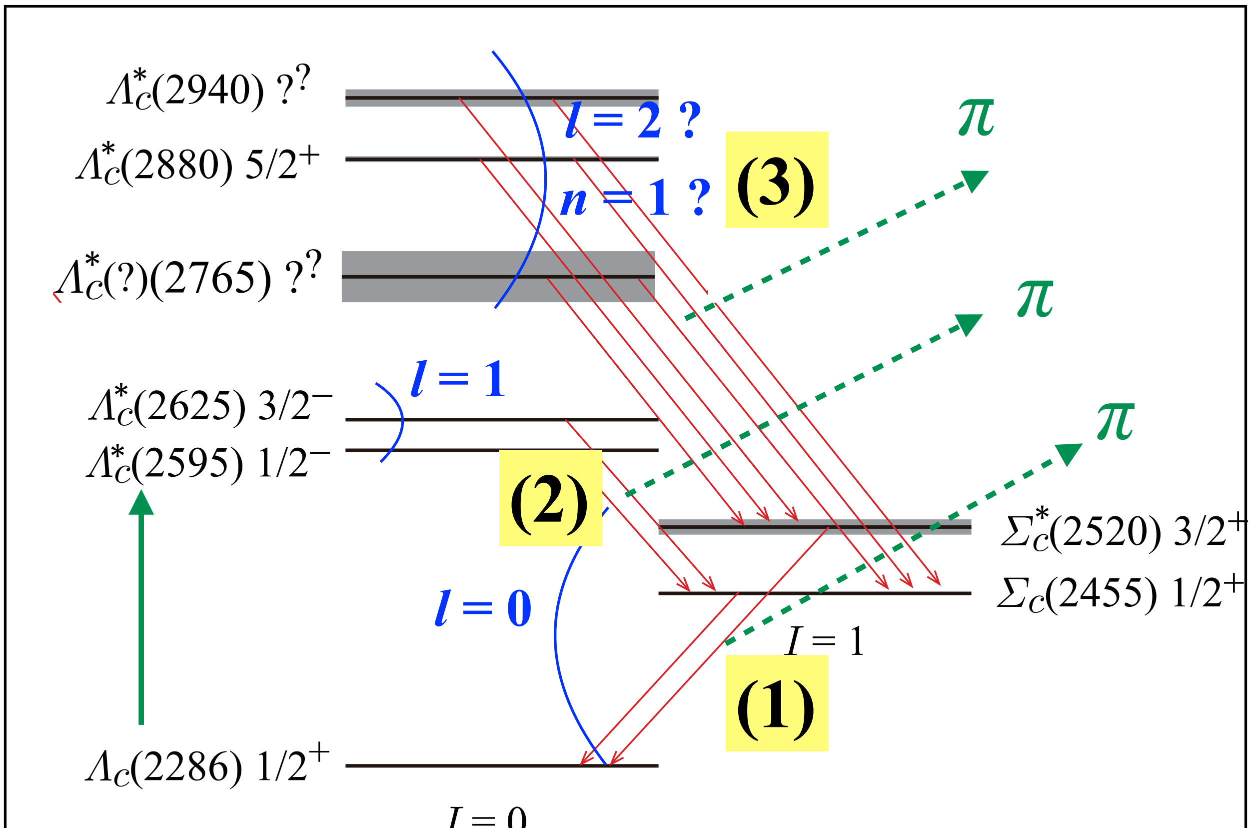
Two-body decays
and
Three-body decays

2. Decays —Pion emission—

On going, Nagahiro, Yasui, …, Arifi

Nagahiro et al, arXiv:1609.01085

Two-body decays



(1) 0hω → 0hω

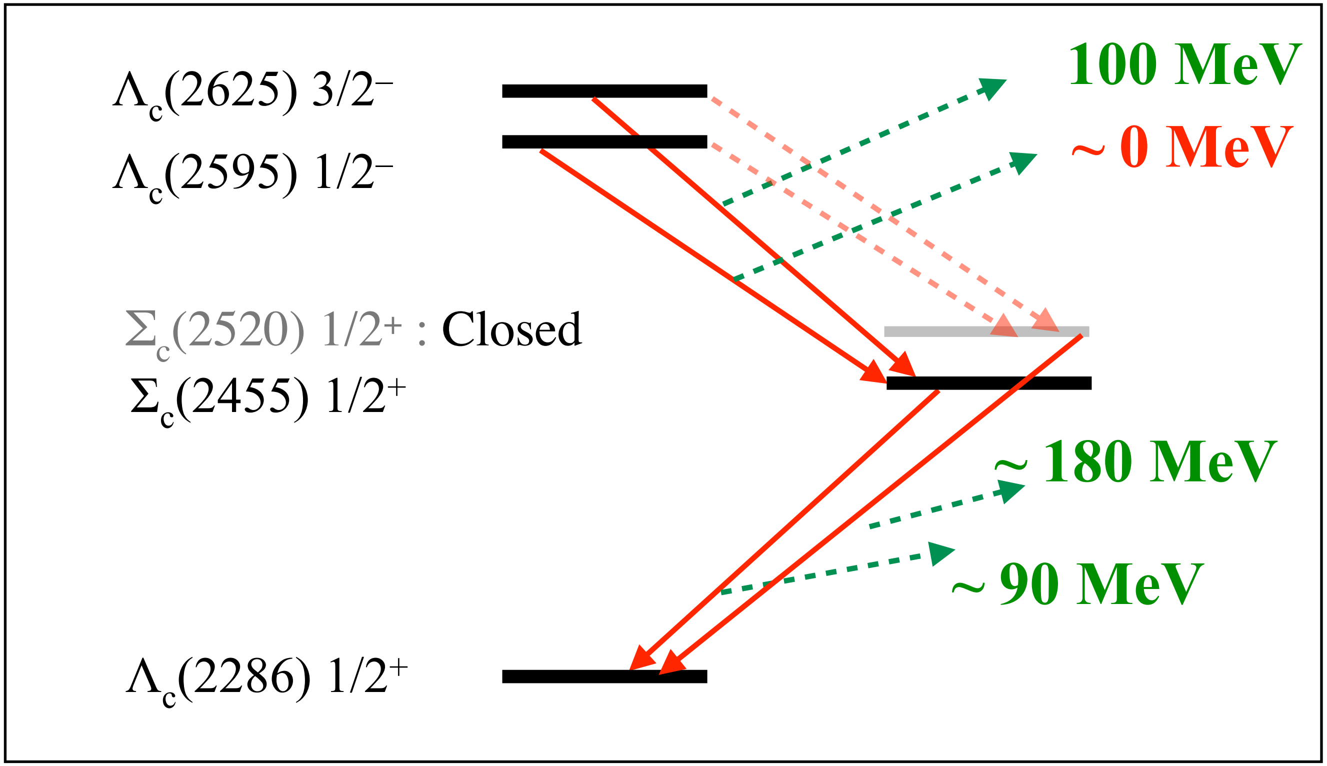
(2) 1hω → 0hω

(3) 2hω → 0hω

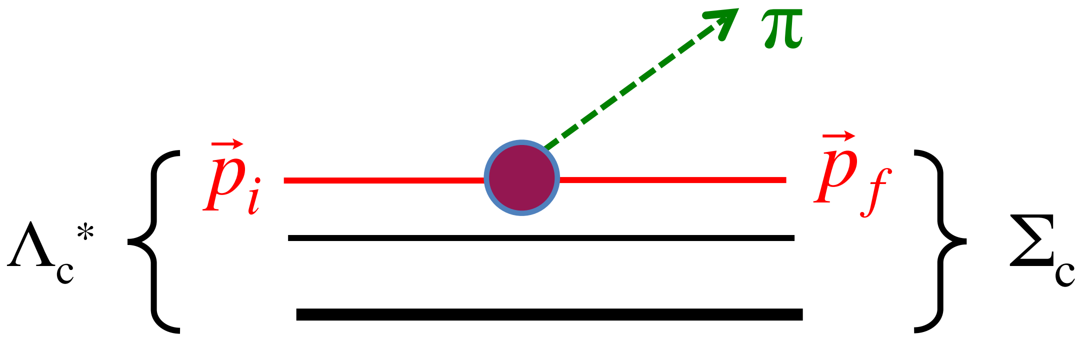
Low lying decays with small pion momentum p_π (MeV)

To compare with $\Delta \to \pi N$ at $p_\pi \sim 230$ MeV

Low energy pion dynamics works well



Low energy πqq interaction



Non-relativistic $\vec{\sigma}\cdot\vec{p}_i,\ \vec{\sigma}\cdot\vec{p}_f$

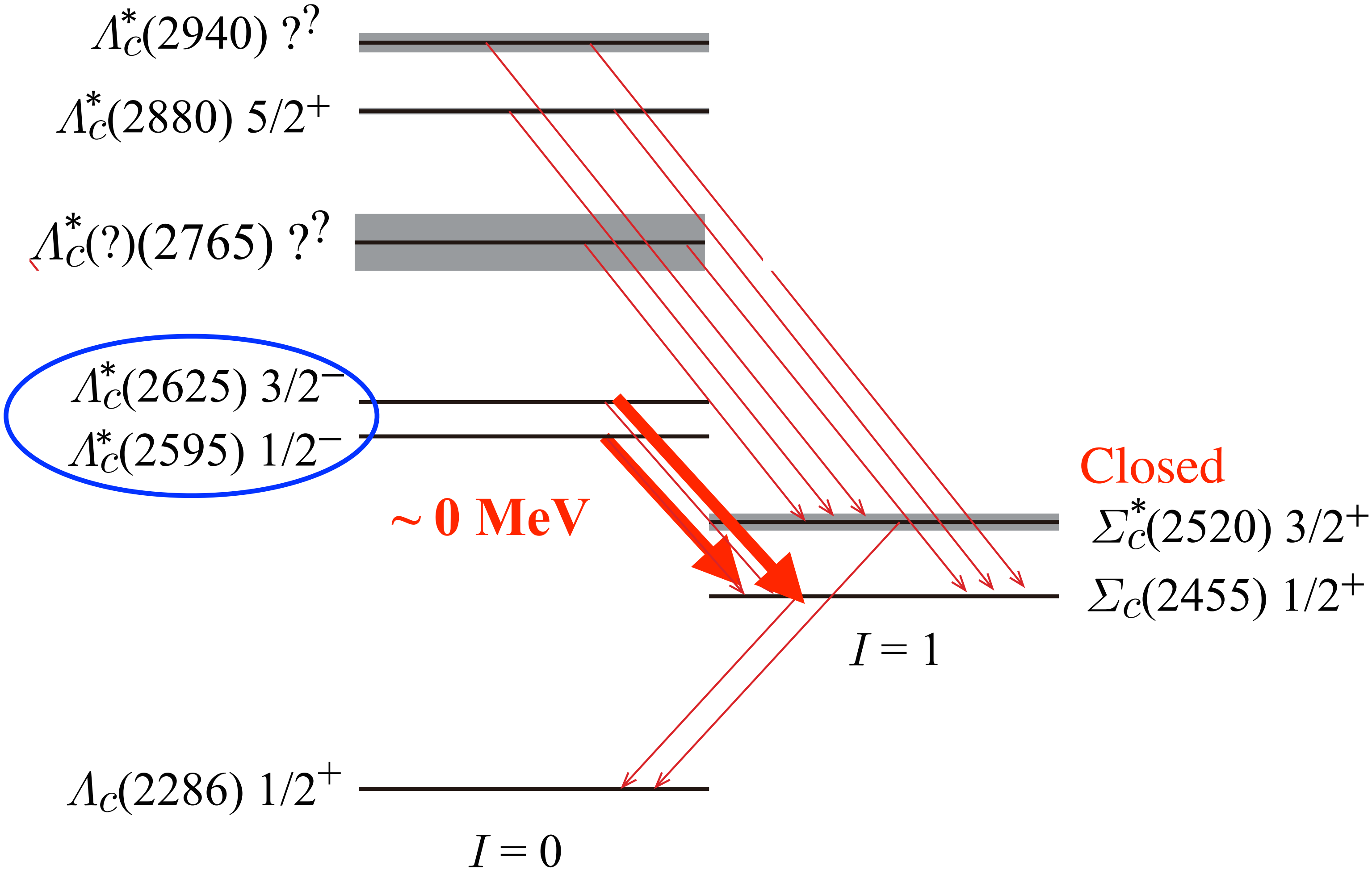
Relativistic $\bar{q}\gamma_5 q\phi_\pi,\ \bar{q}\gamma^\mu\gamma_5 q\,\partial_\mu\phi_\pi$

PS *PV: preferable*

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

${g^q}_A \sim 1$: Quark axial coupling

(2) P-wave to ground transitions, 1hω → 0hω



P-wave (1/2⁻, 3/2⁻) to ground state (1/2⁺)

Nagahiro et al, arXiv:1609.01085

$\Lambda_c(2595)\ 1/2^-$

	decay channel	full	$[\Sigma_c\pi]^+$	$\Sigma_c^{++}\pi^-$	$\Sigma_c^0\pi^+$	$\Sigma_c^+\pi^0$
Experiments	(MeV) [5]	2.6 ± 0.6	-	0.624 (24%)	0.624 (24%)	-
Momentum	q (MeV/c)	-	-	†	†	29
$(n_\lambda, \ell_\lambda), (n_\rho, \ell_\rho)$	$J_\Lambda(j)^P$					
(0, 1), (0, 0)	$1/2(1)^-$		1.5–2.9	0.13–0.25	0.15–0.28	1.2–2.4
(0, 0), (0, 1)	$1/2(0)^-$		0	0		
	$1/2(1)^-$		6.5–11.9	0.57–1.04	0.63–1.15	5.3–9.7

isospin violated

- 80 % of the decay of is explained with strong isospin breaking
- λ-mode results consistent, ρ-mode results overestimate

P-wave $(1/2^-, 3/2^-)$ to ground state $(1/2^+)$

Nagahiro et al, arXiv:1609.01085

$\Lambda_c(2625)\ 3/2^-$

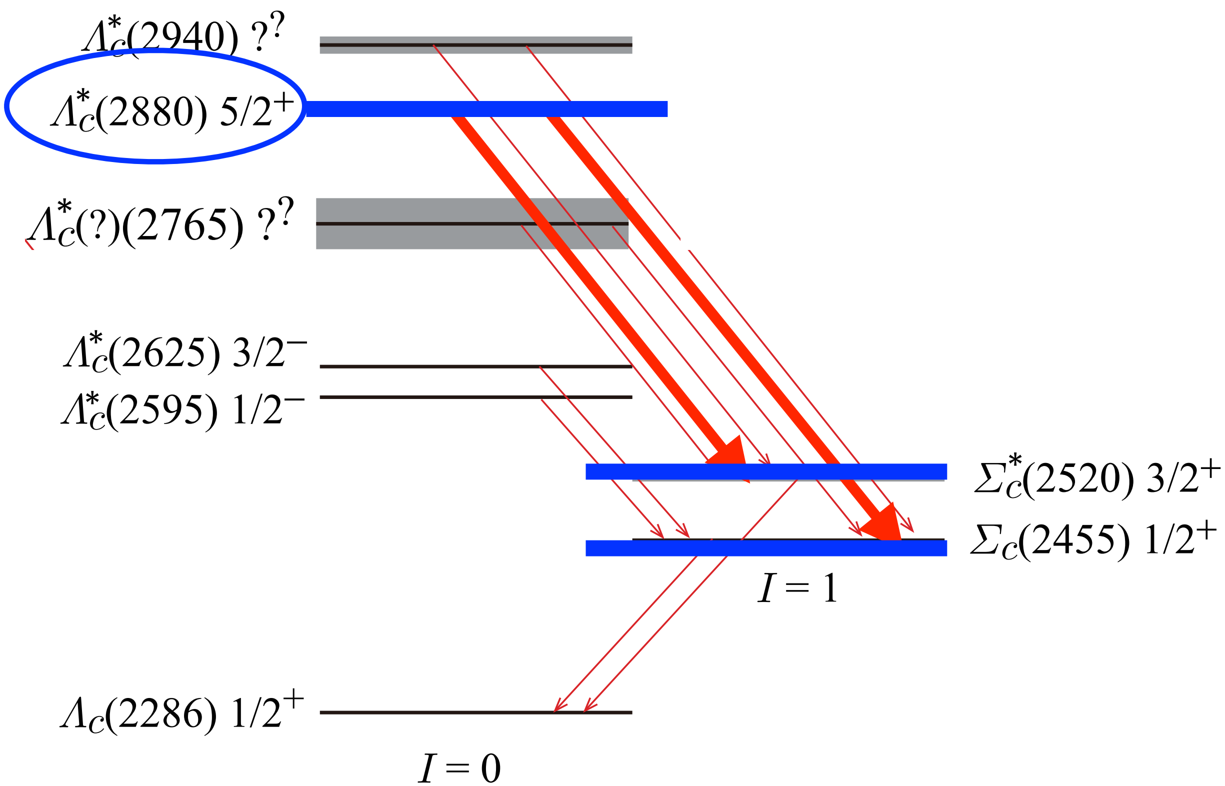
decay channel	full	$\Sigma_c^{++}\pi^-$
Experimental value Γ (MeV) [5]	< 0.97	$< 0.05 (< 5\%)$
momentum of final particle q (MeV/c)	-	101

D-wave decay

this work	$(n_\lambda, \ell_\lambda)$, (n_ρ, ℓ_ρ)	$J_\Lambda(j)^P$	
Γ	$(0, 1)$, $(0, 0)$	$1/2(1)^-$	5.4–10.7
(MeV)		$3/2(1)^-$	0.024–0.039
	$(0, 0)$, $(0, 1)$	$1/2(0)^-$	0

- Only a small part of the decay width is from the two-body
- The remaining is considered later

(3) Transitions from higher states, 2hω → 0hω



$$R = \frac{\Gamma(\Sigma_c^*(3/2^+)\pi)}{\Gamma(\Sigma_c(1/2^+)\pi)}$$

Sensitive to J^P and the structure of the decaying particle

$\Lambda_c(2880)\ 5/2^+$

	decay channel	full	$[\Sigma_c^{(*)}\pi]_{total}$	$[\Sigma_c\pi]^+$	$[\Sigma_c^*\pi]^+$	R
Experimental value Γ_{exp} (MeV)		5.8 ± 1.1 [24]				0.225 [40]
ıtum of final particle q (MeV/c)				375	315	
$(n_\lambda, \ell_\lambda), (n_\rho, \ell_\rho)$	$J_\Lambda(j)^P$					
(0, 2), (0, 0)	$5/2(2)^+$		11.2–26.1	1.2–2.8	9.9–23.3	8.1–8.4
(0, 0), (0, 2)	$5/2(2)^+$		27.8–52.2	1.4–2.6	26.4–49.5	18.7–18.9
(0, 1), (0, 1)	$5/2(2)_2^+$		51.7–109.6	1.8–3.5	49.9–106.1	27.5–30.1
	$5/2(2)_1^+$		0.63–1.68	0	0.63–1.68	(∞)
	$5/2(3)_2^+$		2.9–5.8	2.1–4.0	0.85–1.73	0.41–0.43

- Both absolute values and R ratio are sensitive to configurations
- Brown muck of $j = 3$ seems preferred.
- This implies that $\Lambda_c(2940)$ could be $7/2^+$

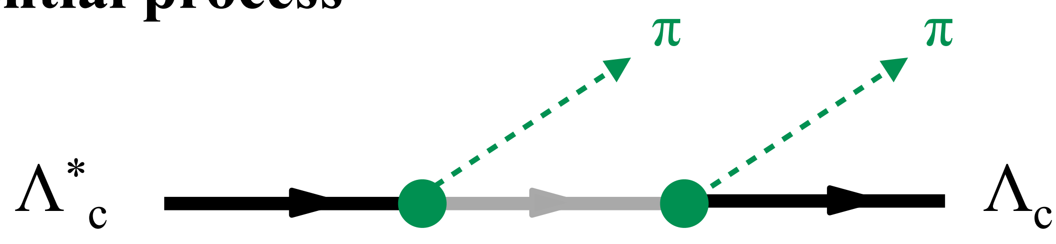
$$R = \frac{\Gamma(\Sigma_c^*(3/2^+)\pi)}{\Gamma(\Sigma_c(1/2^+)\pi)}$$

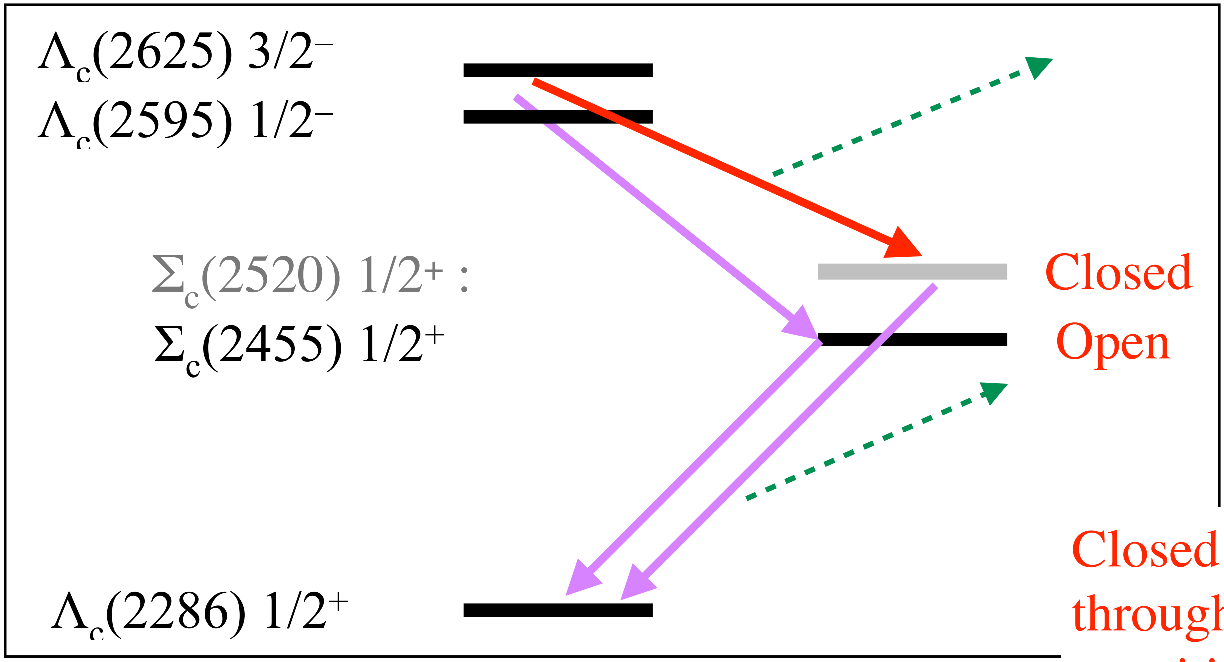
Three-body decay

Three-body decay

Experimentally, $\Lambda_c(2625)\ 3/2^-$, $\Lambda_c(2595)\ 1/2^- \rightarrow \pi\pi\Lambda_c(2286)\ 1/2^+$

Sequential process





Closed one allowed through virtual transition

$\Lambda_c(2595)$

		λ-mode	ρ-mode $j=0$	ρ-mode $j=1$		Exp.
Two-body to open Σ_c	$\Sigma_c^{++}\pi^-$	0.161	-	0.680		0.624 (24%)
	$\Sigma_c^{0}\pi^+$	0.248	-	1.075		0.624 (24%)
	$\Sigma_c^{+}\pi^0$	1.628	-	6.891		-
					Three-body	0.468 (18%)
Three-body through closed Σ_c^*	$\Sigma_c^{*++}\pi$	10^{-6}	-	10^{-6}		-
	$\Sigma_c^{*0}\pi$	10^{-6}	-	10^{-6}		-
	$\Sigma_c^{*+}\pi$	10^{-6}	-	10^{-6}		-
	Interference	0.047	-	0.198		-
	Total	2.084	-	8.844		2.6 ± 0.6

- 80 % of the decay of $\Lambda_c(2595)$ is due to the two body decay: confirmed
- The virtual process of $\Sigma_c(2520)$ has only minor role due to the D-wave nature
- The remaining ~ 20 % is from other ππ couplings (σ, …?)

$\Lambda_c(2520)$

Two-body to open Σ_c

Three-body through closed Σ_c^*

	λ-mode	ρ-mode $j=1$	ρ-mode $j=2$		Exp.
$\Sigma_c^{++}\pi^-$	0.036	0.018	0.033		<0.05 (<5%)
$\Sigma_c^{0}\pi^+$	0.032	0.016	0.030		<0.05 (<5%)
$\Sigma_c^{+}\pi^0$	0.053	0.027	0.049		-
				Three-body	(large)
$\Sigma_c^{*++}\pi^-$	0.044	0.189	0		-
$\Sigma_c^{*0}\pi^+$	0.064	0.285	0		-
$\Sigma_c^{*+}\pi^0$	0.071	0.339	0		-
Interference	0.034	0.148	10^{-4}		-
Total	0.334	1.022	0.112		< 0.97

- The two body decay of $\Lambda_c(2625)$ is only minor
- The virtual process of $\Sigma_c(2520)$ is large due to S-wave nature
- With the ρ mode excitation, the width is overestimated

➡ $\Lambda_c(2595)$ and $\Lambda_c(2625)$ are most likely the λ mode HQ doublet of l_λ (=1) + $1/2_Q = 1/2^-, 3/2^-$

Summary

- There are X, Y, Z, Pc states are observed
  Their properties have brought us many questions about hadron interactions.

- Charmed baryons may provide a simple system of (di)quark dynamics
  Separation of the $\lambda\rho$ mode is important
  Decay rates of low lying states seem consistent with quark model
  supplemented by chiral symmetry

- More on the quark correlations will be studied