Decays of heavy baryons

Atsushi Hosaka
RCNP, Osaka University
YITP Molecule
November 22nd (Tue), 2016

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

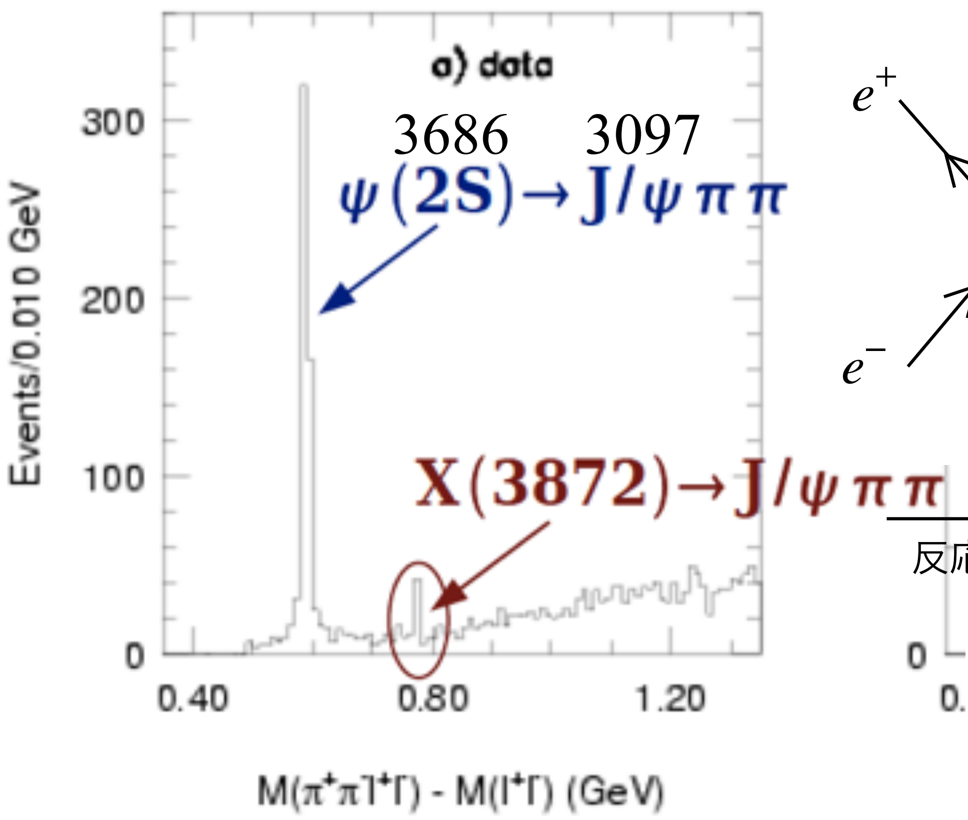
1. Exotic hadrons

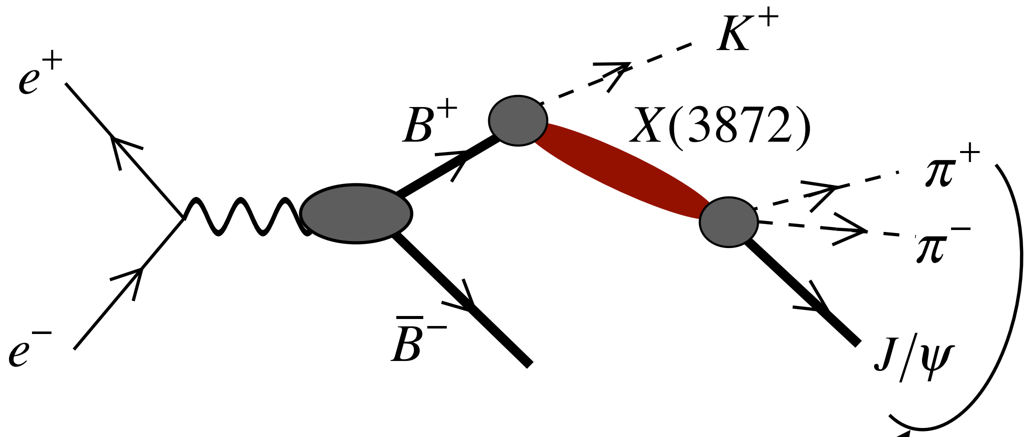
1. Exotic hadrons

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 fb^{-1}

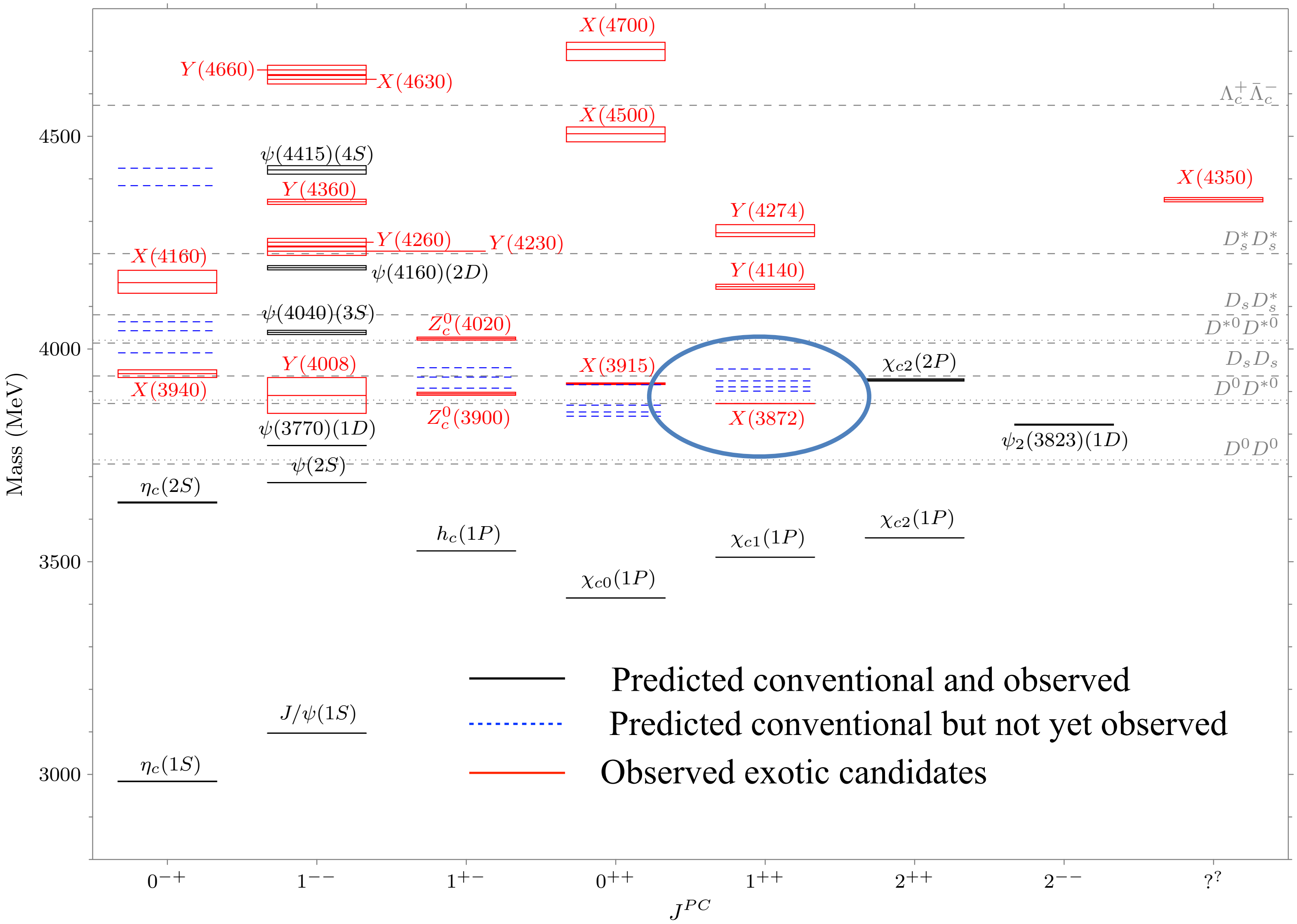




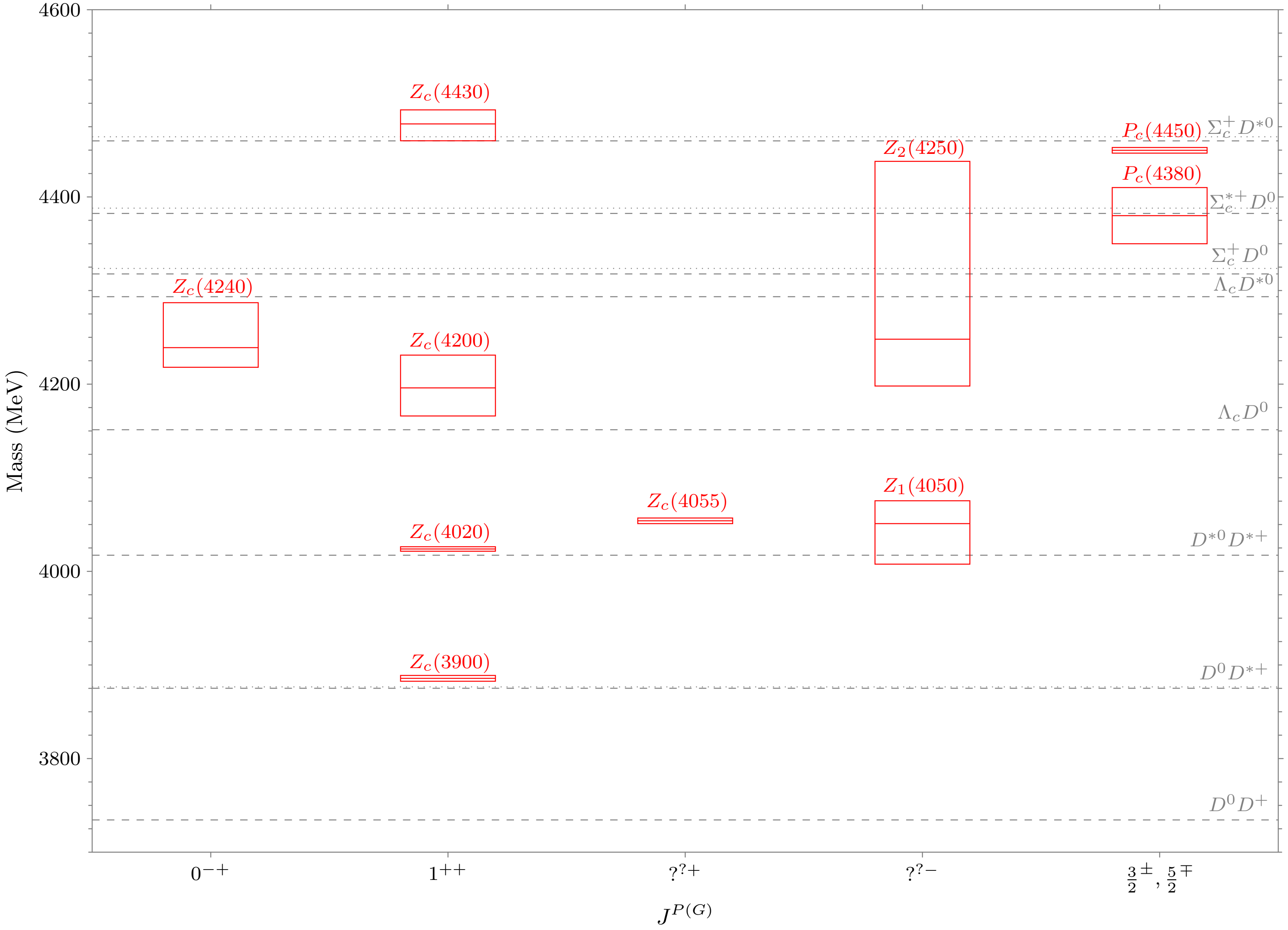
反応の進む方向

これらを測定し
X(3872）を突き止める

Neutral X, Y, Z_0 states



Charged Z states



Properties of *X*(3872)

1. *X*(3872) exists
2. The mass is close to the threshold
3. The decay with is small = long life time
4. No isospin partner
5. Isospin is broken
6. Spin and parity 1^{++}
7. The large decay rate into *DD**
8. A large production rate in the prompt reactions

Dominated by DD* molecule but with a small fraction of $c\bar{c}$

2. The mass is close to the threshold
3. The decay with is small = long life time
4. No isospin partner
5. Isospin is broken

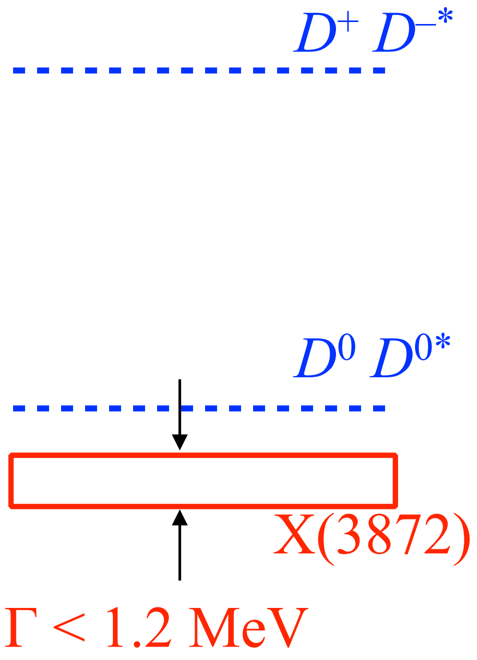
$$M\left(D^{\pm}+D^{*\mp}\right)=1869.61+2010.29=3879.87\,\mathrm{MeV}$$

~ 8.07 MeV

$$M\left(D^{0}+D^{*0}\right)=1864.84+2006.96=3871.80\,\mathrm{MeV}$$

~ 0.11 MeV

$$M(X(3872))=3871.69\,\mathrm{MeV}$$



$$\frac{\mathrm{Br}(X(3872)\to J/\psi+3\pi(\omega))}{\mathrm{Br}(X(3872)\to J/\psi+2\pi(\rho))}\simeq 1$$

Decay Rate of $X(3872)$

	Mode	Fraction (Γ_i / Γ)	Scale Factor/ Confidence Level	P (MeV/c)
Γ_1	e^+e^-			1936
Γ_2	$\pi^+\pi^- J/\psi(1S)$	$> 2.6\%$		650
Γ_3	$\rho^0 J/\psi(1S)$			-1
Γ_4	$\omega J/\psi(1S)$	$> 1.9\%$		-1
Γ_5	$D^0 \overline{D}^0 \pi^0$	$> 32\%$		117
Γ_6	$\overline{D}^{*0} D^0$	$> 24\%$		3
Γ_7	$\gamma\gamma$			1936
Γ_8	$D^0 \overline{D}^0$			520
Γ_9	$D^+ D^-$			502
Γ_{10}	$\gamma \chi_{c1}$			344
Γ_{11}	$\gamma \chi_{c2}$			303
Γ_{12}	$\gamma J/\psi$	$> 6 \times 10^{-3}$		697
Γ_{13}	$\gamma \psi(2S)$	$> 3.0\%$		181
Γ_{14}	$\pi^+\pi^- \eta_c(1S)$	not seen		746
Γ_{15}	$p\overline{p}$	not seen		1693

▸ *C*-violating decays

Prompt reactions in comparison with the deuteron

A.Guerrieri,F.Piccinini,A.Pilloni,A.Polosa Phys.Rev.D90(2014)034003.arXiv:1405.7929

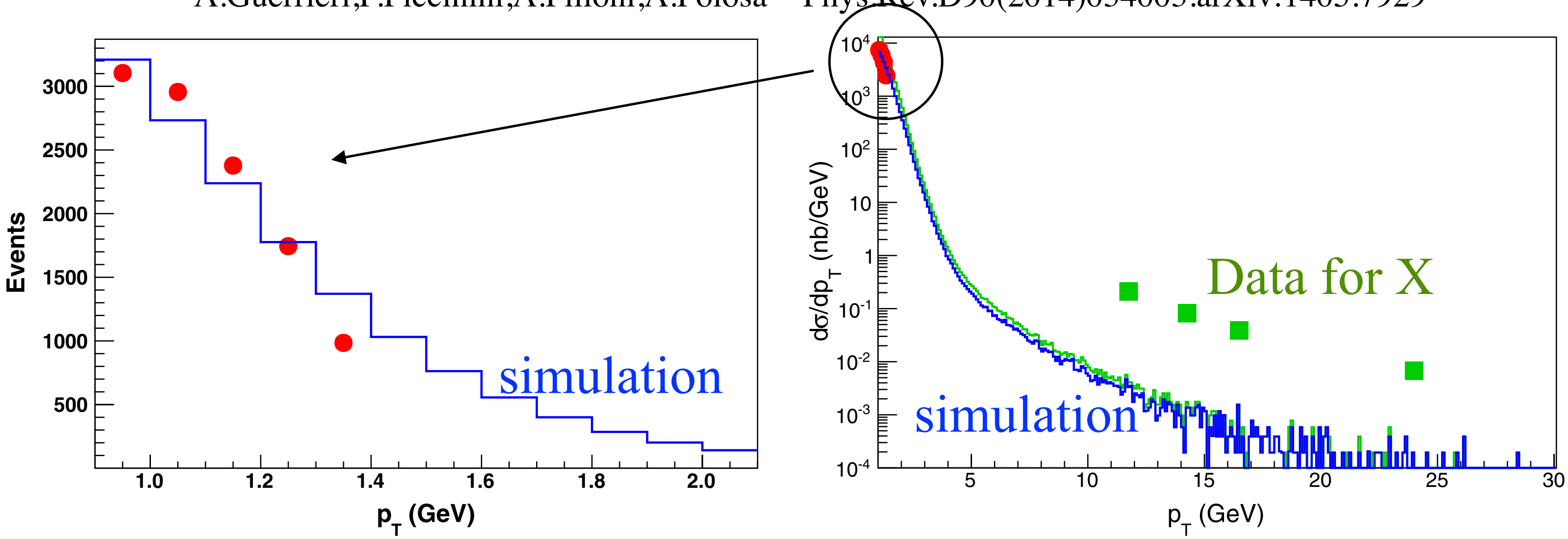


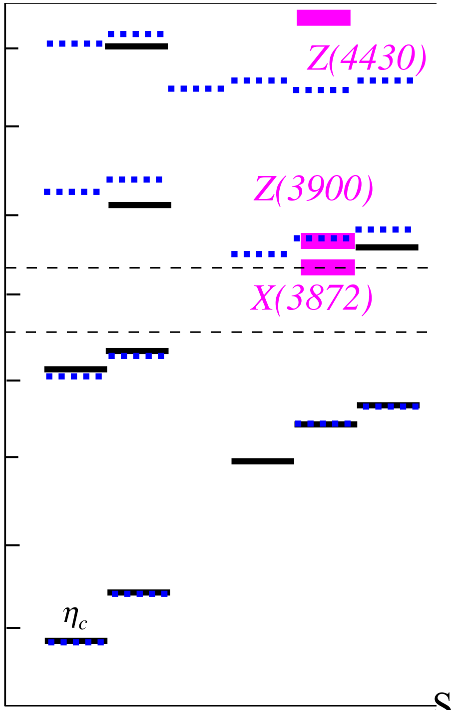
FIG. 6 (color online). Antideuteron events produced in pp according to 10^9 HERWIG events. We confront with ALICE deuteron production data (red circles) [23], and with CMS $X(3872)$ data (green squares) [26]. The blue solid line is the MC prediction in the $|\eta| < 0.9$ region, as in ALICE data, which we use for the normalization. The green line (a bit higher in the right panel) corresponds to the $|y| < 1.2$ region, as in CMS data, and is normalized accordingly.

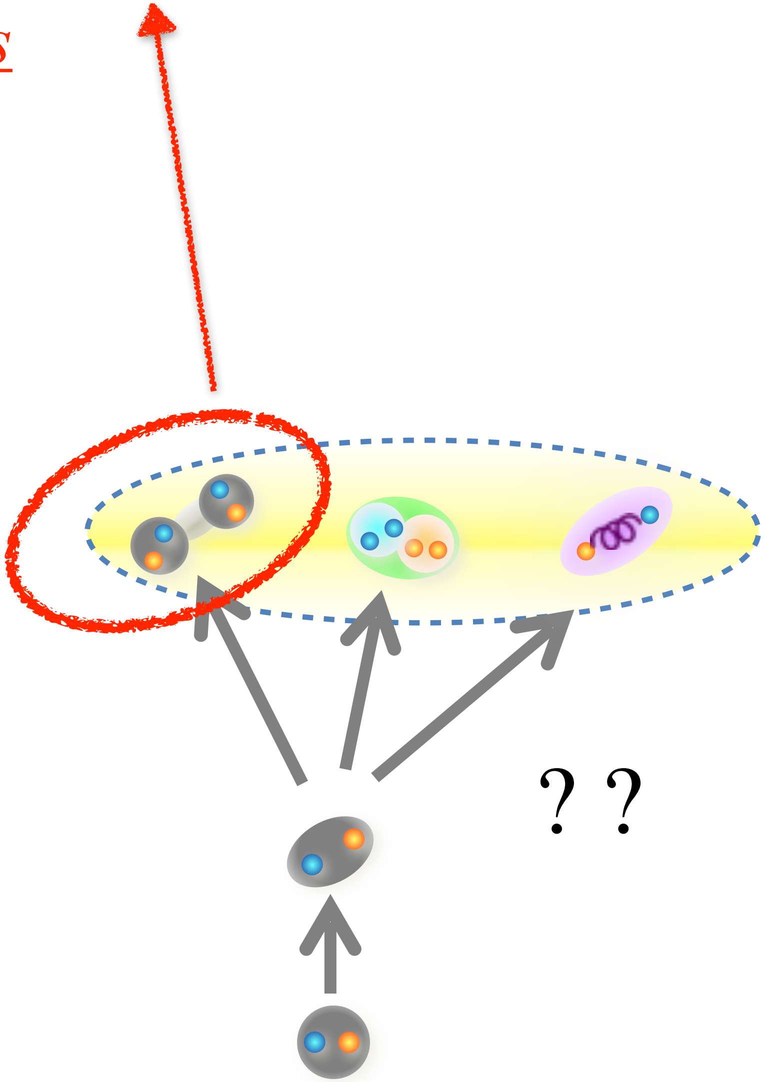
What is *X*(3872)

- It is mostly a *DD* molecular like state* just at the threshold.
- It also contains a *$c\bar{c}$ components*

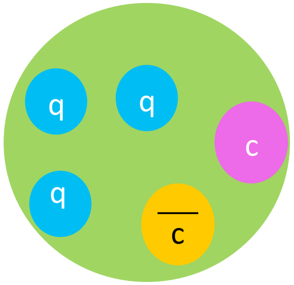
To be solved:

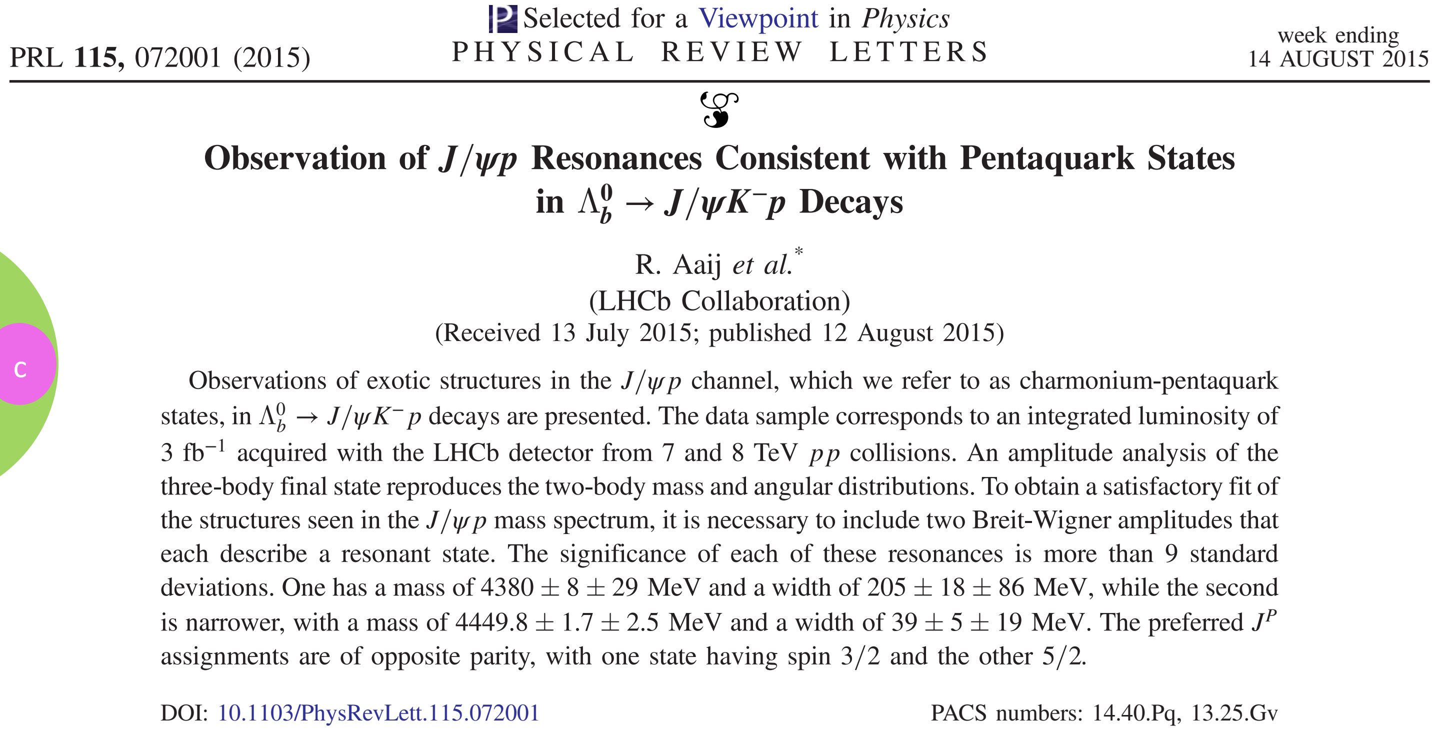
- What is the size of the *X*
- Interaction between *D* and *D**
- Identification of χ_{CJ}(2s)





LHCb found Pentaquarks





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

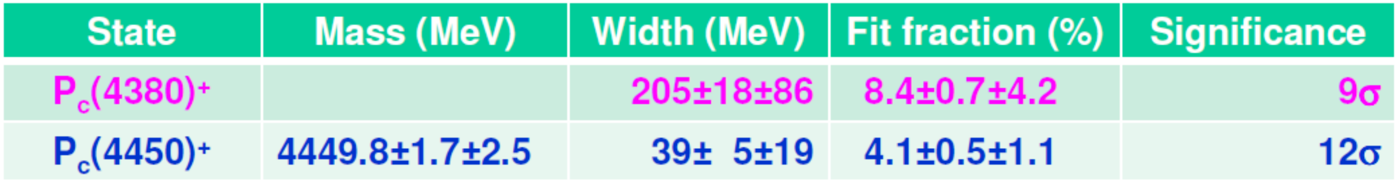
Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

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

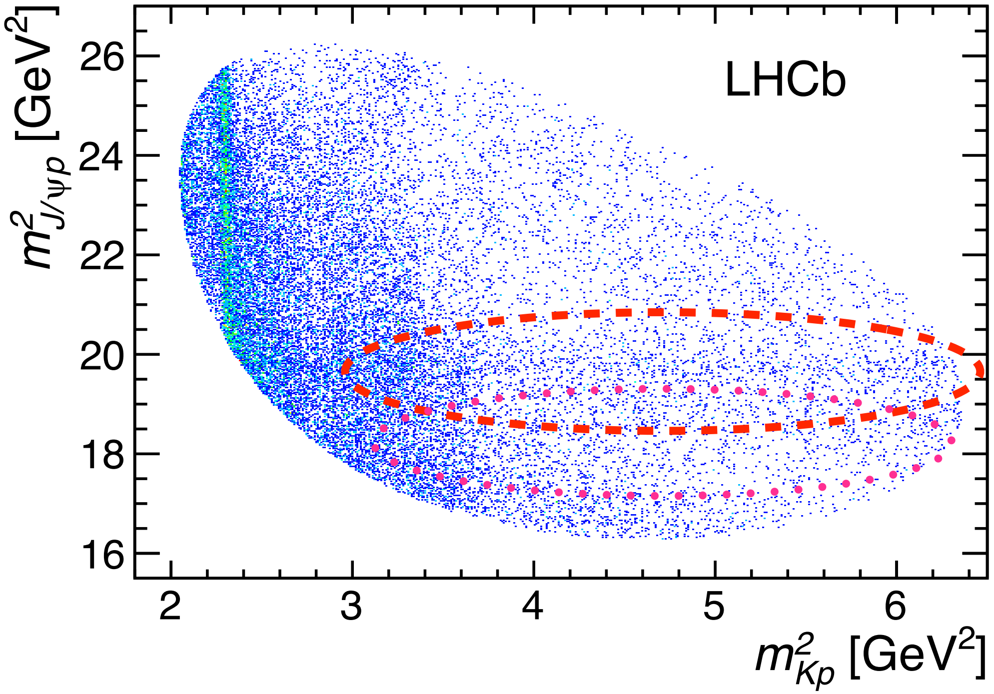
- Best fit has J^P=(3/2$^-$, 5/2$^+$), also (3/2$^+$, 5/2$^-$) & (5/2$^+$, 3/2$^-$) are preferred

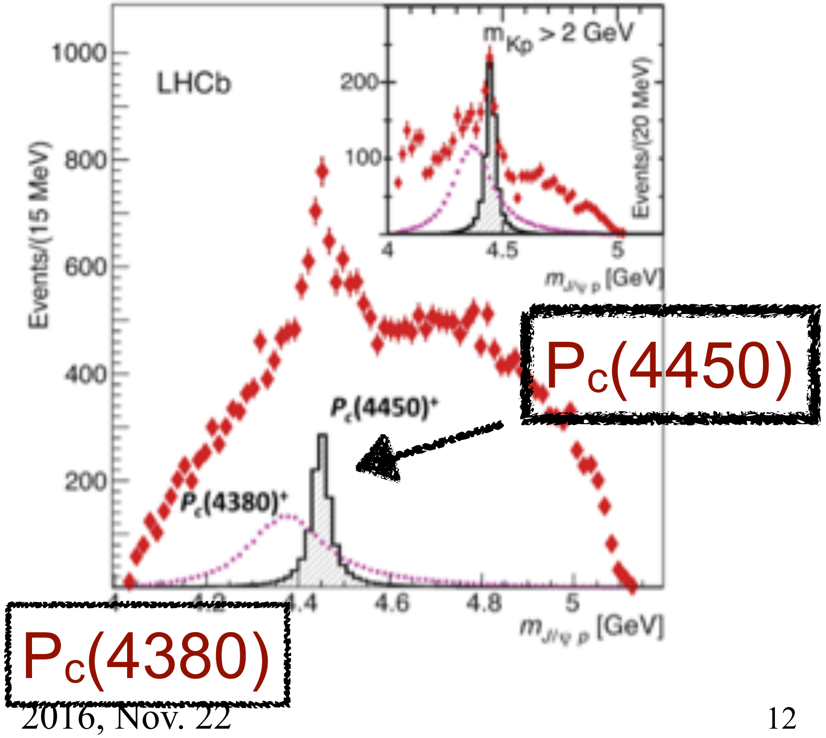
LHCb found Pentaquarks

7-8 TeV pp collision —> Λ_b

$$\Lambda_b \longrightarrow J/\psi, p, K^-$$

This provides pseudo J/ψ-p scattering





$P_c(4450)$

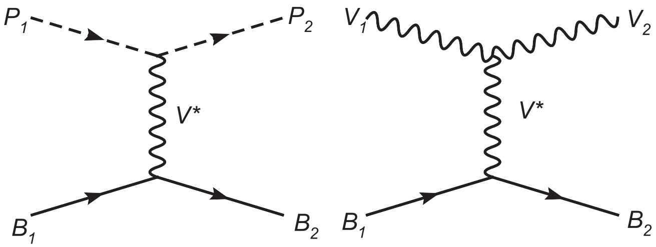
$P_c(4380)$

Either resonance or cusp?

PRL **105,** 232001 (2010) PHYSICAL REVIEW LETTERS week ending 3 DECEMBER 2010

Prediction of Narrow N^* and Λ^* Resonances with Hidden Charm above 4 GeV

Jia-Jun Wu,[1,2] R. Molina,[2,3] E. Oset,[2,3] and B. S. Zou[1,3]



$$V_{ab(P_1B_1\to P_2B_2)} = \frac{C_{ab}}{4f^2}(E_{P_1} + E_{P_2}),$$

$$V_{ab(V_1B_1\to V_2B_2)} = \frac{C_{ab}}{4f^2}(E_{V_1} + E_{V_2})\vec{\epsilon}_1 \cdot \vec{\epsilon}_2,$$

$1/2^-$

TABLE II. Pole positions z_R and coupling constants g_a for the states from $PB \to PB$.

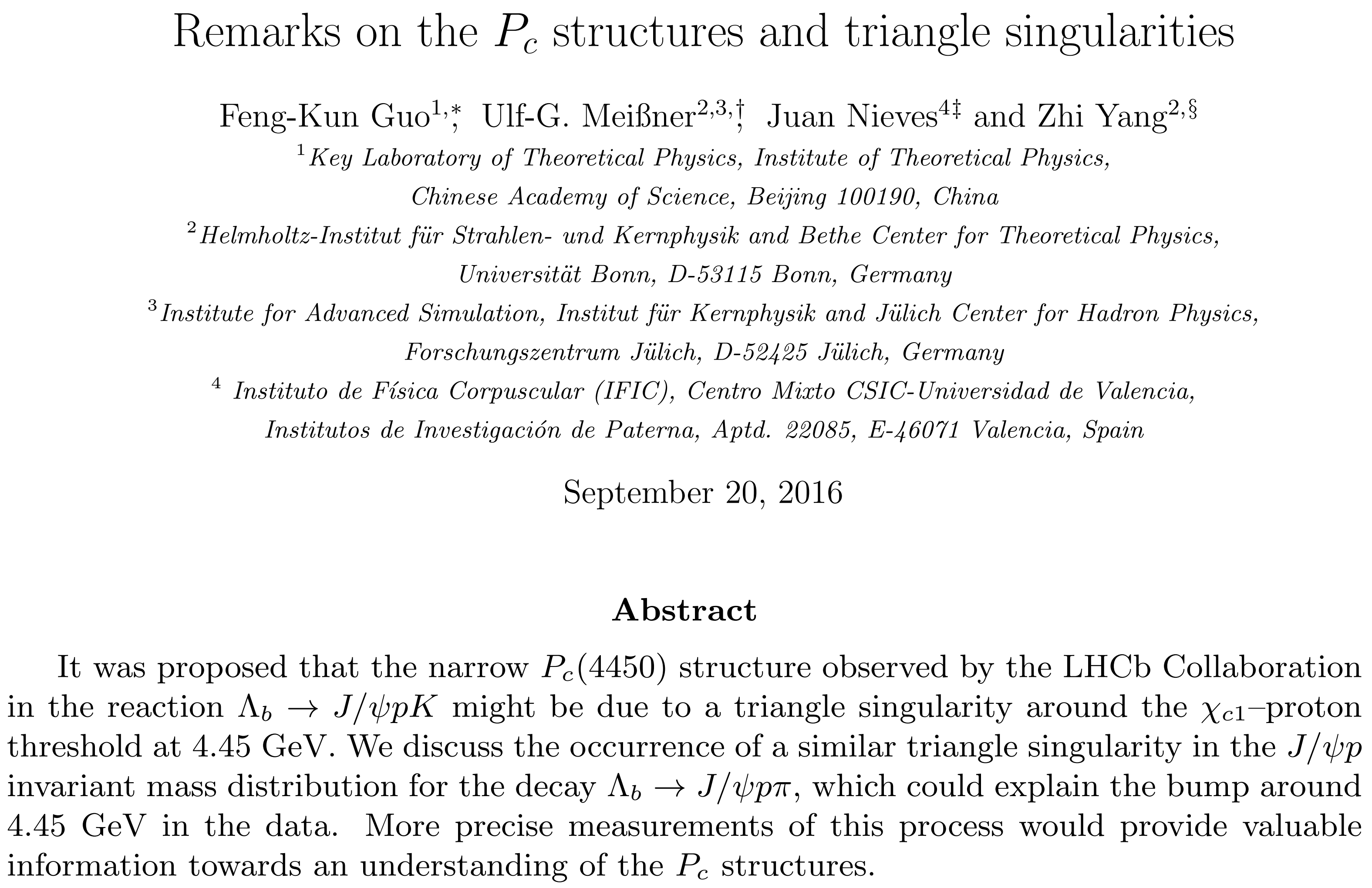
(I, S)	z_R (MeV)	g_a		
$(1/2, 0)$		$\bar{D}\Sigma_c$	$\bar{D}\Lambda_c^+$	
	4269	2.85	0	
$(0, -1)$		$\bar{D}_s\Lambda_c^+$	$\bar{D}\Xi_c$	$\bar{D}\Xi_c'$
	4213	1.37	3.25	0
	4403	0	0	2.64

$1/2^-, 3/2^-$

TABLE III. Pole position and coupling constants for the bound states from $VB \to VB$.

(I, S)	z_R (MeV)	g_a		
$(1/2, 0)$		$\bar{D}^*\Sigma_c$	$\bar{D}^*\Lambda_c^+$	
	4418	2.75	0	
$(0, -1)$		$\bar{D}_s^*\Lambda_c^+$	$\bar{D}^*\Xi_c$	$\bar{D}^*\Xi_c'$
	4370	1.23	3.14	0
	4550	0	0	2.53

Threshold effects?



Remarks on the P_c structures and triangle singularities

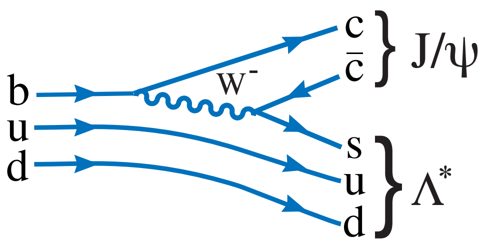
Feng-Kun Guo[1,*], Ulf-G. Meißner[2,3,†], Juan Nieves[4‡] and Zhi Yang[2,§]
[1] *Key Laboratory of Theoretical Physics, Institute of Theoretical Physics,*
Chinese Academy of Science, Beijing 100190, China
[2] *Helmholtz-Institut für Strahlen- und Kernphysik and Bethe Center for Theoretical Physics,*
Universität Bonn, D-53115 Bonn, Germany
[3] *Institute for Advanced Simulation, Institut für Kernphysik and Jülich Center for Hadron Physics,*
Forschungszentrum Jülich, D-52425 Jülich, Germany
[4] *Instituto de Física Corpuscular (IFIC), Centro Mixto CSIC-Universidad de Valencia,*
Institutos de Investigación de Paterna, Aptd. 22085, E-46071 Valencia, Spain

September 20, 2016

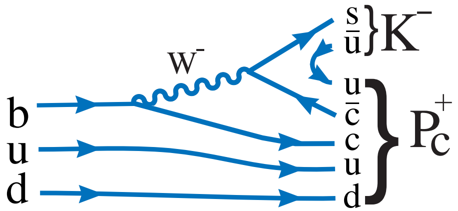
Abstract

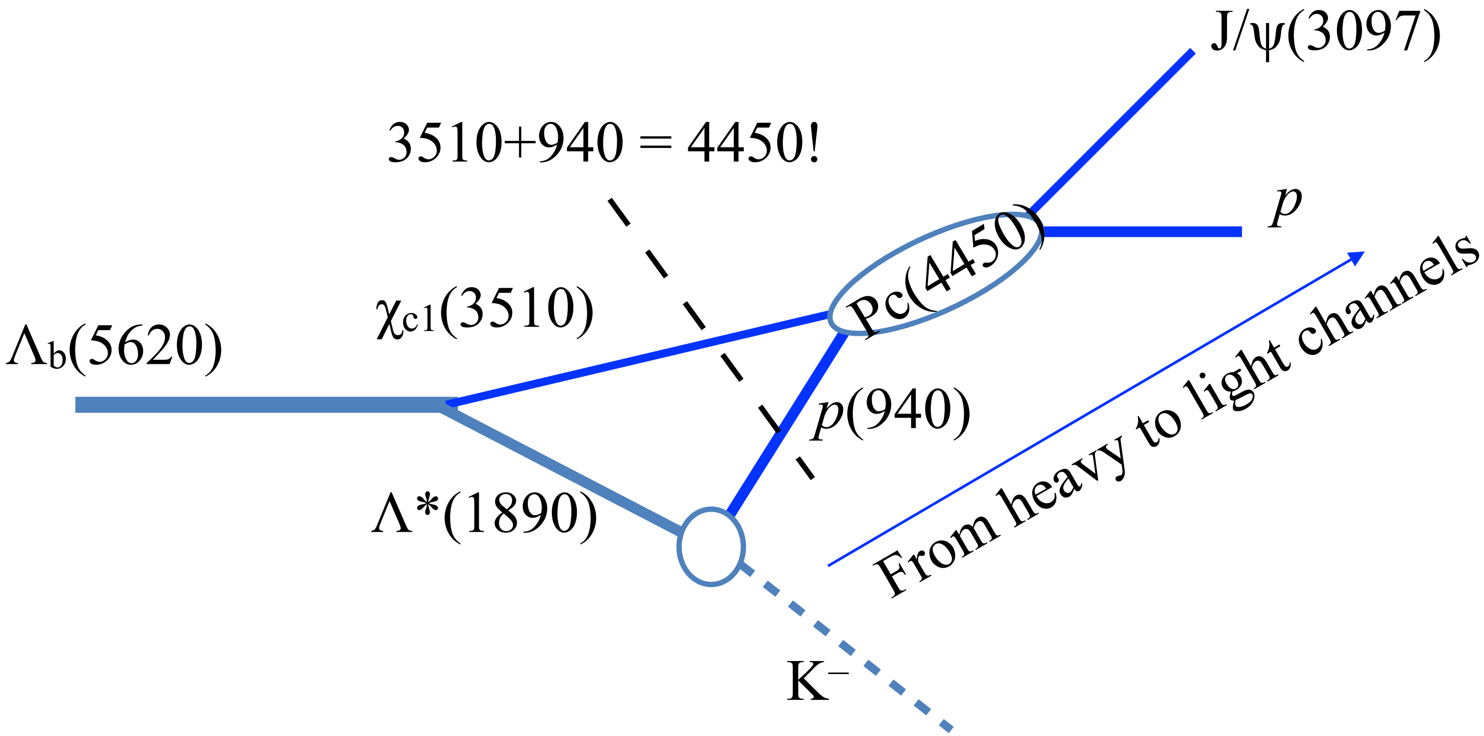
It was proposed that the narrow $P_c(4450)$ structure observed by the LHCb Collaboration in the reaction $\Lambda_b \to J/\psi p K$ might be due to a triangle singularity around the χ_{c1}–proton threshold at 4.45 GeV. We discuss the occurrence of a similar triangle singularity in the $J/\psi p$ invariant mass distribution for the decay $\Lambda_b \to J/\psi p \pi$, which could explain the bump around 4.45 GeV in the data. More precise measurements of this process would provide valuable information towards an understanding of the P_c structures.

Diagrams



+





3510+940 = 4450!

From heavy to light channels

P_c

- There is a structure at 4450 MeV decaying into $p\ J/\psi$
- *There was a prediction as molecular of* Σ_c+D^*
- Very neat the threshold of χ_{c1}(3510) + p(940)
- Resonance or cusp?

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

- Keywords:
- Correlations, thresholds, coupled channels, …
- Heavy baryon systems may provide opportunities for the study of some simple aspects of them.

2. Charmed baryons

Charmed baryons

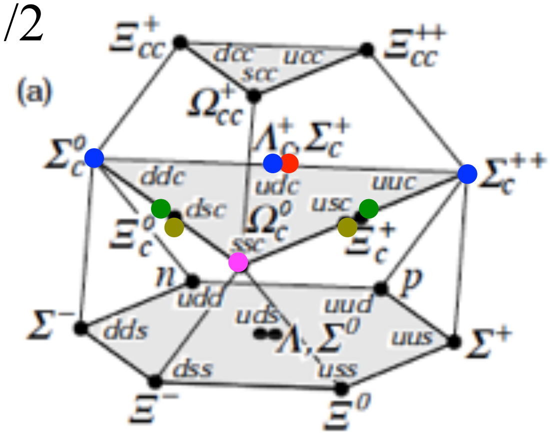
Ground states

● Λ_c^+ 2286	****
$\Lambda_c(2595)^+$	***
$\Lambda_c(2625)^+$	***
$\Lambda_c(2765)^+$ or $\Sigma_c(2765)$	*
$\Lambda_c(2880)^+$	***
$\Lambda_c(2940)^+$	***
● $\Sigma_c(2455)$	
● $\Sigma_c(2520)$	
$\Sigma_c(2800)$	***

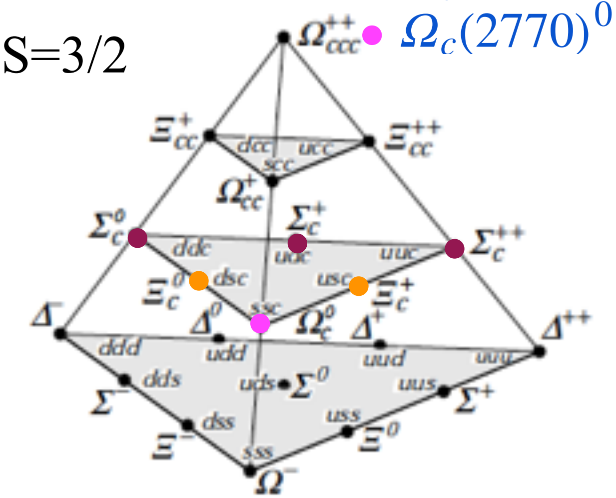
● Ξ_c^+ 2468	***
● Ξ_c^0 2471	***
● $\Xi_c'^+$ 2576	***
● $\Xi_c'^0$ 2578	***
● $\Xi_c(2645)$	***
$\Xi_c(2790)$	***
$\Xi_c(2815)$	***
$\Xi_c(2930)$	*
$\Xi_c(2970)$ was $\Xi_c(2980)$	***
$\Xi_c(3055)$	***
$\Xi_c(3080)$	***
$\Xi_c(3123)$	*
● Ω_c^0	***
● $\Omega_c(2770)^0$	***

Excited states

S=1/2



S=3/2



p
n
$N(1440)\ 1/2^+$
$N(1520)\ 3/2^-$
$N(1535)\ 1/2^-$
$N(1650)\ 1/2^-$
$N(1675)\ 5/2^-$
$N(1680)\ 5/2^+$
$N(1700)\ 3/2^-$
$N(1710)\ 1/2^+$
$N(1720)\ 3/2^+$
$N(1860)\ 5/2^+$
$N(1875)\ 3/2^-$
$N(1880)\ 1/2^+$
$N(1895)\ 1/2^-$
$N(1900)\ 3/2^+$
$N(1990)\ 7/2^+$
$N(2000)\ 5/2^+$
$N(2040)\ 3/2^+$
$N(2060)\ 5/2^-$
$N(2100)\ 1/2^+$
$N(2120)\ 3/2^-$
$N(2190)\ 7/2^-$
$N(2220)\ 9/2^+$
$N(2250)\ 9/2^-$
$N(2300)\ 1/2^+$
$N(2570)\ 5/2^-$
$N(2600)\ 11/2^-$
$N(2700)\ 13/2^+$

$\Delta(1232)\ 3/2^+$
$\Delta(1600)\ 3/2^+$
$\Delta(1620)\ 1/2^-$
$\Delta(1700)\ 3/2^-$
$\Delta(1750)\ 1/2^+$
$\Delta(1900)\ 1/2^-$
$\Delta(1905)\ 5/2^+$
$\Delta(1910)\ 1/2^+$
$\Delta(1920)\ 3/2^+$
$\Delta(1930)\ 5/2^-$
$\Delta(1940)\ 3/2^-$
$\Delta(1950)\ 7/2^+$
$\Delta(2000)\ 5/2^+$
$\Delta(2150)\ 1/2^-$
$\Delta(2200)\ 7/2^-$
$\Delta(2300)\ 9/2^+$
$\Delta(2350)\ 5/2^-$
$\Delta(2390)\ 7/2^+$
$\Delta(2400)\ 9/2^-$
$\Delta(2420)\ 11/2^+$
$\Delta(2750)\ 13/2^-$
$\Delta(2950)\ 15/2^+$

Λ
$\Lambda(1405)\ 1/2^-$
$\Lambda(1520)\ 3/2^-$
$\Lambda(1600)\ 1/2^+$
$\Lambda(1670)\ 1/2^-$
$\Lambda(1690)\ 3/2^-$
$\Lambda(1710)\ 1/2^+$
$\Lambda(1800)\ 1/2^-$
$\Lambda(1810)\ 1/2^+$
$\Lambda(1820)\ 5/2^+$
$\Lambda(1830)\ 5/2^-$
$\Lambda(1890)\ 3/2^+$
$\Lambda(2000)$
$\Lambda(2020)\ 7/2^+$
$\Lambda(2050)\ 3/2^-$
$\Lambda(2100)\ 7/2^-$
$\Lambda(2110)\ 5/2^+$
$\Lambda(2325)\ 3/2^-$
$\Lambda(2350)\ 9/2^+$
$\Lambda(2585)$ Bumps

Σ^+
Σ^0
Σ^-
$\Sigma(1385)\ 3/2^+$
$\Sigma(1480)$ Bumps
$\Sigma(1560)$ Bumps
$\Sigma(1580)\ 3/2^-$
$\Sigma(1620)\ 1/2^-$
$\Sigma(1620)$ Producti
$\Sigma(1660)\ 1/2^+$
$\Sigma(1670)\ 3/2^-$
$\Sigma(1670)$ Bumps
$\Sigma(1690)$ Bumps
$\Sigma(1730)\ 3/2^+$
$\Sigma(1750)\ 1/2^-$
$\Sigma(1770)\ 1/2^+$
$\Sigma(1775)\ 5/2^-$
$\Sigma(1840)\ 3/2^+$
$\Sigma(1880)\ 1/2^+$
$\Sigma(1900)\ 1/2^-$
$\Sigma(1915)\ 5/2^+$
$\Sigma(1940)\ 3/2^+$
$\Sigma(1940)\ 3/2^-$
$\Sigma(2000)\ 1/2^-$
$\Sigma(2030)\ 7/2^+$
$\Sigma(2070)\ 5/2^+$
$\Sigma(2080)\ 3/2^+$
$\Sigma(2100)\ 7/2^-$
$\Sigma(2250)$
$\Sigma(2455)$ Bumps
$\Sigma(2620)$ Bumps
$\Sigma(3000)$ Bumps
$\Sigma(3170)$ Bumps

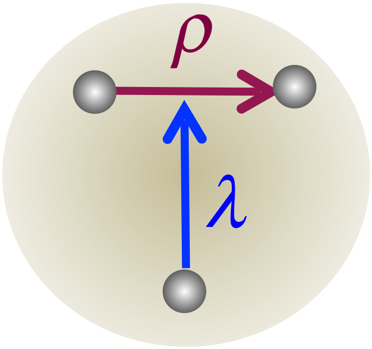
Ξ^0
Ξ^-
$\Xi(1530)\ 3/2^+$
$\Xi(1620)$
$\Xi(1690)$
$\Xi(1820)\ 3/2^-$
$\Xi(1950)$
$\Xi(2030)$
$\Xi(2120)$
$\Xi(2250)$
$\Xi(2370)$
$\Xi(2500)$

Ω^-
$\Omega(2250)^-$
$\Omega(2380)^-$
$\Omega(2470)^-$

Heavy quarks distinguish the internal modes $\boldsymbol{\lambda}$ and $\boldsymbol{\rho}$

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

N, Δ, …

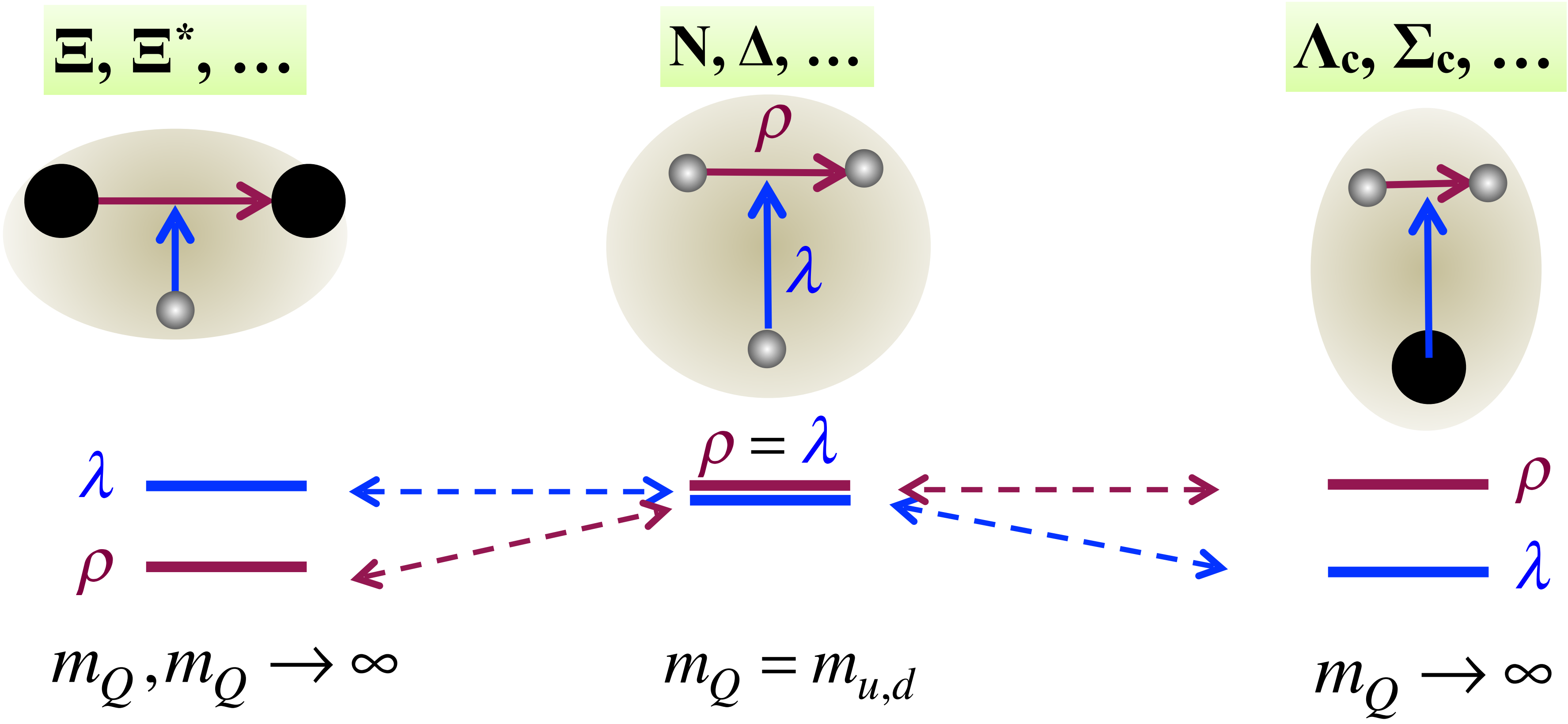


$$\underline{\underline{\rho = \lambda}}$$

$$m_Q = m_{u,d}$$

Heavy quarks distinguish the internal modes λ and ρ

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



Ξ, Ξ*, …

N, Δ, …

Λ_c, Σ_c, …

$m_Q, m_Q \to \infty$

$m_Q = m_{u,d}$

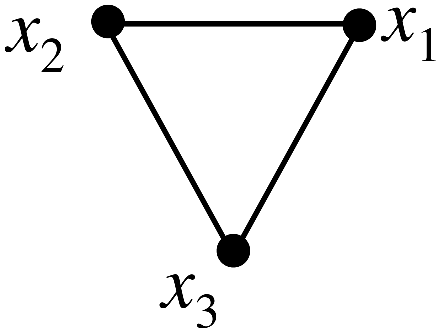
$m_Q \to \infty$

These structures should be sensitive to reactions

Harmonic oscillator

$$H = \frac{{p_1}^2}{2m} + \frac{{p_2}^2}{2m} + \frac{{p_3}^2}{2M} + \frac{k}{2}\left((x_1 - x_2)^2 + (x_2 - x_3)^2 + (x_3 - x_1)^2\right)$$

$$= \frac{{p_\rho}^2}{2m_\rho} + \frac{{p_\lambda}^2}{2m_\lambda} + \frac{k_\rho \rho^2}{2} + \frac{k_\lambda \lambda^2}{2}$$



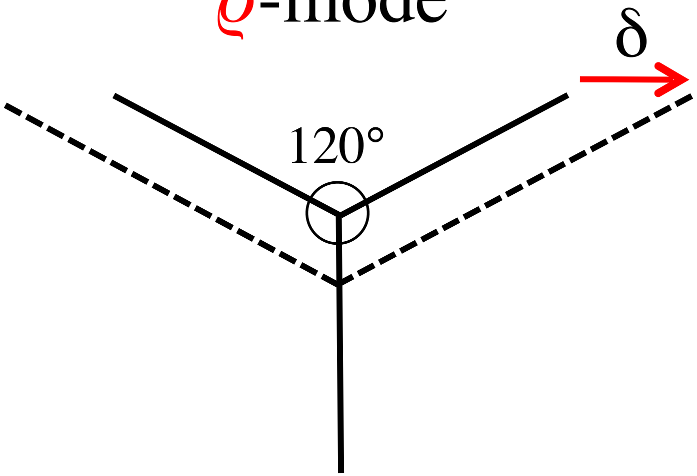
$$m_\rho = \frac{m}{2}, \quad m_\lambda = \frac{2mM}{M + 2m}$$

$$k_\rho = \frac{3}{2}k, \quad k_\lambda = 2k$$

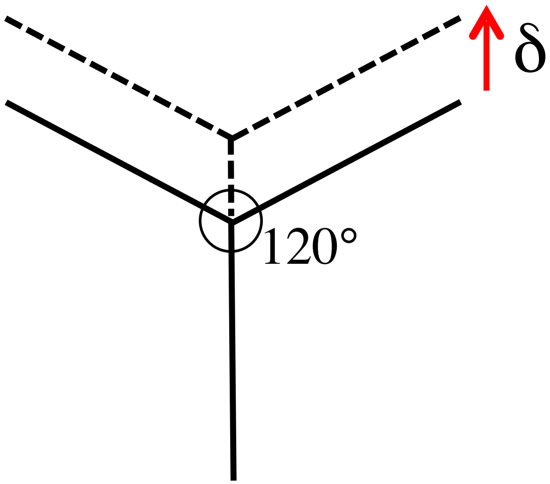
$$\omega_\rho = \sqrt{3}\omega \quad > \quad \omega_\lambda = \sqrt{\frac{M + 2m}{M}}\omega$$

String

ϱ-mode



λ-mode



$$\delta L_\rho = \frac{\sqrt{3}}{2}\delta \qquad\qquad \delta L_\lambda = \delta$$

$$m_\rho = \frac{m}{2} \qquad\qquad m_\lambda = \frac{2mM}{M+2m} \to 2m$$

$$\omega_\rho = \left(\frac{\sigma^2}{m}\right)^{1/3} \to \left(\frac{3}{2}\right)^{1/3}\left(\frac{\sigma^2}{m}\right)^{1/3} \quad > \quad \omega_\lambda \to \left(\frac{1}{2}\right)^{1/3}\left(\frac{\sigma^2}{m}\right)^{1/3}$$

Wave functions ~ Harmonic oscillator

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

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

$m = 0.35 \pm 0.05$ GeV

$M = 1.5 \pm 0.1$ GeV

$k = 0.02 - 0.04$ GeV^3

$\hbar\omega_\lambda \sim 0.3 - 0.4$ GeV

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

Λ^*_c, Σ_c, …

charm spin

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

H.O.(gauss)

flavor

$$\Sigma_c(1/2^+) = \left[\left[\psi_0(\vec{\lambda})\psi_0(\vec{\rho}), d^1\right]^1, \chi_c\right]^{\frac{1}{2}} D^1 c$$

etc.

di-quark spin

Quark model states

Λ-states

qq is made isosinglet

Ground states charmed baryons $n = 0$

$(n_\lambda, \ell_\lambda)$	(n_ρ, ℓ_ρ)	d^s	j^P	J^P	possible assignment
$(0,0)$	$(0,0)$	d^0	0^+	$1/2^+$	$\Lambda_c(2286)$
$(0,0)$	$(0,0)$	d^1	1^+	$(1/2,3/2)^+$	$\Sigma_c(2455)$, $\Sigma_c^*(2520)$
				3	3

Negative parity excited charmed baryons $n = 1$

$(n_\lambda, \ell_\lambda)$	(n_ρ, ℓ_ρ)	d^s	j^P	J^P	possible assignment
$(0,1)$	$(0,0)$	d^0	1^-	$(1/2,3/2)^-$	$\Lambda_c^*(2595)$, $\Lambda_c^*(2625)$
$(0,0)$	$(0,1)$	d^1	0^-	$1/2^-$	
			1^-	$(1/2,3/2)^-$	
			2^-	$(3/2,5/2)^-$	$\Lambda_c^*(2880)(?)$
				7	3

Positive parity excited charmed baryons $n = 2$

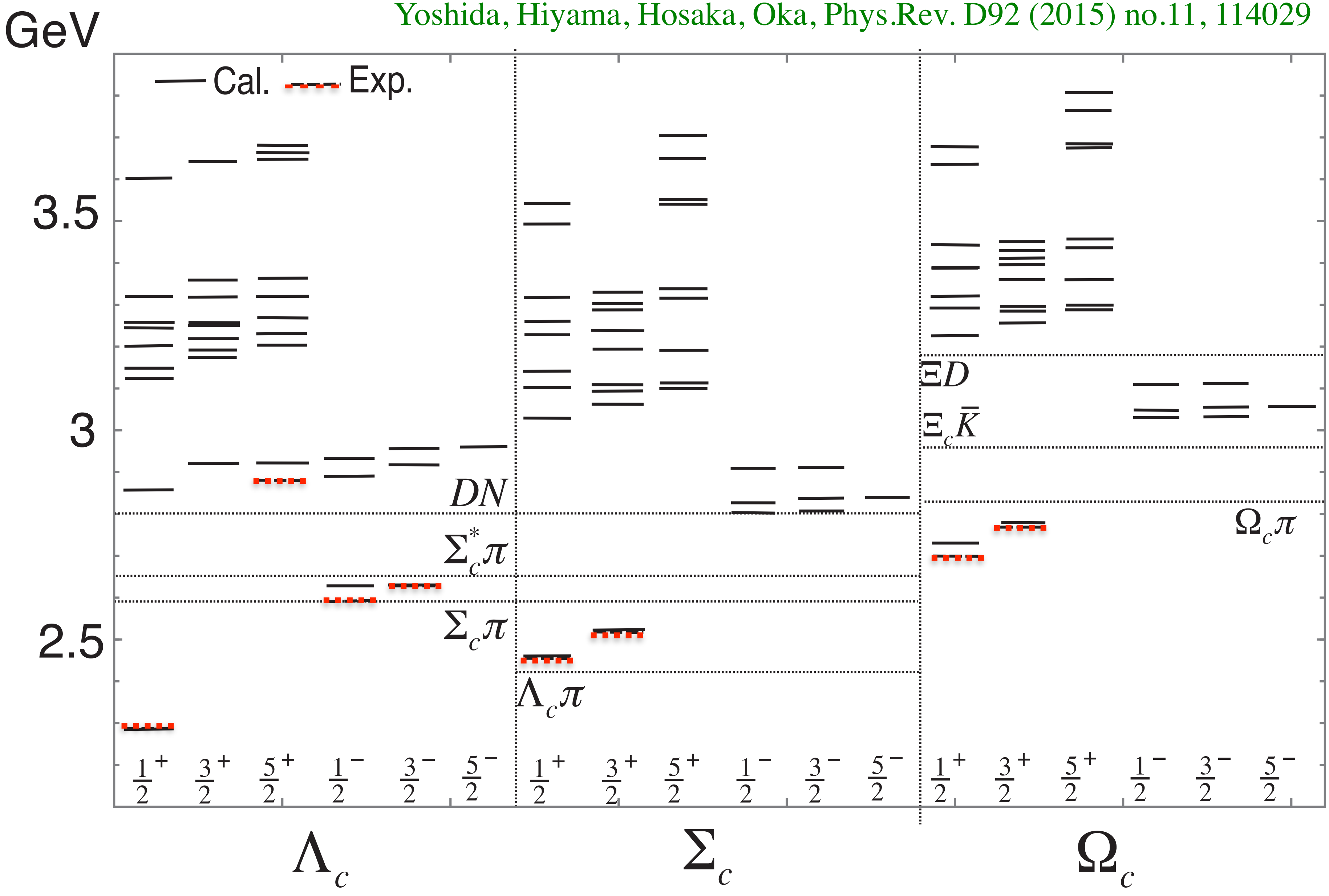
$(n_\lambda, \ell_\lambda)$	(n_ρ, ℓ_ρ)	d^s	j^P	J^P	possible assignment
$(1,0)$	$(0,0)$	d^0	0^+	$1/2^+$	
$(0,2)$	$(0,0)$	d^0	2^+	$(3/2,5/2)^+$	$\Lambda_c^*(2880)(?)$
$(0,0)$	$(1,0)$	d^0	0^+	$1/2^+$	
$(0,0)$	$(0,2)$	d^0	2^+	$(3/2,5/2)^+$	$\Lambda_c^*(2880)(?)$
				7	1

Positive parity excited charmed baryons ($\lambda\rho$-mode) $n = 2$

$(n_\lambda, \ell_\lambda)$	(n_ρ, ℓ_ρ)	d^s	ℓ	j^P	J^P	possible assignment
$(0,1)$	$(0,1)$	d^1	0	1^+	$(1/2,3/2)^+$	
			1	0^+	$1/2^+$	
				1^+	$(1/2,3/2)^+$	
				2^+	$(3/2,5/2)^+$	$\Lambda_c^*(2880)(?)$
			2	1^+	$(1/2,3/2)^+$	
				2^+	$(3/2,5/2)^+$	$\Lambda_c^*(2880)(?)$
				3^+	$(5/2,7/2)^+$	$\Lambda_c^*(2880)(?)$
					13	1

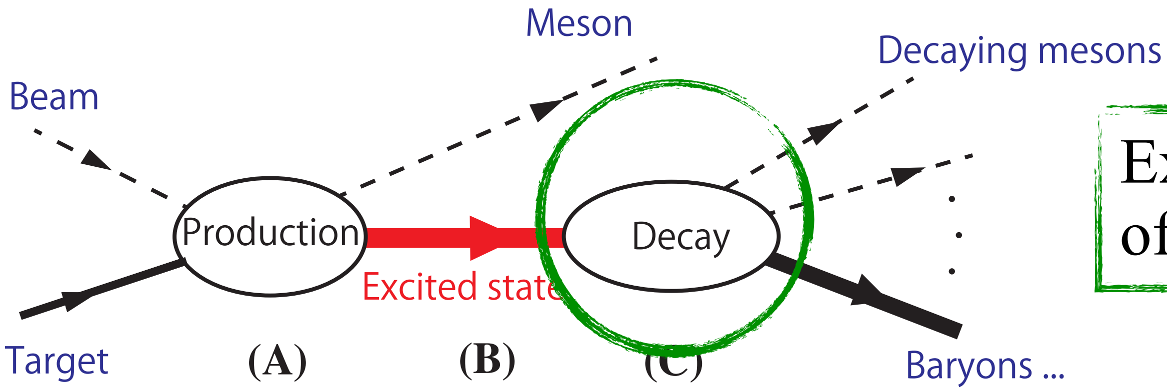
Masses

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



Decays of hadrons

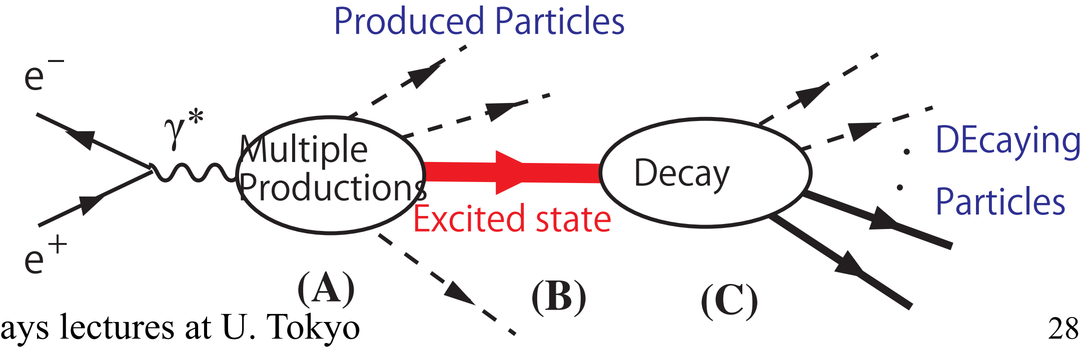
(A) Production
(B) Formation of resonances
(C) Decay of resonances



Exclusive reactions of this part

- Fixed target
  JLab, Spring-8 (photon beam)
  J-PARC (hadron beam), …

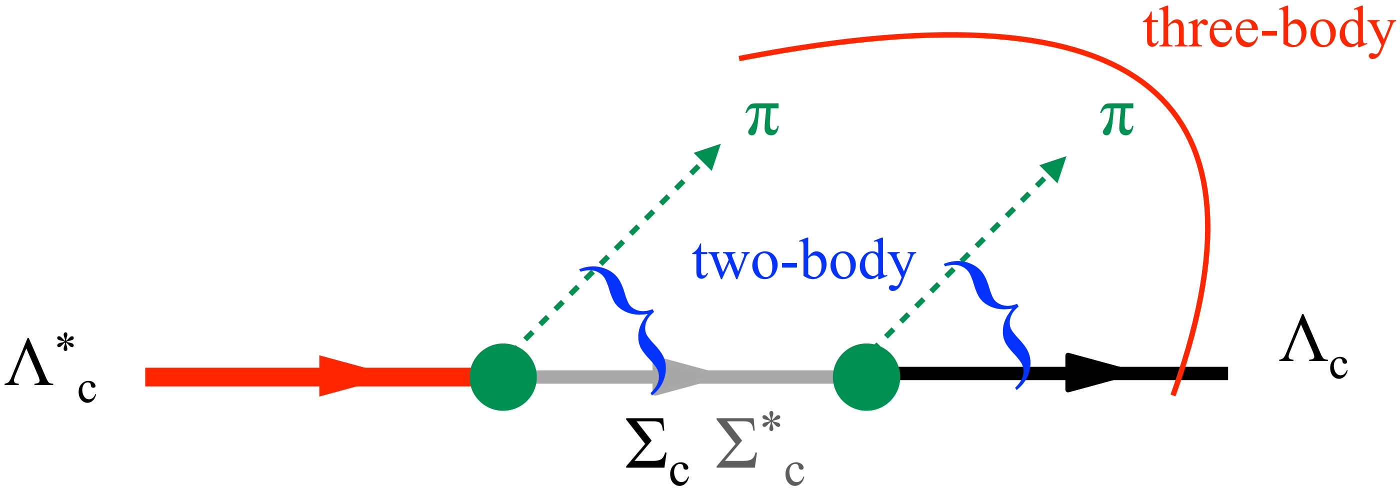
- Collider
  KEK (e+e–), LHCb (pp), …



Decays —Pion emission—

On going, Nagahiro, Yasui, …, Arifi

Nagahiro et al, arXiv:1609.01085



Two-body decays

and

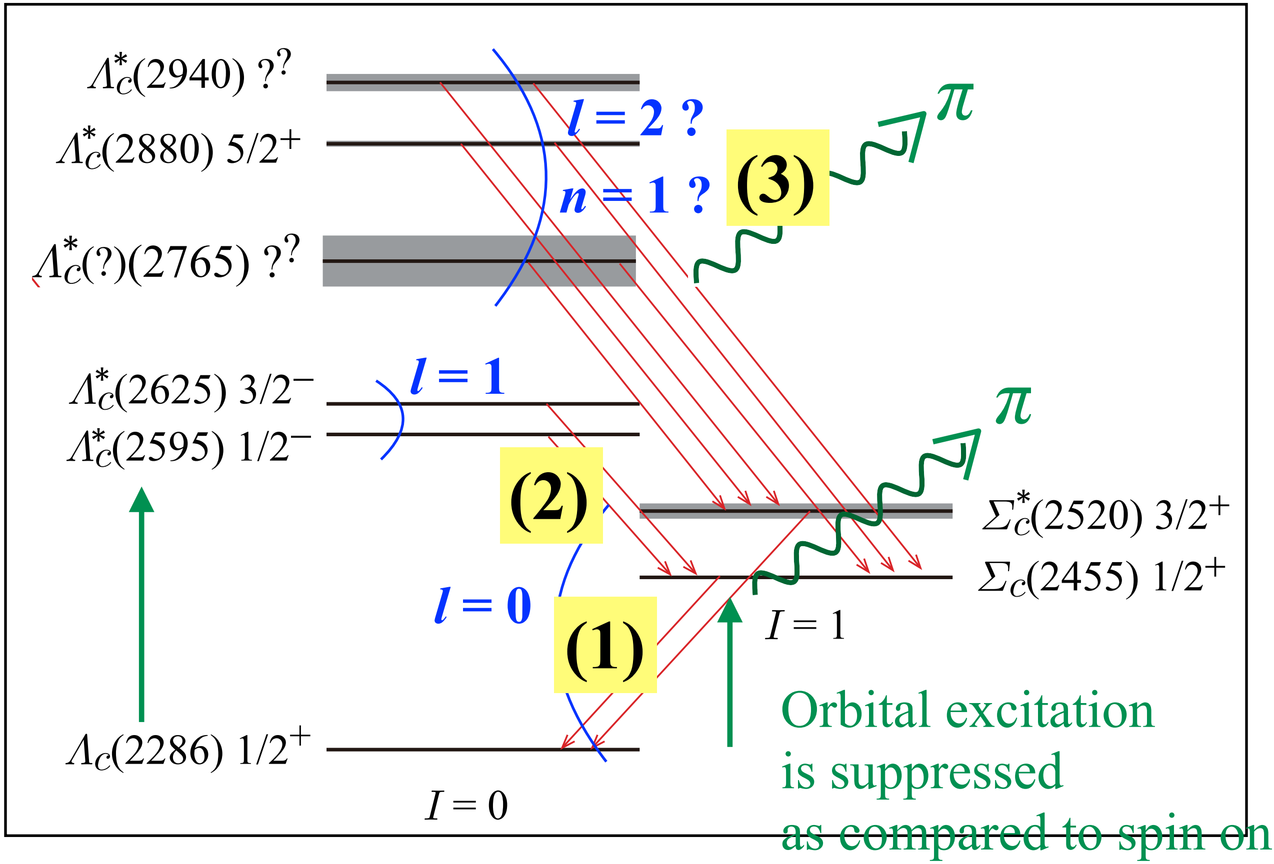
Three-body decays

2. Decays —Pion emission—

On going, Nagahiro, Yasui, …, Arifi

Two-body decays

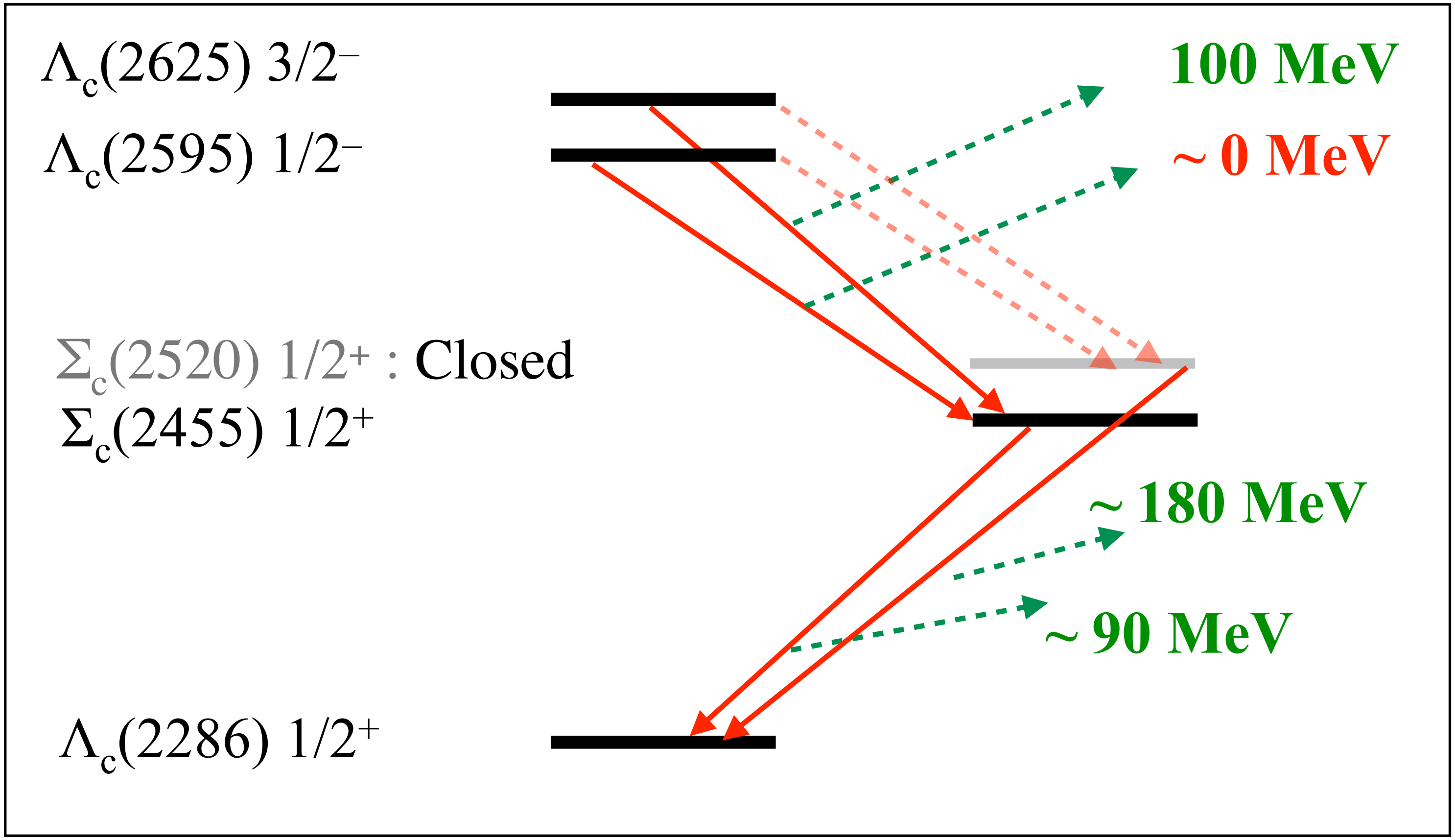
Nagahiro et al, arXiv:1609.01085



Orbital excitation
is suppressed
as compared to spin one

(1) 0hω → 0hω
(2) 1hω → 0hω
(3) 2hω → 0hω

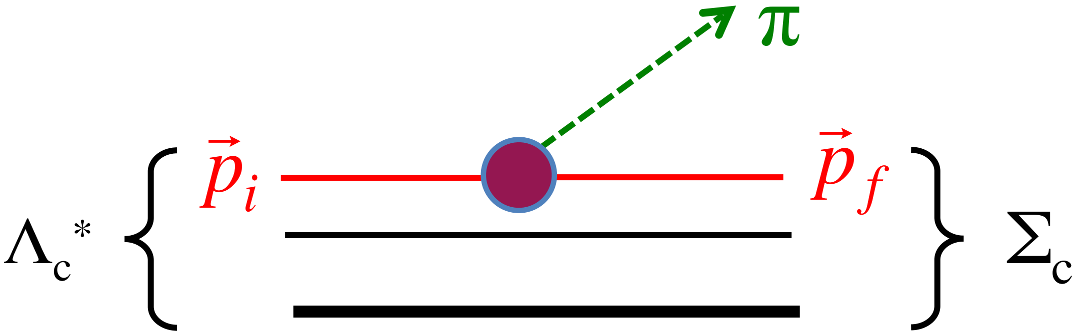
Low lying decays, 0hω → 0hω, 1hω → 0hω with small p_π (MeV)



To compare with Δ → πN at p_π ~ 230 MeV

Low energy pion dynamics works well

Low energy πqq interaction



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

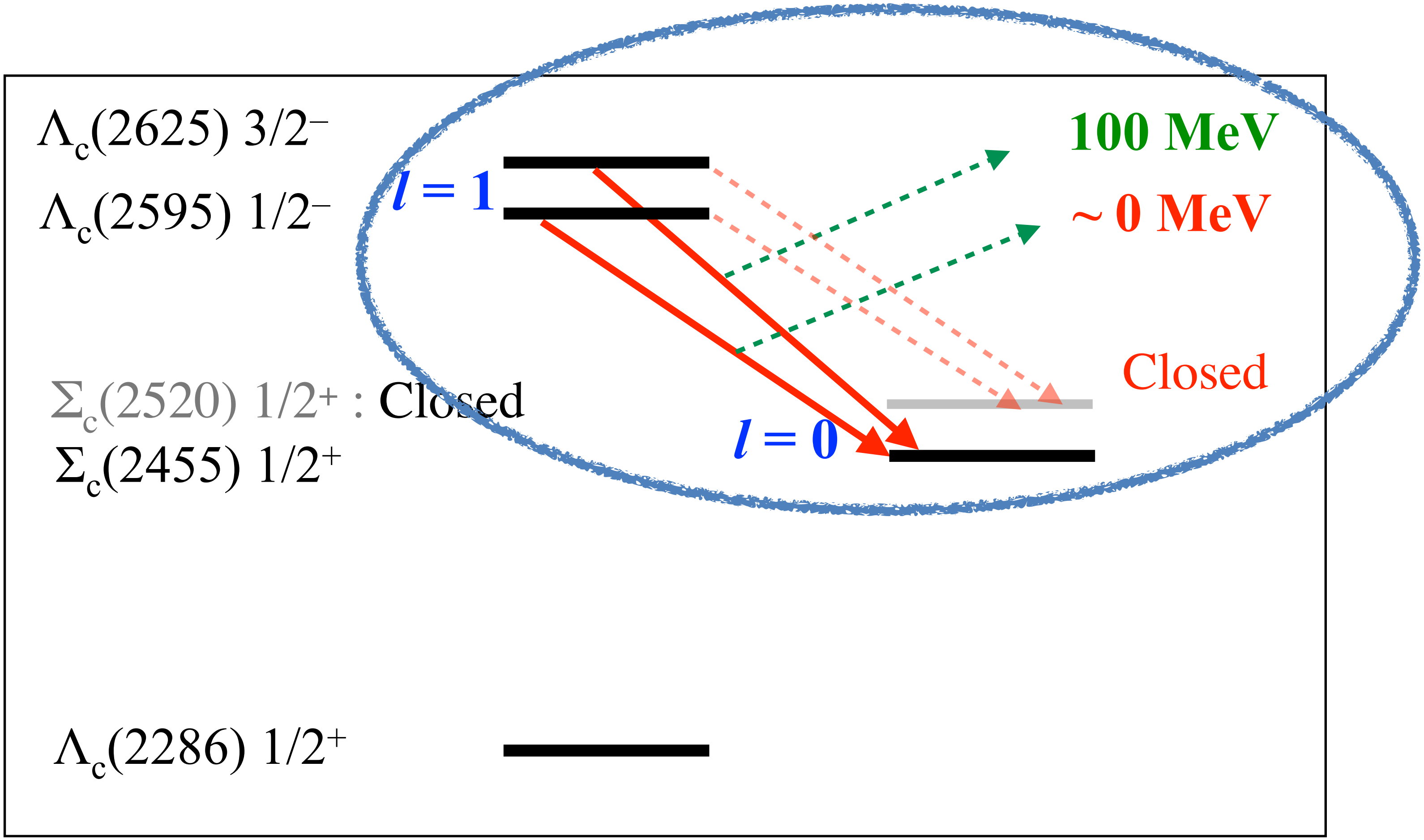
Relativistic $\bar{q}\gamma_5 q\phi_\pi,\ \underline{\bar{q}\gamma^\mu\gamma_5 q\partial_\mu\phi_\pi}$

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

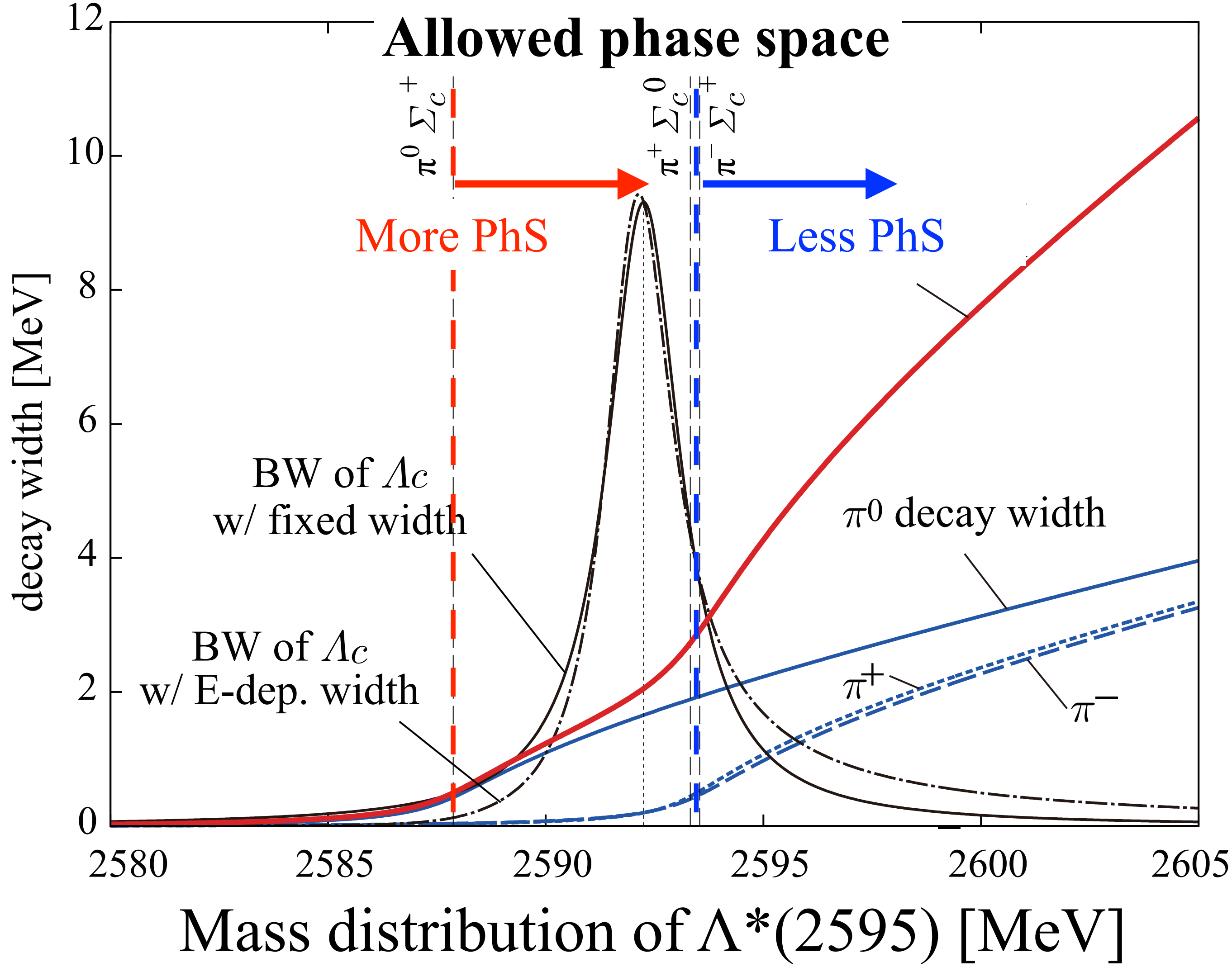
$\Lambda_c(2595)\ 1/2^-$

	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	isospin violated	
	$1/2(1)^-$		6.5–11.9	0.57–1.04	0.63–1.15	5.3–9.7

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

Isospin breaking between $\pi^0\Sigma_c^+$ and $\pi^+\Sigma_c^0$, $\pi^-\Sigma_c^{++}$

Mass distribution of Λ*(2595) and different phase space



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

Nagahiro et al, arXiv:1609.01085

Λ_c(2625) 3/2$^-$

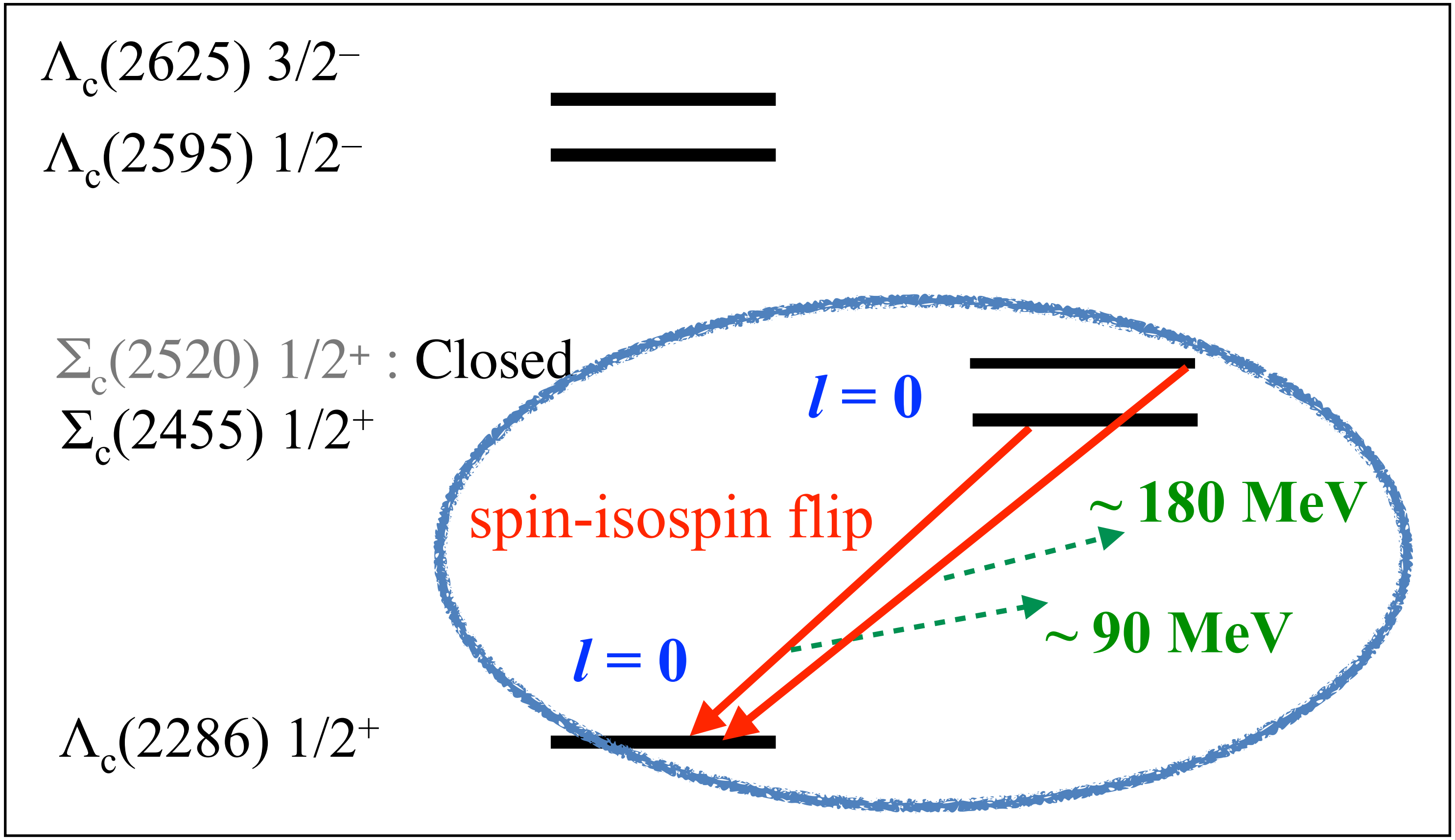
decay channel	full	$\Sigma_c^{++}\pi^-$
Experimental value Γ (MeV) [5]	< 0.97	$< 0.05 (< 5\%)$
momentum of final particle q (MeV/c)	-	101

D-wave decay

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

(1) Ground to ground transitions, 0hω → 0hω



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

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

$\Sigma_c(2520)\ 1/2^+$: Closed

$\Sigma_c(2455)\ 1/2^+$

$\Lambda_c(2286)\ 1/2^+$

$l = 0$

$l = 0$

spin-isospin flip

~ 180 MeV

~ 90 MeV

Ground (1/2, 3/2$^+$) –> Ground (1/2$^+$)

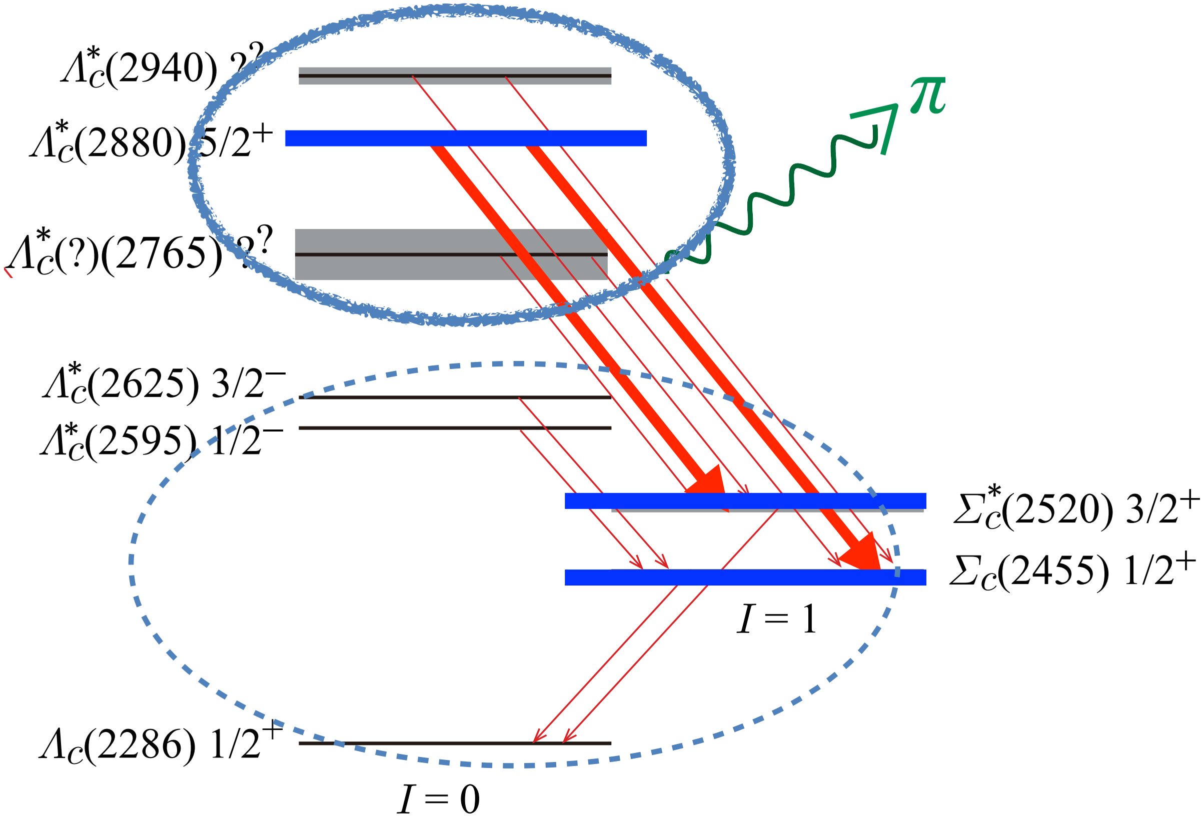
Nagahiro et al, arXiv:1609.01085

$B_i J^P$ (MeV)	$\Gamma^{\rm full}_{\rm exp}(\Gamma_i)$ (MeV)	q (MeV)	$\Gamma_{\rm th}(\Sigma_c(J^+)^{++} \to \Lambda_c^{gs}(1/2^+;2286)^+\pi^+)$ (MeV)
$\Sigma_c(2455)\ 1/2^+$ (2453.98) $(\omega_\pi = 0$ limit$)$	2.26 (2.26) (2.26)	89	4.27–4.33
$\Sigma_c(2520)\ 3/2^+$ (2517.9) $(\omega_\pi = 0$ limit$)$	14.9 (14.9)	176	30.0–31.2

Factor 2 difference, which is due to …

$$\boxed{g_A{}^q = 1 \quad \rightarrow \quad g_A{}^N = 5/3 \ < \ 1.25_{\rm exp}}$$

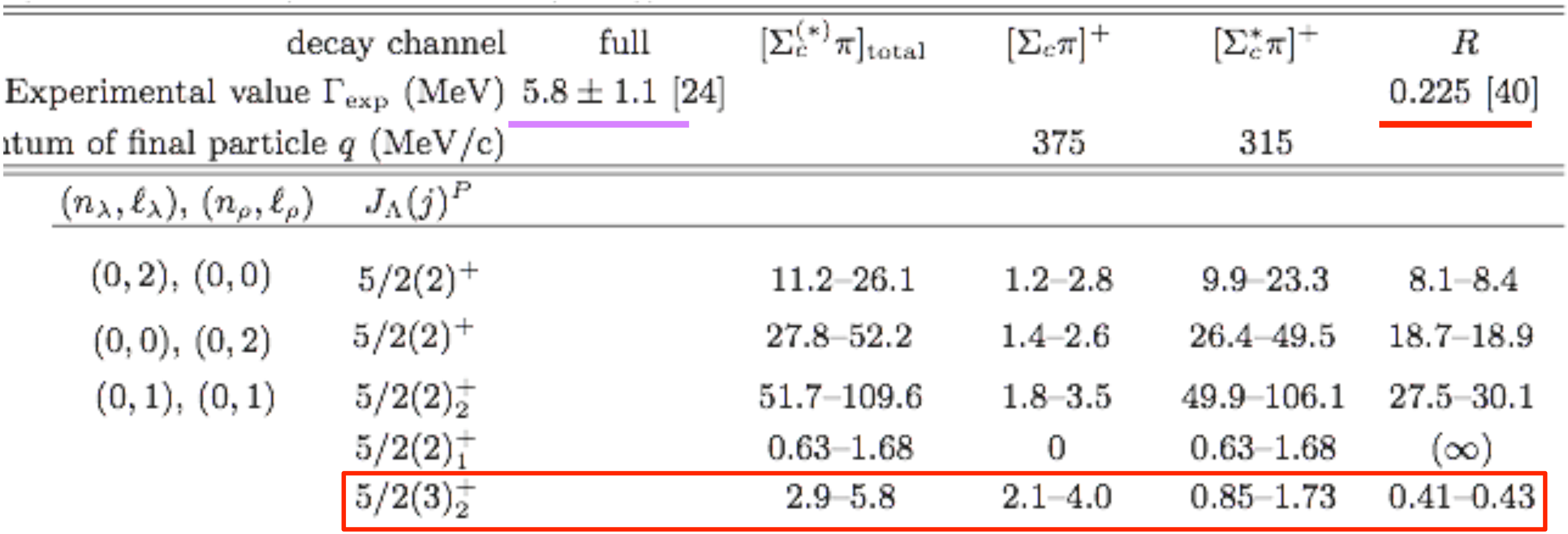
(3) Transitions from higher states, 2hω → 0hω



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

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

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



decay channel		full	$[\Sigma_c^{(*)}\pi]_{\mathrm{total}}$	$[\Sigma_c\pi]^+$	$[\Sigma_c^*\pi]^+$	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

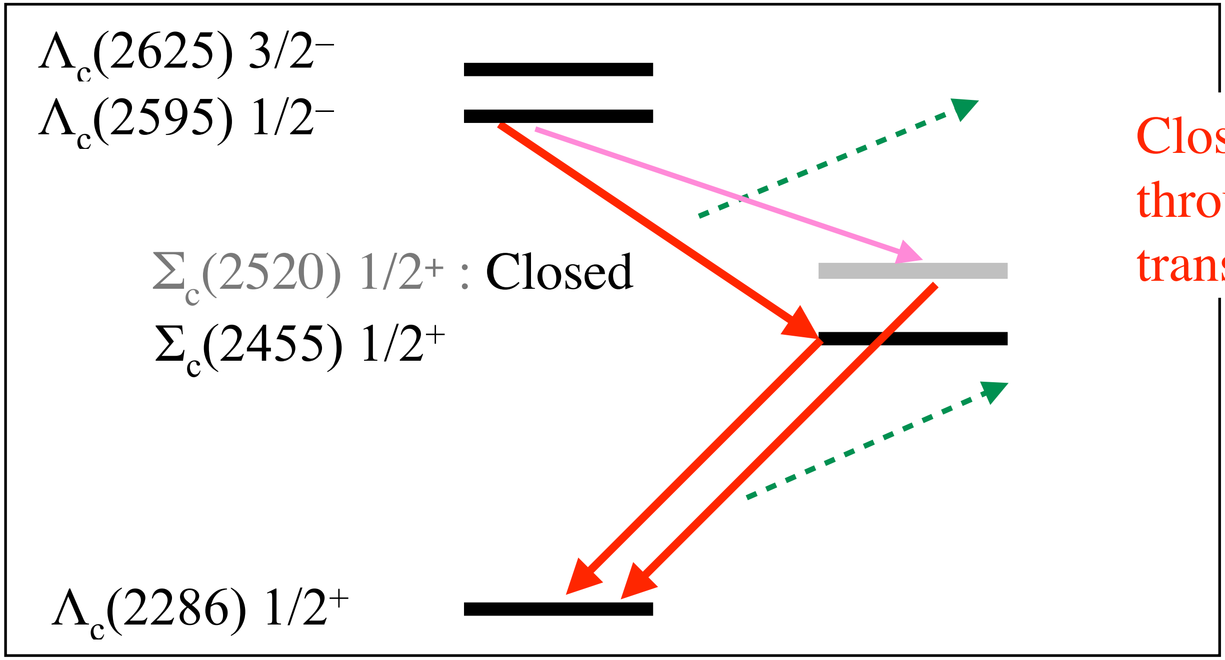
- Both absolute values and *R* ratio are sensitive to configurations
- Brown muck of *j* = 3 seems preferred.
- This implies that $\Lambda_c(2940)$ could be $7/2^+$

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

Three-body decay

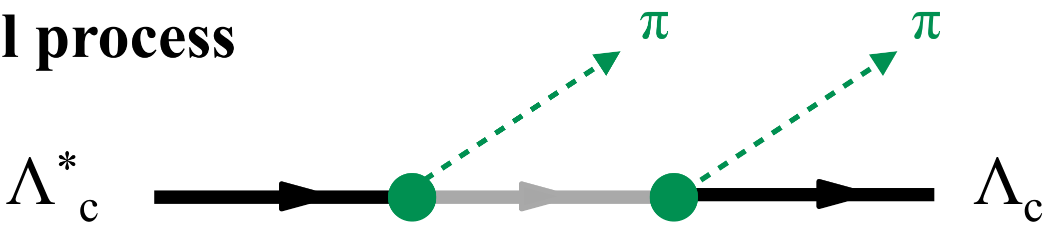
Three-body decay

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



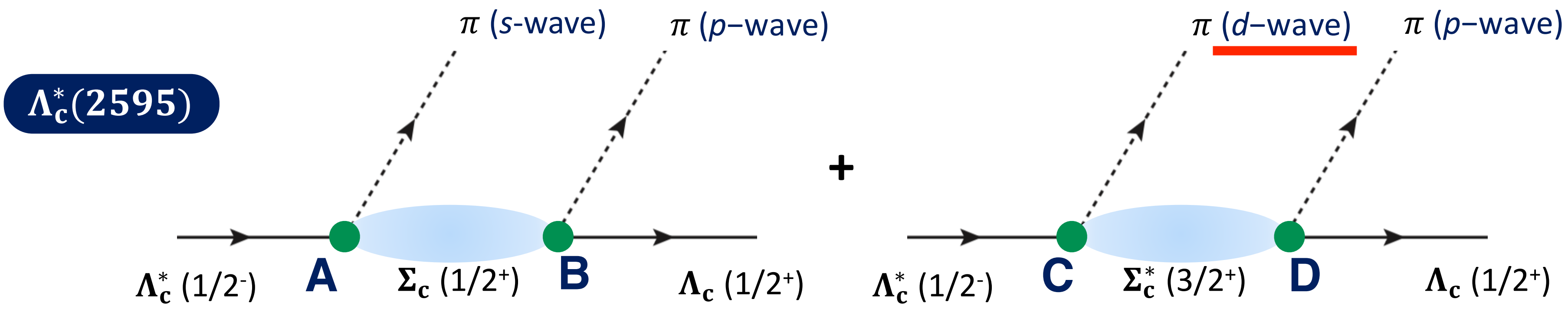
Closed one allowed through virtual transition

Sequential process



Effective Lagrangian

Three-Body Decay of $\Lambda_c^*(2595)$



Non-Relativistic

Coupling constants are determined by the quark model

A $\mathcal{L}_A = g_a \chi^\dagger_{\Sigma_c} \chi_{\Lambda_c^*}$

B $\mathcal{L}_B = i g_b \chi^\dagger_{\Lambda_c} \left(\vec{\sigma} \cdot \vec{p}_\pi\right) \chi_{\Sigma_c}$

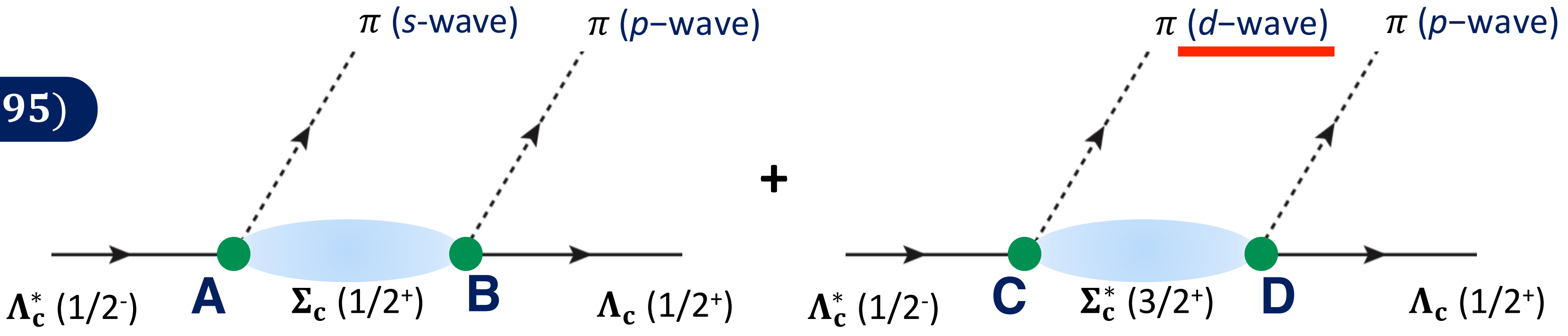
C $\mathcal{L}_C = g_c \chi^\dagger_{\Sigma_c^*} \left(\vec{S}^\dagger \cdot \vec{p}_\pi \vec{\sigma} \cdot \vec{p}_\pi - \frac{1}{3} \vec{S}^\dagger \cdot \vec{\sigma} |\vec{p}_\pi|^2 \right) \chi_{\Lambda_c^*}$

D $\mathcal{L}_D = i g_d \chi^\dagger_{\Lambda_c} \left(\vec{S} \cdot \vec{p}_\pi \right) \chi_{\Sigma_c^*}$

Effective Lagrangian

Three-Body Decay of $\Lambda_c^*(2595)$

$\Lambda_c^*(2595)$



Non-Relativistic

Coupling constants are determined by the quark model

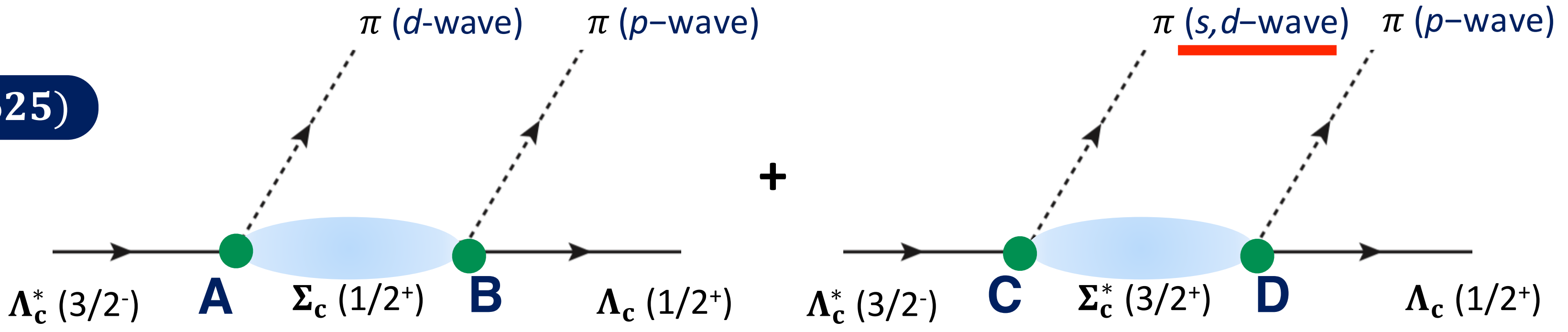
A $\mathcal{L}_A = g_a \chi^\dagger_{\Sigma_c} \chi_{\Lambda_c^*}$

B $\mathcal{L}_B = i g_b \chi^\dagger_{\Lambda_c} \left(\vec{\sigma}\cdot\vec{p}_\pi\right) \chi_{\Sigma_c}$

C $\mathcal{L}_C = g_c \chi^\dagger_{\Sigma_c^*} \left(\vec{S}^\dagger\cdot\vec{p}_\pi \vec{\sigma}\cdot\vec{p}_\pi - \frac{1}{3}\vec{S}^\dagger\cdot\vec{\sigma}|\vec{p}_\pi|^2\right) \chi_{\Lambda_c^*}$

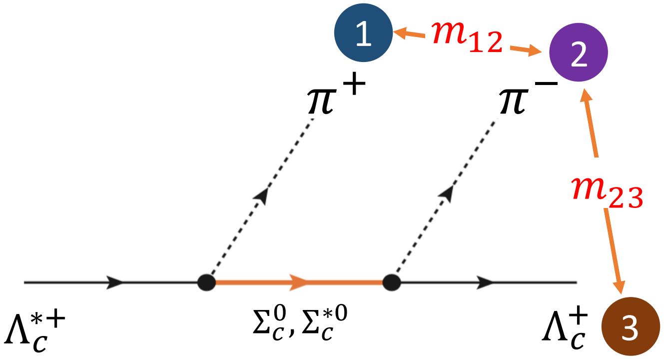
D $\mathcal{L}_D = i g_d \chi^\dagger_{\Lambda_c} \left(\vec{S}\cdot\vec{p}_\pi\right) \chi_{\Sigma_c^*}$

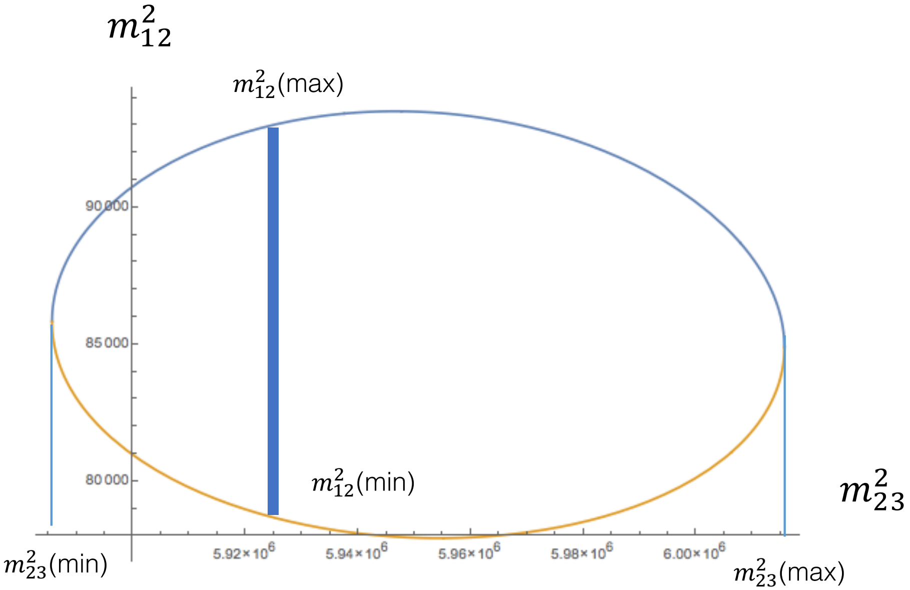
$\Lambda_c^*(2625)$



Decay Kinematics

Decay Width and Dalitz Region





Dalitz Region

Decay Width

$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M^3}\overline{|\mathcal{M}|^2}dm_{12}^2 dm_{23}^2$$

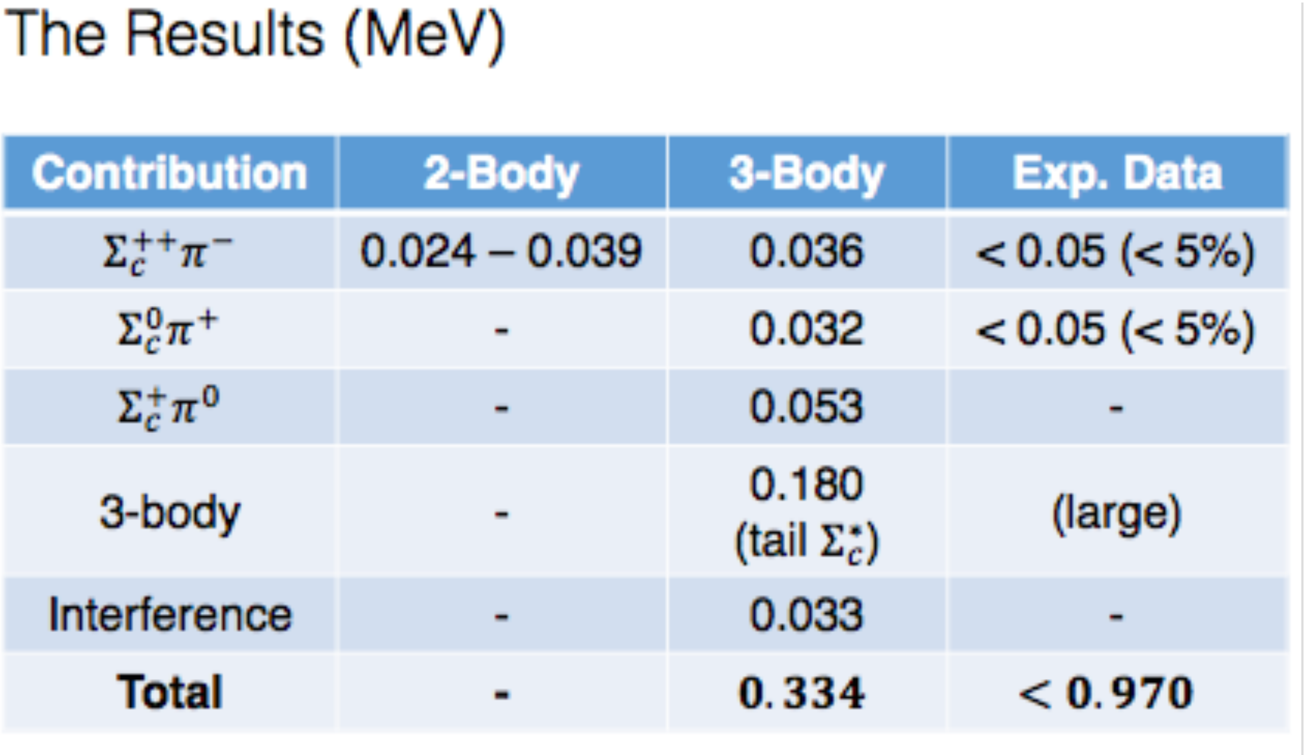
Λ_c(2595) Assuming the λ-mode excitations

The Results (MeV)

Contribution	2-Body	3-Body	Exp. Data
$\Sigma_c^{++}\pi^-$	0.13 – 0.25	0.16	0.624 (24%)
$\Sigma_c^{0}\pi^+$	0.15 – 0.28	0.25	0.624 (24%)
$\Sigma_c^{+}\pi^0$	1.2 – 2.4	1.63	-
3-body	-	10^{-6} (tail Σ_c^*)	0.468 (18%)
Interference	-	0.05	-
Total	**1.5 – 2.9**	$\mathbf{2.09}$	$\mathbf{2.6 \pm 0.6}$

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

$\Lambda_c(2520)$



The Results (MeV)

Contribution	2-Body	3-Body	Exp. Data
$\Sigma_c^{++}\pi^-$	0.024 – 0.039	0.036	< 0.05 (< 5%)
$\Sigma_c^{0}\pi^+$	-	0.032	< 0.05 (< 5%)
$\Sigma_c^{+}\pi^0$	-	0.053	-
3-body	-	0.180 (tail Σ_c^*)	(large)
Interference	-	0.033	-
Total	**-**	**0.334**	**< 0.970**

- 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
  - X(3872) is the best confirmed, the mass, spin parity, decay rates
  - But the total decay with is not yet determined.
  - Pc is well observed
  - Their interpretations are not finalized
- Charmed baryons may provide a simple system of (di)quark dynamics
  - Separation of the λρ 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