



Spectroscopic study of the diquark correlation using hadron beams at J-PARC

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for the MARQ collaboration

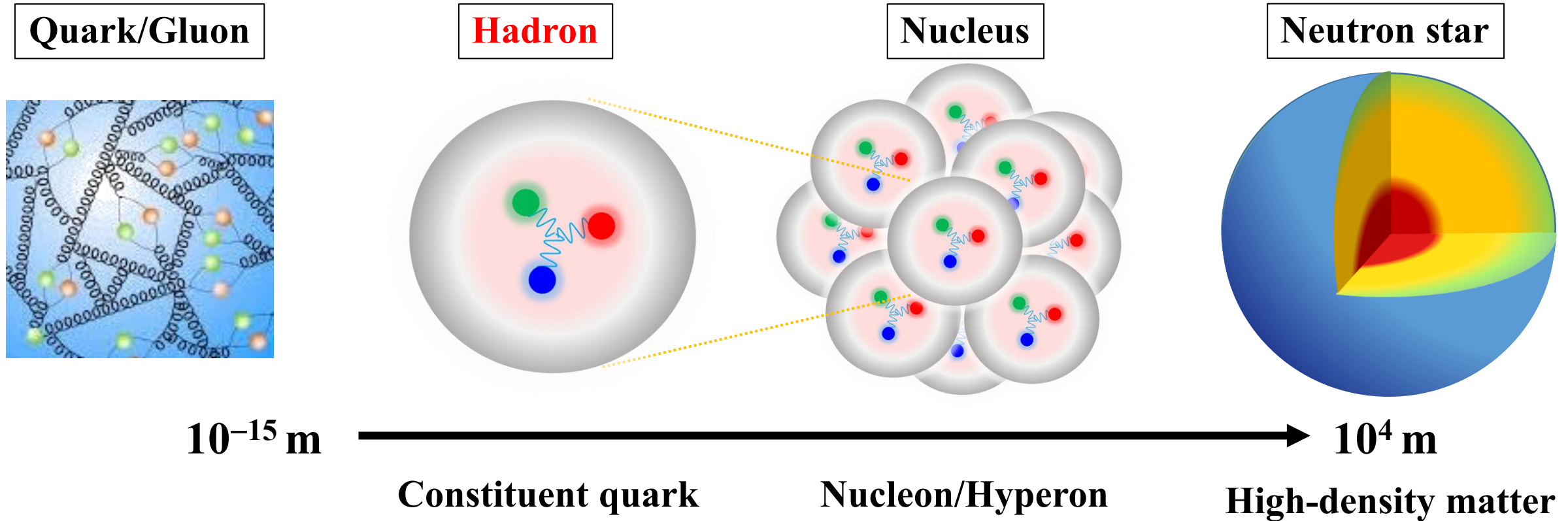
Research Center for Nuclear Physics (RCNP)
The University of Osaka

New Perspectives on exotic and heavy hadrons, 25–29 August 2026

28th Aug. 2026

Exploration of “Origin and Evolution of Matter”

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* How quarks build hadrons ?

- Investigation of QCD dynamics in the low-energy regime

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

$\pi 20$ & Hadron Experimental Facility Extension: K10

- $\pi 20$: π^- beam (Unseparated)

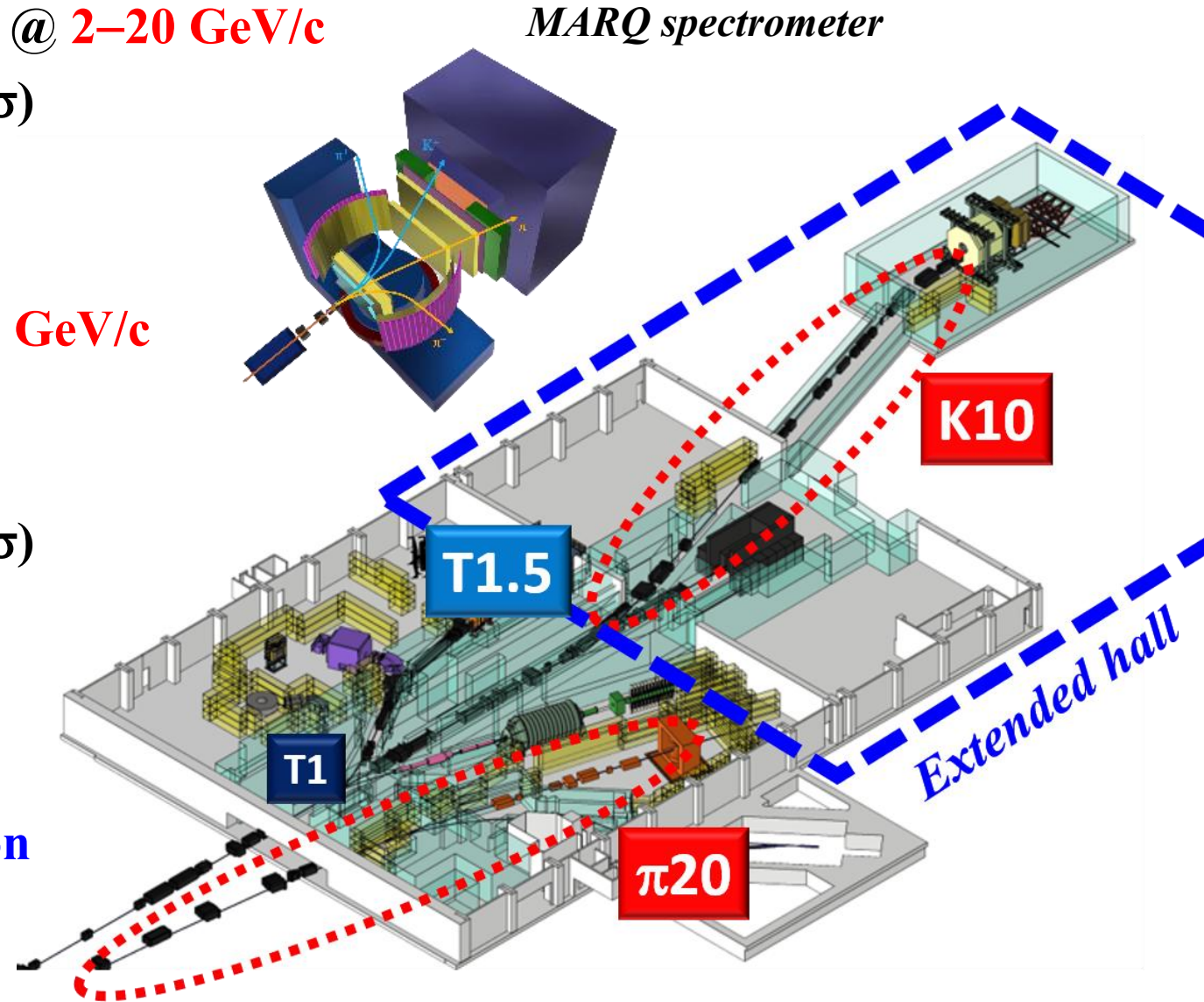
- Intensity: $>10^7$ /spill π^- (K^- , $\bar{p}$: 1–2%) @ 2–20 GeV/c
- Momentum resolution: $\Delta p/p = 0.1\%(\sigma)$

- 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



Study of hadron excited state property

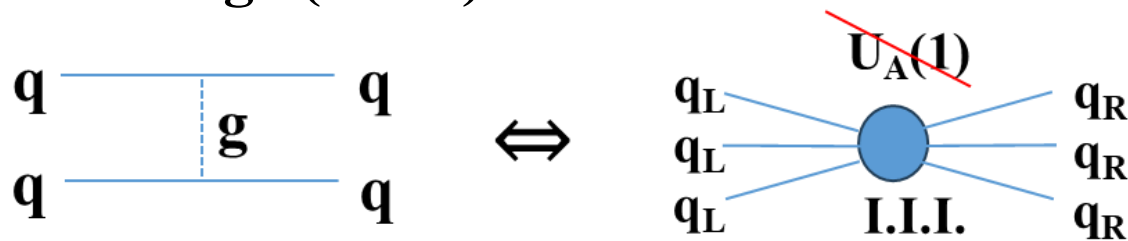
*** Dynamics of non-trivial QCD vacuum**

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

• **Diquark correlation & Spin-dependent forces**

⇒ **Color-magnetic integration and Instanton* dynamics**

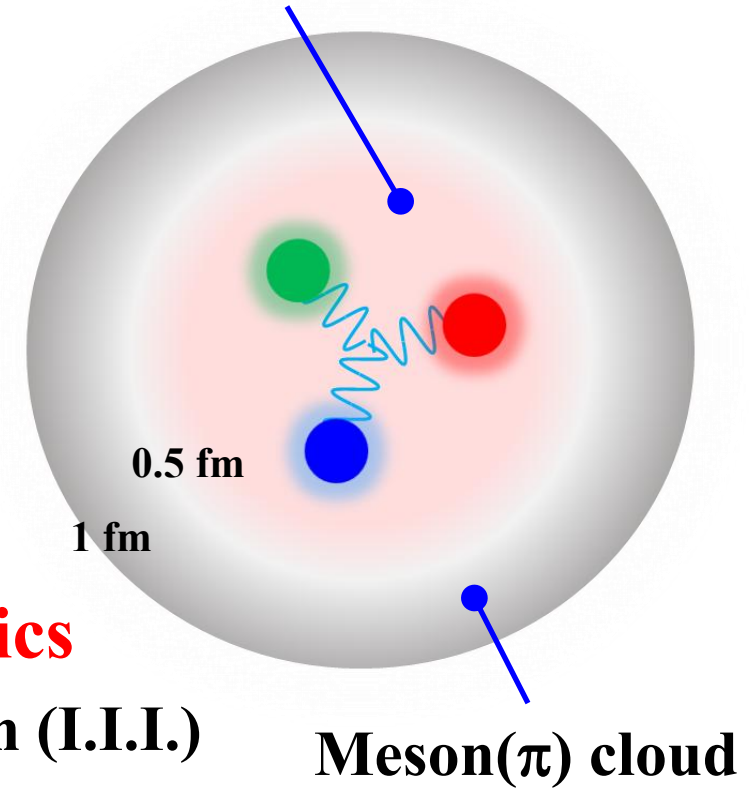
• Gluon exchange (OGE) $\Leftrightarrow$ Instanton Induced Interaction (I.I.I.)



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

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

“Quark core” region



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

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- The diagram illustrates the decomposition of a three-qubit state into a q-q-q state and a q-Q state. On the left, a three-qubit state is shown with three qubits (green, blue, red) and their associated Bloch spheres. A large blue arrow points to the right, where the state is decomposed into two parts. The first part is a q-q-q state, showing three qubits (green, blue, red) and their associated Bloch spheres, with a label $q-q$ in red. The second part is a q-Q state, showing a qubit (green) and a qubit (blue) with a label Q in black, and a label q in black.

Multiquark states: Exotic hadrons

- All-charm tetraquark states: $T_{cc\bar{c}\bar{c}}$

$J^{PC} = 2^{++}$: $X(6600)^0$, $X(6900)^0$ and $X(7100)^0$

- $J/\psi J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$ invariant mass
- A family of radial excitations (1S, 2S, 3S)

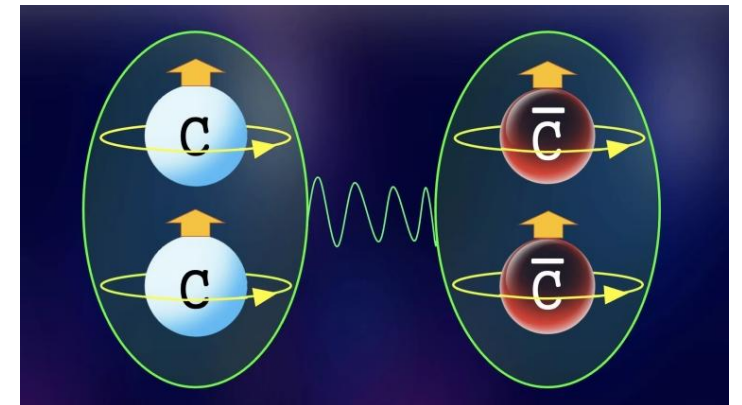
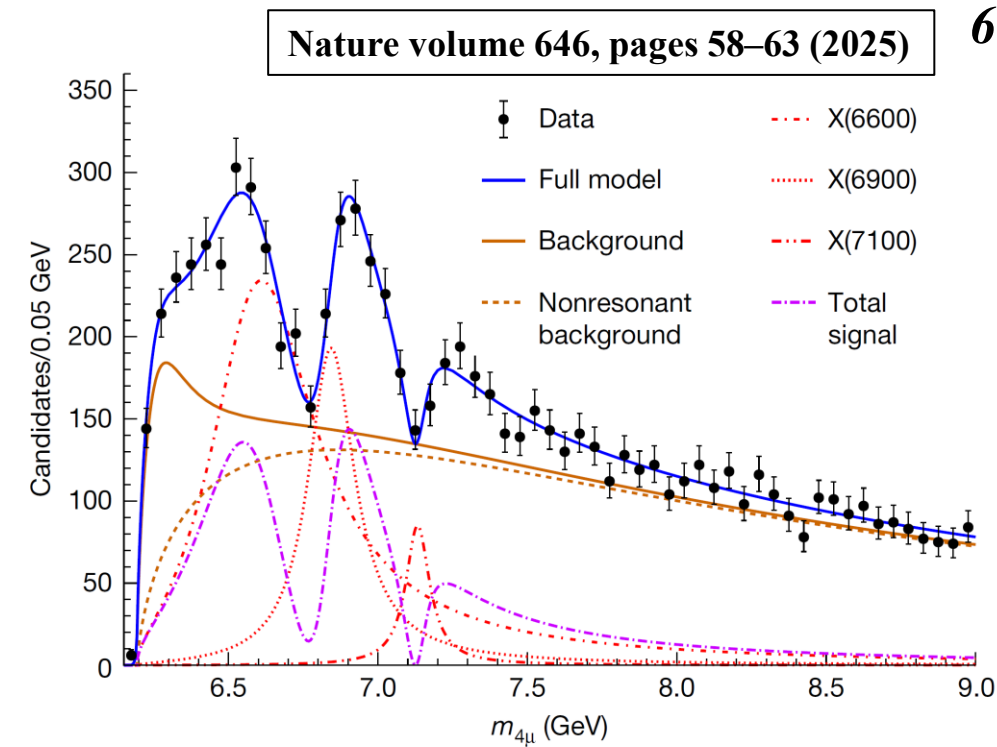
- Interpretation of $T_{cc\bar{c}\bar{c}}$

$\Rightarrow$ **Multiquark: 2 axial-vector diquarks (1^+) form $T_{cc\bar{c}\bar{c}}$ state**

- Diquarks: cc and $\bar{c}\bar{c}$ with $J^P = 1^+ \Rightarrow$ Parallel diquark spin direction
- Narrow width: Quark recombination (2 diquarks $\Rightarrow J/\psi J/\psi$)

- **How diquarks form exotic hadrons ?**

- Disentangle dynamics of effective degrees of freedom

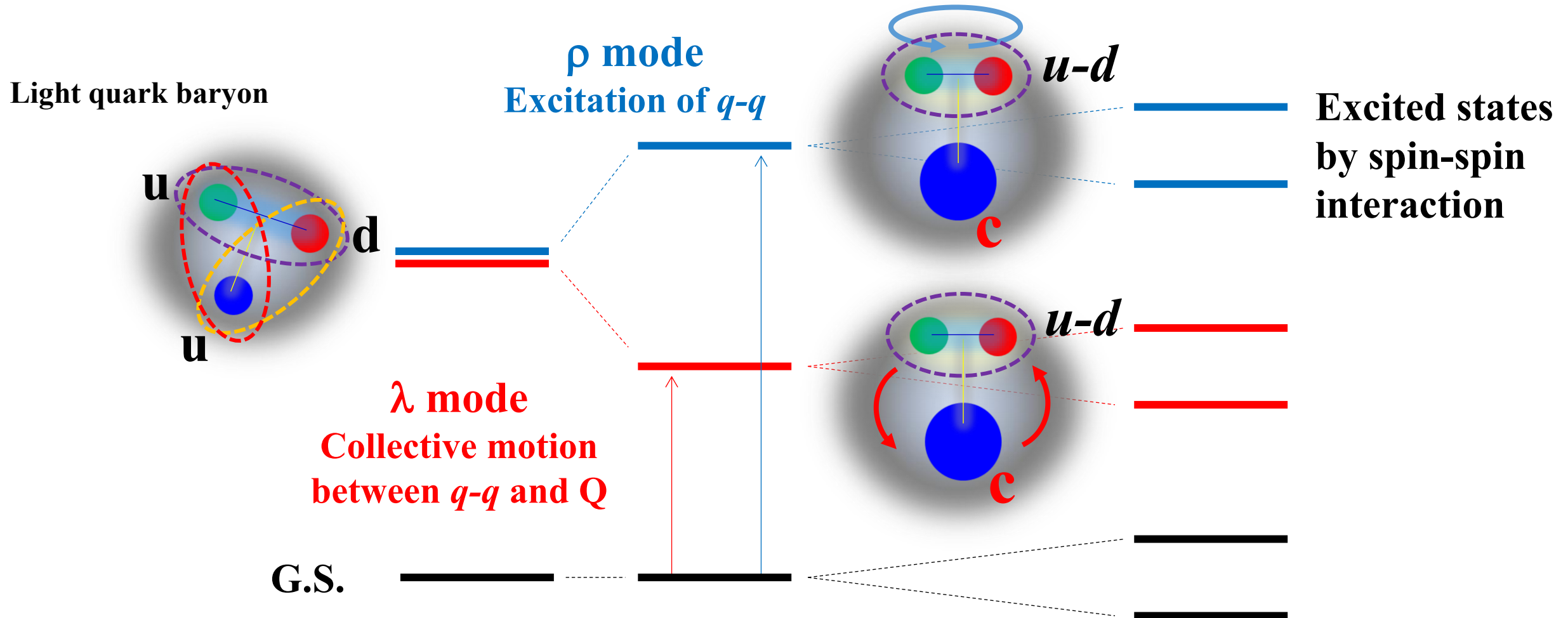


Charmed baryon spectroscopy: J-PARC E50

“Excitation mode”: λ and ρ modes reflected by **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** $\rightarrow R \sim \langle \varphi_f | \sqrt{2} \sigma_- \exp(i \vec{q}_{eff} \vec{r}) | \varphi_i \rangle$

$\Rightarrow$ **Production rates: λ/ρ mode assignment**

• **Production rate of LS doublet = $L : L+1$**

• **Large production rate of highly excited states**

$$I_L \sim (q_{eff}/\alpha)^L \exp(-q_{eff}^2/\alpha^2)$$

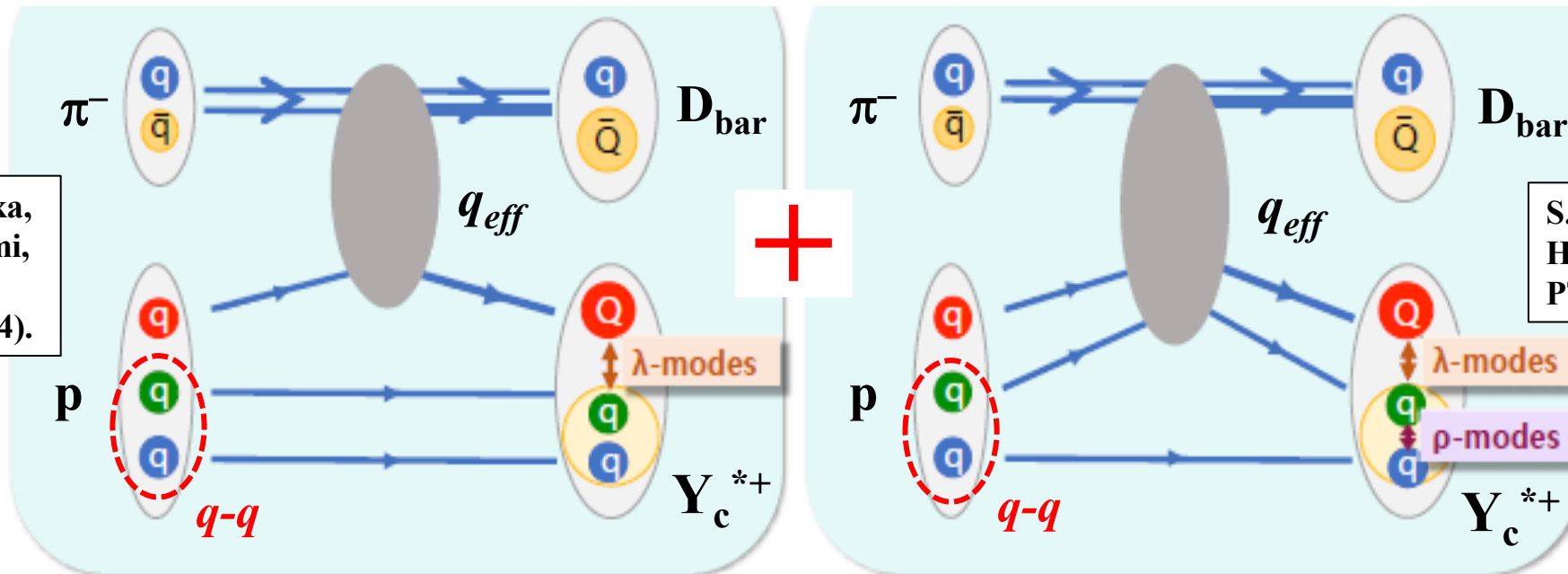
Mom. Trans.: $q_{eff} \sim 1.4$ GeV/c
 $\alpha \sim 0.4$ GeV ([Baryon size] $^{-1}$)

One-quark process

Two-quark process

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

* 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

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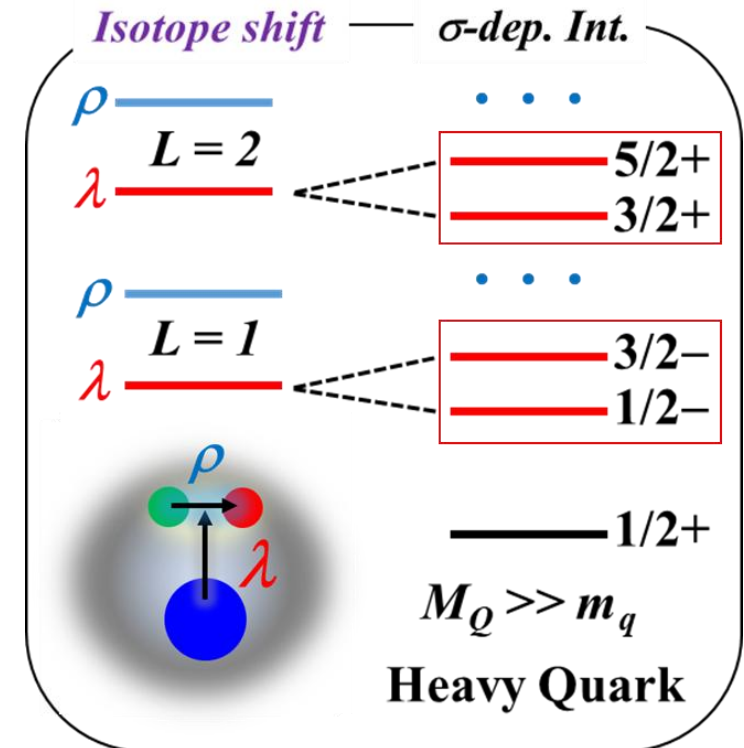
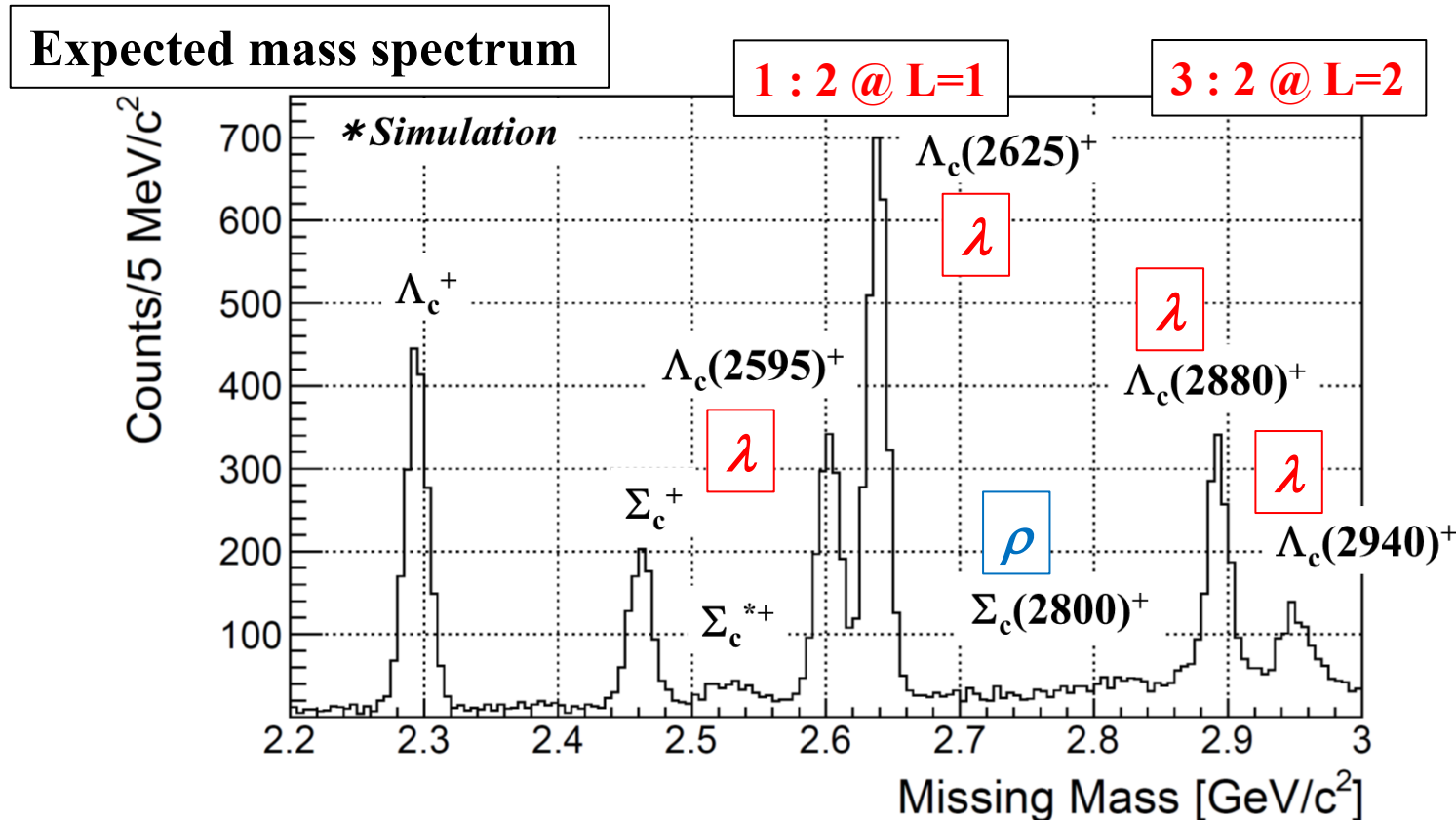
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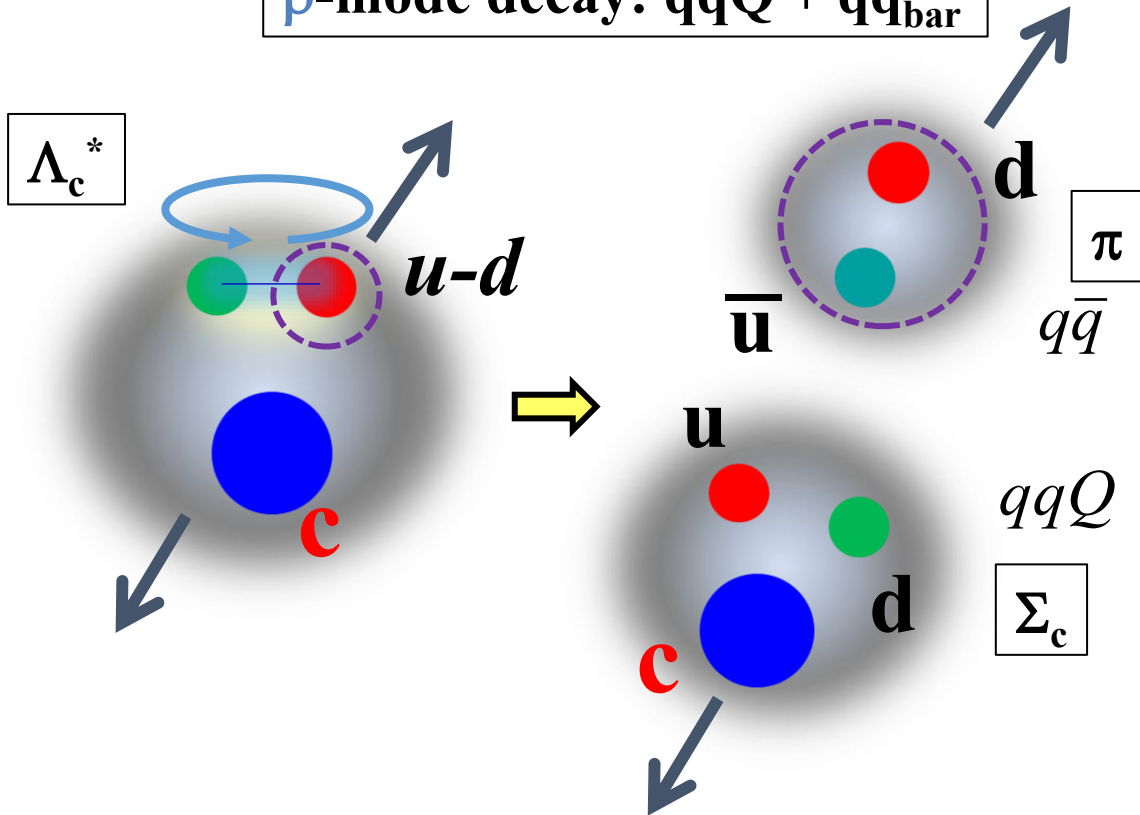
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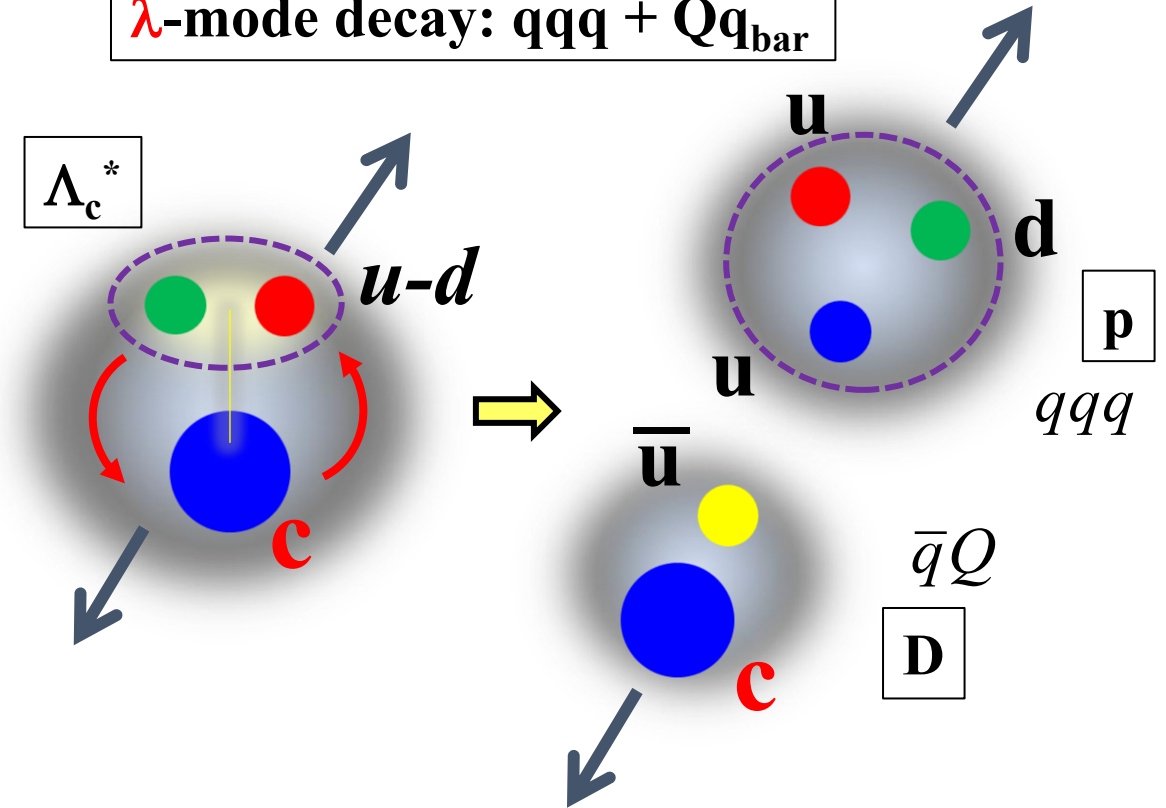


Decay property

ρ -mode decay: $qqQ + qq_{\text{bar}}$



λ -mode decay: $qqq + Qq_{\text{bar}}$

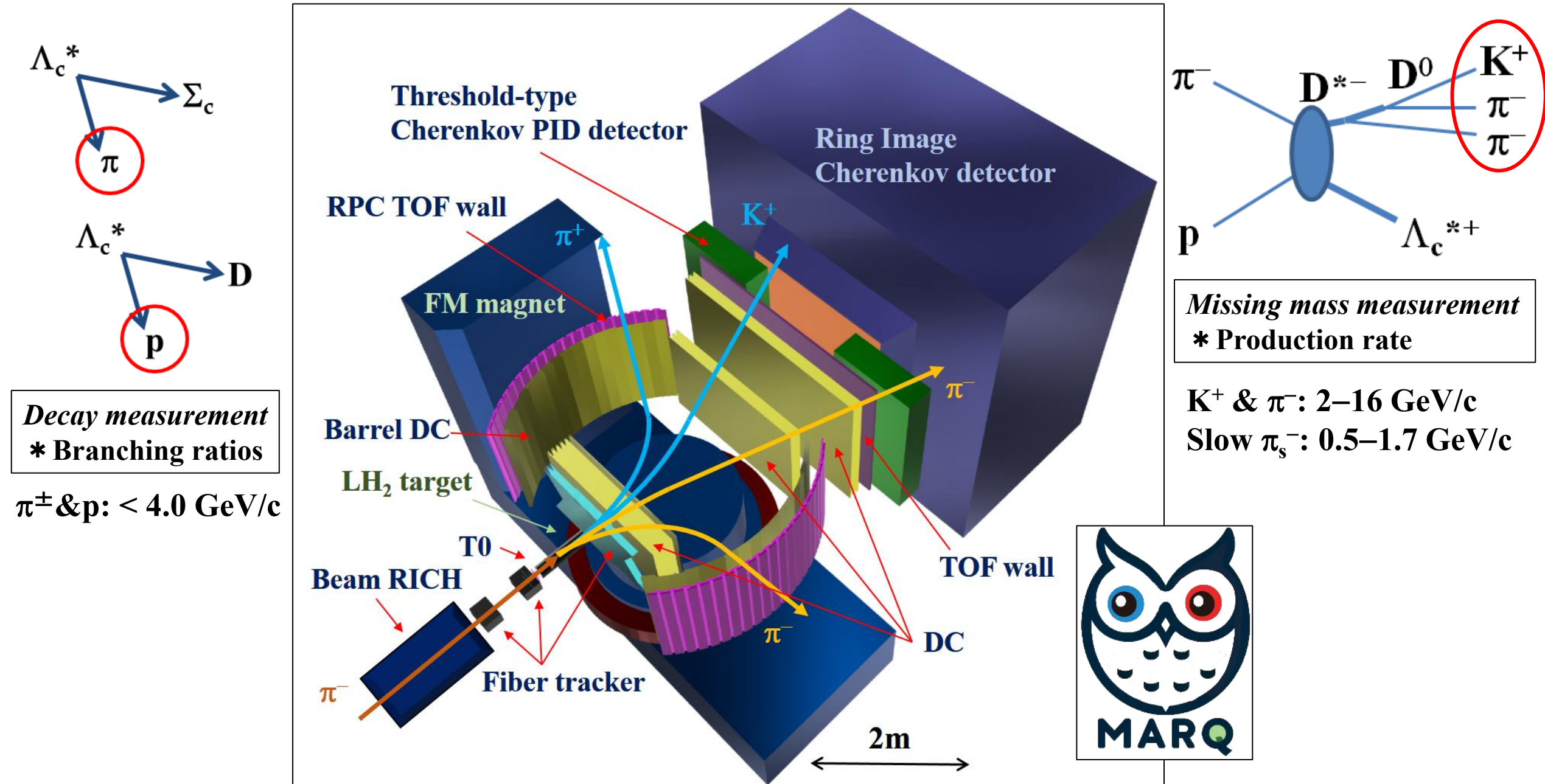


• Decay measurement: $\Gamma_{\pi\Sigma_c} \Leftrightarrow \Gamma_{pD}$ ($\pi^{-/+} \Sigma_c^{++/0} \Leftrightarrow p + D^0$)

$\Rightarrow$ **Absolute value of branching ratios**

• Complementary to high-energy experiments

MARQ spectrometer at $\pi 20$

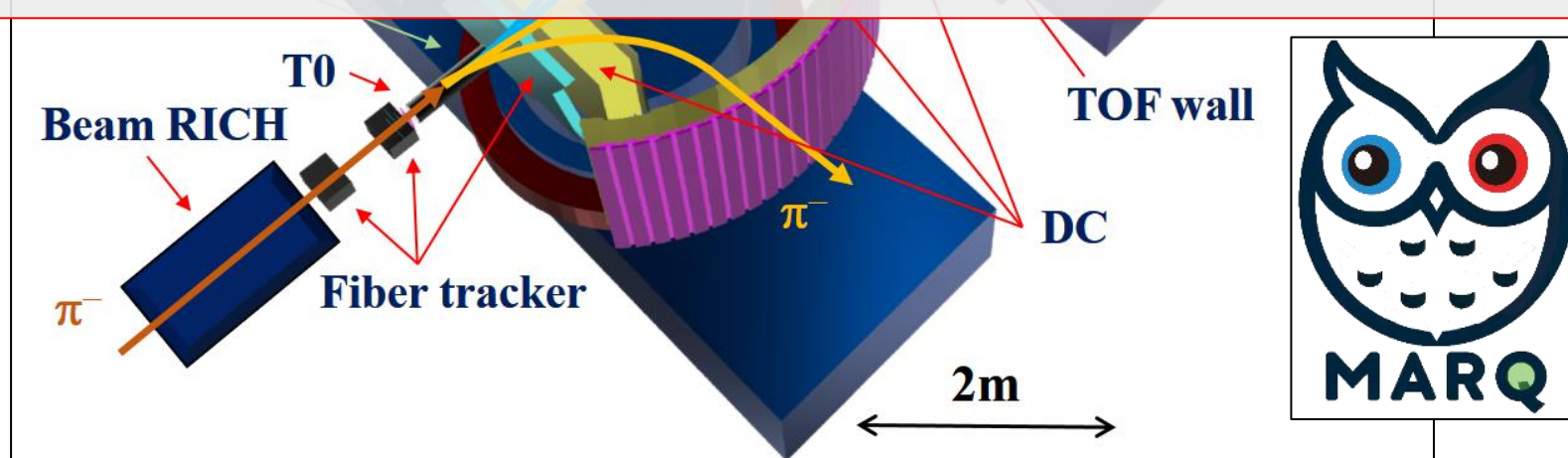


MARQ spectrometer at $\pi 20$

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

Multipurpose Analyzer
for Resonances and Quark dynamics (MARQ)

⇒ New platform for hadron experiment



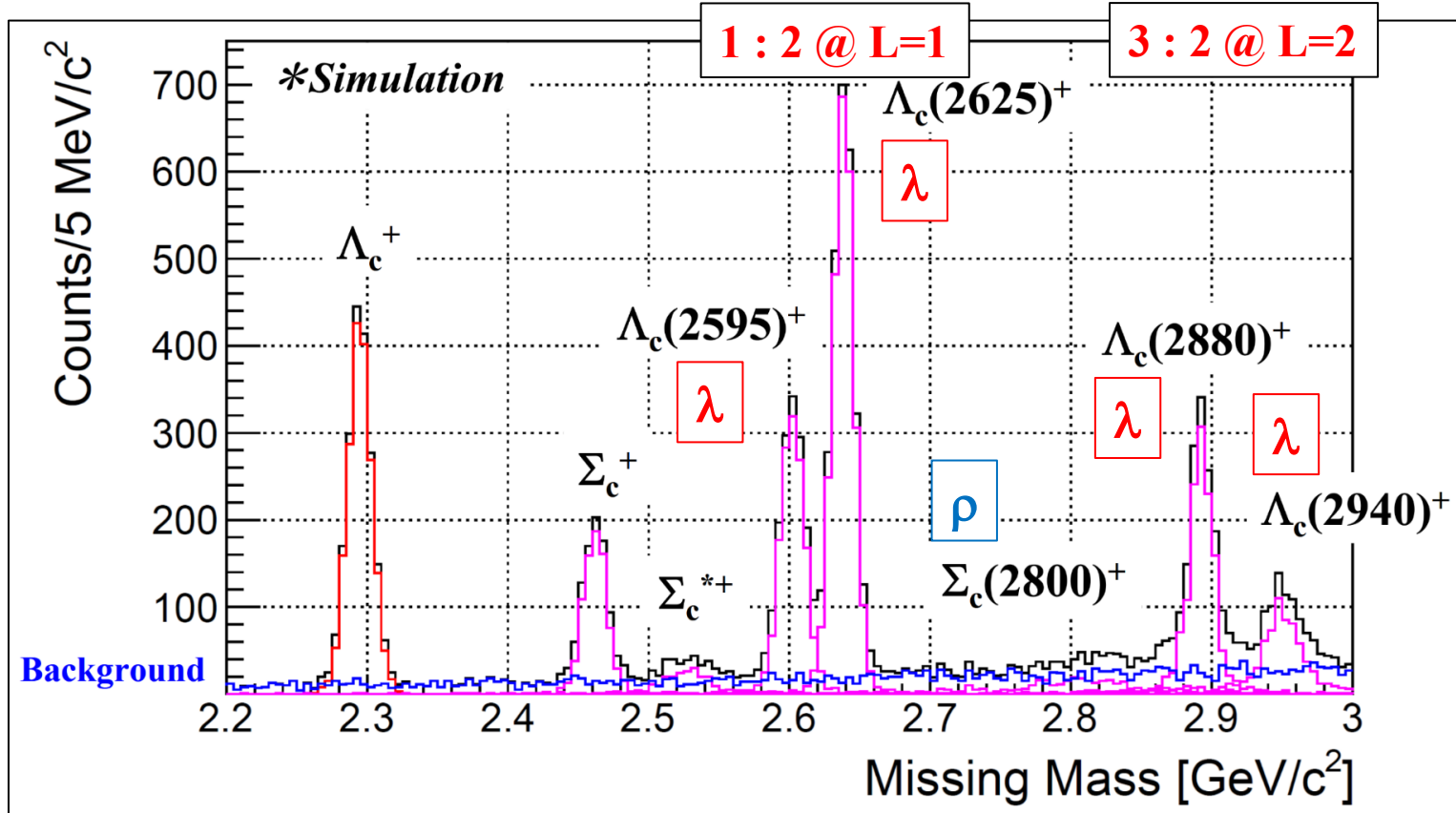
Missing mass measurement
 * Production rate

Fast π^- : 0.5–1.7 GeV/c
 Slow π^- : 0.5–1.7 GeV/c

Decay measurement
 * Branching ratios

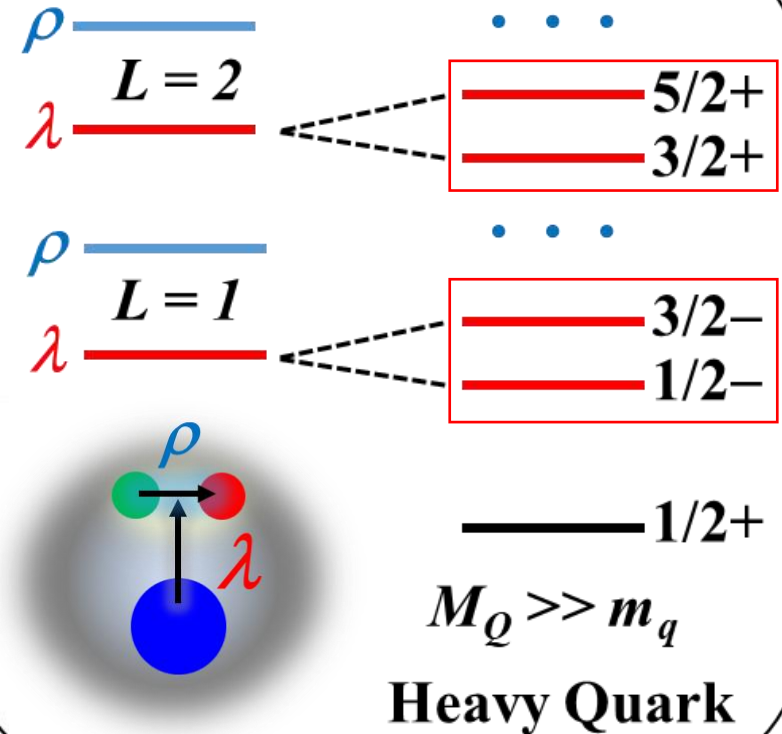
$\pi^\pm$ & p: < 4.0 GeV/c

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



* Production rate of LS doublet = $L : L+1$

Isotope shift — σ -dep. Int.



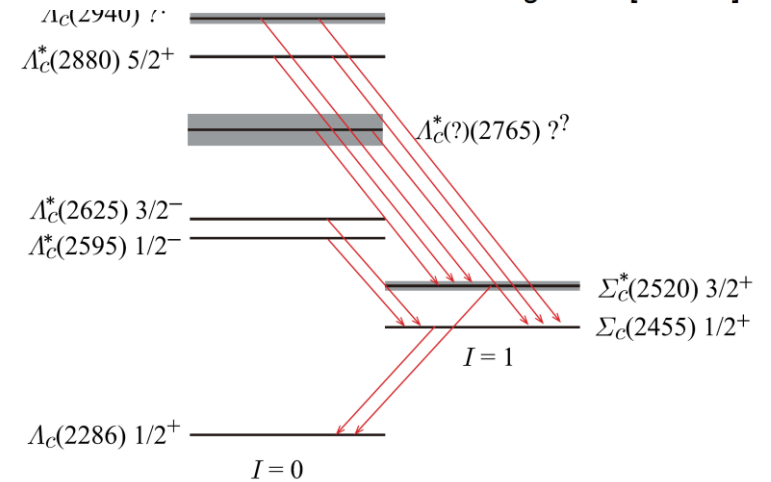
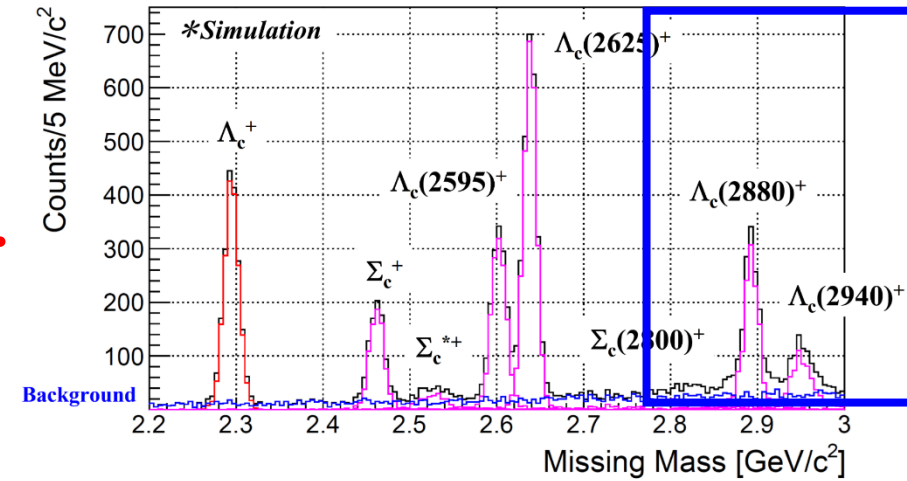
• Production rates $\Rightarrow \lambda/\rho$ mode assignment

- Production rate of LS doublet = $L : L+1$
 - λ mode enhanced + Small production rate of ρ mode (0.2 nb w/ $\Gamma = 100$ MeV)
- Angular distribution (t -dependence: $d\sigma/dt$) contains structure information.

HQ doublet

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 $\Lambda_b^0 \rightarrow D^0 p \pi^-$ (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)

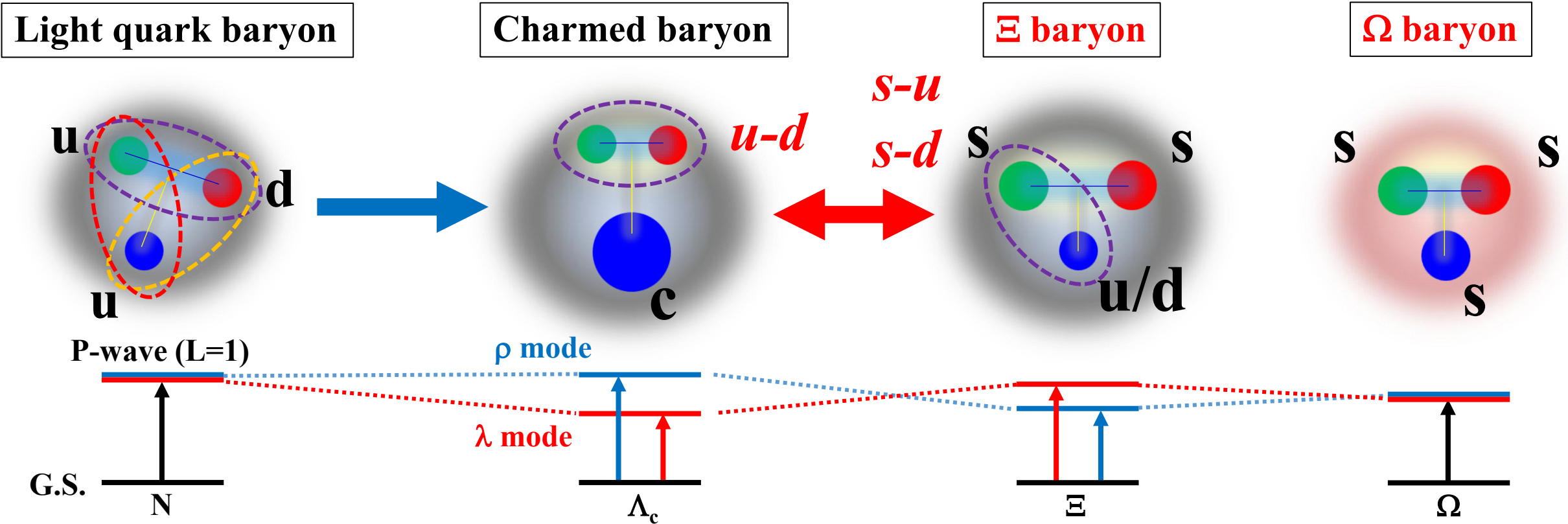


* Where are HQ doublet states ? ($\lambda = 2$ mode)

- Brown muck: $J=2 \Rightarrow \Lambda_c(2860) ? \Lambda_c(2910) ?$
- Properties of highly excited states can be tested by production.

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

Systematic study of diquark correlation



- Charmed baryon: ud diquark
- Ξ : us/ds diquark $\Rightarrow$ Flavor (mass) dependence
- Ω : ss diquark $\Rightarrow$ Axial-vector diquark (No I.I.I.)

*** Production and decay branching ratios: From low-lying to highly excited states**

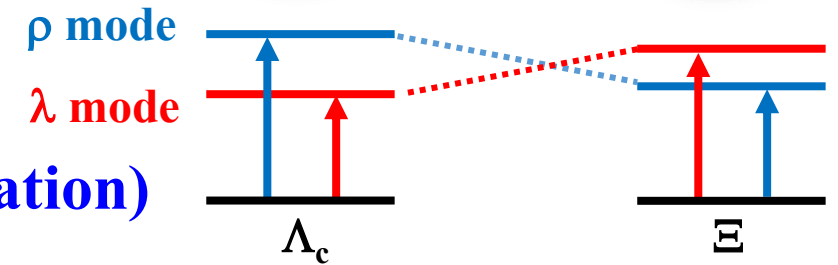
Study of Ξ baryon

- Ξ baryon: us/ds diquark correlation

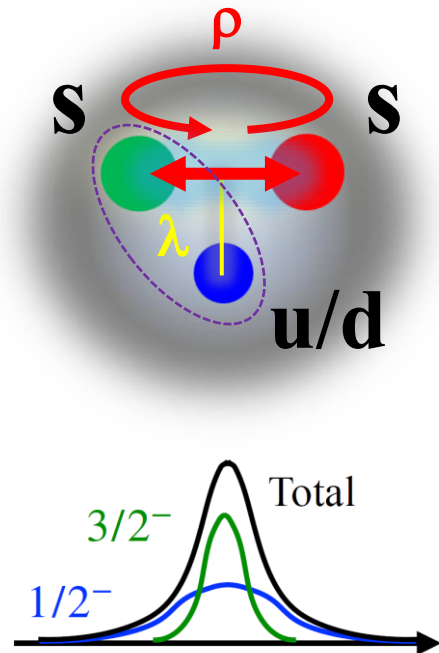
- Inversion of excitation energy: ρ mode $<$ λ mode

- Strength of us/ds diquark correlation: LS splitting

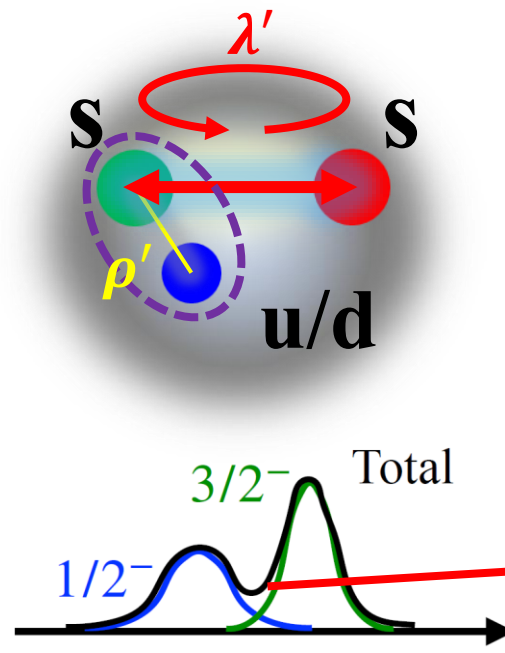
- * Identification of LS partner is necessary. ($L:L+1$ relation)



Weakly correlated us/ds

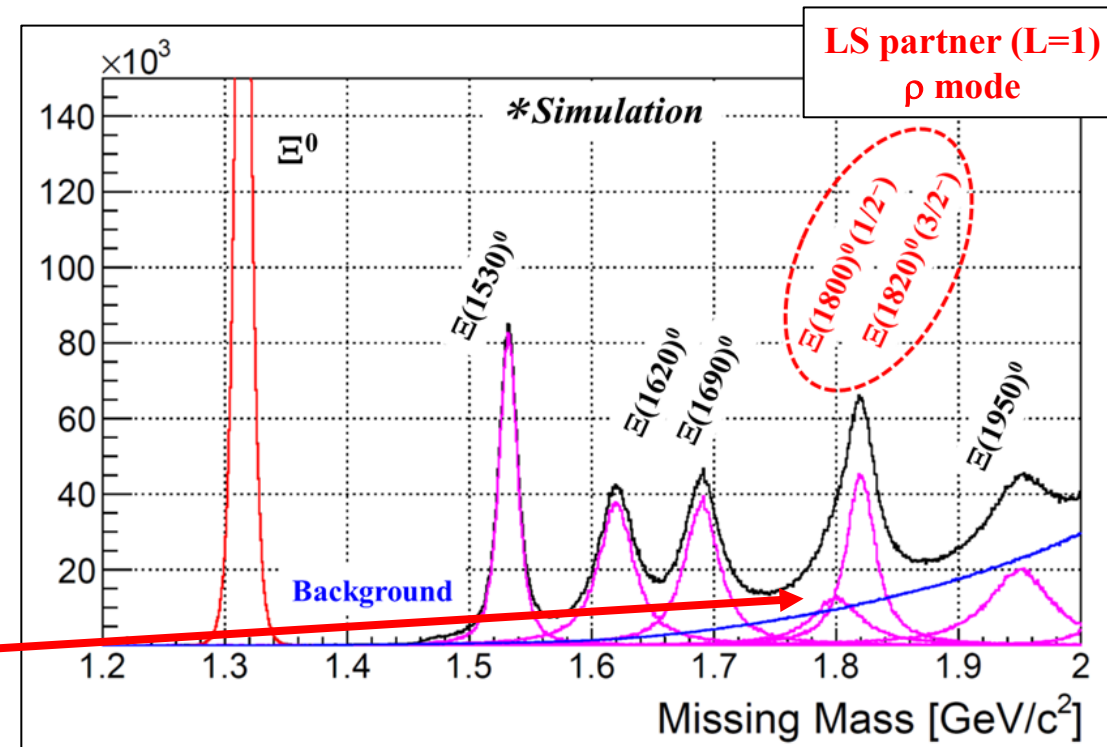


Strongly correlated us/ds



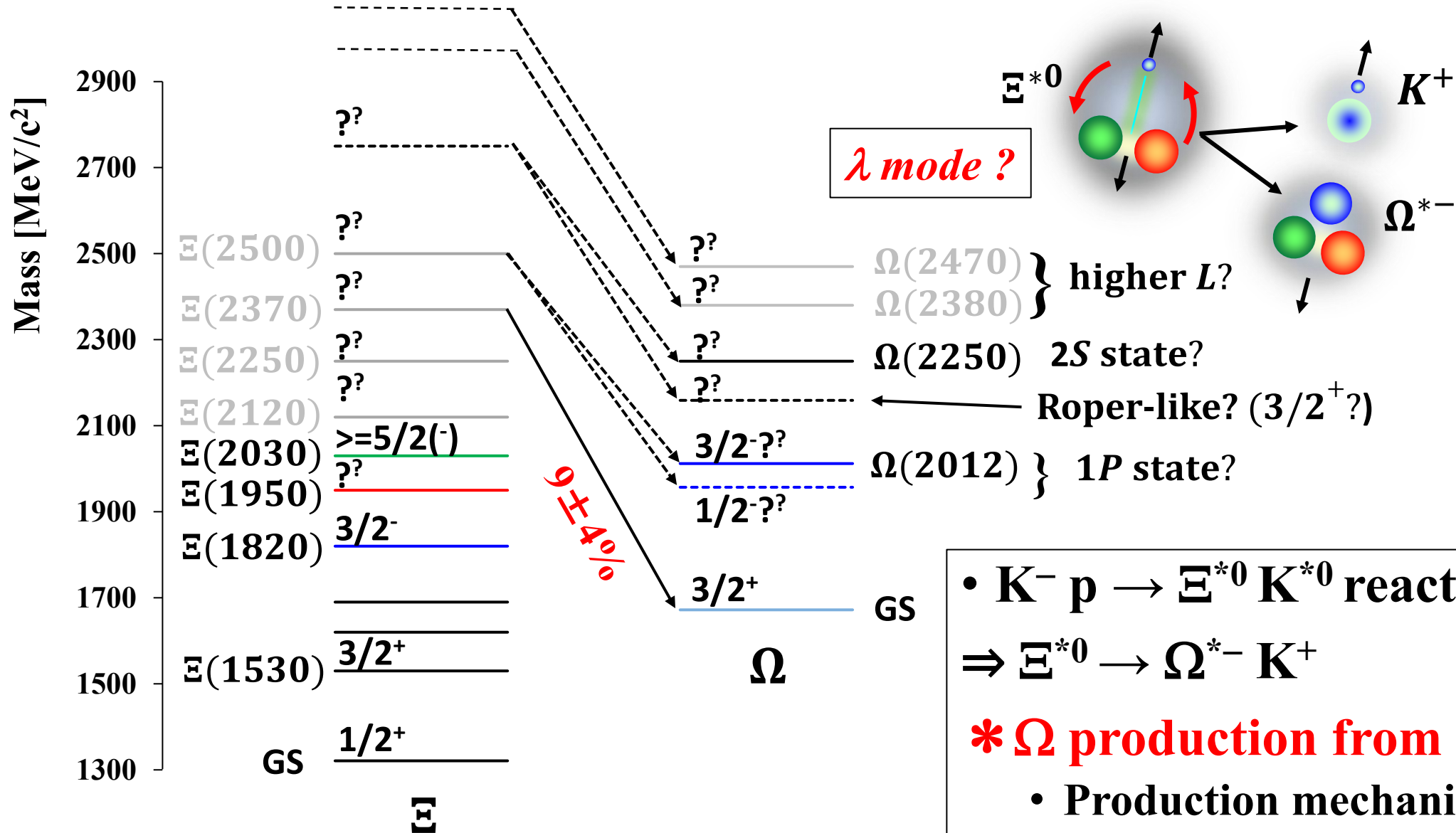
$$\begin{aligned}\rho &= \frac{\sqrt{3}}{2}\lambda' + \frac{1}{2}\rho' \\ \lambda &= -\frac{1}{2}\lambda' + \frac{\sqrt{3}}{2}\rho'\end{aligned}$$

LS partner ($L=1$)
 ρ mode



* $\Xi(1800)^0(1/2^-)$: Assumed in simulation

Relation between Ξ and Ω baryons: Production process



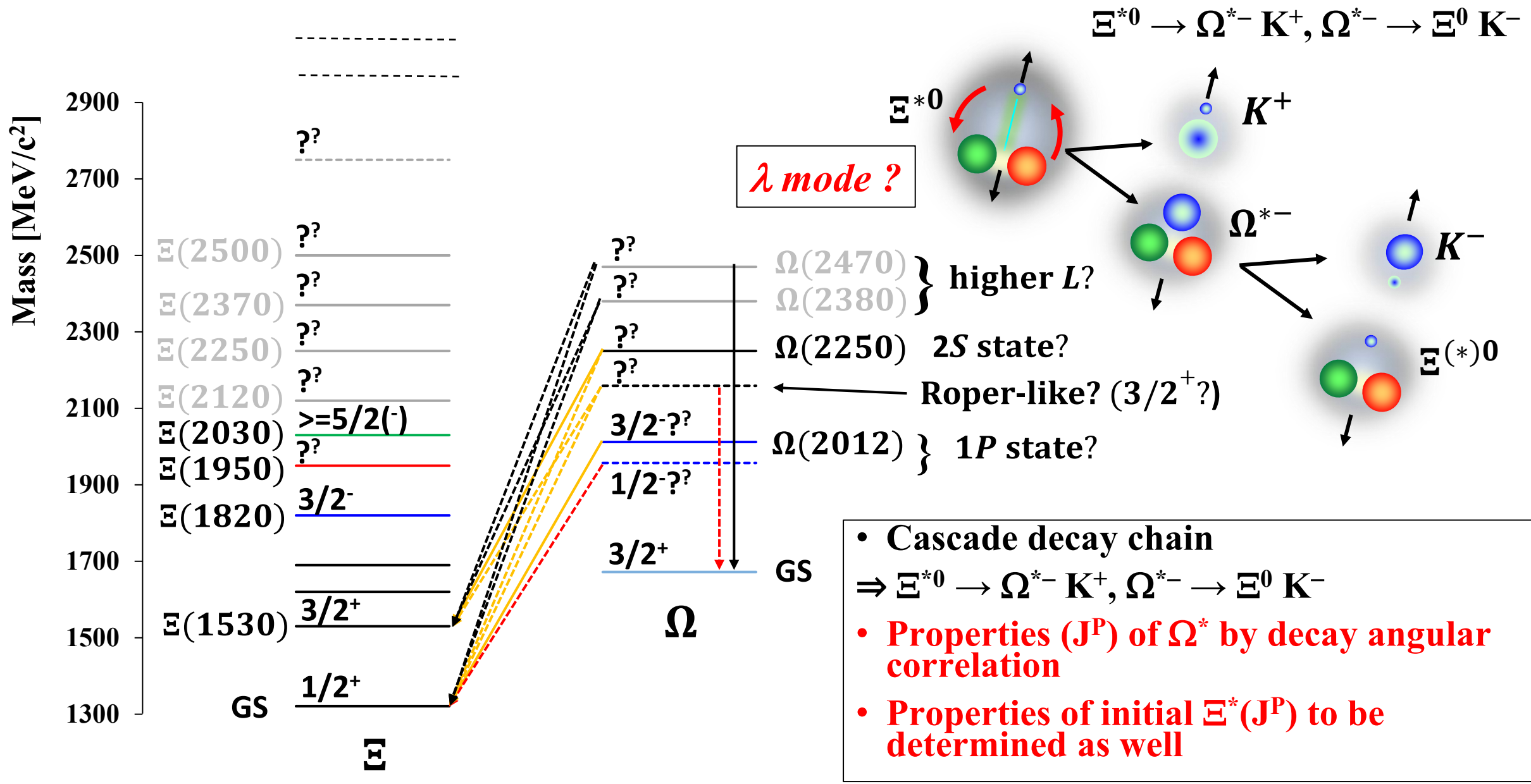
• $K^- p \rightarrow \Xi^{*0} K^{*0}$ reaction

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

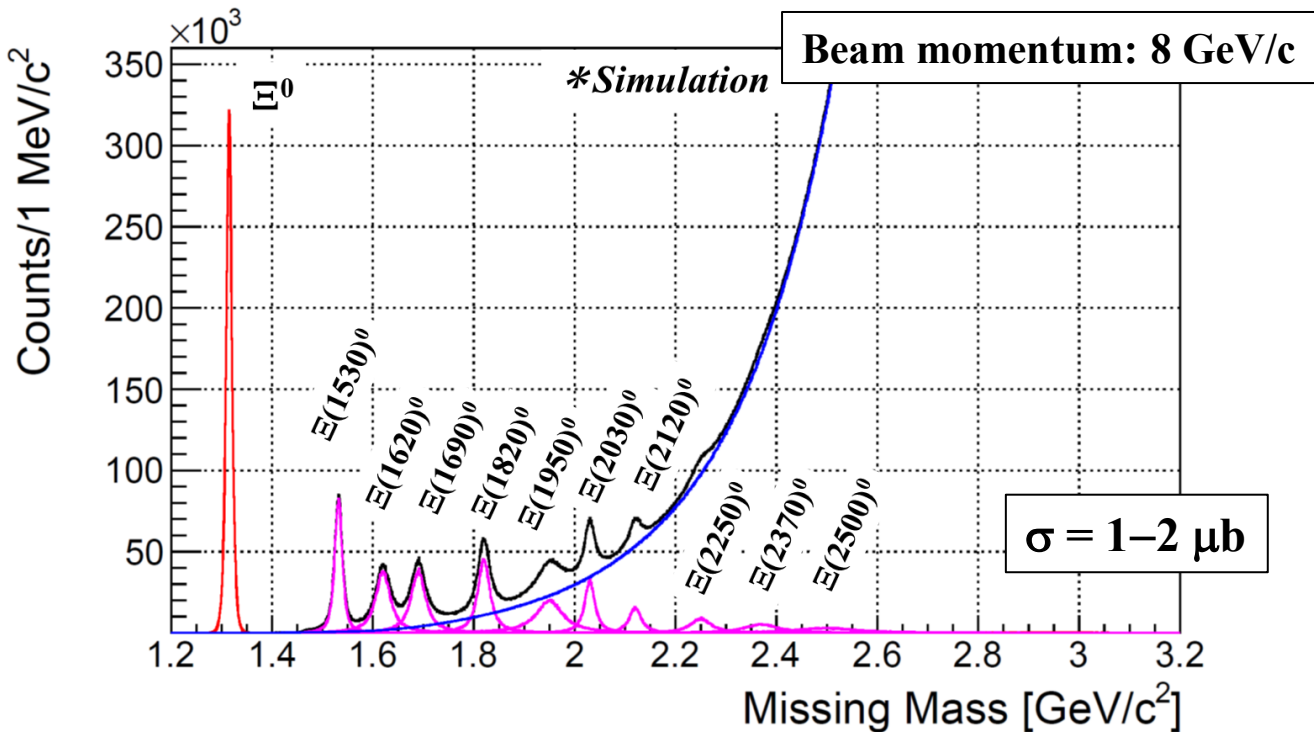
*** Ω production from λ mode Ξ^***

• Production mechanism of Ω

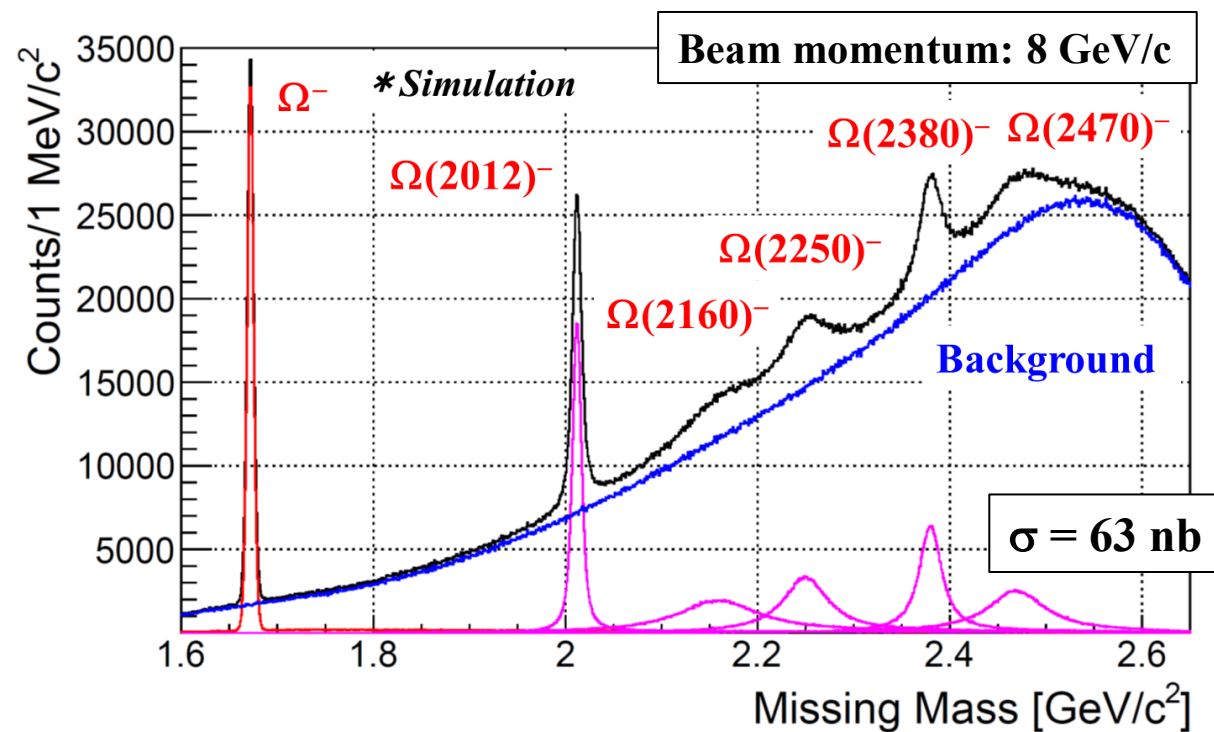
Relation between Ξ and Ω baryons: Decay process



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: $\Delta M \sim 7 \text{ MeV}(\sigma)$



- Reaction: $K^- p \rightarrow \Omega^{*-} K^{*0} K^+$
 - Beam: 7–10 GeV/c
- Missing mass: $K^{*0} \& K^+$
 - Mass resolution: $\Delta M \sim 5 \text{ MeV}(\sigma)$

* High momentum transfer = Highly excited state
 $\Rightarrow$ Systematic studies: Identify λ/ρ modes

Summary

- **How quarks build hadrons ?**
 - Understanding of QCD dynamics in the low-energy regime
- **Study of charmed baryon: Disentangle diquark correlation**
 - Charmed baryon spectroscopy via $\pi^- p \rightarrow D^{*-} Y_c^{*+}$ @ 20 GeV/c: J-PARC E50
 - λ/ρ mode assignment by production rate and decay branching ratio
- **Systematic measurements of baryon excited states: Λ_c/Σ_c , Ξ , Ω systems**
 - Investigation of ud , us/ds and ss diquark correlations
- **High-intensity & High-momentum hadron beam: J-PARC $\pi 20$ /K10**
 - Multipurpose spectrometer: MARQ at $\pi 20$

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