Spectroscopic study of heavier quark baryons using hadron beam at J-PARC

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The XVIth Quark Confinement and the Hadron Spectrum Conference

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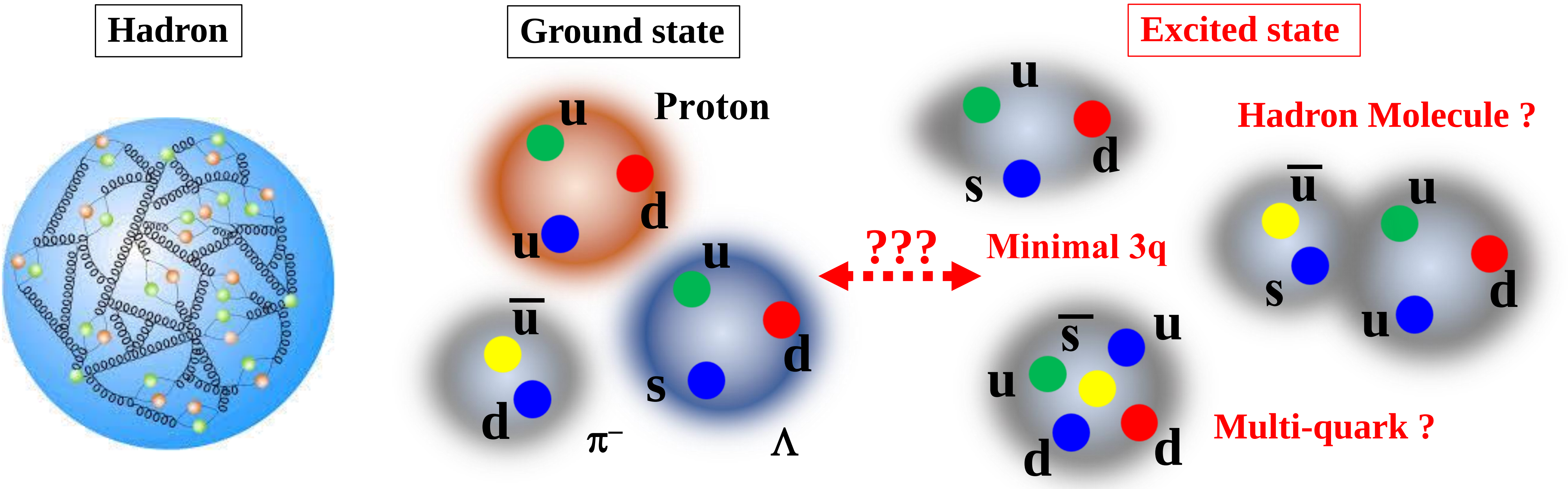
Introduction

How quarks build hadrons ?

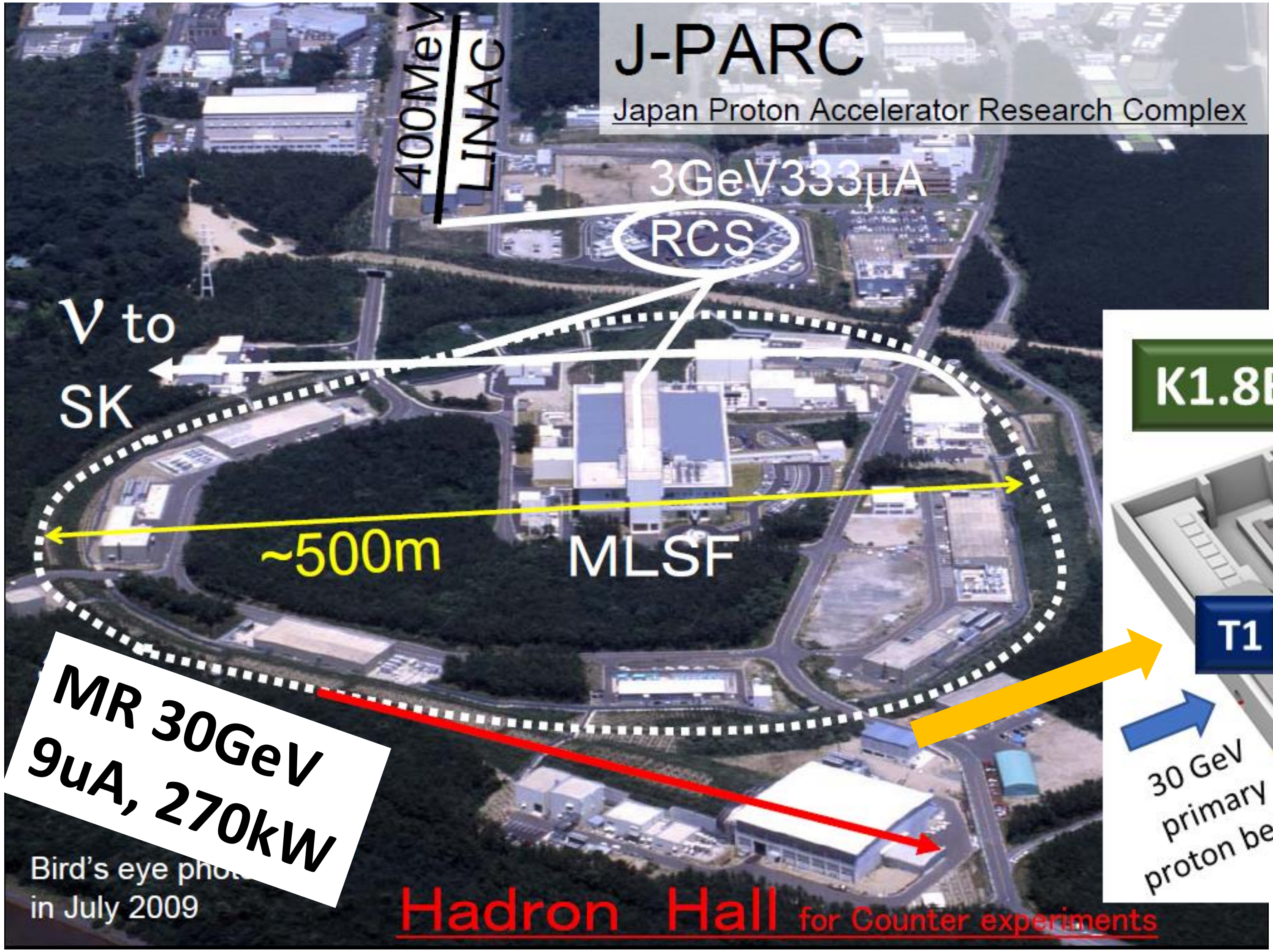


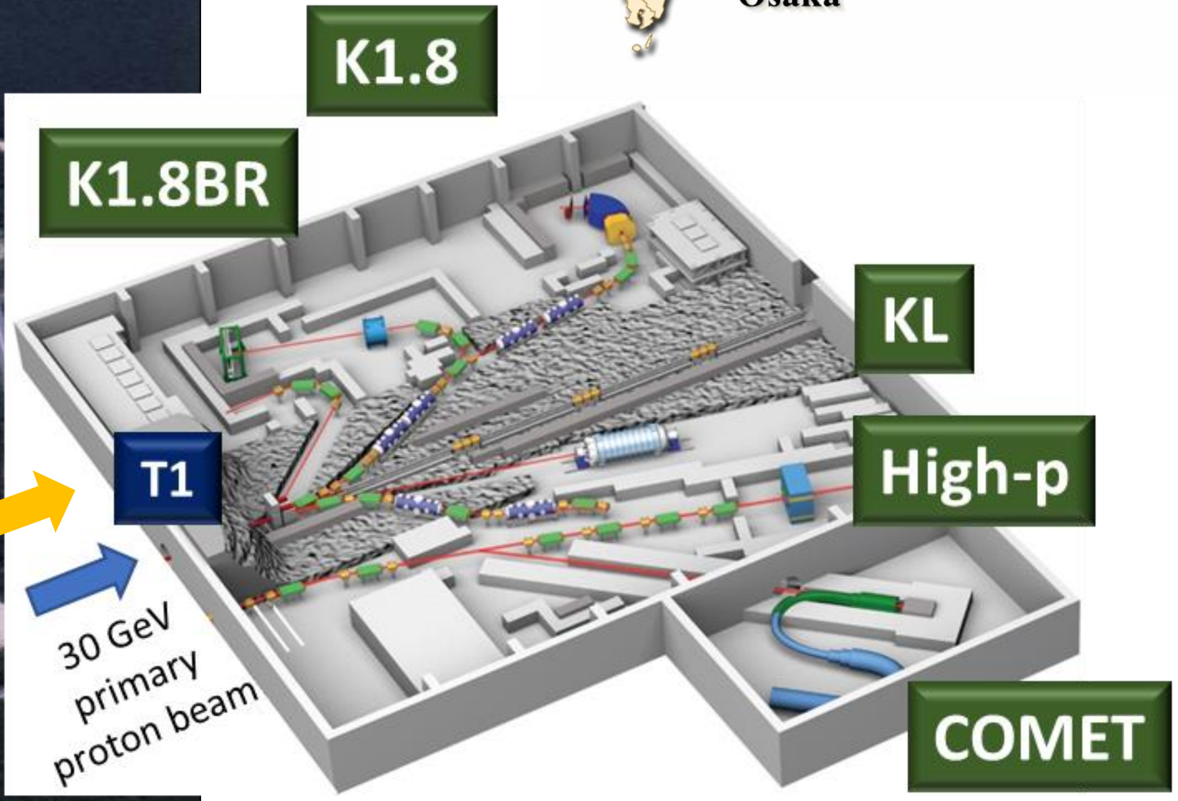
＊Dynamics of non-trivial QCD vacuum in low energy regime

• Investigation of effective degrees of freedom and their interactions

⇒ Spectroscopy experiment for investigating excited states by hadron beam

J-PARC & Hadron Experimental Facility



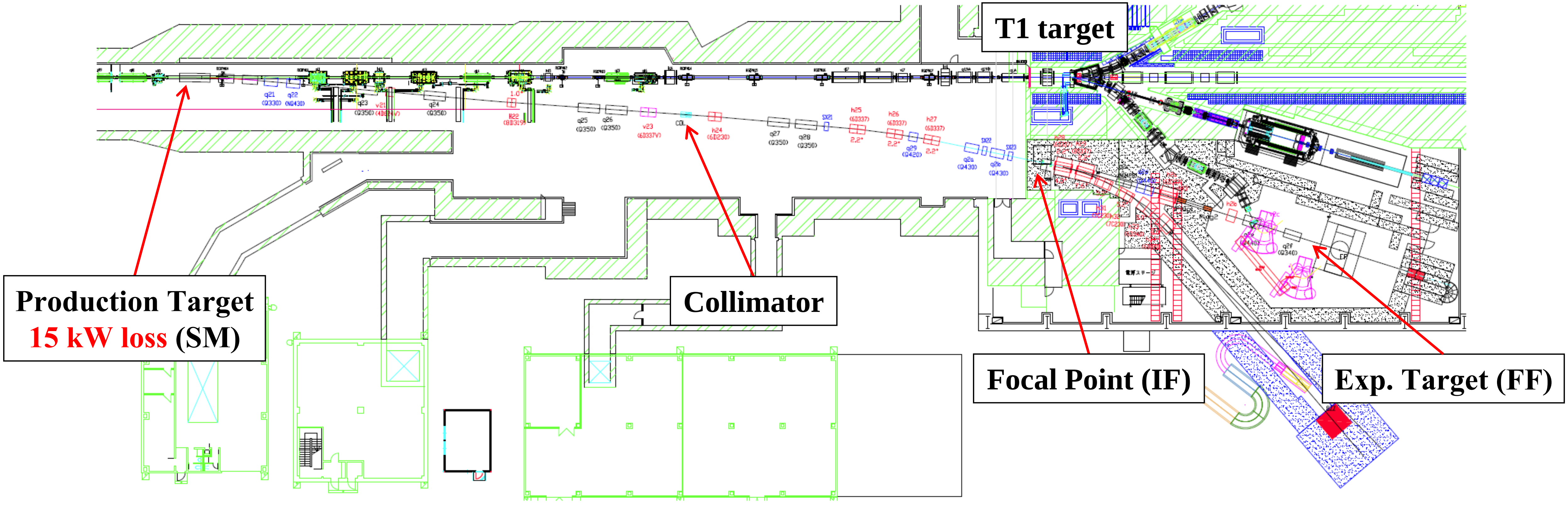


World's highest level intensity proton beam ⇒ Beam power 82 kW

High-p beam line for 2^{ndary} beam: π20

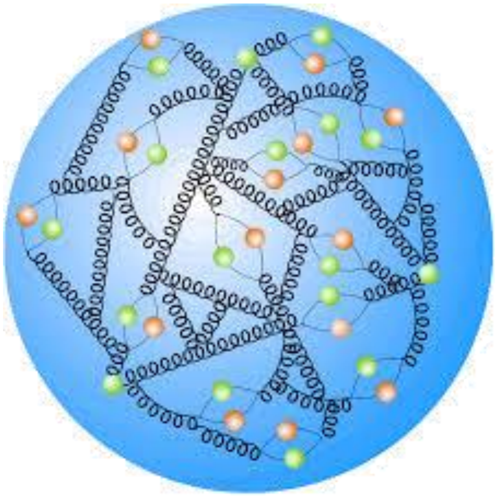
＊High-p: 2^{ndary} beams can be provided from the primary proton beam.

- High intensity: $>10^7$ /spill for $\pi^\pm$, p ($>10^5$ /spill for K^-, $\bar{p}$) up to 20 GeV/c
- High momentum-resolution beam: $\Delta p/p = 0.1\%(\sigma)$

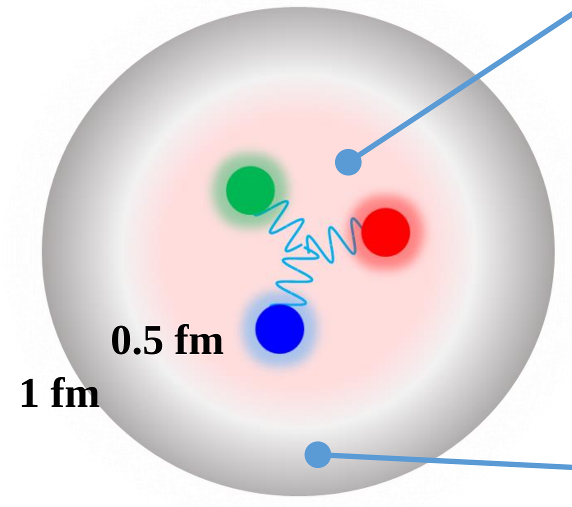


Baryon structure in the low-energy regime

High energy
perturbative



Low energy
non-perturbative



- **Non-perturbative region**

⇒ "Quark core" region

  - **Non-trivial gluon field: Instanton***
  - **Chiral condensate $\langle \bar{q}q \rangle \neq 0$**
    - **Dressed quark (Constituent quark)**
    - **Emergence of π**

- **Meson (pion) Cloud**

✱ How quarks build hadrons ?

- **Dynamics of non-trivial QCD vacuum ⇒ Dynamics of Effective DoF**
  - **Effective degrees of freedom: Diquark correlation**
  - **Origin of spin-dependent force: Spontaneous breaking of chiral symmetry, $U_A(1)$ anomaly**
  - **Quark motions in "quark core" with "cloud": Confinement**

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

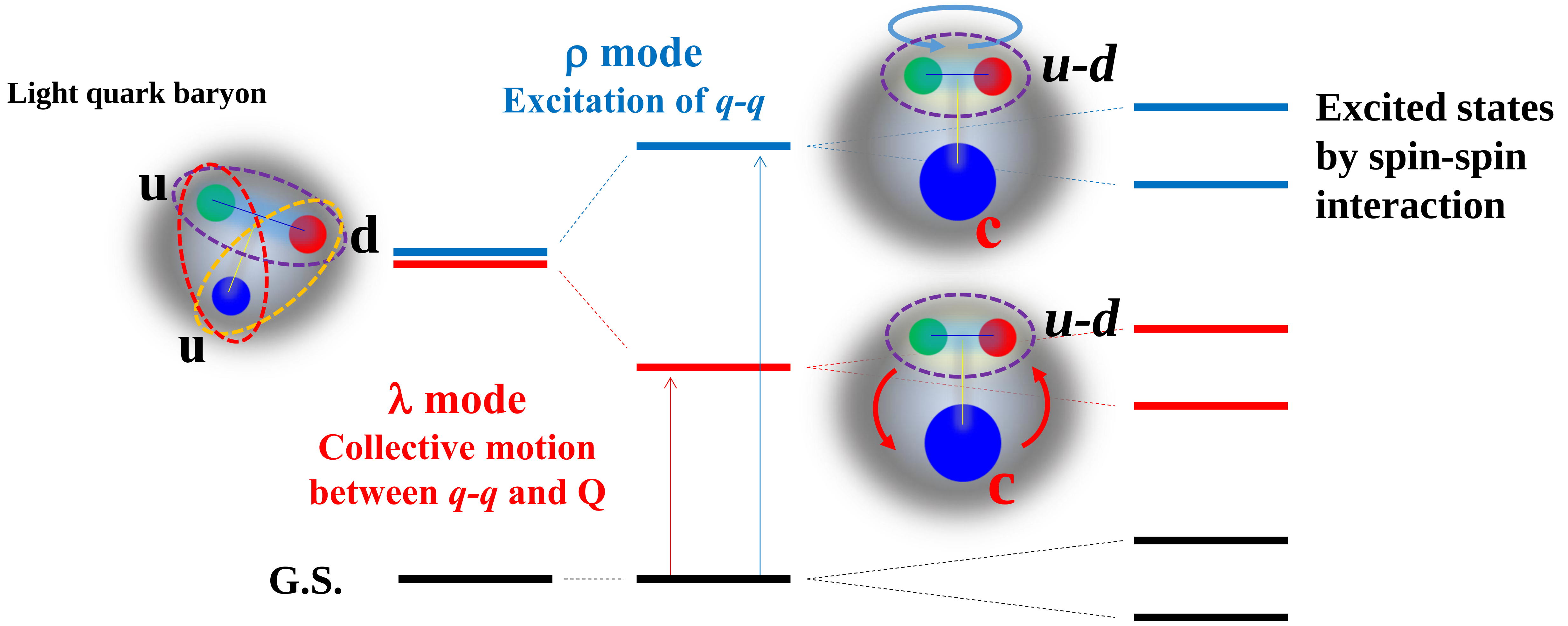
Charmed baryon spectroscopy

Charmed baryon spectroscopy: J-PARC E50

"Excitation mode": λ and ρ modes reflected by Diquark correlation

* Dynamical information: Production rates and absolute decay branching ratios

- Missing mass method: $\pi^- p \rightarrow D^{*-} Y_c^{*+}$ reaction at 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 → $R \sim \langle \varphi_f | \sqrt{2}\sigma_- \exp(i\vec{q}_{eff}\vec{r}) | \varphi_i \rangle$
  - ⇒ Reflection from λ/ρ excitation modes
    - Inclusion of one- and two-quark processes ($\sigma_\Lambda : \sigma_\Sigma = 2:1$)
  - 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]$^{-1}$)

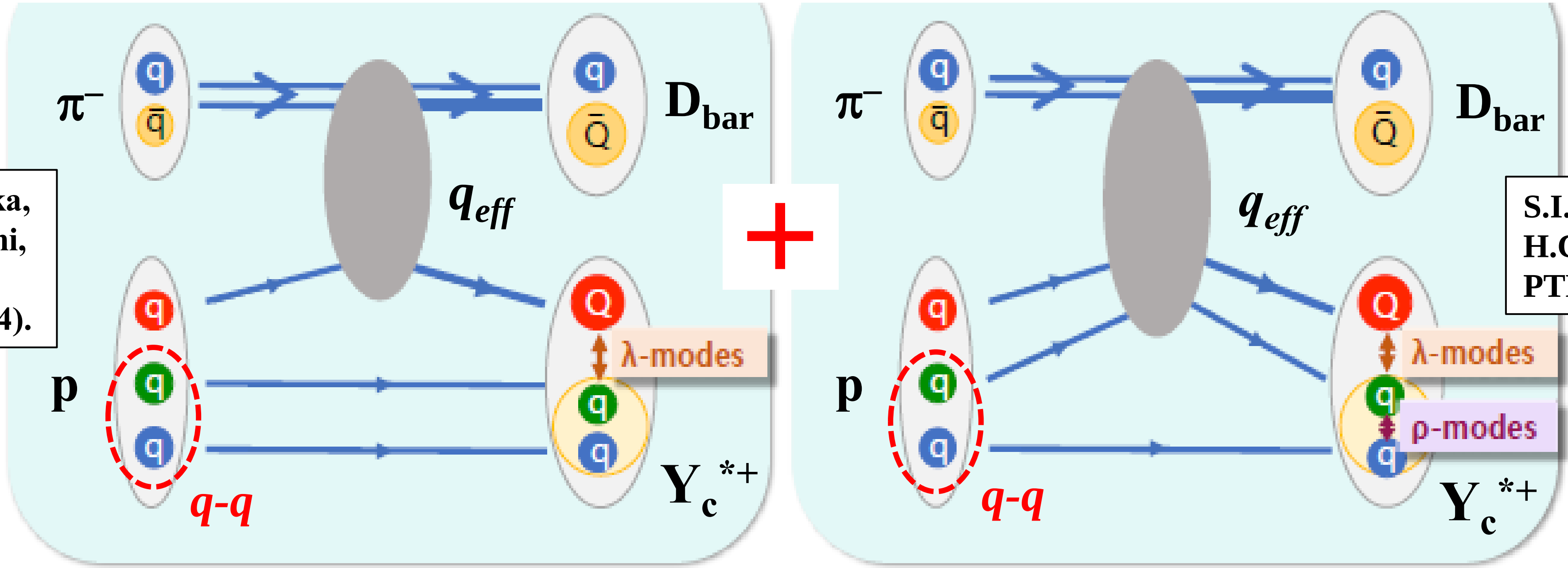
One-quark process

∗ 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

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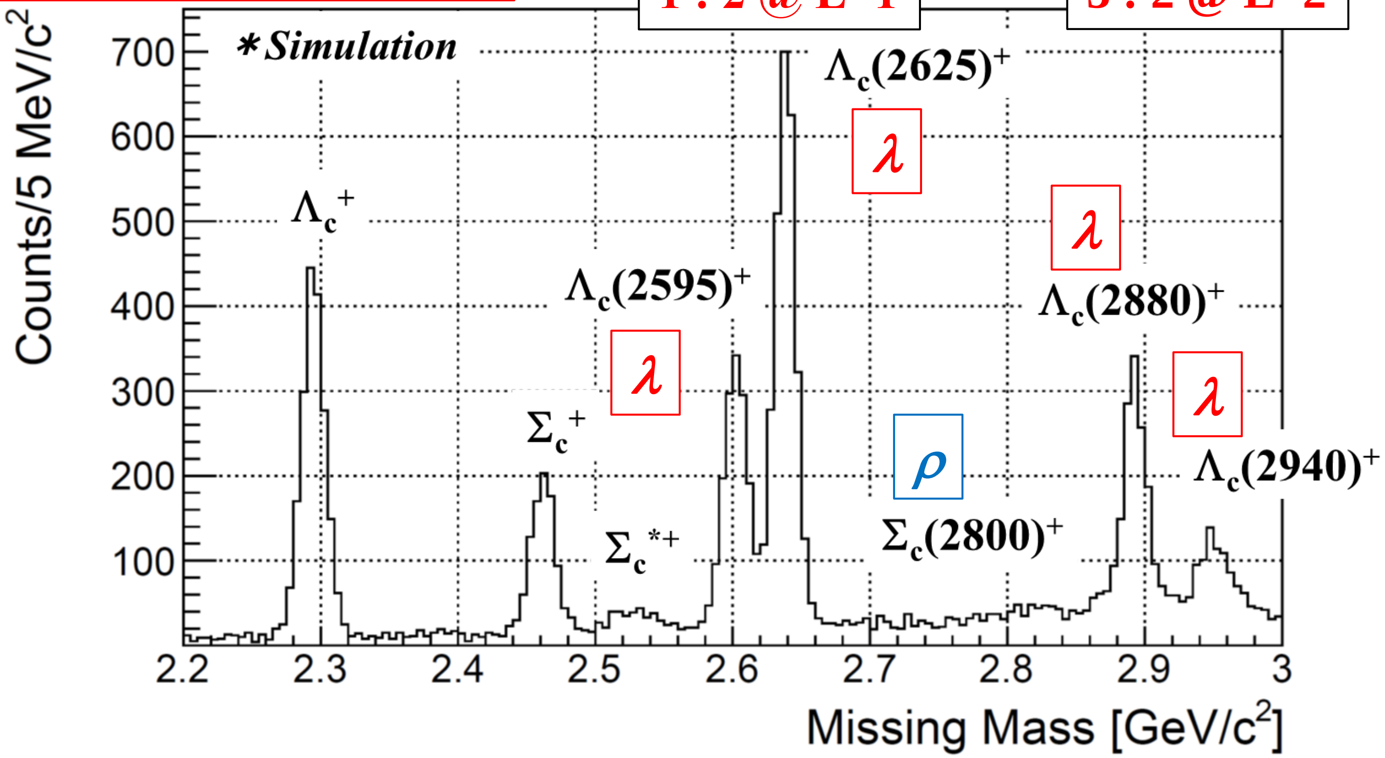
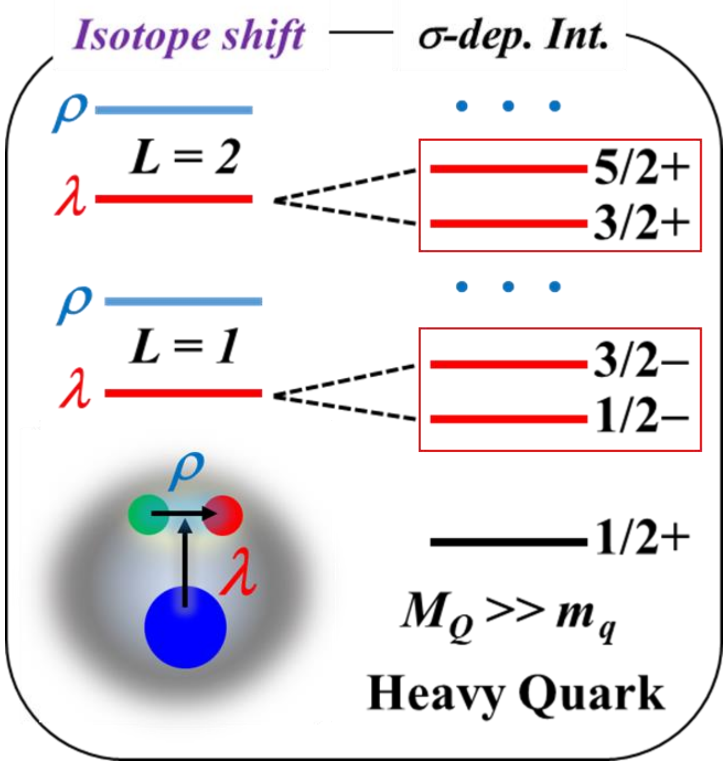
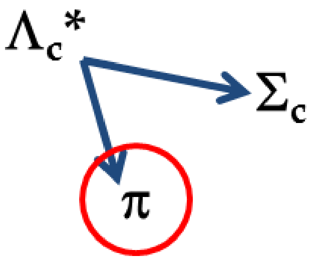
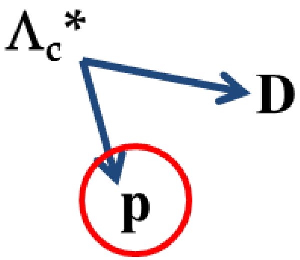
∗ Production rate = $L : L+1$





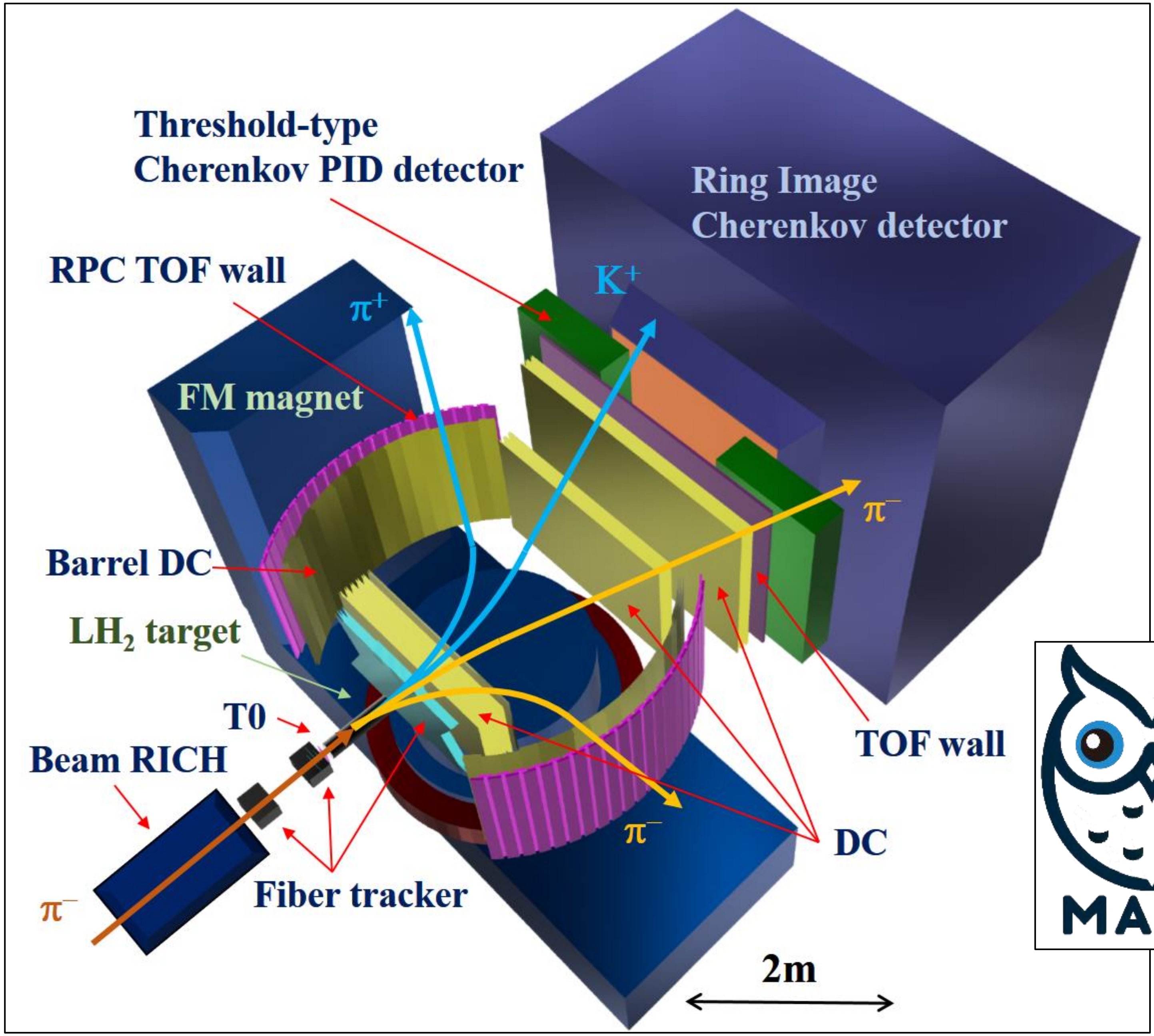
MARQ spectrometer

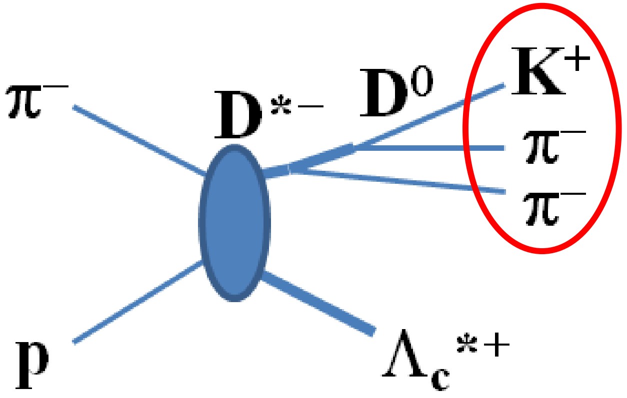




Decay measurement
∗ Branching ratios

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

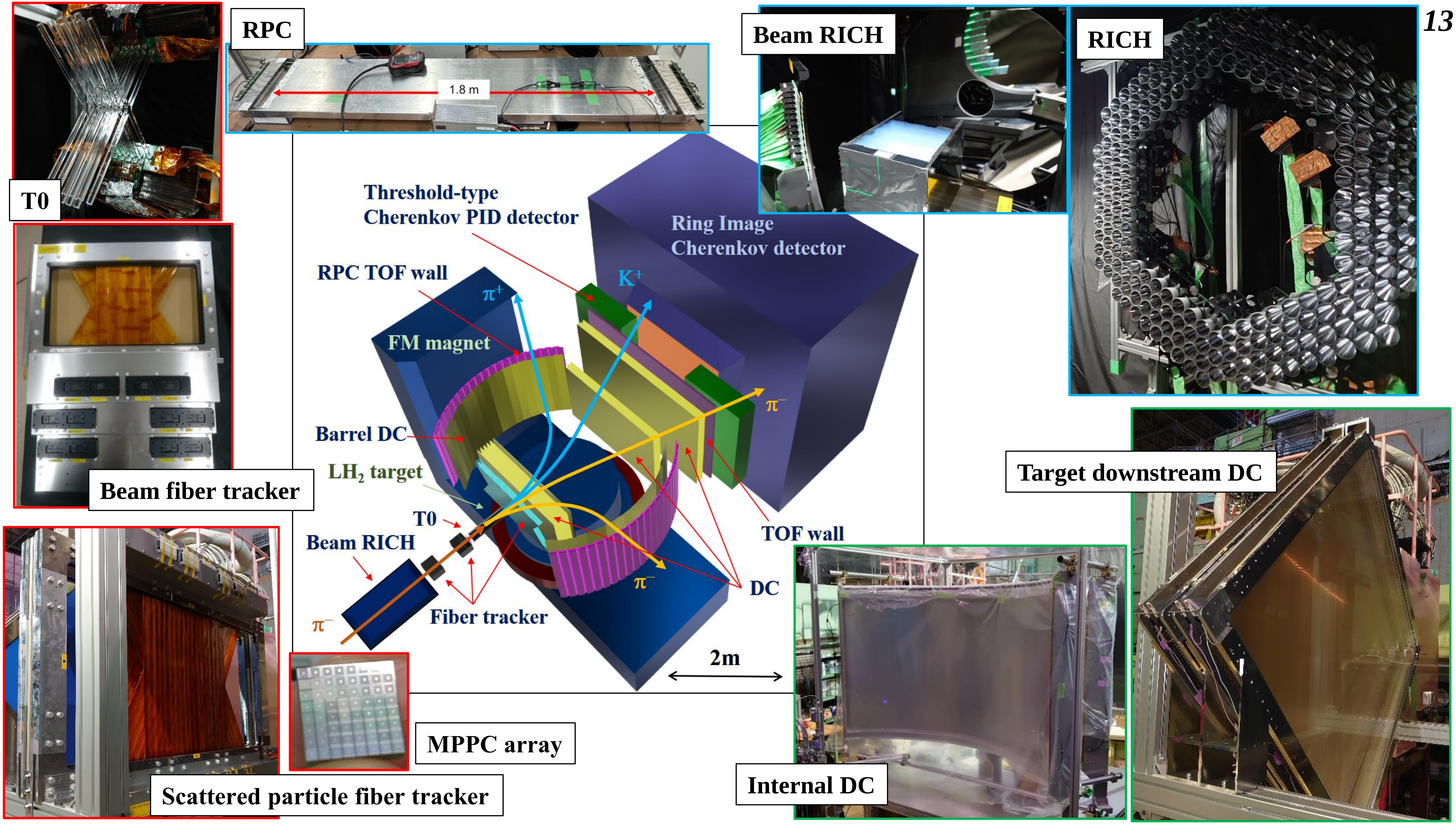


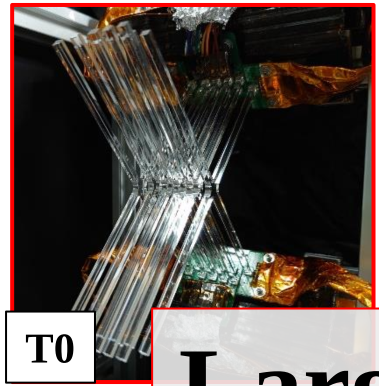


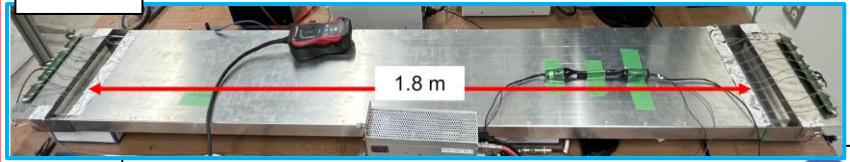
Missing mass measurement
∗ Production rate

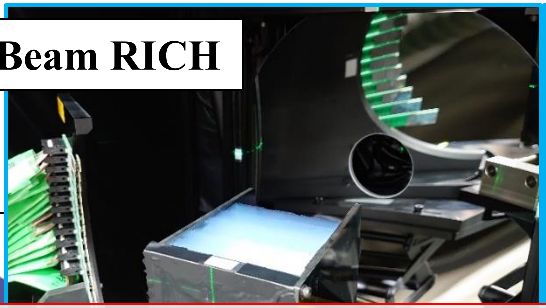
K^+ & π^-: 2–16 GeV/c
Slow π_s^-: 0.5–1.7 GeV/c

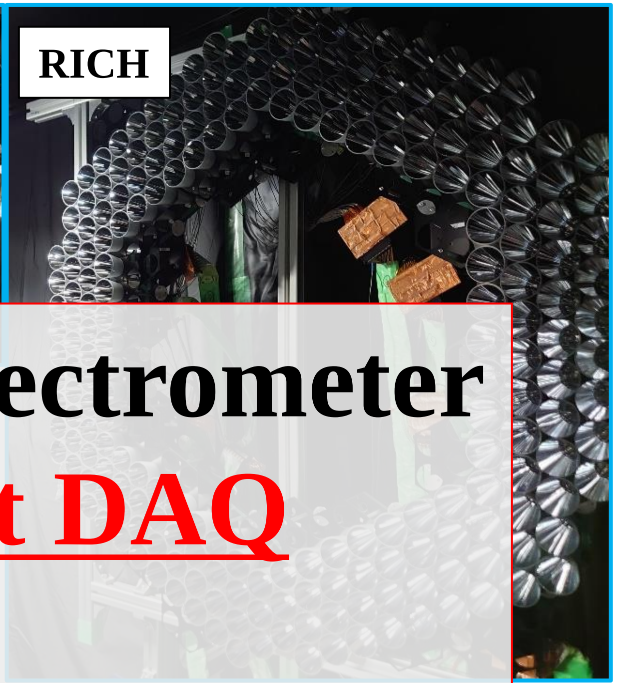
MARQ


T0
RPC
1.8 m
Beam RICH
RICH
Beam fiber tracker
Threshold-type
Cherenkov PID detector
Ring Image
Cherenkov detector
RPC TOF wall
FM magnet
Barrel DC
LH_2 target
T0
Beam RICH
Fiber tracker
TOF wall
DC
2m
π^+
K^+
π^-
π^-
π^-
Target downstream DC
MPPC array
Scattered particle fiber tracker
Internal DC





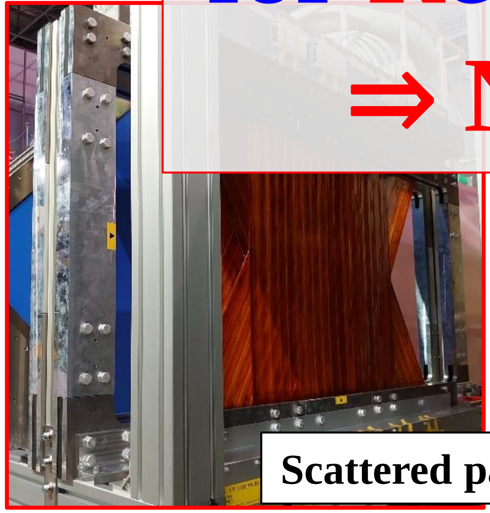




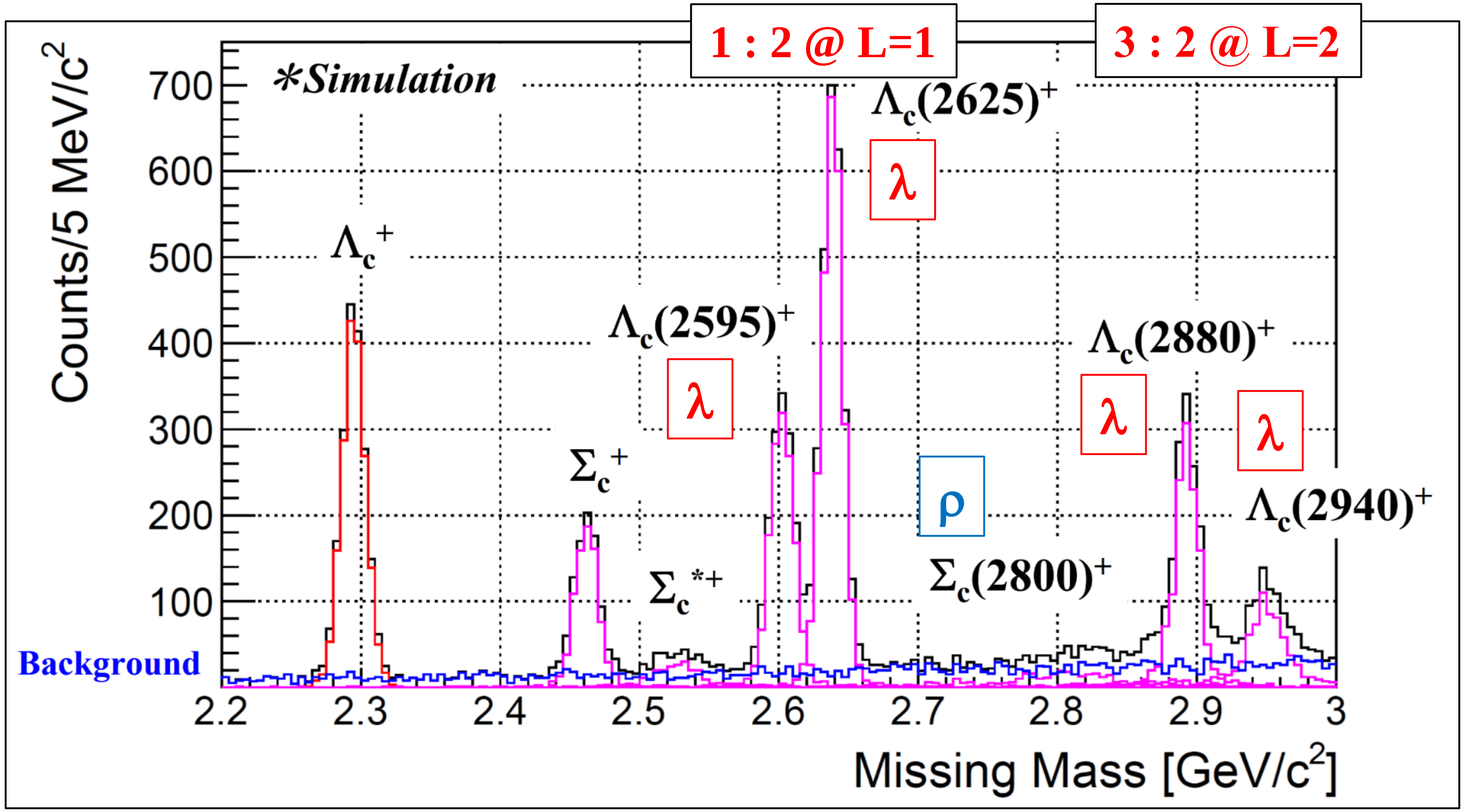
Large Acceptance Multi-Purpose Spectrometer
+ Trigger-less streaming-readout DAQ

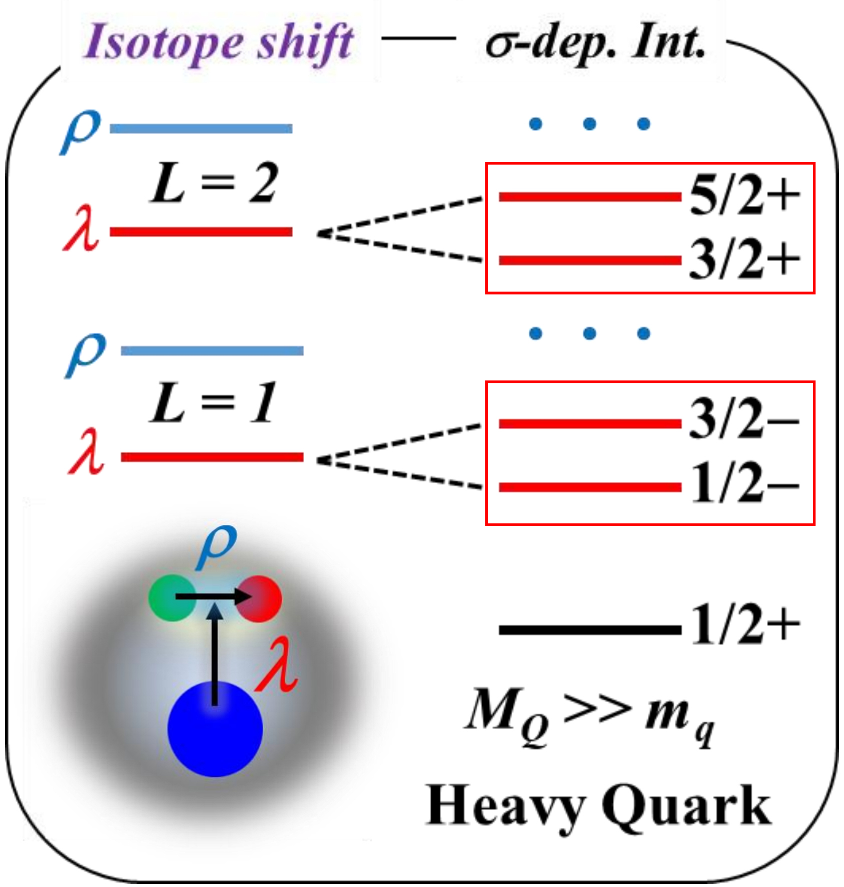
Multipurpose Analyzer for Resonances and Quark dynamics (MARQ)

⇒ New platform for Hadron experiment



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

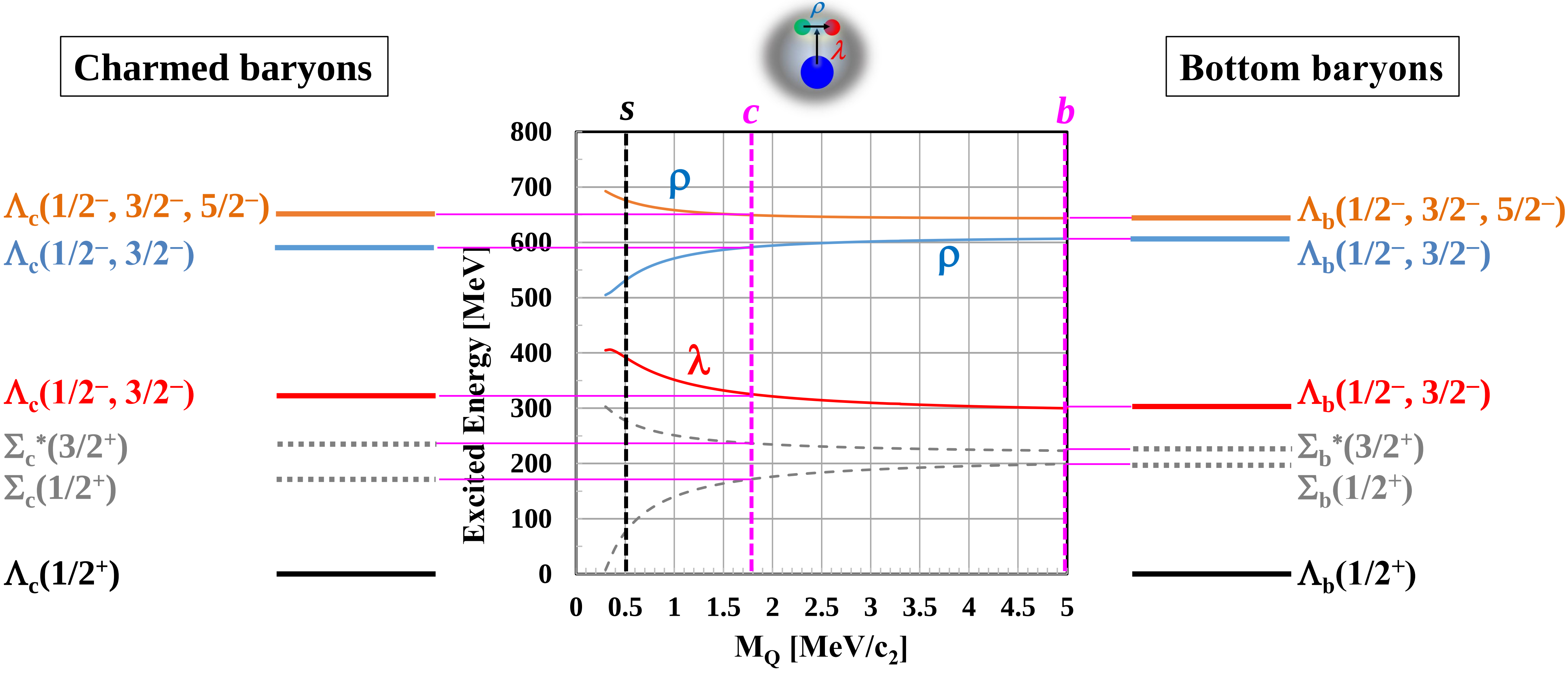




HQ doublet

- **Production rates ⇒ 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/dt) contains structure information.**

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)

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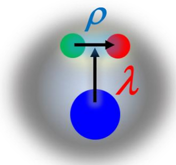
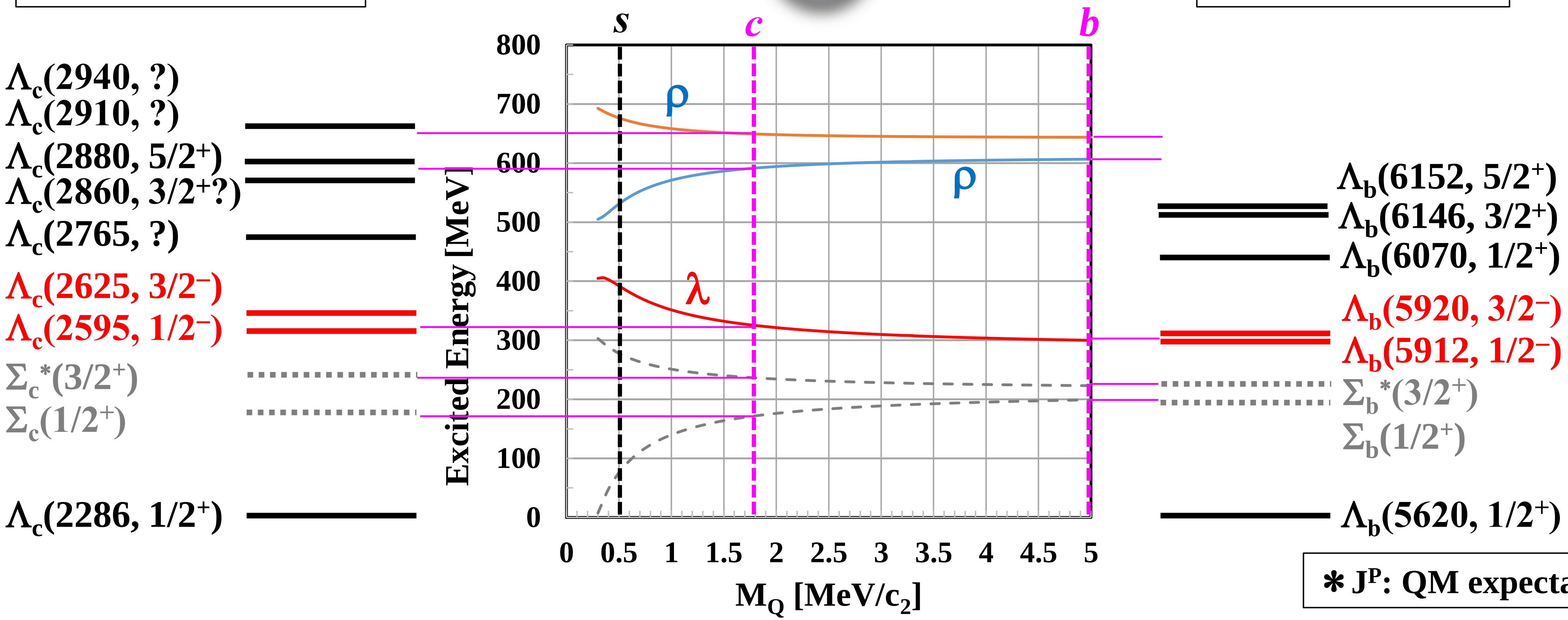


Charmed baryons | **Bottom baryons**



＊J^P: QM expectation

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＊Experimental data (Λ_c/Λ_b states)

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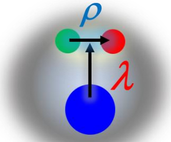

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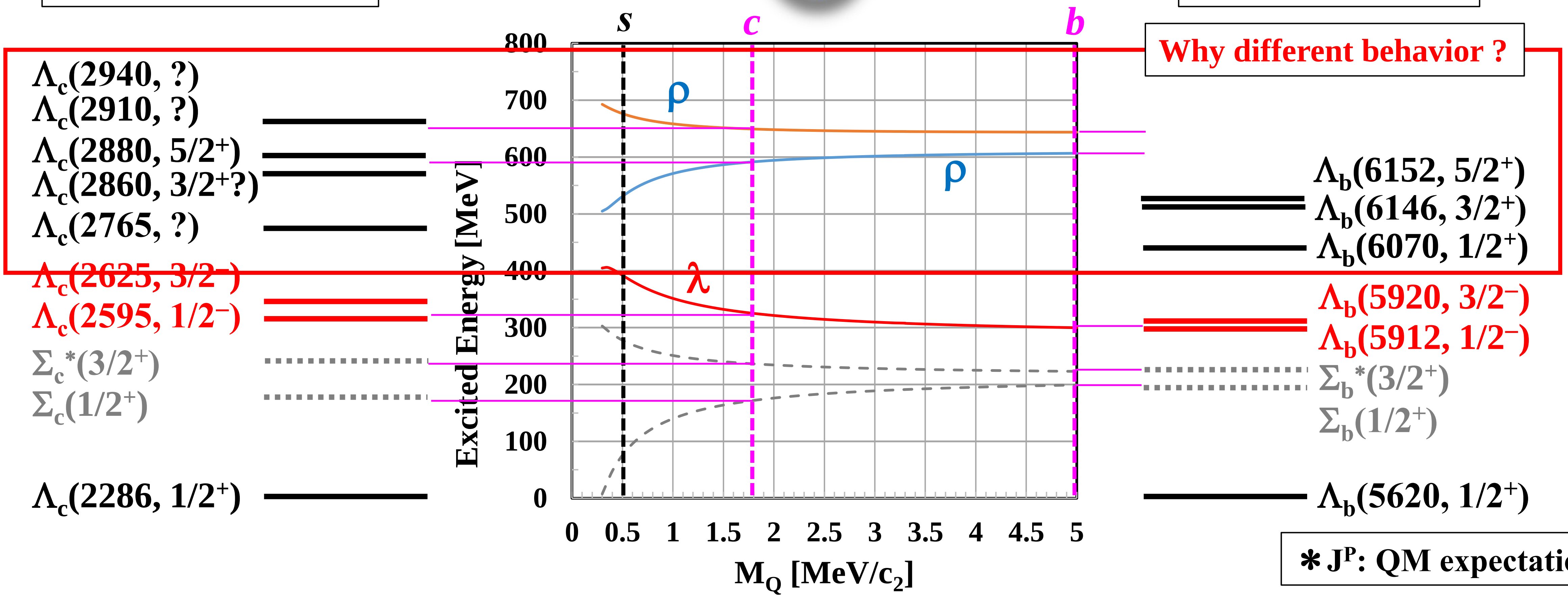

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∗ Diquark correlation: λ & ρ
∗ Experimental data (Λ_c/Λ_b states)

Excited energy of highly excited states

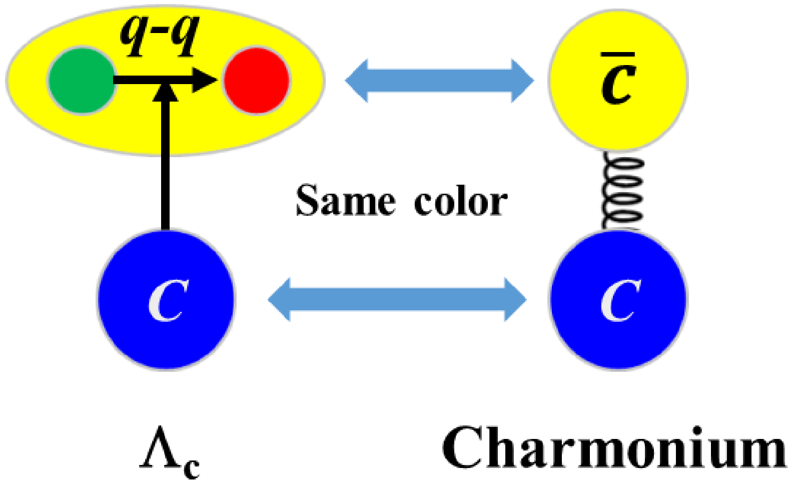
- **Excitation energy ⇔ Quark confinement potential**
  - **Quark-diquark model:** $V(r) = -\frac{4}{3}\frac{\alpha}{r} + kr + V_0$
    - D. Jido and M. Sakashita, PTEP2016(16)083D02

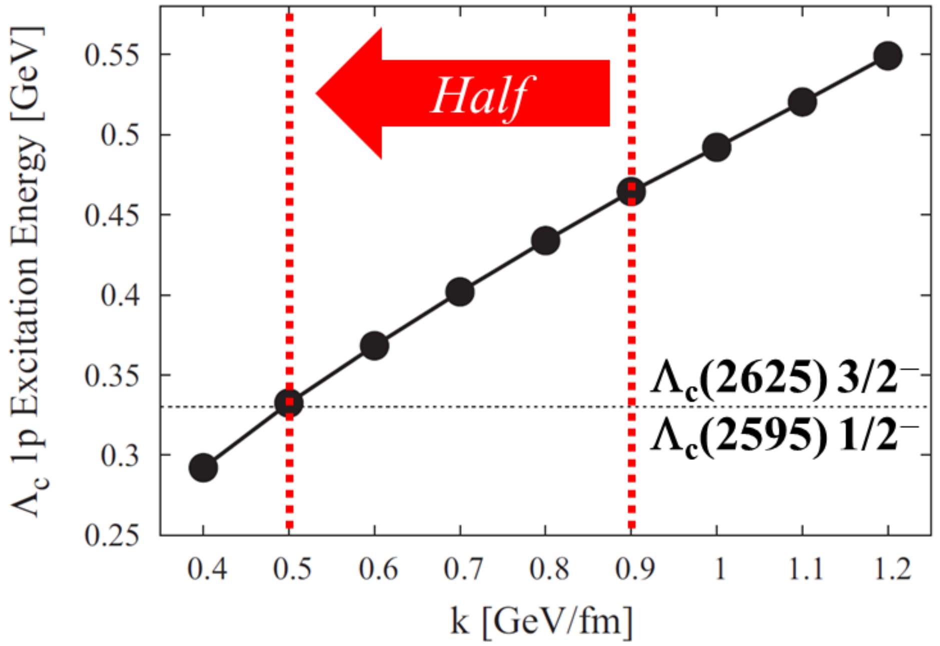
⇒ ***k*** **for Λ_c & Λ_b should be half of $c\bar{c}$ case.**

＊ $k = 0.9$ GeV/fm ⇒ $k = 0.5$ GeV/fm

- Relativistic correction can be solved ?
  - Including internal color structure of diquark
    - H. Nagahiro, private communication
- Diquark mass dependence ?
- Potential is deformed at highly excited states ?
  - Weak string tension: $q\bar{q}$ bubble in string ?

＊ **Trying to solve string tension puzzle**



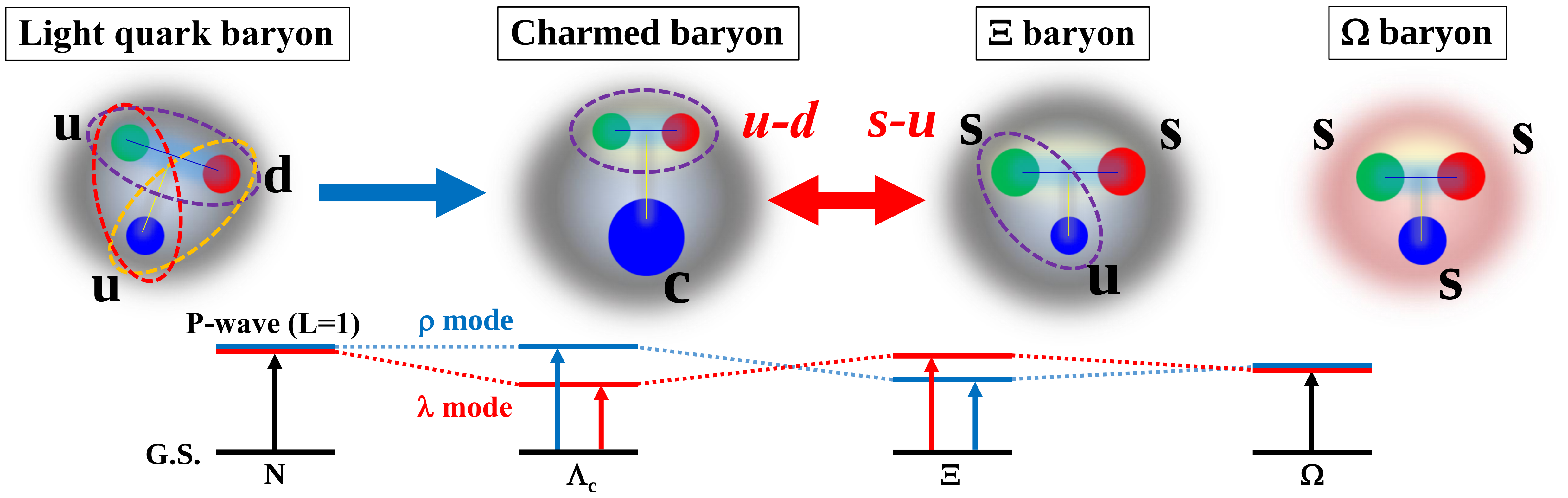


＊ **Production rate tells us "Sticking probability".**

- Wave function information of quark and diquark
- Key: Large production rate of highly excited states by hadron beam reaction

Systematic measurements of heavier flavor baryons

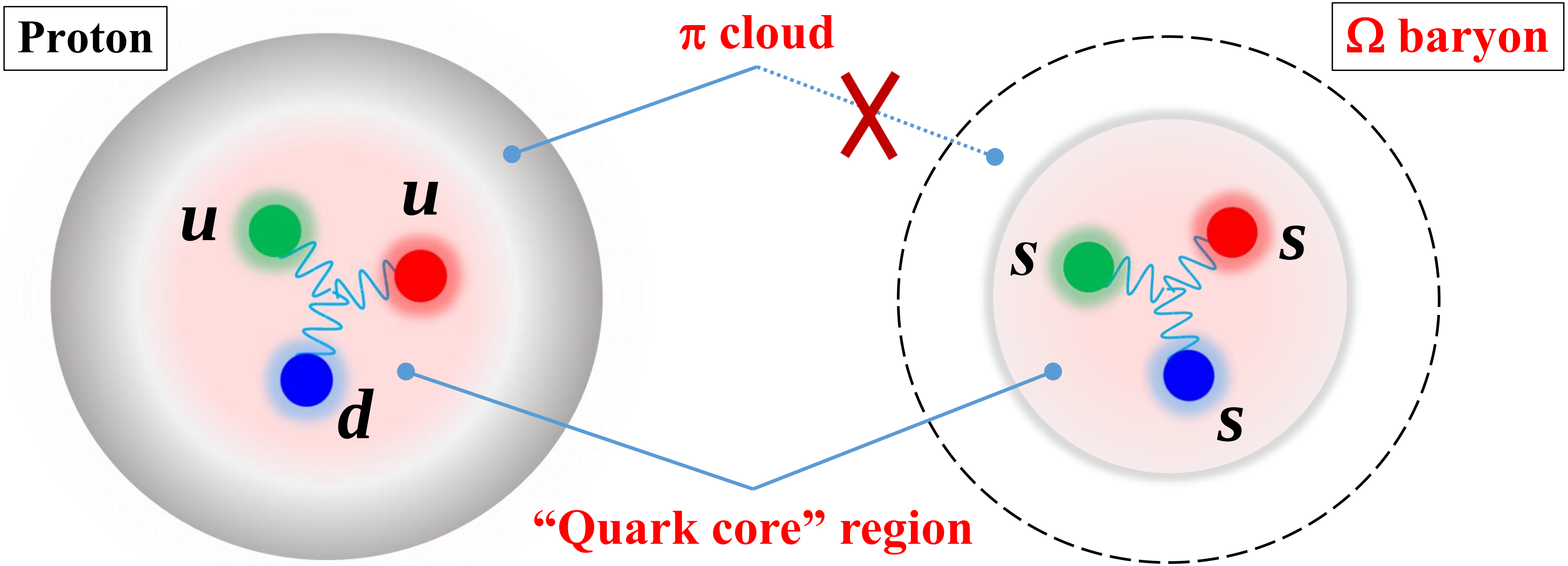
Heavy flavors for revealing diquark correlation



＊Systematic studies for baryon systems with heavier flavors: *c* & *s*

- **Charmed baryon (E50): Disentangle *ud* diquark correlation**
- **Ξ baryon (E97): *us*/*ds* diquark correlation ⇒ Flavor dependence**
- **Ω baryon (P85): Only axial-vector diquark correlation ⇒ Reference system**

Ω baryon: Single flavor system



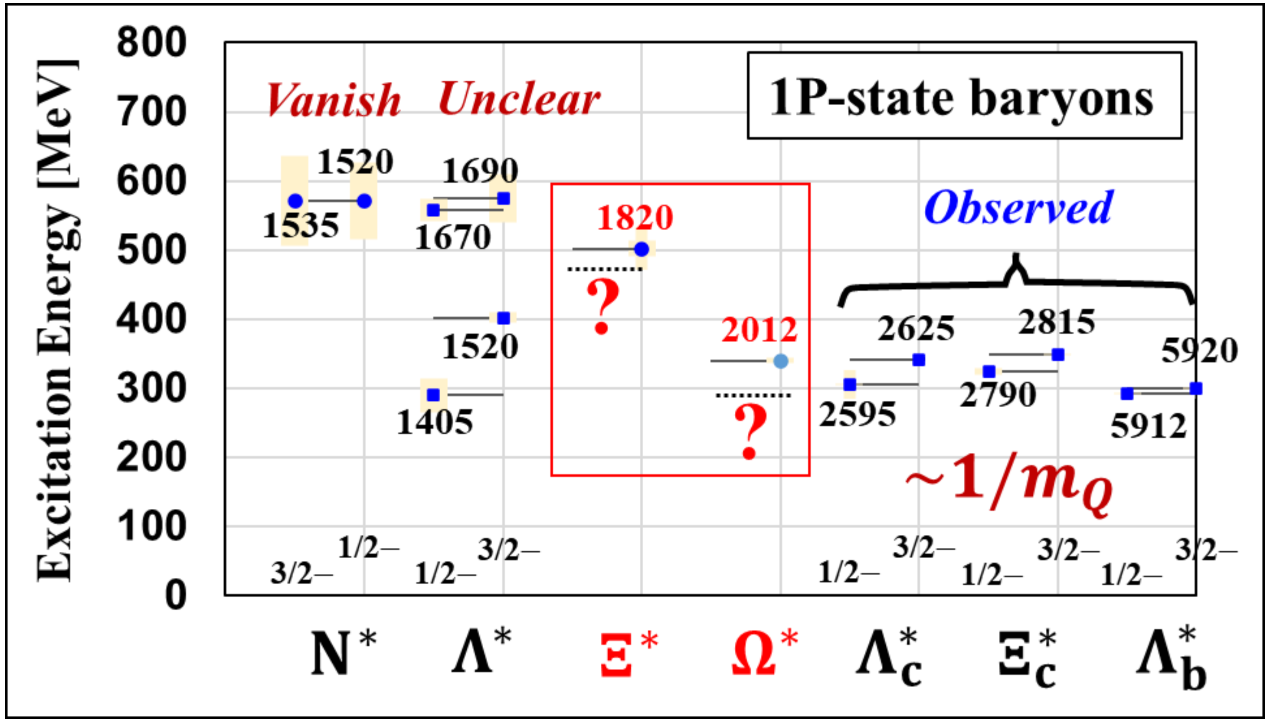
- Ω(sss) baryon

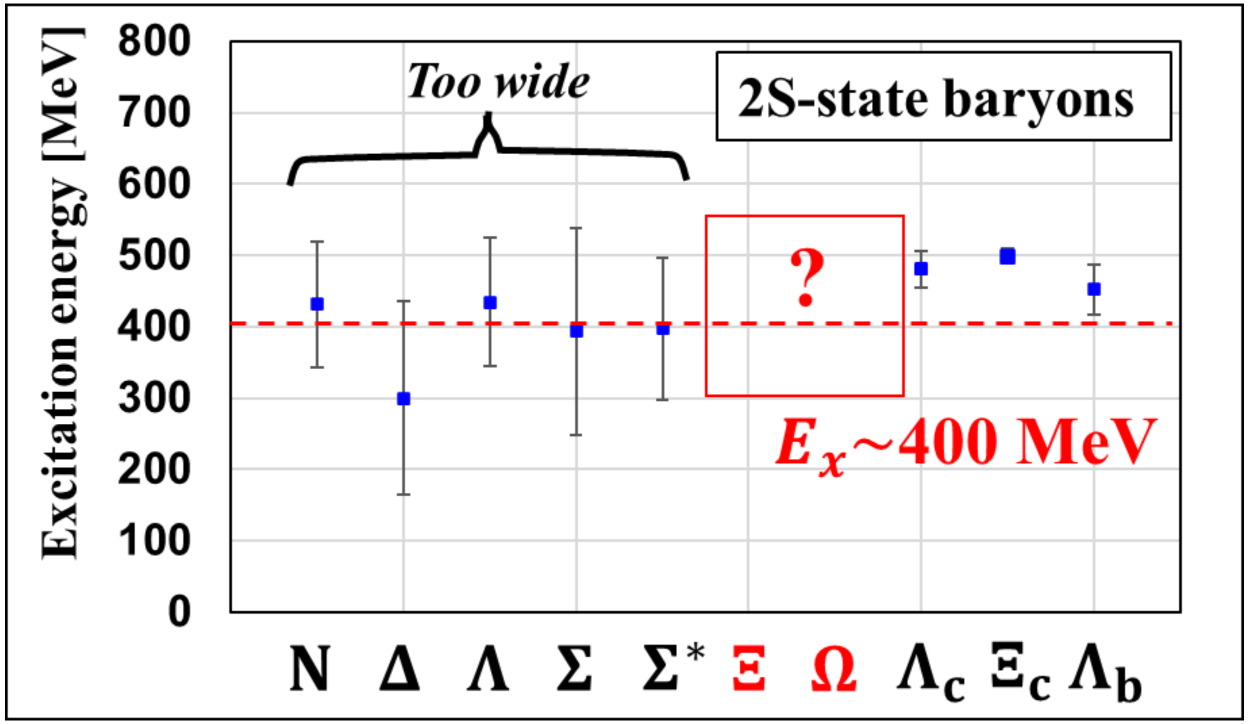
1. **Simple excited state property** due to **flavor symmetric** system
2. **Free from π cloud:** Discriminate "π" contribution
   - No *u* and *d* quarks which strongly couple to π meson.

⇒ **Direct access to properties of "Quark core" region**

Studies of Ξ/Ω baryons: J-PARC E97/P85

- **Investigate spin-dependent forces and quark motion**
  - **In terms of One Gluon Exchange(OGE), Instanton Induced Interaction(III) and Pion cloud**





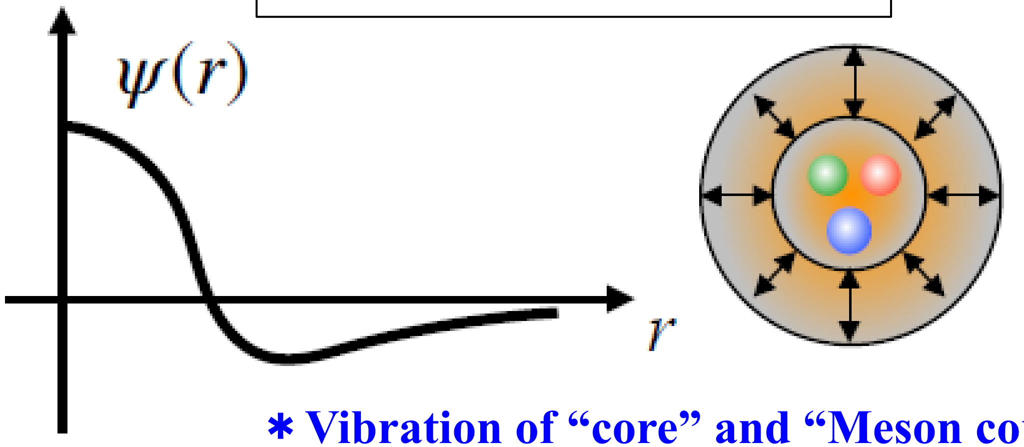
- **Systematics of LS force**
- **Ω(2012)⁻(3/2⁻?) ⇔ Ω*⁻ (1/2⁻?)**
  - **2B LS force canceled**
  - **3B confinement force spilites states.**

- **Systematics of Roper-like resonances**
  - **Small excitation energy and wide width**
- **Mass & width of Ω w/o π cloud**
  - **Width: Quark core size ?**

Roper-like resonances: 2S state

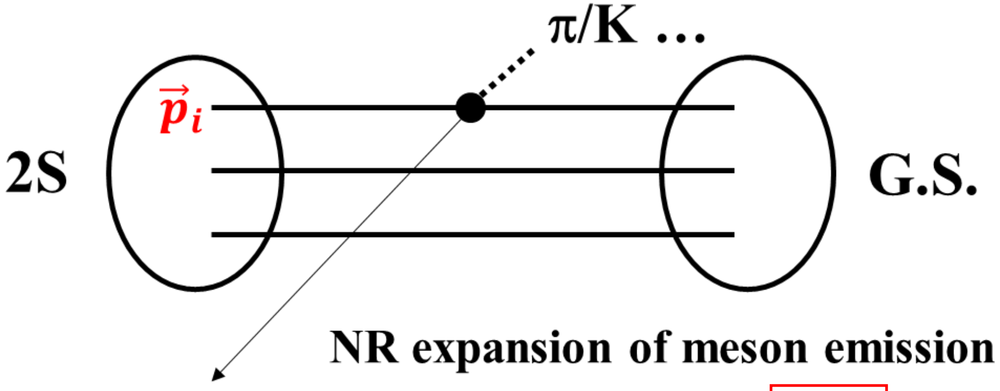
- Systematics of **Roper-like states**
  - Small excitation energy and wide width
  - Mass universality ?
  - What does determine its width ?

Radial excitation 2S states



∗ Vibration of "core" and "Meson could" ?

- Decay width of 2S state



NR expansion of meson emission

$$< \text{Roper}|\mathcal{O}|\text{G.S.} > \sim < \vec{\sigma}\cdot\vec{p} > (\cancel{a_0} + a_2\vec{p}_i^{\,2} + \cdots)$$

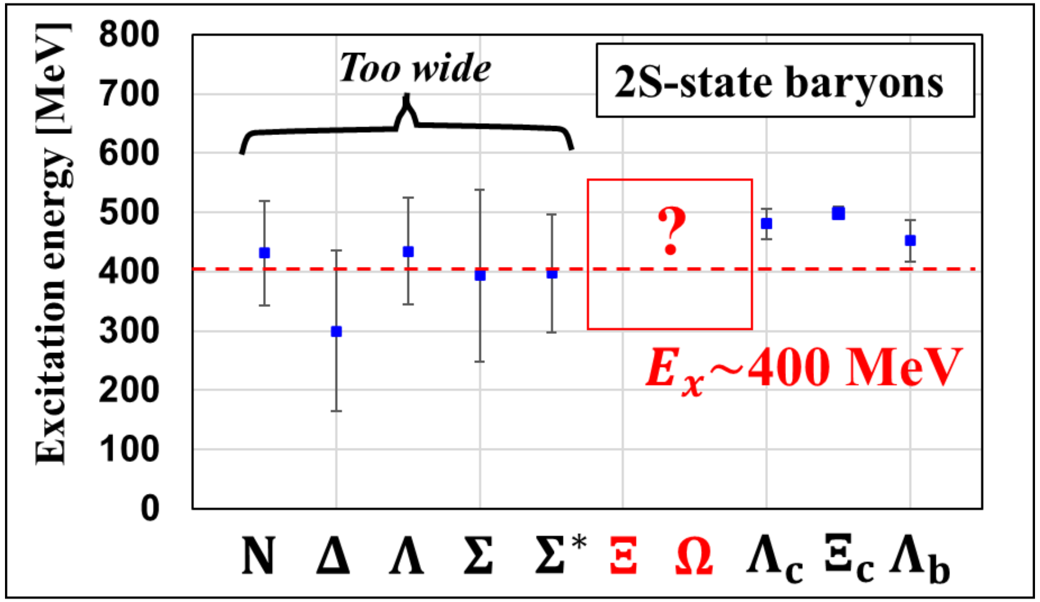
Leading order (LO) suppressed by selection rule

Next to leading order (NLO)
$\Rightarrow \Gamma \sim \langle p_q^2 \rangle$ internal quark motion

∗ $\Omega^{*-}(3/2^+)(2S)$: Γ = 50–100 MeV

J. Arifi *et al.*, PRD105, 094006 (2023)
J. Arifi *et al.*, PRD103, 094003 (2021)

Systematics of the Roper-like resonances



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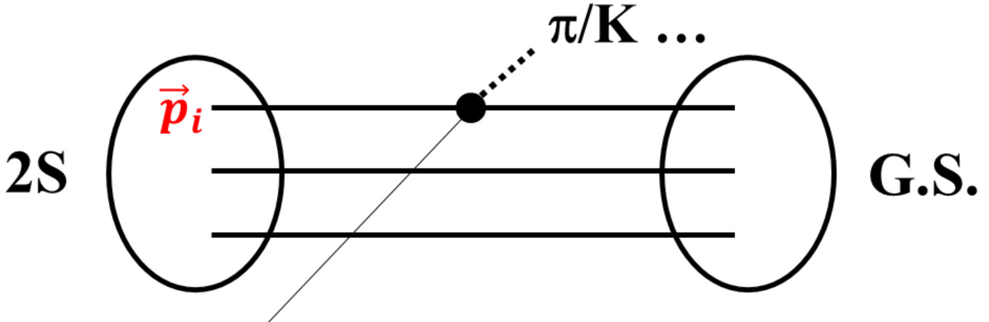

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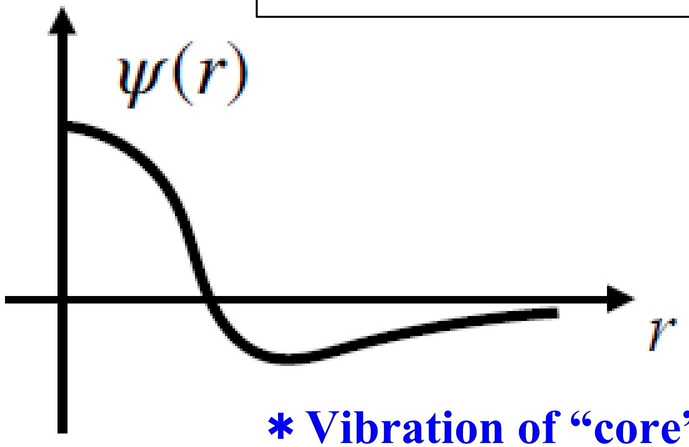

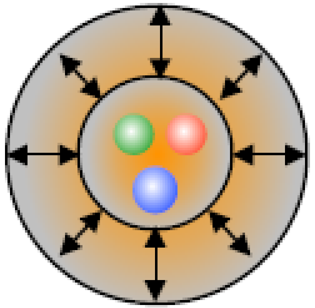

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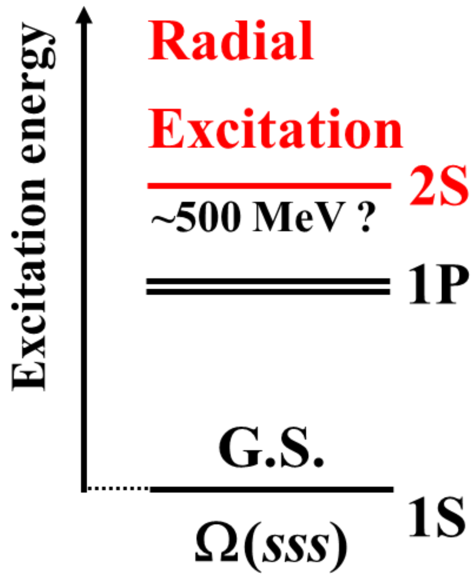
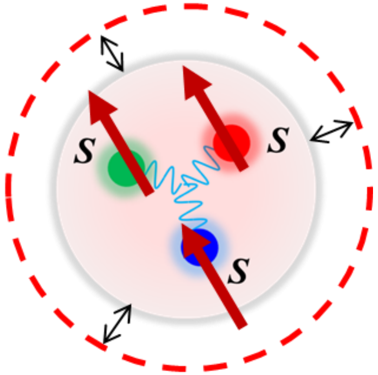
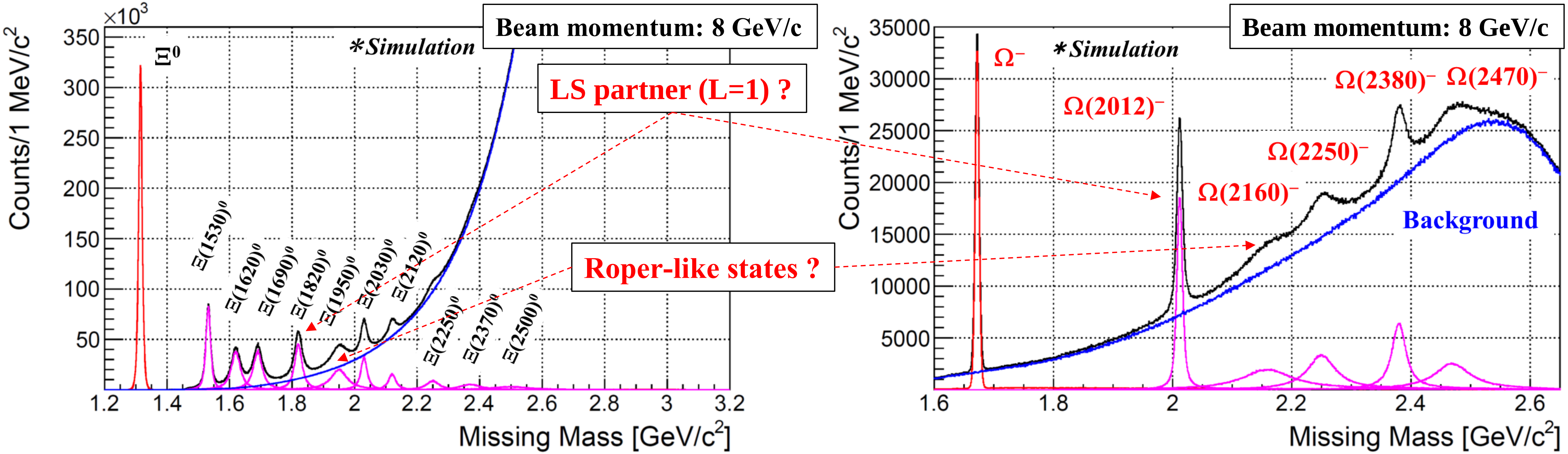




∗ $\langle r_q^2 \rangle \sim 1/\langle p_q^2 \rangle$: Quark core size ?

Expected mass spectra: K⁻ p reactions



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

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

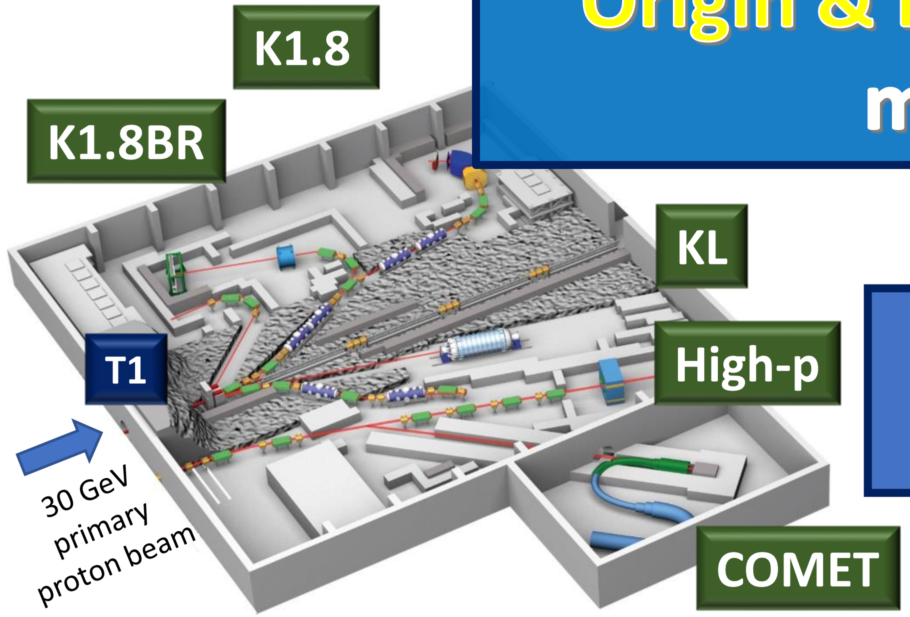
*** Only a few established states in PDG**

⇒ Systematic studies: Identify λ/ρ modes, SS/LS forces and internal quark motion

Hadron Experimental Facility extension (HEF-ex) Project

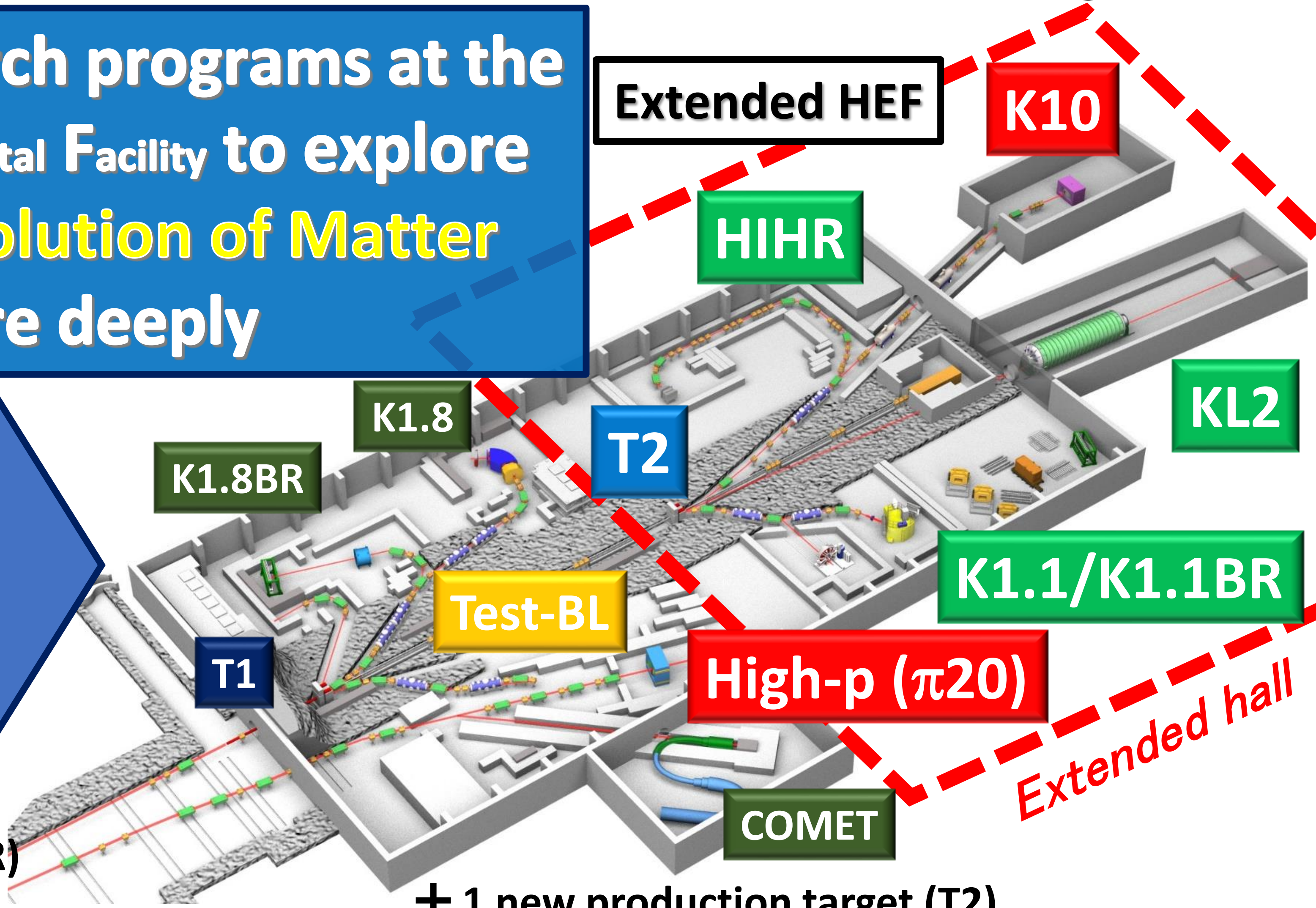
Expand research programs at the Hadron Experimental Facility to explore Origin & Evolution of Matter more deeply

Present HEF (2009〜)



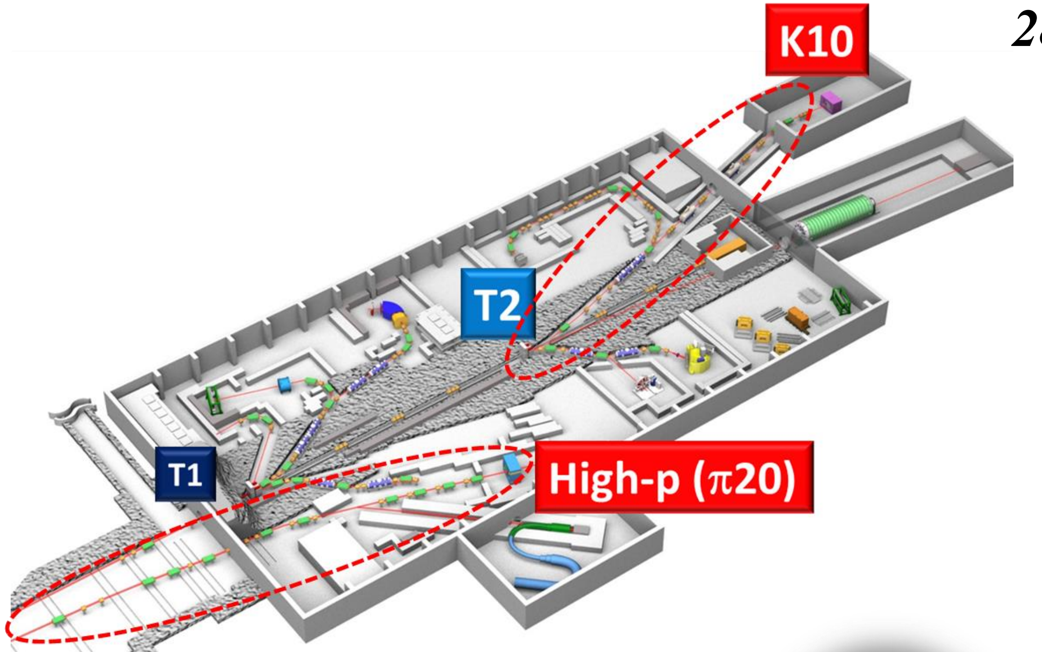
1 production target (T1)
1 secondary-charged beamline (K1.8/K1.8BR)
1 neutral beamline (KL)
1 primary beamline (High-p)
1 muon beamline (COMET)

Extended HEF



＋1 new production target (T2)
＋4 new beamlines (HIHR, K1.1/K1.1BR, KL2, K10)
＋ 2 updated beamlines (High-p (π20), Test-BL)

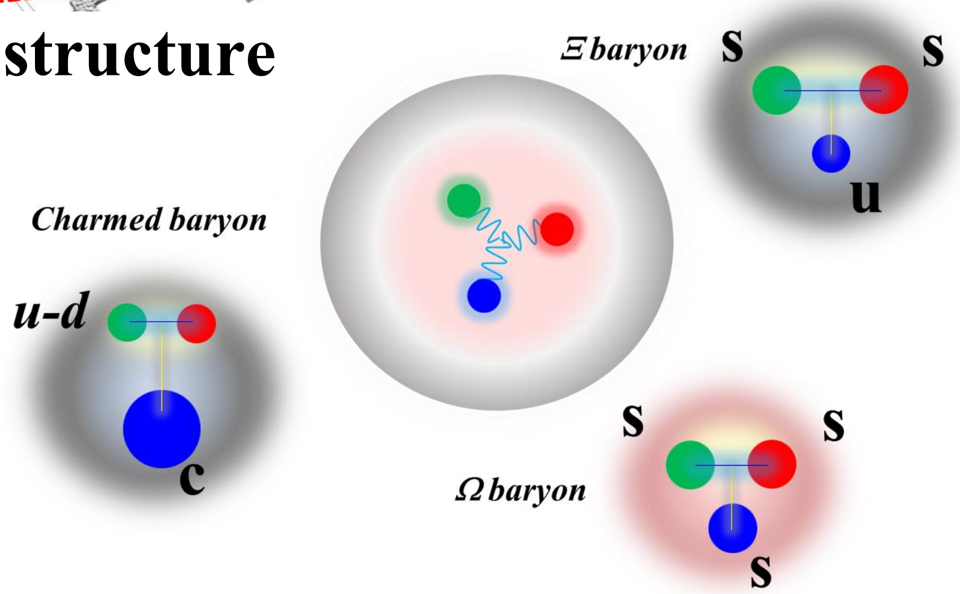
Baryon spectroscopy at J-PARC



- **π20: π beam (unseparated beam)**
  - **High intensity: >10^7 /spill for π^- up to 20 GeV/c**
- **K10: K^- & $\bar{p}$ beam (K/π ~ 1/2, $\bar{p}$/π ~ 2/1)**
  - **High intensity: >10^6 /spill up to 10 GeV/c**

＊Systematic *c*- and *s*-baryon spectroscopy:

Dynamics of non-trivial QCD vacuum in baryon structure



- **Diquark correlation**
  - ***ud* diquark: Λ_c/Σ_c**
  - ***us/ds* diquark: Ξ**
  - **Only axial-vector diquark: Ω**
- **Origin of spin-dependent forces**
  - **Excited state data of Λ_c/Σ_c, Ξ, Ω systems**

＊Systematic measurements of "total cross sections" and "branching ratios" will provide the internal structure of the excited baryons.

Summary

Summary

- **How quarks build hadrons ?**
  - **Dynamics of non-trivial QCD vacuum in baryon structure**

- **Charmed baryon spectroscopy**
  - **Disentangle diquark correlation by production rate measurement**
  - **String tension puzzle in highly excited states ⇒ Production rate**
  - **High-intensity & High-momentum hadron beam: J-PARC π20 beam line**
  - **Construction of multi-purpose spectrometer: MARQ**

- **Spectroscopy of heavier flavors for understanding "Baryon system"**
  - **Systematic spectroscopy of Λ_c/Σ_c, Ξ, Ω baryons**
  - **Disentangle diquark correlation and origin of spin-dependent forces**
  - **Role of Ω: Free from π cloud ⇒ Investigation of internal quark motion**

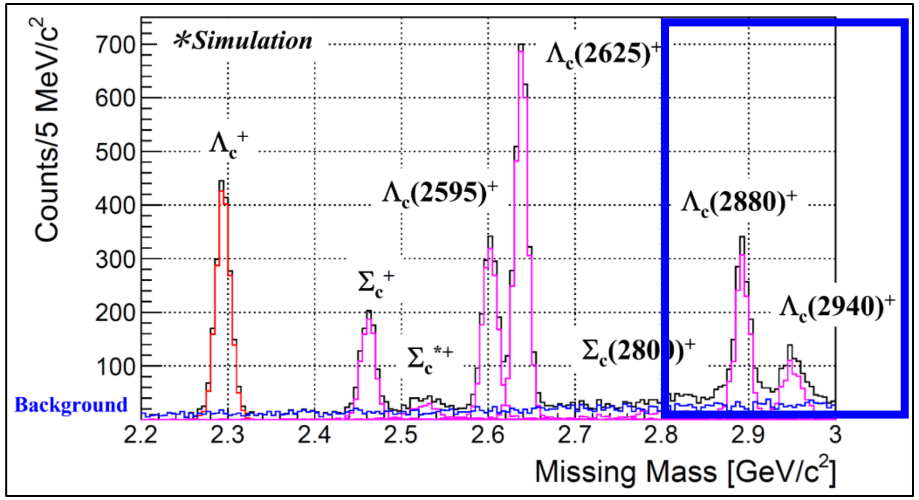
⇒ Systematic studies at π20 and K10 beam lines at J-PARC

✱J-PARC hadron experimental facility provides unique opportunity for hadron spectroscopy experiments.

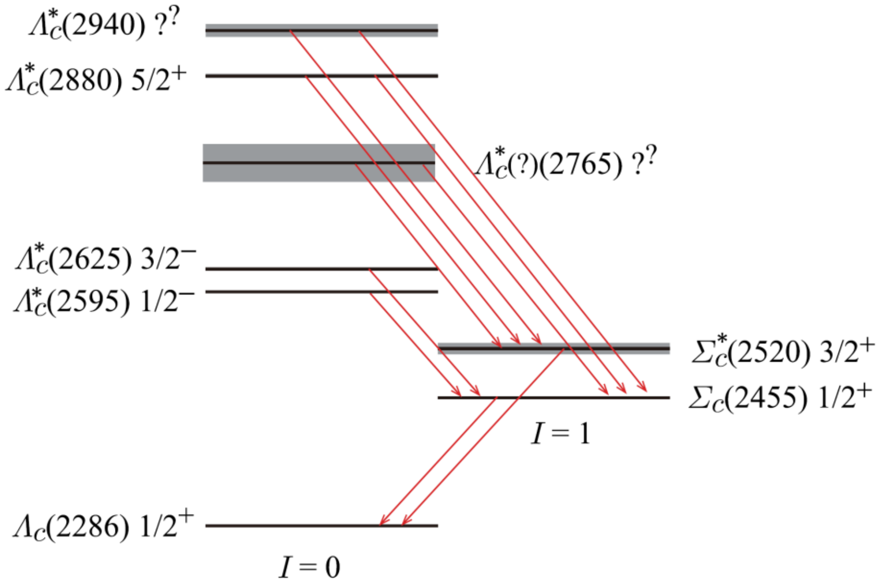
Backup slides

Heavy quark doublet in highly excited states

- $\Lambda_c(2880)$
  - $J^P = 5/2^+$ measured by Belle (PRL98, 262001(2007))
    - If D-wave Λ_c^* state ⇔ HQ doublet partner ?
  - $\Lambda_c(2880)(5/2^+)$ 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)



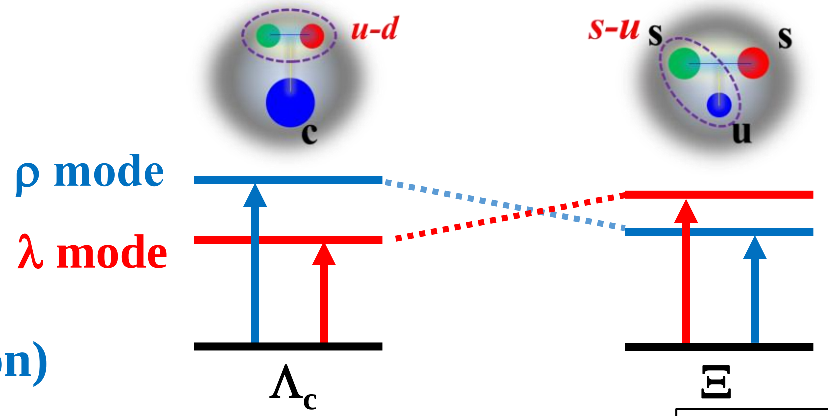
- $\Lambda_c(2940)$
  - J^P is not determined.
  - LHCb data: $3/2^-$? (1/2 and 7/2 cannot be excluded)
    - D^0 p amplitude in $\Lambda^0_b \rightarrow D^0\, p\, \pi^-$ (arXiv:1701.07873v2)
  - If partner is $\Lambda_c(2880)(5/2^+)$, $J^P = 7/2^+$
    - H. Nagahiro et al., Phys. Rev. D 95, 014023 (2017)



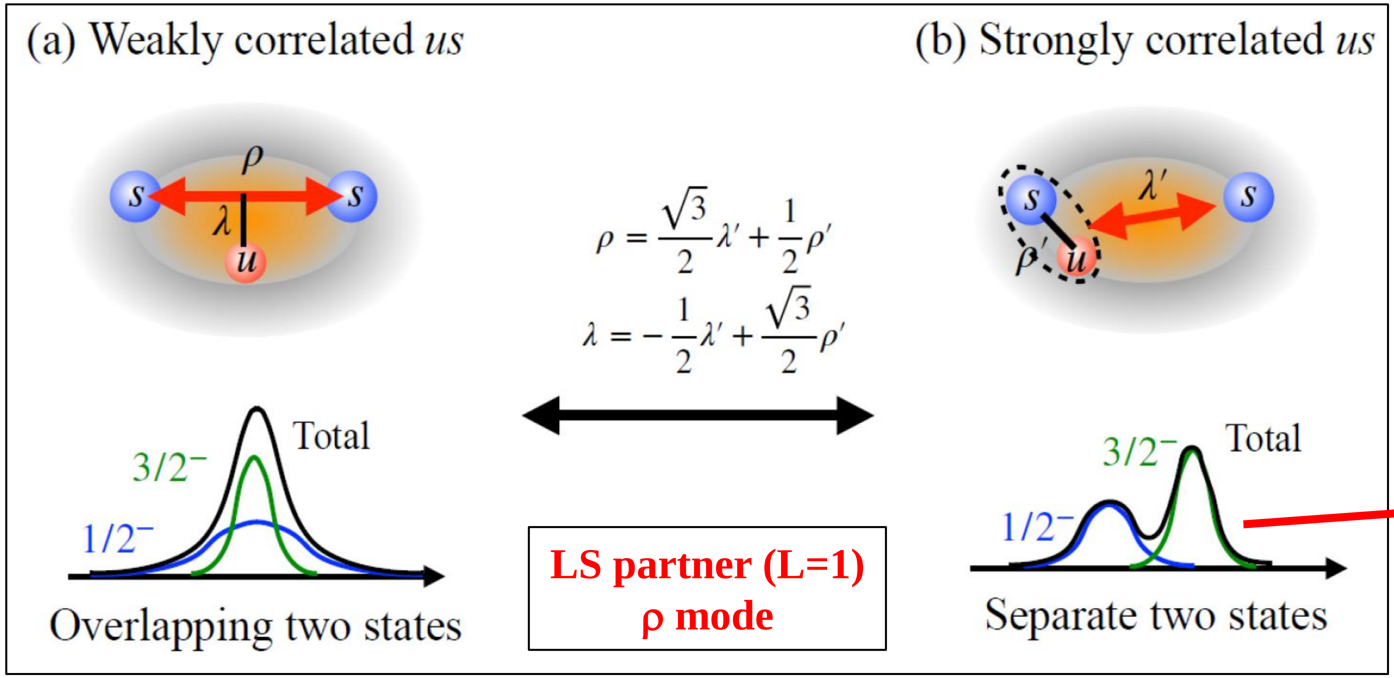
*** Where are HQ doublet states ? ($\lambda = 2$ mode)**

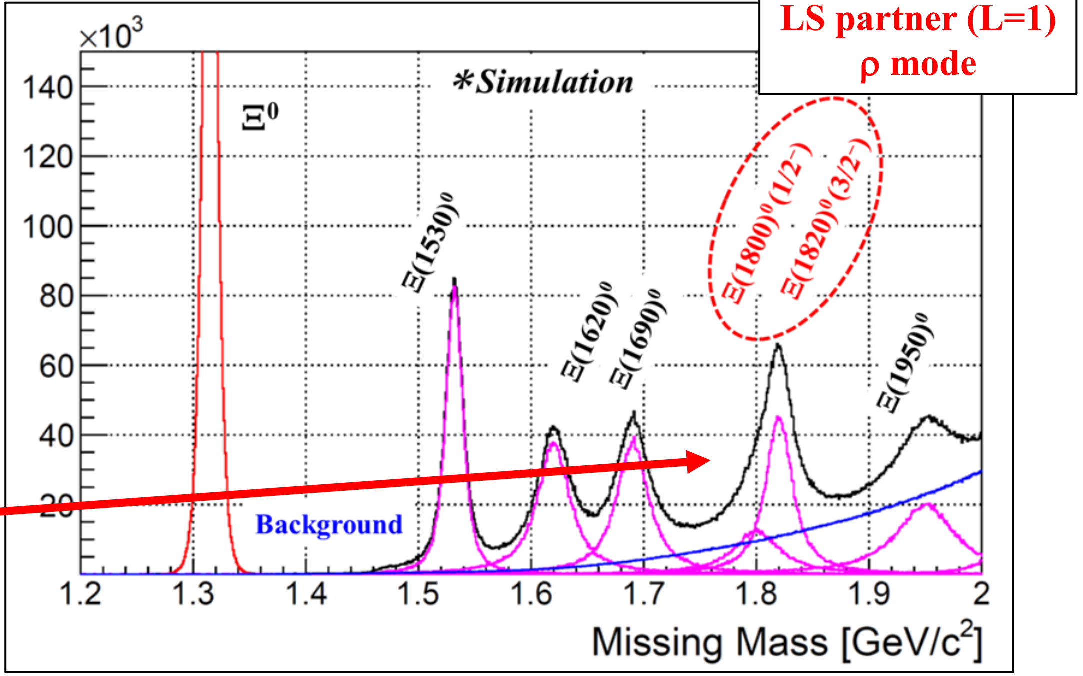
- Brown much J=2
- Properties of highly excited states can be tested by production.

Studies of Ξ : J-PARC E97



- **Ξ baryon: *us*/*ds* diquark correlation**
  - **Excitation energy: ρ mode < λ mode**
  - **Strength of *us/ds* correlation: LS splitting**
    - **Production rate of LS partner (L=1) = 1:2 (L:L+1 relation)**





*Ξ(1800)⁰(1/2⁻): Assumed for simulation

- **Ω baryon: Suppression of diquark correlation ⇒ "Reference"**
  - **Suppression of spin-dependent forces and pion cloud**

  ⇒ Investigation of origin of spin-dependent forces and quark motion

Size measurement of Ω baryon 2S state

∗ Measurement of 2S state width(Γ)

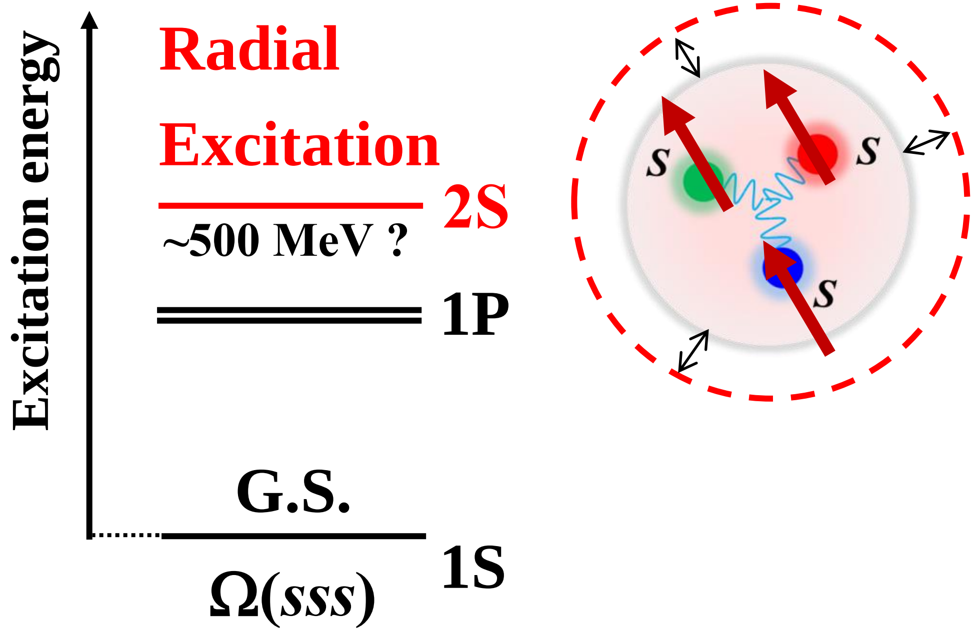
$\Rightarrow \Gamma \sim \langle p_q^2 \rangle$

- Internal quark momentum: $\langle p_q^2 \rangle$
  - J. Arifi *et al.*, PRD105, 094006 (2023)
  - J. Arifi *et al.*, PRD103, 094003 (2021)

$\Rightarrow \langle r_q^2 \rangle \sim 1/\langle p_q^2 \rangle$

$\Rightarrow$ Size of "quark core": $\langle r_q^2 \rangle$

- Essential of free from π cloud



∗ Effects of K cloud need to be investigated.

- Minor contribution ?: $M_K/M_\pi = 3.5 \Rightarrow$ Range of Yukawa coupling ~0.4 fm
- Branching ratio of $\Omega^{*-} \rightarrow K + \Xi$: Coupling of K and Ω
- (Future study) ΩN bound state: Strength of K meson exchange