Spectroscopic experiments of charmed and strange baryons at J-PARC

K. Shirotori

Research Center for Nuclear Physics (RCNP)
Osaka University

16^{th} Hadron Spectroscopy Cafe
"Recent hot topics and future prospects of hadron experiments at J-PARC"

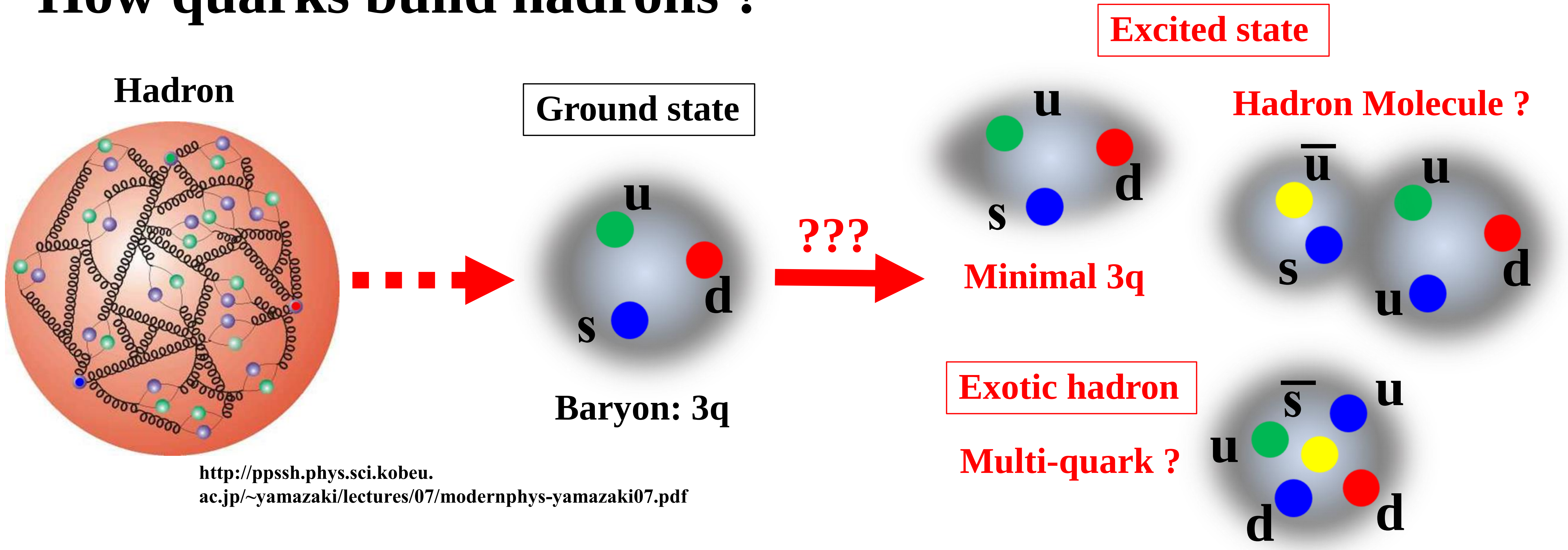
20^{th} Jul. 2022

Contents

- Introduction
  - Motivation
  - Diquark correlation
  - Spin-dependent forces
- Experiments with high-momentum hadron beam
  - Charmed baryon @ High-p (π20) beam line
  - Ξ and Ω baryons @ K10 beam line
- Further studies
- Summary

Hadron Experimental Facility Extension project
3rd white paper, arXiv:2110.04462

How quarks build hadrons ?



http://ppssh.phys.sci.kobeu.ac.jp/~yamazaki/lectures/07/modernphys-yamazaki07.pdf

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

- **Investigation of effective degrees of freedom and their interactions**

⇒ Study of excited state by spectroscopy experiment using hadron beam

- **Understand "dynamics" of confined DoF from their "response"**

Investigations of hadrons at J-PARC

- **Spectroscopy of Heavier flavors for understanding "Baryon system"**
  - Charmed baryon (Λ_c/Σ_c): ud + c
  - Ξ baryons: u/d + ss
  - Ω baryons: sss

⇒ **Systematic spectroscopy measurement** by high-momentum hadron beam:

Hadron Experimental Facility Extension

- **High-p(π20) beam line**: π^- up to 20 GeV/c
- **K10 beam line**: K^- up to 10 GeV/c

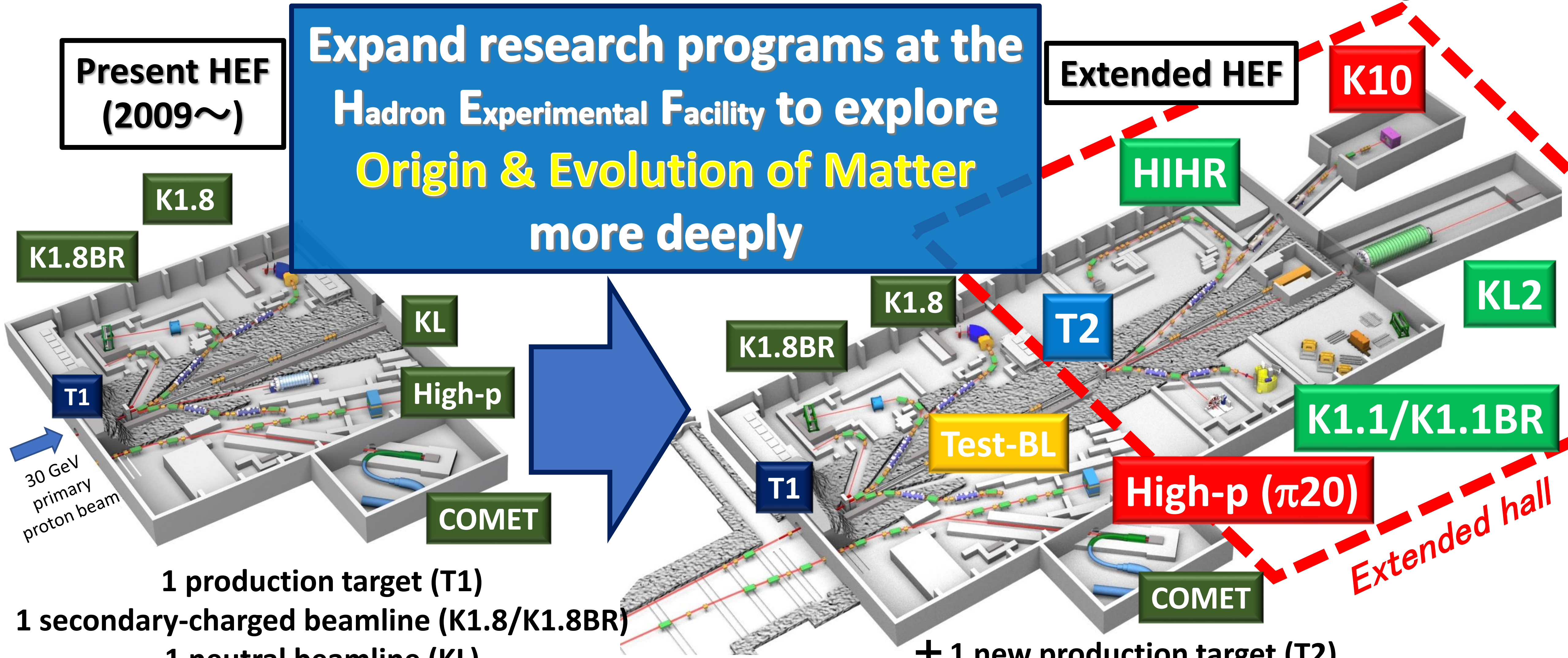
- **Investigation of exotic states for understanding "Exotic property"**

⇒ **Specific measurement** by dedicated experiments

- Mass and width: e.g., narrow Λ^*, D_{30} (Non-strange dibaryon)
- Spectrum line shape: e.g., $\Lambda(1405) \Rightarrow K_{bar}N$ structure
- Spin/parity: e.g., narrow Λ^*
- Number of quarks: e.g., $\Lambda(1405)$ by quark counting rule (5q ⇔ 3q)

Hadron Experimental Facility extension (HEF-ex) Project

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



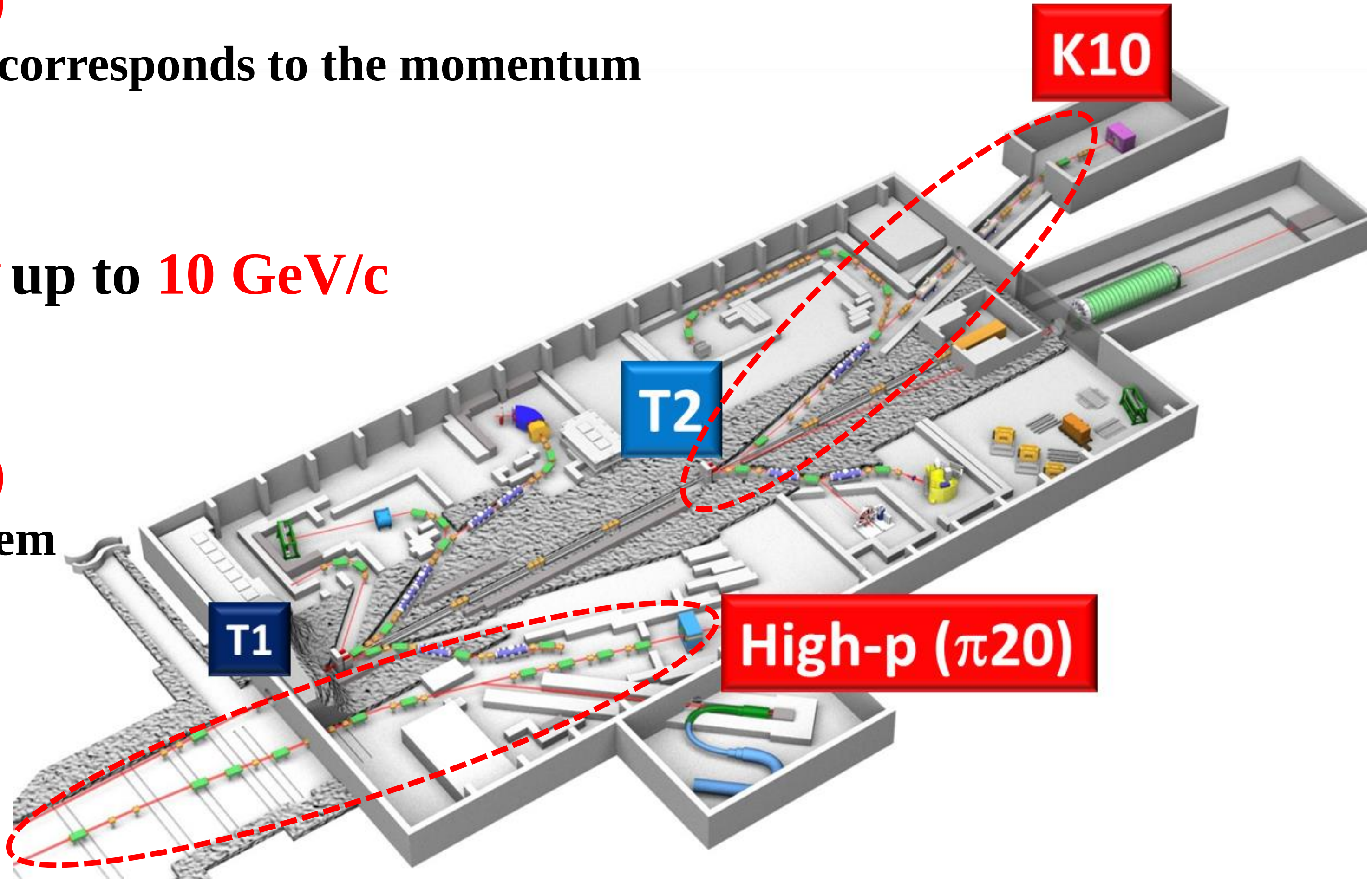
1 production target (T1)
1 secondary-charged beamline (K1.8/K1.8BR)
1 neutral beamline (KL)
1 primary beamline (High-p)
1 muon beamline (COMET)

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

High-momentum hadron beam lines: π20 and K10

- High-p(π20): Primary proton ⇒ 2ndary beam (unseparated)
  - High intensity: >10^7 /spill for π^- (K^-, p_{bar}: 1–2%) up to 20 GeV/c
    - Production target and 0-degree beam extraction
  - High resolution: Δp/p = 0.1%(σ)
    - Dispersion matching: the position corresponds to the momentum

- K10 beam line: K^- beam
  - High intensity: >10^6 /spill for K^- up to 10 GeV/c
  - High-purity: K : π ~ 1 : 2
    - Radio Frequency(RF) separator
  - High resolution: Δp/p = 0.1%(σ)
    - Beam spectrometer: QQDDQ system



*Beam line name: ○XX

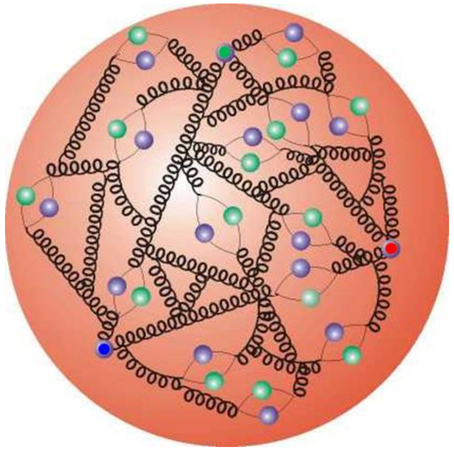
○: Main beam particle

XX: Maximum beam momentum

Introduction

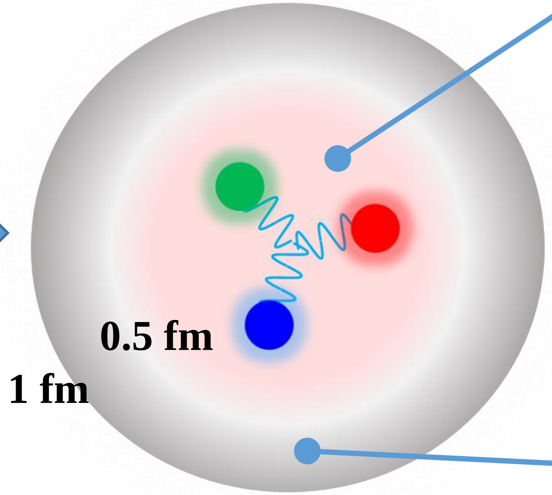
Baryon structure in the low-energy regime

High energy
perturbative



$\boldsymbol{\alpha_s = \infty}$
at Λ_{QCD}

Low energy
non-perturbative



- **Non-perturbative region**

⇒ “Quark core” region

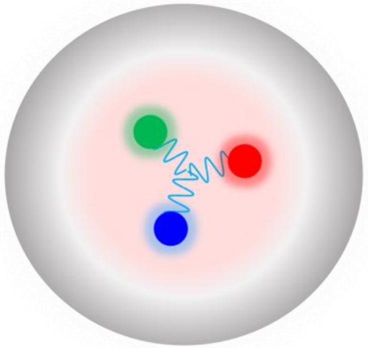
- **Non-trivial gluon field: Instanton***
- **Chiral condensate $\langle \bar{q}q \rangle \neq 0$**
  - **Dressed quark (Constituent quark)**
  - **Emergence of π**

- **Meson (pion) Cloud**

- **Dynamics of non-trivial QCD vacuum ⇒ Dynamics of Effective DoF**
  - **Short-range spin-spin correlation: Diqaurk correlation**
  - **Origin of spin-dependent forces: Systematics of spin-spin/spin-orbital forces**
  - **Quark motions in “quark core”: Size of “core” and ”cloud”**

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

Baryon spectroscopy at J-PARC



- **Dynamics of non-trivial QCD vacuum in baryon structure**
  - **Massive quarks and NG bosons (effective degrees of freedom)**
    - **Their dynamics has not been understood.**
- ***c*- and *s*-baryon spectroscopy: Disentangle diquark correlation and spin-dependent forces**

∗ Charm baryon @ High-p (π20)

Disentangle *ud* diquark correlation

∗ Ξ and Ω baryons @ K10

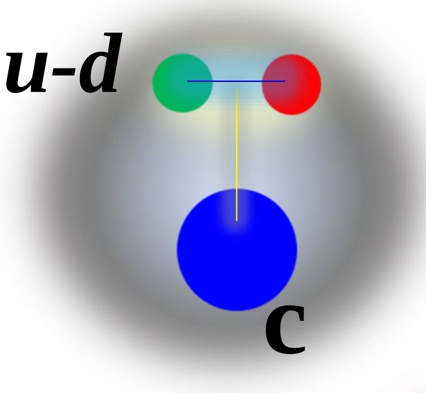
Ξ : *us/ds* diquark correlation

Ω : Suppression of diquark correlation

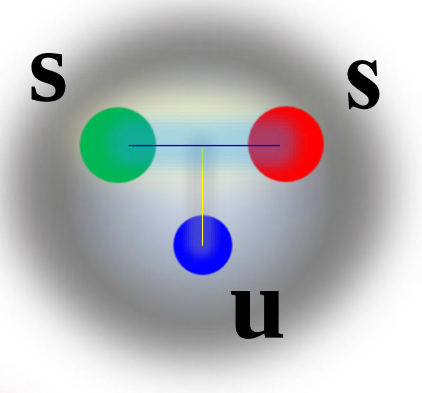
∗ Both π20 and K10

- **Spin-dependent forces**
- **Internal quark motion**

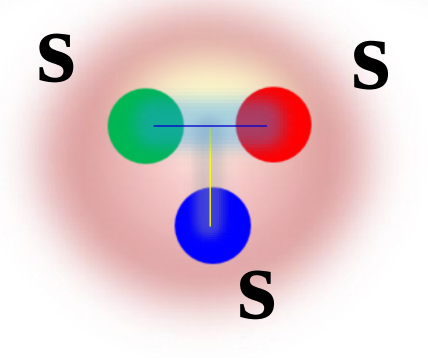
Charmed baryon



Ξ baryon



Ω baryon

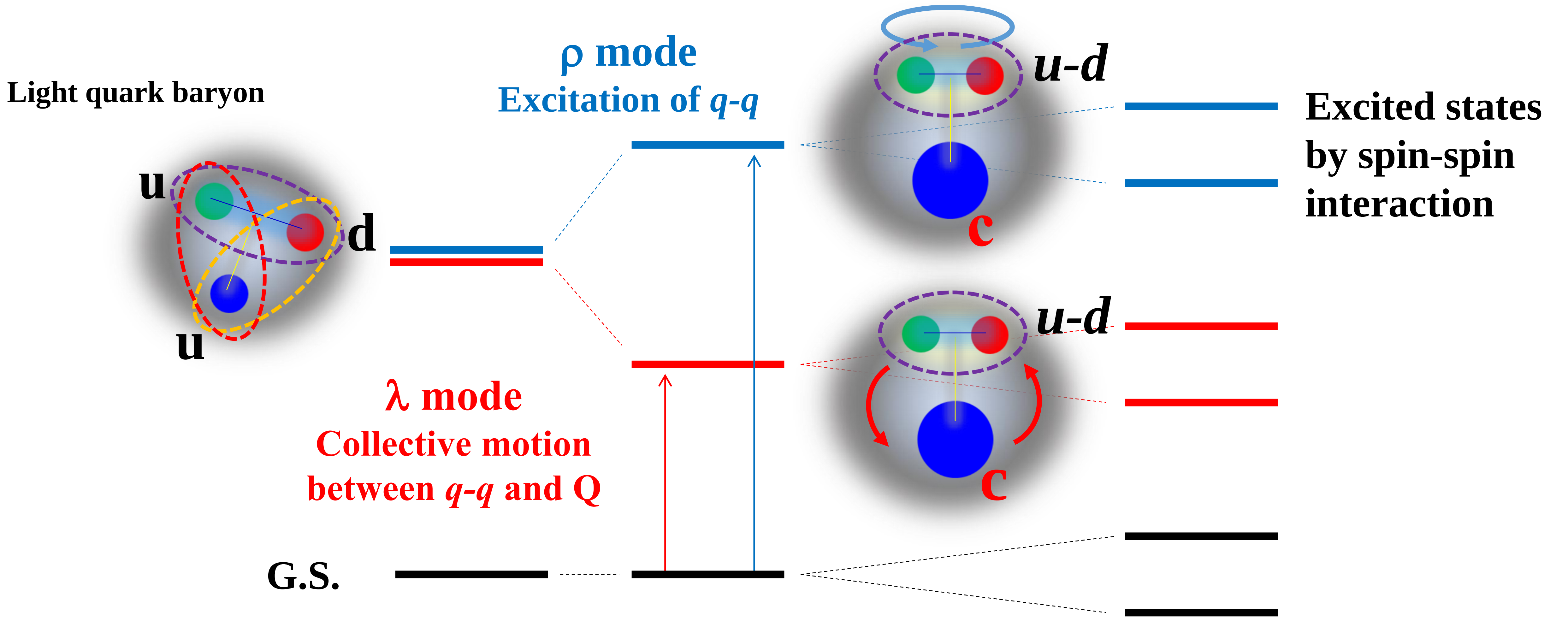


Studies of diquark correlation: J-PARC E50

"Excitation mode": λ and ρ modes in heavy baryon excited states (*q-q* + Q system)

⇒ Diquark correlation: *q-q* isolated and develops

＊Dynamical information: Production rates and absolute decay branching ratios



Production rates by hadronic reaction

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

    ⇒ Sensitive to excitation modes
  - Large production rate of highly excited states → $I_L \sim (q_{eff}/\alpha)^L \exp(-q_{eff}^2/\alpha^2)$
  - Both one- and two-quark processes ($\sigma_\Lambda : \sigma_\Sigma = 2:1$)

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

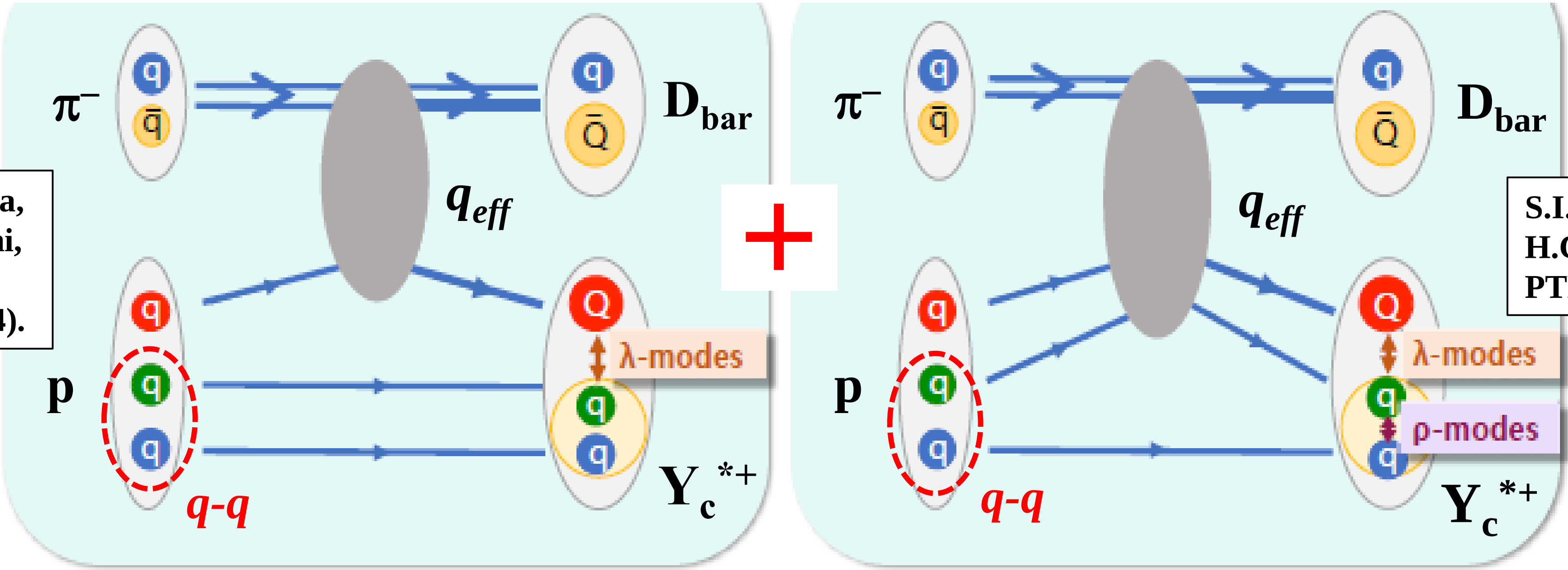
One-quark process

＊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).



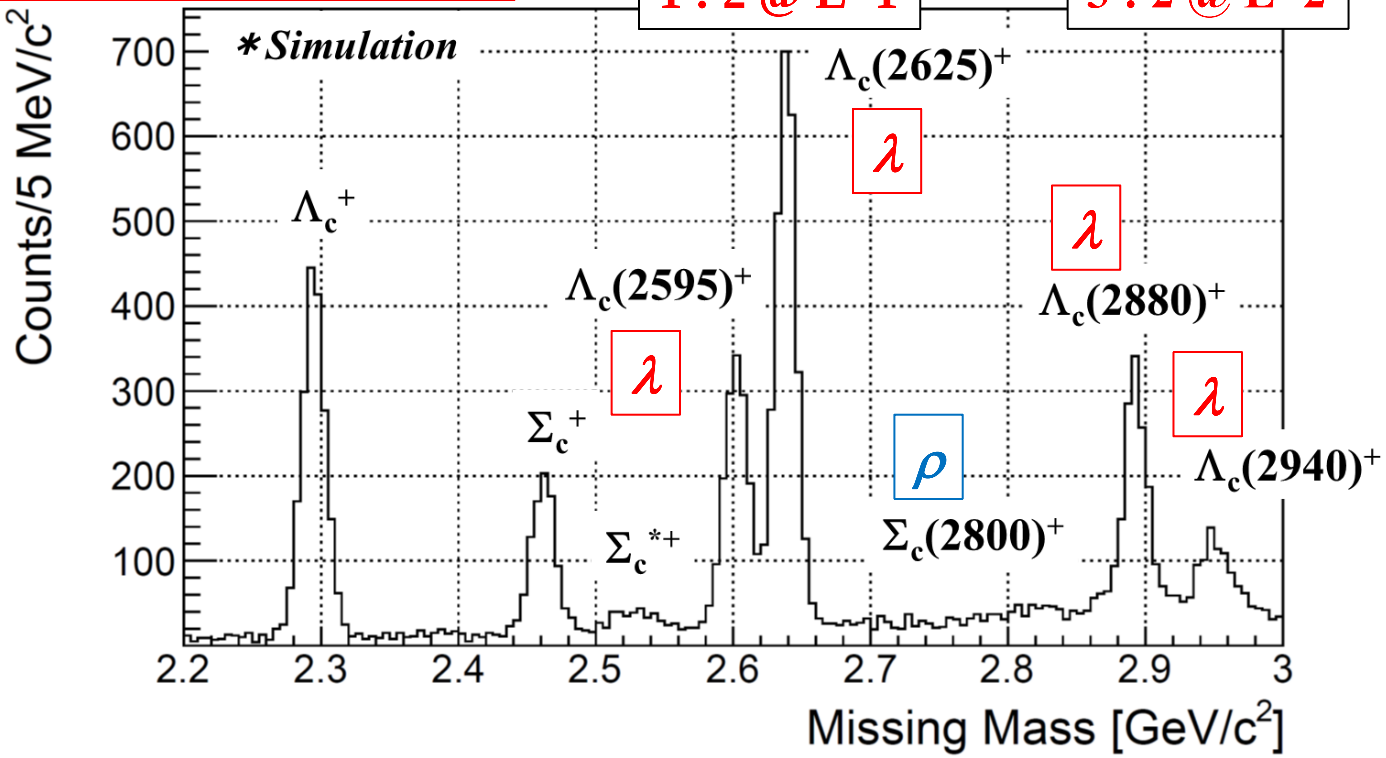
S.I. Shim, A. Hosaka, H.C. Kim, PTEP 2020, (2020) 5, 053D01

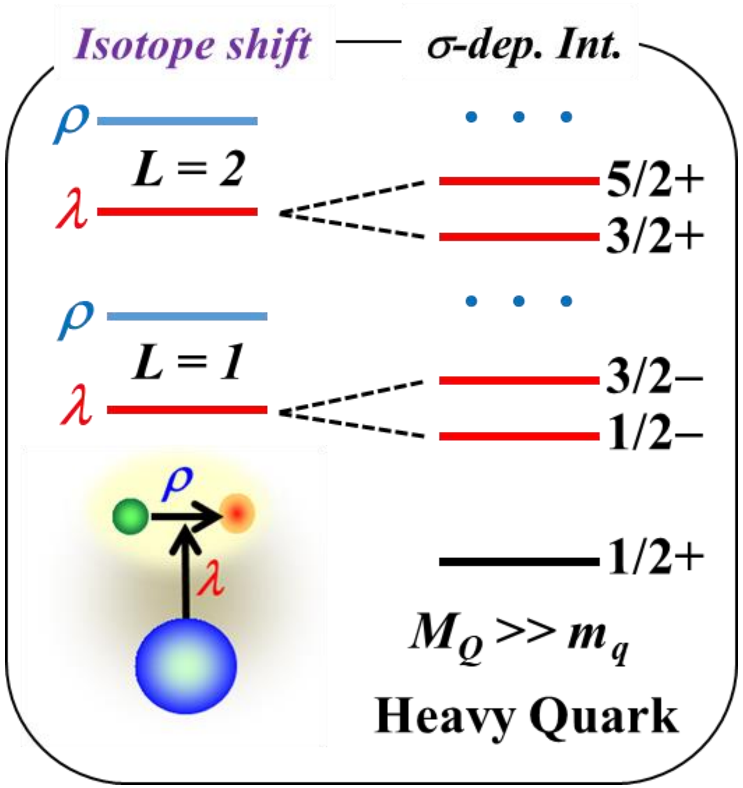
Production rates by hadronic reaction

- $\pi^- p \rightarrow D^{*-} Y_c^{*+}$ reaction @ 20 GeV/c
  - Production cross section(0°): Overlap of wave function → $R \sim \langle \varphi_f | \sqrt{2}\sigma_- \exp(i\vec{q}_{eff}\vec{r}) | \varphi_i \rangle$
    ⇒ Sensitive to excitation modes
  - Large production rate of highly excited states → $I_L \sim (q_{eff}/\alpha)^L \exp(-q_{eff}^2/\alpha^2)$
  - Both one- and two-quark processes ($\sigma_\Lambda : \sigma_\Sigma$ = 2:1)

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

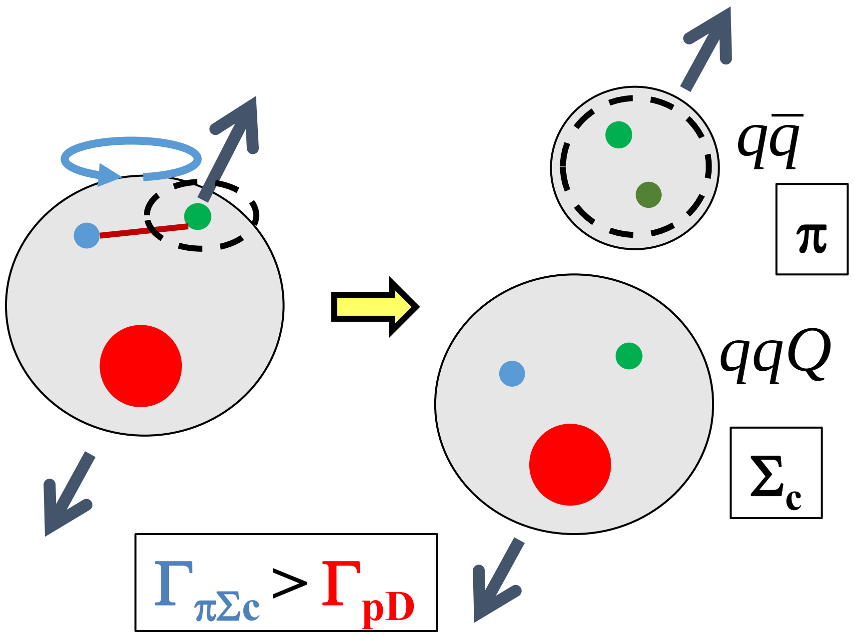
∗ Production rate = *L* : *L*+1



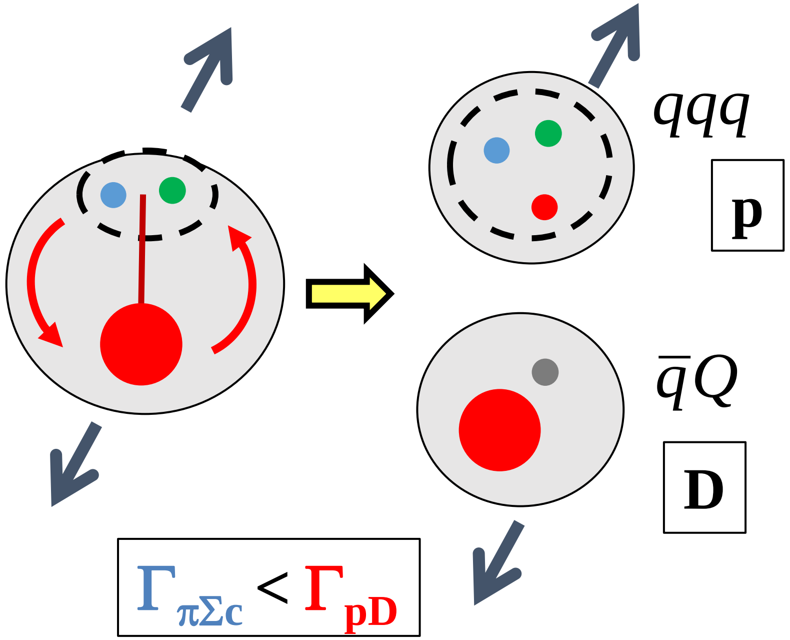


Decay properties of charmed baryon

ρ-mode decay: qqQ + qq_{bar}



λ-mode decay: qqq + Qq_{bar}



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

⇒ Absolute value of branching ratios

- **Complementary to high-energy experiments**

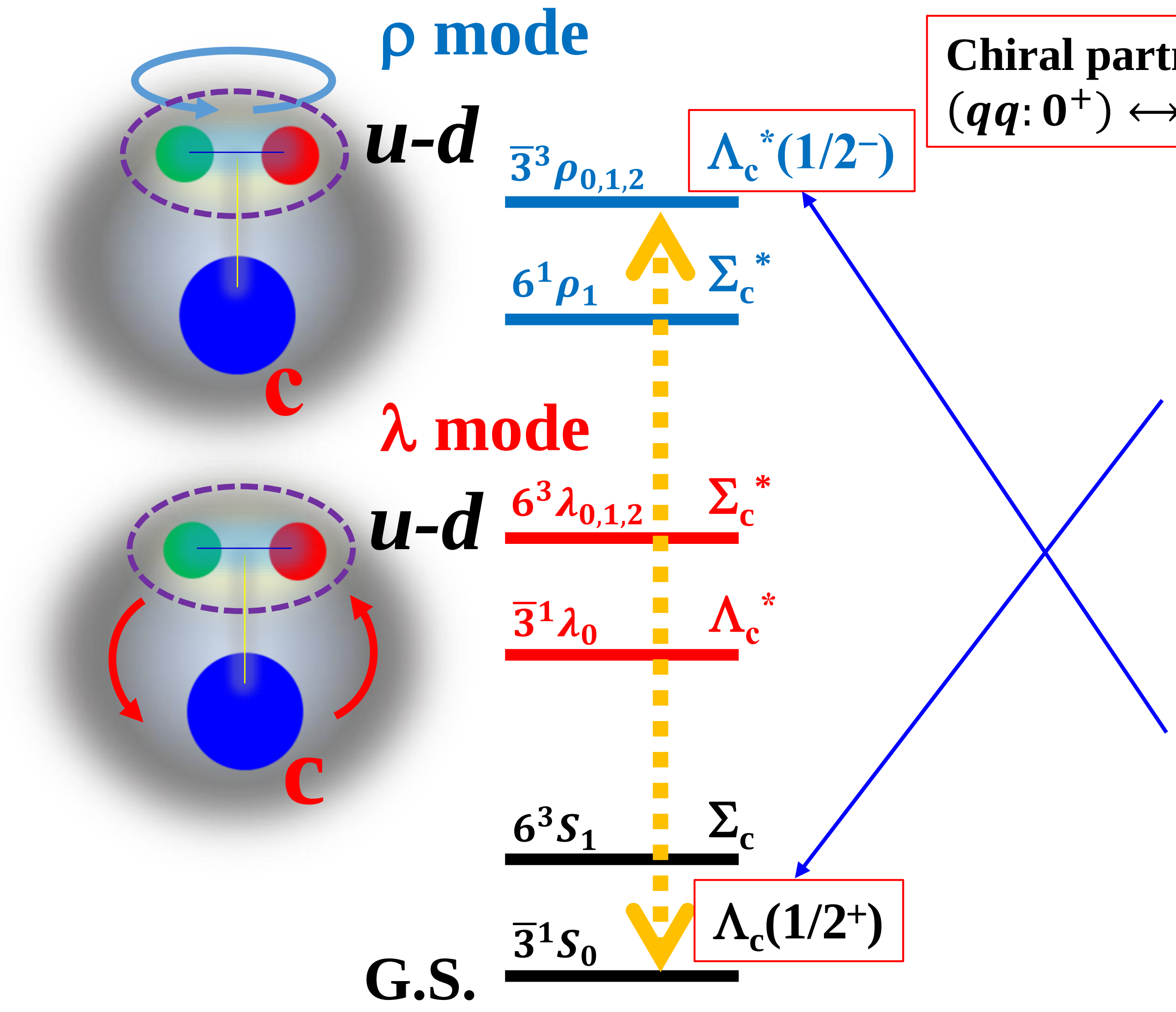
- **Studies by pionic decays: $\Lambda_c^* \rightarrow \Sigma_c \pi \rightarrow \Lambda_c \pi\, \pi$**
  - $\Lambda_c(2595)$, $\Lambda_c(2625)$, $\Lambda_c(2765)$, $\Lambda_c(2880)$, $\Lambda_c(2940)$
  - **Essential role of Heavy Quark Symmetry**

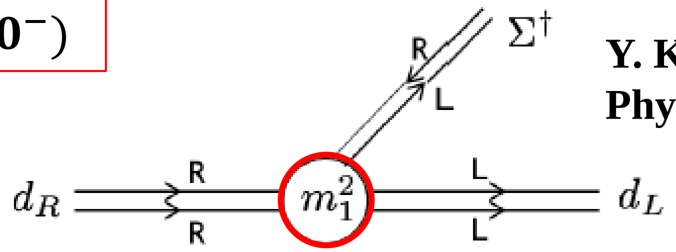
(H. Nagahiro et al., Phys. Rev. D 95, 014023 (2017))

Diquark in heavy baryons

$U_A(1)$ anomalous singlet current in Chiral diquark effective theory

Chiral partner
$(qq\!:0^+) \leftrightarrow (qq\!:0^-)$





Y. Kim *et al.*,
Phys.Rev.D 102, 014004, 2020

Scalar diquark

$$S_i^a = \frac{1}{\sqrt{2}}(d_{R,i}^a - d_{L,i}^a)$$

$$\longrightarrow M(0^+) = \sqrt{m_0^2 - m_1^2 - m_2^2},$$

Pseudo-scalar diquark

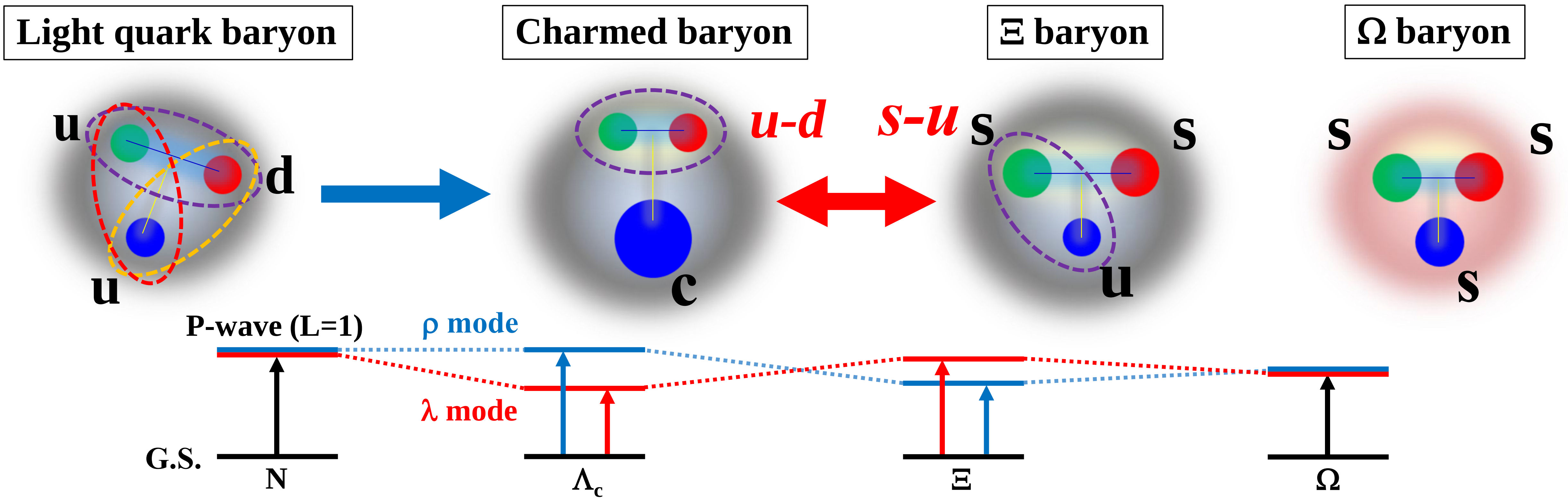
$$P_i^a = \frac{1}{\sqrt{2}}(d_{R,i}^a + d_{L,i}^a)$$

$$\longrightarrow M(0^-) = \sqrt{m_0^2 + m_1^2 + m_2^2},$$

m_0: Chiral invariant mass term
m_1: UA(1) anomaly
m_2: CSB mass terms

- Mass and width of ρ mode $\Lambda_c^*(1/2^-)$ ⇒ How the $U_A(1)$ anomaly works in baryons ?
    - Decay width suppression depending on its mass ($\Lambda_c\eta$, $\Sigma_c\pi\pi$ threshold)

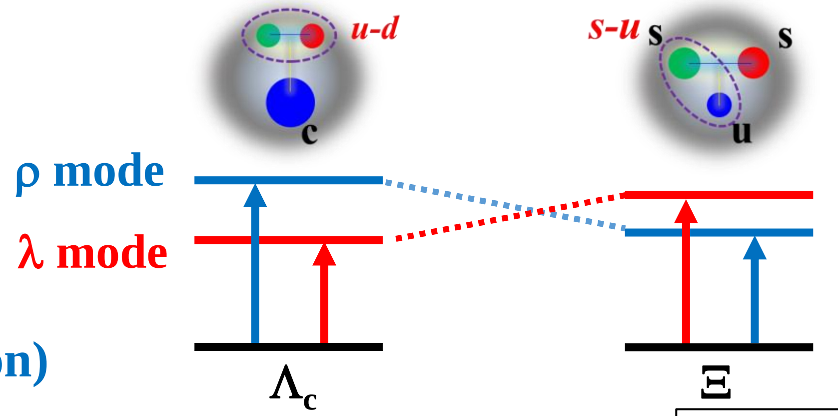
Heavy flavors for revealing diquark correlation



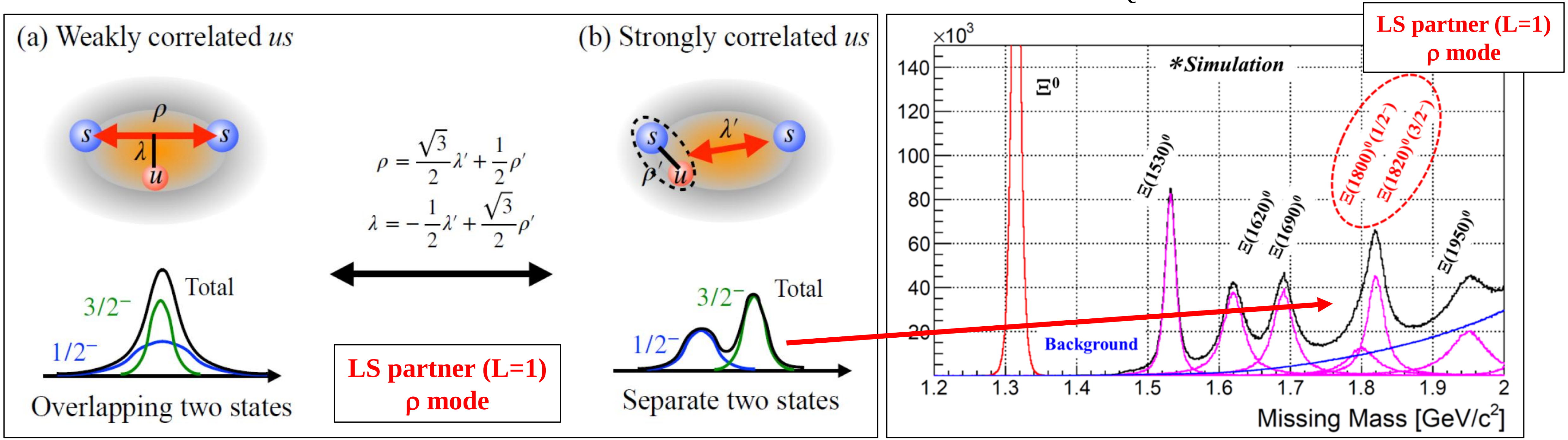
＊Systematic studies for baryon systems with heavier flavors: *c* & *s*

- **Charmed baryon: Disentangle *ud* diquark correlation**
  - **Comparison with hyperons (Λ/Σ) : *ud* + s system**
- **Ξ baryon: *us*/*ds* diquark correlation ⇒ Flavor dependence**
- **Ω baryon: Suppression of diquark correlation**

Studies of Ξ and Ω: J-PARC P85



- **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)**

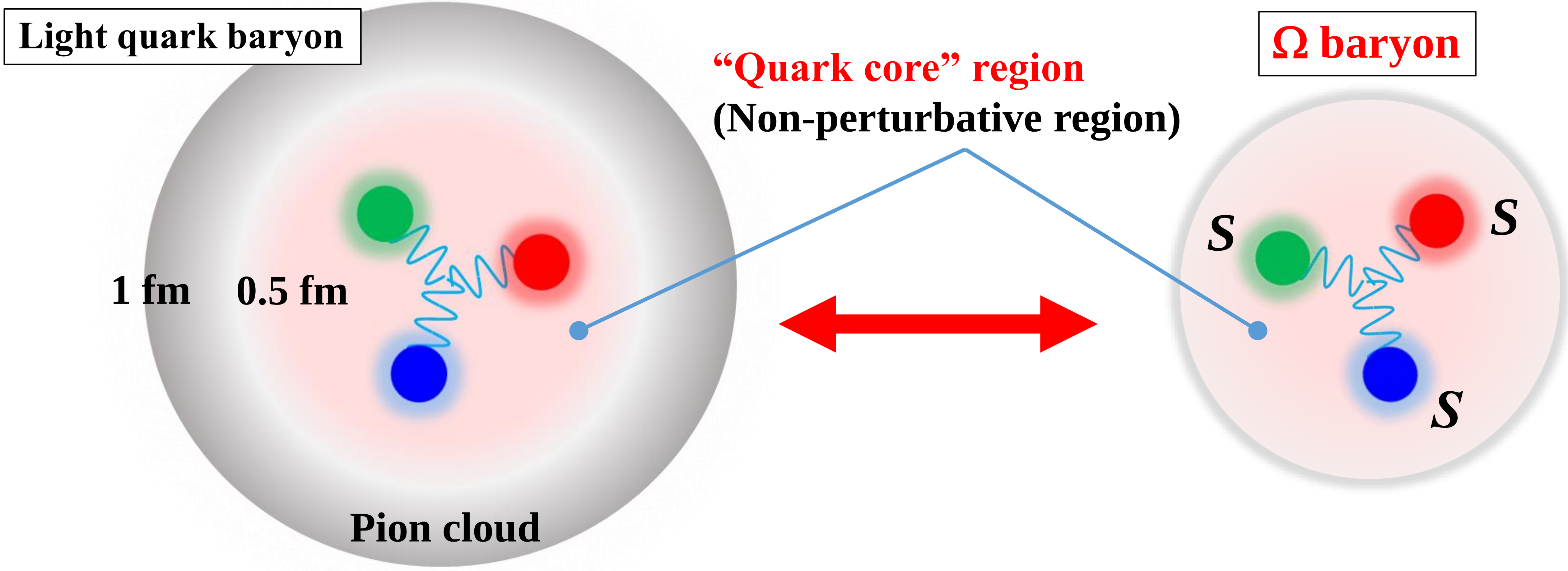


＊Ξ(1800)^0(1/2⁻): Assumed for simulation

- **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

Role of Ω baryon: Single flavor system



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

⇒ Origin of spin-dependent forces and quark motion

＊Long-standing problems

- Too large α_S^{ss} (>1) of SS force, Missing LS force, Roper-like resonances

⇒ In terms of One Gluon Exchange(OGE), Instanton Induced Interaction(III) and Pion cloud

Spin-dependent forces

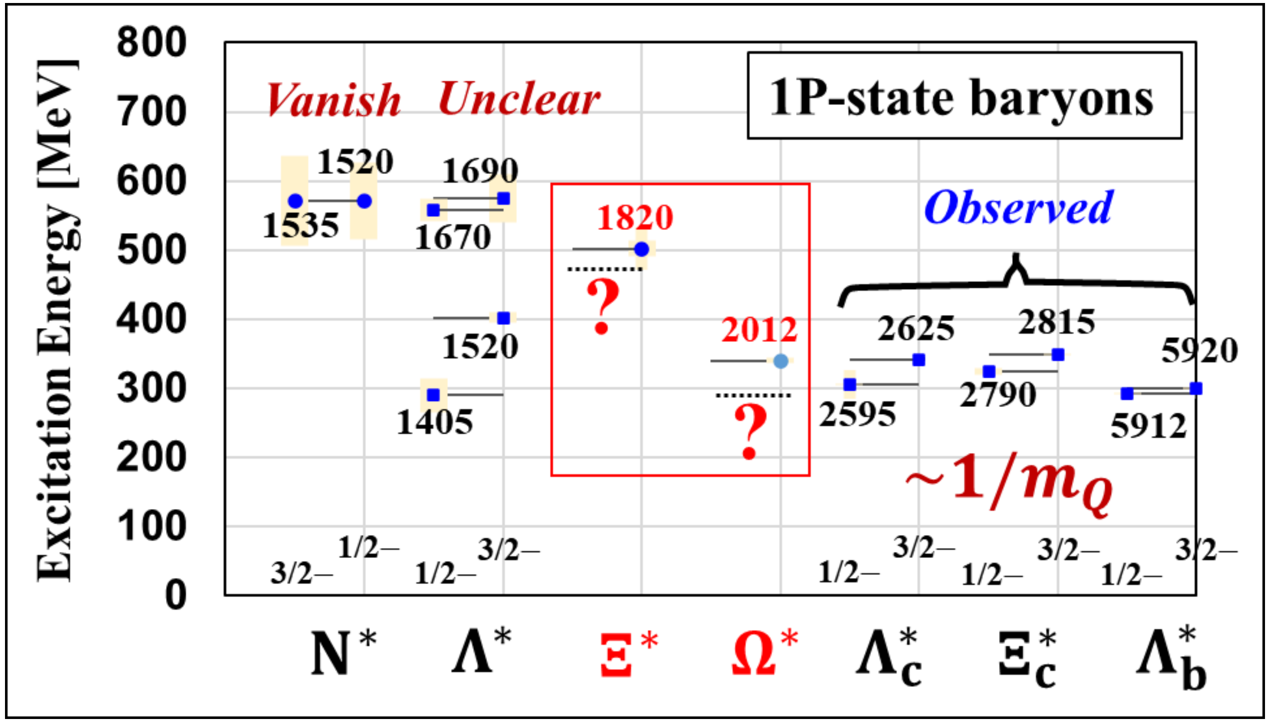
- **Investigate origin of spin-dependent forces and quark motion**
  - **In terms of One Gluon Exchange(OGE), Instanton Induced Interaction(III) and Pion cloud**

- **Systematics of spin-orbital interaction**
  - **Disappears in N^* (OGE/III cancelled)**
  - **Appears in Λ_c^*, Ξ_c^* and Λ_b^* (OGE only)**

- **Ω^* baryon**
  - **Flavor-symmetric system**
  - **Free from pion cloud**
  - **III forbidden**

⇒ LS splitting: No OGE&III(2BF)
- **$\Omega(2012)^-(3/2^-?)$ ⇔ $\Omega^{*-}(1/2^-?)$**
  - **Degenerate ?**
- **$\Xi(1820)^-(3/2^-?)$ ⇔ $\Xi^{*-}(1/2^-?)$**
- **LS partners (L=2 states)**

Systematics of the spin-orbit (LS) force



Roper-like resonances

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

- Systematics of Roper-like states (Radial excitation 2S states)
  - Small excitation energy and wide width
  - Mass universality ?
  - What does determine its width ?

- Ω^* baryon
  - Flavor-symmetric system
  - Free from pion cloud

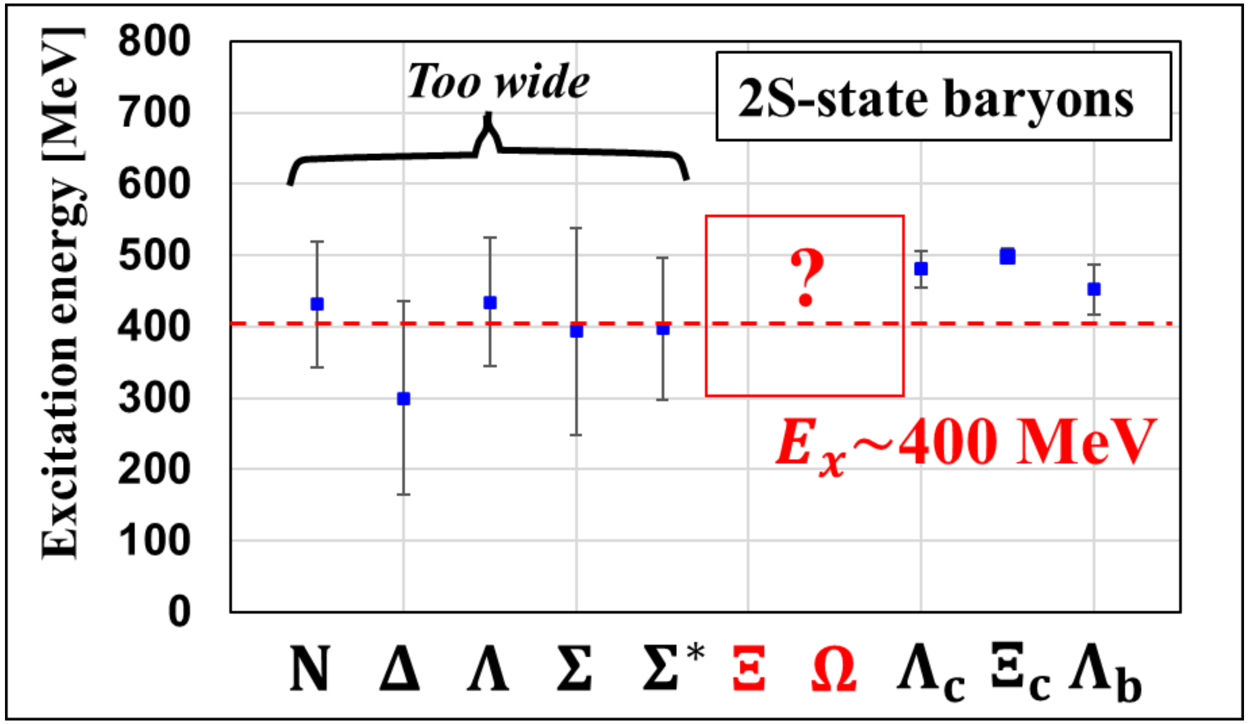
  $\Rightarrow$ No contribution from pion cloud

＊Width tells quark motion.: $\Gamma \sim \langle p_q \rangle$

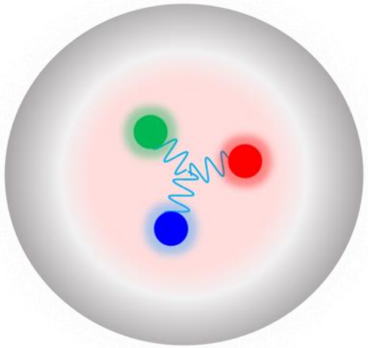
$\Rightarrow$ Size of "quark core": $\langle r_q \rangle \sim 1/\langle p_q \rangle$

  - Roper-like state: Where is it ?

Systematics of the Roper-like resonances



Baryon spectroscopy at J-PARC



- **Dynamics of non-trivial QCD vacuum in baryon structure**
  - **Massive quarks and NG bosons (effective degrees of freedom)**
    - **Their dynamics has not been understood.**
- ***c*- and *s*-baryon spectroscopy: Disentangle diquark correlation and spin-dependent forces**

*** Charm baryon @ High-p (π20)**

Disentangle *ud* diquark correlation

*** Ξ and Ω baryons @ K10**

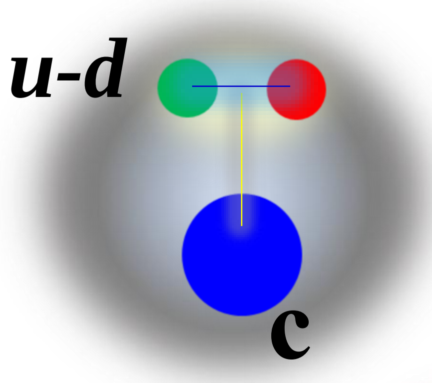
Ξ : *us/ds* diquark correlation

Ω : Suppression of diquark correlation

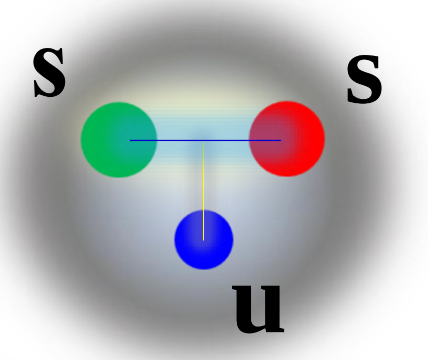
*** Both π20 and K10**

- **Spin-dependent forces**
- **Internal quark motion**

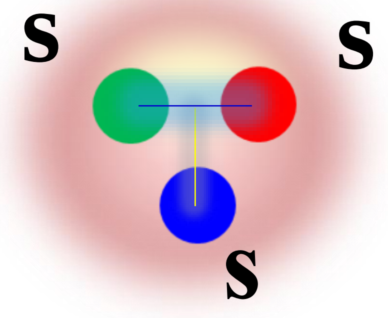
Charmed baryon



Ξ baryon



Ω baryon

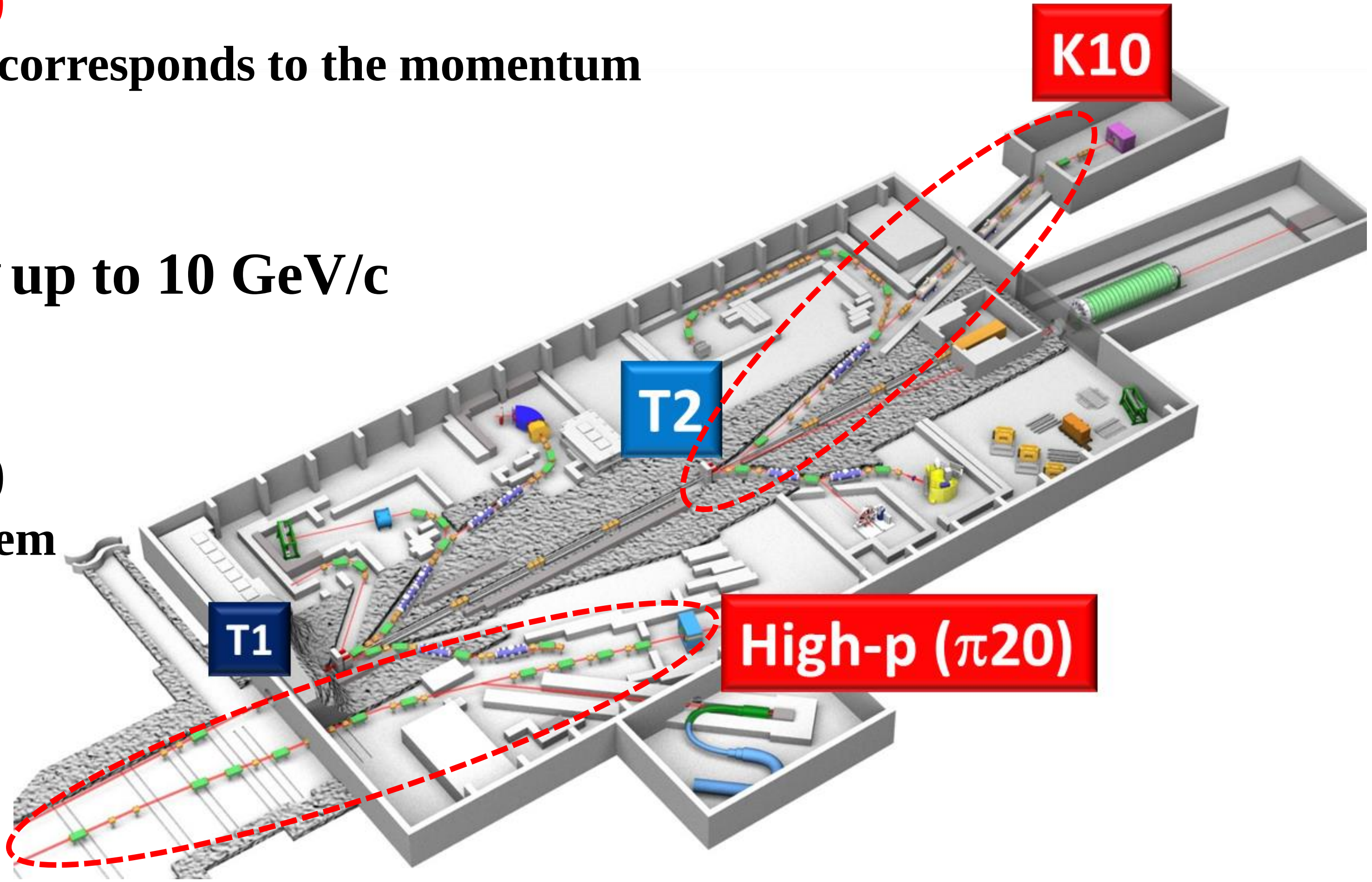


Charmed baryon spectroscopy @ High-p (π20)

High-momentum hadron beam lines: π20 and K10

- **High-p(π20): Primary proton ⇒ 2^{ndary} beams (unseparated)**
  - **High intensity: $>10^7$ /spill for π^- (K^-, p_{bar}: 1–2%) up to 20 GeV/c**
    - Production target and 0-degree beam extraction
  - **High resolution: $\Delta p/p = 0.1\%(\sigma)$**
    - Dispersion matching: the position corresponds to the momentum

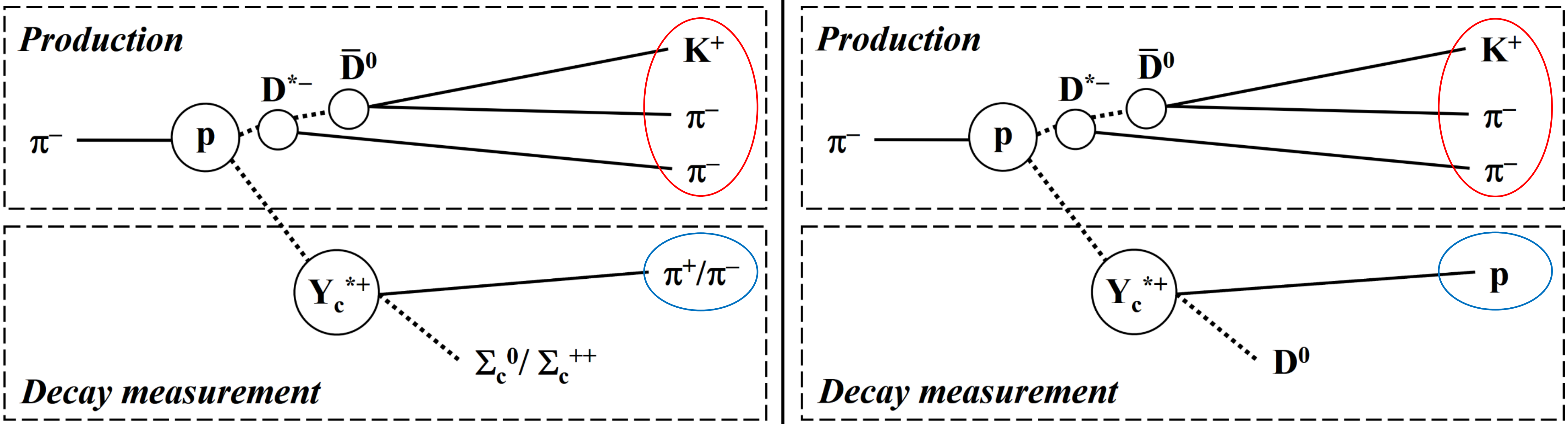
- **K10 beam line: K^- beam**
  - High intensity: $>10^6$ /spill for K^- up to 10 GeV/c
  - High-purity: $K : \pi \sim 1 : 2$
    - Radio Frequency(RF) separator
  - High resolution: $\Delta p/p = 0.1\%(\sigma)$
    - Beam spectrometer: QQDDQ system



*Beam line name: ○XX
○: Main beam particle
XX: Maximum beam momentum

Experiment: Missing mass method

K^+ & π^-: 2–16 GeV/c
π^- from D^{*-}: 0.5–1.7 GeV/c



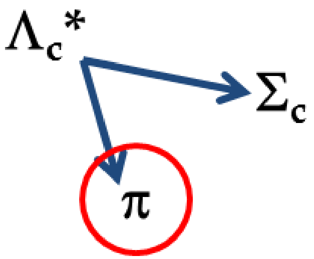
$\pi^\pm$ & p: 0.2–4.0 GeV/c

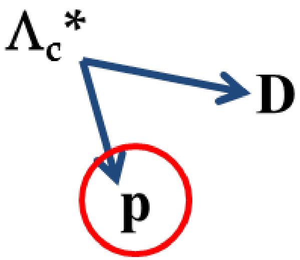
$\pi^- + p \to D^{*-} + Y_c^{*+}$ reaction @ 20 GeV/c

1) Missing mass spectroscopy: Y_c^{*+} mass (>1 GeV excited states)
- $D^{*-} \to \bar{D}^0 \pi_s^- \to K^+ \pi^- \pi_s^-$: $D^{*-} \to \bar{D}^0 \pi_s^-$ (67.7%), $\bar{D}^0 \to K^+ \pi^-$ (3.88%)

2) Decay measurement: Absolute B.R. and angular distribution
- Decay particles ($\pi^\pm$& proton) from Y_c*

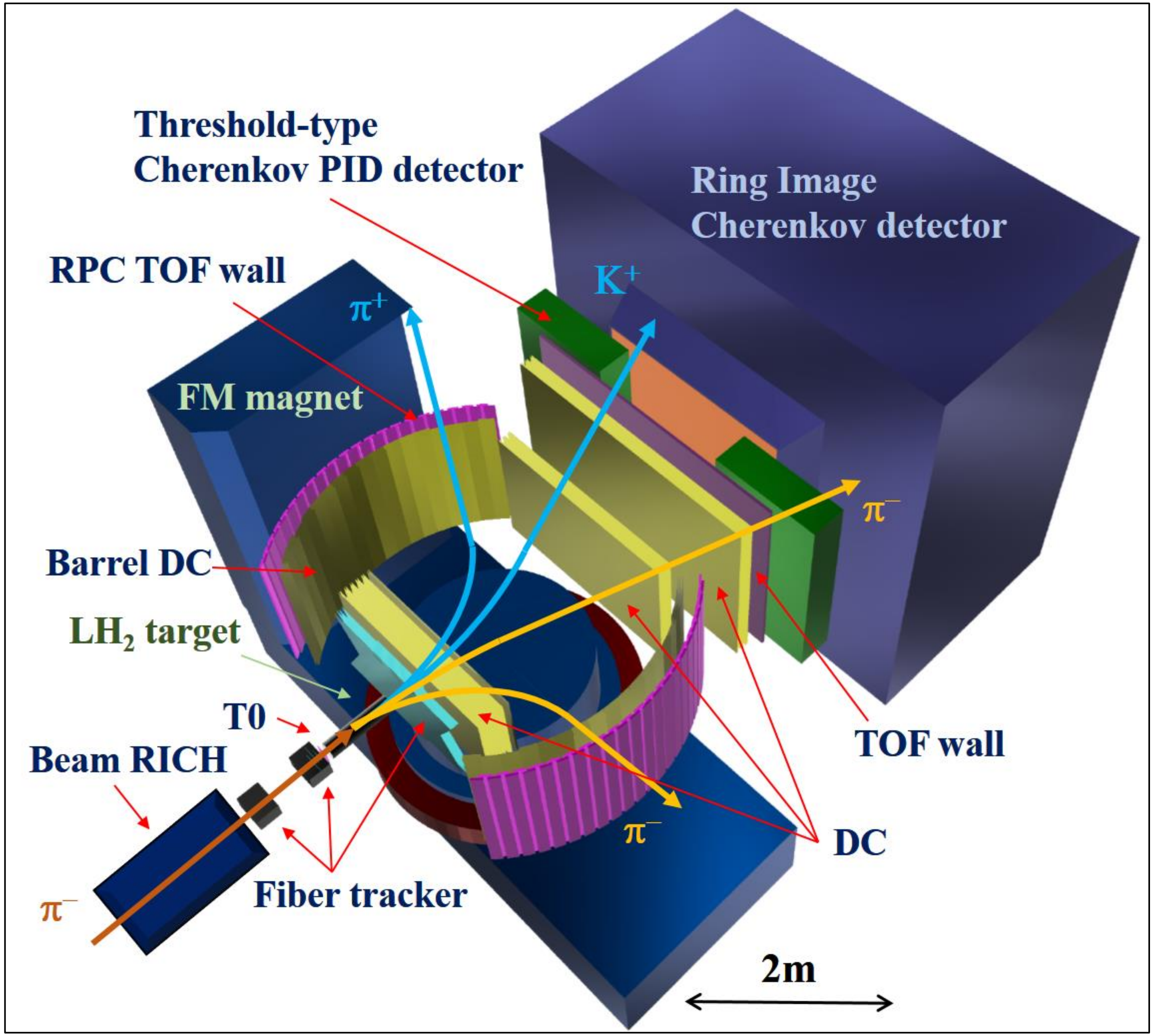
A spectrometer for charmed baryon spectroscopy

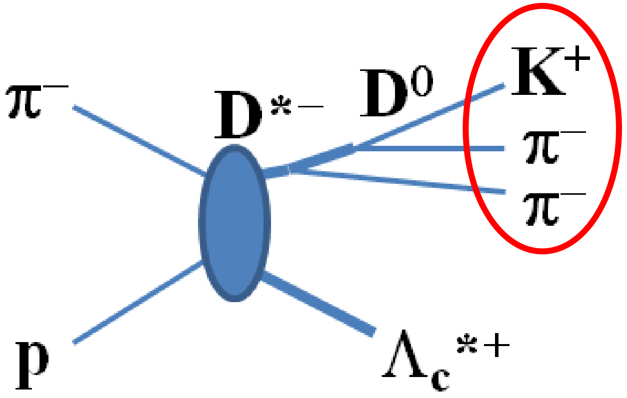




Decay measurement
∗ Branching ratios

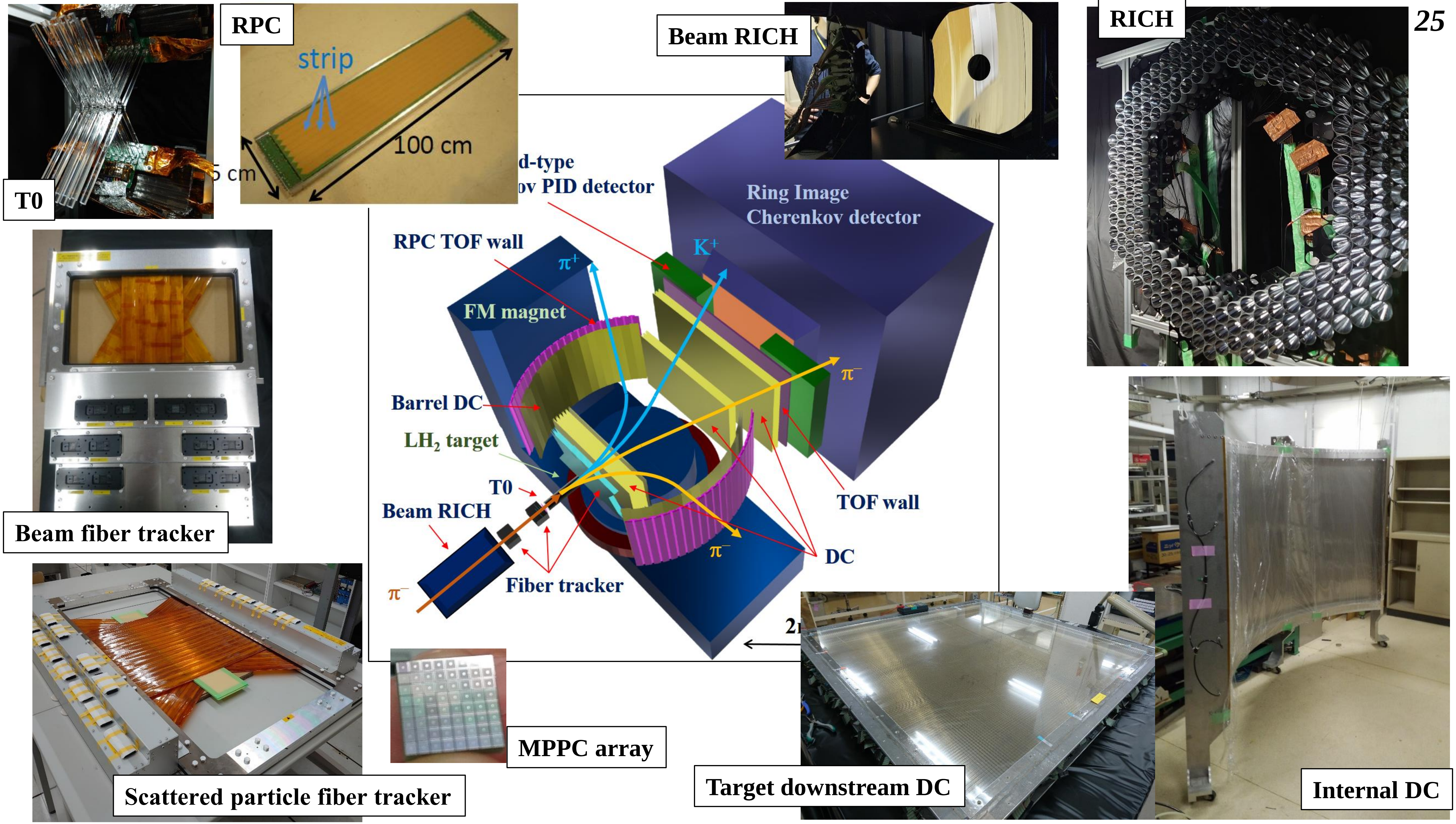
$\pi^{\pm}$&p: < 4.0 GeV/c

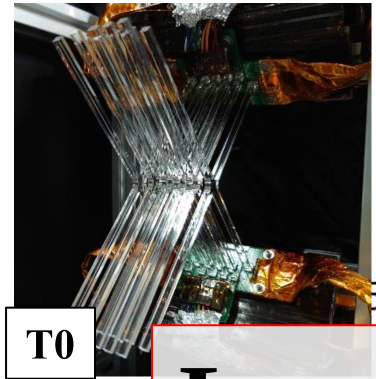


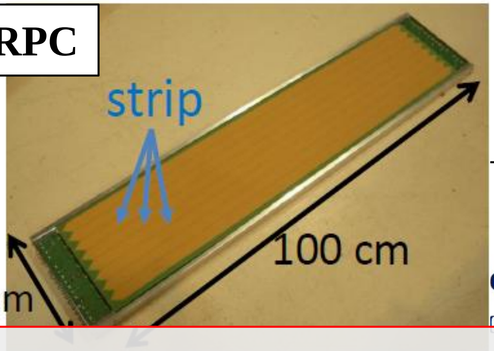


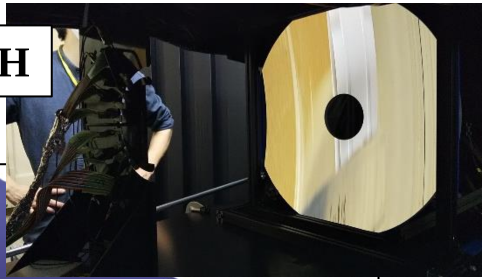
Missing mass measurement
∗ Production rate

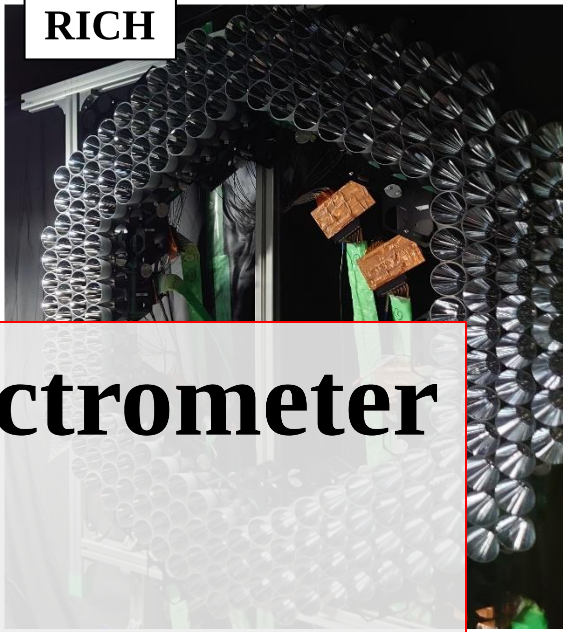
K^+ & π^-: 2–16 GeV/c
Slow π_s^-: 0.5–1.7 GeV/c


T0
RPC
strip
100 cm
cm
Beam RICH
RICH
d-type
ov PID detector
Ring Image
Cherenkov detector
RPC TOF wall
π^+
K^+
FM magnet
Barrel DC
LH_2 target
T0
Beam RICH
π^-
Fiber tracker
π^-
π^-
TOF wall
DC
Beam fiber tracker
Scattered particle fiber tracker
MPPC array
Target downstream DC
Internal DC









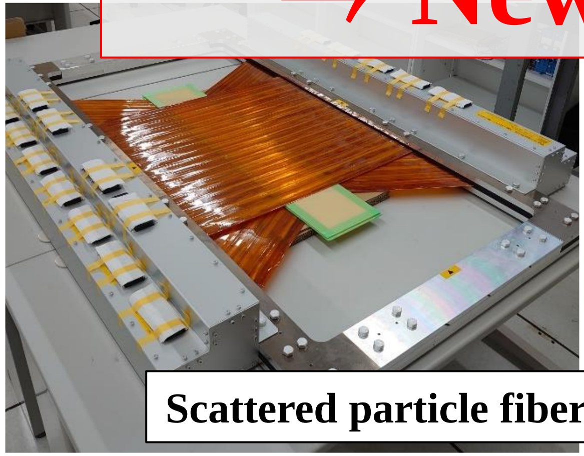
Large Acceptance Multi-Purpose Spectrometer

+ Trigger–less DAQ system

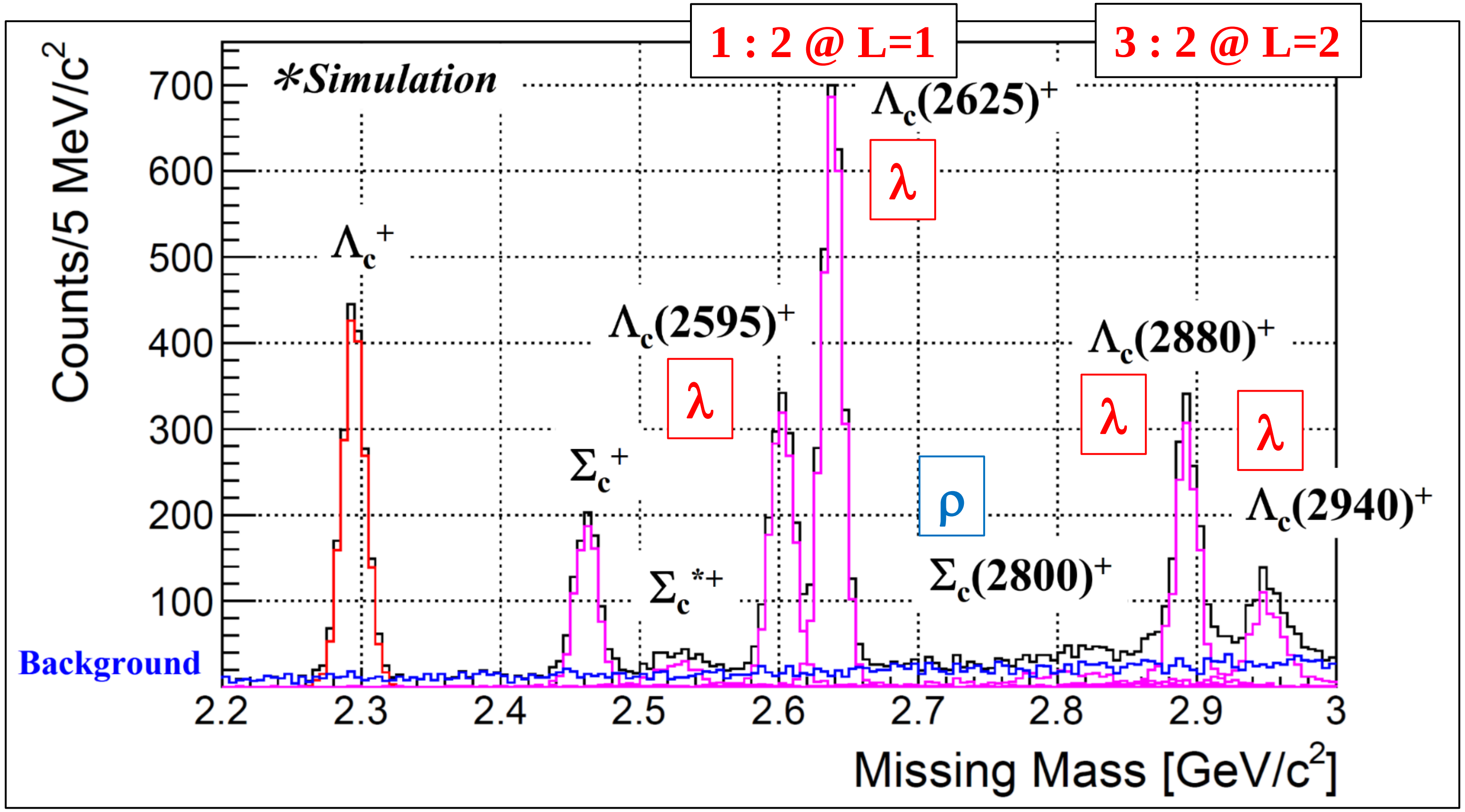
R. Honda *et al.*, PTEP2021, 123H01 (2021).

Charmed baryon spectrometer

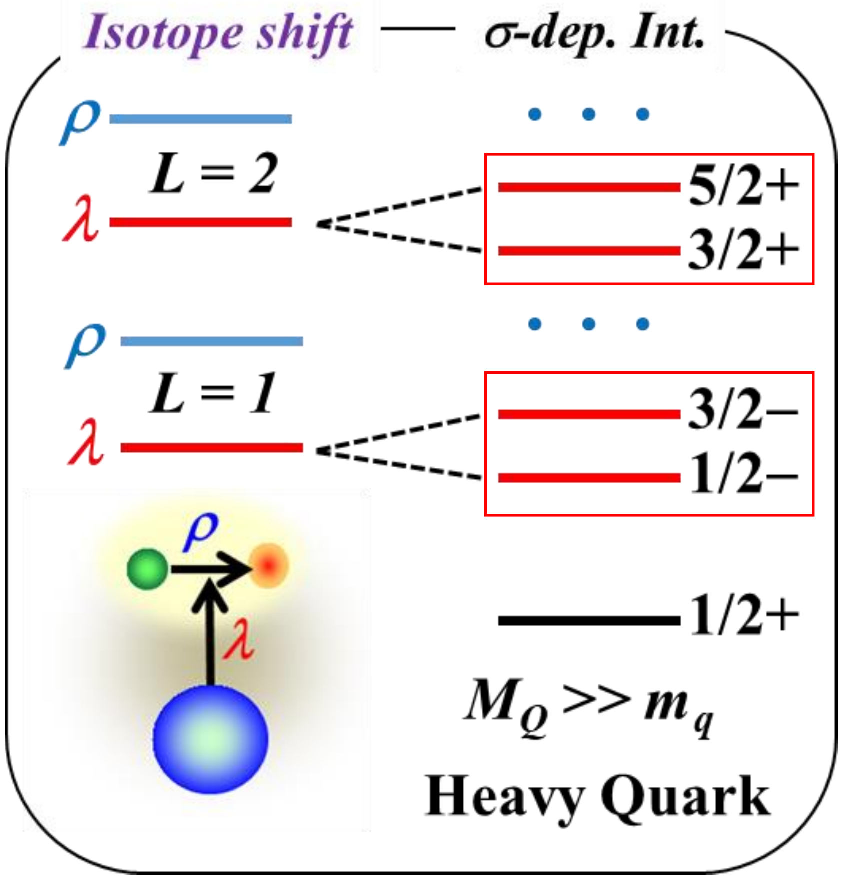
⇒ New platform for Hadron experiment



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



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

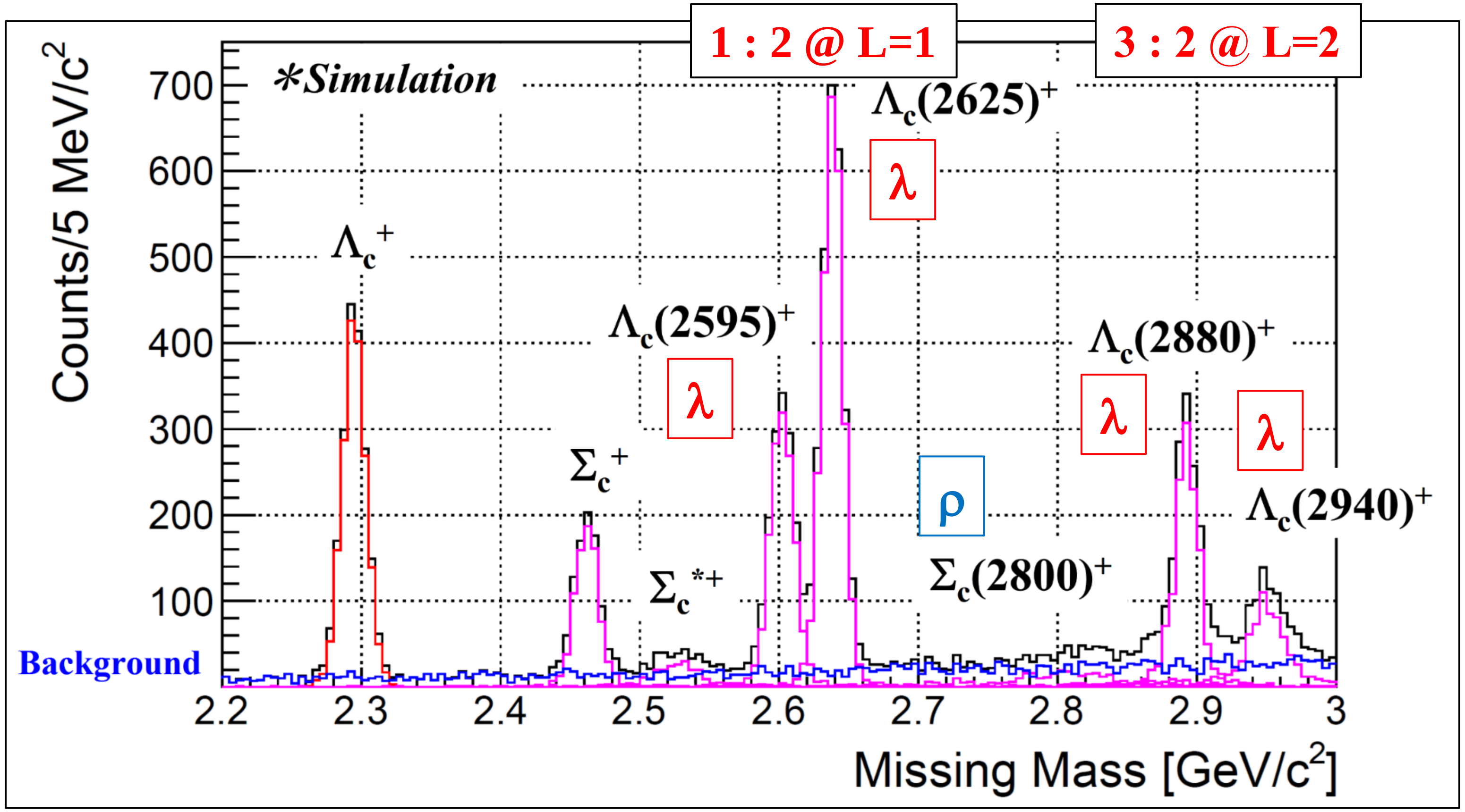


HQ doublet

- **Y_c^{*+} events: ~2000 events ($\sigma_{G.S.}$ = 1 nb @ 100 days)**
  - **Known states in PDG and background by hadronic reaction code**

- **Production rates tell excitation mode of excites states. ⇒ λ/ρ mode assignment**
  - **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.**

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



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

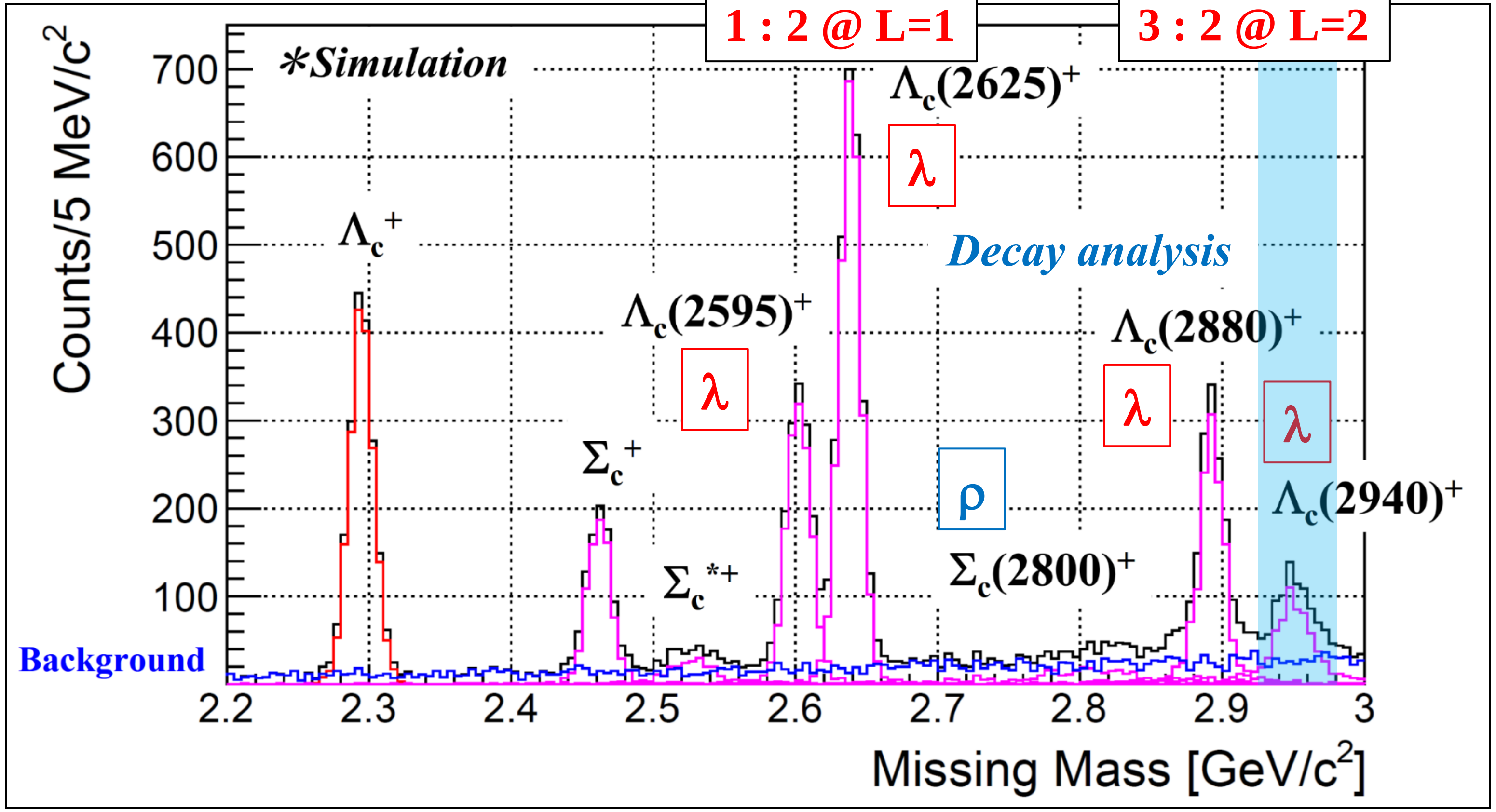
PDG	J^P	J^P (simulation)
$\Lambda_c(2940)^+$	?	$3/2^+$
$\Lambda_c(2880)^+$	$5/2^+$	$5/2^+$
$\Lambda_c(2860)^+$	$3/2^+$	–
$\Sigma_c(2800)^+$	?	$1/2^-$
$\Lambda_c(2750)^+$	$1/2^+$?	–
$\Lambda_c(2625)^+$	$3/2^-$?	$3/2^-$
$\Lambda_c(2590)^+$	$1/2^-$	$1/2^-$
$\Sigma_c(2520)^+$	$3/2^+$?	$3/2^+$
$\Sigma_c(2455)^+$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

Not experimentally determined (PDG)

λ mode
ρ mode

- Y_c^{*+} events: ~2000 events ($\sigma_{G.S.}$ = 1 nb @ 100 days)
  - Known states in PDG and background by hadronic reaction code
- **Production rates** tell excitation mode of excites states. ⇒ λ/ρ mode assignment
  - 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.

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



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

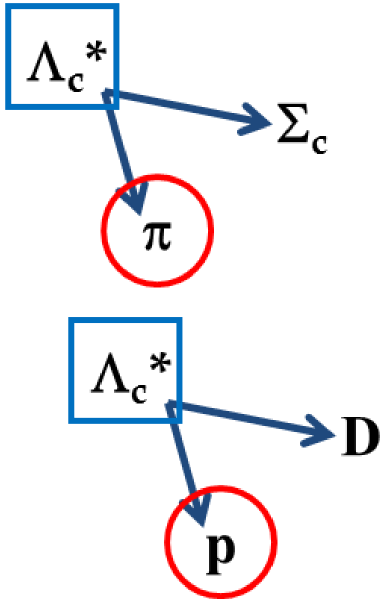
PDG	J^P	J^P (simulation)
$\Lambda_c(2940)^+$	?	$3/2^+$
$\Lambda_c(2880)^+$	$5/2^+$	$5/2^+$
$\Lambda_c(2860)^+$	$3/2^+$	–
$\Sigma_c(2800)^+$	?	$1/2^-$
$\Lambda_c(2750)^+$	$1/2^+$?	–
$\Lambda_c(2625)^+$	$3/2^-$?	$3/2^-$
$\Lambda_c(2590)^+$	$1/2^-$	$1/2^-$
$\Sigma_c(2520)^+$	$3/2^+$?	$3/2^+$
$\Sigma_c(2455)^+$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

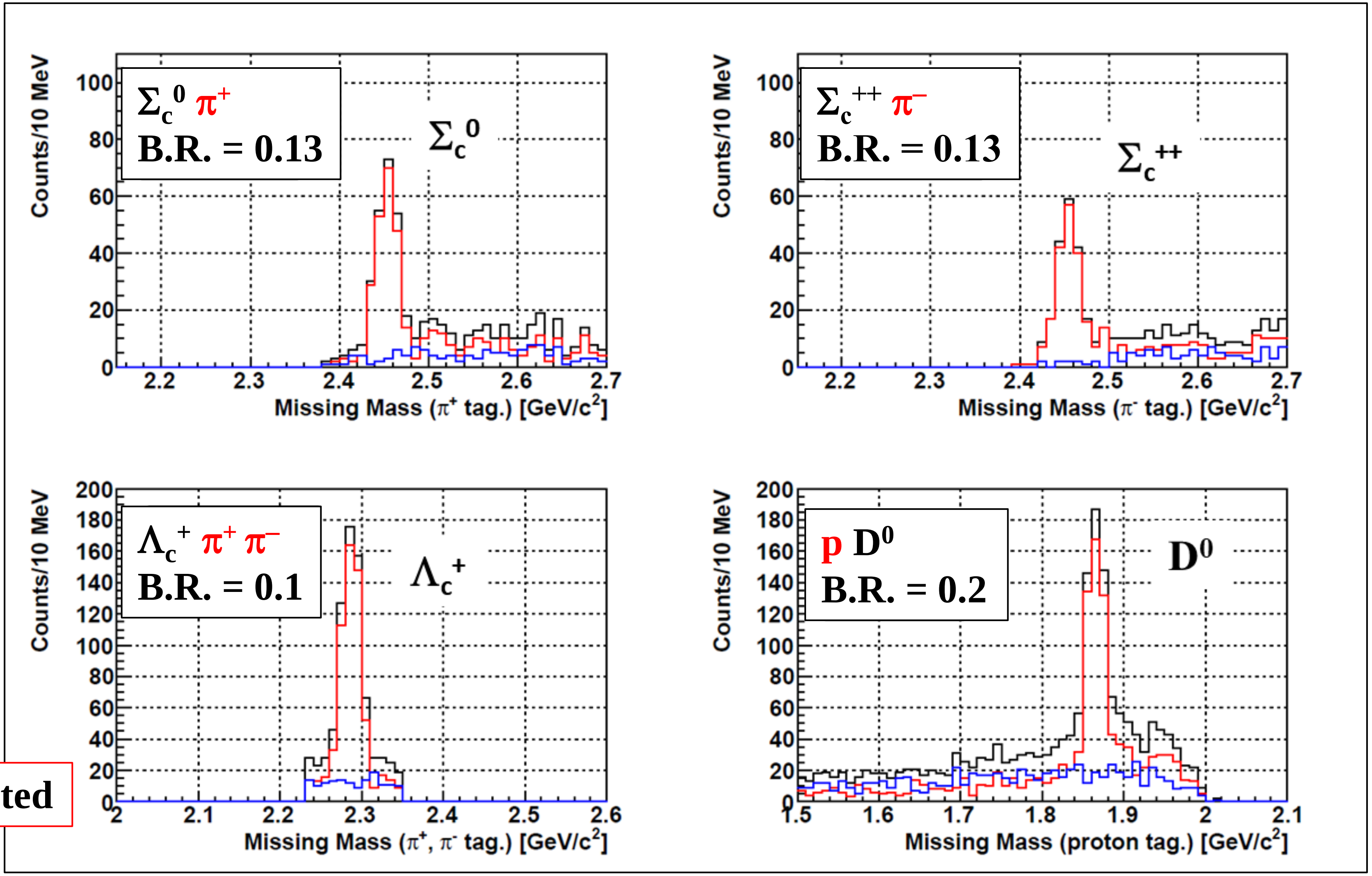
Not experimentally determined (PDG)

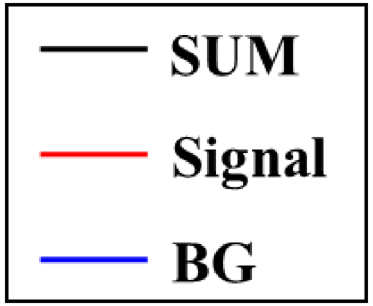
λ mode
ρ mode

- Y_c^{*+} events: ~2000 events ($\sigma_{G.S.}$ = 1 nb @ 100 days)
  - Known states in PDG and background by hadronic reaction code
- Production rates tell excitation mode of excites states. ⇒ λ/ρ mode assignment
  - 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.

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







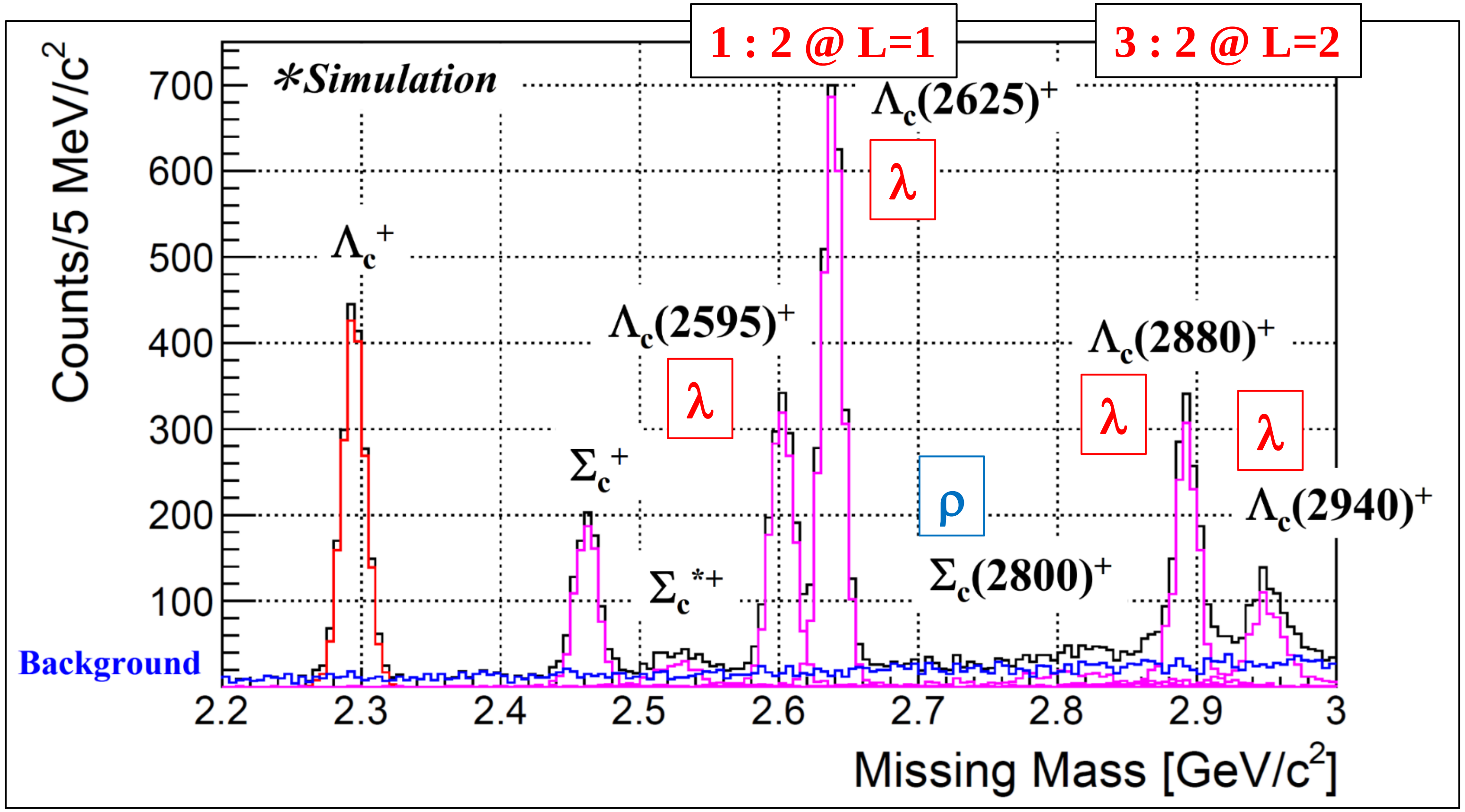
B.R.: Assumed

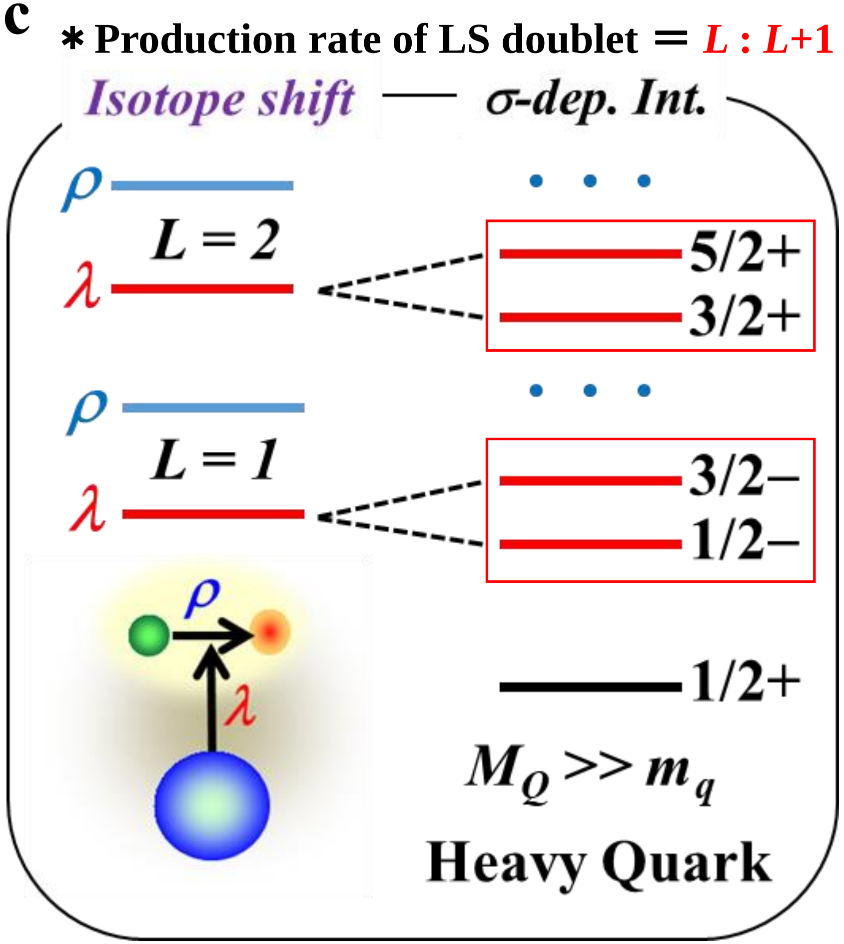
W/ $\Lambda_c^+\,\pi^+\,\pi^-$ selected

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

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

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





- **Dynamical information: Production rates & Absolute decay branching ratios**

⇒ 1st identification of λ/ρ mode for revealing *ud* diquark correlation

Ξ and Ω baryon spectroscopy @ K10

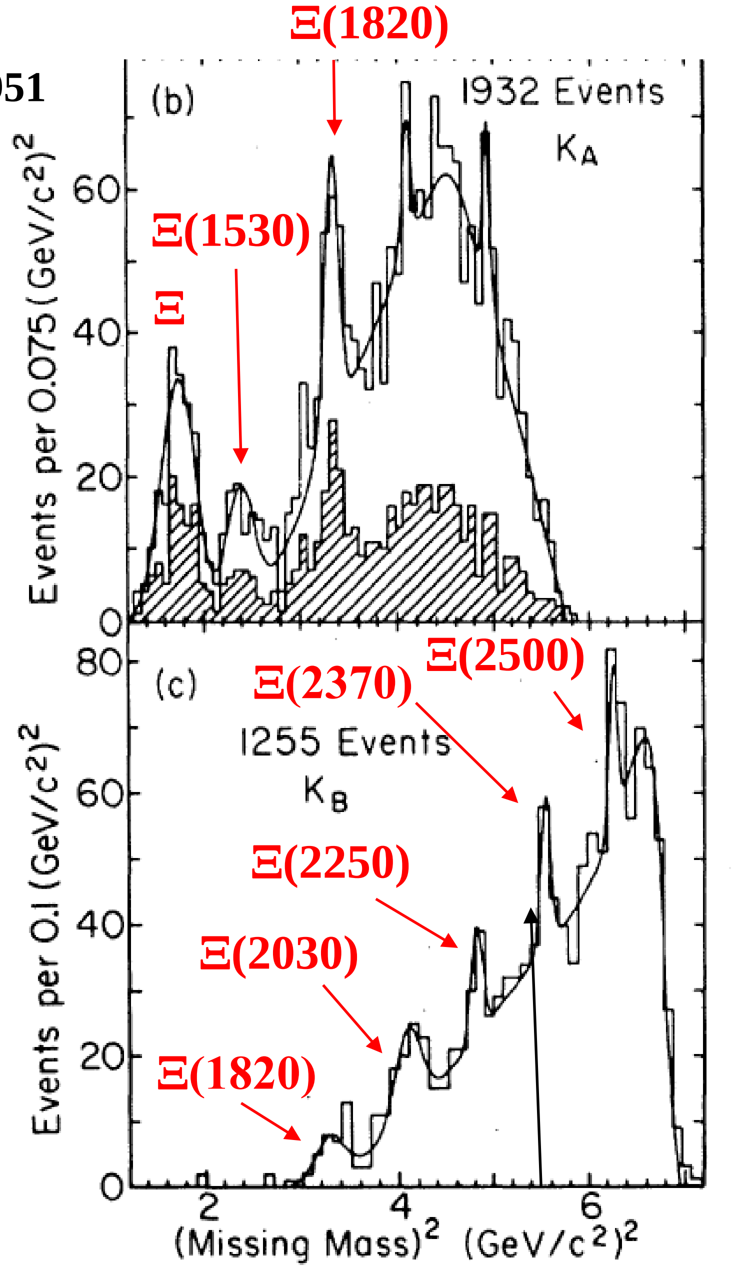
Experimental situations: Ξ*

	J^P	rating	Width [MeV]	Ξπ [%]	Λ K [%]	Σ K [%]	Ω K [%]
Ξ(2500)	??	1*	150?				
Ξ(2370)	??	2*	80?				~9±4
Ξ(2250)	??	2*	47+-27?				
Ξ(2120)	??	1*	25?				
Ξ(2030)	>=5/2?	3*	20^{+15}_{-5}	small	~20	~80	
Ξ(1950)	??	3*	60±20	seen	seen		
Ξ(1820)	3/2–	3*	24^{+15}_{-10}	small	Large	Small	
Ξ(1690)	??	3*	< 30	seen	seen	seen	
Ξ(1620)	??	1*	20–40?				
Ξ(1530)	3/2+	4*	10	100			

Existence is certain : 2
Need confirmation : 4
Evidence is fair : 2
Evidence is poor : 3

- 11 states were reported.
- Quark Model prediction ⇒ 44 states up to 2.3 GeV

$K^- p \rightarrow K^+ X$ @ 5 GeV/c
Jenkins at al., PRL51 (1983) 951



Measured Ω^{*-} states in PDG

2021 Review of Particle Physics.
P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020) and 2021 update

Ω BARYONS ($S = -3$, $I = 0$)

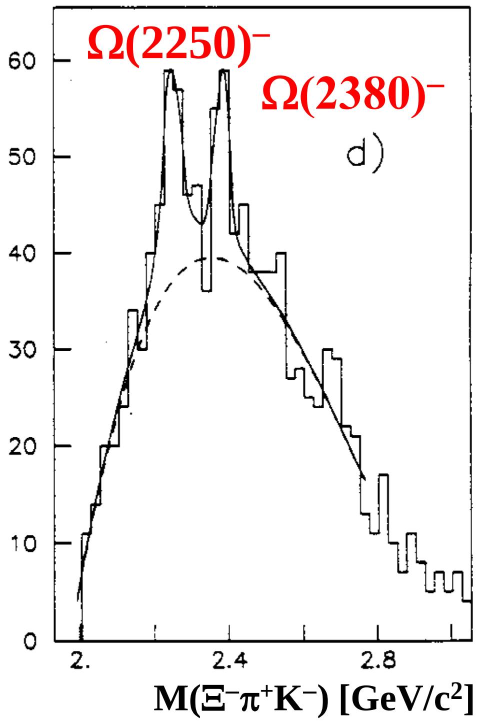
$\Omega^- = s\ s\ s$

Ω^-	$3/2^+$	****
$\Omega(2012)^-$	$?^-$	***
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**

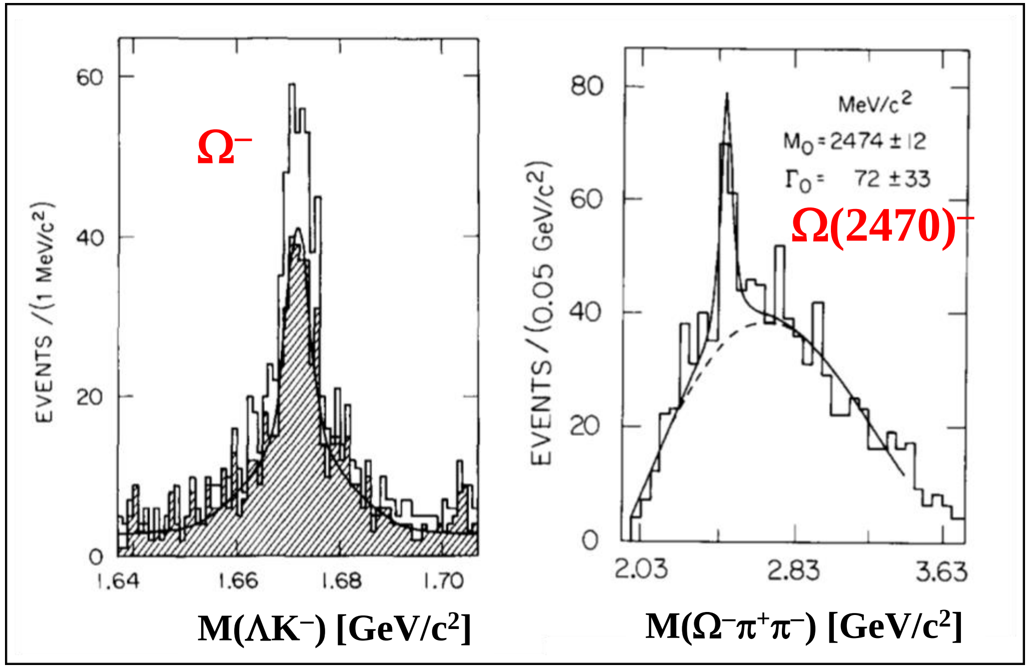
**** Existence is certain, and properties are at least fairly explored.
*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.
** Evidence of existence is only fair.

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

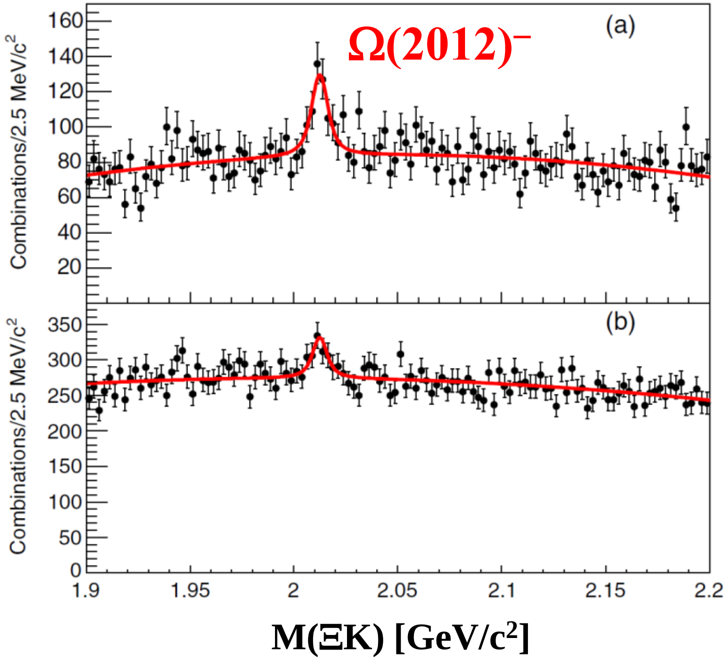
Experimental situations



Ξ⁻ beam on Be @ 116 GeV/c
S.F. Biagi *et al.*, Z.Phys.C 31, 33 (1986)



K⁻ p data by LASS @ 11 GeV/c
D. Aston *et al.*,
Phys. Rett. B 215 799-804 (1988)



Belle collaboration
J. Yelton *et al.*,
Phys. Rev. Lett. 121, 052003 (2018)

- **Need data by experiment with a modern technique**

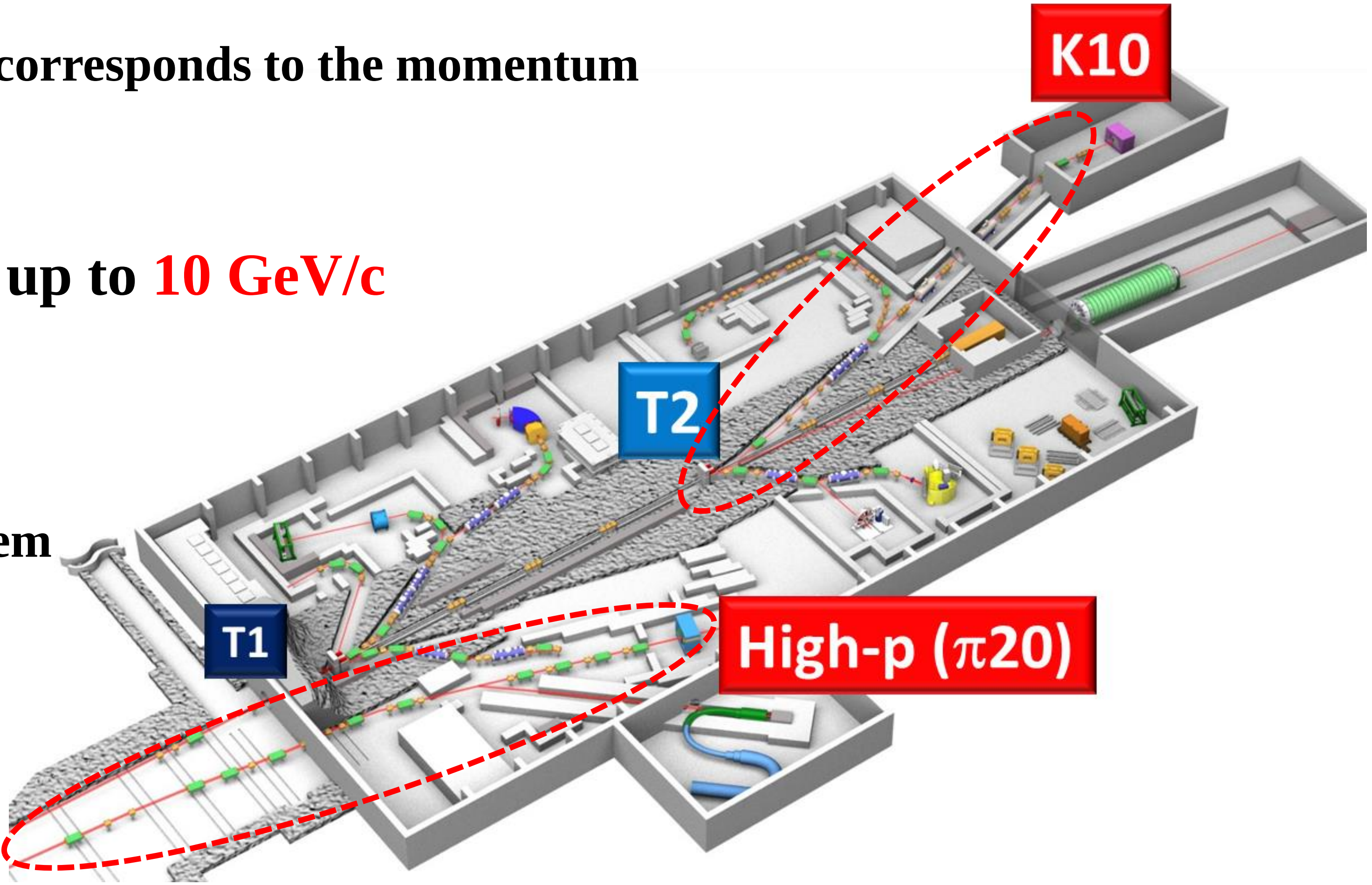
⇒ **High-performance facility and suitable experimental setup ⇒ K10**

- **High-intensity K⁻ beam and large acceptance spectrometer**

High-momentum hadron beam lines: π20 and K10

- High-p(π20): Primary proton ⇒ 2ndary beam (unseparated)
  - High intensity: >10^7 /spill for π^- (K^-, p_{bar}: 1–2%) up to 20 GeV/c
    - Production target and 0-degree beam extraction
  - High resolution: $\Delta p/p$ = 0.1%(σ)
    - Dispersion matching: the position corresponds to the momentum

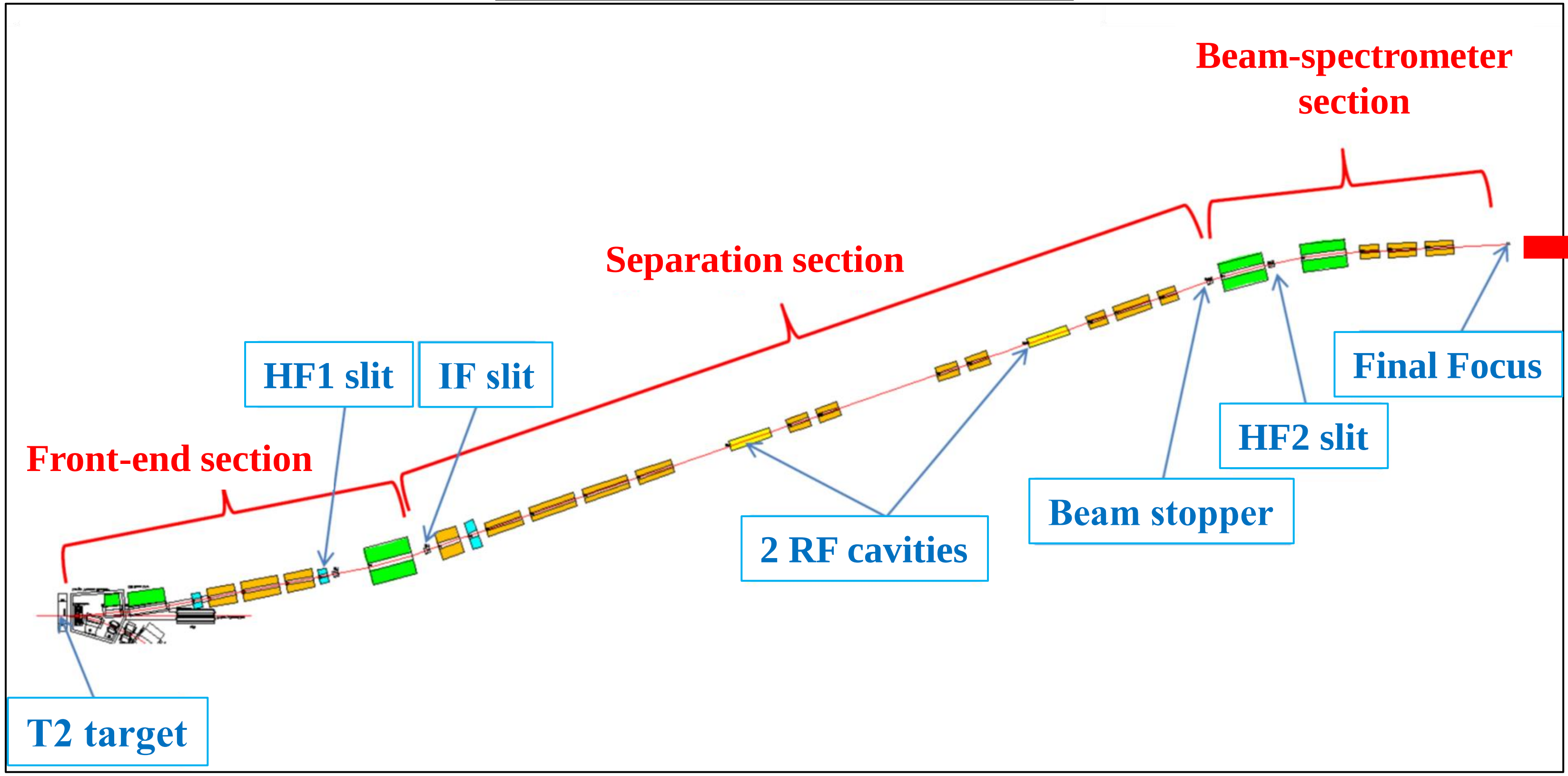
- K10 beam line: K^- beam
  - High intensity: >10^6 /spill for K^- up to 10 GeV/c
  - High-purity: K : π ~ 1 : 2
    - Radio Frequency(RF) separator
  - High resolution: $\Delta p/p$ = 0.1%(σ)
    - Beam spectrometer: QQDDQ system



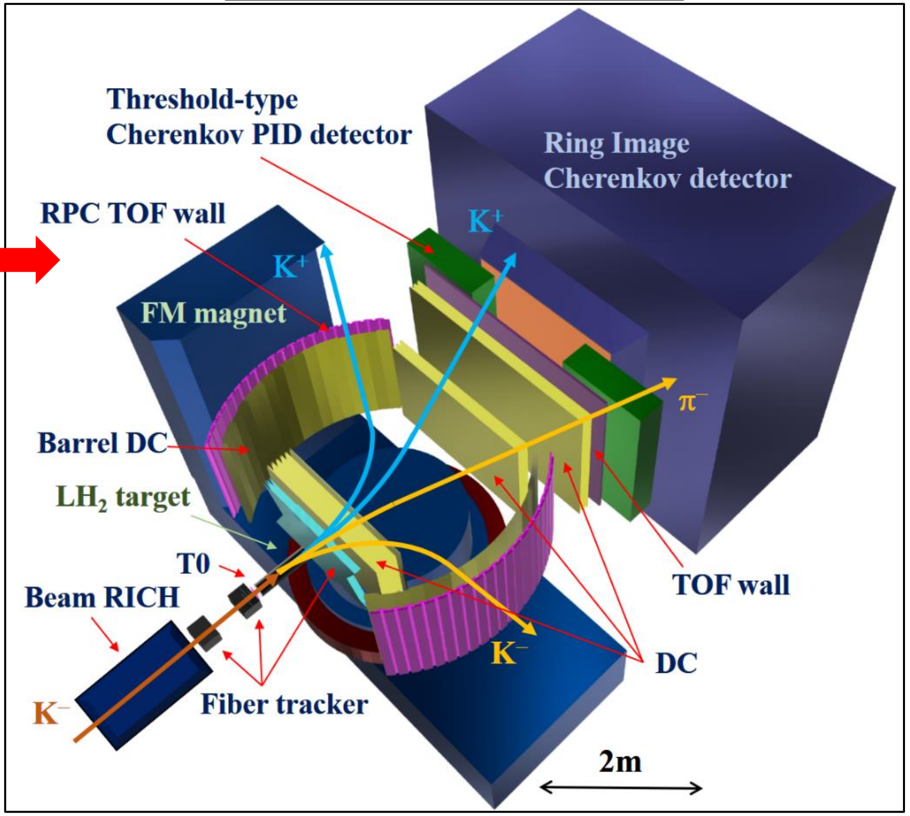
*Beam line name: ○XX
○: Main beam particle
XX: Maximum beam momentum

K10 beam line and spectrometer

Layout of K10 beam line

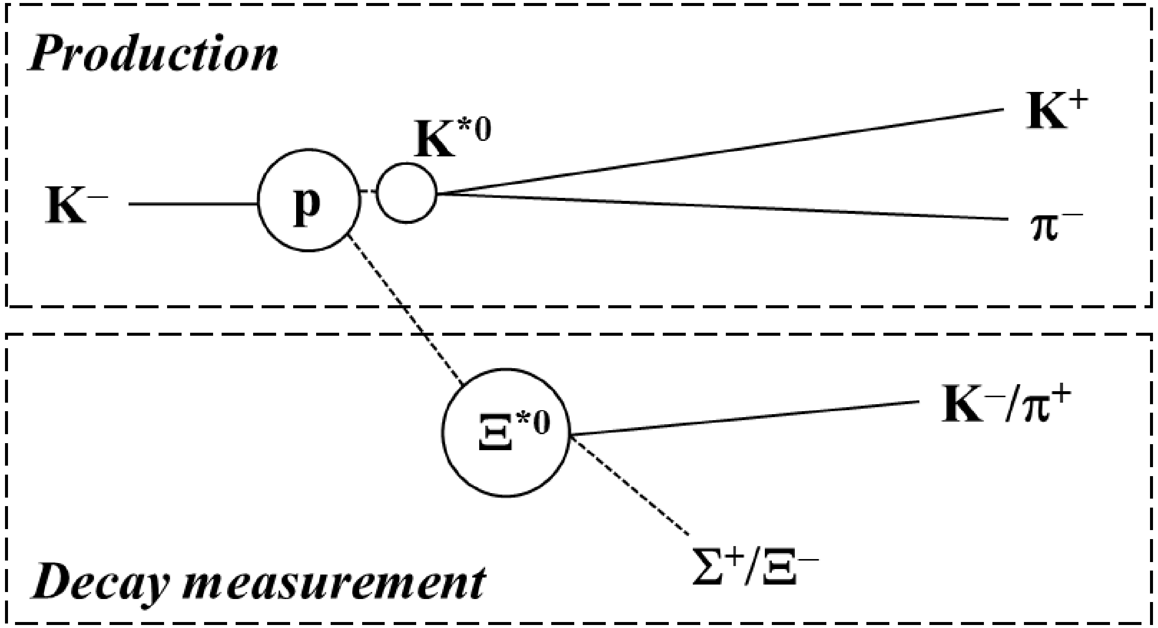


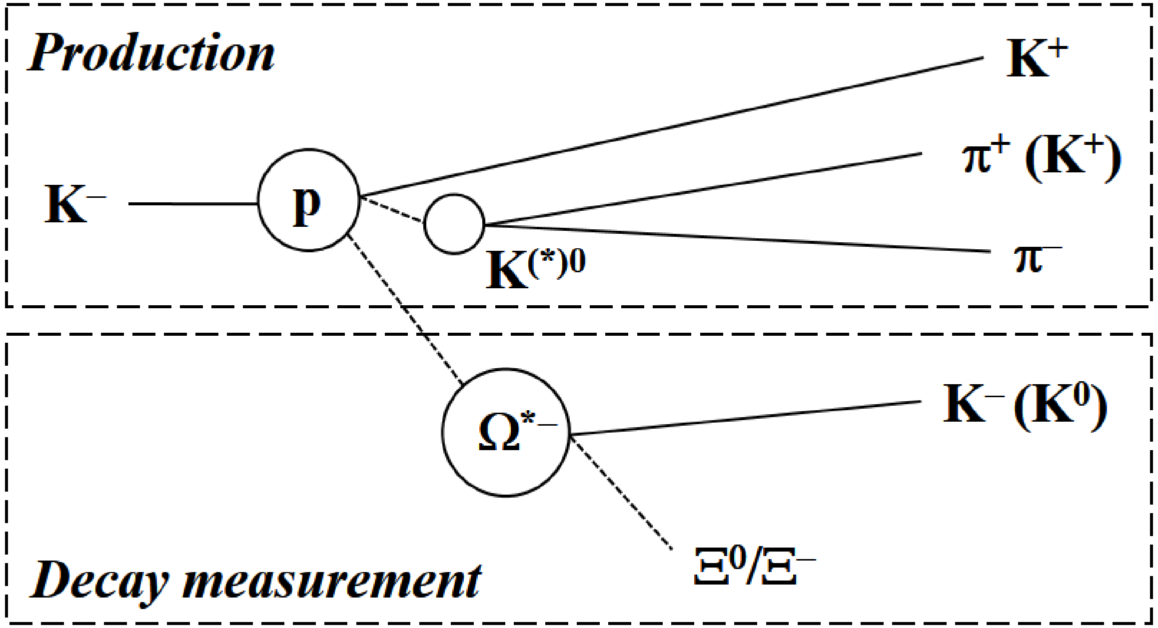
K10 Spectrometer



- K10 beam line
  - High-intensity high-momentum K⁻ beam with high purity
- Spectrometer (under designing)
  - Multi-purpose system to detect Ξ/Ω baryon production events

Experimental method: Ξ and Ω baryon spectroscopy



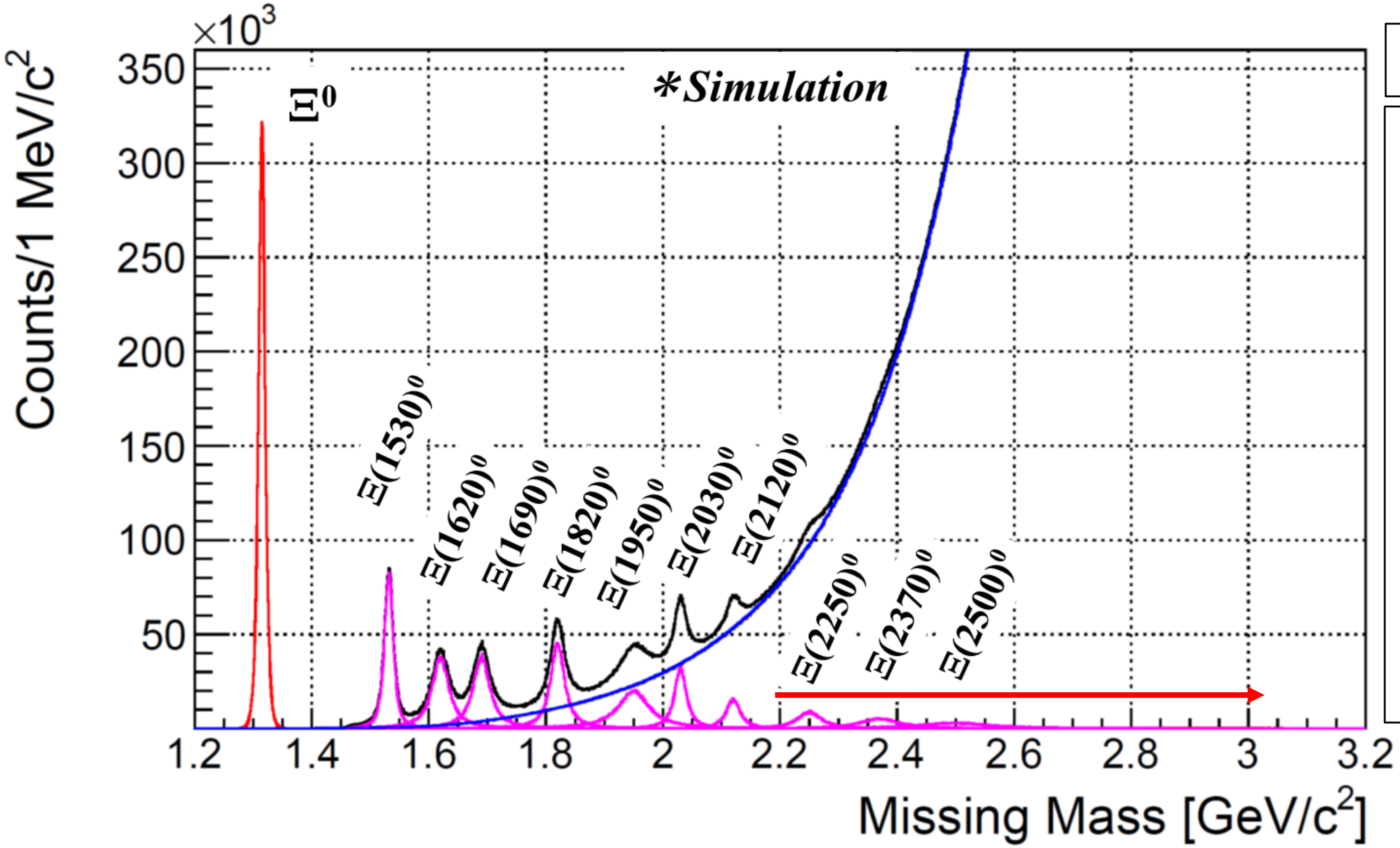


- Reaction: $K^- p \to K^+ \Xi^{*-}$ / $K^- p \to K^{*0} \Xi^{*0}$
  - Beam: 5–8 GeV/c
- Missing mass: K^+ / K^{*0}
  - K^+ or K^{*0} detection ⇒ s = –2 tagging
- Decay measurement: K^- / $\pi^{-/+}$
  - Decay products obtained as missing mass
  - $\Lambda/\Sigma^0/\Sigma^+$ and $\Xi^{0/-}$

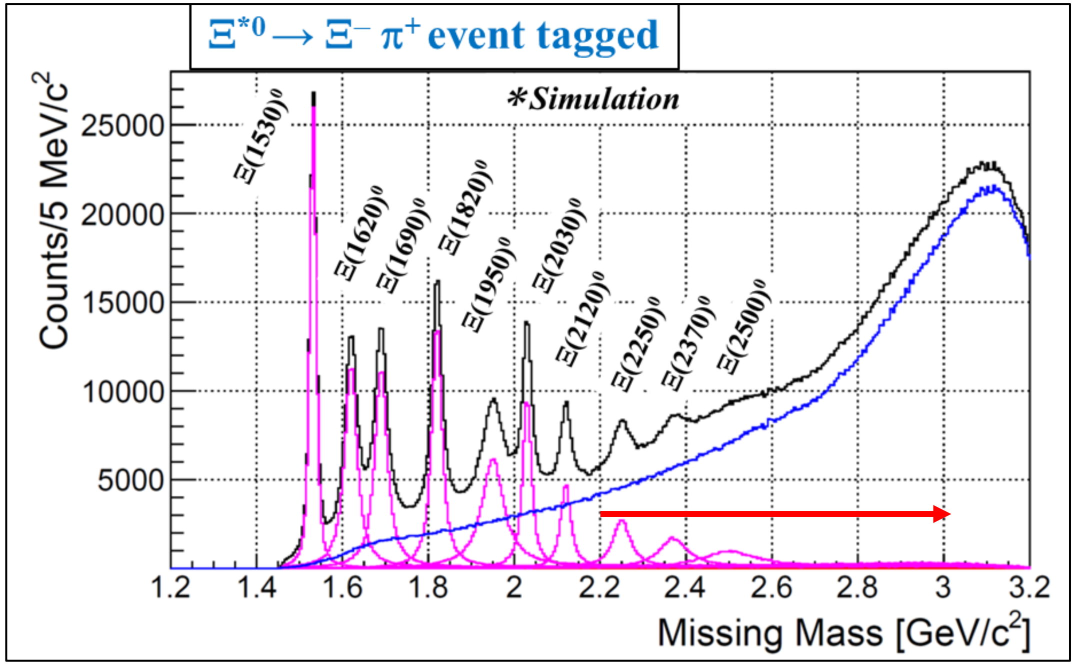
- Reaction: $K^- p \to \Omega^{*-} K^{*0} K^+$
  - Beam: 7–10 GeV/c
- Missing mass: K^{*0} & K^+
  - K^{*0} detection ⇒ s = –3 tagging
- Decay measurement: K^- / $\pi^+ \pi^-$
  - Decay products obtained as missing mass
  - $\Xi^{(*)0}$ and Ω^-

∗ High momentum transfer = Highly excited state

Expected mass spectrum: $K^- p \rightarrow K^{*0}\, \Xi^{*0}$



Background reduction



- **$\sigma_{G.S.}$ = 2 μb @ 8 GeV/c assumed ⇒ 5.3×10^6 events (30-days beam time)**
  - **Excited states: Scaling old data (Jenkins *et al*., PRL51, 951 1983)**
- **Mass resolution: ΔM ~7 MeV(σ) < Width (several 10 MeV)**
- **Background reduction by decay event selection: $\Xi^{*0} \rightarrow \Xi^- \pi^+$ (B.R. = 0.1) ⇒ S/N×30**

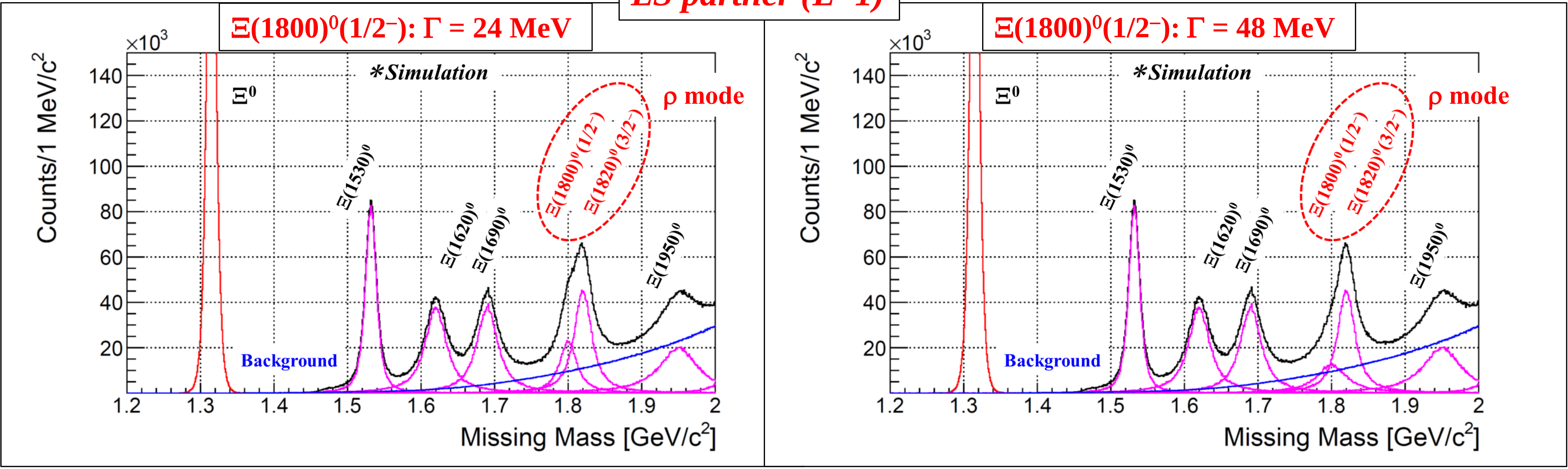
us/*ds* diquark correlation: ρ/λ mode assignment

- **Combining J^P, production rates and decay branching ratios**
  - **Assigned by J^P from decay measurement (Several 10^4 events w/o uncertainty)**
  - **Production rates: ρ-mode LS partner = 1:2 @ L = 1 (L:L+1 relation)**
  - **Decay branching ratios: $\Gamma(\Xi^* \rightarrow \Lambda/\Sigma\, K^-) \Leftrightarrow \Gamma(\Xi^* \rightarrow \Xi\, \pi)$**

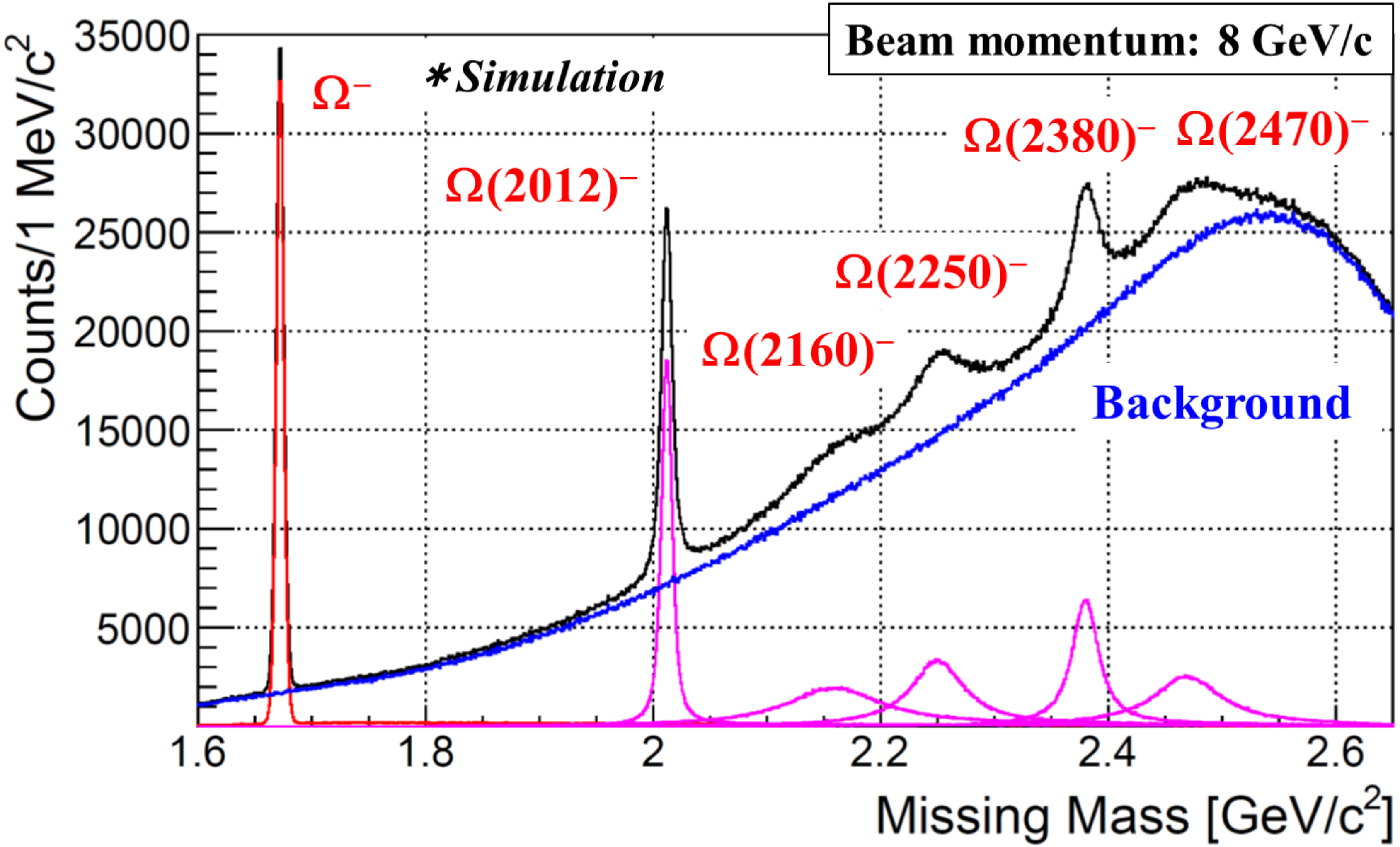
＊High-statistic data are essential.: K^- beam intensity @ K10

LS partner (L=1)

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



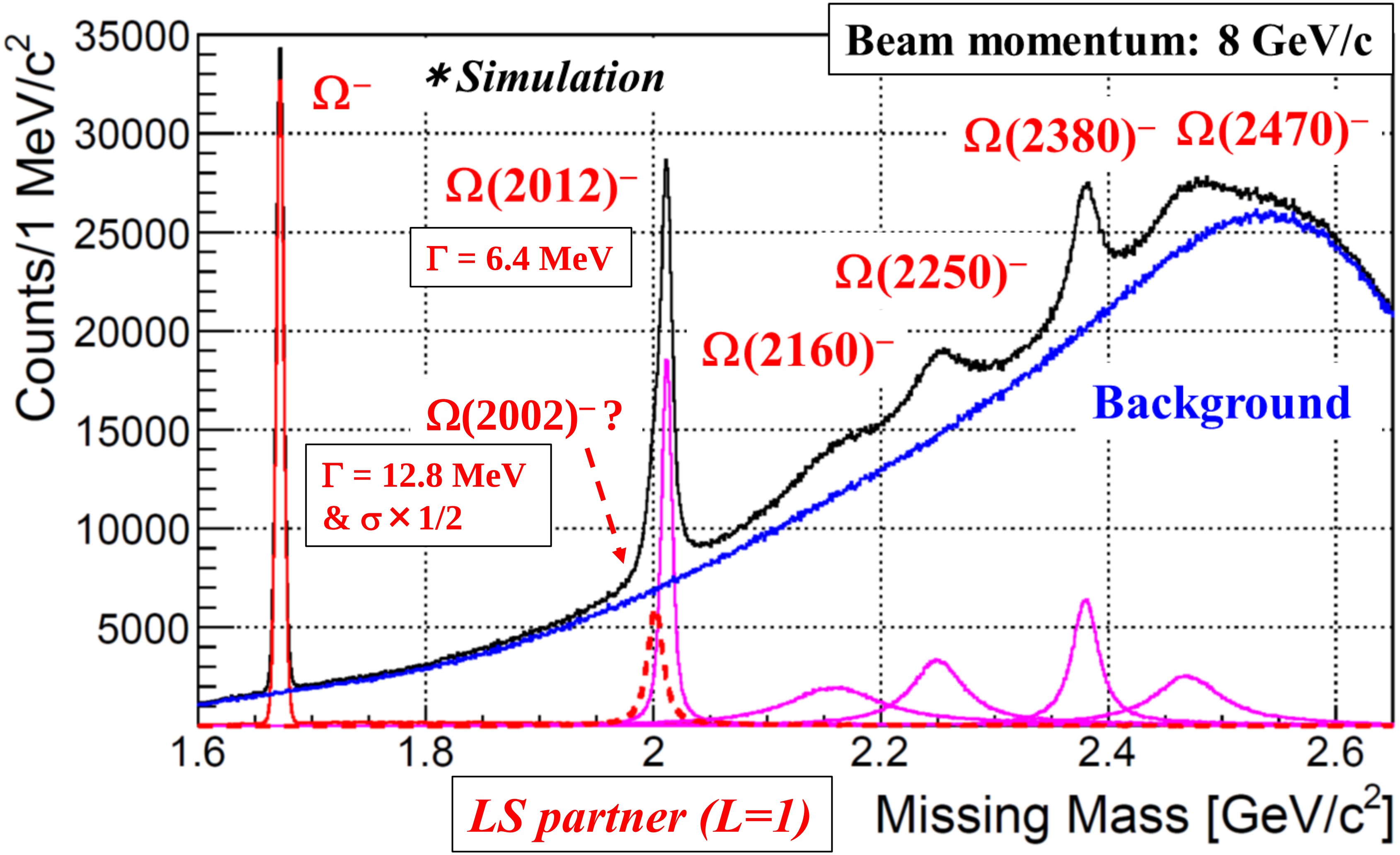
Expected mass spectrum: $K^- p \rightarrow \Omega^{*-} K^{*0} K^+$



- Ω^{*-} states in PDG are generated.
- Roper-like state: $\Omega(2160)^-$, Γ = 100 MeV (assumed)
- Breit-Wigner type resonances

- Ω^{*-} events: 3.3×10^5 events @ 100 days (63 nb: Same cross section for all resonances)
  - Mass resolution: ΔM ~5 MeV < Width (several 10 MeV)
- Background reduction by decay event: $\Omega^{*-} \rightarrow \Xi^{*0} K^-$ (B.R. = 0.3) $\Rightarrow$ S/N$\times$10

Expected mass spectrum: $K^- p \rightarrow \Omega^{*-} K^{*0} K^+$

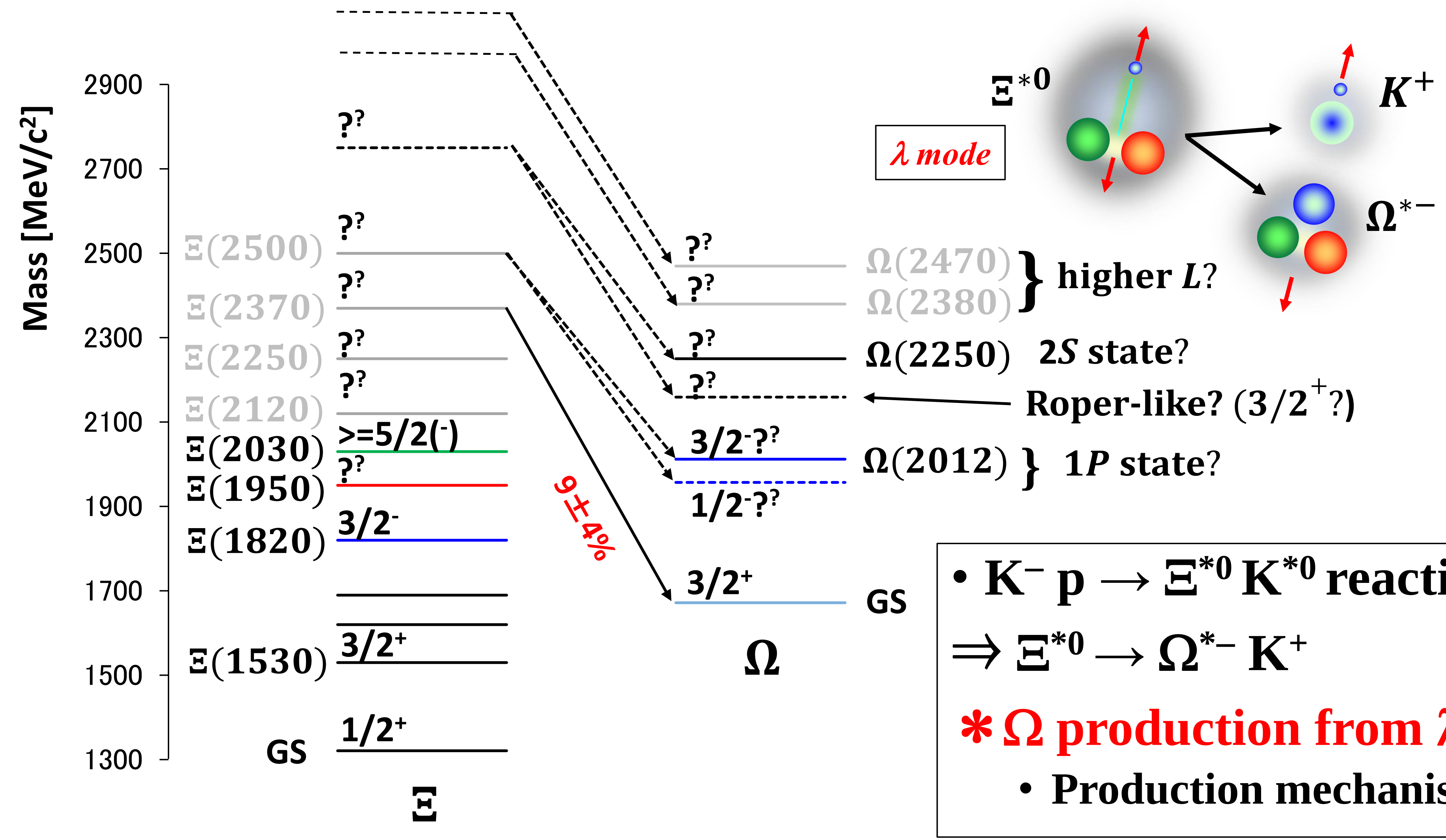


- Ω^{*-} states in PDG are generated.
- Roper-like state: $\Omega(2160)^-$, Γ = 100 MeV (assumed)
- Breit-Wigner type resonances

*$\Omega(2002)^-(1/2^-)$: Assumed for simulation

- Ω^{*-} events: 3.3×10^5 events @ 100 days (63 nb: Same cross section for all resonances)
  - Mass resolution: ΔM ~5 MeV < Width (several 10 MeV)
- Background reduction by decay event: $\Omega^{*-} \rightarrow \Xi^{*0} K^-$ (B.R. = 0.3) ⇒ S/N × 10

Relation between Ξ and Ω baryons: Production process



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

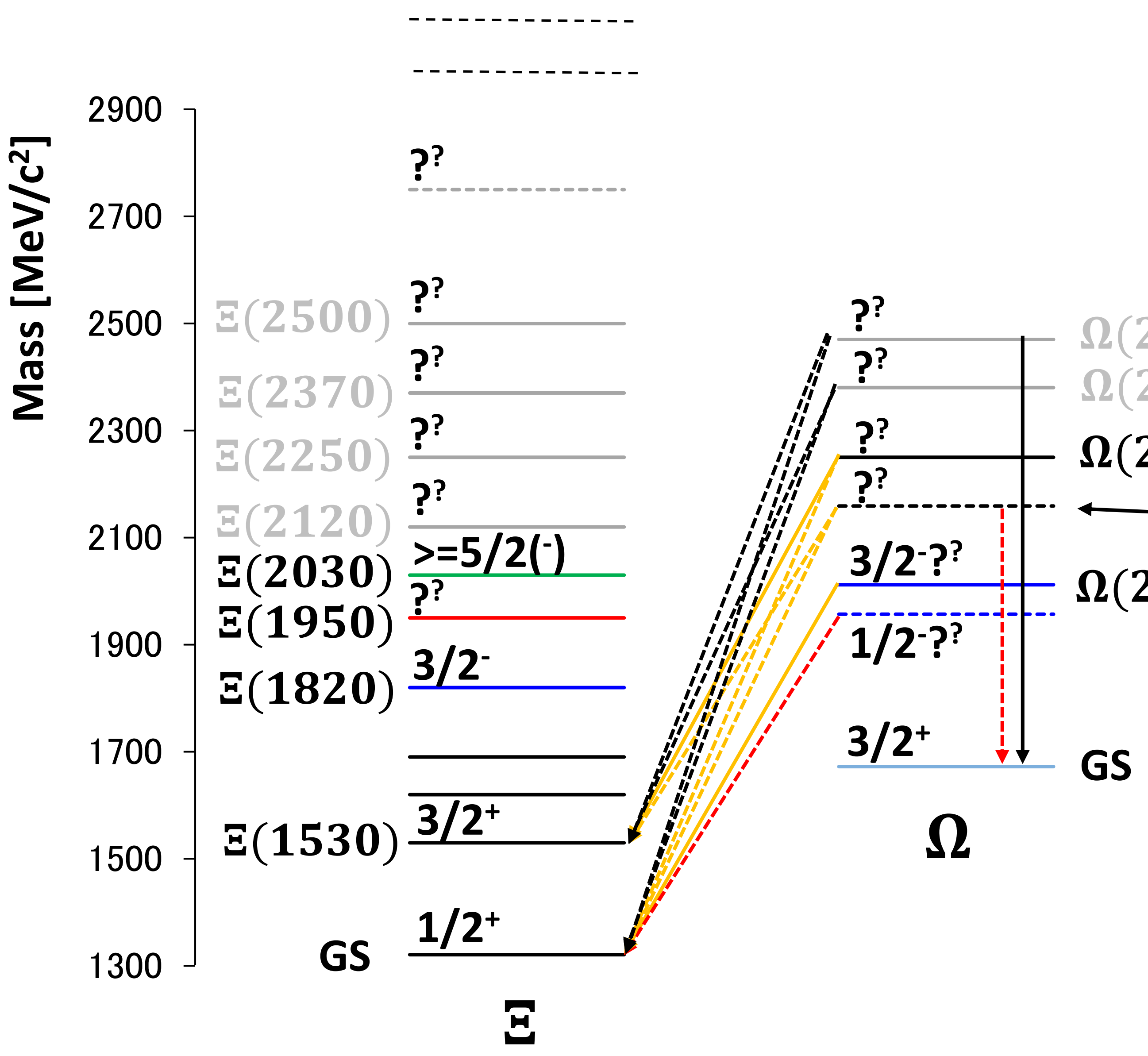
$\Rightarrow \Xi^{*0} \to \Omega^{*-} K^+$

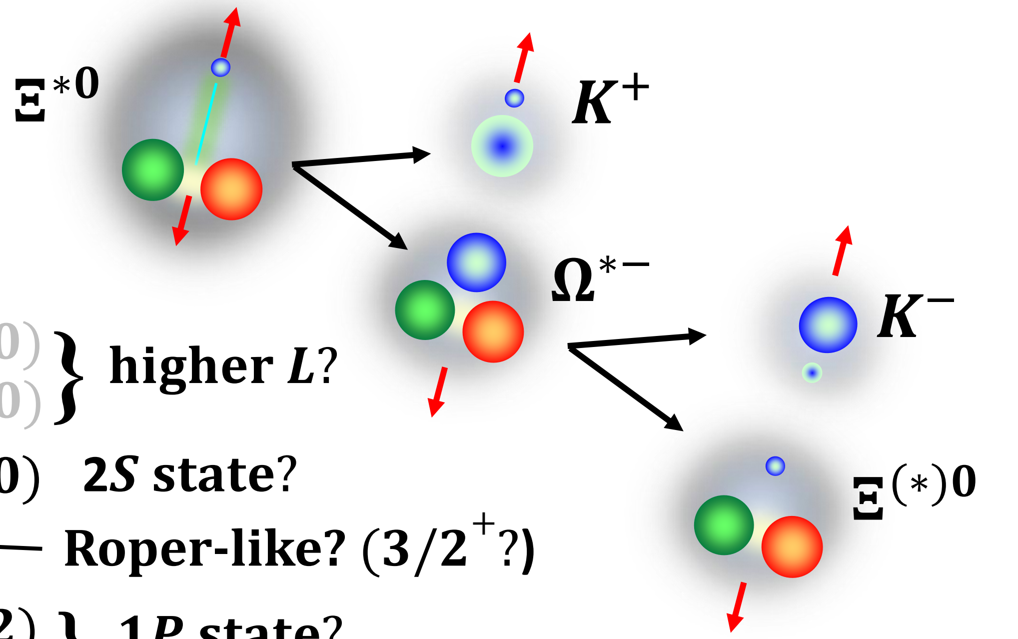
＊Ω production from λ mode Ξ*

- Production mechanism of Ω

Relation between Ξ and Ω baryons: Decay process

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





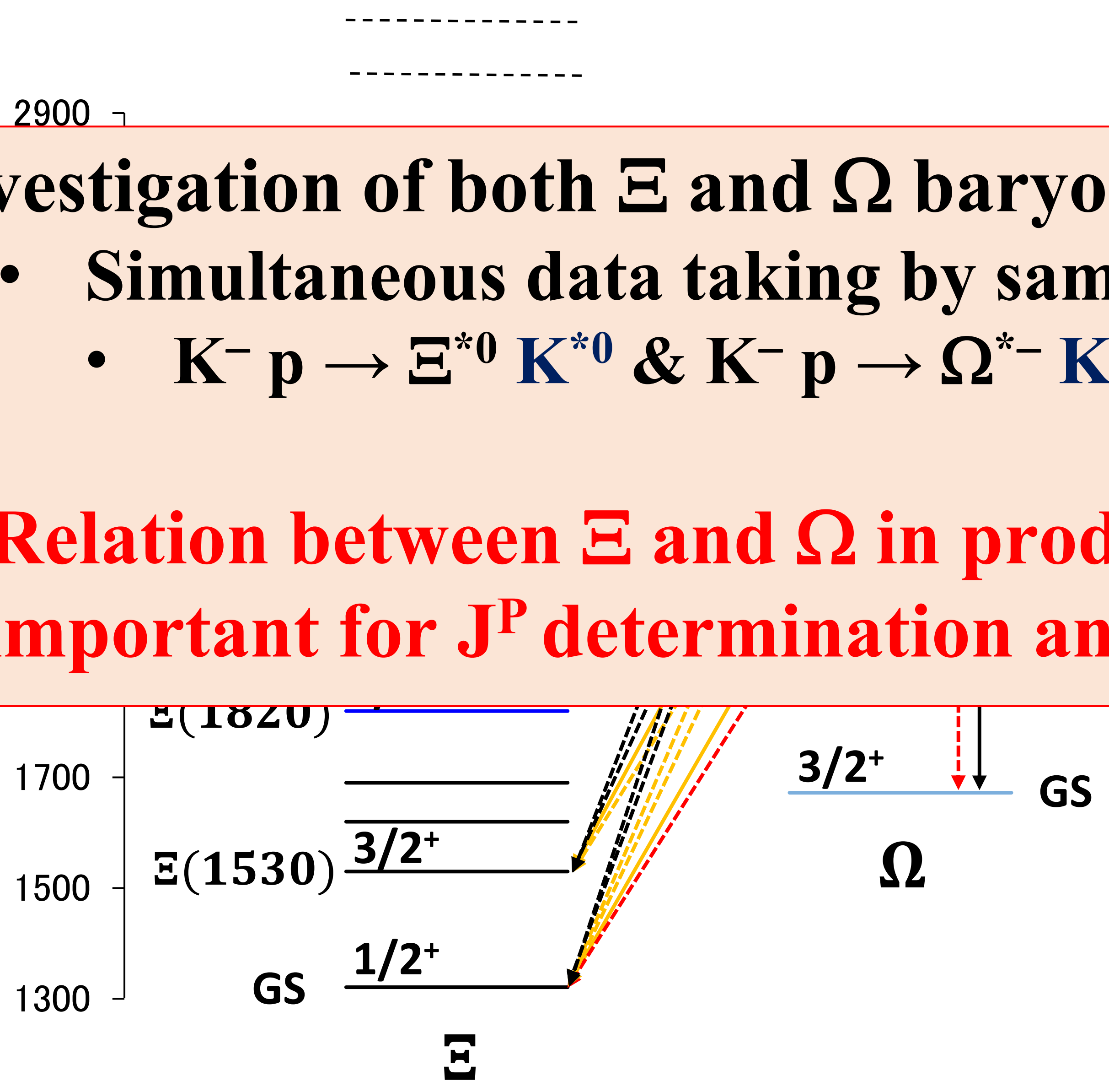
- Cascade decay chain

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

- 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 K10 beam line

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

＊Relation between Ξ and Ω in production and decay processes is important for J^P determination and ρ/λ 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 $\Xi^*(J^P)$ to be determined as well**

Paucity of data: Ξ and Ω excited states

- **Many excited states predicted by the quark model have not been found.**
- **Spin/Parity: Most of spins and parities have not been determined.**
  - **LS partners and Roper-like resonances have not been established.**
- **Diquark correlation: No ρ/λ mode assignment**
- **Production mechanism and cross section of hadronic reaction (K^- beam)**
  - ***u*-channel and 2-step for Ξ^* ? ($K^- p \rightarrow \Xi^{*0} K^+$)**
  - **Doorway from Ξ^* for Ω^* ? ($K^- p \rightarrow \Omega^{*-} K^+ K^{*0}$)**
- **Decay properties: Why width seems to be narrow ?**
  - **What determines decay width and branching ratio ? (small coupling to pion ?)**
- **Exotic states: Not well studied**
  - **ex. Ξ(1620), Ξ(1690) and Ω(2012)?**

Further studies

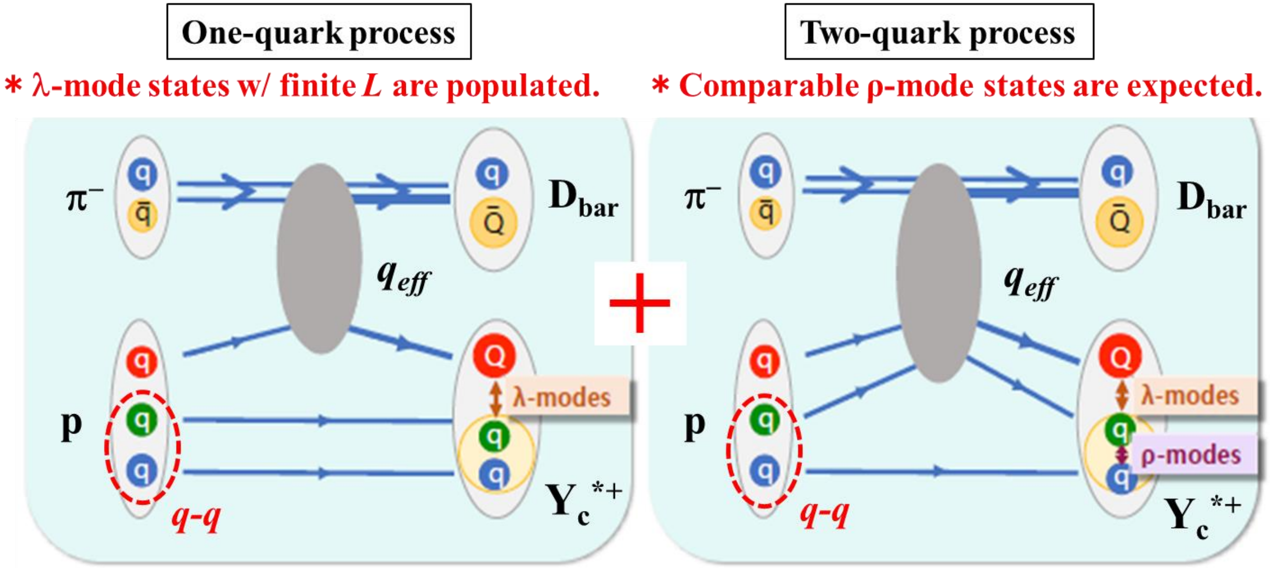
Baryon spectroscopy at J-PARC: π20 and K10

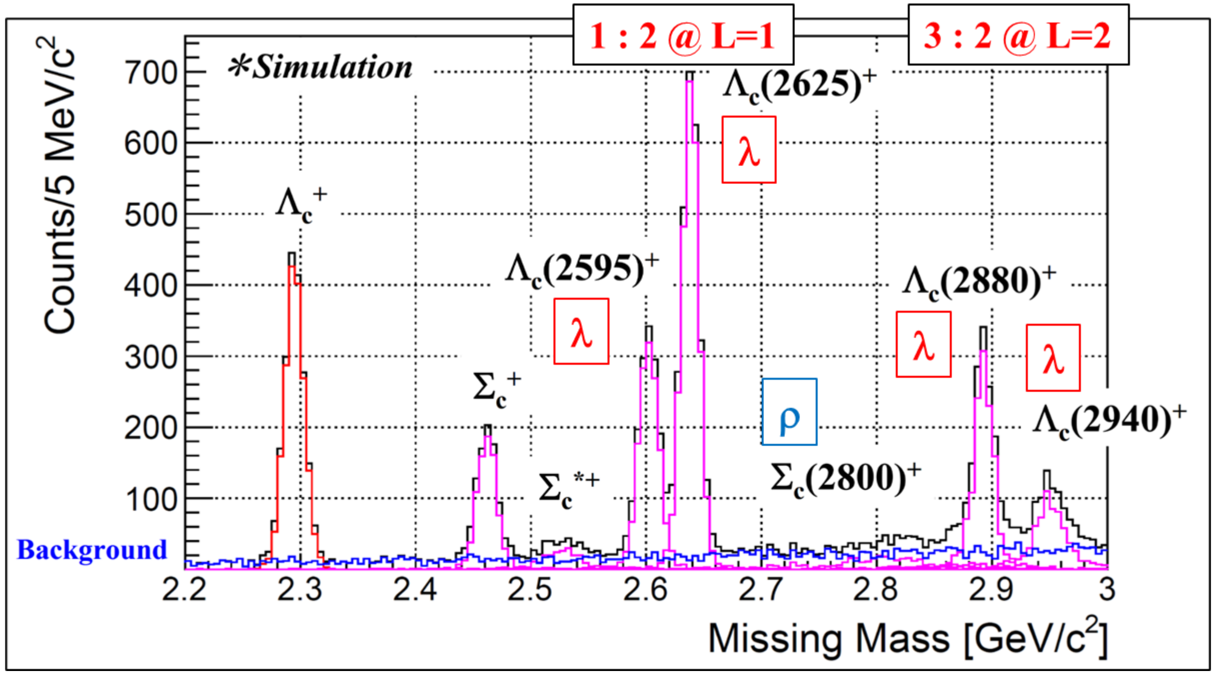
1. **Systematic measurements:** Excited states properties of $\Lambda_c/\Sigma_c(\Lambda/\Sigma)$, Ξ, Ω
   - Mass, width, spin-parity, decay branching ratio, production rate

2. **λ/ρ mode assignment by J^P, production rates and decay branching ratios**
   - Determination of LS partner (HQ doublets) in L=1 and 2… states
     - Production rate of LS partner = $L : L+1$

⇒ Establish diquark correlation as building block of baryon
- A starting point toward understanding of dense quark matter

＊Key information: Production mechanism



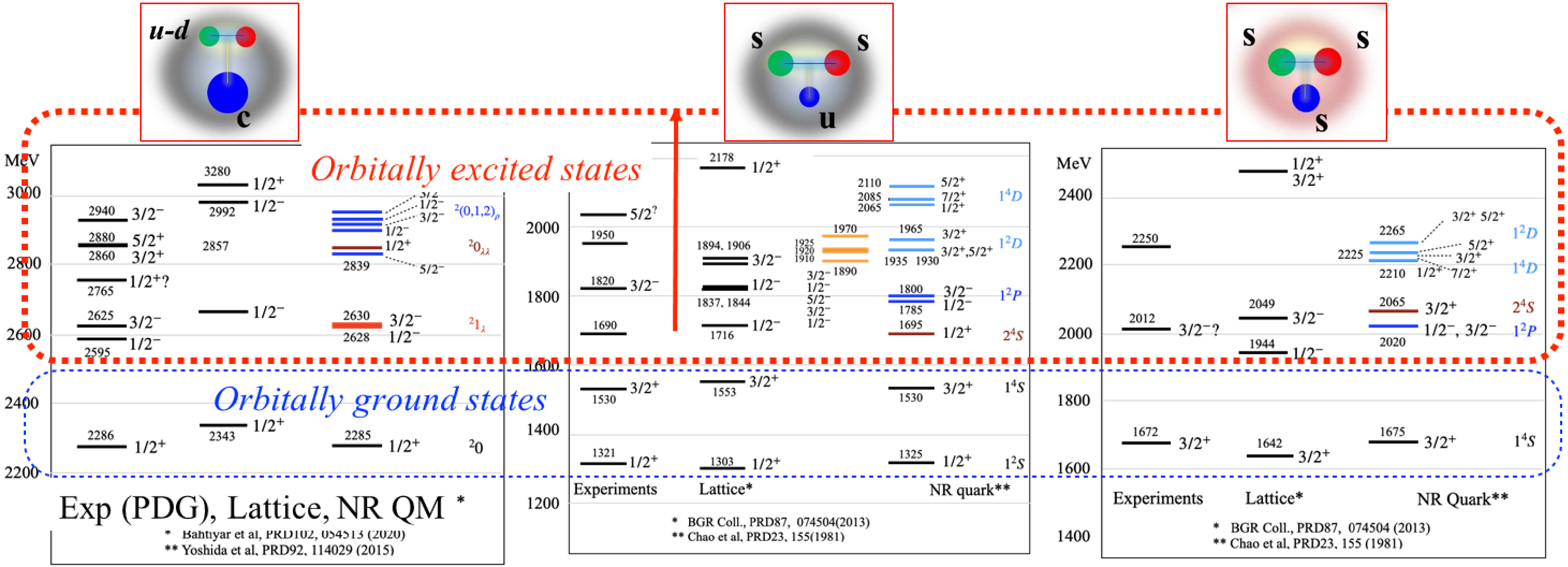


Baryon spectroscopy at J-PARC: π20 and K10

3. **Abundant data of excited states (A few MeV accuracy of mass and width)**
   - **Information of interactions: More than 10 MeV splitting**
     - **Systematics by changing quark configuration in Λ_c/Σ_c, Ξ, Ω**

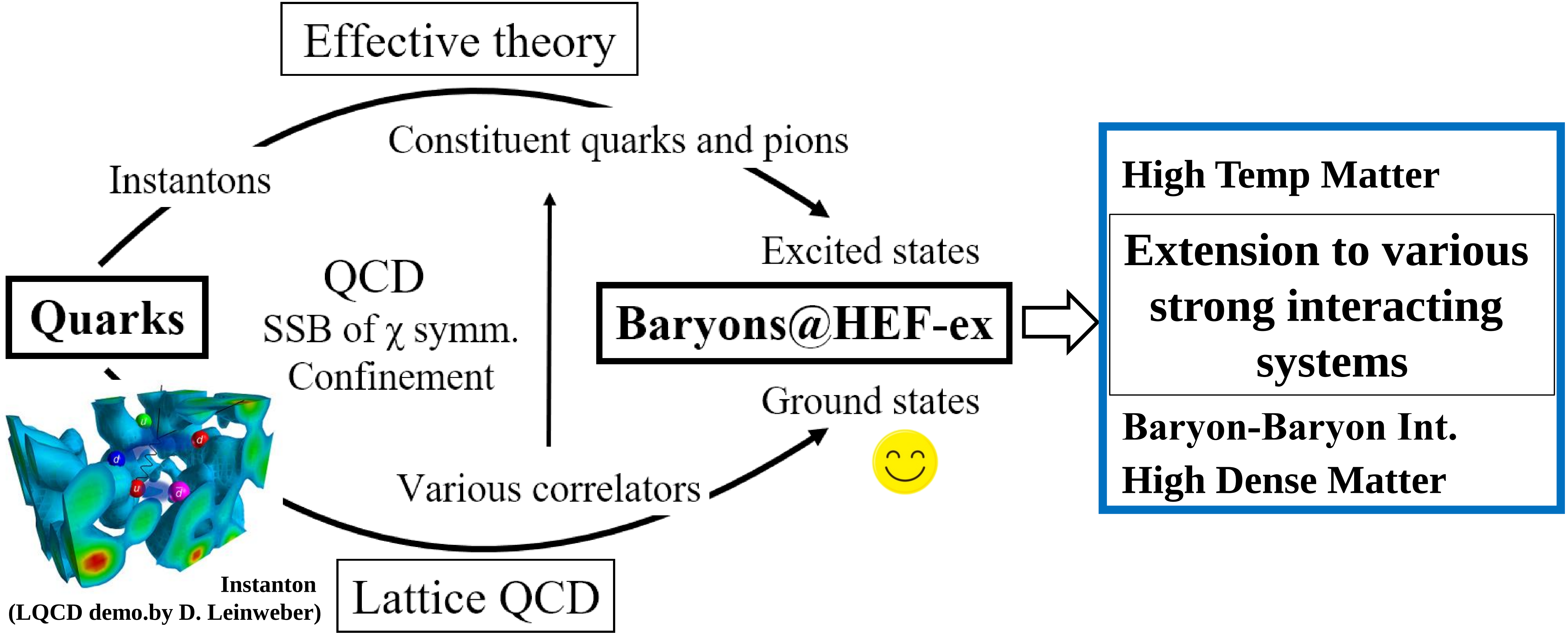
⇒ Systematics description of excited state properties over different flavors by quarks and diquark correlation: Effective theory based on QCD

⇒ Understand dynamics of non-trivial QCD vacuum



Baryon Spectroscopy

- **Experiment**: Spectroscopy of Heavy flavors, Λ_c … Ω, Ξ, …
- **Theory**: excited states by effective theories with their parameter origins in QCD, lattice and analytic methods



Baryon Spectroscopy: Dynamics of non-trivial QCD vacuum

- Diquark correlation
- Spin-dependent forces
- Quark motion

- **Experiment**: Spectroscopy of Heavy flavors, Λ_c … Ω, Ξ, …
- **Theory**: excited states by effective theories with their parameter origins in QCD, lattice and analytic methods

effects appear in

Effective theory

Constituent quarks and pions

Instantons

Excited states

QCD

Quarks

SSB of χ symm.

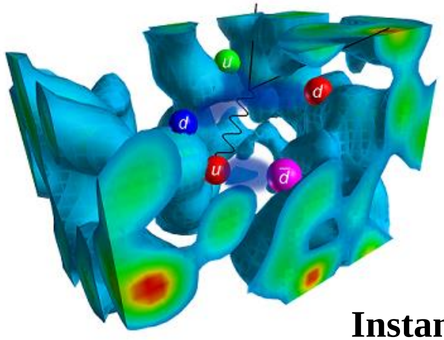
Confinement

Baryons@HEF-ex

Ground states

Various correlators

Lattice QCD



Instanton
(LQCD demo.by D. Leinweber)

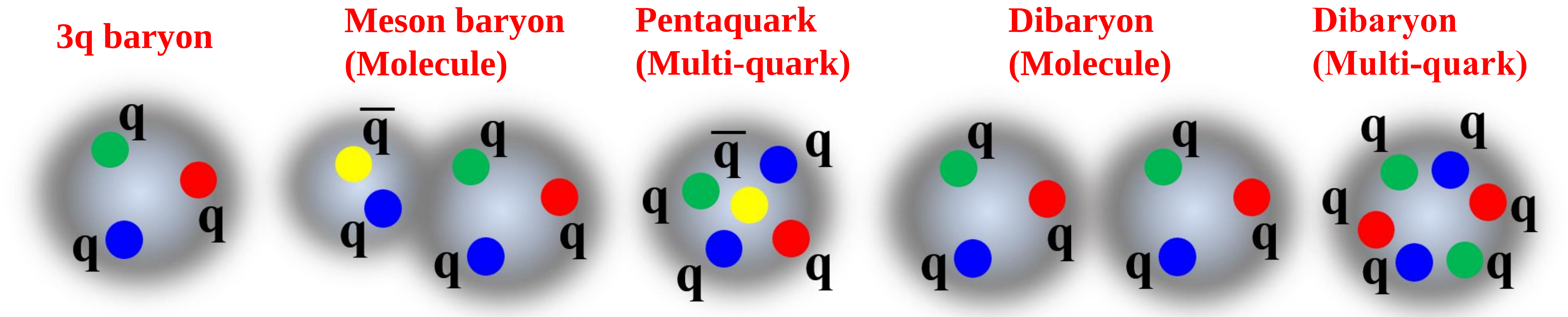
High Temp Matter

Extension to various strong interacting systems

Baryon-Baryon Int.

High Dense Matter

Understanding of exotic states



- Properties of exotic states (Mass, Γ, J^P, production)
- Role of effective degrees of freedom (Hadron/Quark DoF)

⇒ Links to systematic studies of heavy baryons

＊How exotic hadrons emerge ? ⇔ Dynamics of Effective DoF

- Molecule (Colorless = hadron DoF) ⇒ Threshold region ?
- Multi-quark (Colorful = diquark/gluon DoF) ⇒ ?

⇒ Mixed states (Both Colorless and Colorful) ⇒ Threshold region ?

Investigations of exotic states

- Exotic properties of observed states
  - Mass and width
    - Different mass predicted from quark model
    - Narrow width
  - Spectrum line shape
    - Dynamically generated hadron molecule
    - Resonance or cusp ?
  - Spin/parity
    - Essential information to reveal internal structure
  - Number of quarks
    - Only quark counting rule by high-energy reaction

- Production and decay rates

⇔ Difference from systematics ?

⇔ Systematics depending on internal structure (mixed state) ?

⇒ Specific measurements by dedicated experiments

- Reaction control: Reaction modes, momentum transfer and scattering angle
- High-resolution system: Direct measurement of width and precise line shape
- Large coverage system: Decay measurement (PWA is ideal…)
- High-energy beam: Response of differential cross section (quark counting rule)

Summary

- **How quarks build hadrons ? ⇒ Dynamics of non-trivial QCD vacuum in baryon structure**
  - ***c*- and *s*-baryon spectroscopy: Disentangle diquark correlation and spin-dependent forces**

- **Diquark correlation: Effective degrees of freedom**
  - **Charmed baryon: Disentangle *ud* diquark correlation**
  - **Ξ baryon: Systematics of *us*/*ds* diquark correlation**
  - **Ω baryon: Suppression of diquark correlation**

- **Spin-dependent forces and quark motion**
  - **Systematic of Λ_c/Σ_c, Ξ, Ω systems**
  - **Role of Ω : Clear extraction due to free from pion cloud**

- **J-PARC facility: High-intensity & High-momentum hadrons beams**
  - **High-p(π20): Charmed baryon spectroscopy via $\pi^- p \rightarrow D^{*-} Y_c^{*+}$**
  - **K10: Ξ & Ω baryon spectroscopy via $K^- p \rightarrow K^{*0}/K^+ \Xi^{*0/-}$ / $K^- p \rightarrow \Omega^- K^+ K^{*0}$**

⇒ Systematic measurements of excited states properties

- **λ/ρ mode assignment by J^P, production rates and decay branching ratios**

⇔ Mechanism of exotic state emergence: Dynamics of Effective DoF

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