Study of diquark correlations via baryon spectroscopy at J-PARC

K. Shirotori

for the MARQ collaboration

Research Center for Nuclear Physics (RCNP)
The University of Osaka

Theoretical Motivations and Empirical Evidence for Diquark Correlations in Hadrons

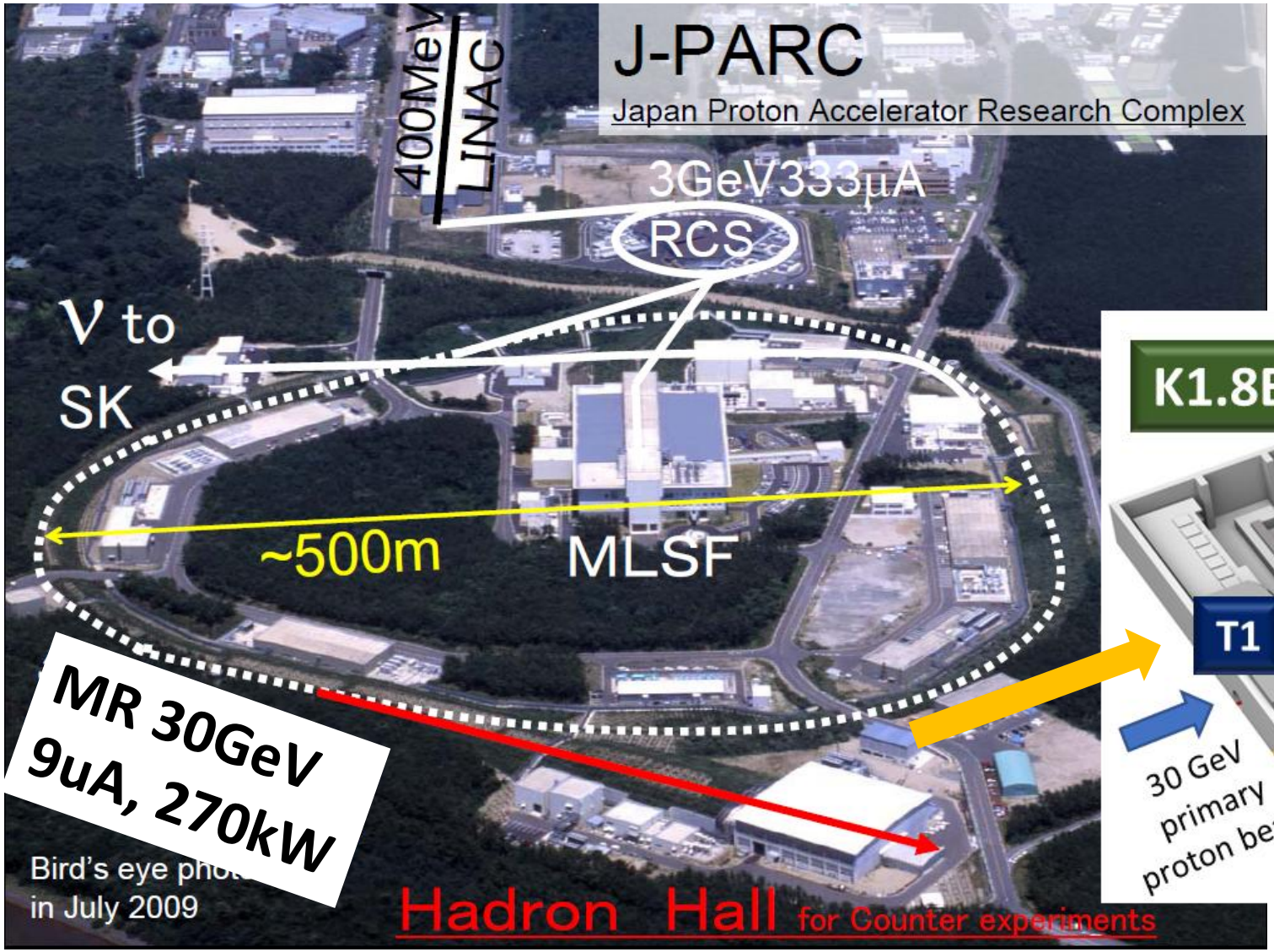
22nd Oct. 2026

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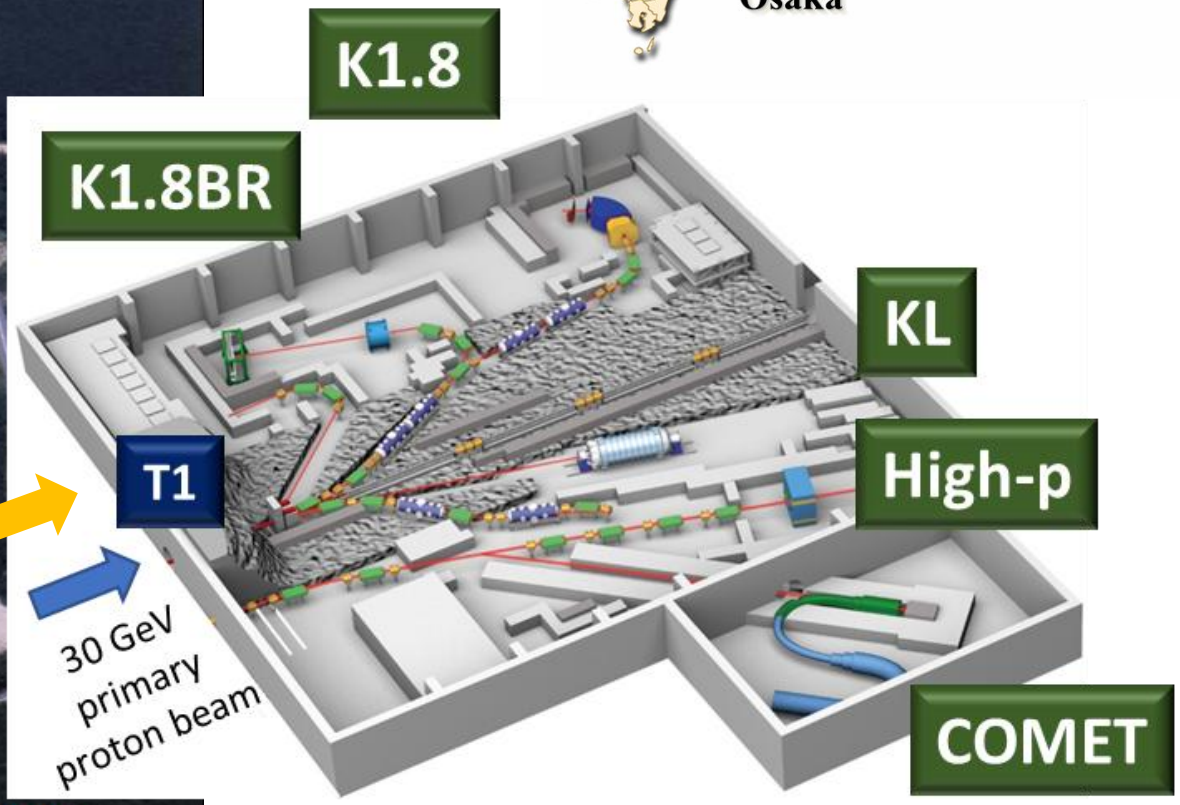
- **Introduction**
  - **Exploration of "Origin and Evolution of Matter" at J-PARC**
- **Charmed baryon spectroscopy at J-PARC**
  - **Λ_c^*: *ud* diquark system**
- **Systematic baryon spectroscopy at J-PARC**
  - **Ξ^*: *us/ds* diquark system**
  - **Ω^*: *ss* diquark system**
- **Summary**

Introduction

J-PARC & Hadron Experimental Facility







World's highest level intensity proton beam ⇒ SX beam power 101 kW

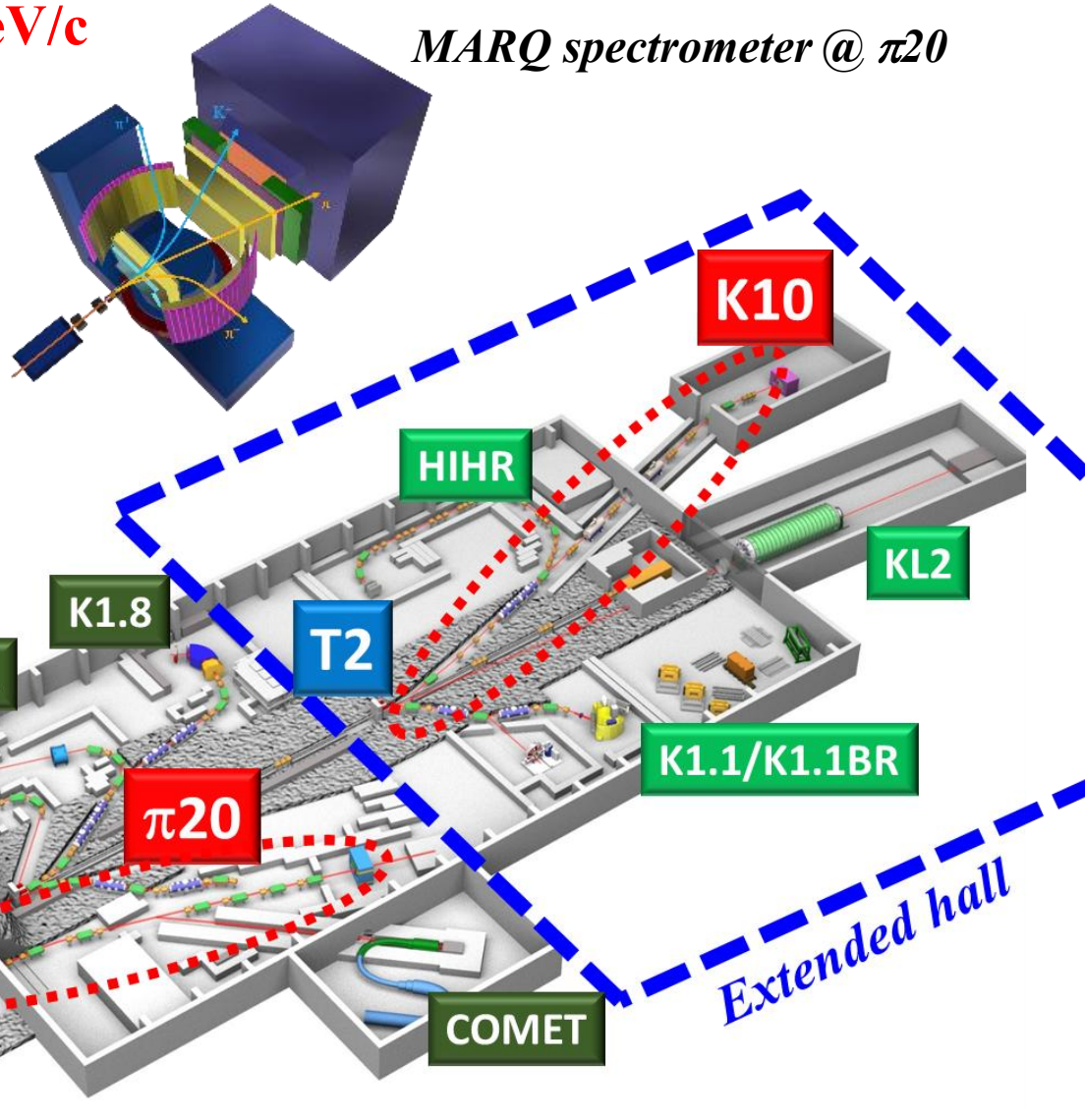
π20 & Hadron Experimental Facility Extension: K10

- **π20: π^- beam (Unseparated)**
  - Intensity: >10^7 /spill π^- (K^-, $\bar{p}$: 1–2%) @ 2–20 GeV/c
  - Momentum resolution: $\Delta p/p = 0.1\%(\sigma)$

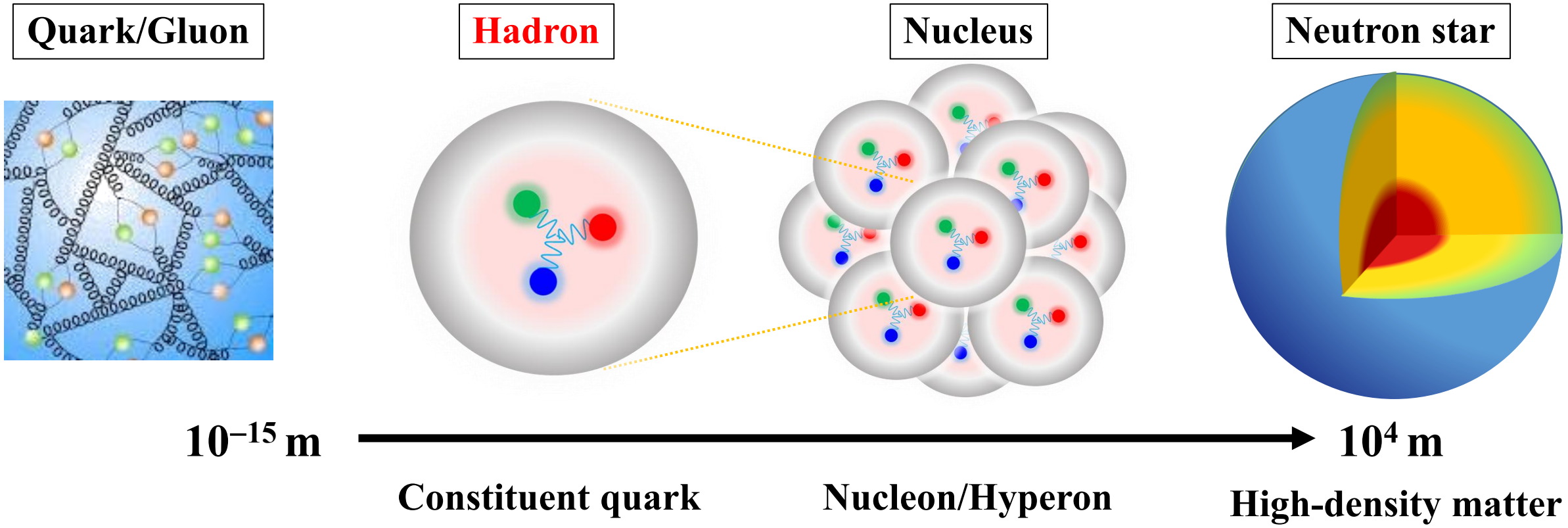
- **K10: K^- & $\bar{p}$ beam**
  - Intensity: >10^6 /spill for $K^-/\bar{p}$ @ 2–10 GeV/c
  - Purity: $K/\pi \sim 1/2$, $\bar{p}/\pi \sim 2/1$
    - Particle separation by RF separator
  - Momentum resolution: $\Delta p/p = 0.1\%(\sigma)$

∗ High-momentum hadron beams
- Unique in the world
- Charm and strange hadron production
- High-intensity: Systematic study

MARQ spectrometer @ π20



Exploration of "Origin and Evolution of Matter"

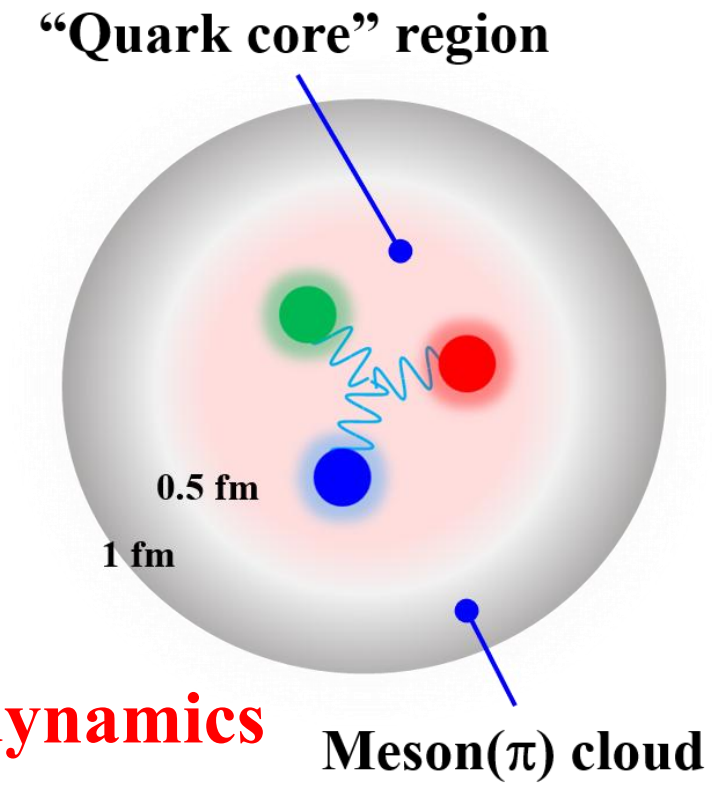


∗ **How quarks build hadrons ?**

- Investigation of QCD dynamics in the low-energy regime

⇒ **Systematic study using intense hadron beams at J-PARC hadron facility**

Study of excited state property



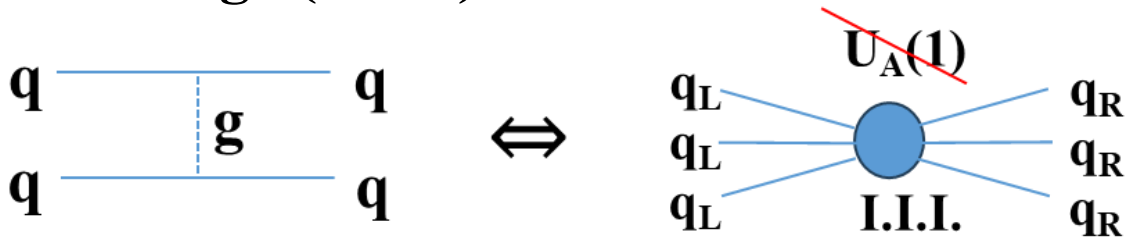
∗ **Dynamics of non-trivial QCD vacuum**

⇒ **Dynamics of Effective degrees of freedom reflects level structure, production and decay rates.**

- **Diquark correlations & Spin-dependent forces**

⇒ **Color-magnetic integration (CMI) and Instanton* dynamics**

- **Gluon exchange (OGE) ⇔ Instanton Induced Interaction (I.I.I.)**



- **Spatial(momentum) distribution of constituent quark**

⇒ **Confinement potential and meson (π) cloud effect**

**Instanton*: *A topological object of gluon that mediates the $U_A(1)$ breaking interaction proposed by Kobayashi, Maskawa, and 't Hoot*

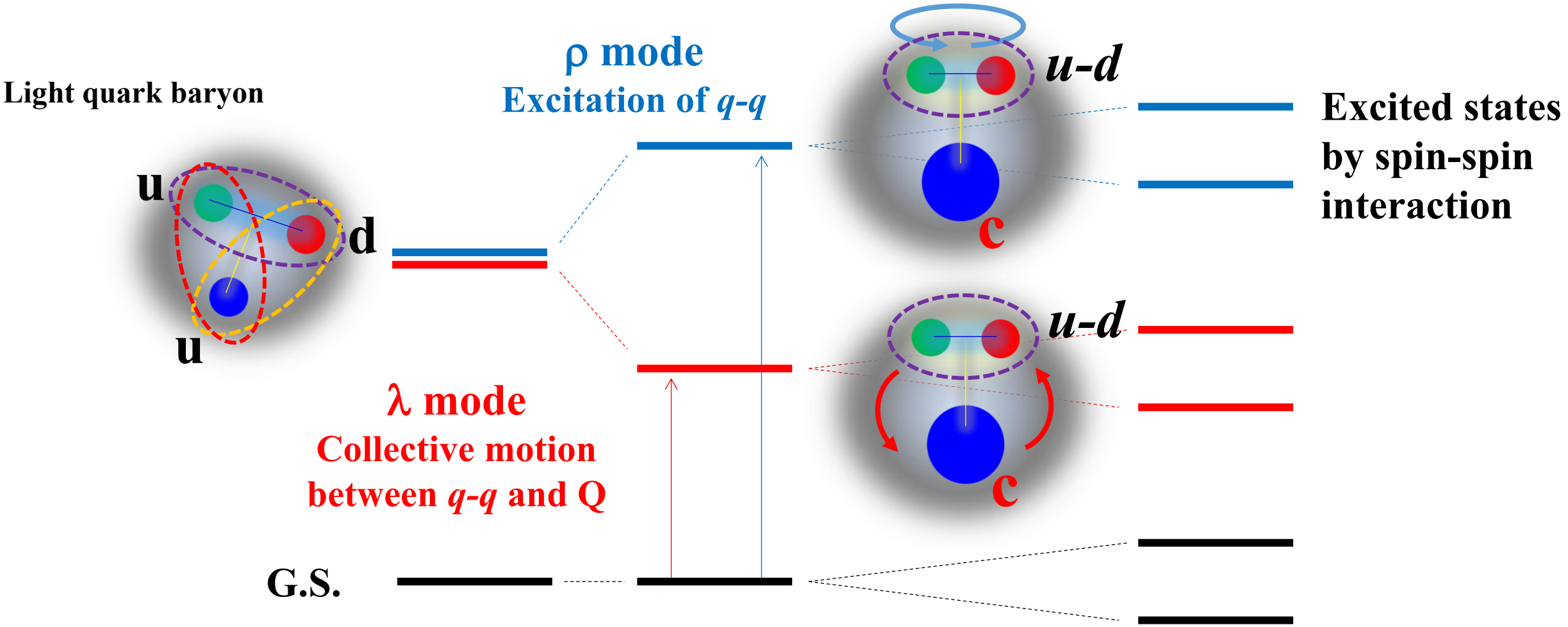
Charmed baryon spectroscopy

Charmed baryon spectroscopy

"Excitation mode": λ and ρ modes reflected by *ud* diquark correlation

✻ Dynamical information: Production rates and absolute decay branching ratios

- $\pi^- p \rightarrow D^{*-} Y_c^{*+}$ reaction @ 20 GeV/c



Production rates by hadronic reaction

- $\pi^- p \rightarrow D^{*-} Y_c^{*+}$ reaction @ 20 GeV/c
  - Production cross section(0°): Overlap of wave function → $R \sim \langle \varphi_f | \sqrt{2}\sigma_- \exp(i\vec{q}_{eff}\vec{r}) | \varphi_i \rangle$

⇒ Production rates: λ/ρ mode assignment

- Production rate of LS doublet = L : L+1
- Large production rate of highly excited states → $I_L \sim (q_{eff}/\alpha)^L \exp(-q_{eff}^2/\alpha^2)$

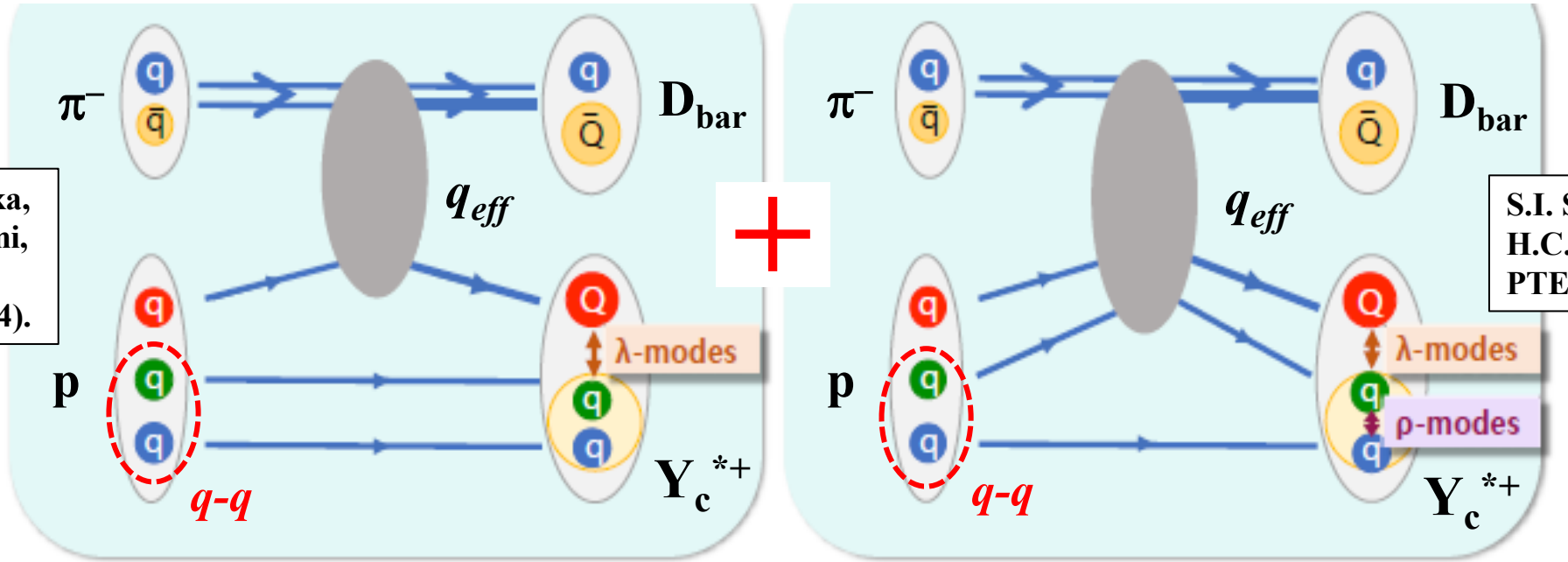
Mom. Trans. : q_{eff}~1.4 GeV/c
α~0.4 GeV ([Baryon size]$^{-1}$)

One-quark process

∗ λ-mode states w/ finite L are populated.

Two-quark process

∗ Comparable ρ-mode states are expected.



S.H. Kim, A. Hosaka, H.C. Kim, H. Noumi, K. Shirotori
PTEP 103D01 (2014).

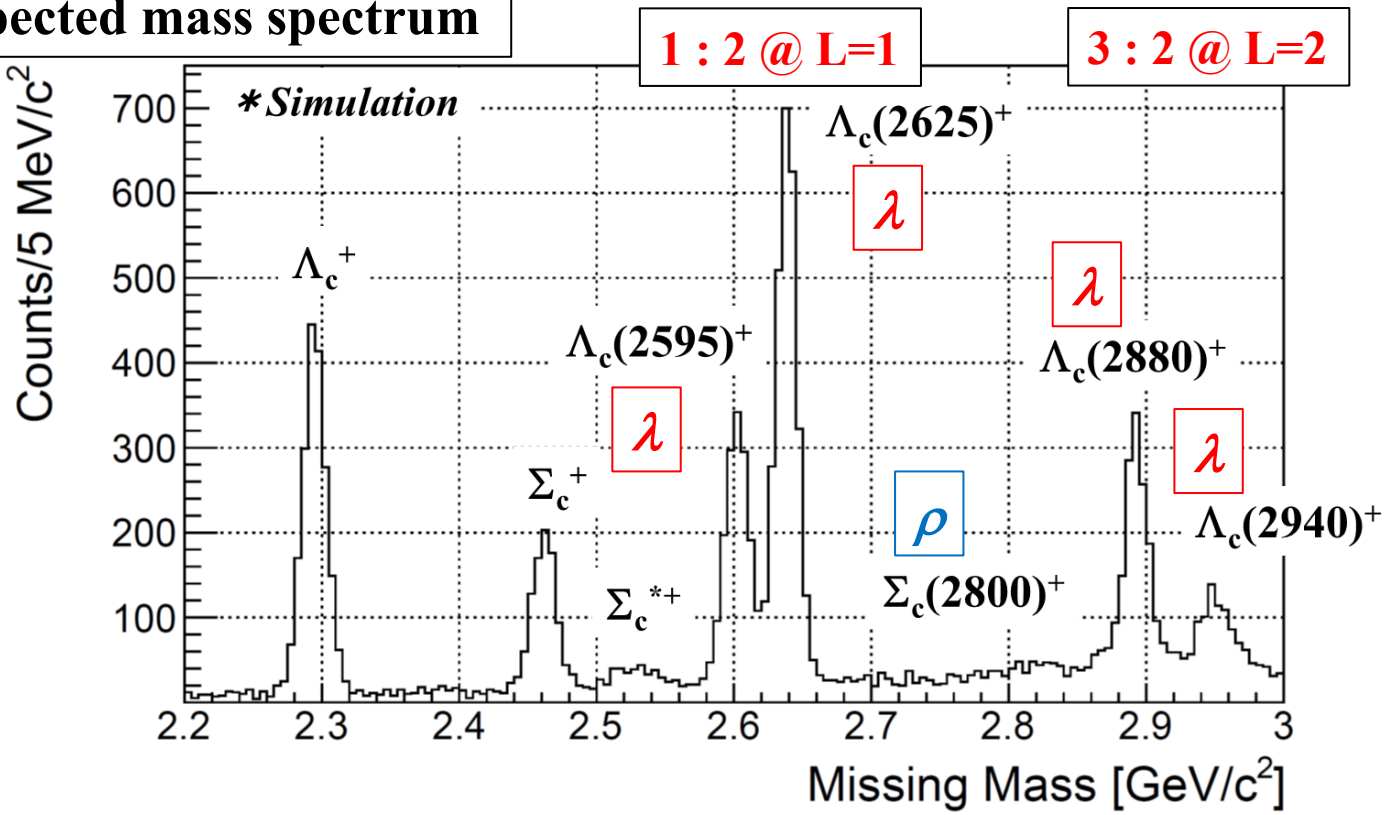
S.I. Shim, A. Hosaka, H.C. Kim,
PTEP 2020, (2020) 5, 053D01

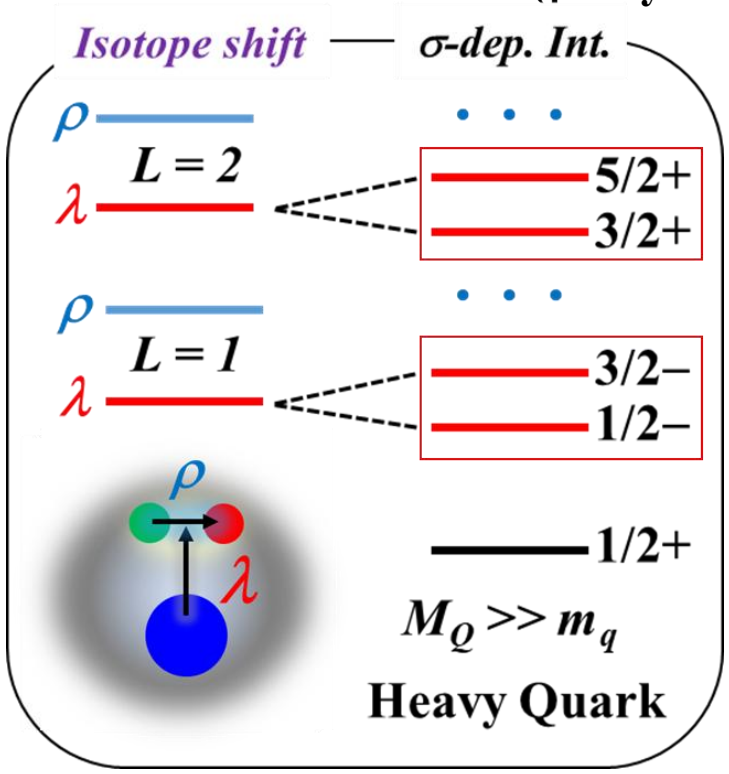
Production rates by hadronic reaction

- $\pi^- p \rightarrow D^{*-} Y_c^{*+}$ reaction @ 20 GeV/c
  - Production cross section(0°): Overlap of wave function → $R \sim \langle \varphi_f | \sqrt{2}\sigma_- \exp(i\vec{q}_{eff}\vec{r}) | \varphi_i \rangle$
  - ⇒ Production rates: λ/ρ mode assignment
    - Production rate of LS doublet = $L : L+1$
  - Large production rate of highly excited states → $I_L \sim (q_{eff}/\alpha)^L \exp(-q_{eff}^2/\alpha^2)$

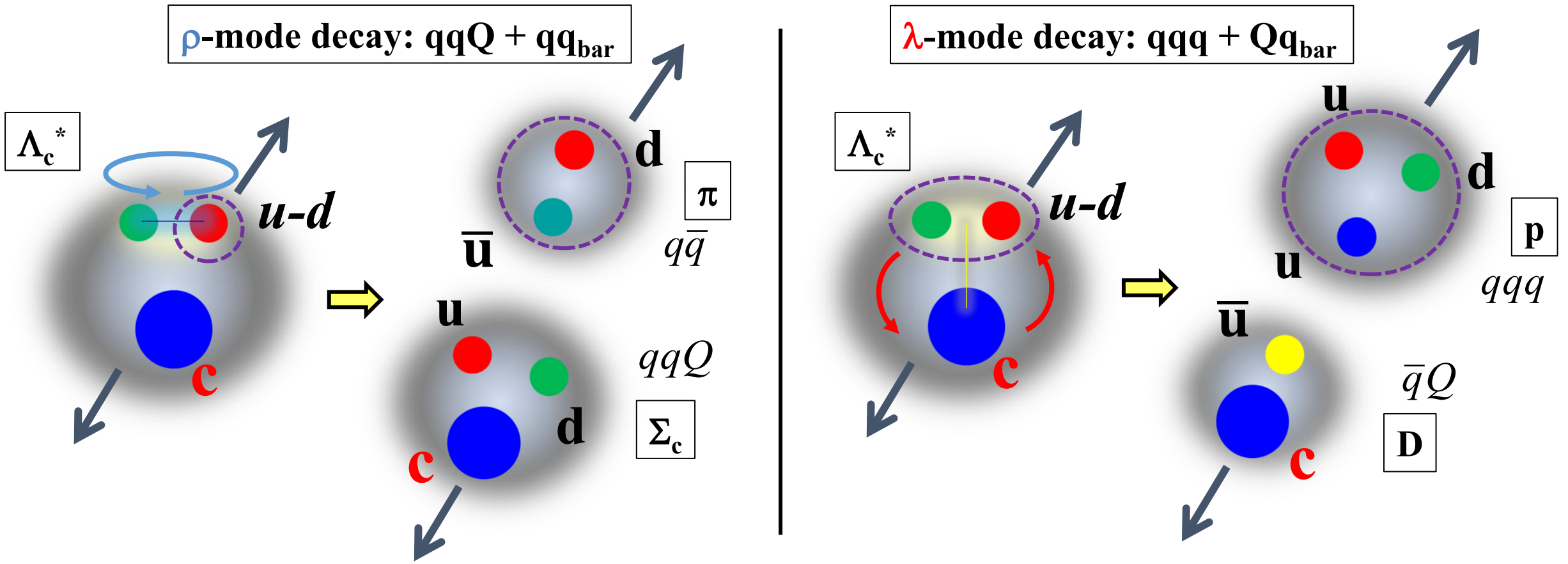
Mom. Trans. : q_{eff}~1.4 GeV/c
α~0.4 GeV ([Baryon size]$^{-1}$)

Expected mass spectrum





Decay property

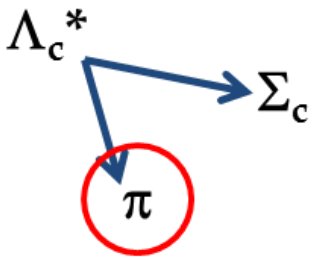


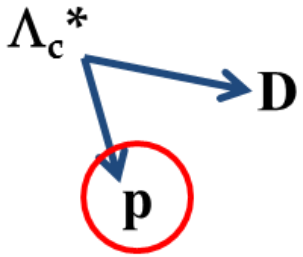
- **Decay measurement: $\Gamma_{\pi\Sigma c} \Leftrightarrow \Gamma_{pD}$ ($\pi^{-/+} + \Sigma_c^{++/0} \Leftrightarrow p + D^0$)**

⇒ Absolute values of branching ratios reflect diquark correlations.

- **Complementary to high-energy experiments**

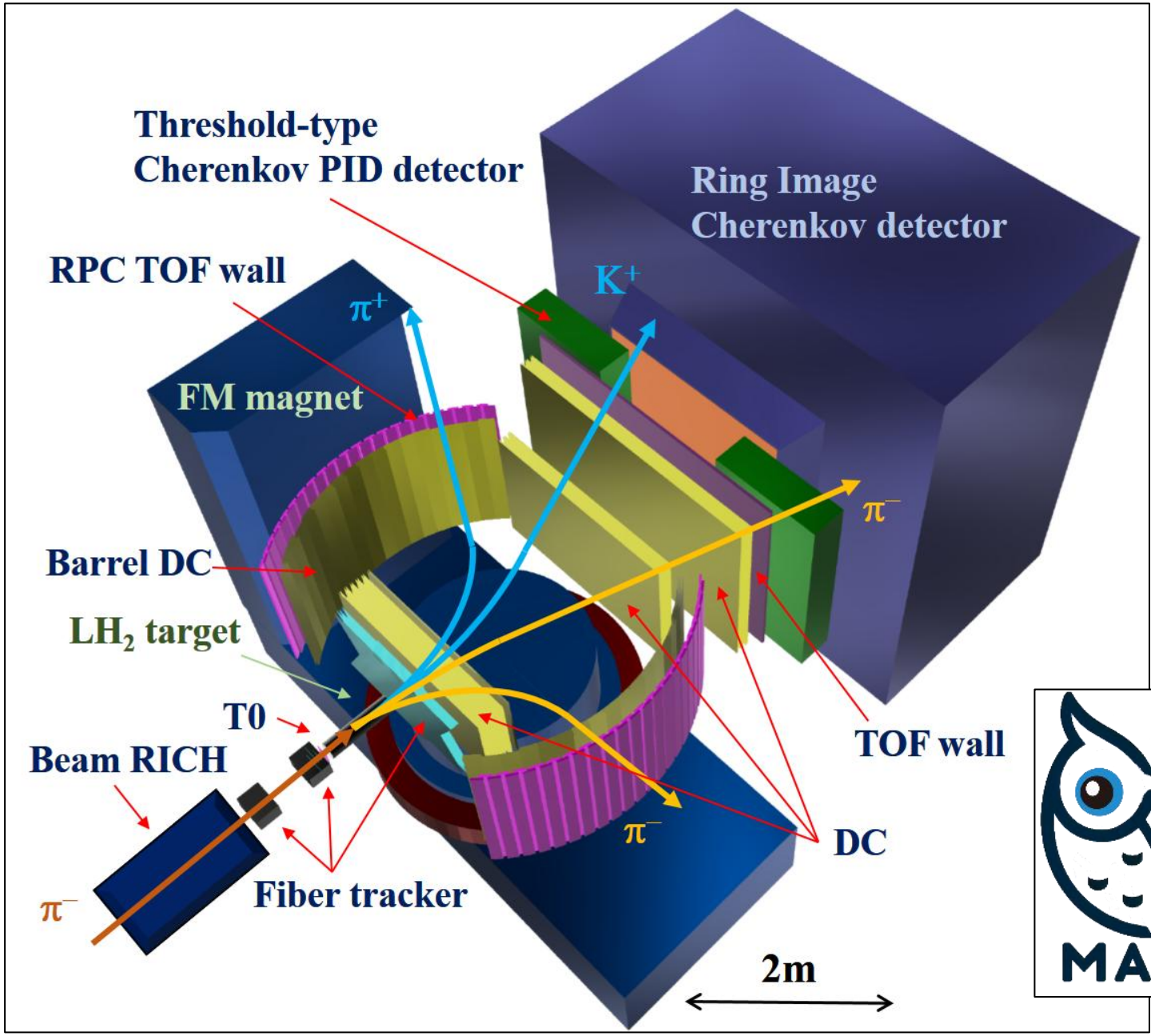
MARQ spectrometer at π20

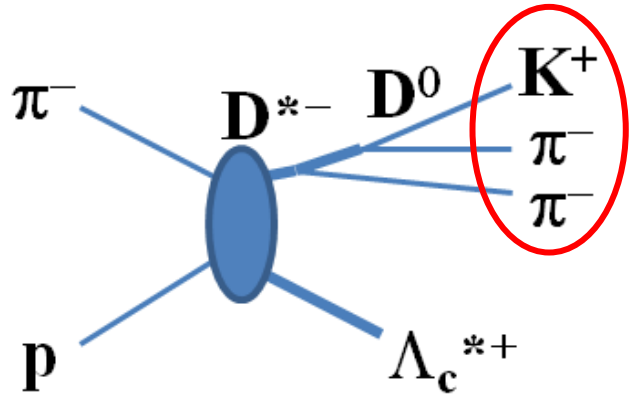




Decay measurement
∗ Branching ratios

$\pi^{\pm}$&p: < 4.0 GeV/c





Missing mass measurement
∗ Production rate

K^+ & π^-: 2–16 GeV/c
Slow π_s^-: 0.5–1.7 GeV/c

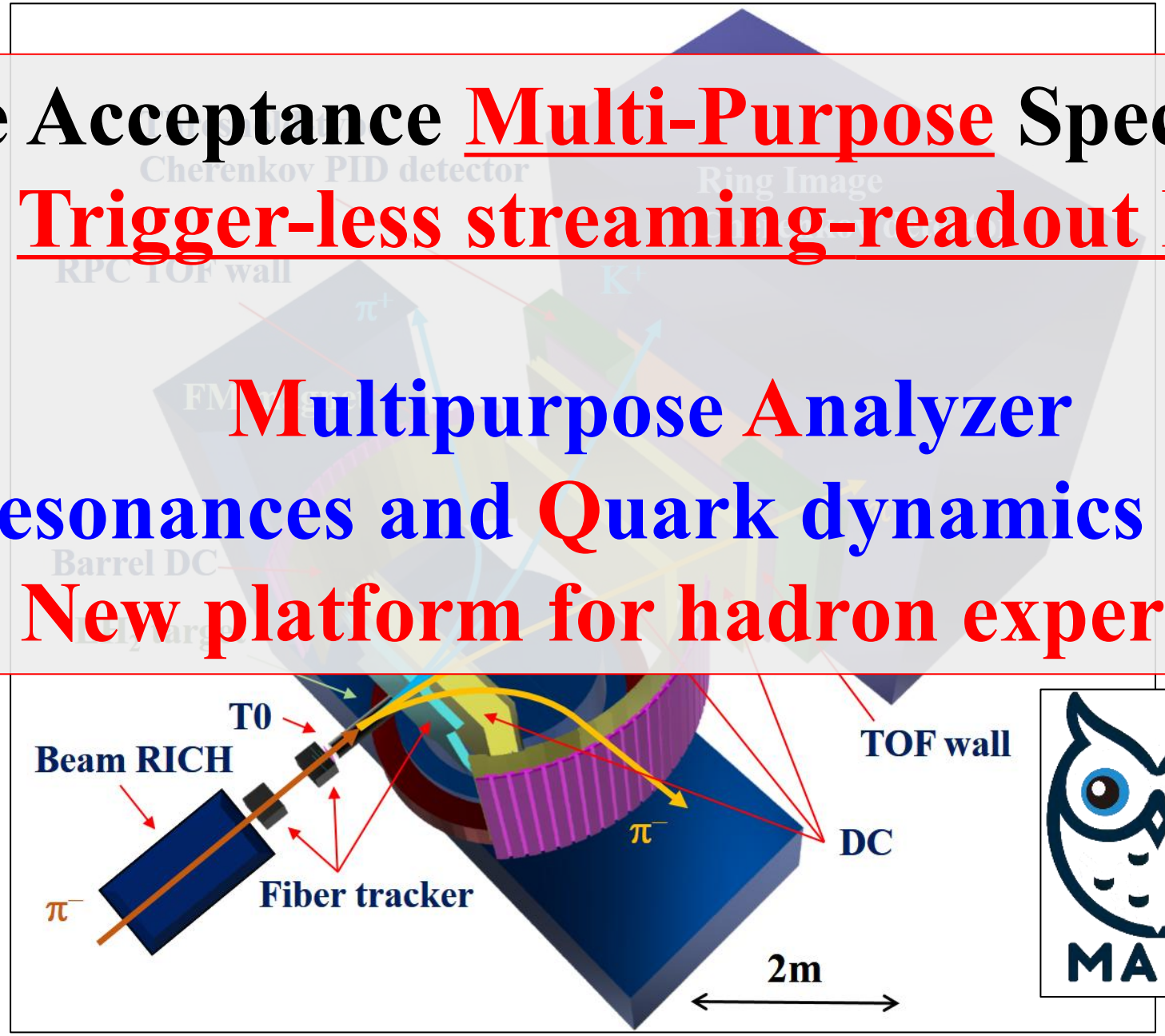
MARQ

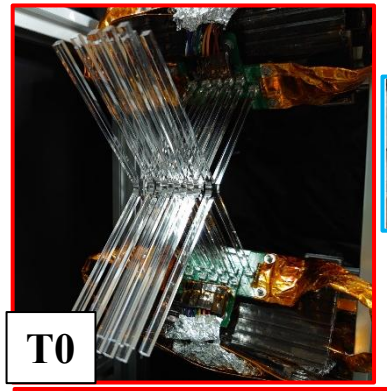
MARQ spectrometer at π20

Large Acceptance Multi-Purpose Spectrometer + Trigger-less streaming-readout DAQ

Multipurpose Analyzer for Resonances and Quark dynamics (MARQ)

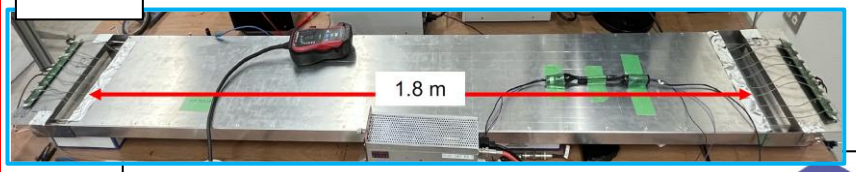
⇒ New platform for hadron experiment



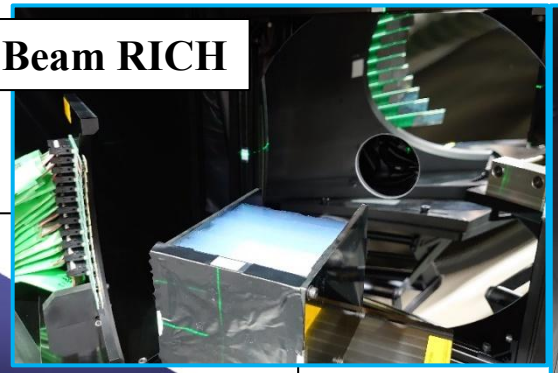


T0

RPC



Beam RICH

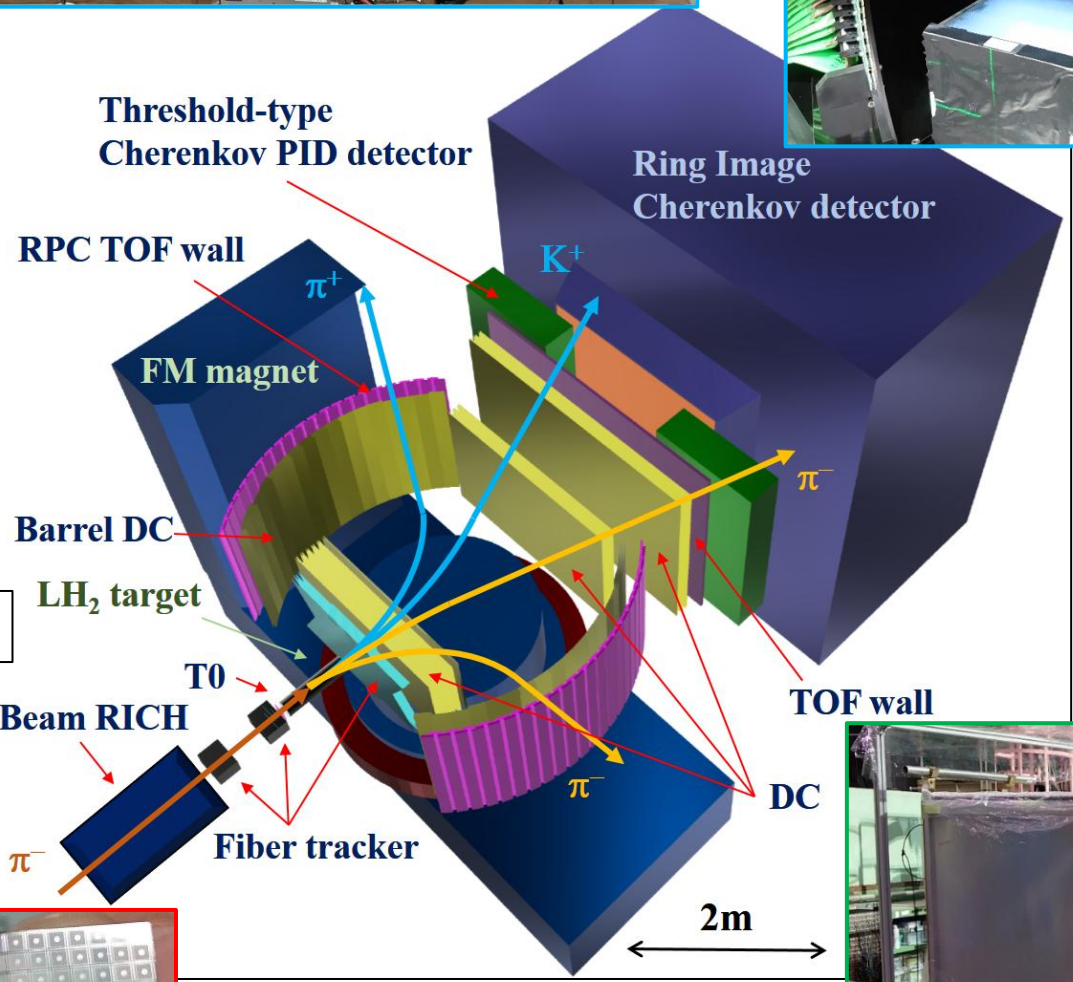


RICH

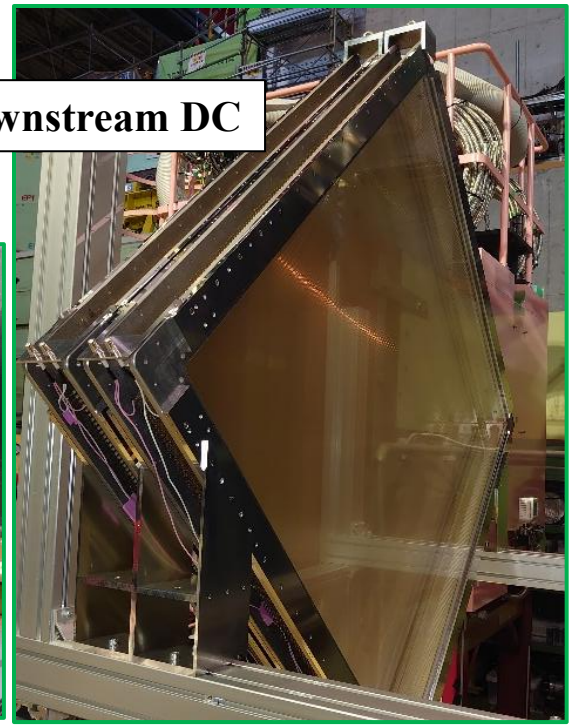


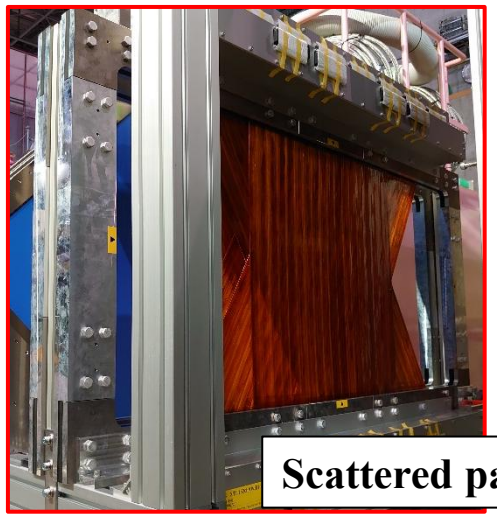


Beam fiber tracker



Target downstream DC





Scattered particle fiber tracker



MPPC array



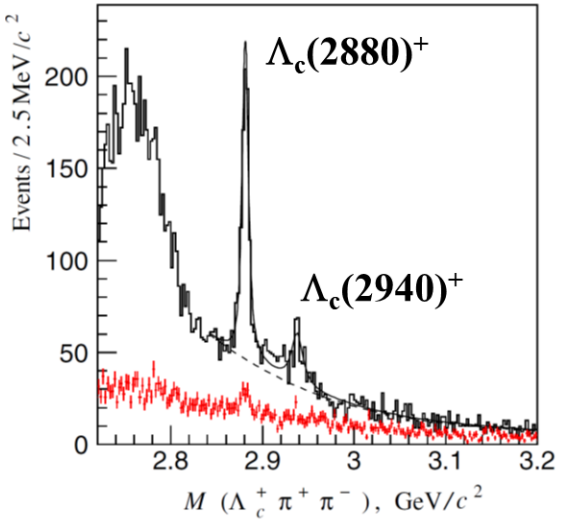
Internal DC

Experimental situations in PDG: Λ_c^*/Σ_c^*

λ mode ?
ρ mode ?

	J^P	Rating	Mass [MeV/c^2]	Width [MeV]	$\Sigma_c\pi$	$\Lambda_c\pi$	$\Lambda_c\pi\pi$	$\bar{D}N$
$\Lambda_c(2940)^+$	$3/2^-$	3*	2939.6	20^{+6}_{-5}	○	-	-	○
$\Lambda_c(2910)^+$	?	1*	~2914	52 ± 27	○	-	-	-
$\Lambda_c(2880)^+$	$5/2^+$	3*	2881.6	$5.6^{+0.8}_{-0.6}$	○	-	○	○
$\Lambda_c(2860)^+$	$3/2^+$	3*	~2856	68^{+12}_{-22}	-	-	-	○
$\Lambda_c(2750)^+$	$1/2^+$	1*	2766.6	50	-	-	○	-
$\Lambda_c(2625)^+$	$3/2^-$	3*	2628.0	< 0.52	○	-	○	-
$\Lambda_c(2590)^+$	$1/2^-$	3*	2592.3	2.6 ± 0.6	○	-	○	-
$\Lambda_c(G.S.)^+$	$1/2^+$	4*	2286.5	-	-	-	-	-
$\Sigma_c(2800)^+$	?	1*	~2792	60^{+60}_{-40}	-	○	-	-
$\Sigma_c(2520)^+$	$3/2^+$	3*	2517.4	$17.2^{+4.0}_{-2.2}$	-	○	-	-
$\Sigma_c(2455)^+$	$1/2^+$	3*	2452.7	2.3 ± 0.4	-	○	-	-

$\Lambda_c\eta$ 2834
nD^+ 2809
pD^0 2802
$\Lambda_c\pi\pi$ 2666
$\Sigma_c^*\pi$ 2660
$\Sigma_c\pi$ 2595
nD^+ 2809
pD^0 2802
$\Lambda_c\pi\pi$ 2666
$\Lambda_c\pi$ 2426



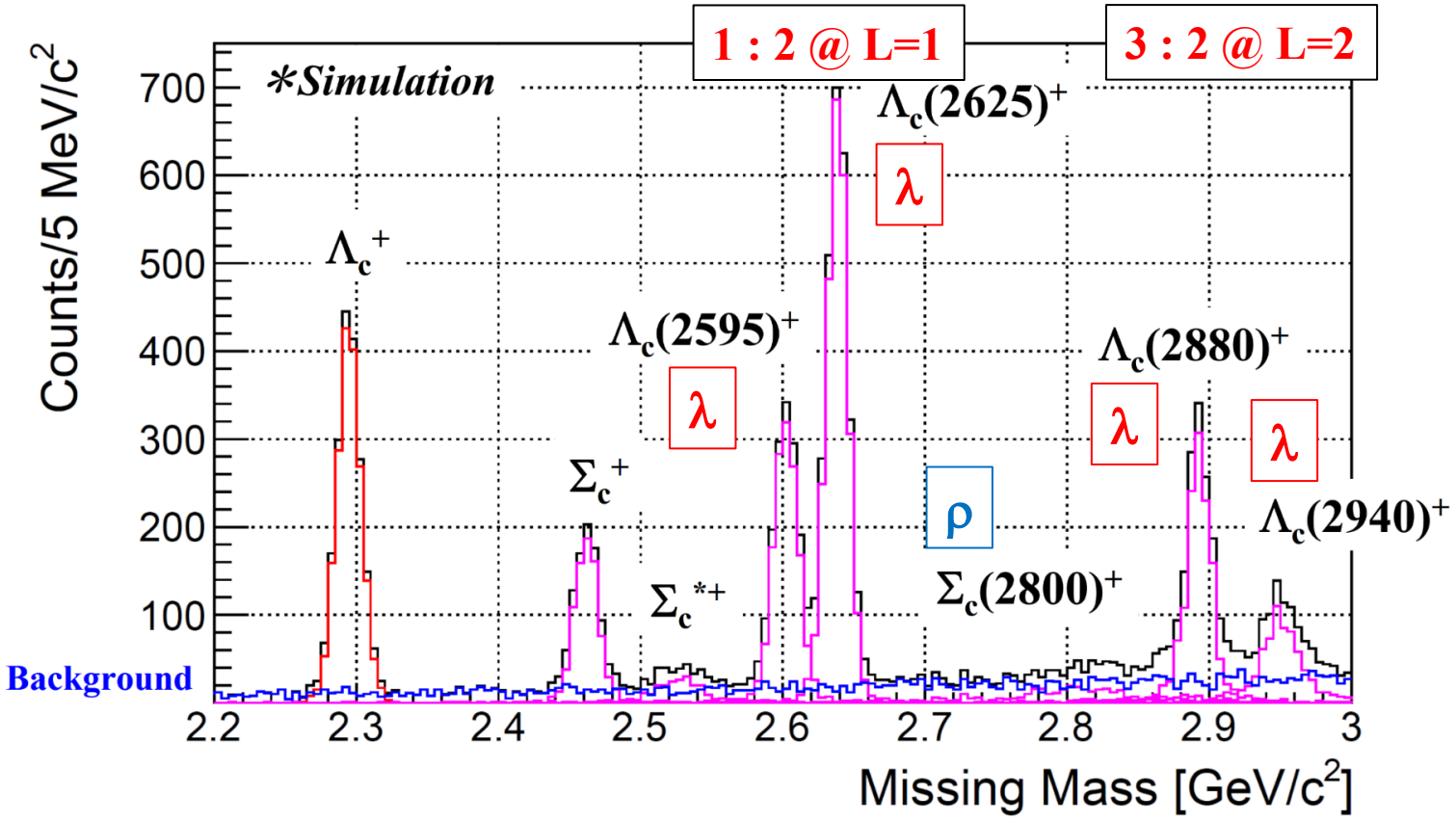
Belle collaboration, PRL98, 262001(2007)

∗ Decay modes
○: Observed mode

∗ J^P determination ⇒ Not experimentally determined (PDG)

- Excited 8 Λ_c and 3 Σ_c states were reported.

Expected mass spectrum: $\pi^- p \rightarrow D^{*-} Y_c^{*+}$



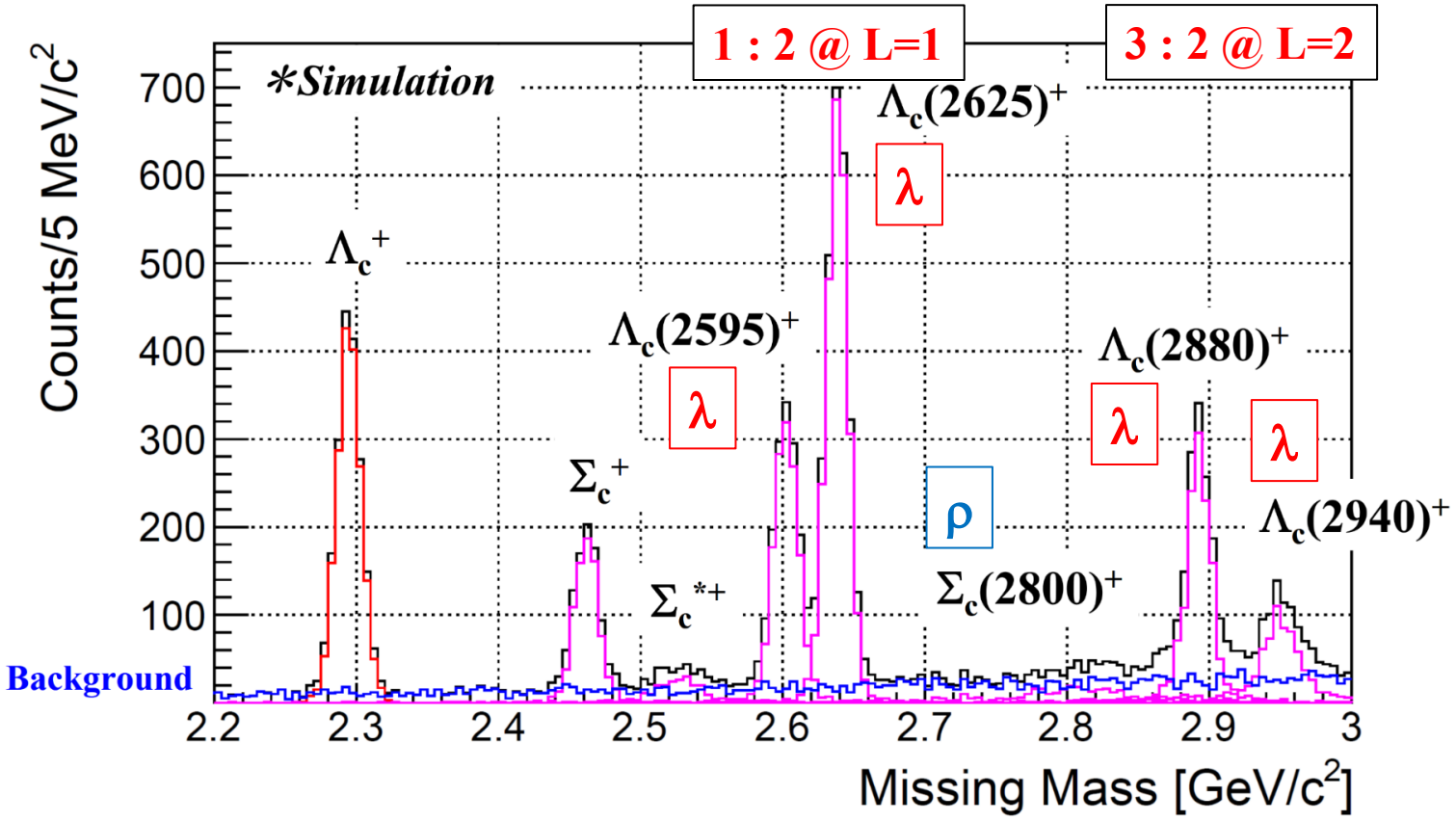
PDG	J^P	J^P (simulation)
$\Lambda_c(2940)^+$	?	$3/2^+$
$\Lambda_c(2880)^+$	$5/2^+$	$5/2^+$
$\Lambda_c(2860)^+$	$3/2^+$	–
$\Sigma_c(2800)^+$	?	$1/2^-$
$\Lambda_c(2750)^+$	$1/2^+$?	–
$\Lambda_c(2625)^+$	$3/2^-$?	$3/2^-$
$\Lambda_c(2590)^+$	$1/2^-$	$1/2^-$
$\Sigma_c(2520)^+$	$3/2^+$?	$3/2^+$
$\Sigma_c(2455)^+$	$1/2^+$	$1/2^+$
$\Lambda_c(G.S.)^+$	$1/2^+$	$1/2^+$

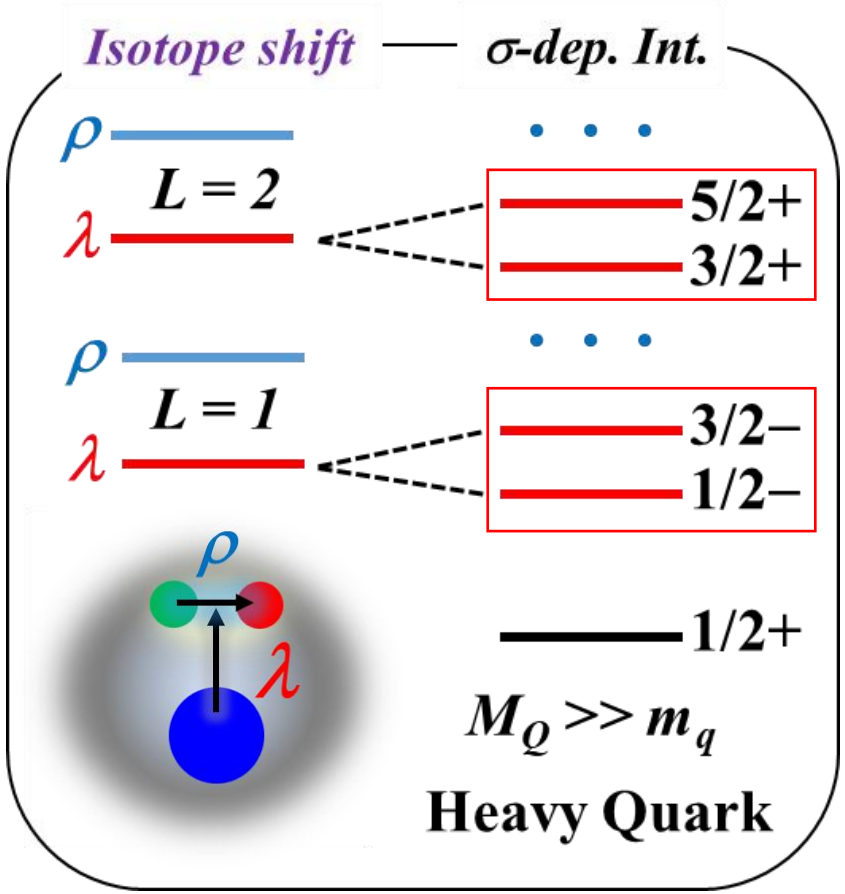
Not experimentally determined (PDG)

λ mode
ρ mode

- **Production measurement ⇒ λ/ρ mode assignment**
  - **Production rate of LS doublet = *L* : *L*+1**
    - **λ mode enhanced + Small production rate of ρ mode (0.2 nb w/ Γ =100 MeV)**
  - **Angular distribution (*t*-dependence: dσ/d*t*) contains structure information.**
    - **Slope response: Internal structure related to diquark correlations**

Expected mass spectrum: $\pi^- p \rightarrow D^{*-} Y_c^{*+}$

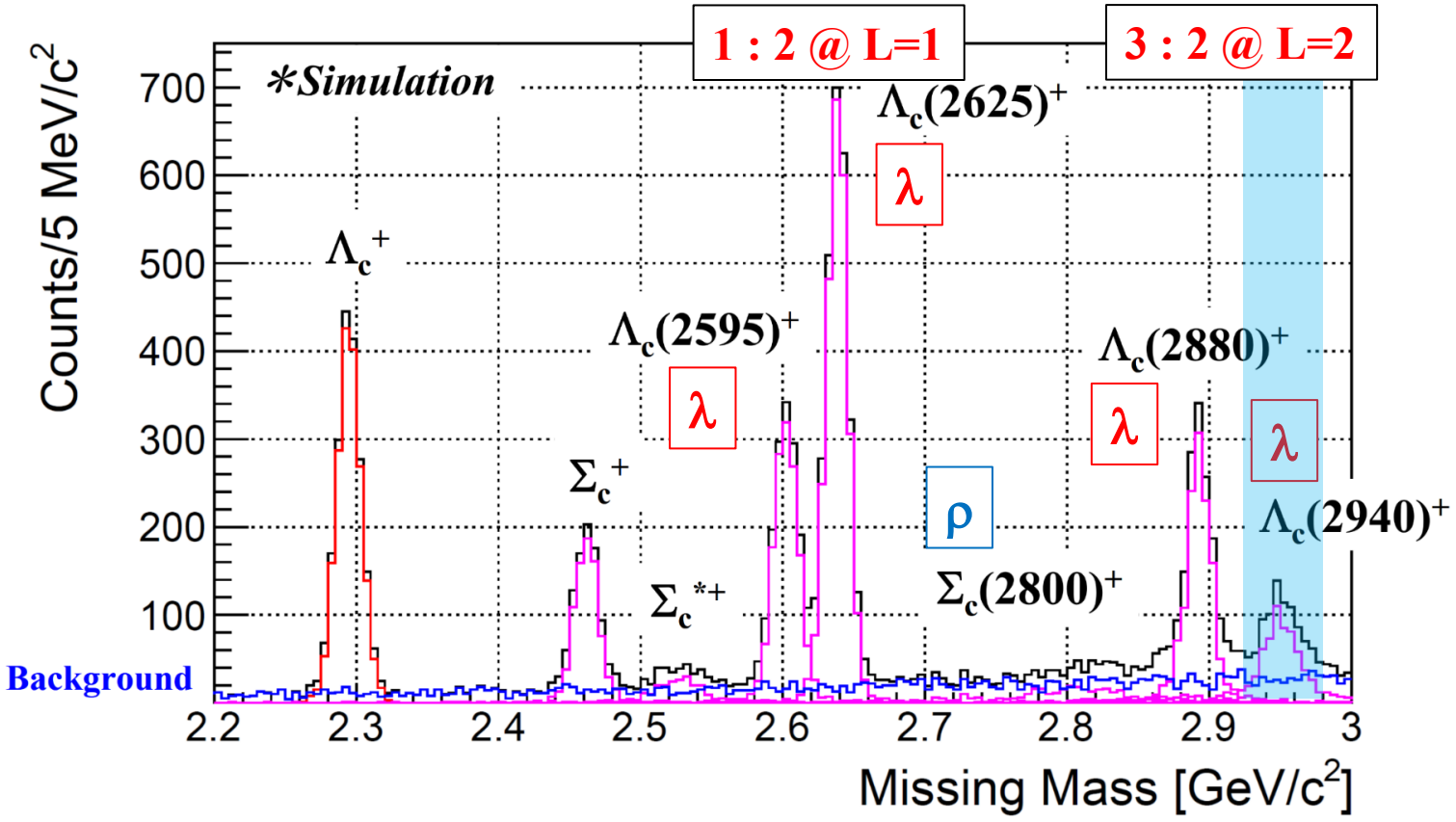


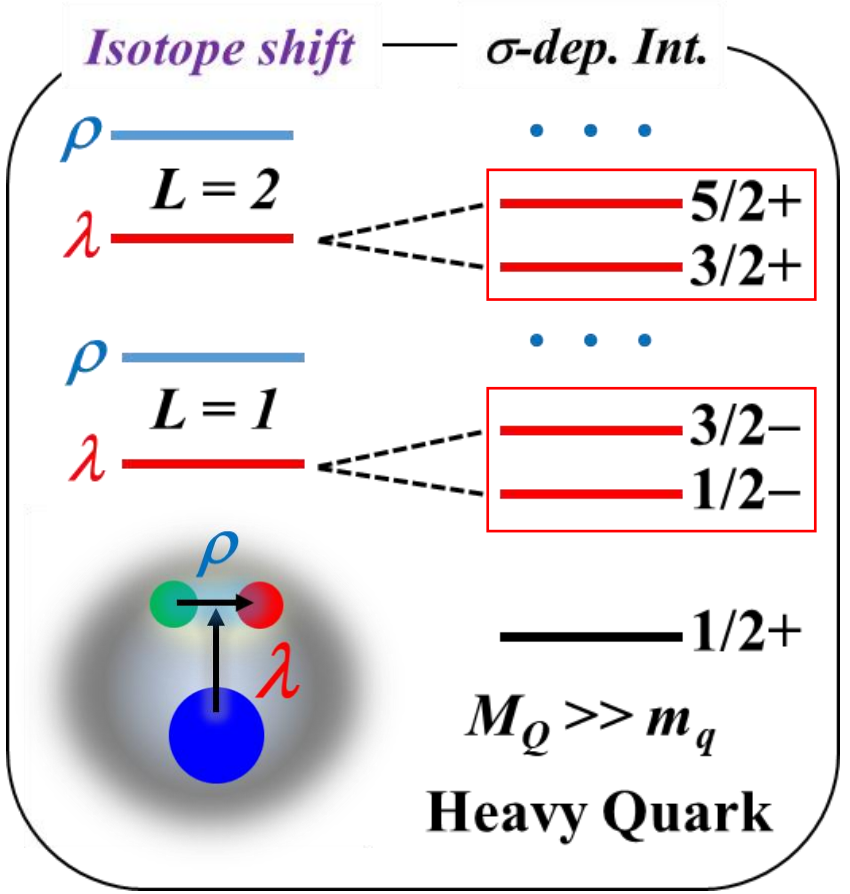


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HQ doublet

Expected mass spectrum: $\pi^- p \rightarrow D^{*-} Y_c^{*+}$

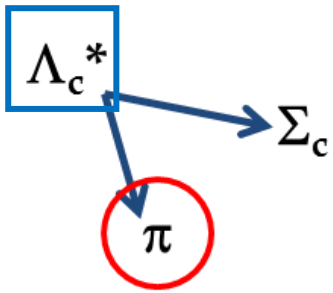


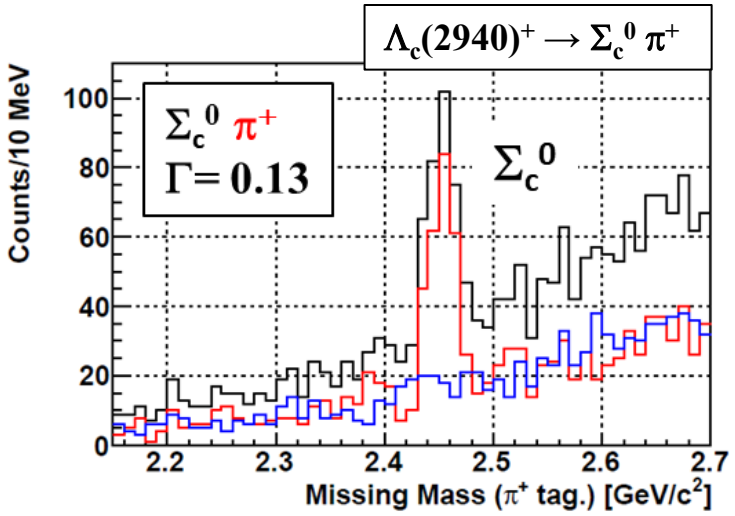


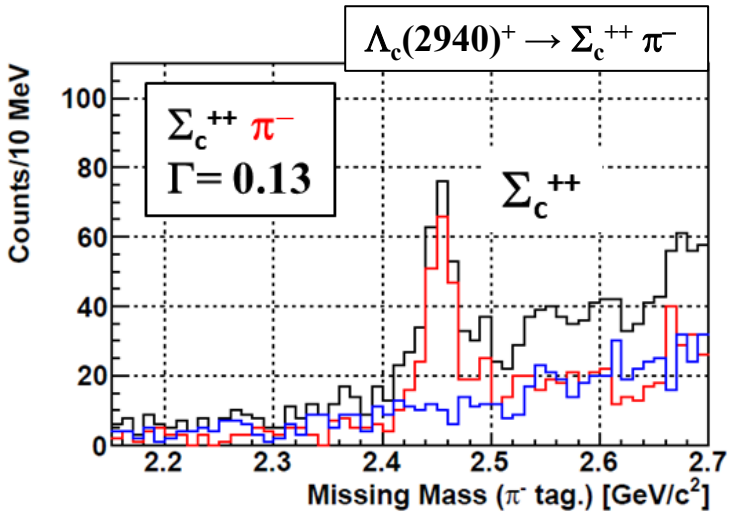
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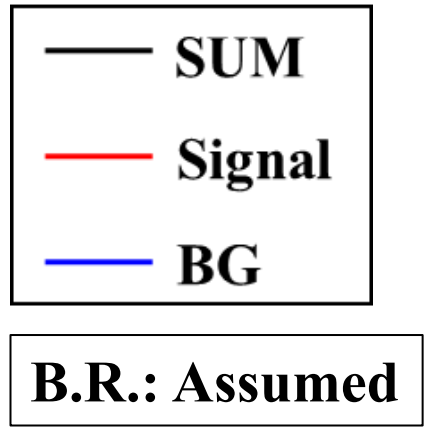
HQ doublet

Decay measurement: $\Lambda_c(2940)^+ \to \Sigma_c^{++/0}\,\pi^{-/+}$ and p D^0

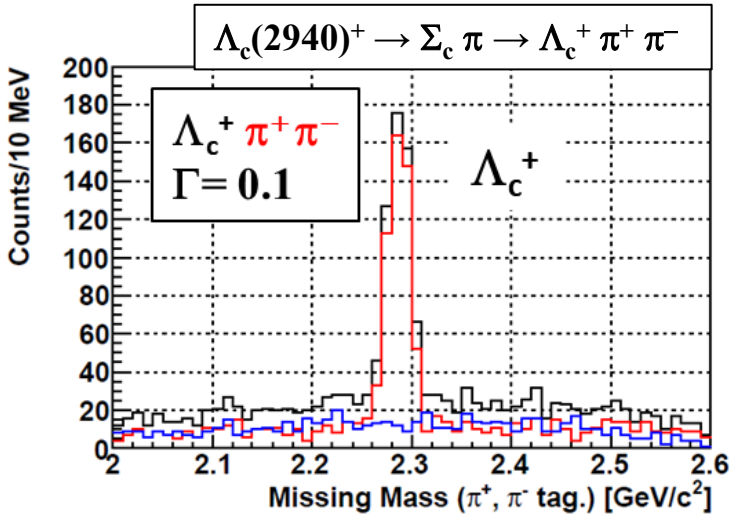


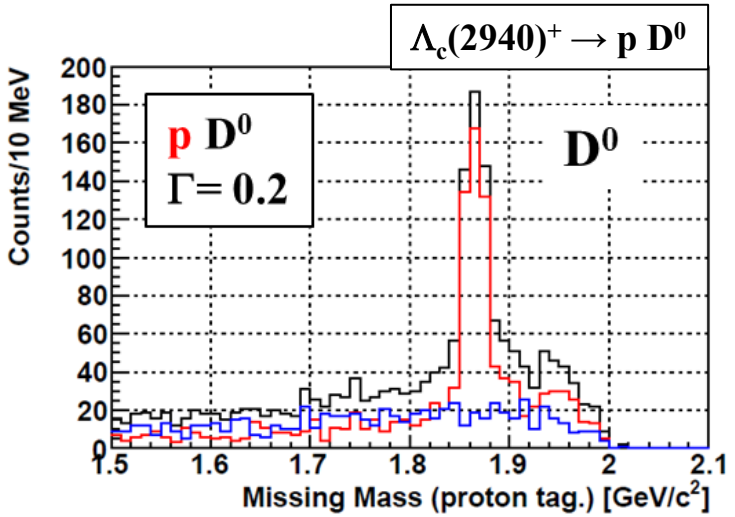


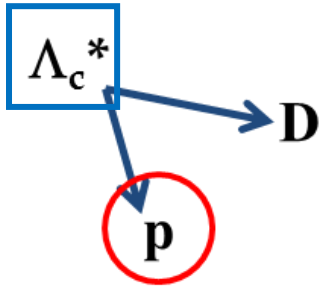




B.R.: Assumed







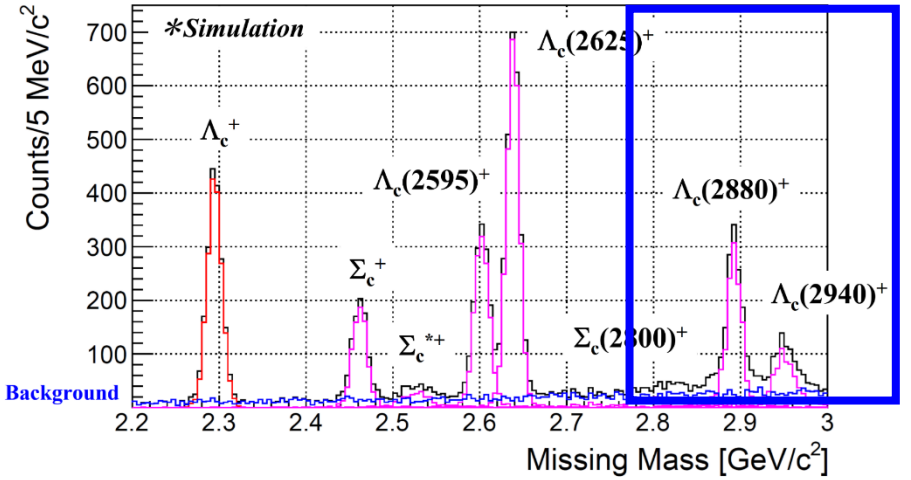
Decay measurements can also give us information of excited state properties.

- **Absolute branching ratios: $\Gamma(\Lambda_c^* \to p\,D) \Leftrightarrow \Gamma(\Lambda_c^* \to \Sigma_c\,\pi) \Rightarrow \lambda/\rho$ mode assignment**

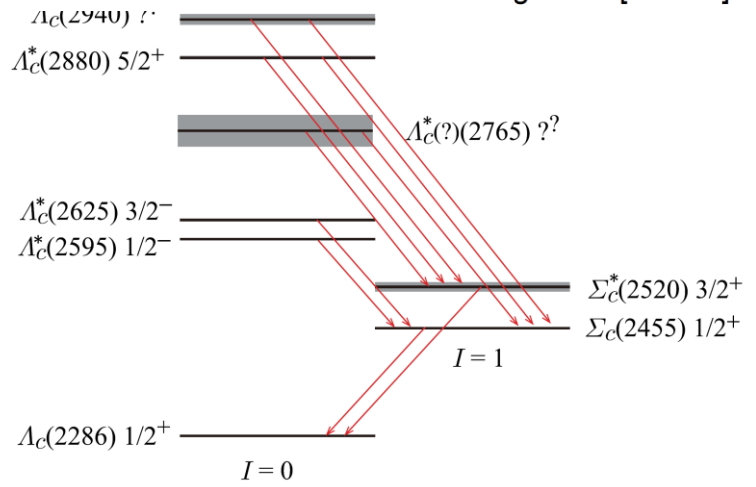
Heavy quark doublet in highly excited states

- $\Lambda_c(2880)$
  - $J^P = 5/2^+$ measured by Belle (PRL98, 262001, 2007)

  ⇒ $\Lambda_c(2880)(5/2^+)$ is likely to be $\lambda\rho$ mode ($\lambda = 1$, $\rho = 1$).
    - Brown muck: J = 3
    - H. Nagahiro et al., Phys. Rev. D 95, 014023 (2017)



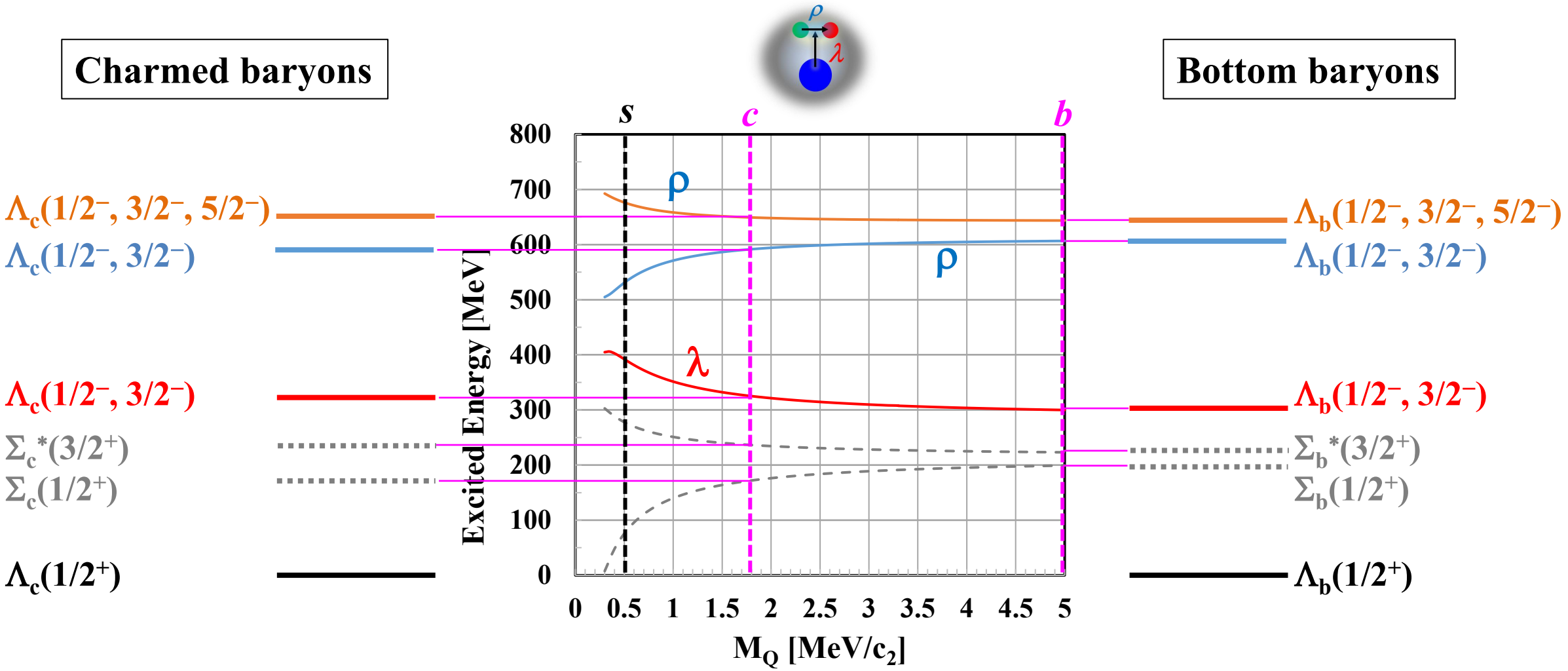
- $\Lambda_c(2940)$
  - J^P is not determined.
  - LHCb data: $3/2^-$? (1/2 and 7/2 cannot be excluded)
    - $D^0 p$ amplitude in $\Lambda^0_b \to D^0 p \pi^-$ (JHEP05(2017)030)
  - If partner is $\Lambda_c(2880)(5/2^+) \Rightarrow J^P = 7/2^+$
    - H. Nagahiro et al., Phys. Rev. D 95, 014023 (2017)



Studies by pionic decays: $\Lambda_c^* \to \Sigma_c \pi \to \Lambda_c^* \pi \pi$
* Essential role of Heavy Quark Symmetry

* Where are HQ doublet states ? ($\lambda = 2$ mode)
  - Brown muck: J=2 ⇒ $\Lambda_c(2860)$? $\Lambda_c(2910)$?
  - Properties of highly excited states can be tested by production measurement.

Level structure of the *q*-*q* + Q system



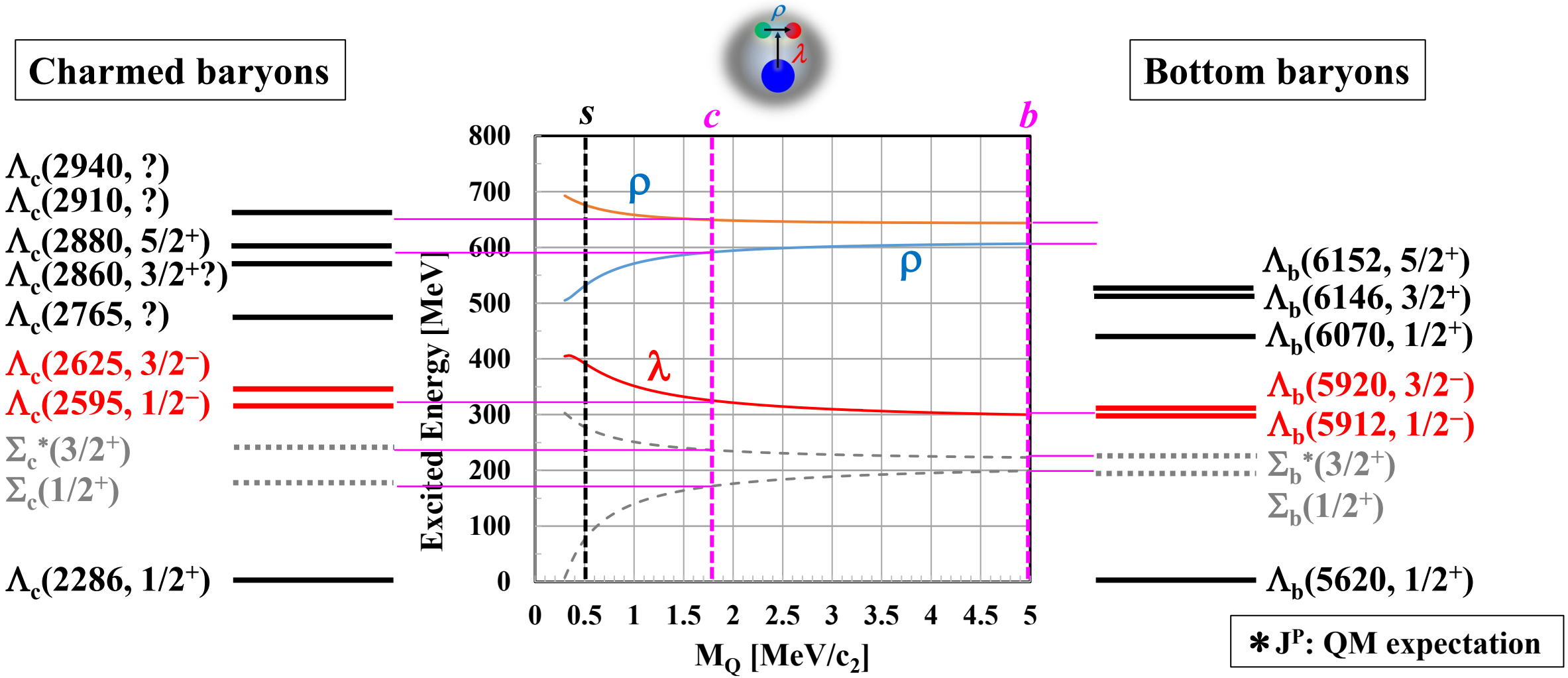
- Non-rel. QM: $H = H_0 + V_{conf} + V_{SS} + V_{LS} + V_T$
- λ-ρ mixing

(cal. By T. Yoshida et al., Phys. Rev. D92 , 114029(2015)

∗ Diquark correlation: λ & ρ

∗ Theoretical calculation (Λ_c/Λ_b states)

Level structure of the *q*-*q* + Q system



- Non-rel. QM: $H = H_0 + V_{conf} + V_{SS} + V_{LS} + V_T$
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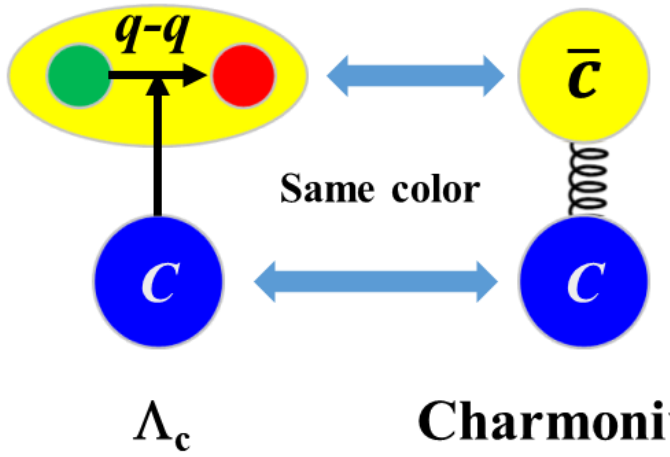
∗ Diquark correlation: λ & ρ

∗ Experimental data (Λ_c/Λ_b states)

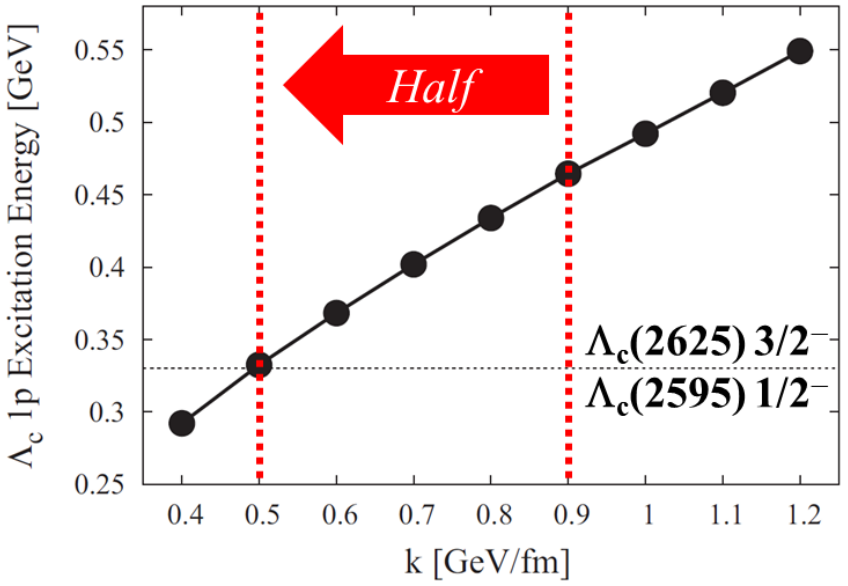
Excited energy of highly excited states

- **Excitation energy ⇔ Quark confinement potential**
  - Quark-diquark model: $V(r) = -\frac{4}{3}\frac{\alpha}{r} + kr + V_0$
    - D. Jido and M. Sakashita, PTEP2016(16)083D02

⇒ ***k*** **for** Λ_c **&** Λ_b **should be half of** $c\bar{c}$ **case.**
  - $k = 0.9$ GeV/fm ⇒ $k = 0.5$ GeV/fm



- **What happens in excited states ?**
  - Three-body calculation gave the same results.
  - Effective treatment of string tension ?
  - Reflect dynamics of diquark correlations ?
    - Different effects from *ud* and *uc*/*dc* configurations ?



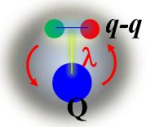
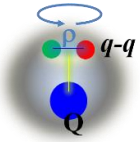
∗ Production rates tell us internal structures.
- Wave function information of quark and diquark
- Production measurement from low-lying to highly excited states

Study of diquark via charmed baryon spectroscopy

- **Effects of spatial distribution of *ud* diquark**
  - **Cross section: Diquark form factor (reduce) ⇔ $(q_{eff}/\alpha)^{L}$ (increase)**
  - **Keep *L*:*L*+1 ratio of LS doublet states**

- **Investigation of diquark configurations**

∗ *ud* ⇒ *uc*/*dc* configuration: Mixing configurations of λ and ρ modes

$\Psi = C_\lambda |$  $> + C_\rho |$  $>$

- **Production mechanism: λ mode are populated.**

⇒ Enhancement of λ-modes but ratio changed depending on excited state property

- **Production rates also contain interference of λ and ρ modes.**

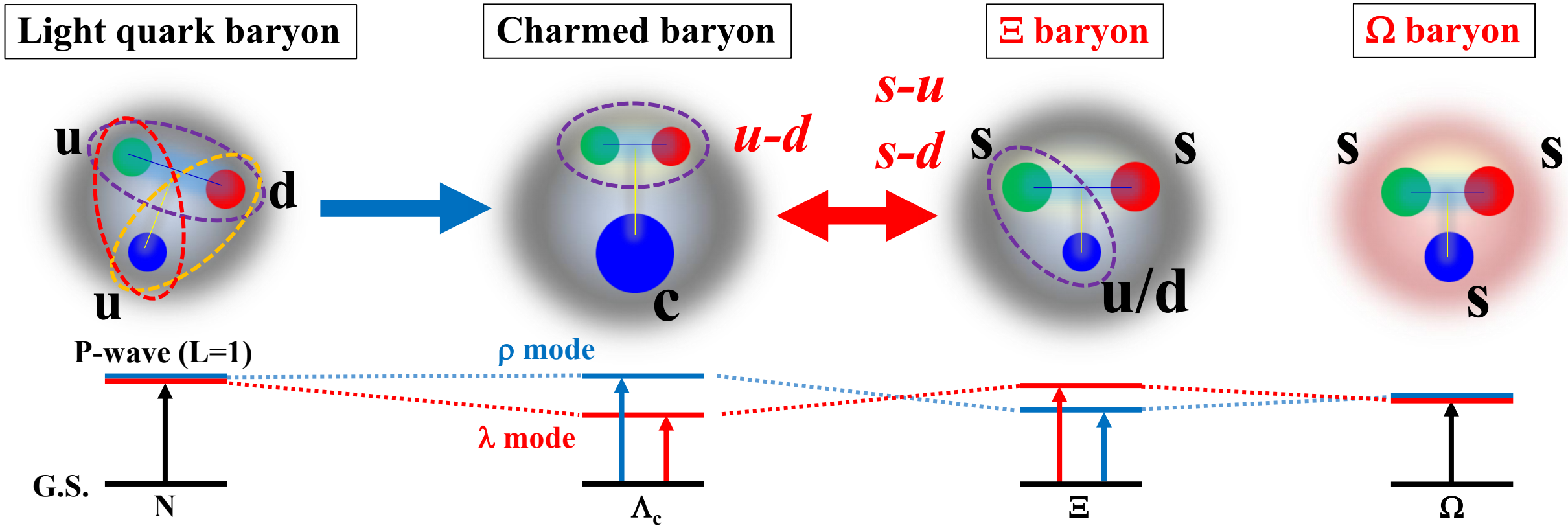
- ***t*-dependence:of dσ/d*t* (slope response) and decay property**
  - **Complementary information of production rates**

⇒ Diquark configurations (ratio of *ud* and *uc*/*dc*) can be determined.

∗ Production mechanism is a key to reveal diquark correlations in Λ_c^*.

Systematic baryon spectroscopy

Systematic study of diquark correlation



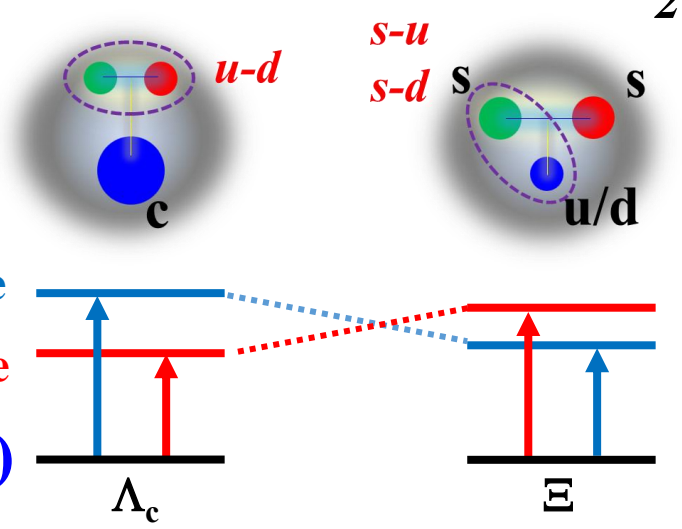
- Charmed baryon: *ud* diquark ⇔ *uc*/*dc* diquark ⇒ CMI ⇔ Instanton
- Ξ: *us*/*ds* diquark ⇒ Weaker attraction due to heavier mass: CMI ⇔ Instanton
- Ω: *ss* diquark (Axial-vector diquark) ⇒ Weaker attraction of CMI and no Instanton

∗ Production and decay measurements from low-lying to highly excited states

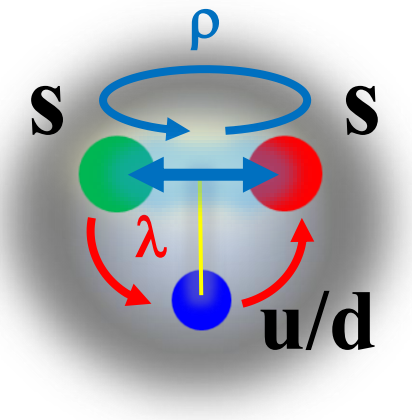
Study of Ξ baryon

- Ξ baryon: *us*/*ds* diquark correlation
  - Inversion of excitation energy: ρ mode < λ mode
  - Strength of *us*/*ds* diquark correlation: LS splitting

∗ Identification of LS partner is necessary. (Production rate)



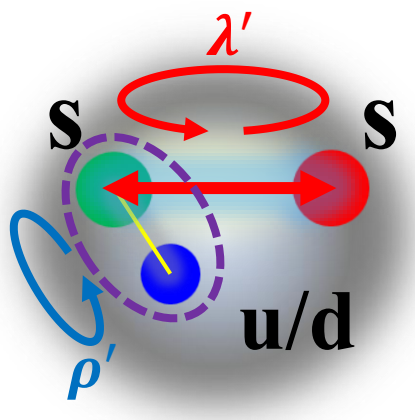
LS partner (L=1)
ρ mode

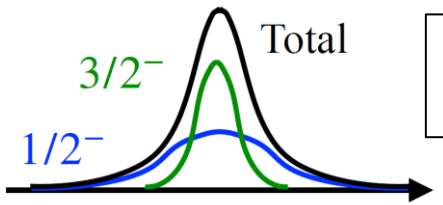


$$\rho = \frac{\sqrt{3}}{2}\lambda' + \frac{1}{2}\rho'$$

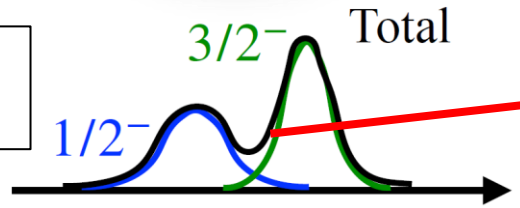
$$\lambda = -\frac{1}{2}\lambda' + \frac{\sqrt{3}}{2}\rho'$$

LS partner (L=1)
λ′ mode

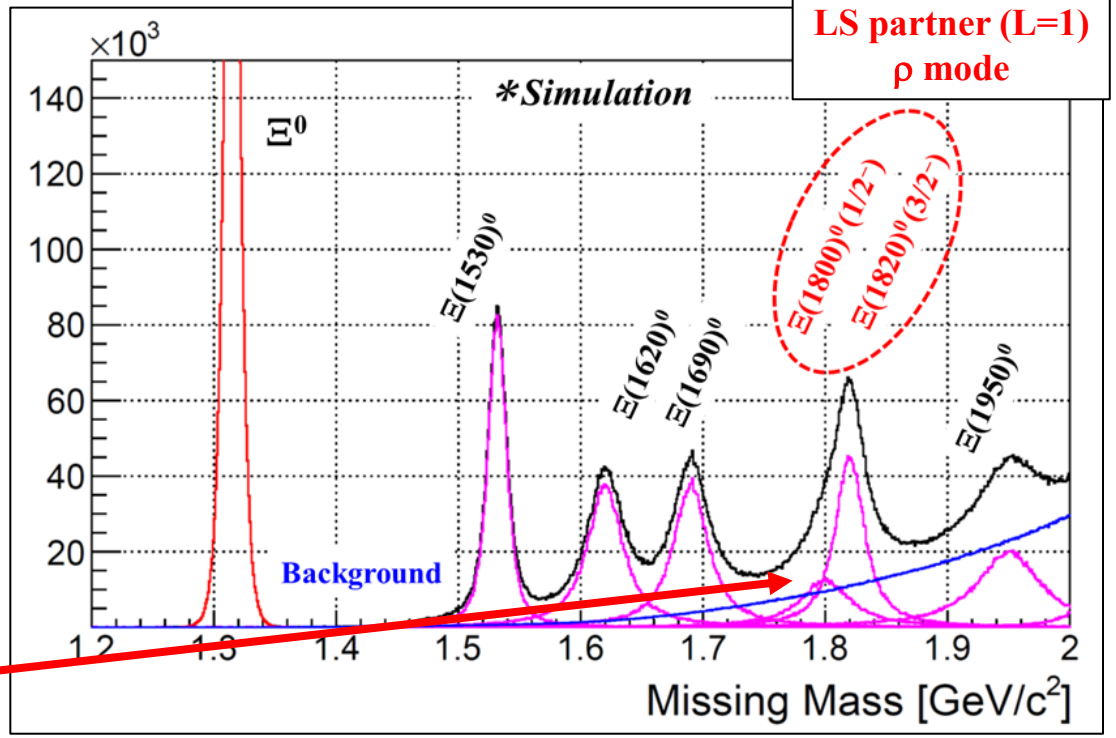




Mixing configuration of λ and ρ modes



LS partner (L=1)
ρ mode

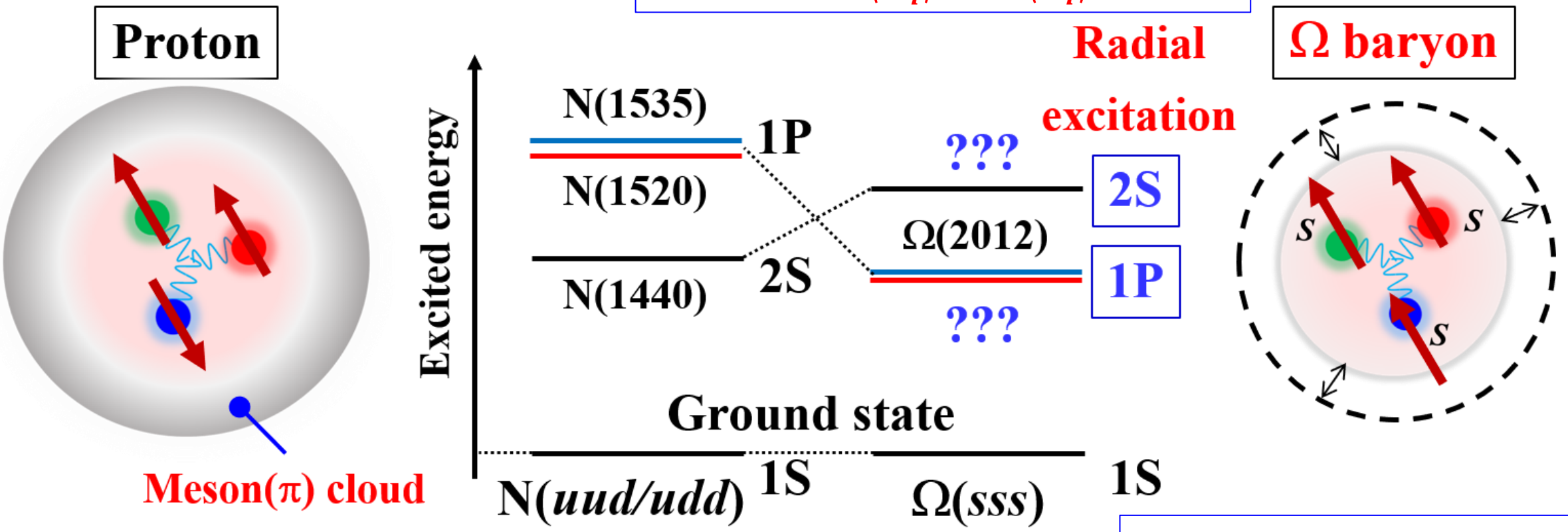


∗ Ξ(1800)⁰(1/2⁻): Assumed in simulation

Role of Ω baryon

Decay width ⇒ Spatial distribution

$$\Gamma \propto \langle p_q^2 \rangle \sim 1/\langle r_q^2 \rangle$$



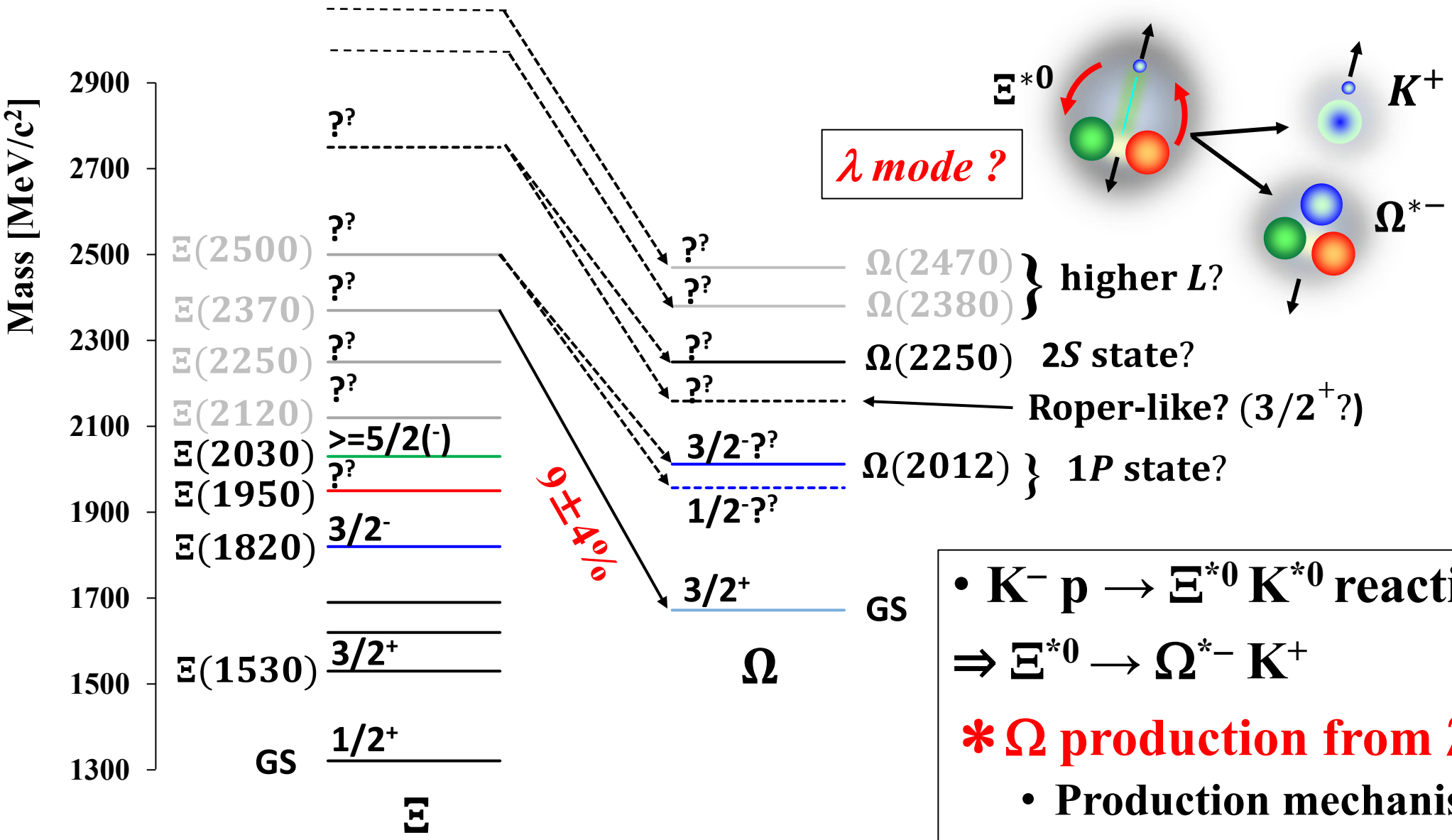
1P states: $1/2^- \Leftrightarrow 3/2^-$

- Degenerate (Quark model)
- Splitting (Origin ?)

- **Ω(sss) baryon: Flavor symmetric system**
- **Axial-vector diquark correlation system**
- **Free from Pion Cloud: Investigation of "Quark core" region (Non-perturbative region)**

⇒ Direct access to CMI contribution without I.I.I. and pion cloud

Relation between Ξ and Ω baryons: Production process



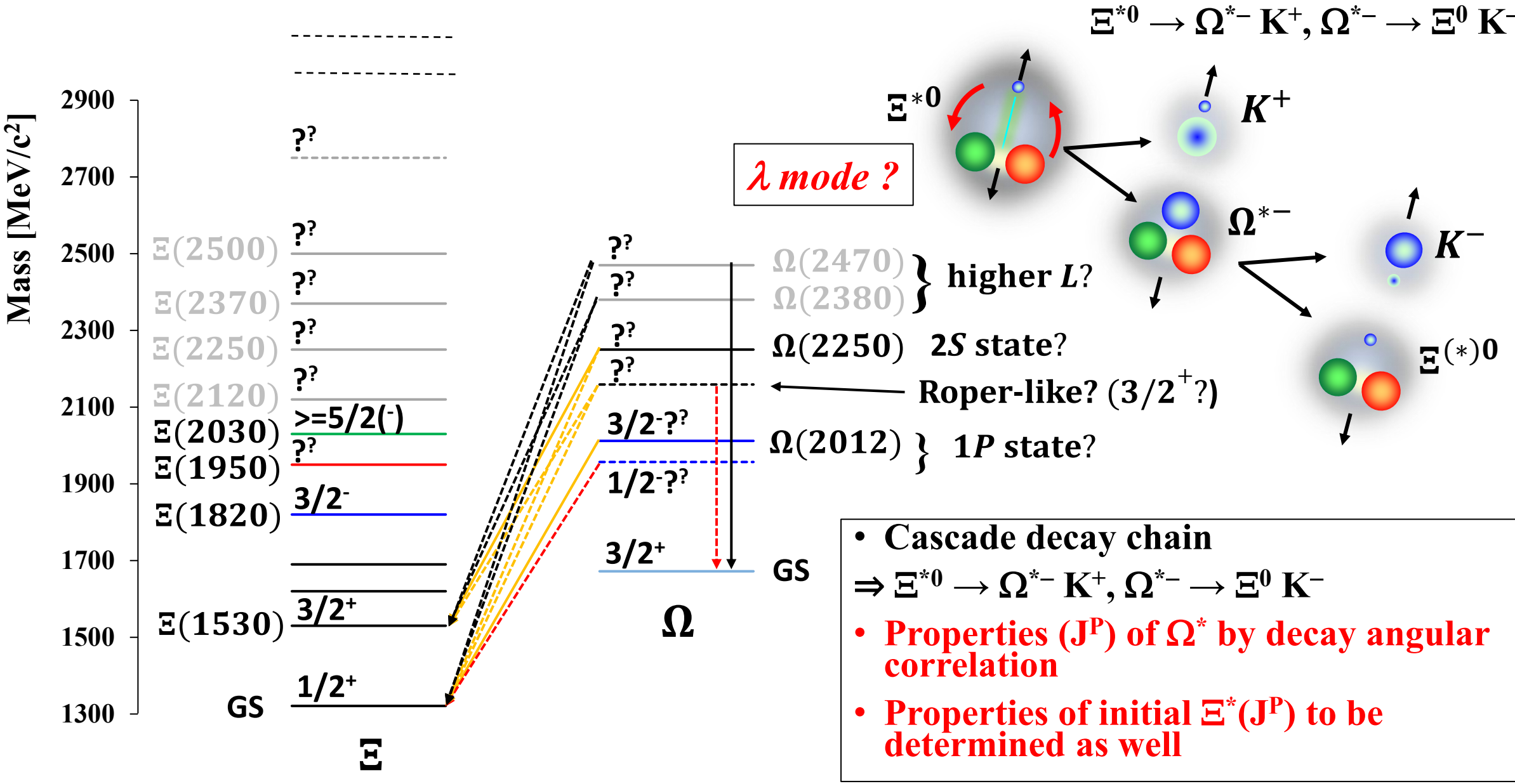
- $K^- p \rightarrow \Xi^{*0} K^{*0}$ reaction

$\Rightarrow \Xi^{*0} \rightarrow \Omega^{*-} K^+$

∗ Ω production from λ mode Ξ^*

- Production mechanism of Ω

Relation between Ξ and Ω baryons: Decay process



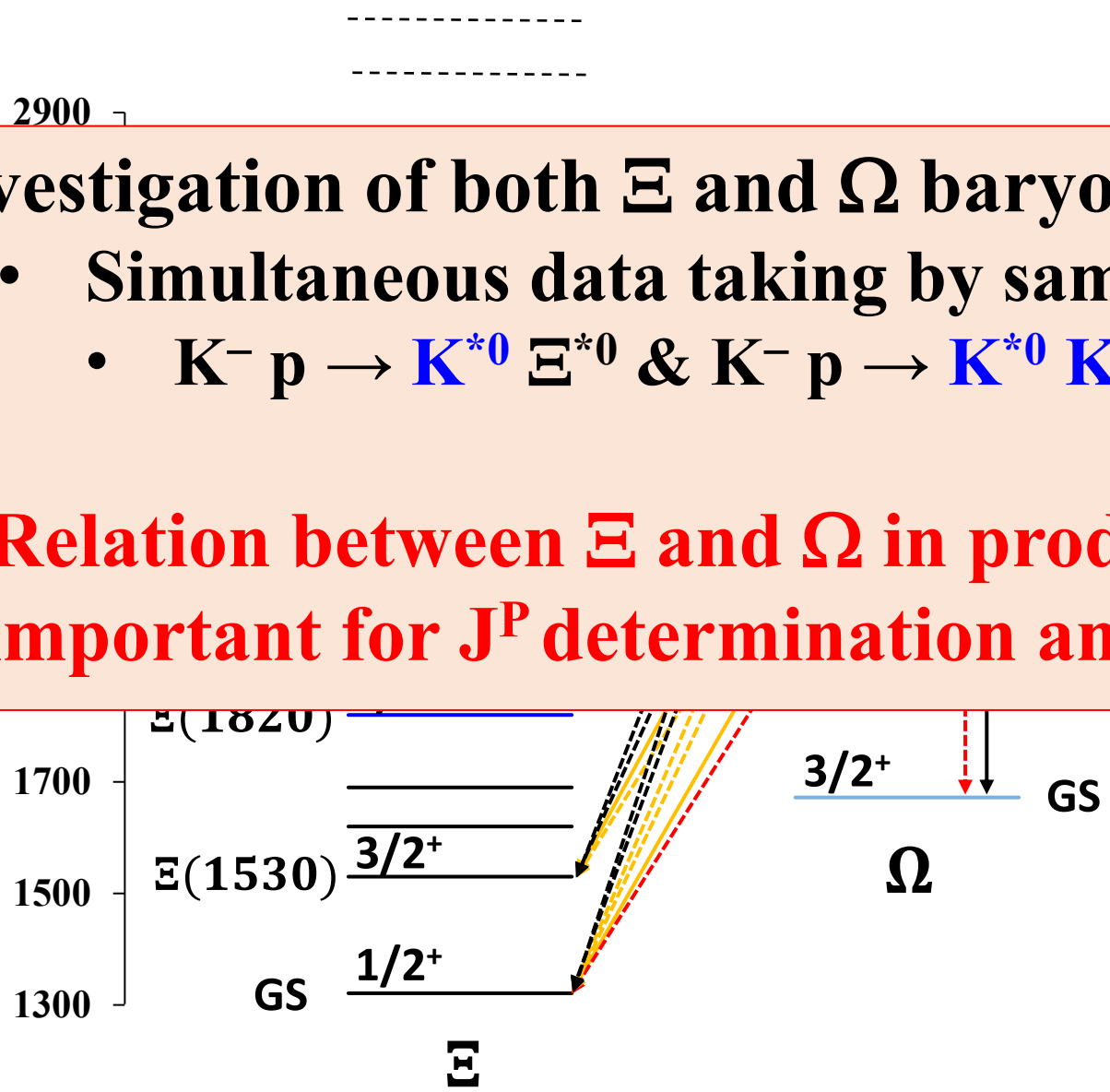
- Cascade decay chain

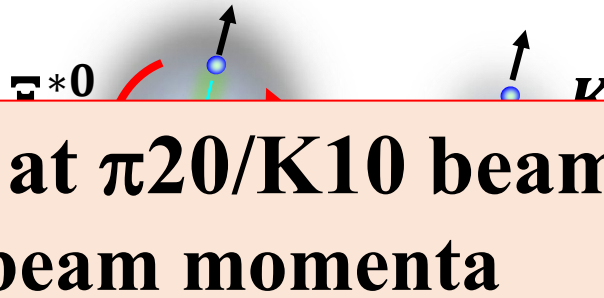
⇒ $\Xi^{*0} \rightarrow \Omega^{*-} K^{+}, \Omega^{*-} \rightarrow \Xi^{0} K^{-}$

- **Properties (J^P) of Ω^* by decay angular correlation**
- **Properties of initial $\Xi^*(J^P)$ to be determined as well**

Relation between Ξ and Ω baryons: Decay process

$\Xi^{*0} \rightarrow \Omega^{*-} K^+, \Omega^{*-} \rightarrow \Xi^0 K^-$





Investigation of both Ξ and Ω baryons at π20/K10 beam line

- **Simultaneous data taking by same beam momenta**
  - **$K^- p \rightarrow K^{*0} \Xi^{*0}$ & $K^- p \rightarrow K^{*0} K^+ \Omega^{*-}$ @ 7–10 GeV/c**

∗ Relation between Ξ and Ω in production and decay processes is important for J^P determination and λ/ρ assignment.

- **Cascade decay chain**

⇒ $\Xi^{*0} \rightarrow \Omega^{*-} K^+, \Omega^{*-} \rightarrow \Xi^0 K^-$

- **Properties (J^P) of Ω^* by decay angular correlation**
- **Properties of initial Ξ^*(J^P) to be determined as well**

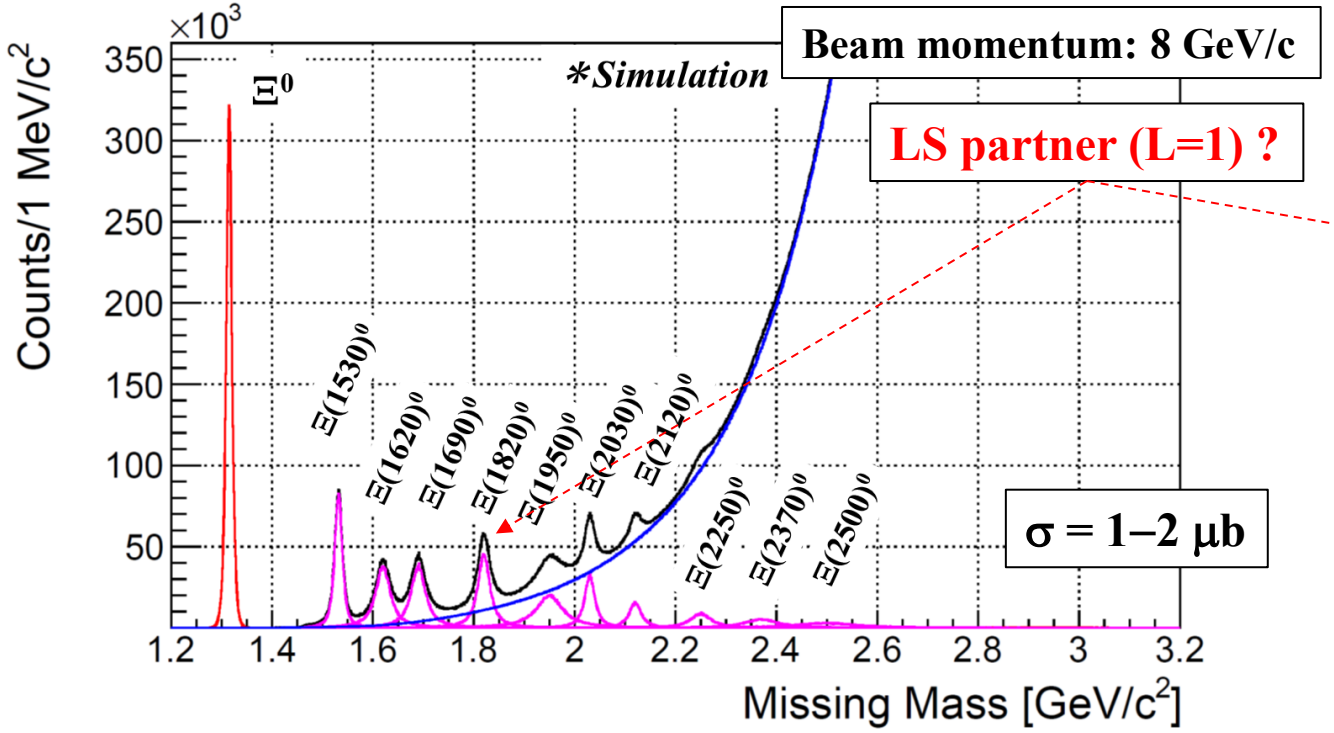
PDG situations: Ξ^* and Ω^*

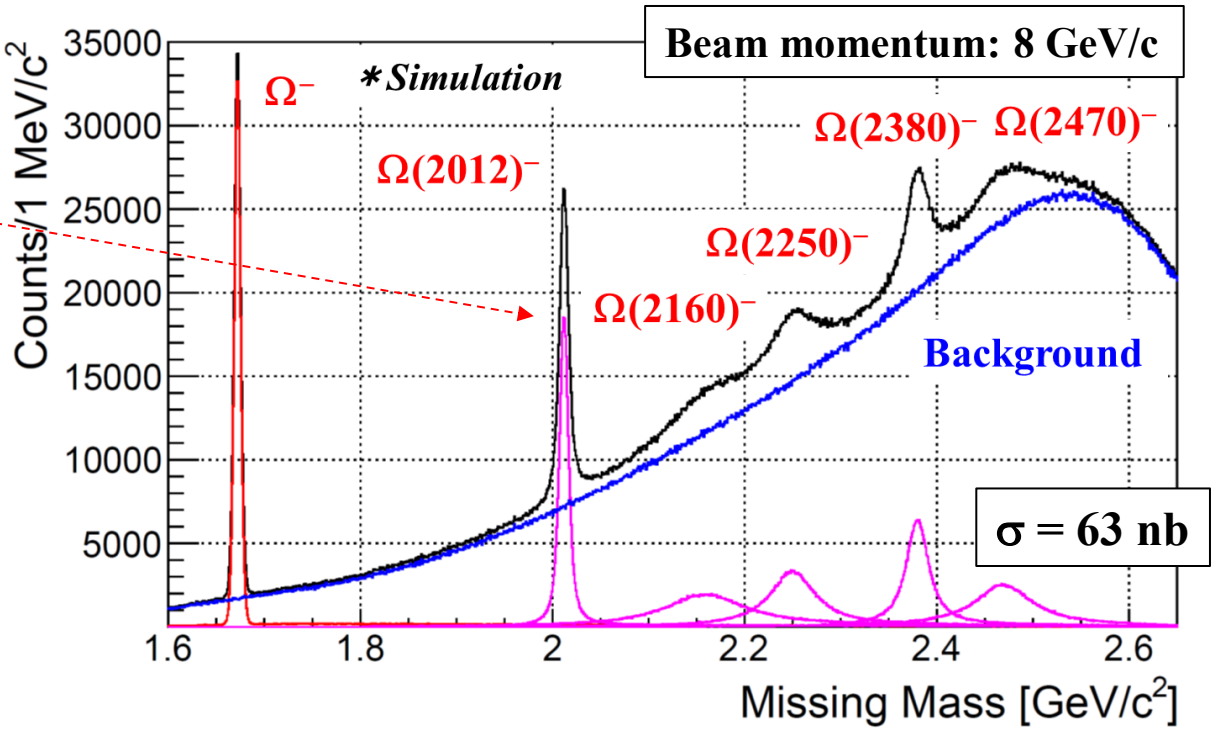
Ξ^*	J^P	Rating	Width [MeV]
Ξ(2500)	??	*	150?
Ξ(2370)	??	**	80?
Ξ(2250)	??	**	47±27?
Ξ(2120)	??	*	25?
Ξ(2030)	>=5/2?	***	20^{+15}_{-5}
Ξ(1950)	??	***	60±20
Ξ(1820)	3/2–	***	24^{+15}_{-10}
Ξ(1690)	??	***	< 30
Ξ(1620)	??	**	20–40?
Ξ(1530)	3/2+	****	10
Ξ(g.s)	1/2+	****	-

Ω^*	J^P	Rating	Width [MeV]
Ω(2470)	??	**	72±33
Ω(2380)	??	**	26±23
Ω(2250)	??	***	55±18
Ω(2012)	??	***	$6.4^{+3.0}_{-2.6}$±1.6
Ω(g.s)	$3/2^+$	****	-

- Most of spins/parities/decay branches have not been determined yet.
- Ω(2380) and Ω(2470) are discarded from PDG table.

Expected mass spectra of Ξ^* and Ω^* by K^- p reaction





- **Reaction: $K^- p \rightarrow K^+ \Xi^{*-}$ / $K^- p \rightarrow K^{*0} \Xi^{*0}$**
  - **Beam: 5–8 GeV/c**
- **Missing mass: K^+ / K^{*0}**
  - **Mass resolution: ΔM ~7 MeV(σ)**

- **Reaction: $K^- p \rightarrow \Omega^{*-} K^{*0} K^+$**
  - **Beam: 7–10 GeV/c**
- **Missing mass: K^{*0} & K^+**
  - **Mass resolution: ΔM ~5 MeV(σ)**

∗ High momentum transfer = Highly excited state

⇒ Systematic studies: Production rate, SS/LS forces and internal quark motion

Summary

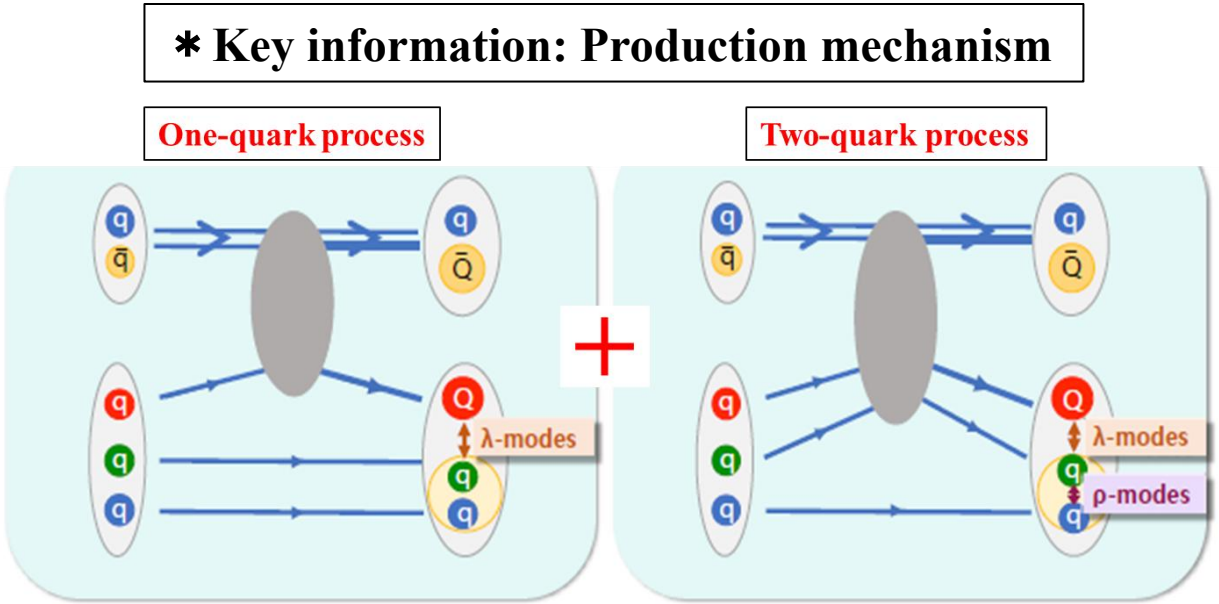
Strategy: π20 and K10

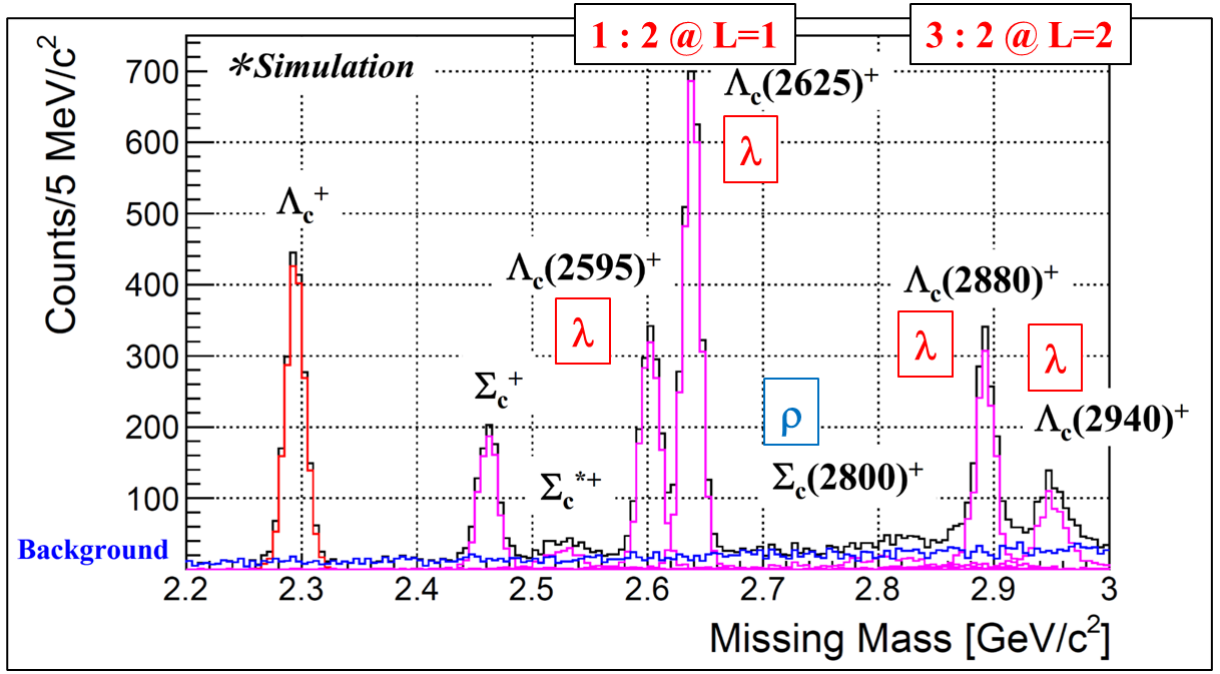
1. **Systematic measurements:** Excited states properties of Λ_c/Σ_c, Ξ, Ω
   - Mass, width, spin-parity, decay branching ratio, production rate
     - From ground states to highly excited states (L = 1 and 2…)

2. λ/ρ mode assignment by combining J^P, production rates and decay branching ratios
   - Production measurement: Access to wave function information of quark and diquark
   - Determination of LS partner (HQ doublets) in L=1 and 2… states
   - Decomposition by decay analysis of all possible channels and production/decay rates

⇒ Establish diquark correlations in baryon excited states

∗ Key information: Production mechanism





Summary

- **How quarks build hadrons ?**
  - **Understanding of QCD dynamics in the low-energy regime**

- **Study of charmed baryons**
  - **Charmed baryon spectroscopy via $\pi^- p \rightarrow D^{*-} Y_c^{*+}$ @ 20 GeV/c**
  - **Key: Disentangle diquark correlations by production mechanism**

- **Systematic measurements of baryon excited states: Λ_c/Σ_c, Ξ, Ω systems**
  - **Systematic investigation of *ud*, *us/ds* and *ss* diquark correlations**
  - **Production and decay measurements from low-lying to highly excited states**

- **High-intensity & High-momentum hadron beam: J-PARC π20/K10**
  - **Multipurpose spectrometer: MARQ at π20**

J-PARC hadron experimental facility provides unique opportunities for investigating diquark correlations.