Baryon spectroscopy with secondary hadronic beams at J-PARC

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for the E50/E31 collaboration

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International symposium on Clustering as a Window on the Hierarchical Structure of Quantum Systems (CLUSHIQ2020)

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- **Study of hadron molecule state: Λ(1405)**
  - **J-PARC E31 experiment**

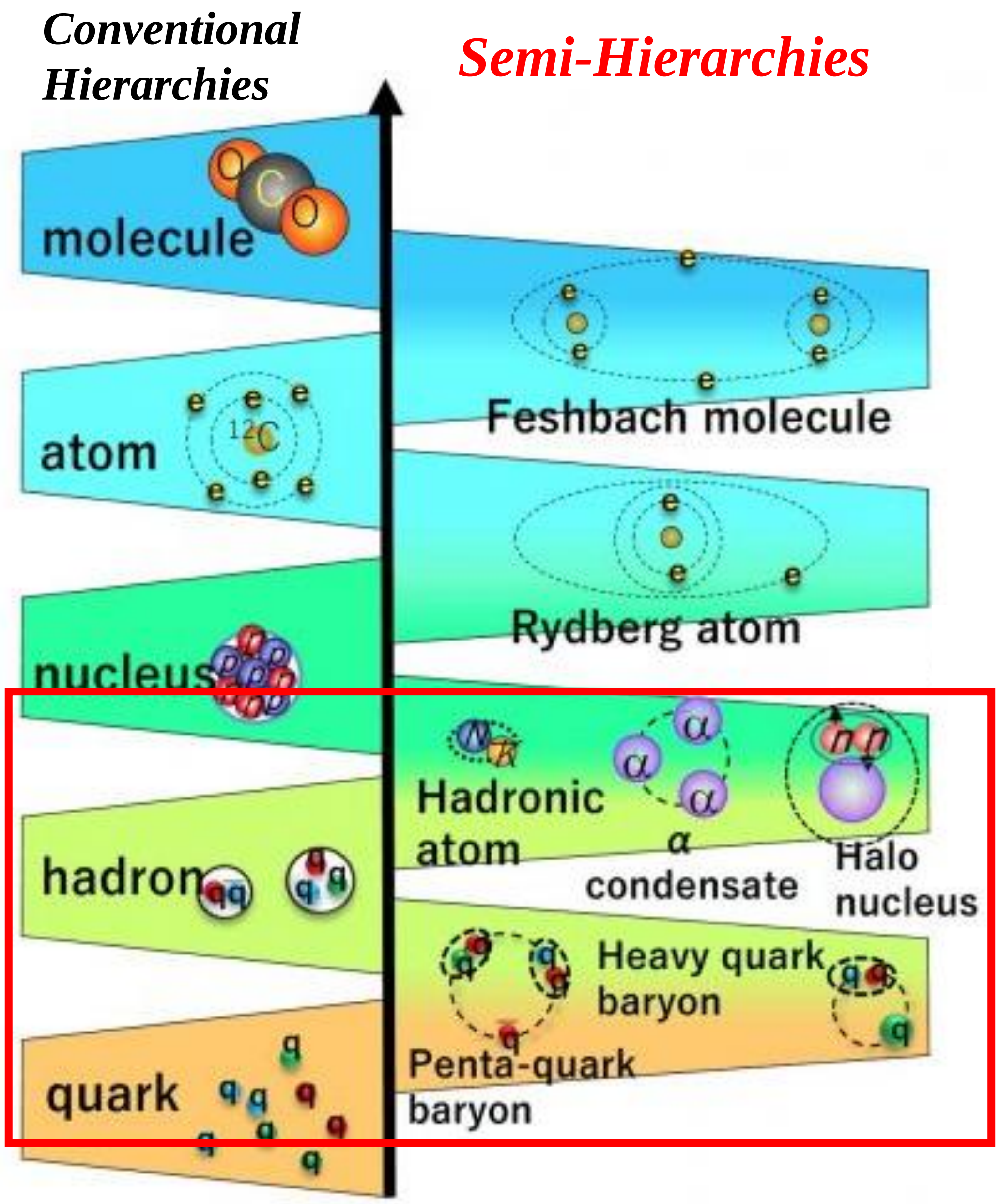
- **Summary**

Motivations

Investigations of excited states

Charmed baryon and hyperon spectroscopy

How hadrons are originated by quark and gluon ?



- Understand hadrons

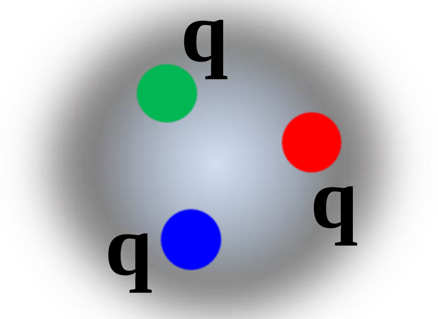
by new **effective degree of freedom**

⇒ **Semi-Hierarchies**

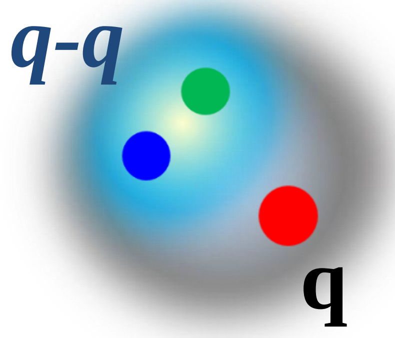
between **Hadron and Quark・Gluon (A02)**

＊**J-PARC** & **LEPS2** projects

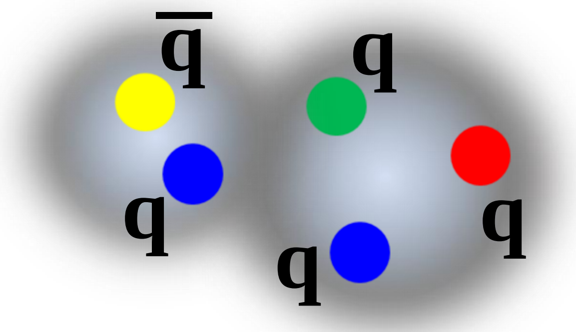
- Constituent quark
- Diquark
- Hadron molecule



Diquark



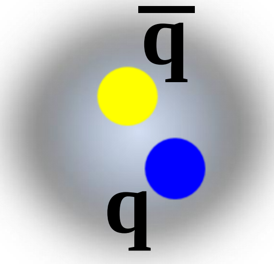
Hadron molecule



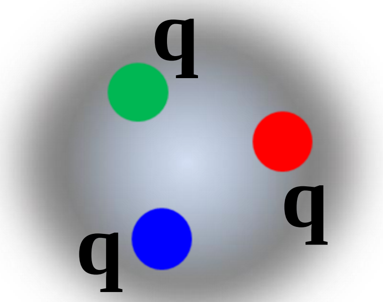
Excited states: Observation of exotic hadrons

Constituent quark

Meson

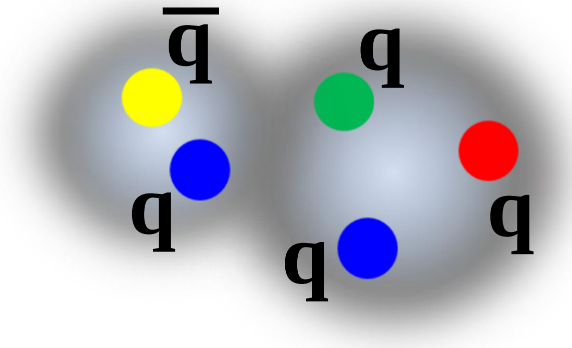


Baryon

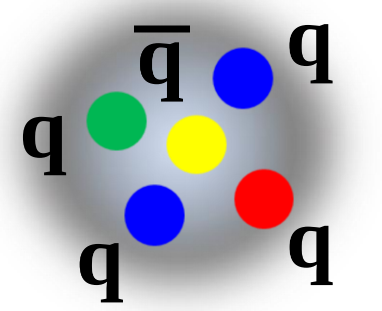


Exotic hadrons

Hadron molecule



Multi-quark



＊Excited states: Rich properties

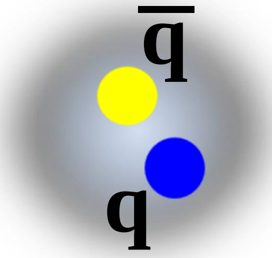
⇒ Mass, width, decay branching ratio, spin and parity

from new effective degree of freedoms extended to ordinary constituent quark model

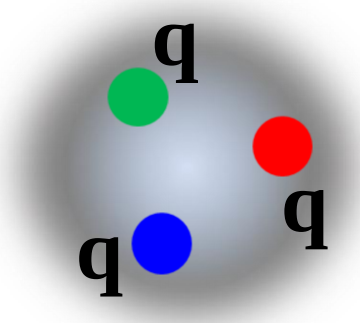
Excited states: Observation of exotic hadrons

Constituent quark

Meson

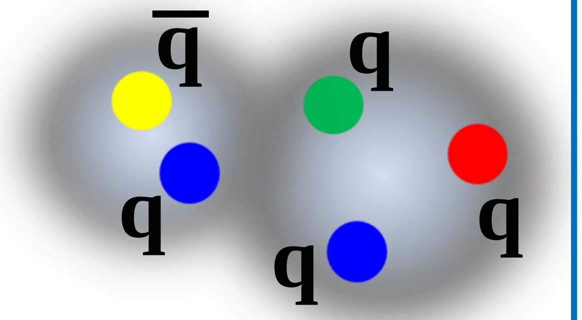


Baryon

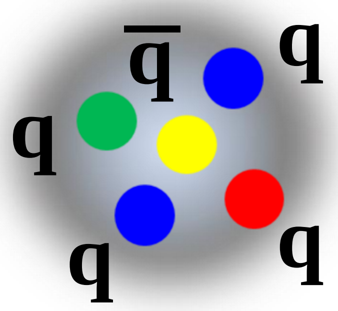


Exotic hadrons

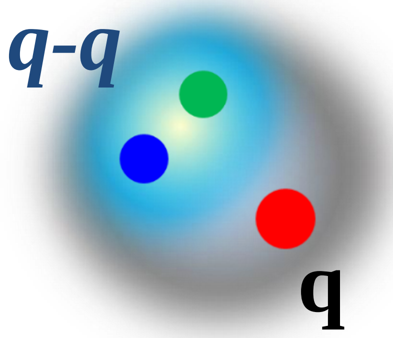
Hadron molecule



Multi quark



Diquark correlation



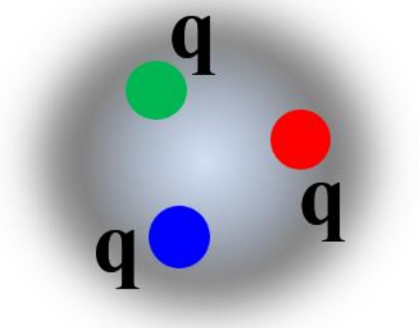
Diquark correlation

&

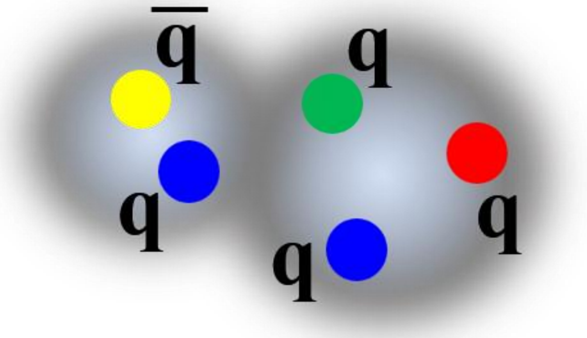
Hadron molecule

Excited states and effective degree of freedoms

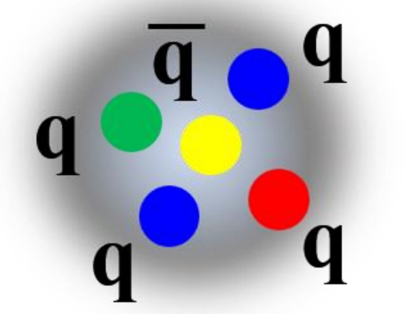
3q baryon



Meson baryon
(Molecule)



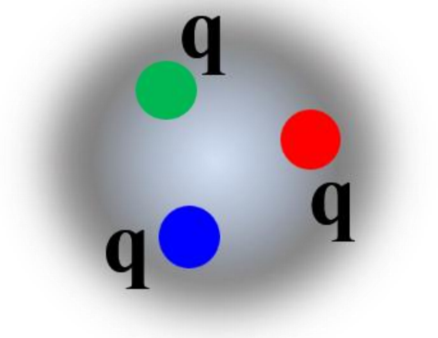
Pentaquark
(Multi quark)



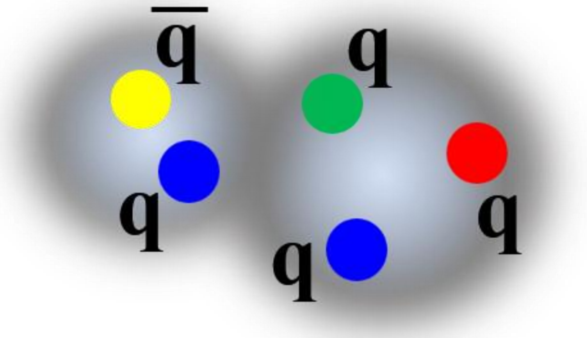
- Properties of excited states ? (Mass, Γ, J^P)
- Role of effective degree of freedoms ? (Systematics)
- How (where) configurations emerge ? (Threshold region …)
- Understand whole hadron properties universally ?

Excited states and effective degree of freedoms

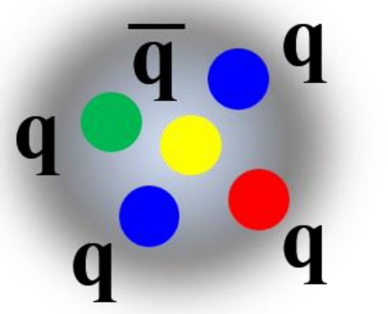
3q baryon



Meson baryon (Molecule)



Pentaquark (Multi quark)

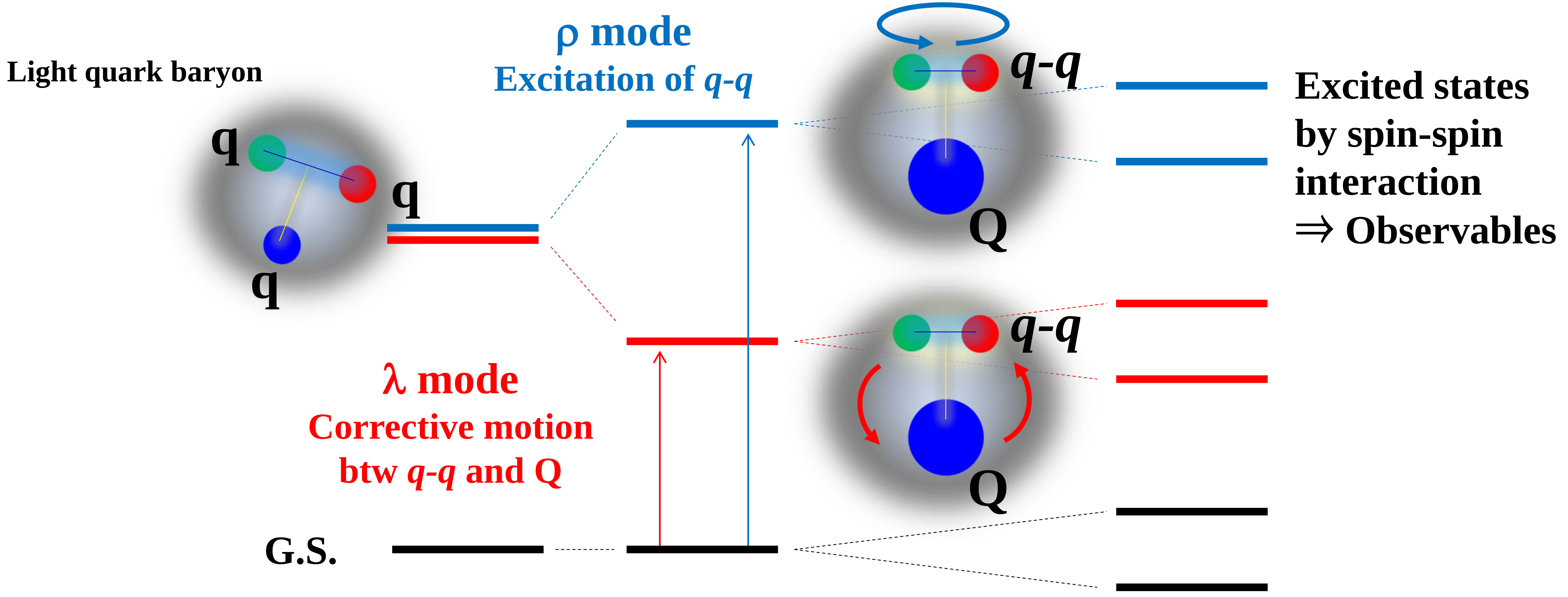


- **Properties of excited states ? (Mass, Γ, J^P)**
- **Role of effective degree of freedoms ? (Systematics)**
- **How (where) configurations emerge ? (Threshold region …)**
- **Understand whole hadron properties universally ?**

Excited states with heavy quark: Diquark

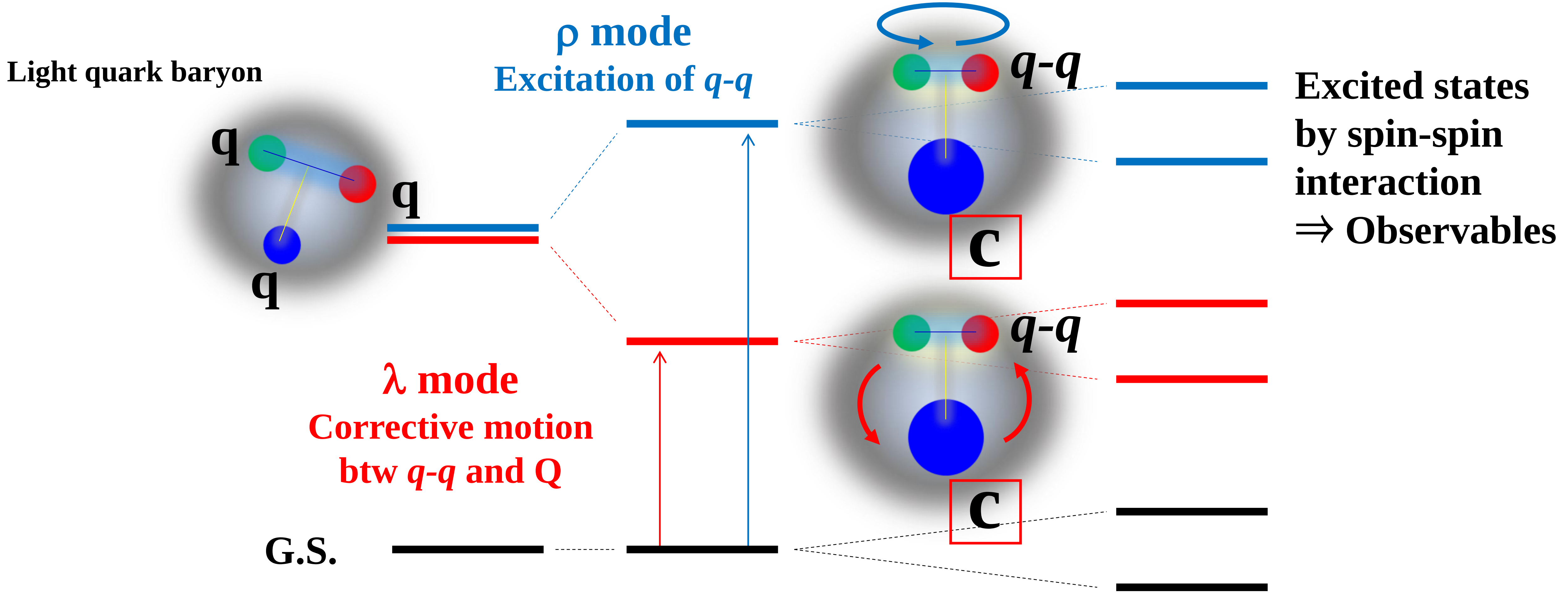
"Excited mode": λ and ρ modes in heavy baryon excited states (*q*-*q* + Q system)

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



Charmed baryon spectroscopy experiment: J-PARC E50

* $\pi^- + p \rightarrow Y_c^{*+} + D^{*-}$ reaction @ 20 GeV/c
  - High-intensity π^- beam: 6.0×10^7 /spill
- Production rates & Decay branching ratios



Production rates by hadronic reaction

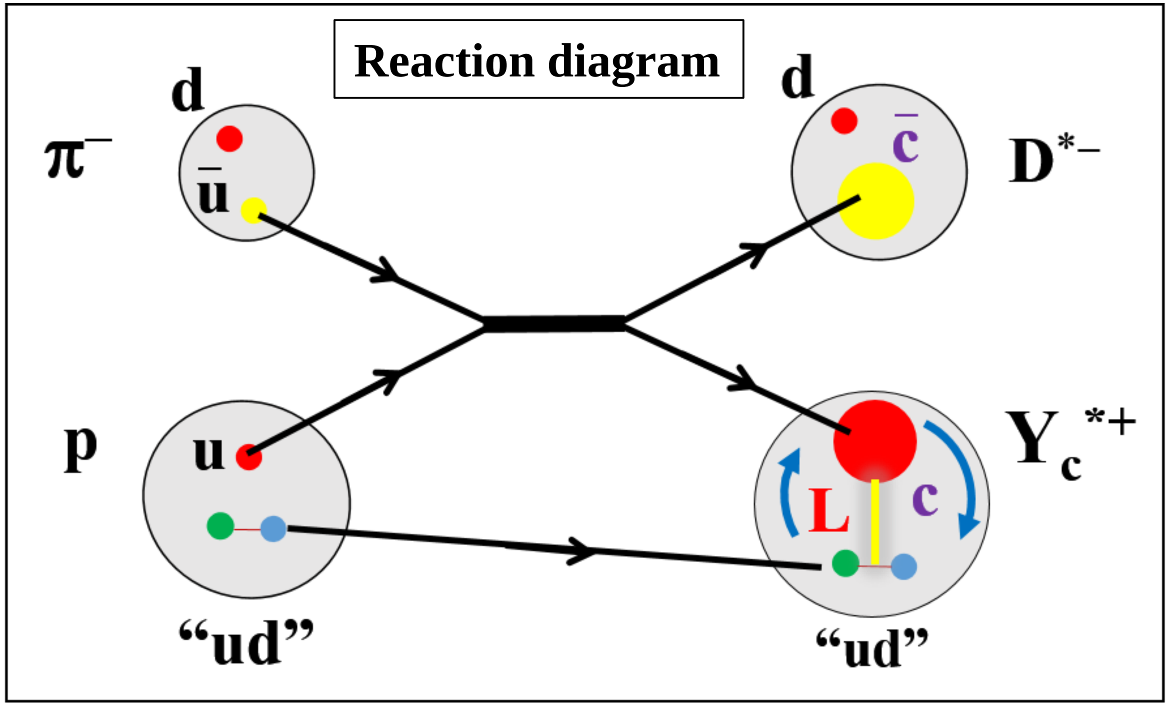
- $\pi^- + p \rightarrow Y_c^{*+} + D^{*-}$ reaction: **Missing mass method**

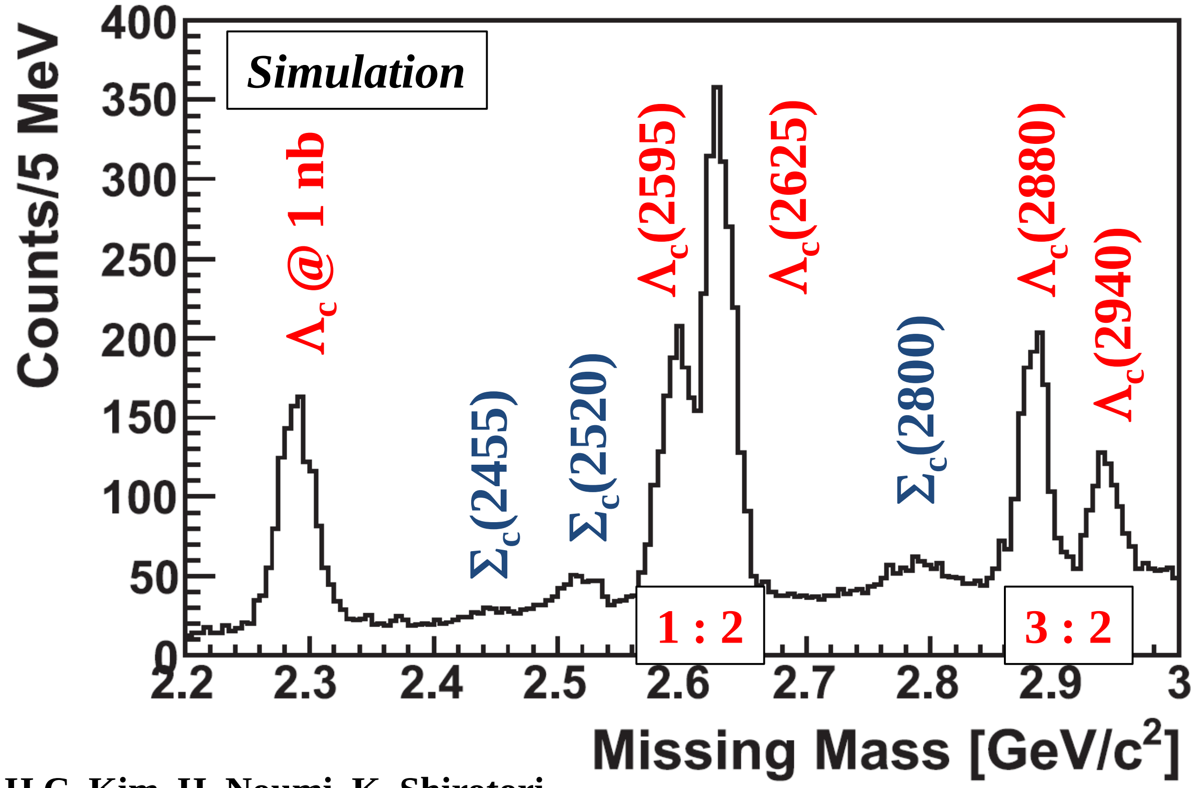
∗ Production rates ⇔ Internal structure of excited states

⇒ Selective production of corrective motion: λ mode

∗ Production cross section
⇒ Overlap of wave function
∗ charm and *q-q* (spectator)

$$R \sim \left\langle \varphi_f \left| \sqrt{2}\sigma_- \exp(i\vec{q}_{eff}\vec{r}) \right| \varphi_i \right\rangle$$

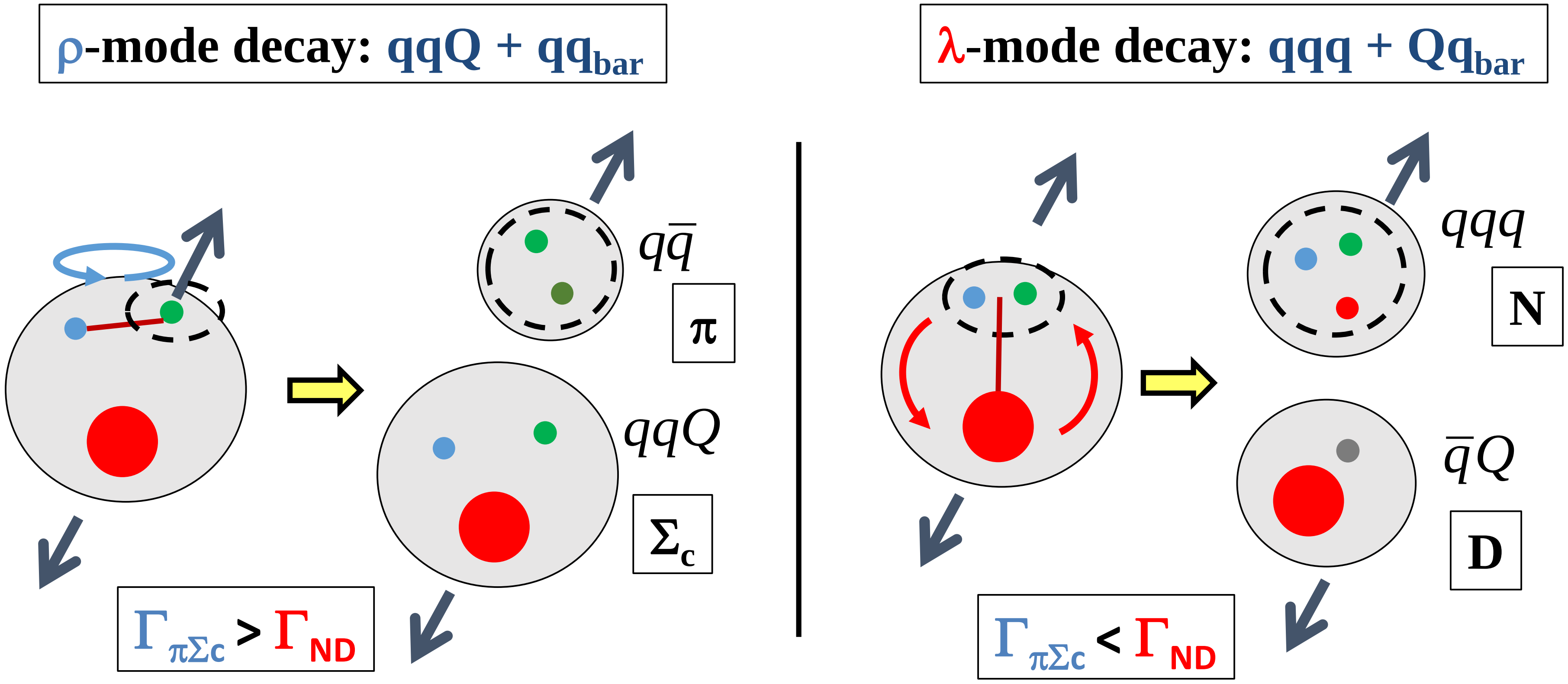




∗ Angular momentum transfer between diquark (*q-q*) and charm quark

S.H. Kim, A. Hosaka, H.C. Kim, H. Noumi, K. Shirotori
Prog. Theor. Exp. Phys. 103D01 (2014).

Decay property



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

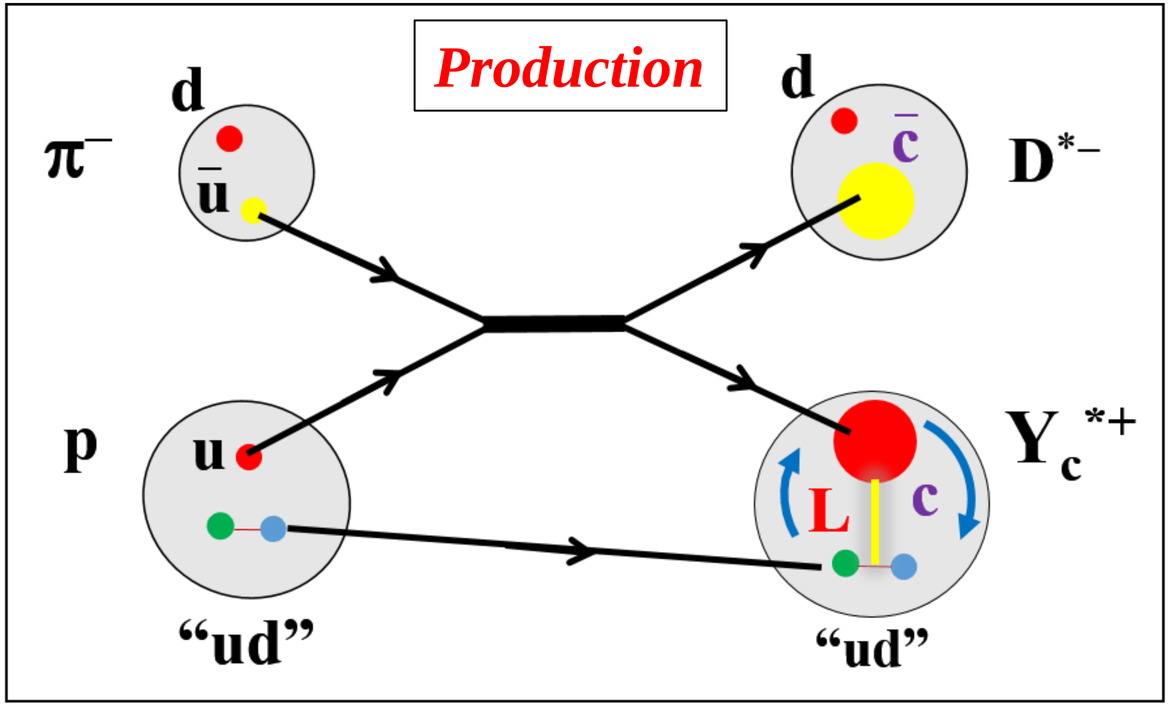
⇒ Absolute value of branching ratio by missing mass method

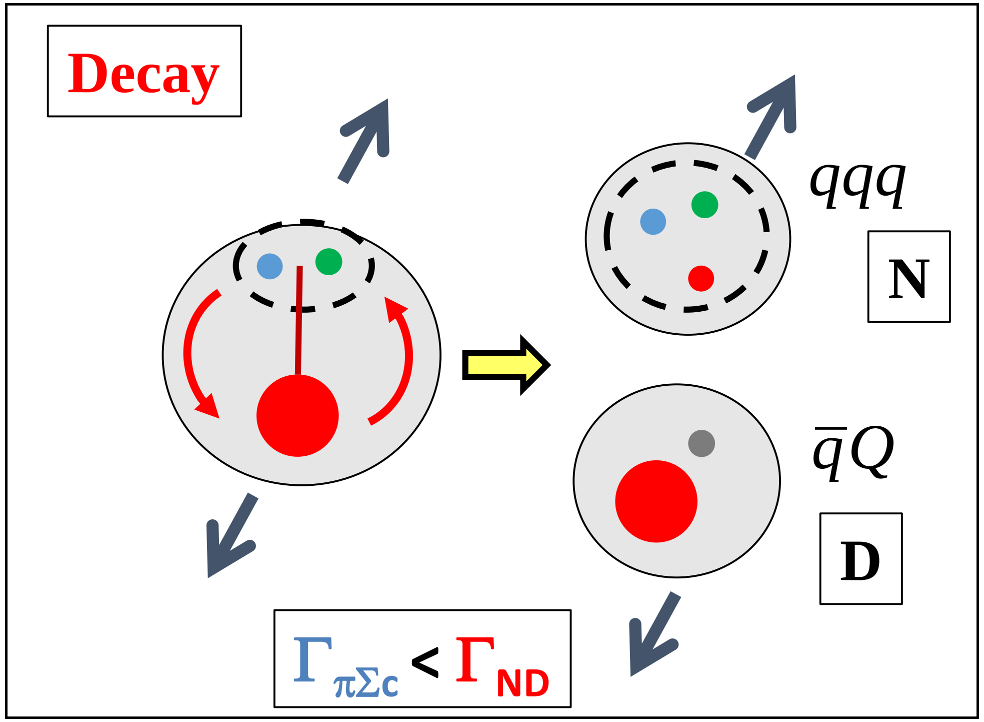
  - **Compliment study with high-energy experiments**

Spectroscopy with heavy quark

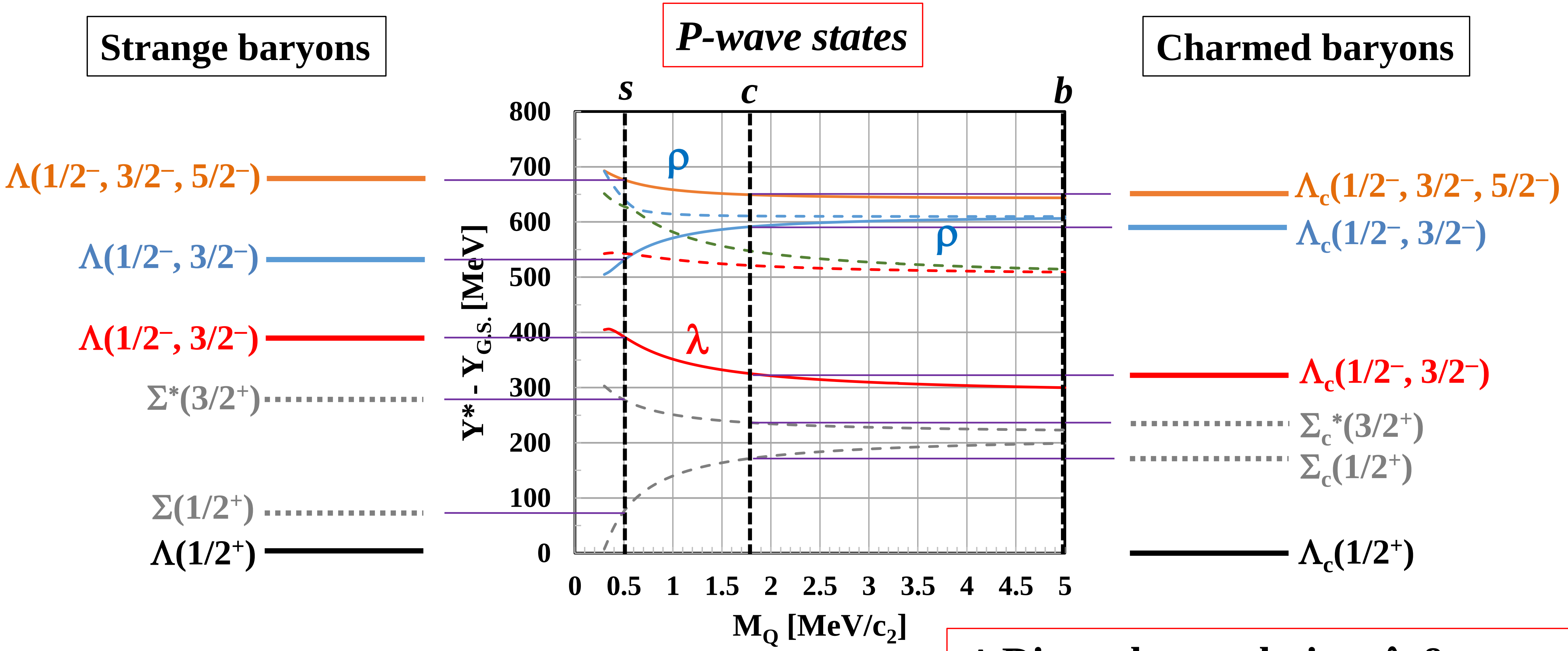
- **Clear distinction by separating effects from one quark**
  - **Systematic study**

- **Charmed baryon spectroscopy: To understand role of diquark correlation**
  - **Dynamical information: Production rates & Decay branching ratios**





Excitation spectrum: *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))

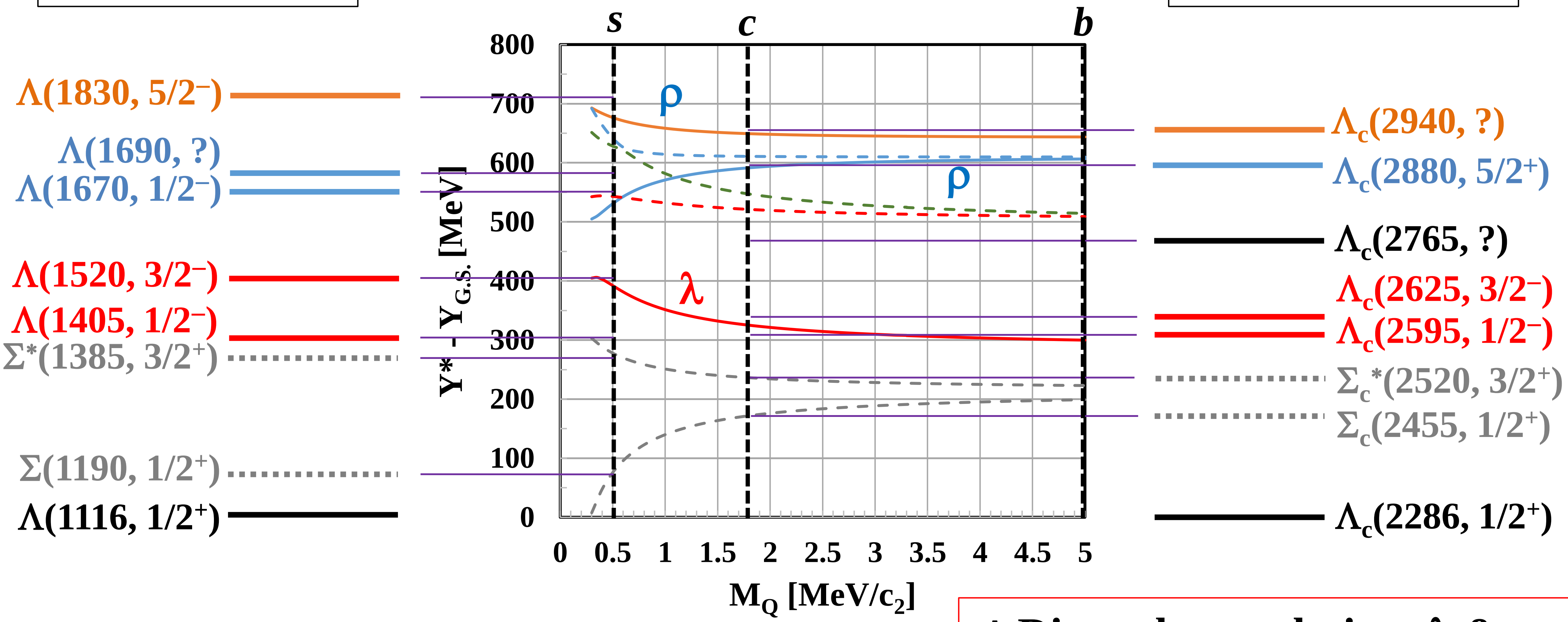
∗ Diquark correlation: λ & ρ

▪Heavy quark sector (charm)

⇒ Light quark sectors (u, d, s)

Excitation spectrum: *q-q* + Q system

Strange baryons | *P-wave states* | Charmed baryons



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

▪Heavy quark sector (charm)

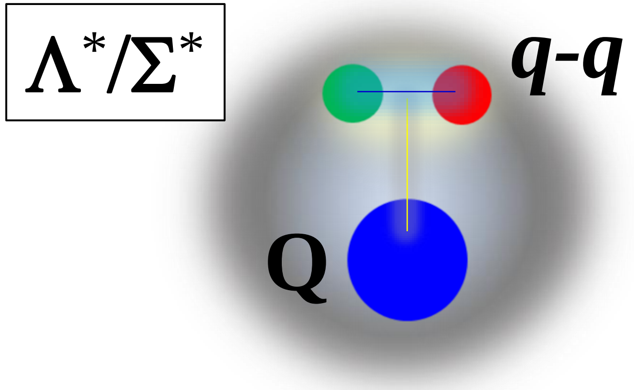
⇒ Light quark sectors (u, d, s)

Strange baryon systems

- Λ^* / Σ^* : *q-q* + Q system

⇒ Systematics with charmed baryon

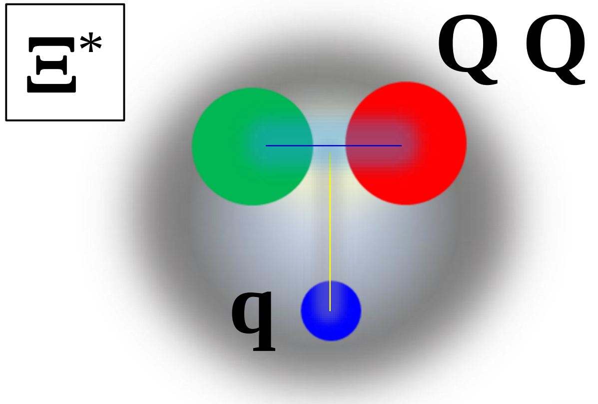
  - Production rate: λ and ρ selection
  - Decay branching ratio



- Ξ^* : q + QQ system

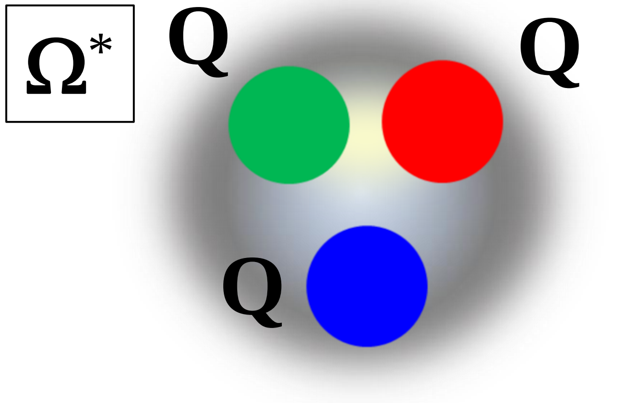
⇒ Excitation with two heavy quarks

  - Interchange of λ and ρ modes



- Ω^* : QQQ system

⇒ Same weight of three heavy quarks



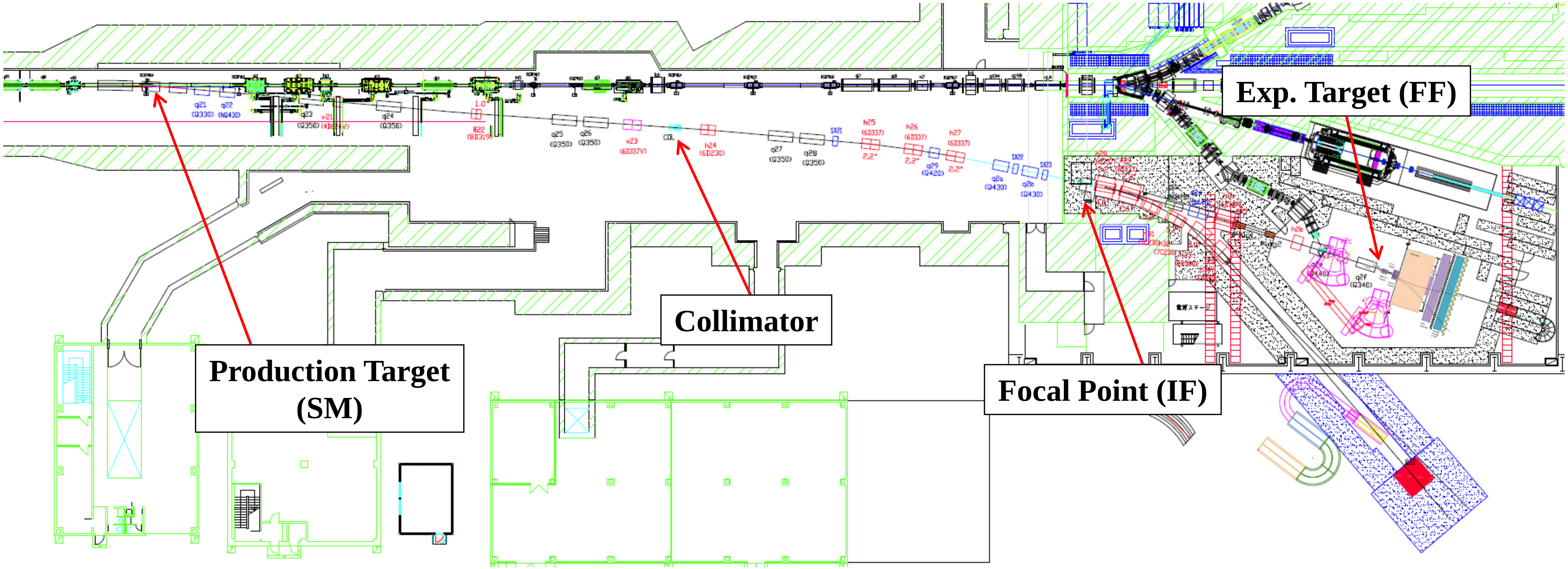
∗ Spectroscopy by high-momentum K^- beam

  - Several GeV/c beam
  - Poor data of Ξ and Ω states
  - Exotic states

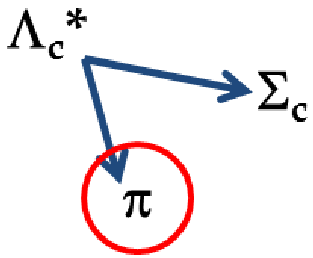
⇒ Systematic measurement is necessary.

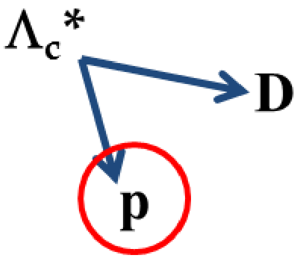
High-momentum beam line for 2^{ndary} beam

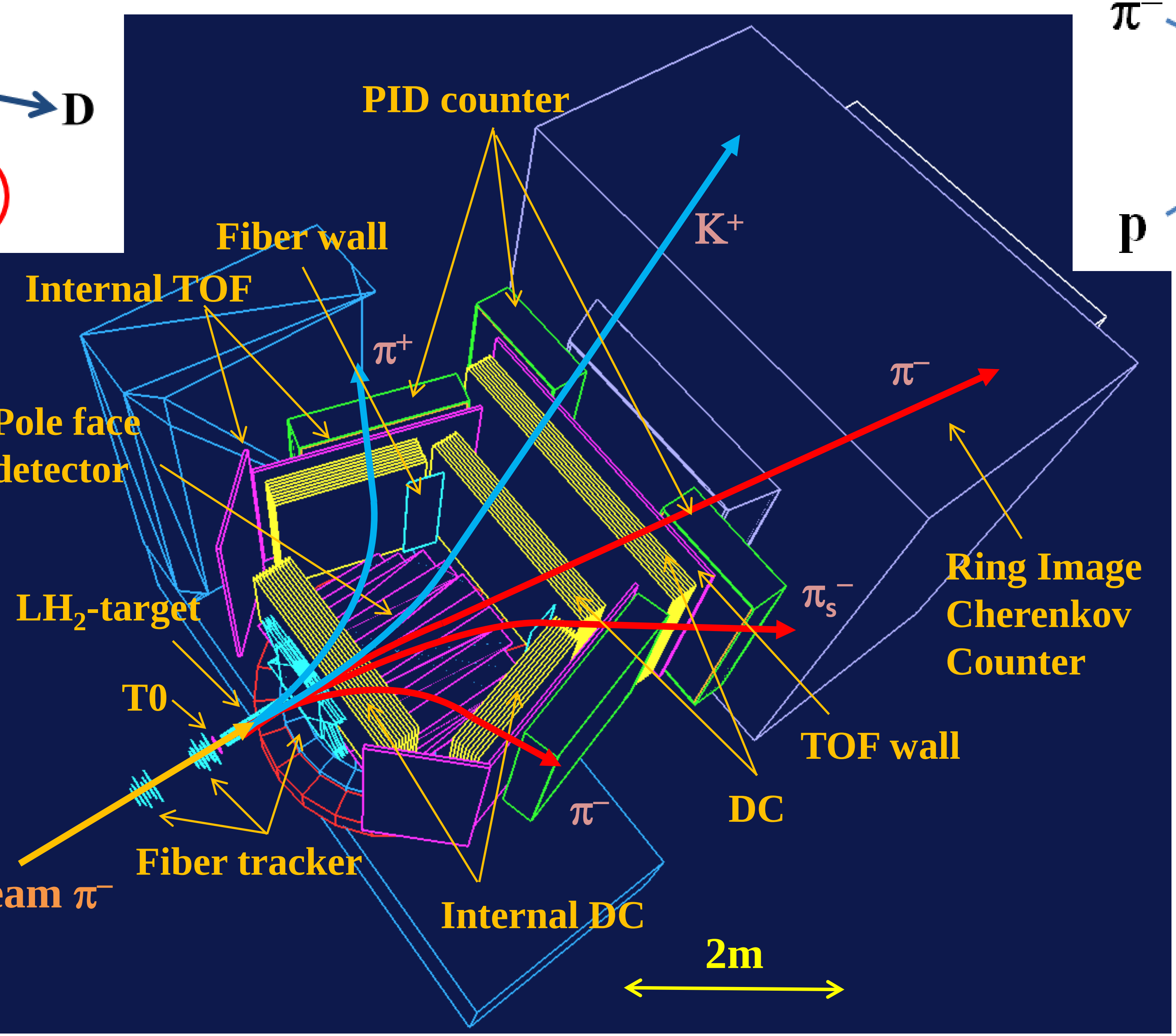
- **High-intensity** beam: **> 10^7 Hz** π (> 10^5 Hz K/p_{bar}) up to 20 GeV/c
  - Unseparated beam: π/K/p_{bar}
- **High-resolution** beam: **Δp/p ~ 0.1%(rms)**
  - Momentum dispersive optics method

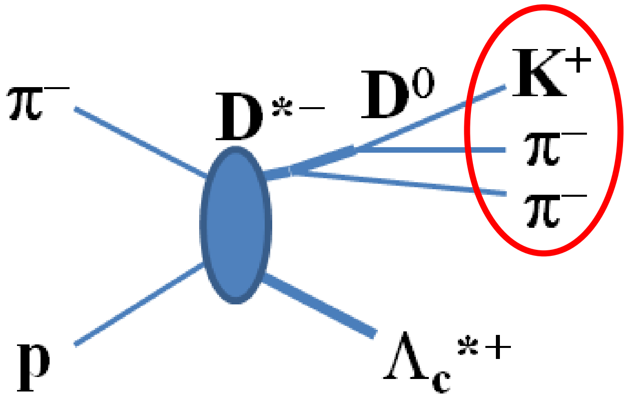


Charmed baryon spectrometer

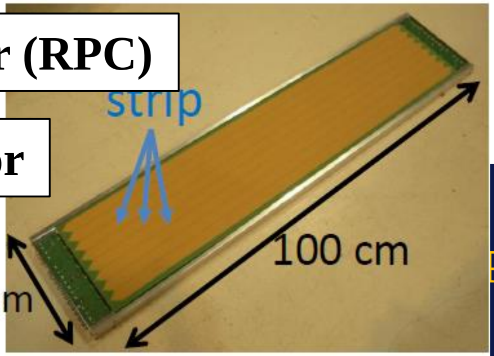




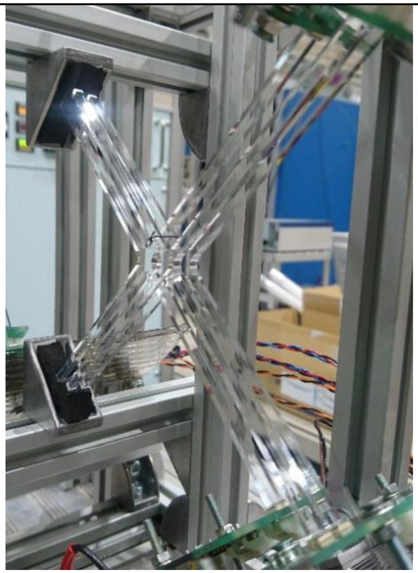




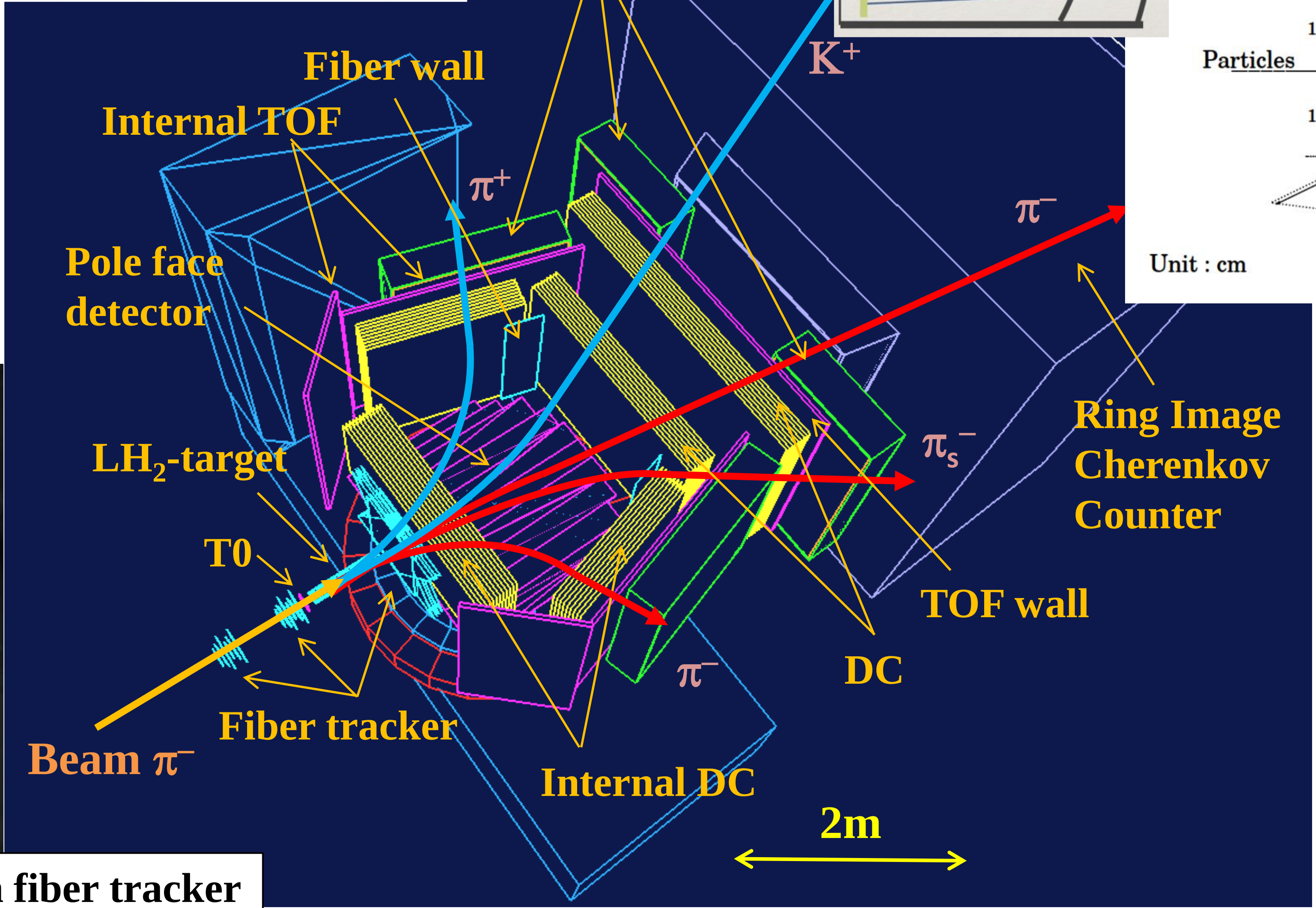
Resistive Plate Chamber (RPC)



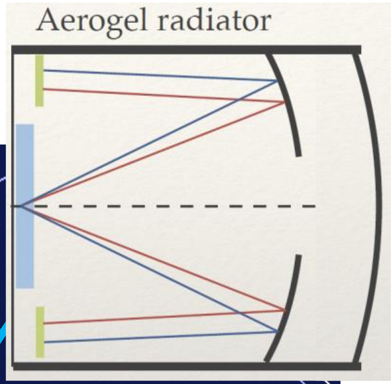
Cherenkov timing detector



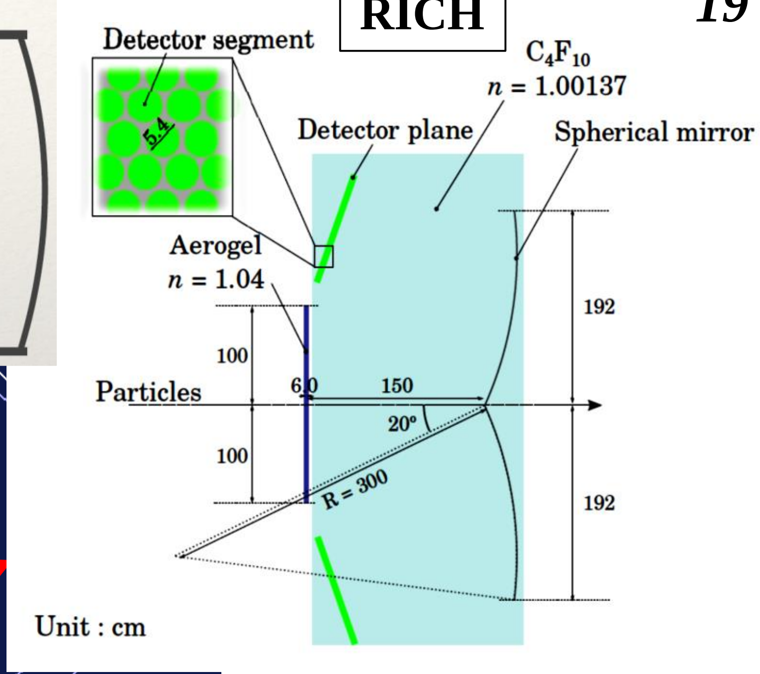
Scintillation fiber tracker



Beam RICH

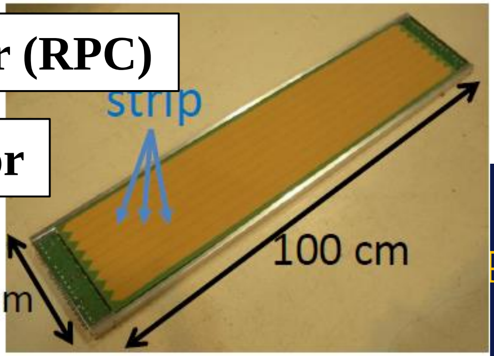


RICH



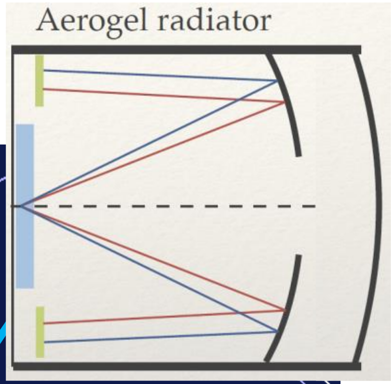
Barrel Drift Chamber

Resistive Plate Chamber (RPC)

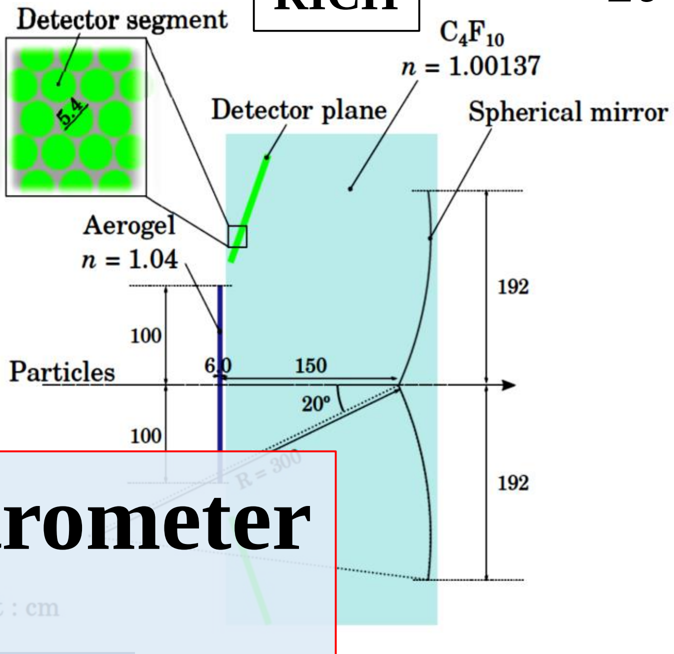


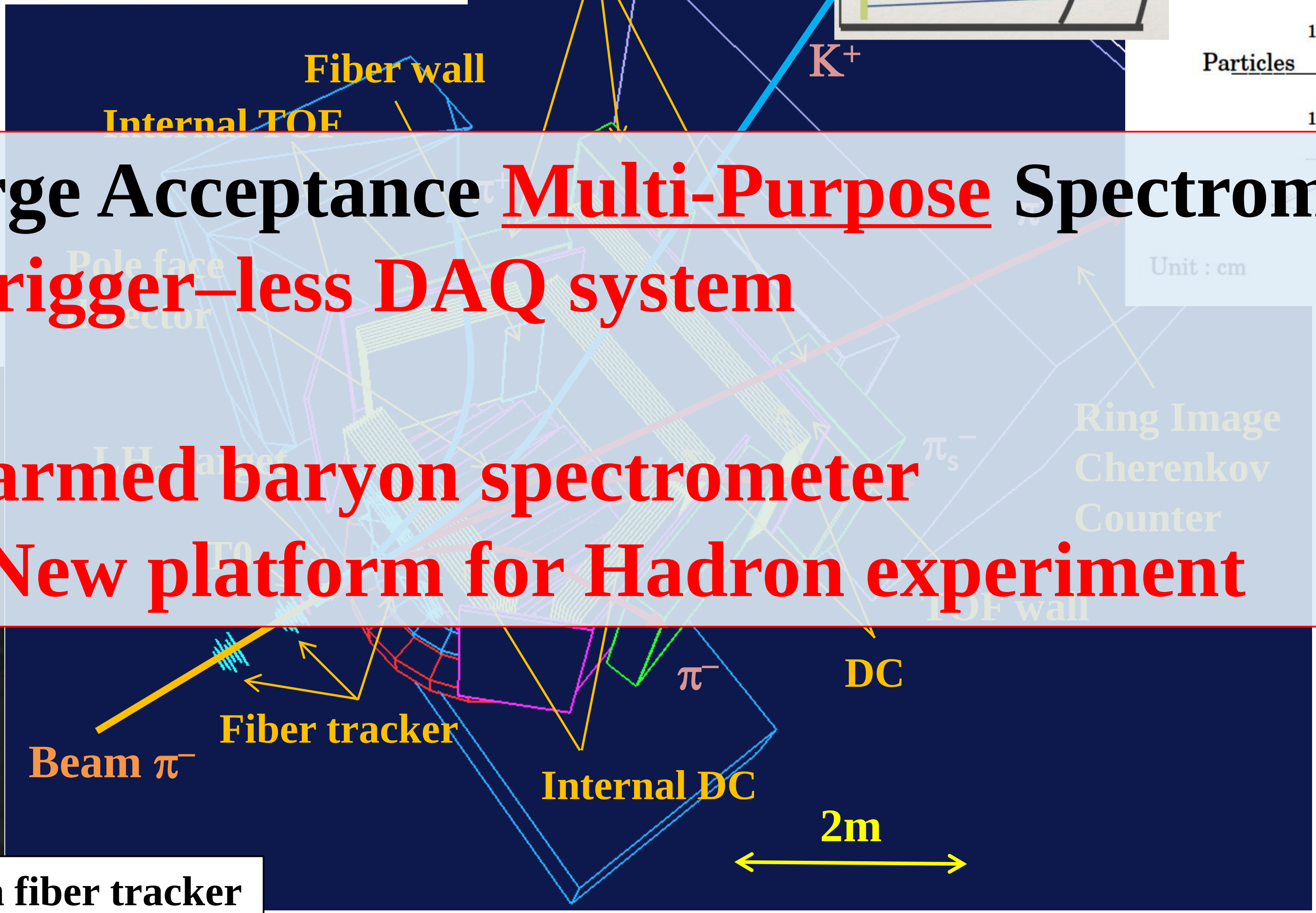
Cherenkov timing detector

Beam RICH



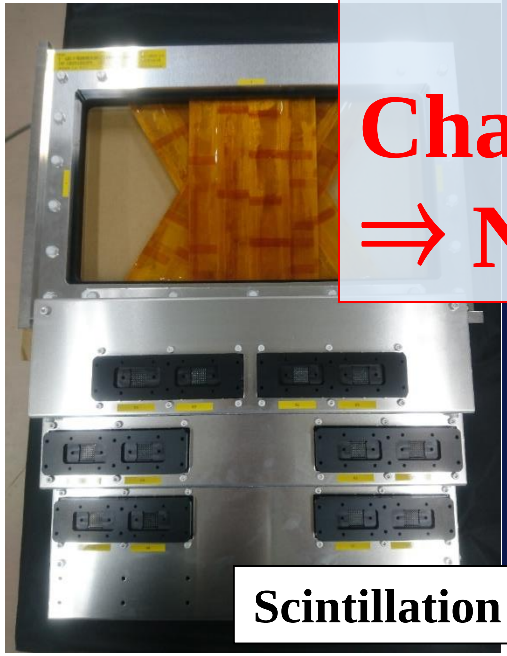
RICH





Large Acceptance Multi-Purpose Spectrometer
+ Trigger–less DAQ system

Charmed baryon spectrometer
⇒ New platform for Hadron experiment



Scintillation fiber tracker

Barrel Drift Chamber

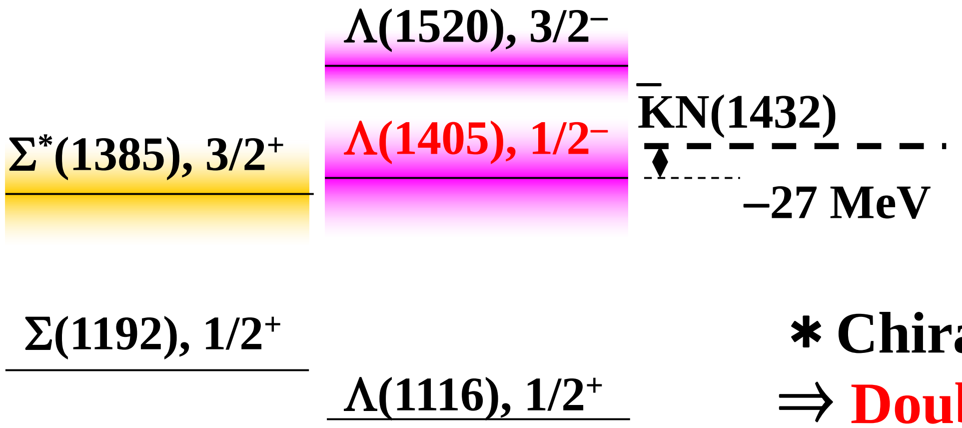
Hadron molecular state

Study of Λ(1405)

J-PARC E31 experiment at K1.8BR

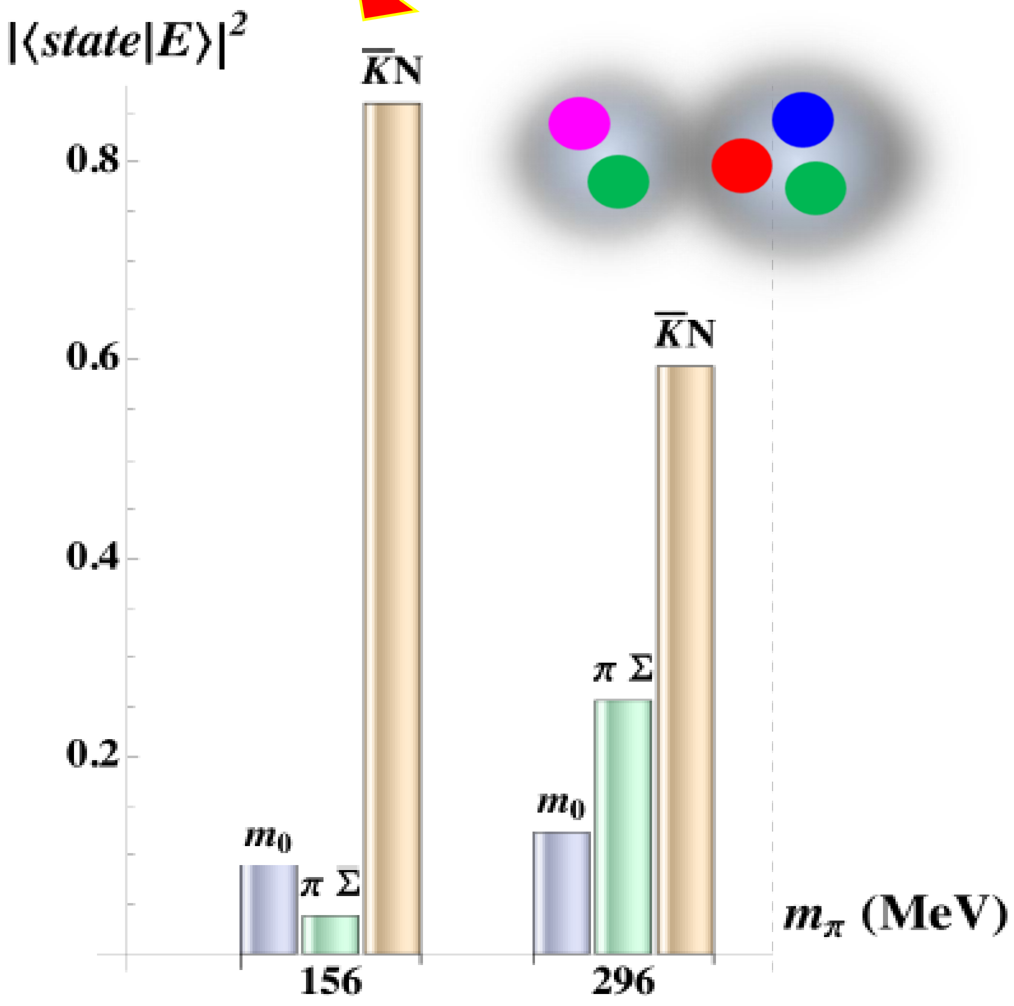
Λ(1405): Lightest in negative parity baryons

* $J^P = 1/2^-$, I = 0, $M_{\Lambda(1405)} < M_{KbarN}$



LQCD: $K_{bar}N$ molecule

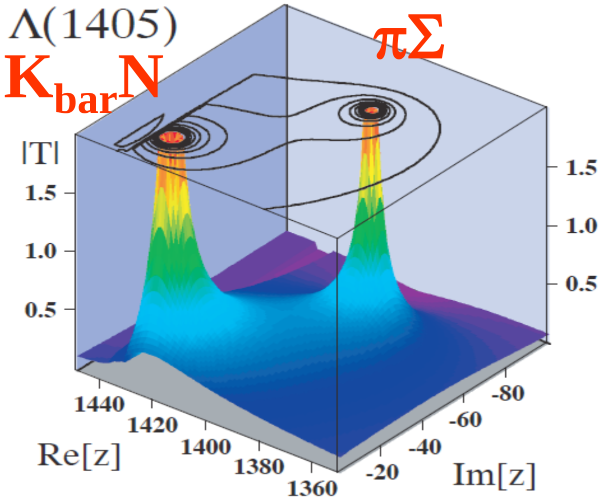
PRL114, 132002 (2015)



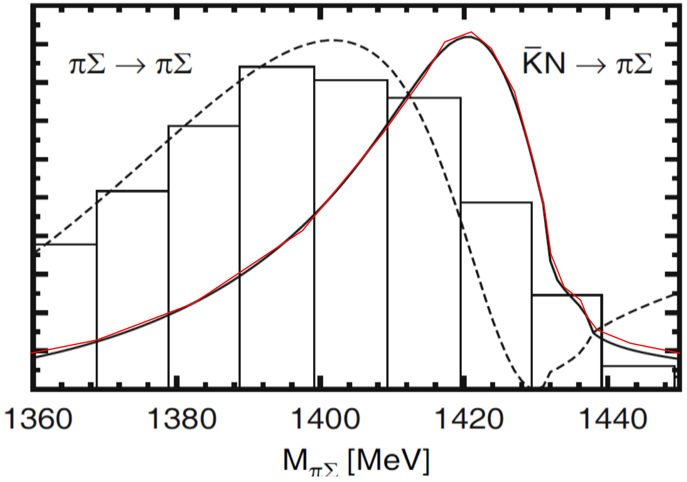
* Chiral Unitary Model

⇒ **Double pole structure**

· $K_{bar}N$ & $\pi\Sigma$



ChU model, T. Hyodo

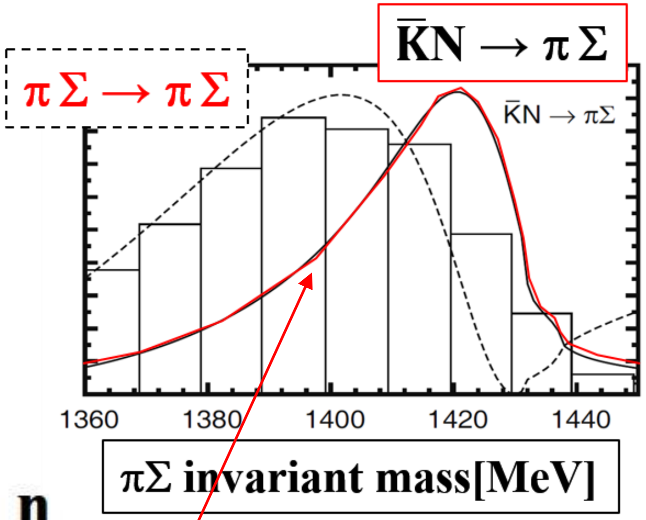


D. Jido et al., NPA725, 181 (2003)

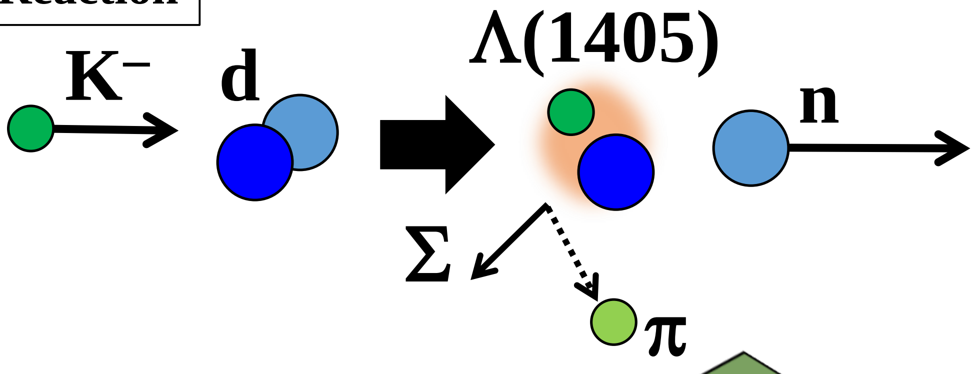
$K_{bar}N$ scattering below the $K_{bar}N$ threshold

- **S-wave $K_{bar}N \rightarrow \pi\Sigma$ scattering below the $K_{bar}N$ threshold**
  - d(K^-,n)$\pi\Sigma$ at a forward angle of n: 1 GeV/c K^- beam

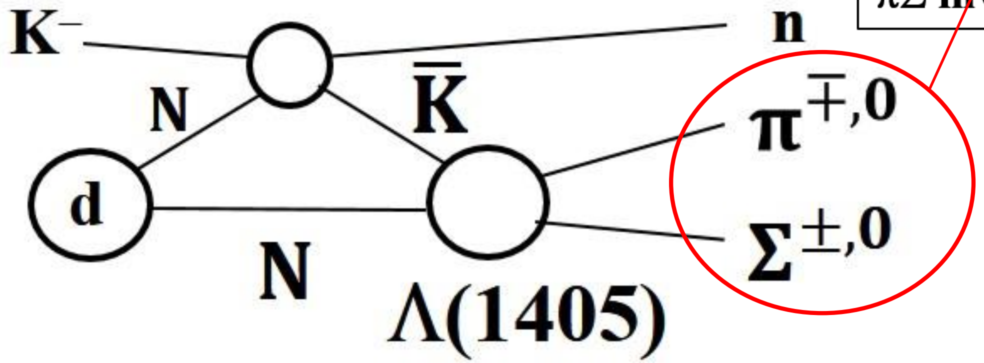
⇒ **Decomposition of all I = 0 and 1 amplitudes**



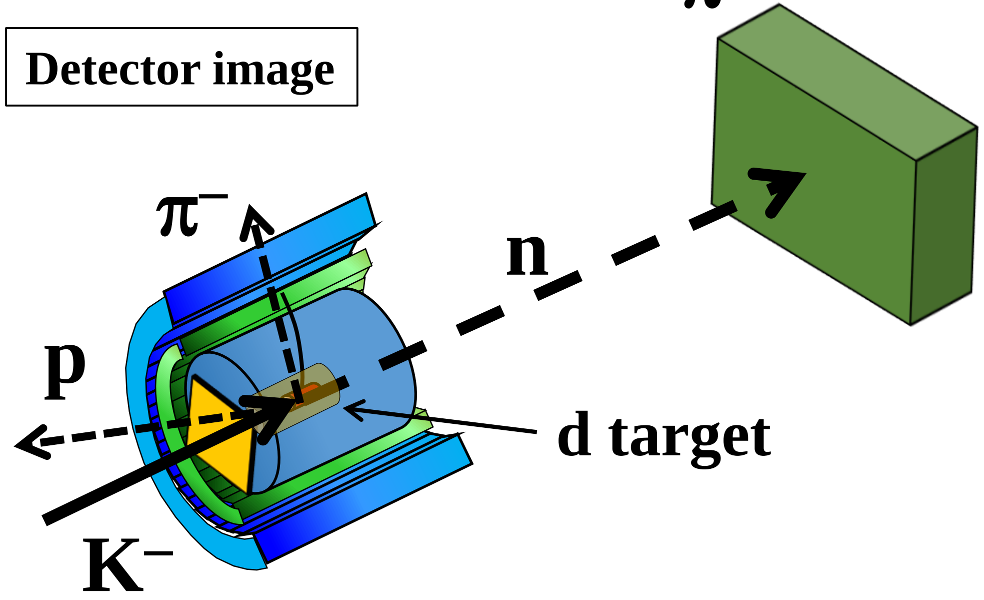
Reaction



Reaction diagram



Detector image

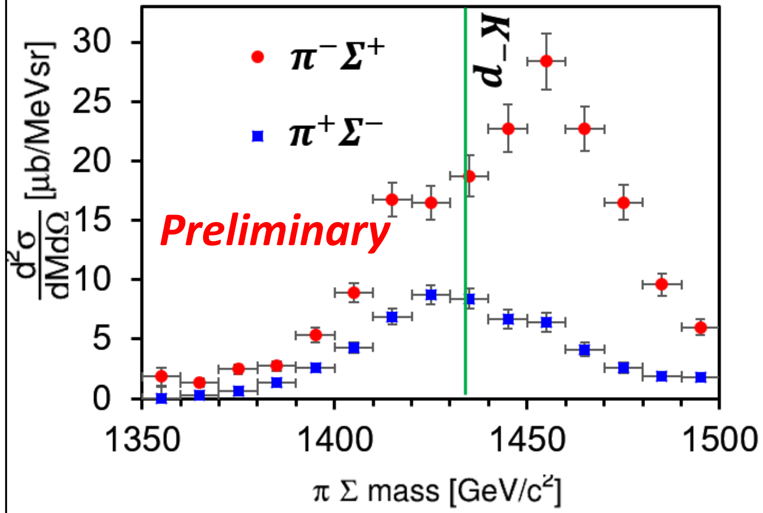


$\pi^{\pm}\Sigma^{\mp}$	I=0, 1	$\Lambda(1405)$ (I=0, S wave), non-resonant[I=0/1] ($\Sigma(1385)$ (I=1, P wave) to be suppressed)
$\pi^-\Sigma^0$ [$\pi^-\Lambda$]	I=1	Non-resonant ($\Sigma(1385)$ to be suppressed) d(K^-, p)$\pi^-\Sigma^0$ [$\pi^-\Lambda$]
$\pi^0\Sigma^0$	I=0	$\Lambda(1405)$ (I=0, S wave), non-resonant

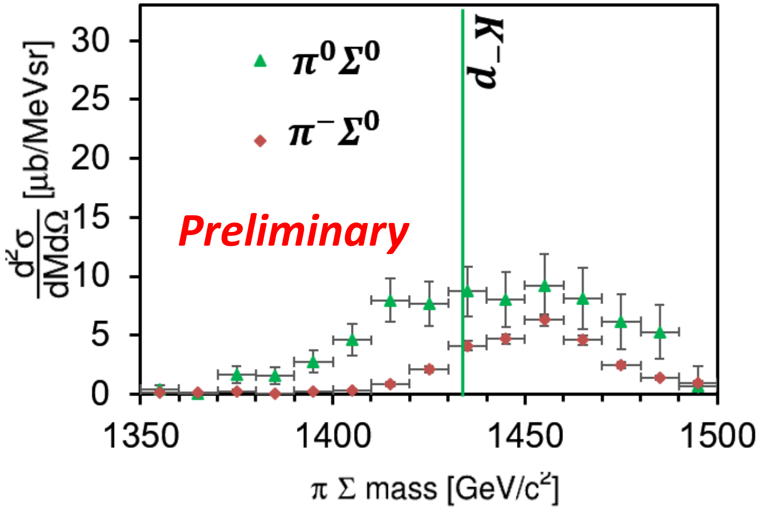
Experimental results: Cross section of πΣ modes

Cross sections of each πΣ mode

$\pi^+\Sigma^-/\pi^-\Sigma^+\ (I=0,1)$



$\pi^-\Sigma^0(I=1)$



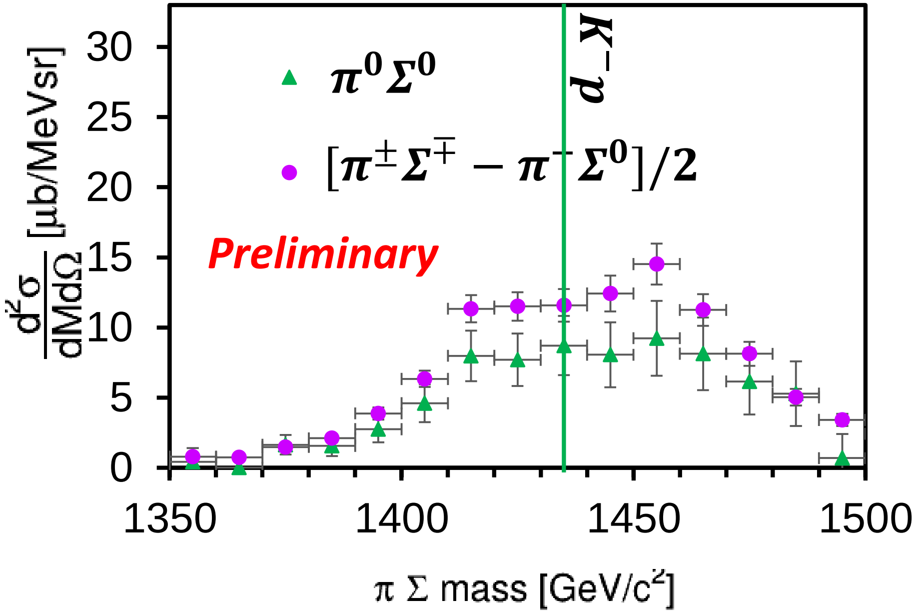
$$\frac{d\sigma}{d\Omega}(\pi^-\Sigma^+/\pi^+\Sigma^-) \propto \frac{1}{3}|f_{I=0}|^2 + \frac{1}{2}|f_{I=1}|^2 \pm \frac{\sqrt{6}}{3}Re(f_{I=0}f^*_{I=1})$$

$$\frac{d\sigma}{d\Omega}(\pi^0\Sigma^0) \propto \frac{1}{3}|f_{I=0}|^2$$

$$\frac{d\sigma}{d\Omega}(\pi^-\Sigma^0) \propto |f_{I=1}|^2$$

∗ I = 0 amplitude seems dominant.

$\frac{[\pi^\pm\Sigma^\mp - \pi^-\Sigma^0]}{2}$ vs $\pi^0\Sigma^0(I=0)$

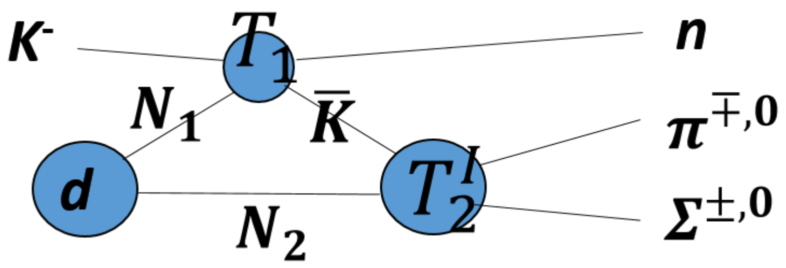


$$\frac{d\sigma}{d\Omega}([\pi^\pm\Sigma^\mp - \pi^-\Sigma^0]/2) \propto \frac{1}{3}|f_{I=0}|^2$$

$$\frac{d\sigma}{d\Omega}(\pi^0\Sigma^0) \propto \frac{1}{3}|f_{I=0}|^2$$

To deduce scattering amplitude and extract pole position

- **2-step process**



$$\left.\frac{d\sigma}{dM_{\pi\Sigma}}\right|_{\theta_n=0} \sim \left|\langle n\pi\Sigma|T_2^I(\bar{K}N_2 \to \pi\Sigma)G_0T_1(K^-N_1 \to \bar{K}n)|K^-\Phi_d\rangle\right|^2$$

$$\sim \left|T_2^I(\bar{K}N \to \pi\Sigma)\right|^2 F_{\text{res}}(M_{\pi\Sigma})$$

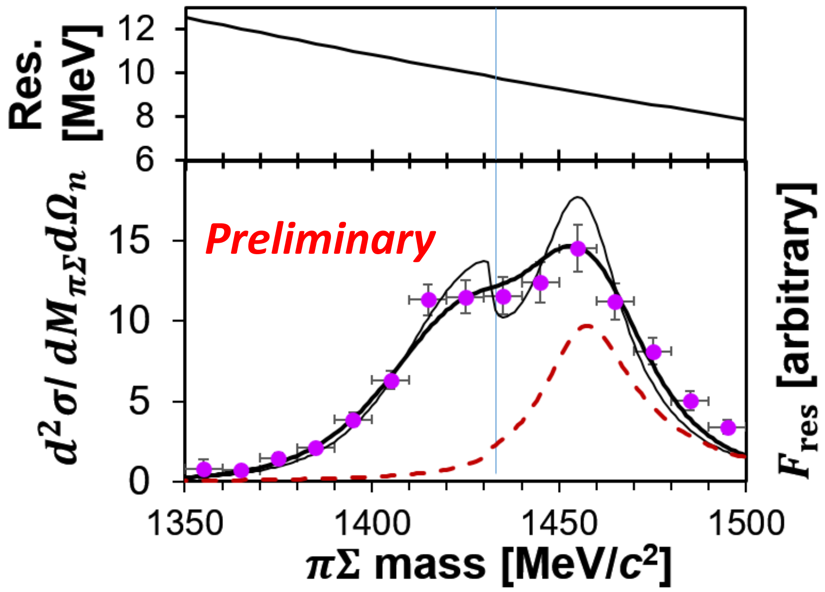
Factorization Approximation

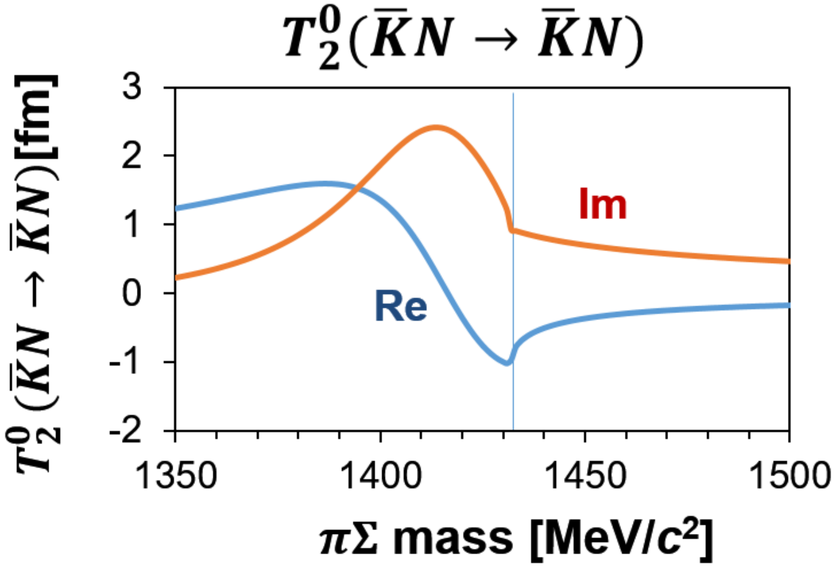
$$F_{res}(M_{\pi\Sigma}) \sim \left|\int_0^\infty dq_{N_2}^3\, T_1 \frac{1}{E_{\bar{K}} - E_{\bar{K}}(q_{\bar{K}}) + i\epsilon}\Phi_d(q_{N_2})\right|^2, q_{\bar{K}} + q_{N_2} = q_{\pi\Sigma}$$

$$\boxed{\left.\frac{d\sigma}{dM_{\pi\Sigma}}\right|_{\theta_n=0} \sim \left|T_2^I(\bar{K}N \to \pi\Sigma)\right|^2 F_{res}(M_{\pi\Sigma})}$$

Pole at ($1417^{+6}_{-7} - i27^{+5}_{-9}$) MeV/c^2

＊Seems consistent with higher pole by the Chiral Unitary Model based calculations





Related subjects and experiments

- **High-p beam line: Beam delivered from 2020 February !**
  - **Measurement of mass modification of ϕ meson: J-PARC E16**

$\Rightarrow$ 2^{ndary} beam line and heavy baryon spectroscopy (charm, Ξ&Ω)

- **Studies of Λ(1405)**
  - **K^- beam @ J-PARC: Production angle dependence**
  - **High-p beam @ J-PARC: Quark counting rule**
  - **γ beam @ LEPS2: Polarized beam**

- **K^-pp state**
  - **Deeply bound state due to help by strong attraction of $K_{bar}N$(Λ(1405))**
  - **Production by K^- and γ beam: Experiments are planned at J-PARC & LEPS2.**

- **H-Dibaryon search: J-PARC E42**
  - **By (K^-, K^+) reaction on nuclear target**

- **π N $\rightarrow$ π π N experiment: J-PARC E45**
  - **Basics data for N^*/Δ^* resonances**

****Hadron spectroscopy***
By Hadronic beams @ J-PARC
and Photon beam @ LEPS, ELPH

Summary

- **Motivations**
  - **Study of excited states: Effective degree of freedoms of hadron**
    - **Diquark correlation and hadron molecular**
  - **Spectroscopy of charmed baryon and hyperon at J-PARC**
    - **To understand role of diquark correlation**
    by dynamical information: Production rates & Decay branching ratios
  - **Systematic measurement: Charm, strangeness = –1, –2, –3**

- **High-p beam line and multi-purpose spectrometer**
  - **Beam line from Feb. 2020 ⇒ 2ndary beam for hadron spectroscopy**
  - **Spectrometer system for many physics reactions: Trigger-less DAQ**

- **Study of hadron molecule state: Λ(1405)**
  - **Cross section of all πΣ modes**
  ⇒ $K_{bar}N$ scattering amplitude to extract pole ⇒ ($1417^{+6}_{-7} - i27^{+5}_{-9}$) MeV/$c^2$

- **Related studies for hadron physics**
  ＊Hadronic and photon beams @ J-PARC, LEPS, ELPH