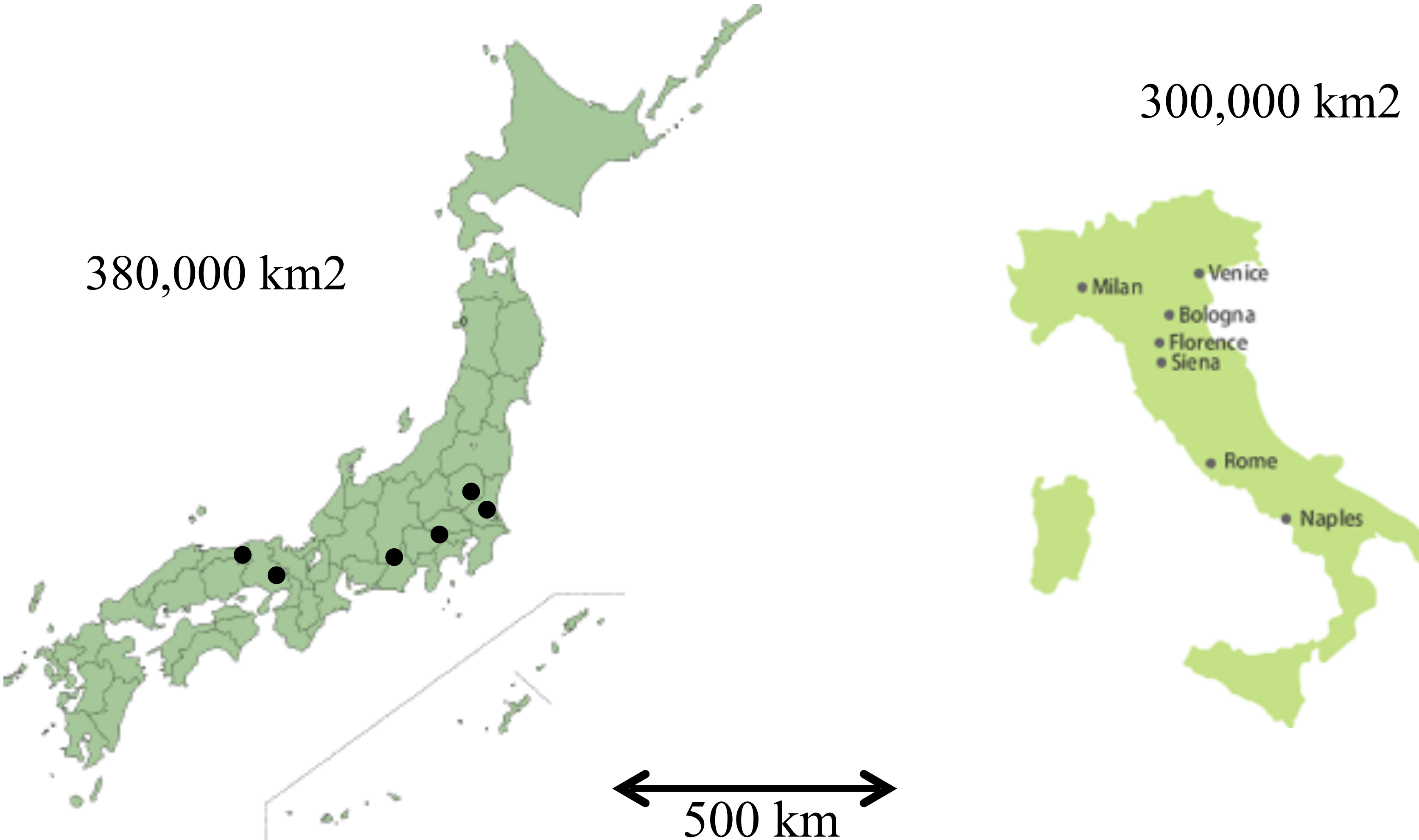
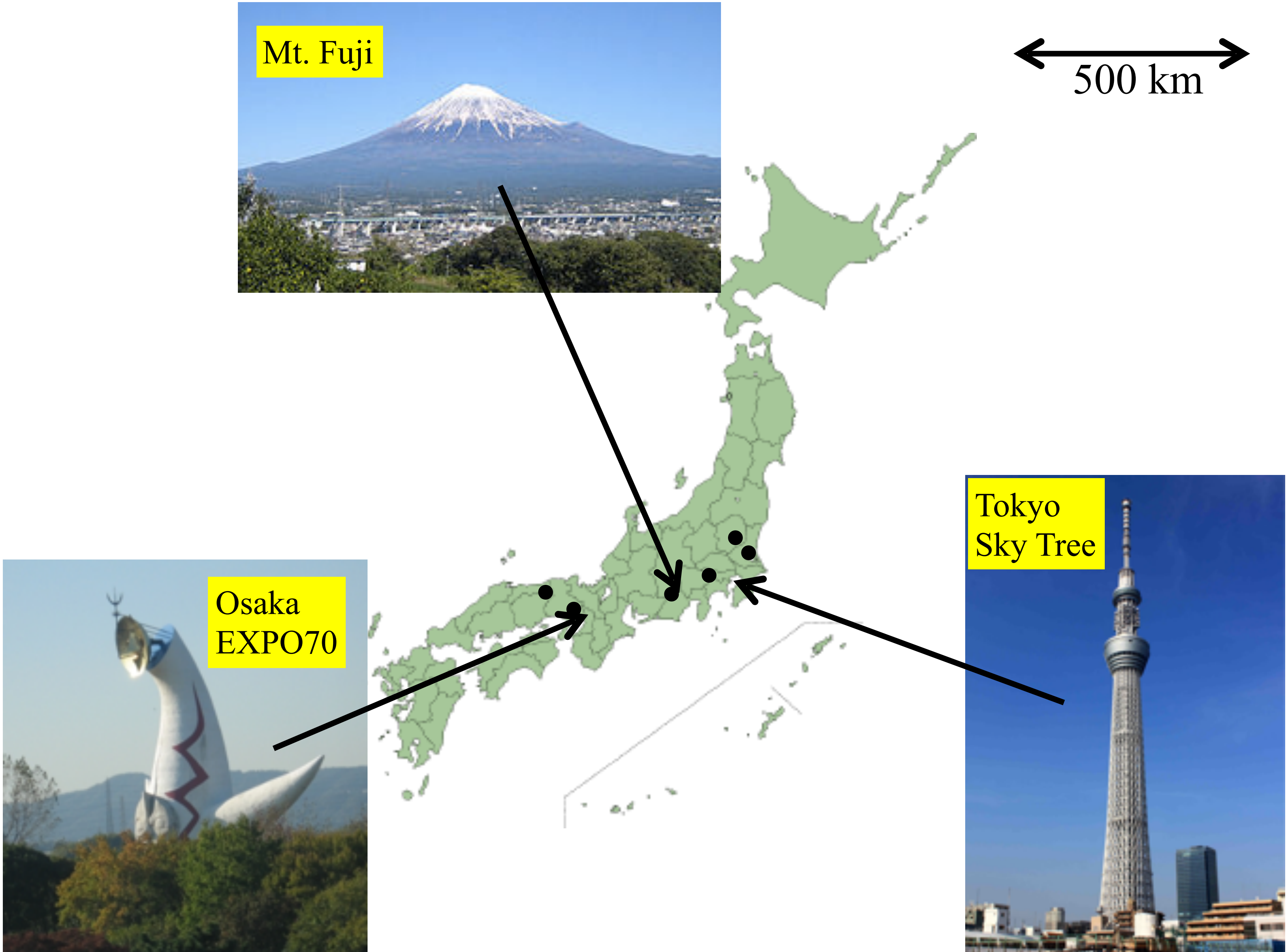
Production and decay of charmed baryons

Atsushi Hosaka
RCNP, Osaka University
Seminar at INFN, Genova, Italy
October 5th (Wed), 2016

1. Introduction of RCNP/Osaka University
2. Introduction — Why charmed baryons? — Separation of λ and ρ modes
3. Pion emission decays
4. Production
5. Summary

Japan → Osaka → OU → RCNP




Mt. Fuji
500 km
Tokyo
Sky Tree
Osaka
EXPO70

Around three campuses

Mino

Suita

Toyonaka

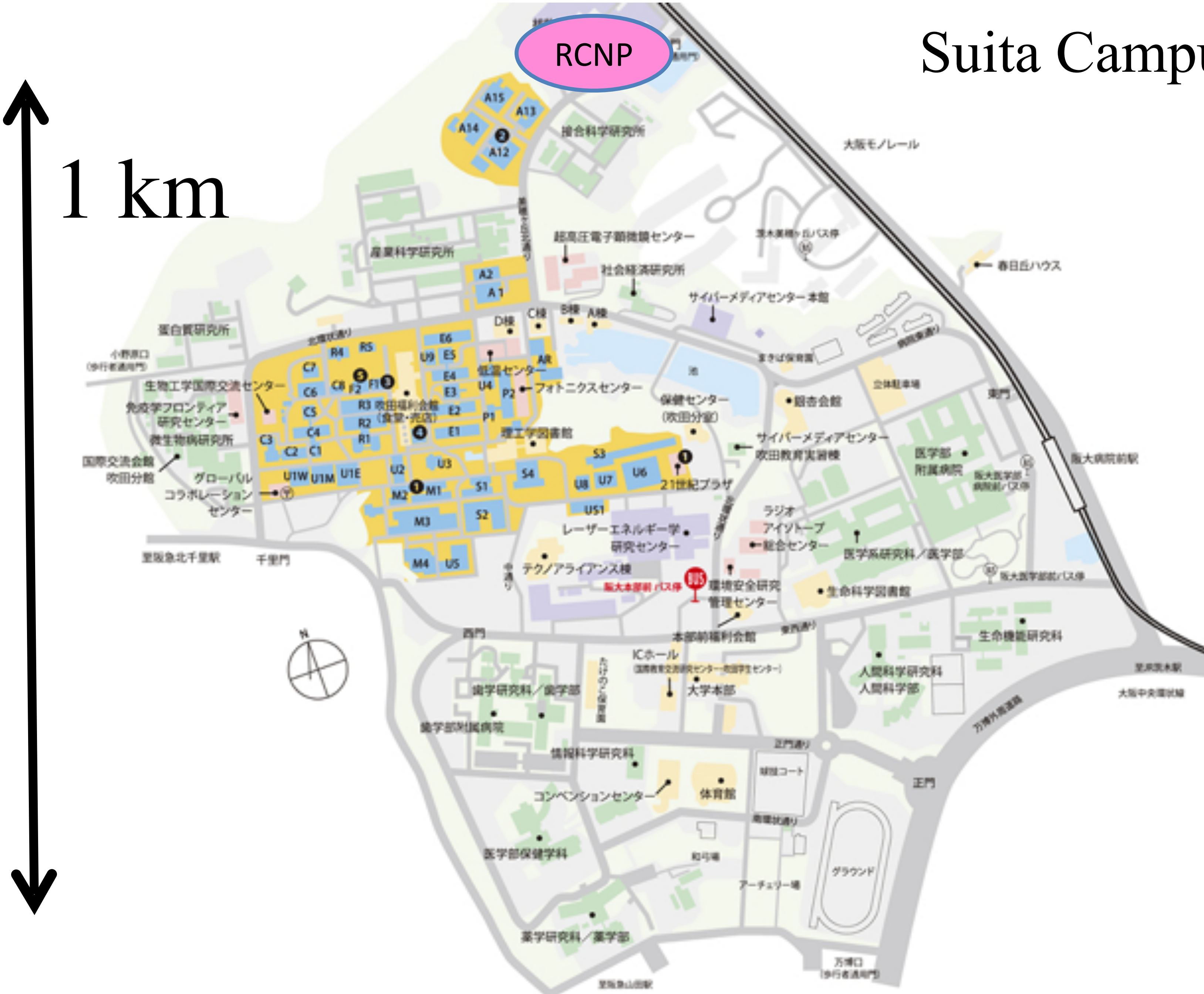
Expo park '70

Downtown

Osaka Castle

10 km

Suita Campus

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センター
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医学部
附属病院
阪大病院前駅
ラジオ
アイソトープ
総合センター
医学系研究科／医学部
環境安全研究
管理センター
生命科学図書館
大学本部
体育館
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C4
C2
C1
R1
E1
U1W
U1M
U1E
U2
U3
M1
M2
M3
S1
S2
S3
S4
U6
U7
U8
US1


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Cherry trees


Hospital

Bamboo woods and bamboo shoots

大阪大学 www.osaka-u.ac.jp

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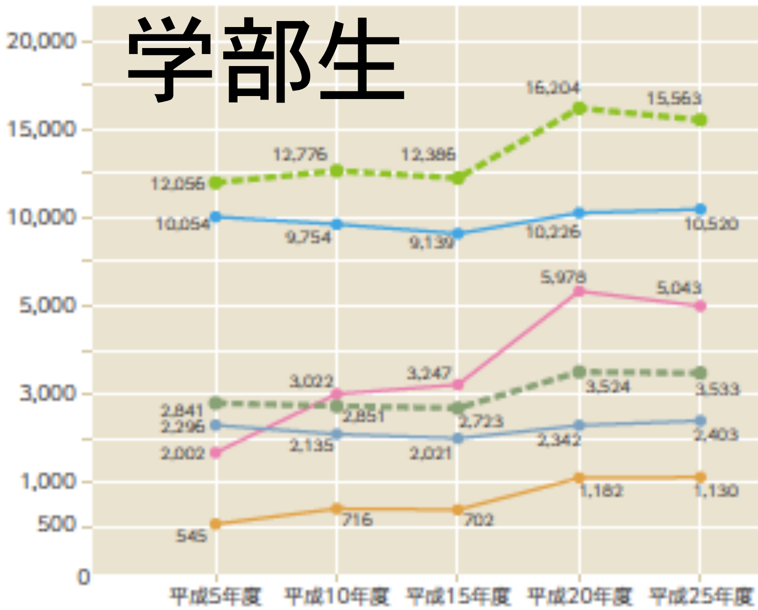
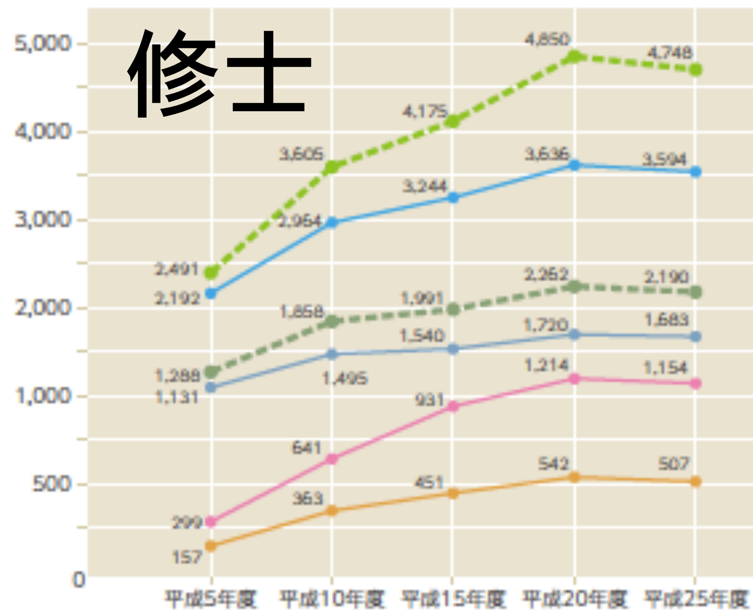
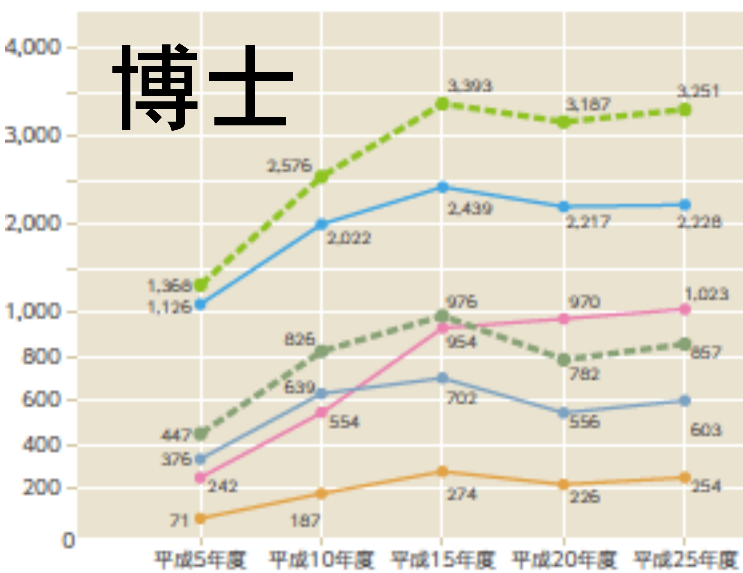






学部生：　15,563

大学院生：　3,251

教員：　3,111

職員：　1,483

* # RCNP Cyclotron Facility

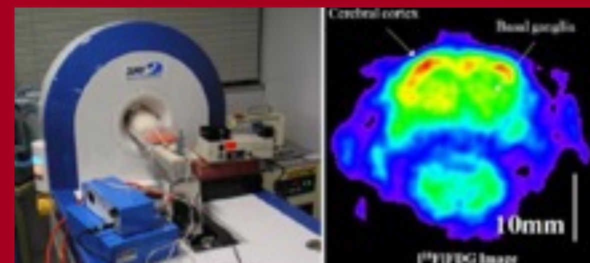
大阪大学

Osaka University Undertaking by cooperation among RCNP and Graduate School of Medicine and Science

Medical and clinical applications of accelerator science, nuclear physics, radiation physics

Graduate School of Medicine

Radio therapy



PET&SPECT inspection

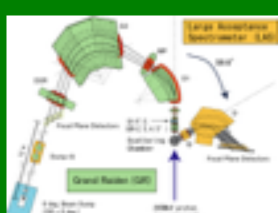
Training of medical physicists by higher education using accelerators

- Heavy-particle gantry
- Next generation BNCT
- High intensity compact accelerator

- Diagnostics
- Nuclear data

RI separation and synthesis

RCNP

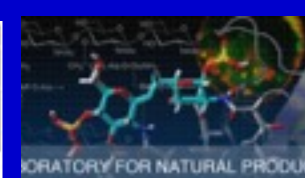



Nuclear physics

Accelerator

R I production

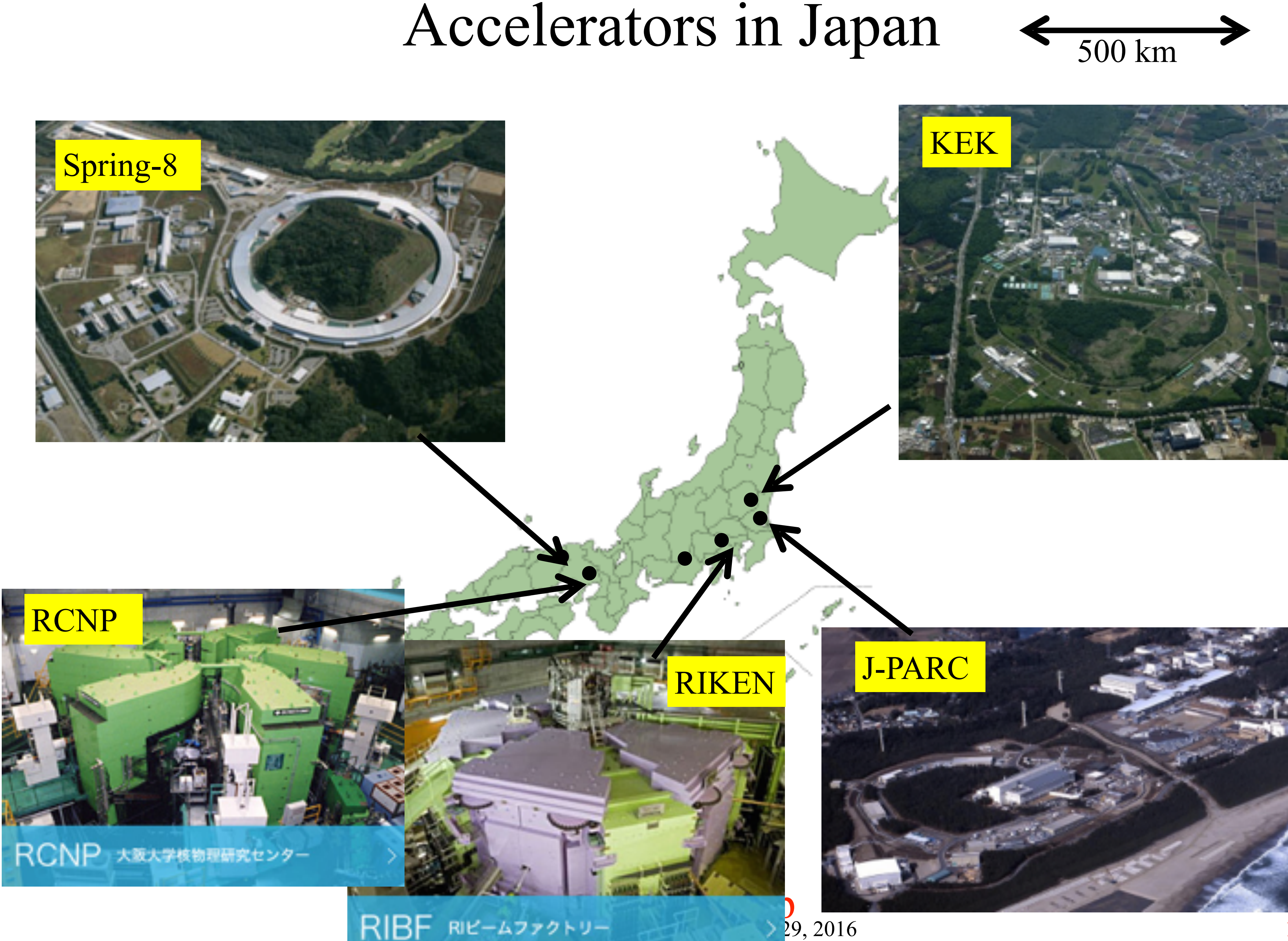
Graduate School of Science



Nuclear chemistry

Organic chemistry

Accelerators in Japan



Supercomputer

- Cooperating **SX-ACE (NEC)** vector processor ~ **393 TF**
- Spend about 20 million yen (~ 0.2 million dollar)/year
- ~ 100 users (about 10 foreign uses), ~ 30 active users
- Lattice QCD, Nuclear structure, Few-body, Supernova
- About 10-20 publications/year

Role in the community

High Performance Computer Infra
with the Japan largest supercomputer. KEI

Physics now

1. Introduction

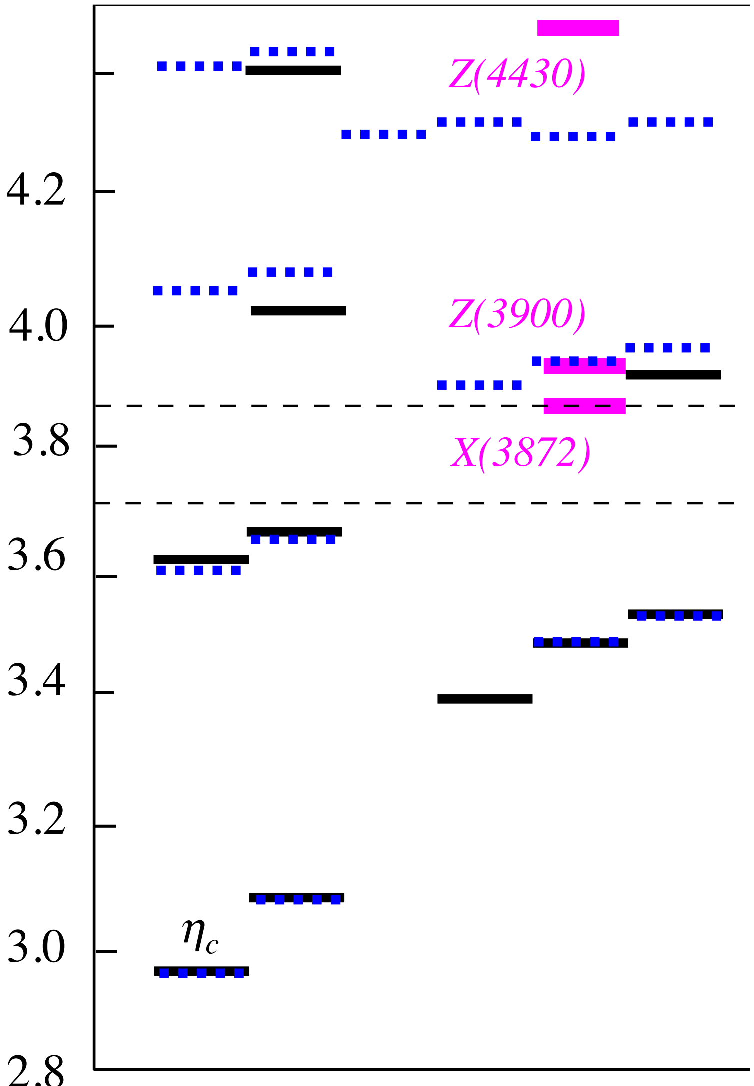
— Why charmed baryons —

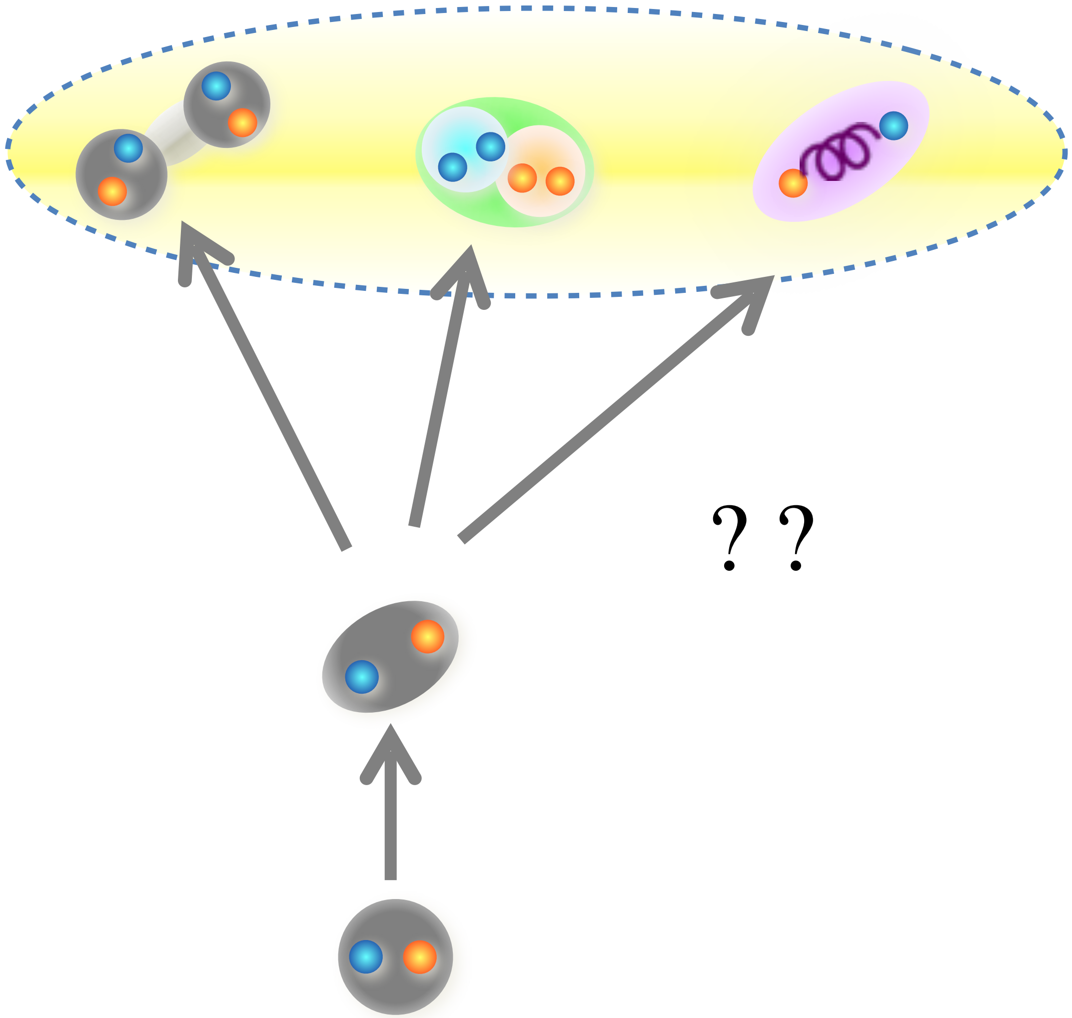
- There are only a few number of heavy baryons known
- Simplest system of a heavy and light quarks
- Helpful to understand exotic hadrons

Next page

Better understanding is needed for exotic hadrons of heavy and light quarks

Charmonium-like states





Physics now

1. Introduction

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Next page

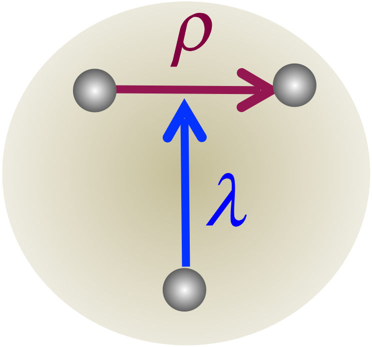
- As a unique feature, separation of two orbital motions

  λ and ρ motions

Heavy quarks distinguish the internal modes λ and ρ

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

N, Δ, …

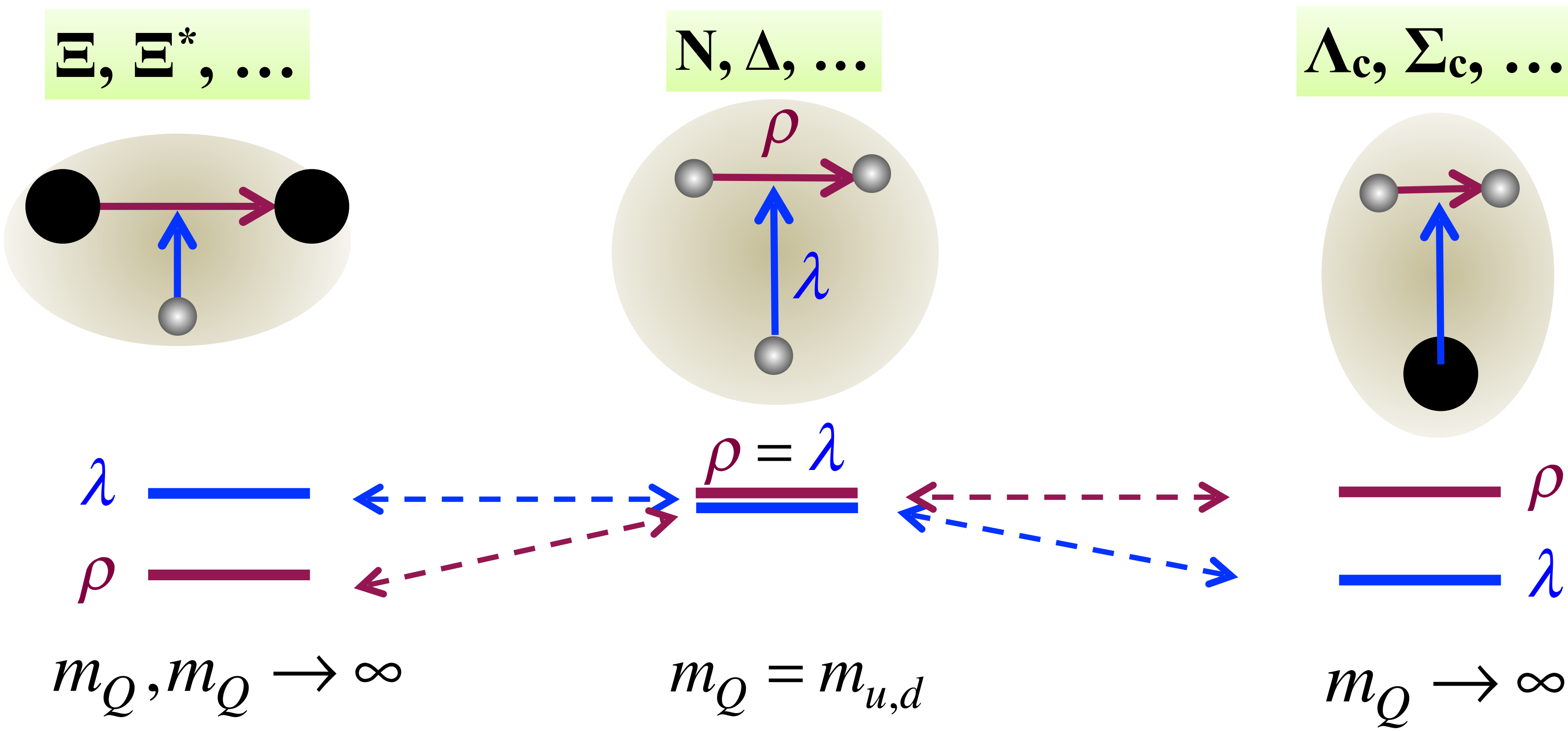


$\rho = \lambda$

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

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

$$H = \frac{p_1^2}{2m_q} + \frac{p_2^2}{2m_q} + \frac{p_3^2}{2M_Q} - \frac{P^2}{2M_{tot}}$$
$$+ V_{conf}(HO) + V_{spin-spin}(Color-magnetic) + \ldots$$

$m = 0.35 \pm 0.05$ 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

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

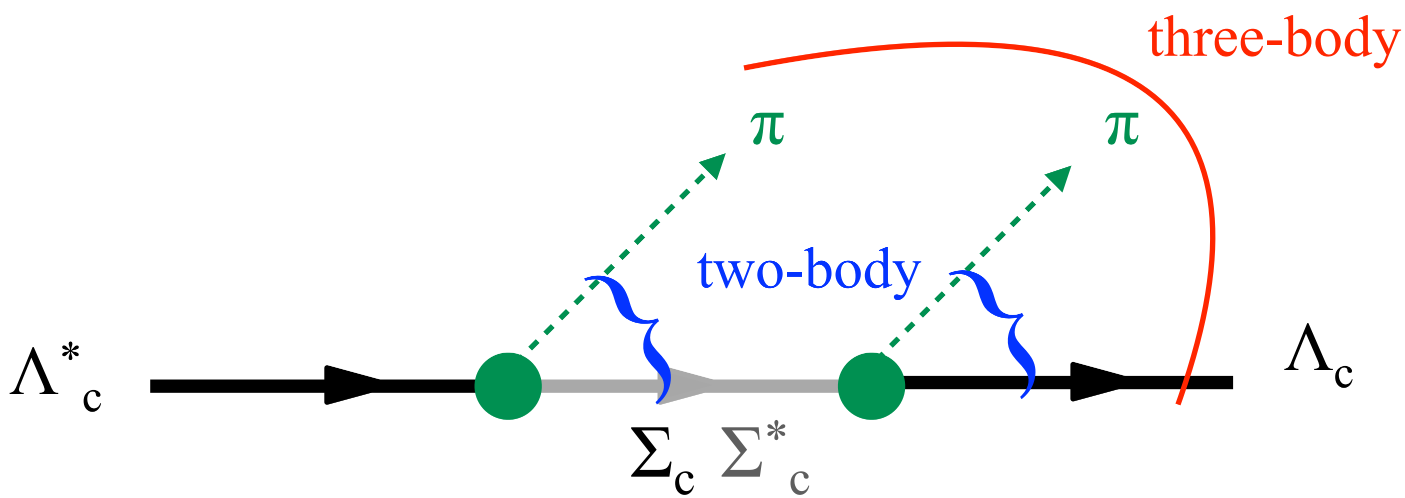
etc.

di-quark spin

2. Decays —Pion emission—

On going, Nagahiro, Yasui, …, Arifi

Nagahiro et al, arXiv:1609.01085



Two-body decays

and

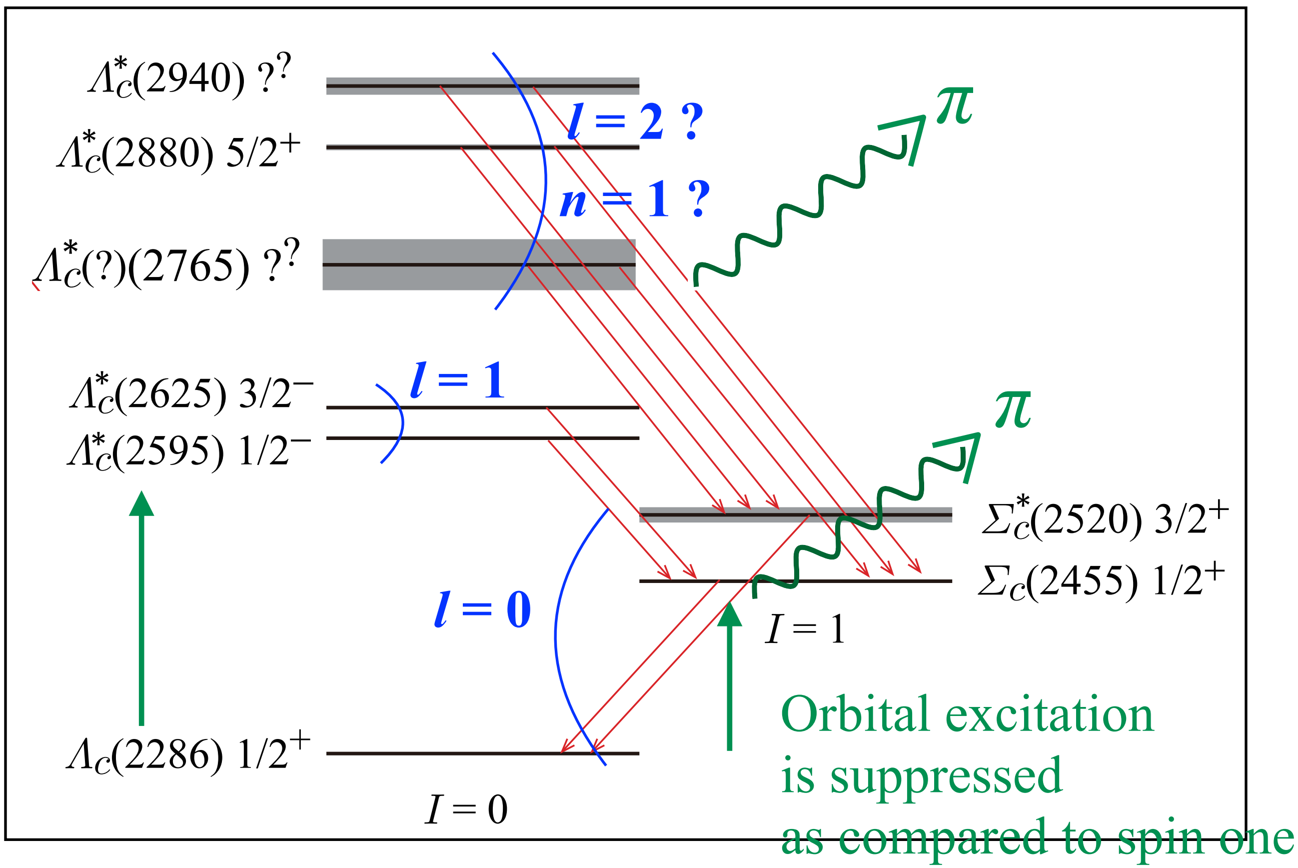
Three-body decays

2. Decays —Pion emission—

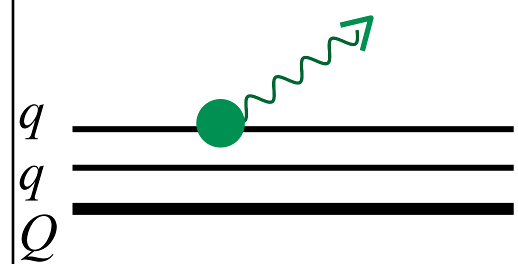
On going, Nagahiro, Yasui, …, Arifi

Nagahiro et al, arXiv:1609.01085

Two-body decays



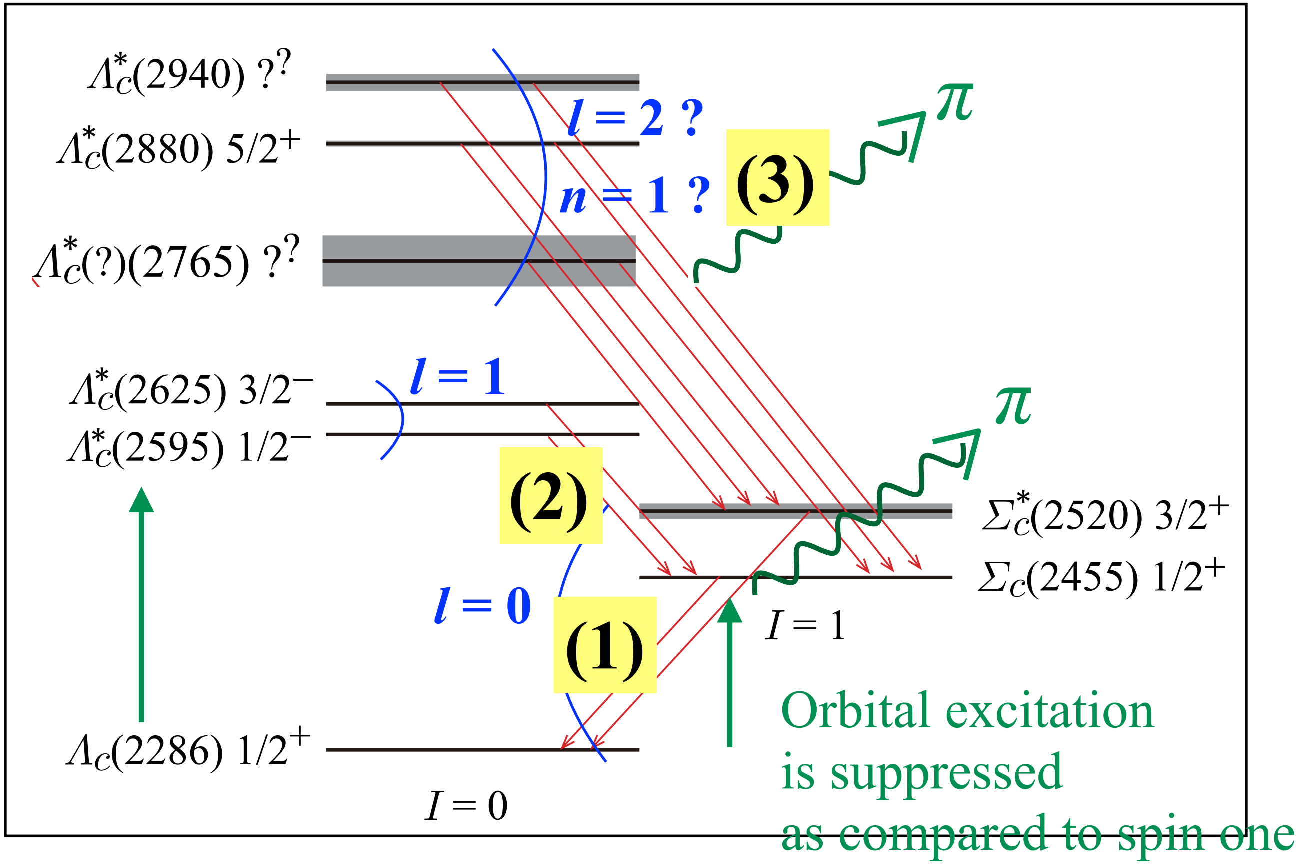
One-body operator
in the quark model



2. Decays —Pion emission—

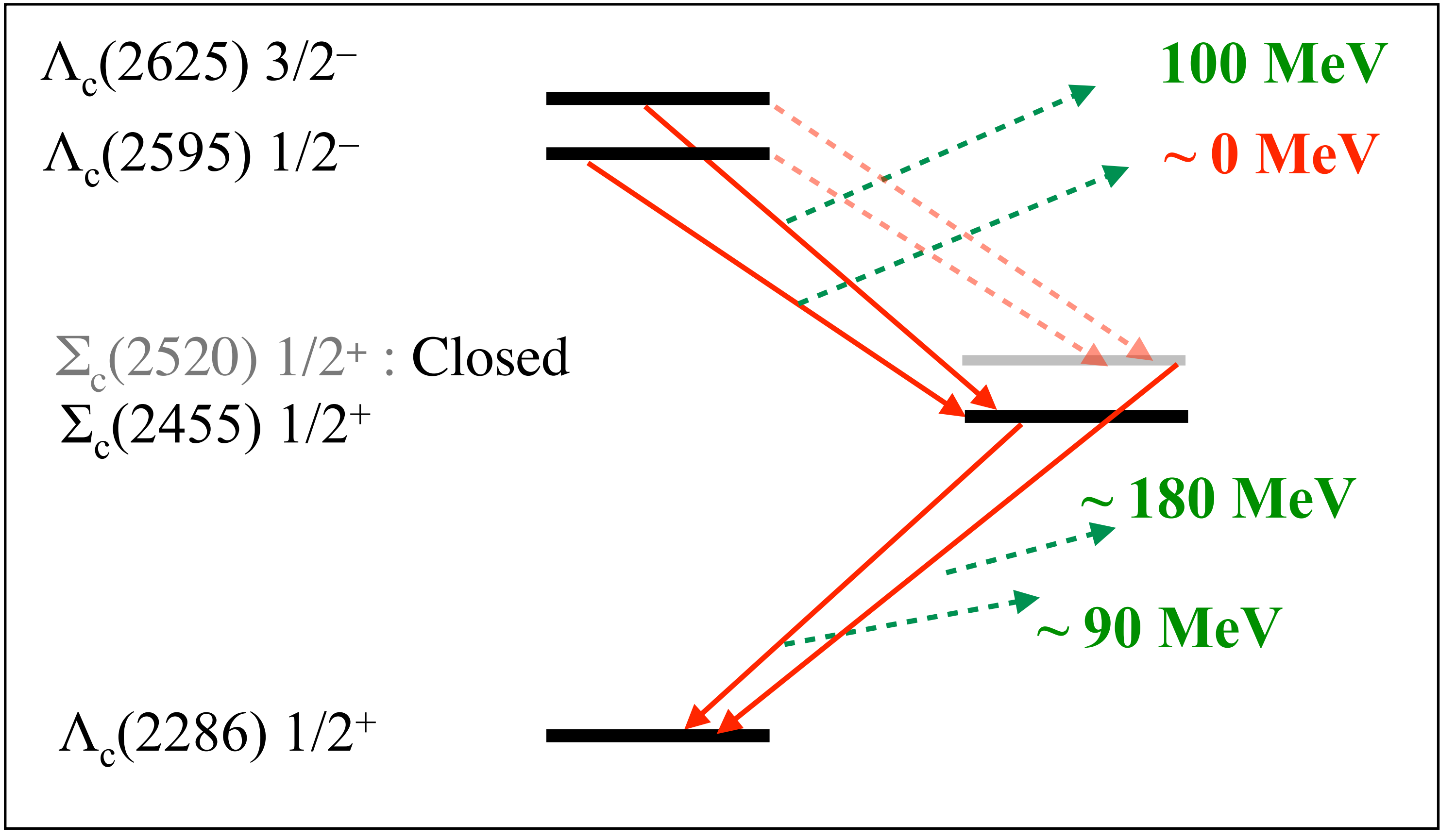
On going, Nagahiro, Yasui, …, Arifi

Two-body decays



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

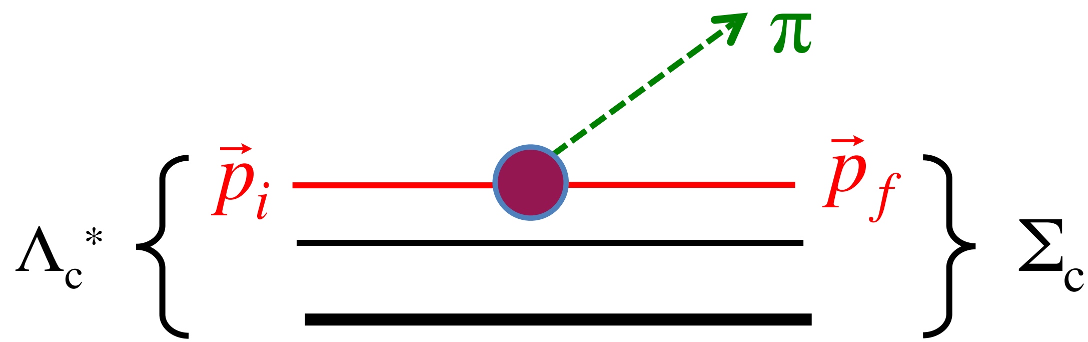
Low lying decays, 0hω → 0hω, 1hω → 0hω with small p_π (MeV)



To compare with Δ → πN at p_π ~ 230 MeV

Low energy pion dynamics works well

Low energy πqq interaction



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

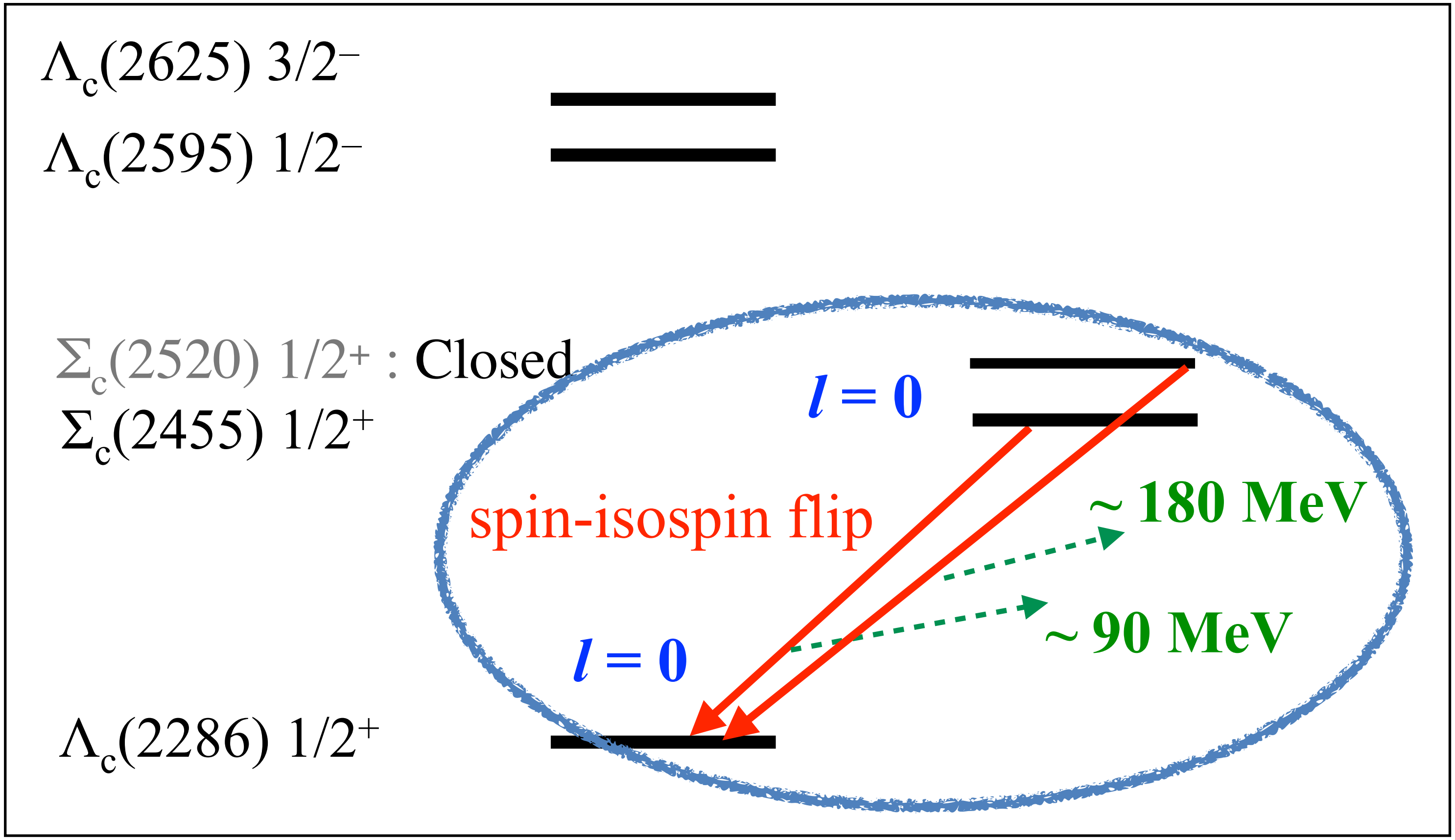
Relativistic $\bar{q}\gamma_5 q\phi_\pi,\ \bar{q}\gamma^\mu\gamma_5 q\,\partial_\mu\phi_\pi$

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

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



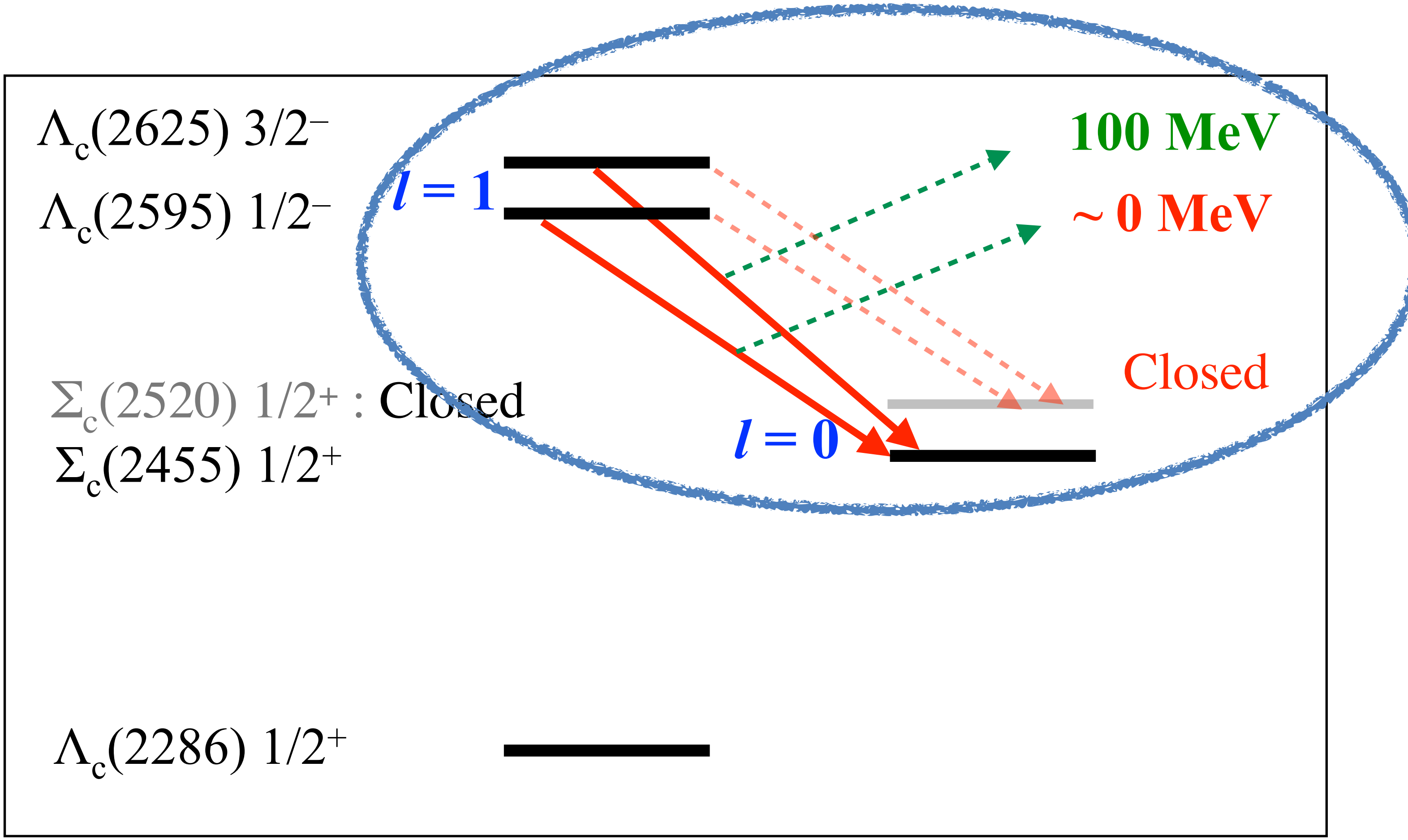
Ground (1/2, 3/2$^+$) –> Ground (1/2$^+$)   Nagahiro et al, arXiv:1609.01085

$B_i J^P$ (MeV)	$\Gamma_{\rm exp}^{\rm full}(\Gamma_i)$ (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 …

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

(2) P-wave to ground transitions, $1\hbar\omega \rightarrow 0\hbar\omega$



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

Nagahiro et al, arXiv:1609.01085

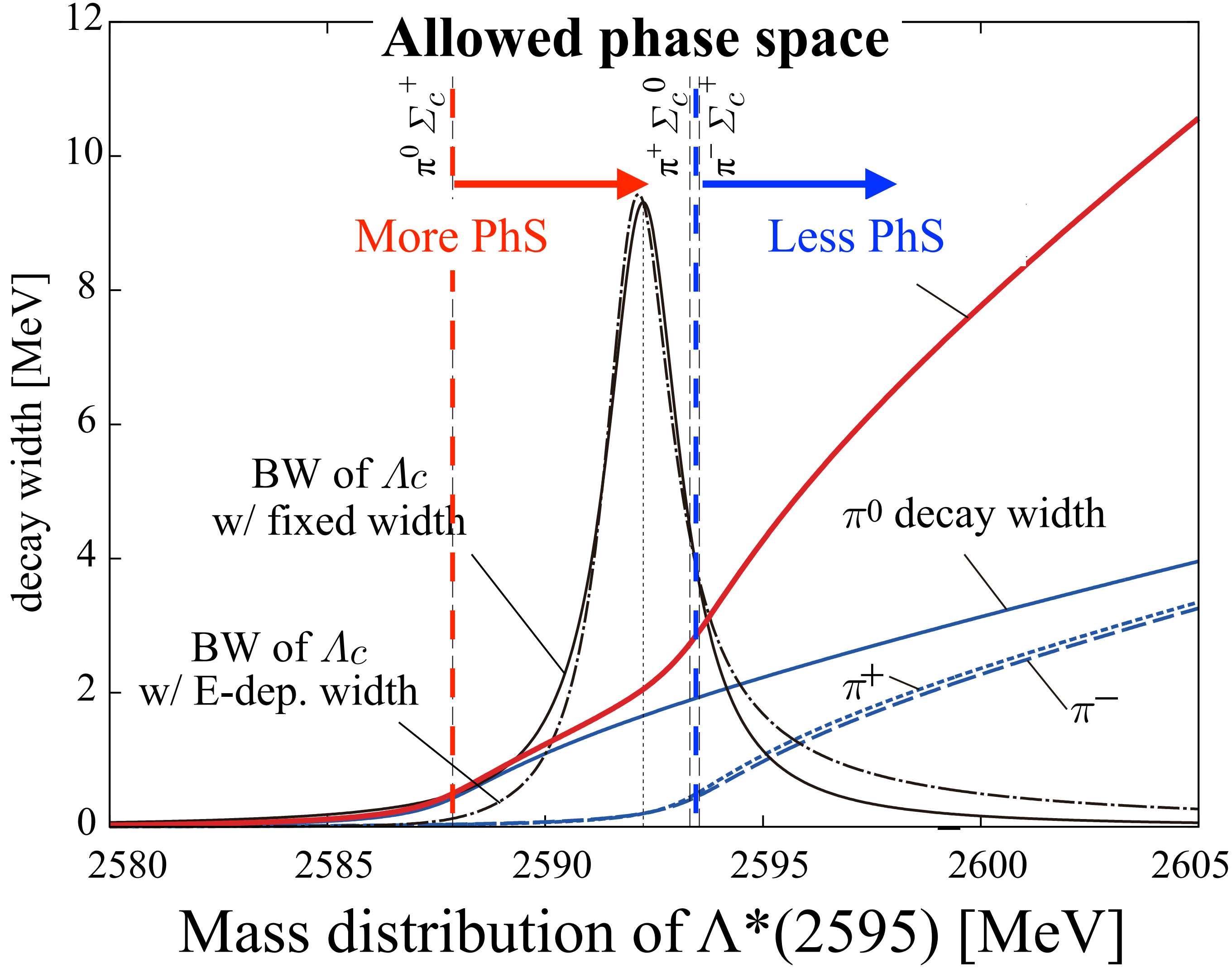
$\Lambda_c(2595)\ 1/2^-$

	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

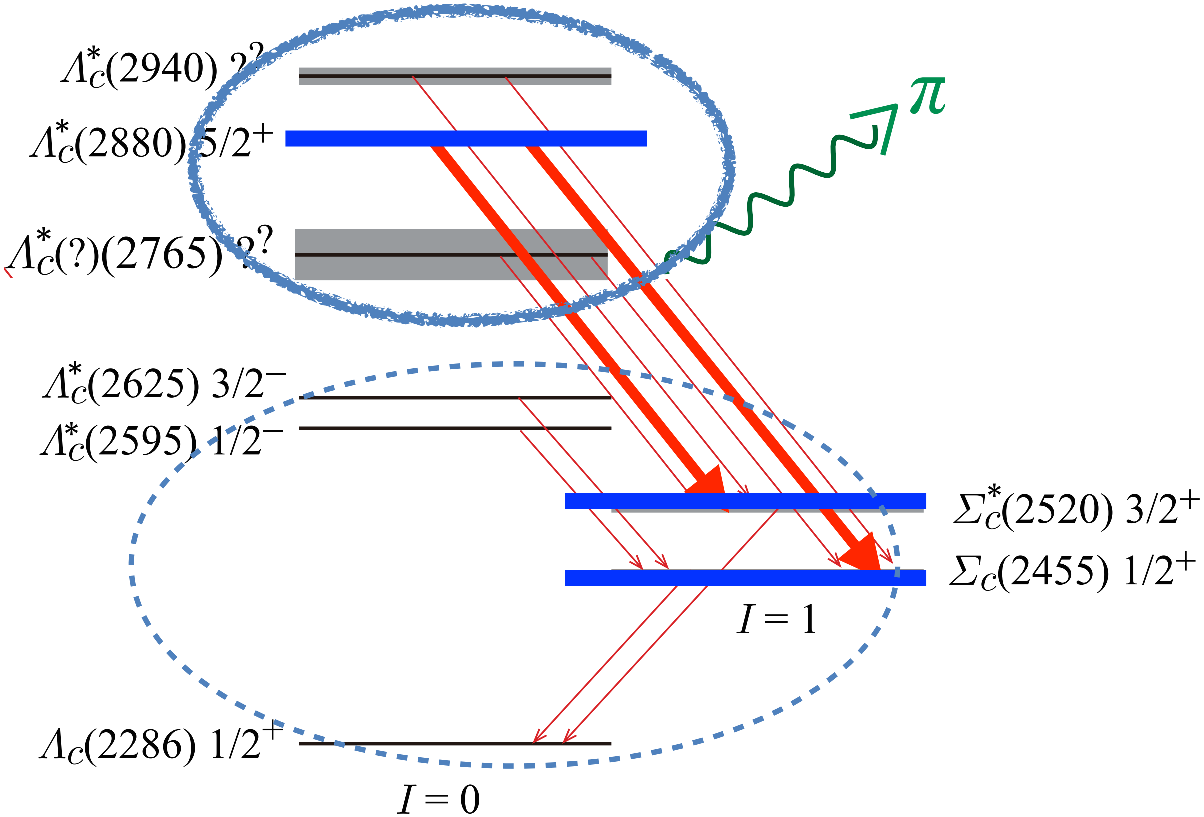
Λ_c(2625) 31/2$^-$

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

D-wave decay

- 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	$[\Sigma_c^{(*)}\pi]_{\rm total}$	$[\Sigma_c\pi]^+$	$[\Sigma_c^*\pi]^+$	R
Experimental value Γ (MeV)		5.8 ± 1.1 [5]				0.225 [14]
m of final particle q (MeV/c)				375	315	
$(n_\lambda, \ell_\lambda), (n_\rho, \ell_\rho)$	$J_\Lambda(j)^P$					
	$5/2(1)^+$		11.2–26.1	1.2–2.8	9.9–23.3	8.1–8.4
$(0,0), (1,0)$	$1/2(0)^+$		16.5–40.2	7.0–18.2	9.5–22.1	1.2–1.4
$(0,0), (0,2)$	$3/2(2)^+$		44.8–85.4	39.5–76.0	5.3–9.4	0.12–0.13
	$5/2(2)^+$		27.8–52.2	1.4–2.6	26.4–49.5	18.7–18.9
$(n_\lambda, \ell_\lambda), (n_\rho, \ell_\rho)$	$J_\Lambda(j)^P_\ell$					
$(0,1), (0,1)$	$5/2(2)^+_2$		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

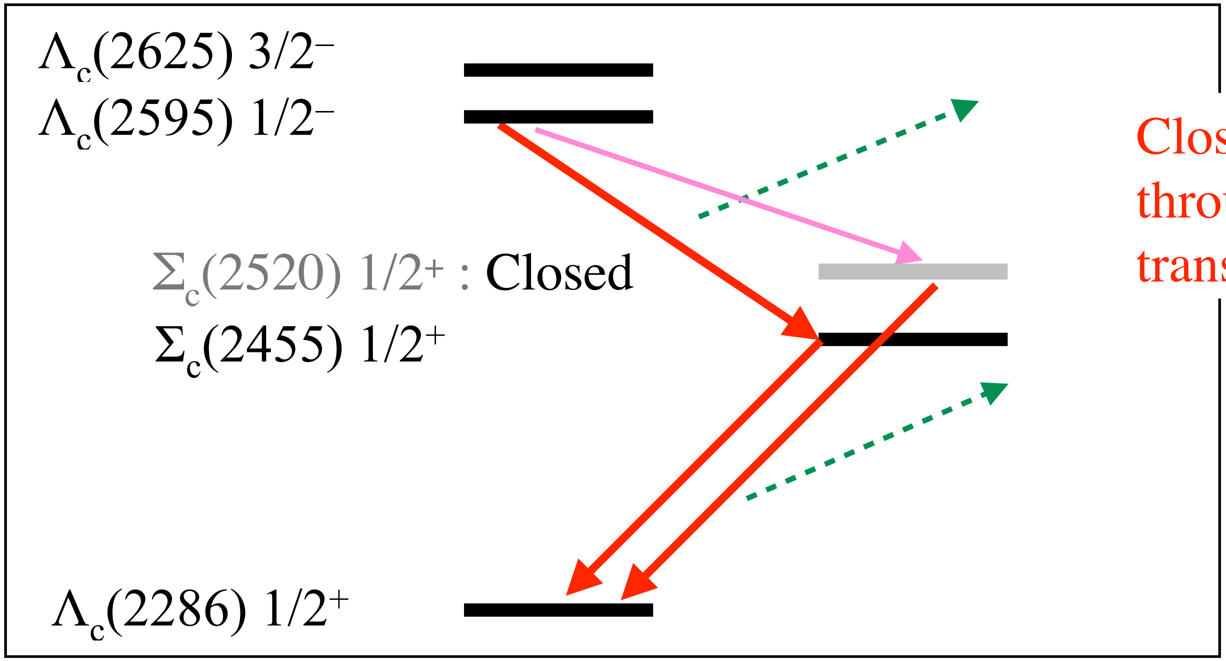
- Both absolute values and R ratio are sensitive to configurations
- Brown muck of $j = 3$ seems preferred.
- This implies that $\Lambda_c(2940)$ could be $7/2^+$

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

Three-body decay

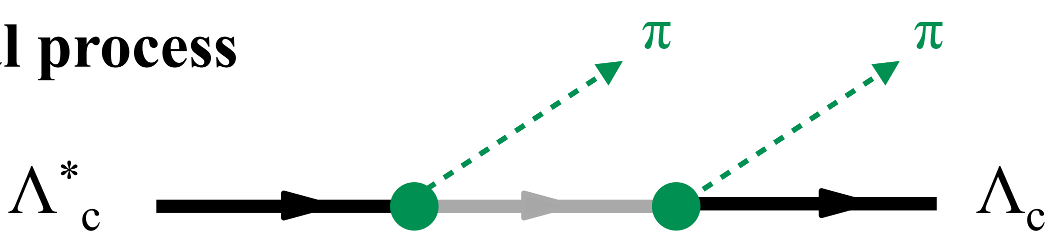
Three-body decay

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



Closed one allowed through virtual transition

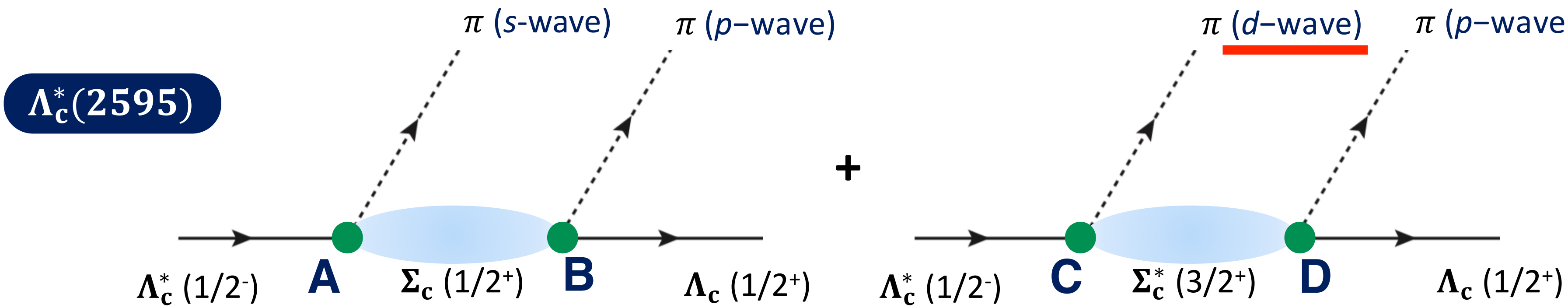
Sequential process



Seminar at Genova, Italy, October 5 (Wed), 2016

Effective Lagrangian

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



Non-Relativistic

Coupling constants are determined by the quark model

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

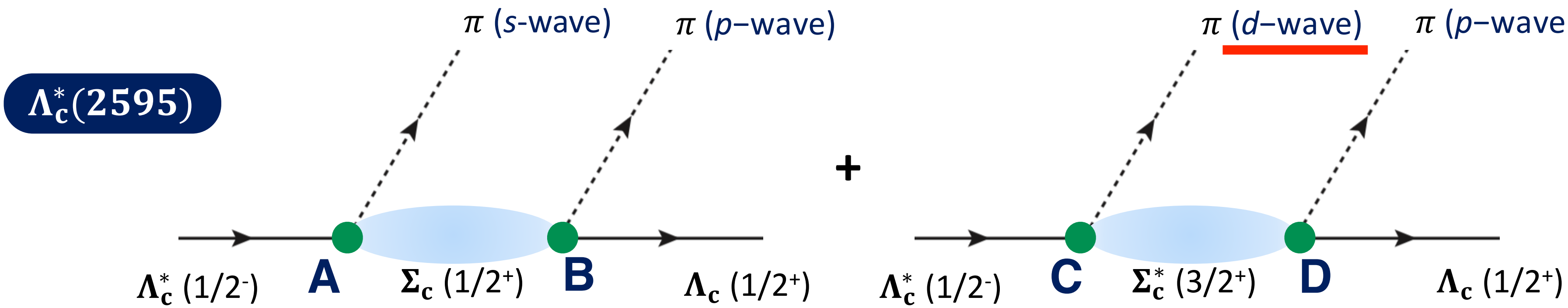
B $\mathcal{L}_B = i g_b \chi^\dagger_{\Lambda_c} \left(\vec{\sigma}\cdot\vec{p}_\pi\right) \chi_{\Sigma_c}$

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 $\Lambda_c^*(2595)$



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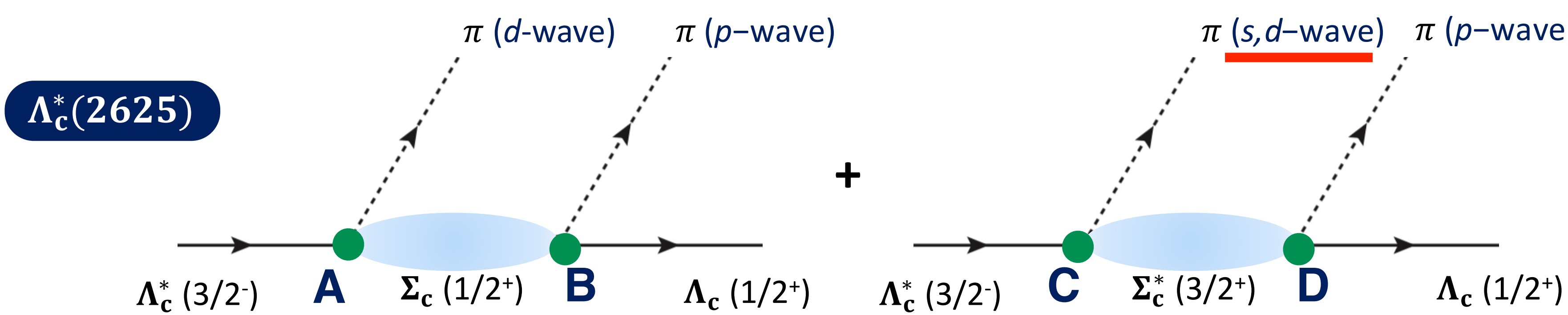
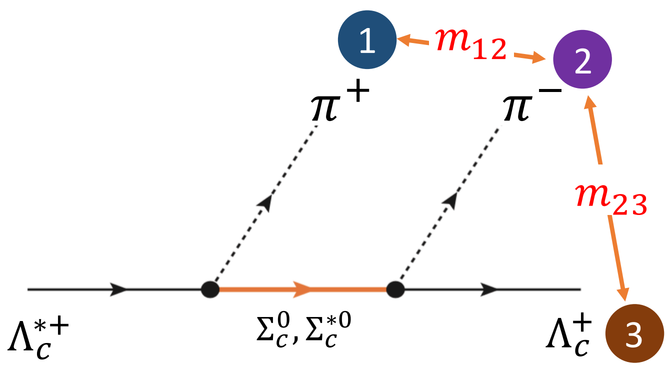
C $\mathcal{L}_C = g_c \chi^\dagger_{\Sigma_c^*} \left(\vec{S}^\dagger \cdot \vec{p}_\pi \vec{\sigma} \cdot \vec{p}_\pi - \frac{1}{3} \vec{S}^\dagger \cdot \vec{\sigma} |\vec{p}_\pi|^2 \right) \chi_{\Lambda_c^*}$

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



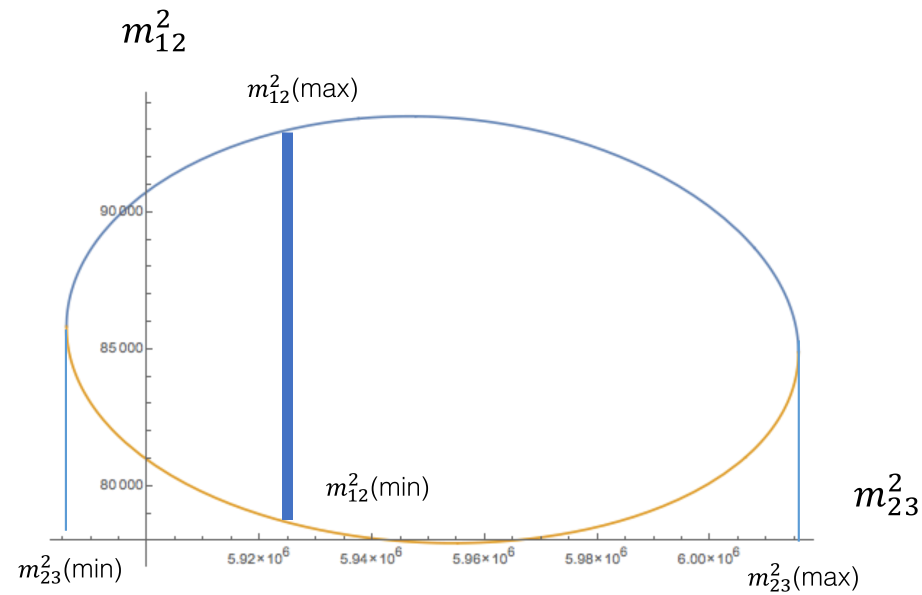
Decay Kinematics

Decay Width and Dalitz Region



Decay Width

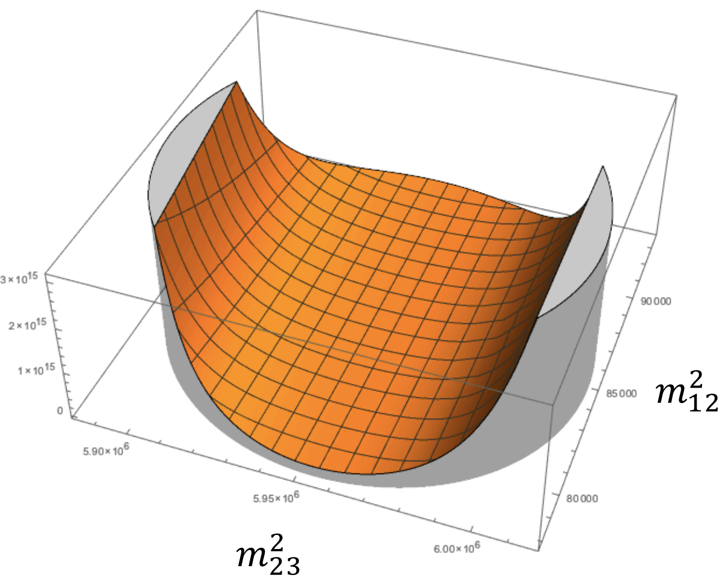
$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M^3}\overline{|\mathcal{M}|^2}dm_{12}^2 dm_{23}^2$$



Dalitz Region

$\Lambda_c^*(2595)$ Assuming the λ-mode excitations

Three-body Decay



Dalitz Plot

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**	**2.09**	**2.6 ± 0.6**

Parameters

$f_\pi = 94$ MeV $a_\lambda = 400$ MeV

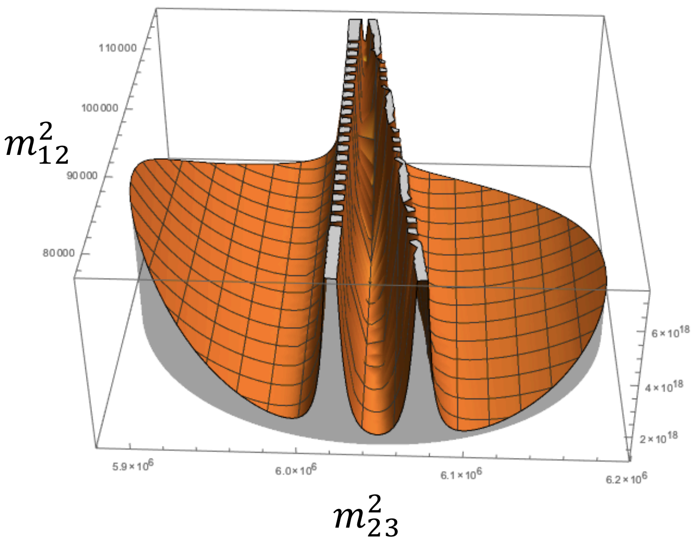
m $= 350$ MeV $a_\rho = 290$ MeV

M $= 1500$ MeV

- 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, …?)

$\Lambda_c^*(2625)$

Three-body Decay



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	**-**	$\mathbf{0.334}$	$< \mathbf{0.970}$

- 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

- Heavy (strange, cherm, bottom) quarks disentangle different modes of baryons, ρ and λ modes
- Productions are useful for the study of structure

  A similar feature with hyper nuclei
- Production rates of excited states may depend on flavor

  Excitations are abundantly produced for charm
- Decay rates are sensitive to the structure
- Also a good laboratory to test low energy chiral dynamics
- The nature of states are well studied,

  $\Lambda_c(2595, 1/2^-)$ and $\Lambda_c(2625, 3/2^-)$ are most likely the λ mode

Charm $k_\pi^{CM} = 2.71$ [GeV] , $k_\pi^{Lab} = 16$ [GeV]

$l = 0$	$\Lambda_c(\frac{1}{2}^+)$	$\Sigma_c(\frac{1}{2}^+)$	$\Sigma_c(\frac{3}{2}^+)$					
	1.00	0.02	0.16					
$l = 1$	$\Lambda_c(\frac{1}{2}^-)$	$\Lambda_c(\frac{3}{2}^-)$	$\Sigma_c(\frac{1}{2}^-)$	$\Sigma_c(\frac{3}{2}^-)$	$\Sigma'_c(\frac{1}{2}^-)$	$\Sigma'_c(\frac{3}{2}^-)$	$\Sigma'_c(\frac{5}{2}^-)$	
	0.90	1.70	0.02	0.03	0.04	0.19	0.18	
$l = 2$	$\Lambda_c(\frac{3}{2}^+)$	$\Lambda_c(\frac{5}{2}^+ -)$	$\Sigma_c(\frac{3}{2}^+)$	$\Sigma_c(\frac{5}{2}^+)$	$\Sigma'_c(\frac{1}{2}^+)$	$\Sigma'_c(\frac{3}{2}^+)$	$\Sigma'_c(\frac{5}{2}^+)$	$\Sigma'_c(\frac{5}{2}^+)$
	0.50	0.88	0.02	0.02	0.01	0.03	0.07	0.07

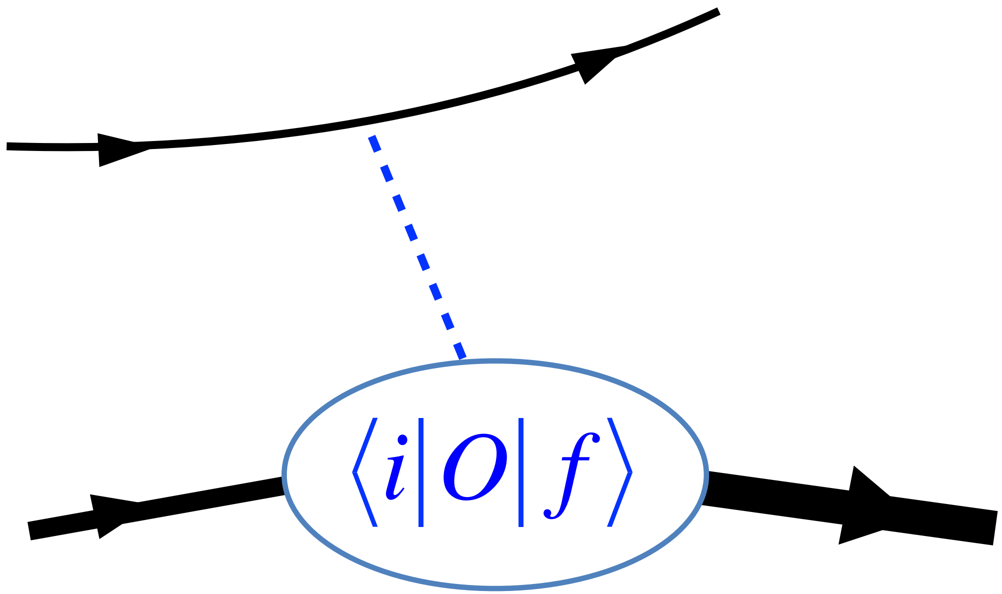
Strange $k_\pi^{CM} = 1.59$ [GeV], $k_\pi^{Lab} = 5.8$ [GeV]

$l = 0$	$\Lambda(\frac{1}{2}^+)$	$\Sigma(\frac{1}{2}^+)$	$\Sigma(\frac{3}{2}^+)$					
	1.00	0.067	0.44					
$l = 1$	$\Lambda(\frac{1}{2}^-)$	$\Lambda(\frac{3}{2}^-)$	$\Sigma(\frac{1}{2}^-)$	$\Sigma(\frac{3}{2}^-)$	$\Sigma'(\frac{1}{2}^-)$	$\Sigma'(\frac{3}{2}^-)$	$\Sigma'(\frac{5}{2}^-)$	
	0.11	0.23	0.007	0.01	0.01	0.07	0.067	
$l = 2$	$\Lambda(\frac{3}{2}^+)$	$\Lambda_c(\frac{5}{2}^+ -)$	$\Sigma(\frac{3}{2}^+)$	$\Sigma(\frac{5}{2}^+)$	$\Sigma'(\frac{1}{2}^+)$	$\Sigma'(\frac{3}{2}^+)$	$\Sigma'(\frac{5}{2}^+)$	$\Sigma'(\frac{5}{2}^+)$
	0.13	0.20	0.007	0.01	0.004	0.02	0.038	0.04

Productions

Productions

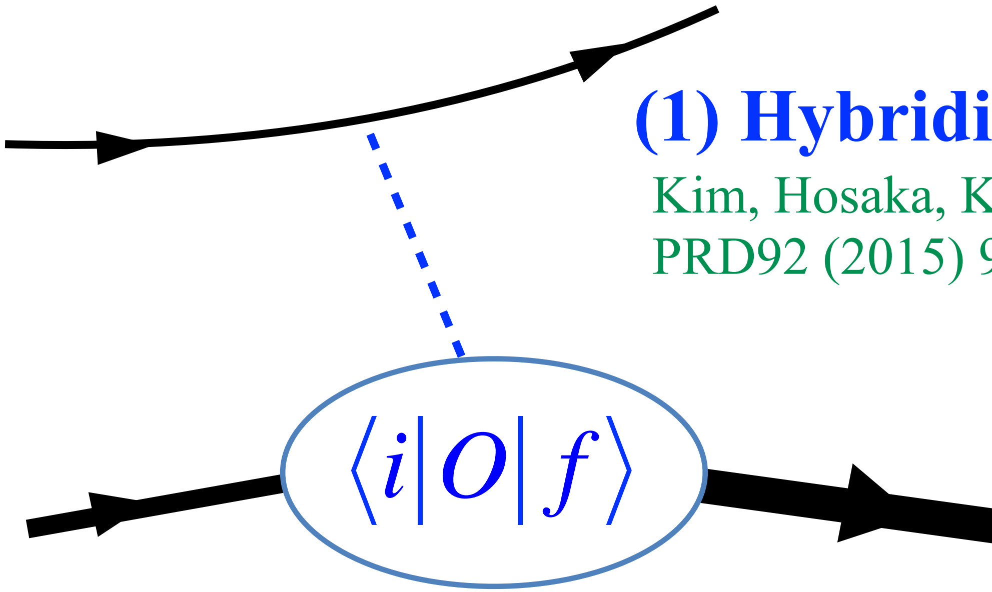
$$\pi + N \rightarrow D^* + \Lambda_c\,,\ K^* + \Lambda$$



(1) How much is charm produced?
(2) How are they related to internal structure of Λ_c*?

Productions

$$\pi + N \rightarrow D^* + \Lambda_c\,,\;\; K^* + \Lambda$$



(1) Hybridized Regge model

Kim, Hosaka, Kim, Noumi
PRD92 (2015) 9, 094021

(2) Quark model

Kim, Kim, Noumi, Shirotori, Hosaka
PTEP 2014 (2014) 10, 103D01,

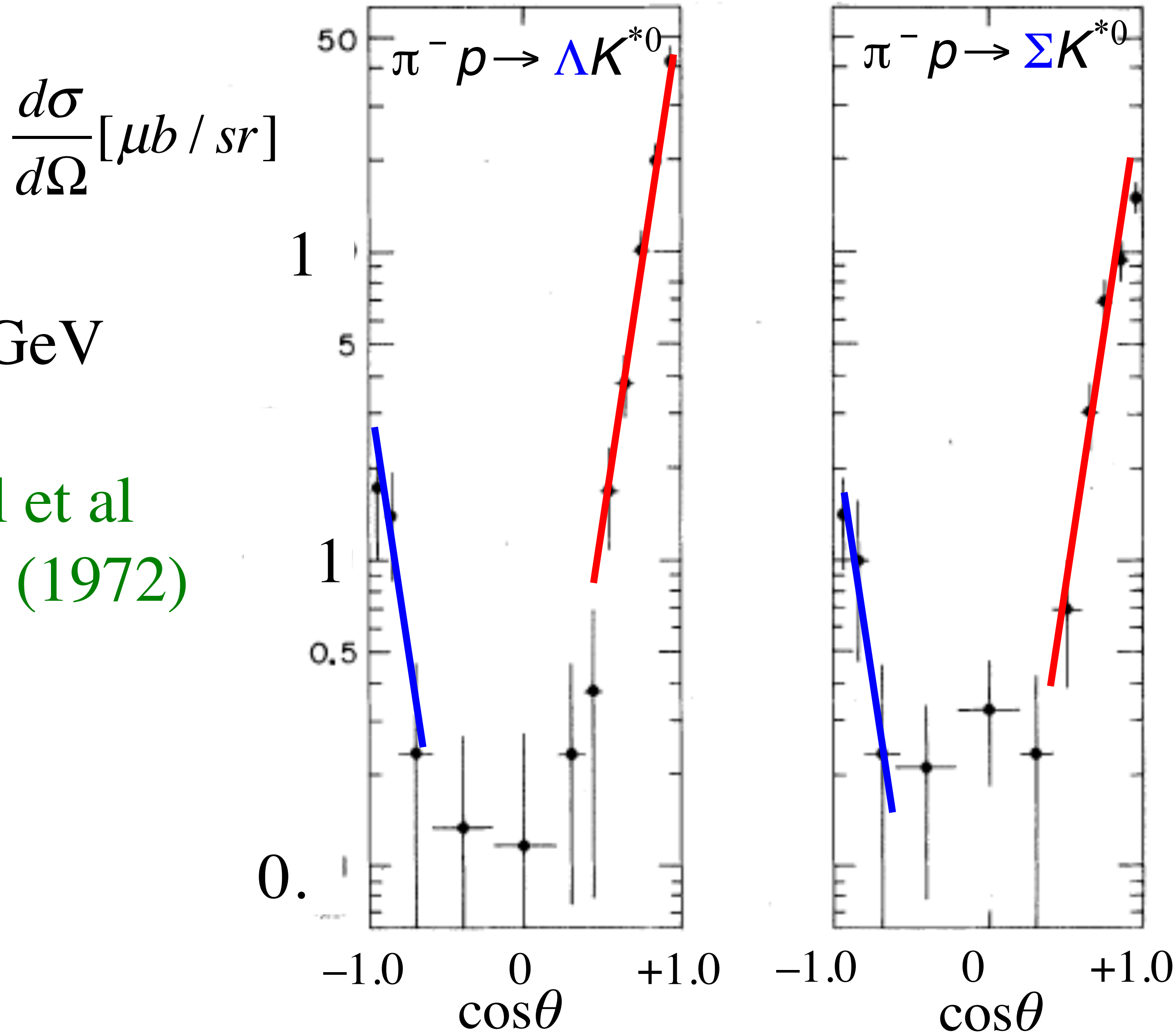
(1) How much is charm produced?
(2) How are they related to internal structure of Λ_c*?

Evidence of the diffractive pattern (t-channel dynamics)

Evidence of the diffractive pattern (t-channel dynamics)

$p_{\pi,\,\mathrm{Lab}} = 4.5$ GeV

D.J. Krennel et al
PRD6, 1220 (1972)

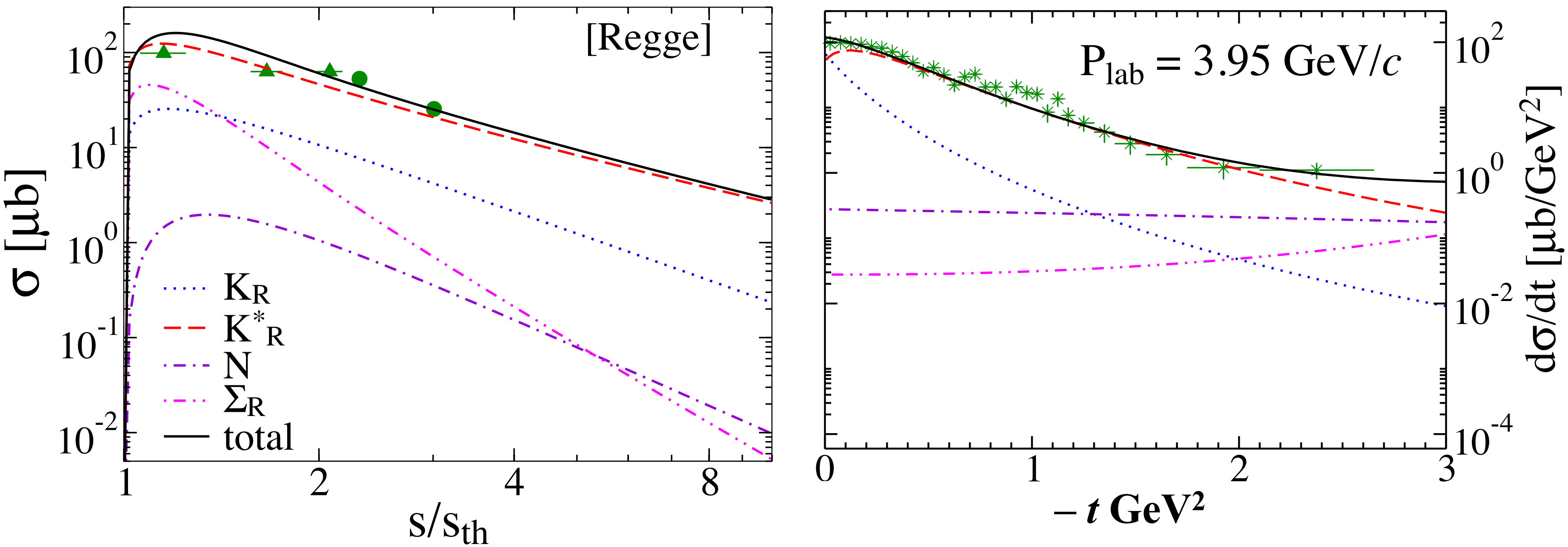


(1) How much is charm produced?

Kim, Hosaka, Kim, Noumi, PRD92 (2015) 9, 094021

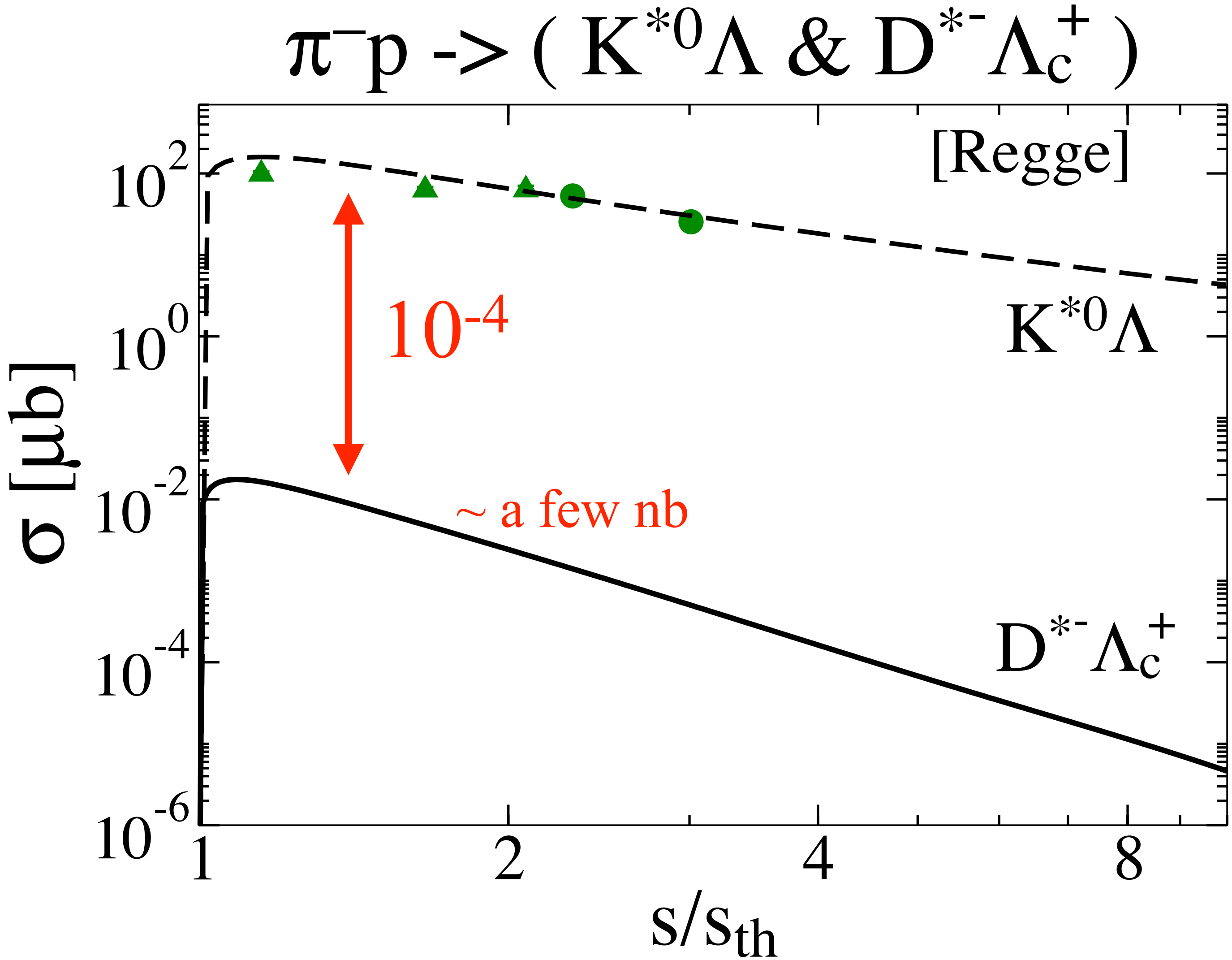
Hybridized Regge model: with effective Lagrangian for low energy

$$\pi^- + N \rightarrow K^{*0} + \Lambda$$



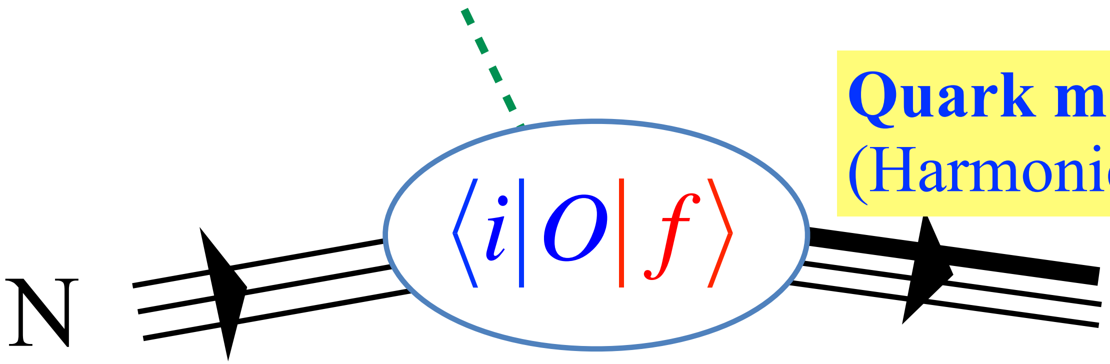
- Vector-Reggeon dominance with some pseudoscalar-Reggeon
- Both angular and energy dependences are well explained

Prediction to the charm production



(2) How are they related to internal structure?

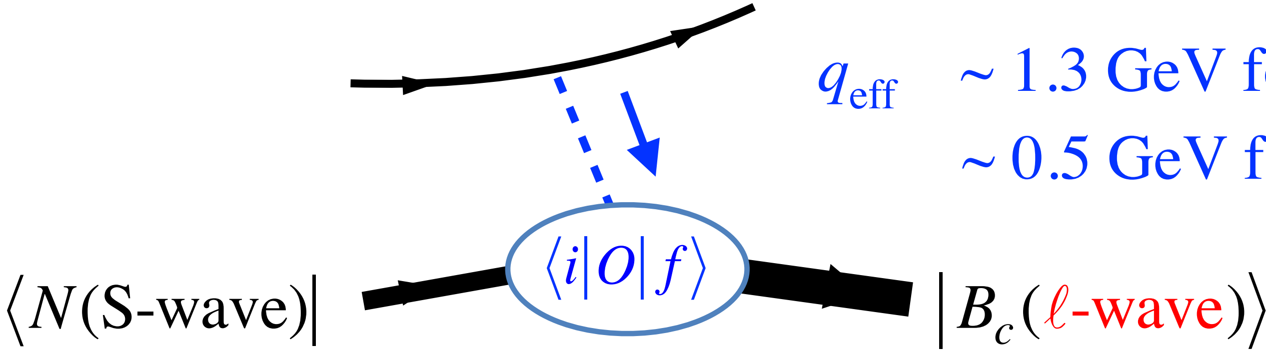
PTEP 2014 (2014) 10, 103D01



Quark model W.F.
(Harmonic oscillator)

Various Y_s, Y_C

Λ			Λ_c^+
$\Lambda(1405)$	$\Sigma(1385)$	$\Xi(1530)$	$\Lambda_c(2595)^+$
$\Lambda(1520)$	$\Sigma(1480)$	$\Xi(1620)$	$\Lambda_c(2625)^+$
$\Lambda(1600)$	$\Sigma(1560)$	$\Xi(1690)$	$\Lambda_c(2765)^+$
$\Lambda(1670)$	$\Sigma(1580)$	$\Xi(1820)$	$\Lambda_c(2880)^+$
$\Lambda(1690)$	$\Sigma(1620)$	$\Xi(1950)$	$\Lambda_c(2940)^+$
$\Lambda(1710)$	$\Sigma(1620)$	$\Xi(2030)$	$\Sigma_c(2455)$
…..			$\Sigma_c(2520)$
			$\Sigma_c(2800)$



q_{eff} ~ 1.3 GeV for charm

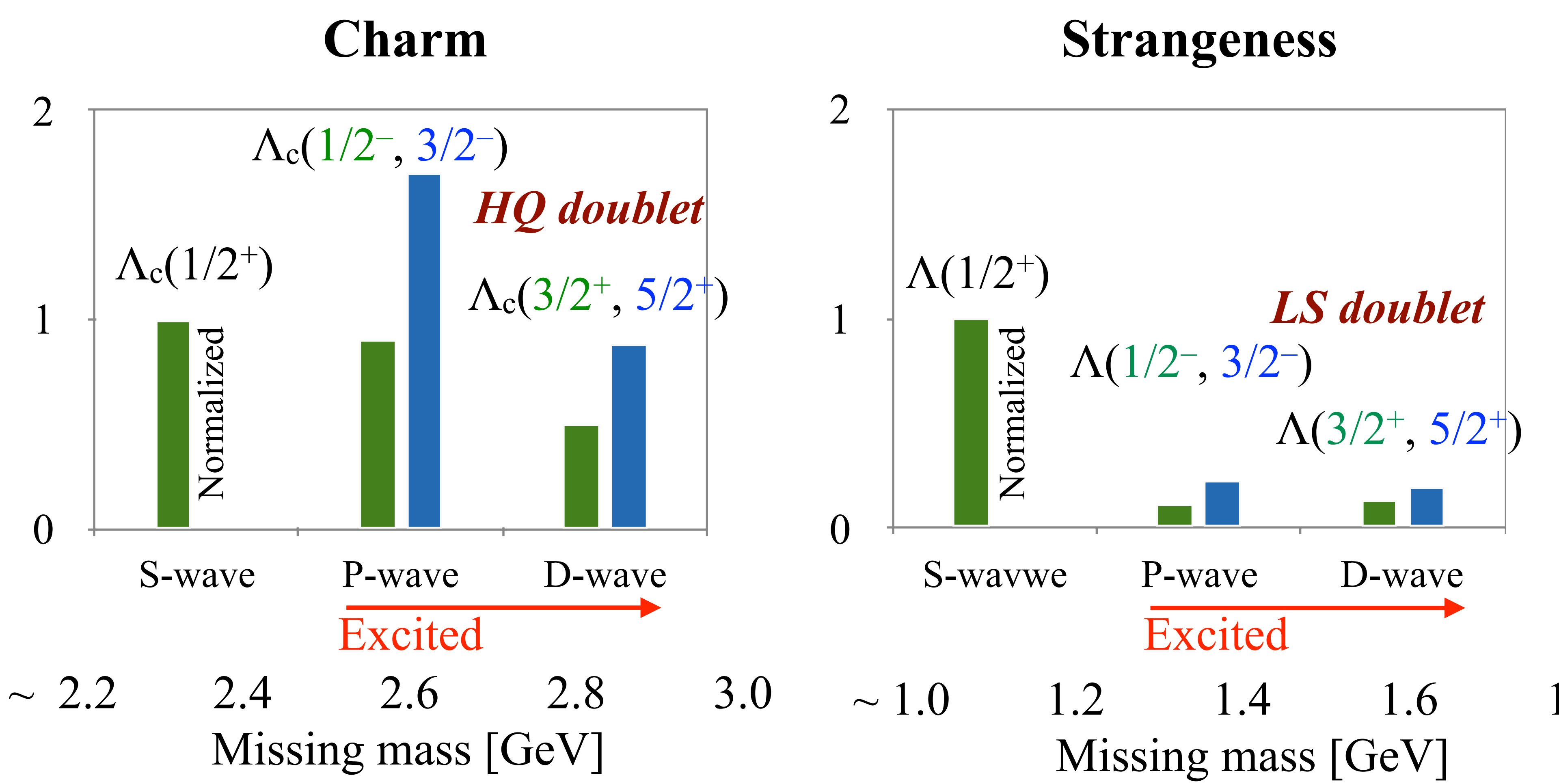
~ 0.5 GeV for strangeness

$$\left\langle B_c(\ell\text{-wave})\right| \vec{e}_\perp \cdot \vec{\sigma} e^{i\vec{q}_{eff}\cdot\vec{x}} \left| N(\text{S-wave})\right\rangle_{radial} \sim \left(\frac{q_{eff}}{A}\right)^{\ell} \times \exp\left(-\frac{q_{eff}^2}{4A^2}\right)$$

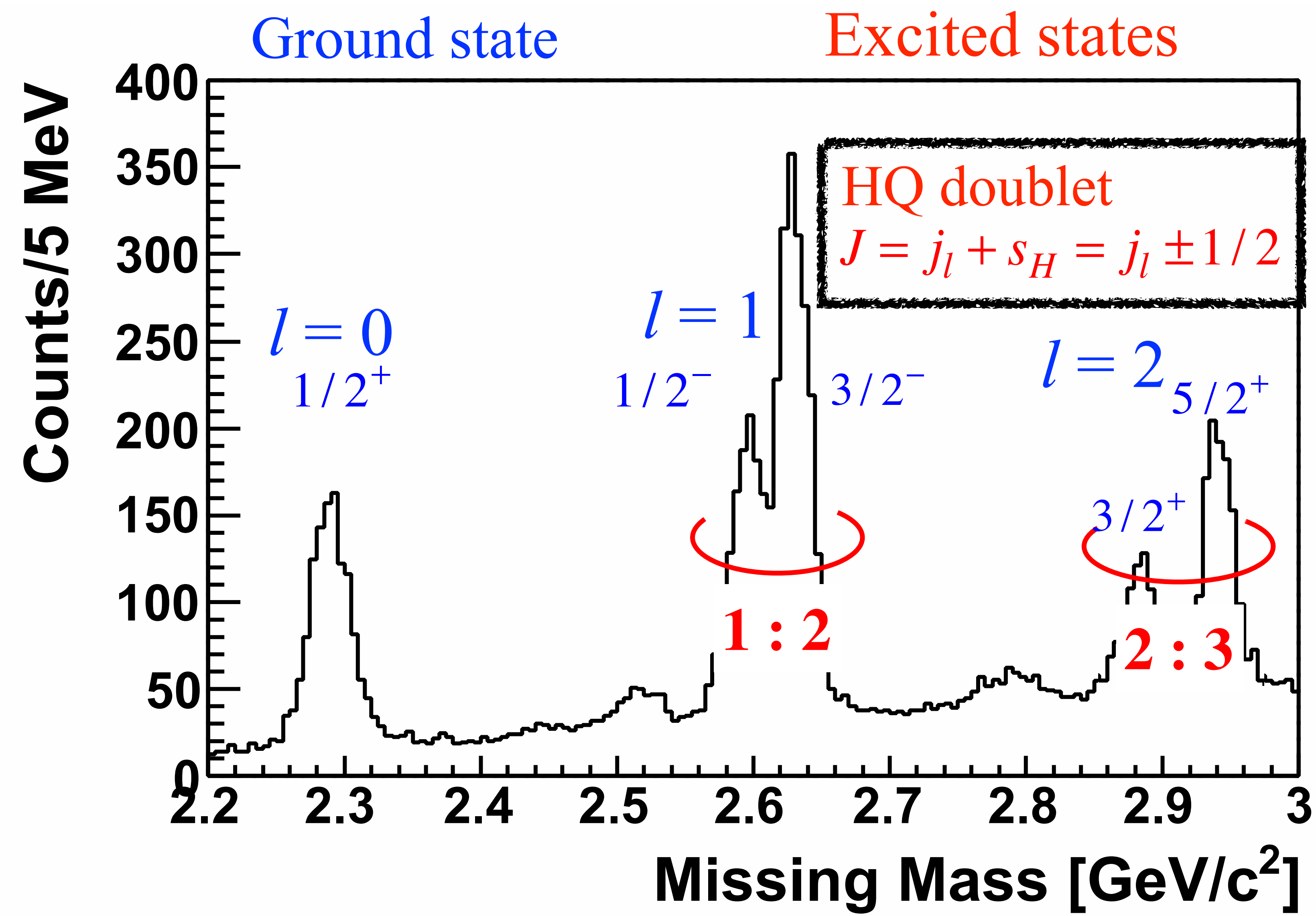
$$\ell_{\max} \sim \frac{q_{eff}}{\sqrt{2}A} \sim \begin{cases} \sim 2 & \text{for} \quad \text{charm} \\ \sim 0 & \text{for} \quad \text{strangeness} \end{cases}$$

For charm: excited states are produced abundantly

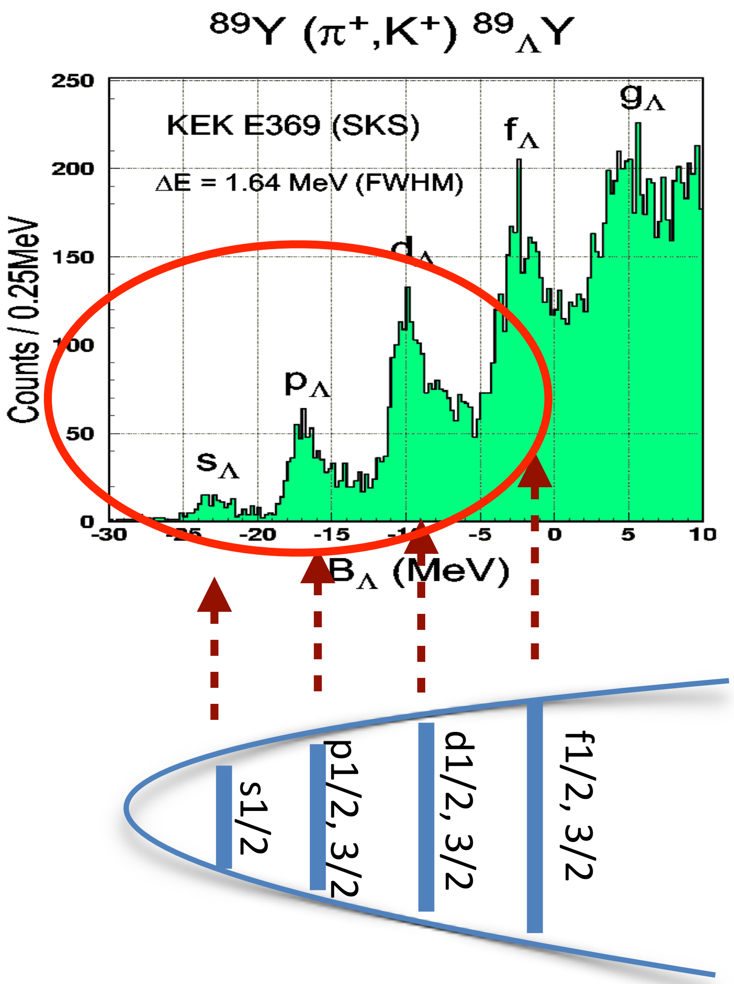
Production rates (relative)



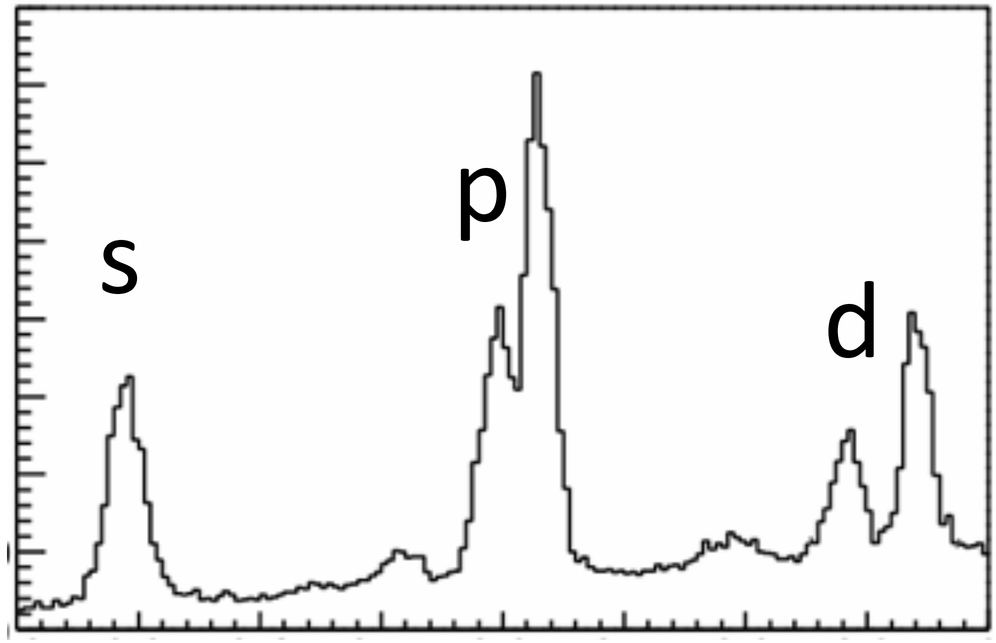
Charm production spectrum



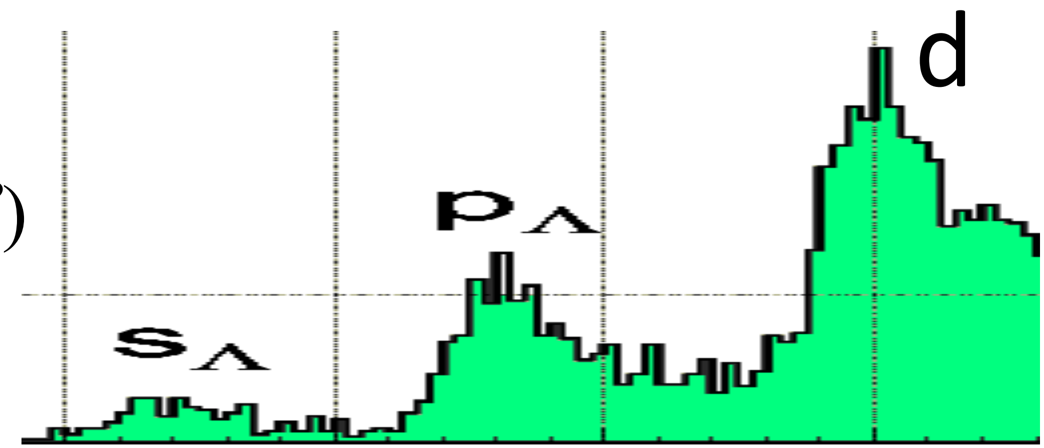
Coming back to this again



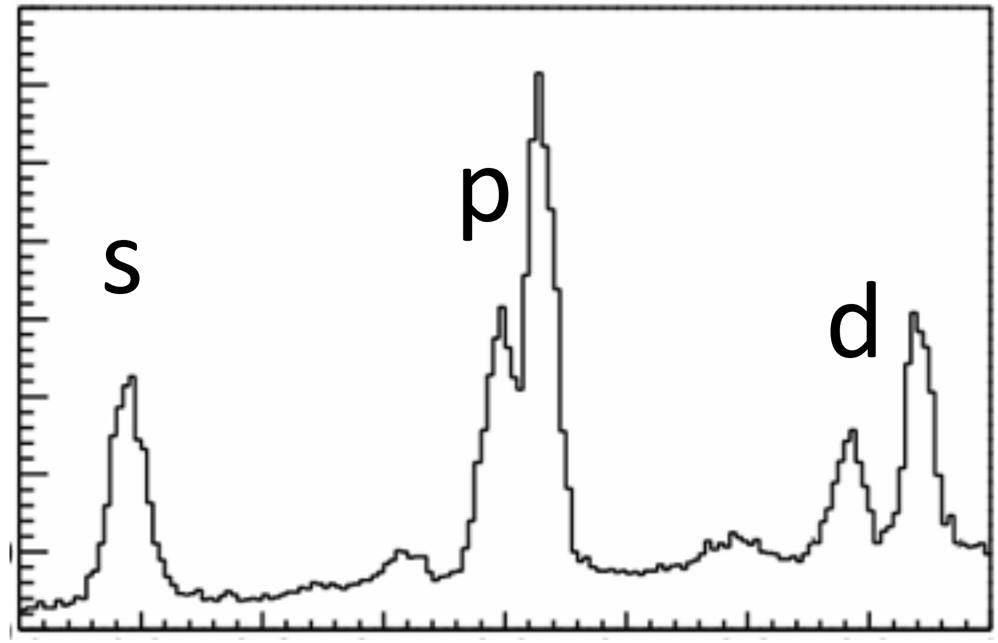
$$\pi + p \rightarrow D^* + B_c^*(J^P)$$



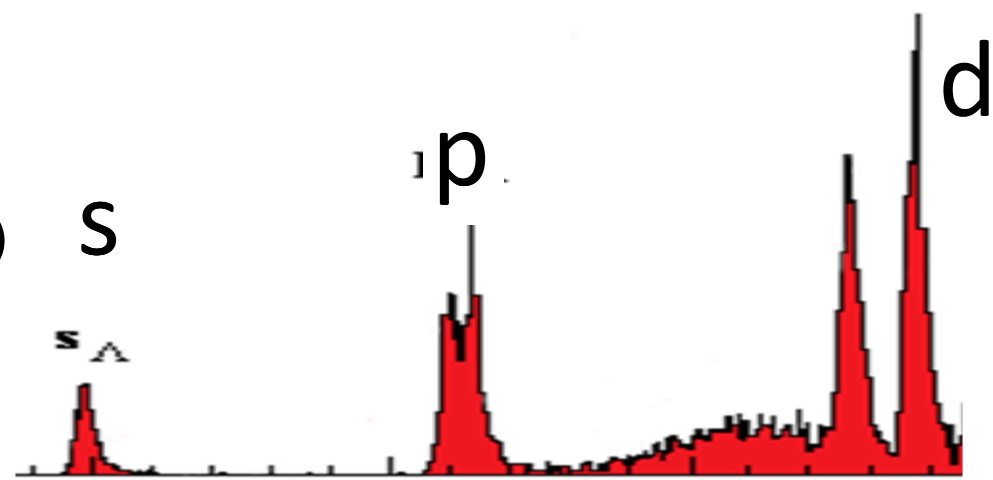
$$\pi^+ + {}^{89}\mathrm{Y} \rightarrow \mathrm{K}^+ + {}^{89}{}_{\Lambda}\mathrm{Y}(J^P)$$



$$\pi + p \rightarrow D^* + B_c^*(J^P)$$



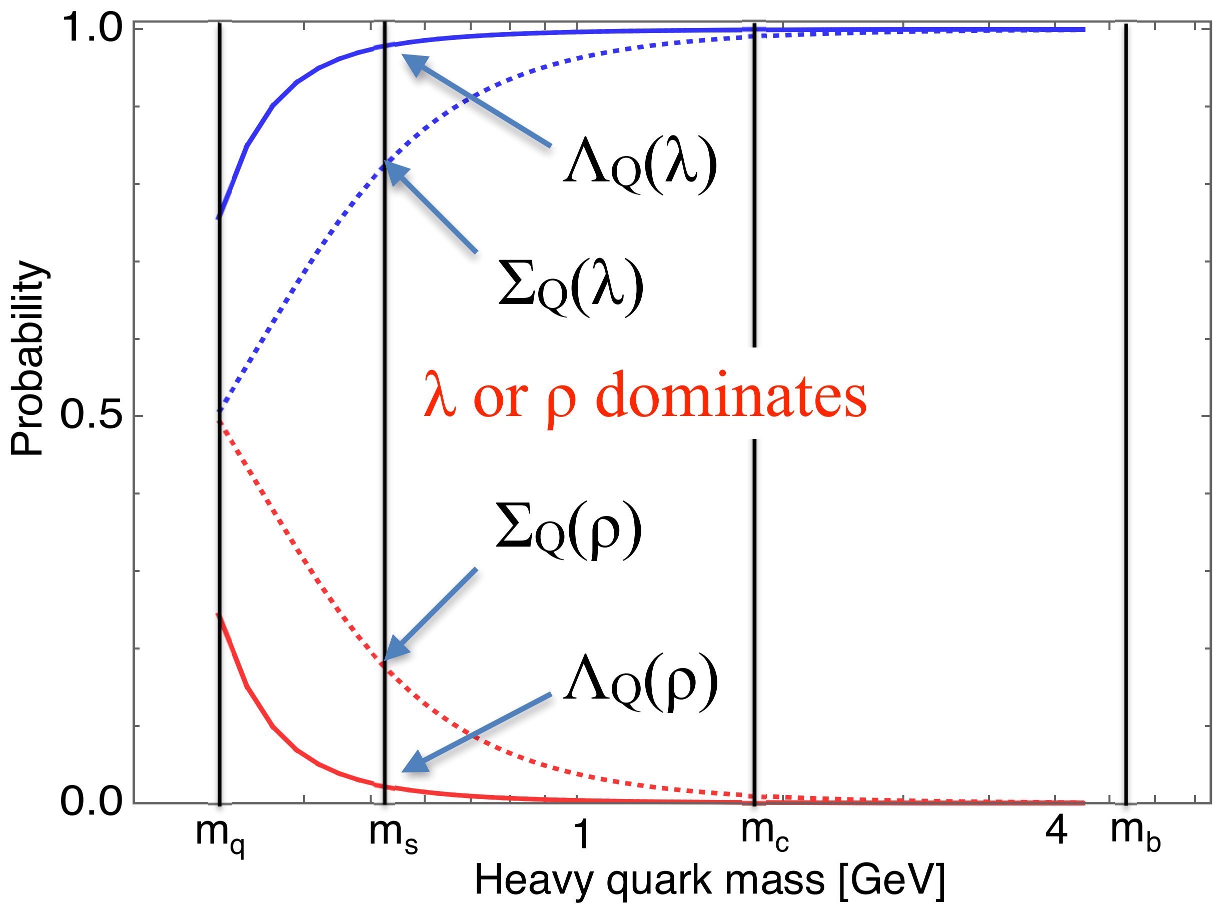
$$\pi^+ + {}^{89}\mathrm{Y} \rightarrow \mathrm{K}^+ + {}^{89}{}_{\Lambda}\mathrm{Y}(J^P)$$



Charm quark is heavy; is strange quark so?

T. Yoshida et al, PRD 92, 114029 (2015)

Wave function mixing for the lowest $1/2^-$ Λ_c and Σ_c



Regard ***s*** and ***c*** as **heavy**