Investigation of hadron effective degrees of freedom from charmed baryon spectroscopy experiment at J-PARC

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for the E50 collaboration

Research Center for Nuclear Physics (RCNP)
Osaka University

第8回クラスター階層領域研究会

10th February 2023

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  - **Study of excited states: Effective degrees of freedom**
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- **Beam line and Spectrometer system**
  - **π20 beam line**
  - **Detector contraction and DAQ system preparation status**

- **Summary**

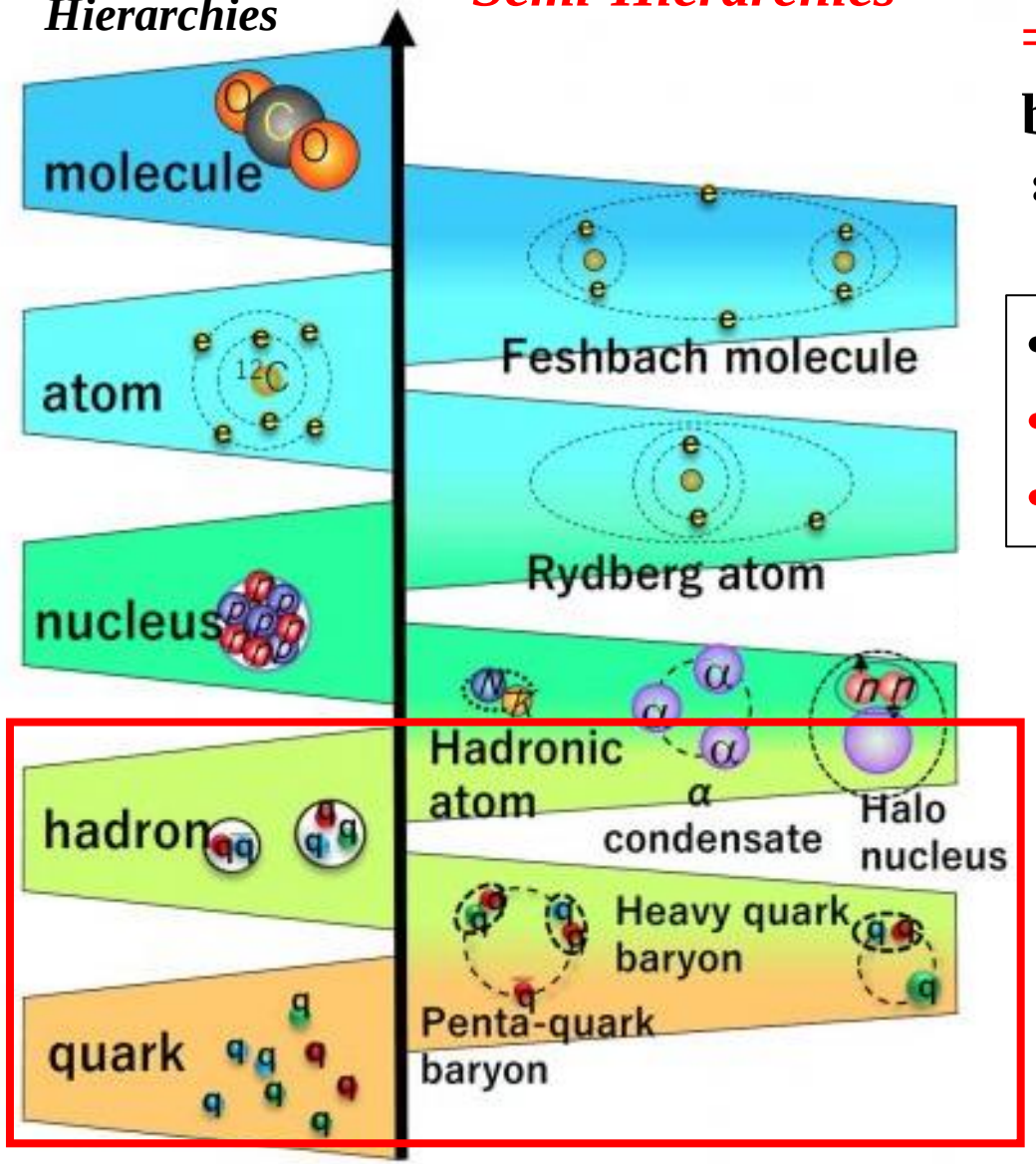
Introduction

Charmed baryon spectroscopy experiment

How hadrons are originated by quark and gluon ?

Conventional Hierarchies

Semi-Hierarchies



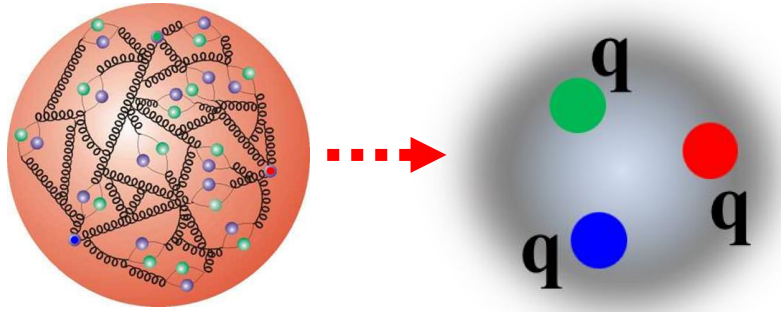
- Understand hadrons by **effective degrees of freedom**

⇒ **Semi-Hierarchies**

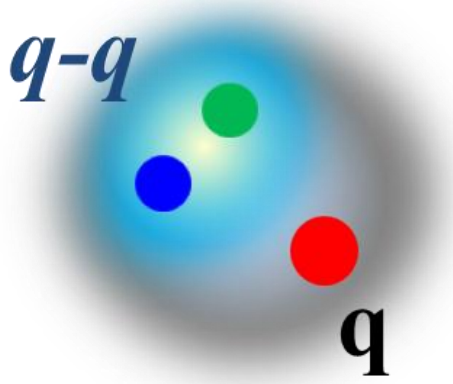
between **Hadron and Quark • Gluon (A02)**

∗ **J-PARC & LEPS2 projects**

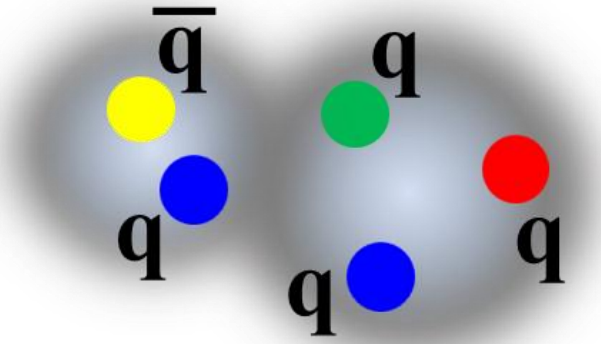
- Constituent quark
- Diquark
- Hadron molecule



Diquark

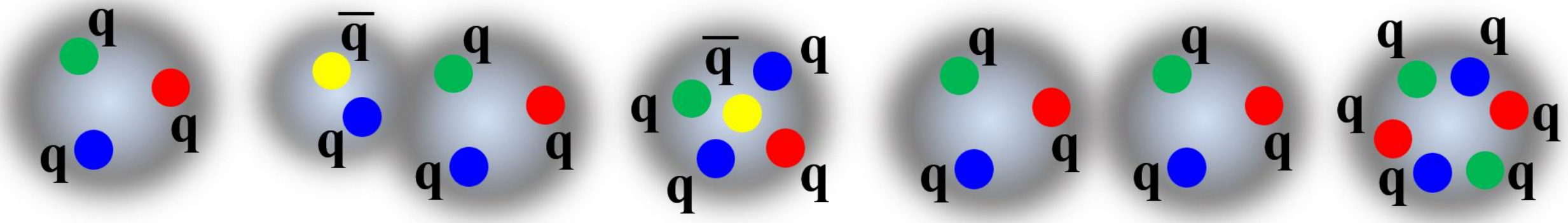


Hadron molecule



Understanding of excited state property

3q baryon | Meson-baryon (Molecule) | Pentaquark (Multi-quark) | Dibaryon (Molecule) | Dibaryon (Multi-quark)



∗ How Effective Degrees of Freedom (DoF) emerge ?

- Hadron molecule (Colorless = Hadron DoF) ⇒ Threshold region?
- Multi-quark (Colorful = Diquark/Gluon DoF) ⇒ ?

∗ Dynamics of Effective DoF

⇒ Investigation of baryon systems: Diqaurk from charmed baryon

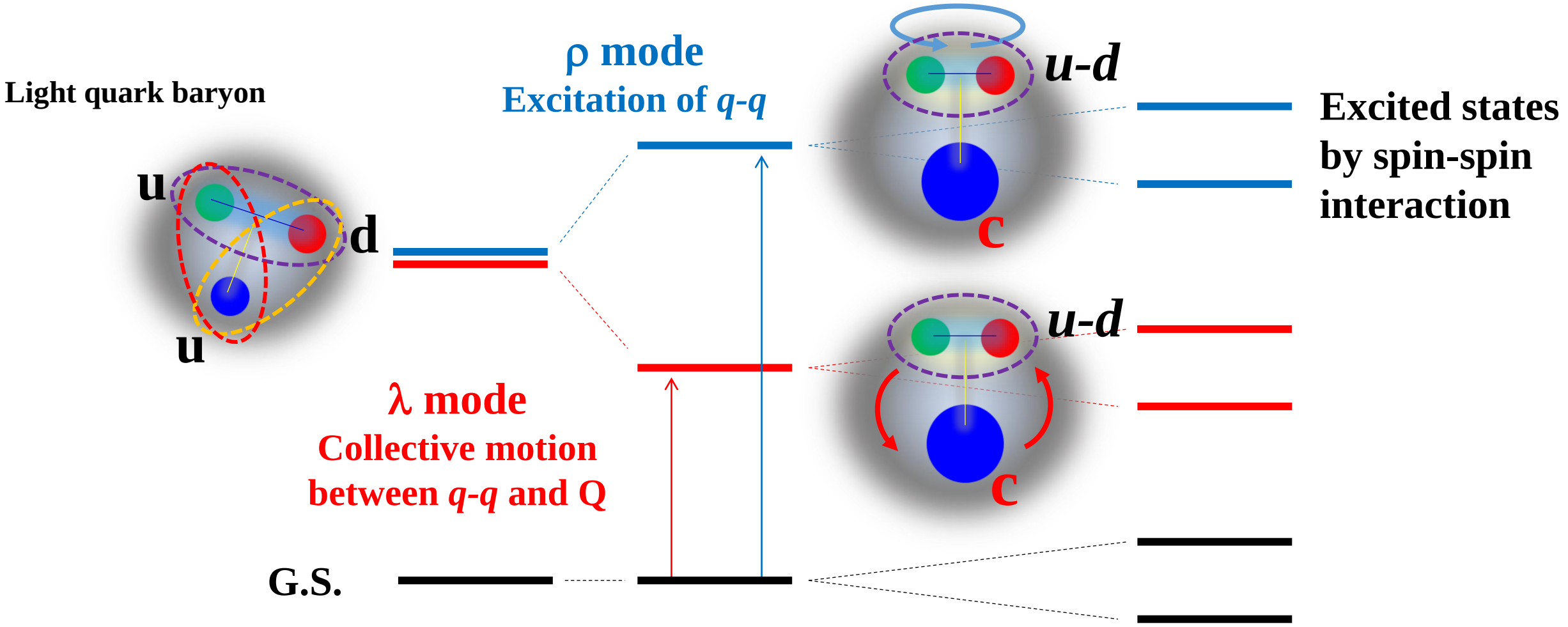
- Systematic measurements of excited states

Study of diquark correlation: J-PARC E50

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

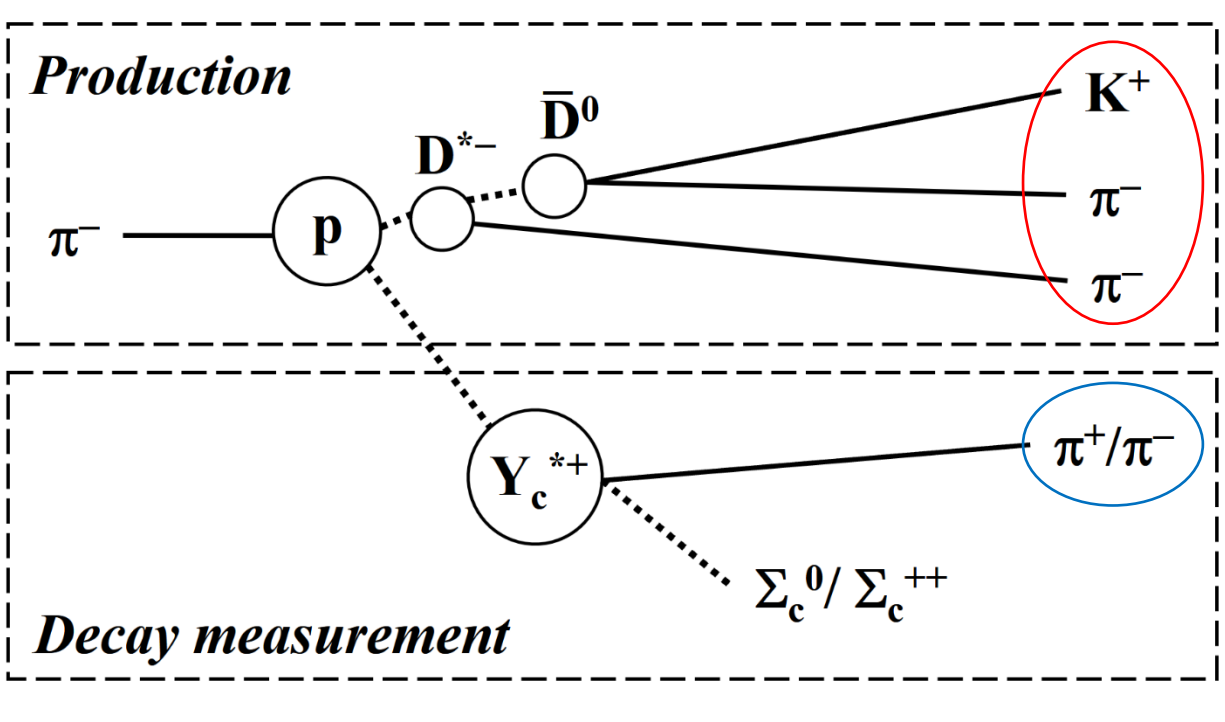
⇒ Diquark correlation: *q*-*q* isolated and develops

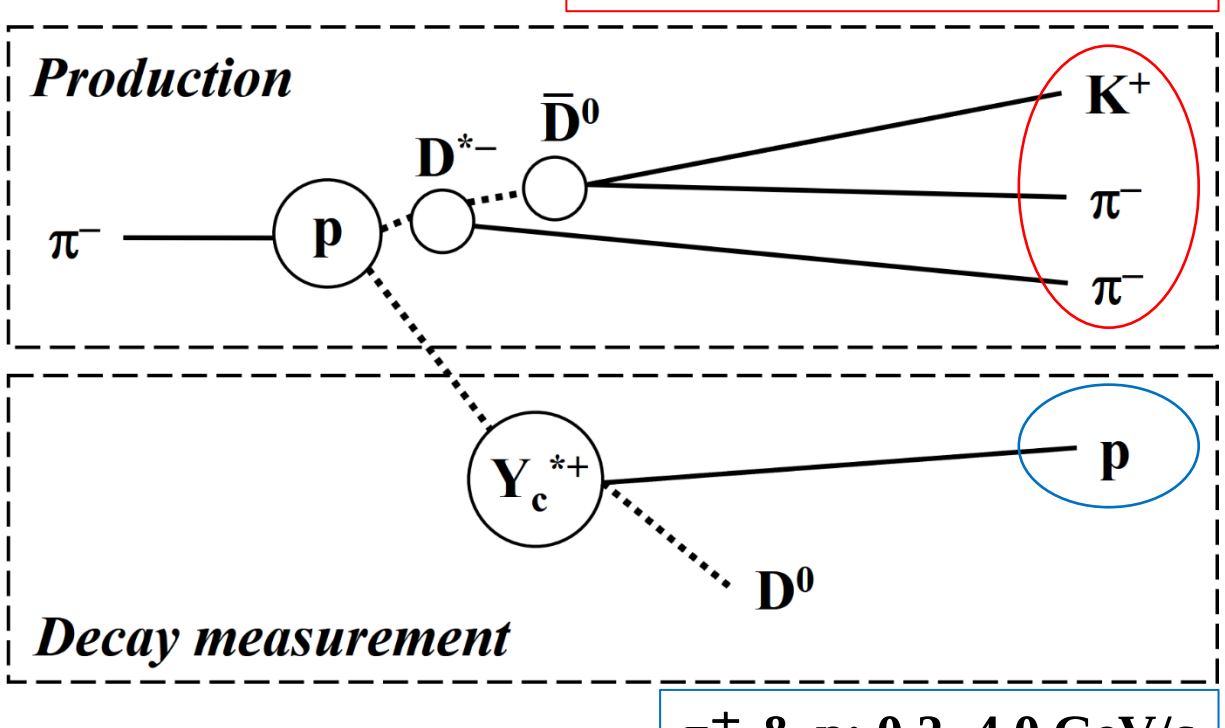
＊λ/ρ mode assignment: Production rates and absolute decay branching ratios



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

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

1) Missing mass spectroscopy: Y_c^{*+} mass (>1 GeV excited states)

- $D^{*-} \rightarrow \bar{D}^0 \pi_s^- \rightarrow K^+ \pi^- \pi_s^-$: $D^{*-} \rightarrow \bar{D}^0 \pi_s^-$ (67.7%), $\bar{D}^0 \rightarrow K^+ \pi^-$ (3.88%)

2) Decay measurement: Absolute B.R. and angular distribution

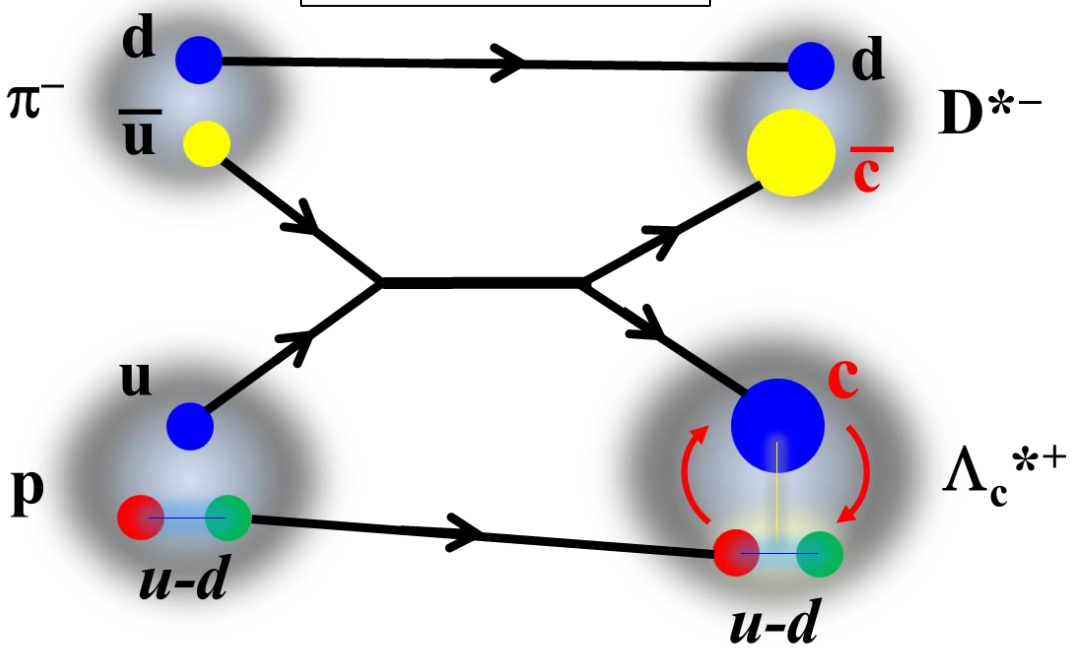
- Decay particles ($\pi^\pm$ & proton) from Y_c^*

Production rate by hadronic reaction

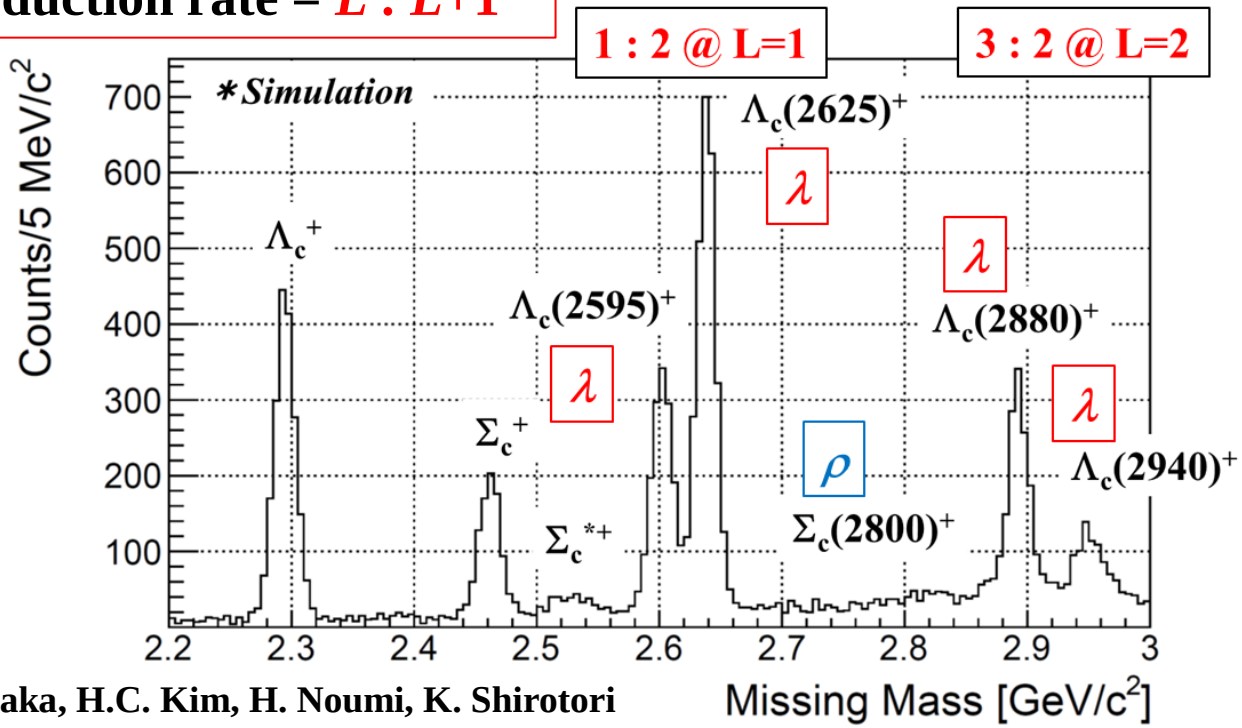
- $\pi^- + p \rightarrow D^{*-} + Y_c^{*+}$ reaction: **Missing mass method**
  - **Production cross section(0°): Overlap of wave function** → $R \sim \langle \varphi_f | \sqrt{2}\sigma_- \exp(i\vec{q}_{eff}\vec{r}) | \varphi_i \rangle$
  - **⇒ Sensitive to excitation modes**
  - **Large production rate of highly excited states** → $I_L \sim (q_{eff}/\alpha)^L \exp(-q_{eff}^2/\alpha^2)$

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

Reaction diagram



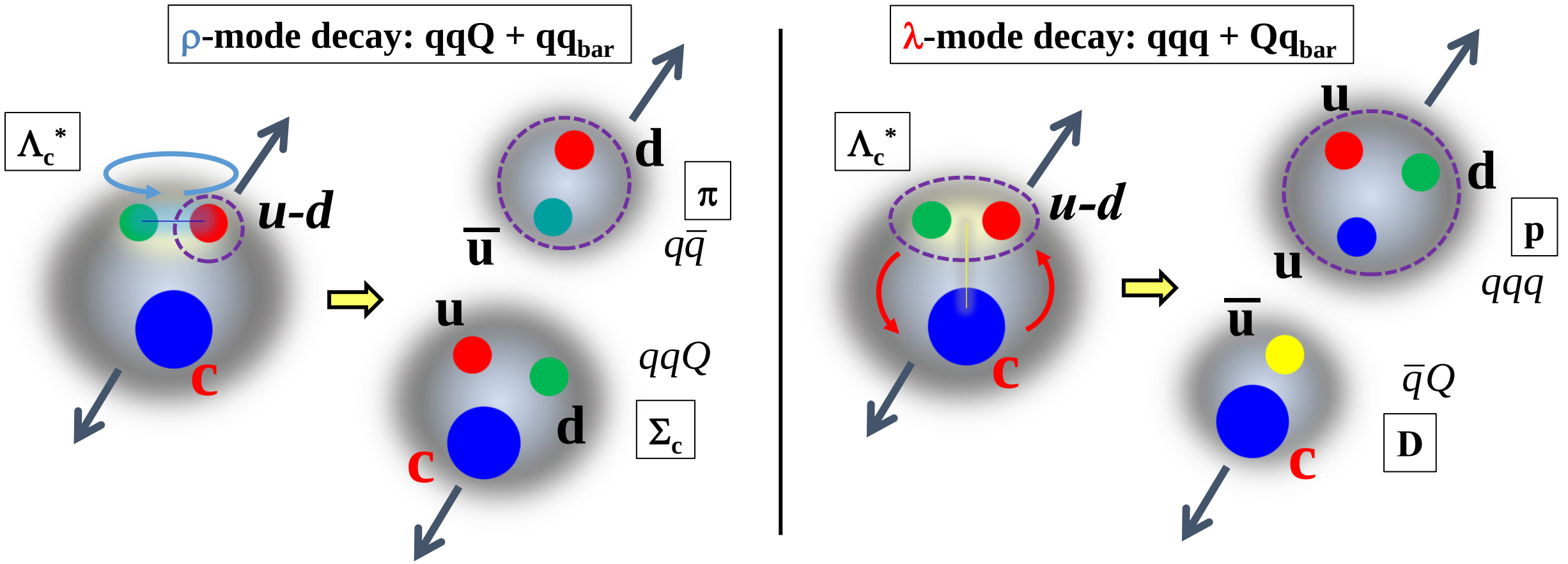
∗ HQ doublet (e.g. $1/2^-$, $3/2^-$)
⇒ Production rate = L : L+1



∗ 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 of charmed baryon

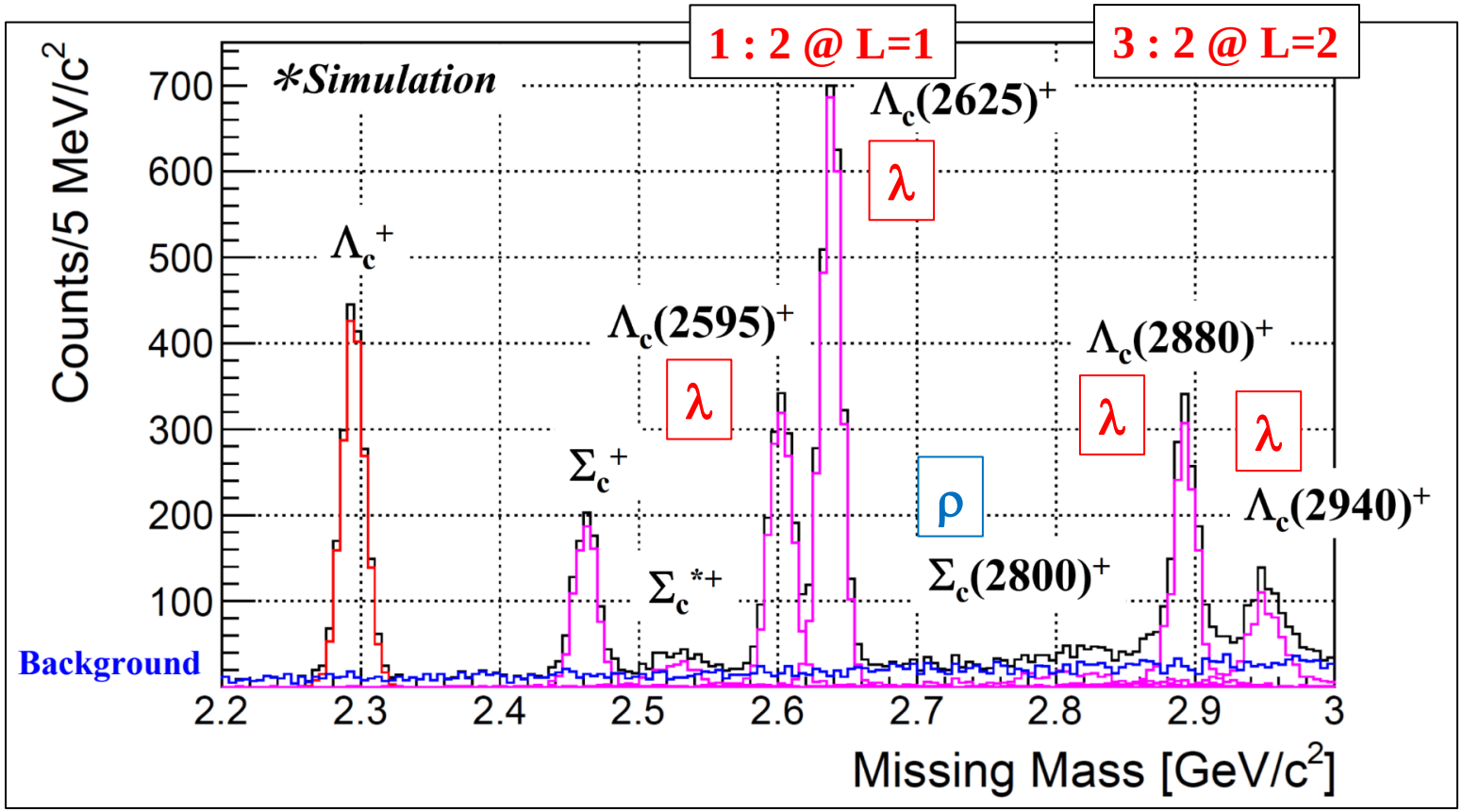


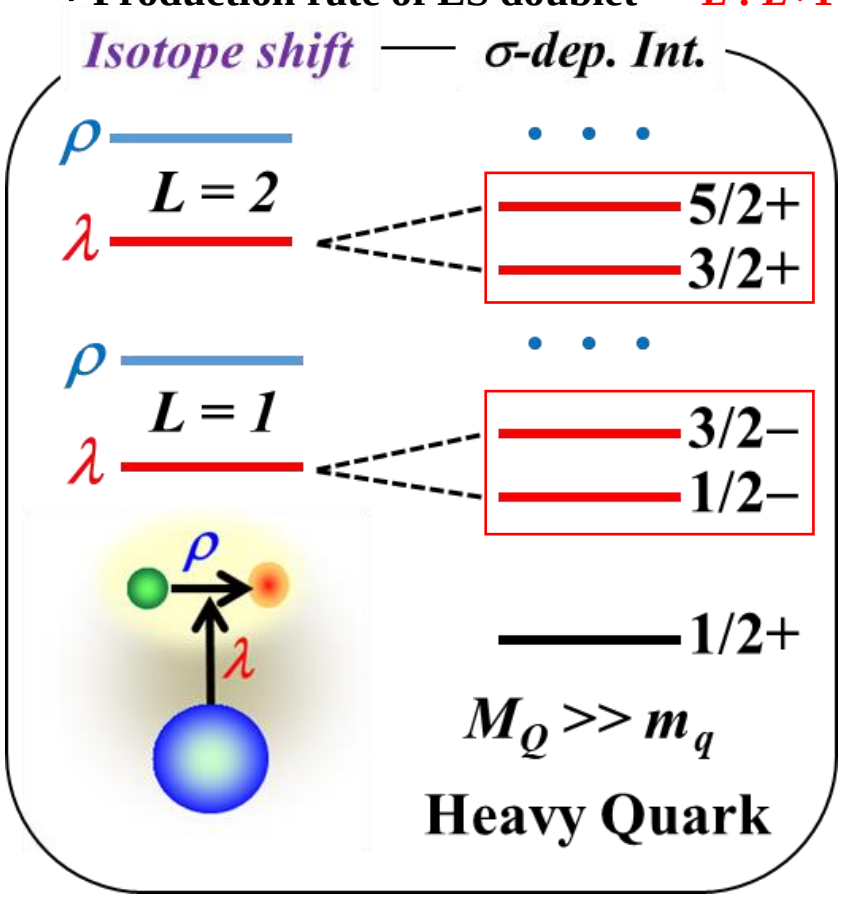
- **Decay measurement: $\Gamma_{\pi\Sigma c} \Leftrightarrow \Gamma_{pD}$ ($\pi^{-/+}$+ $\Sigma_c^{++/0} \Leftrightarrow$ p + D^0)**

⇒ Absolute value of branching ratios

- **Complementary to high-energy experiments**

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



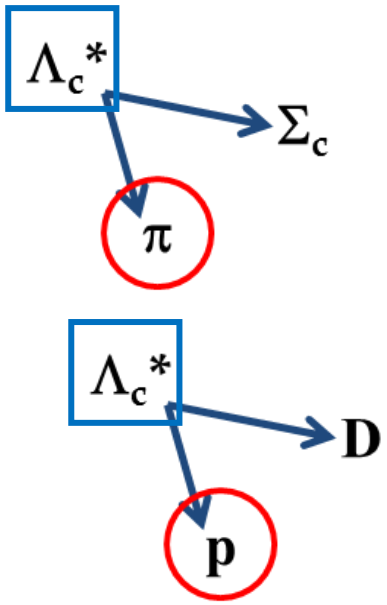


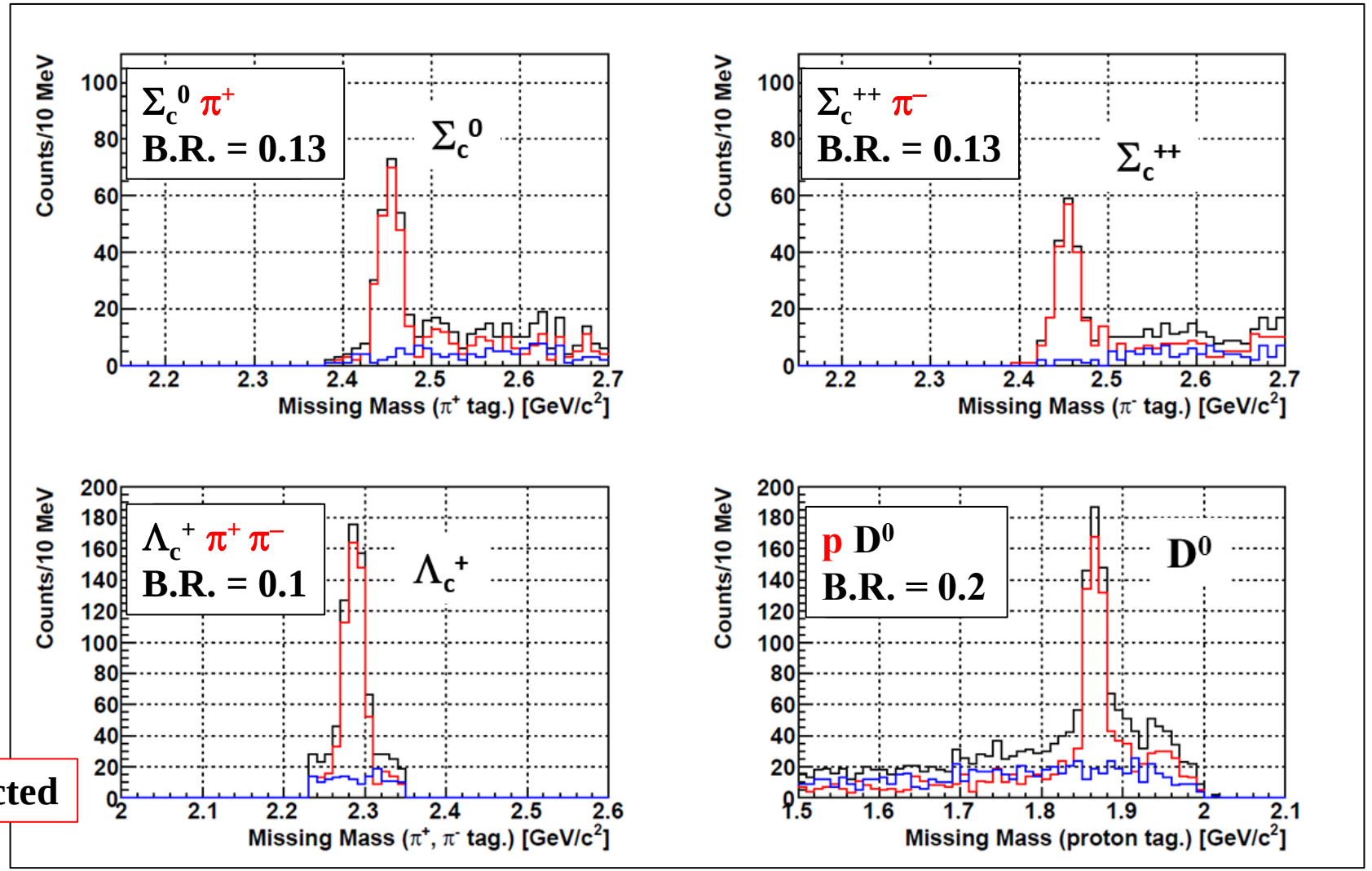
- **Known states in PDG and background by hadronic reaction code**

HQ doublet

- **Production rates ⇒ 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: $\Lambda_c(2940)^+ \to \Sigma_c^{++/0}\,\pi^{-/+}$ and p D^0





SUM
Signal
BG

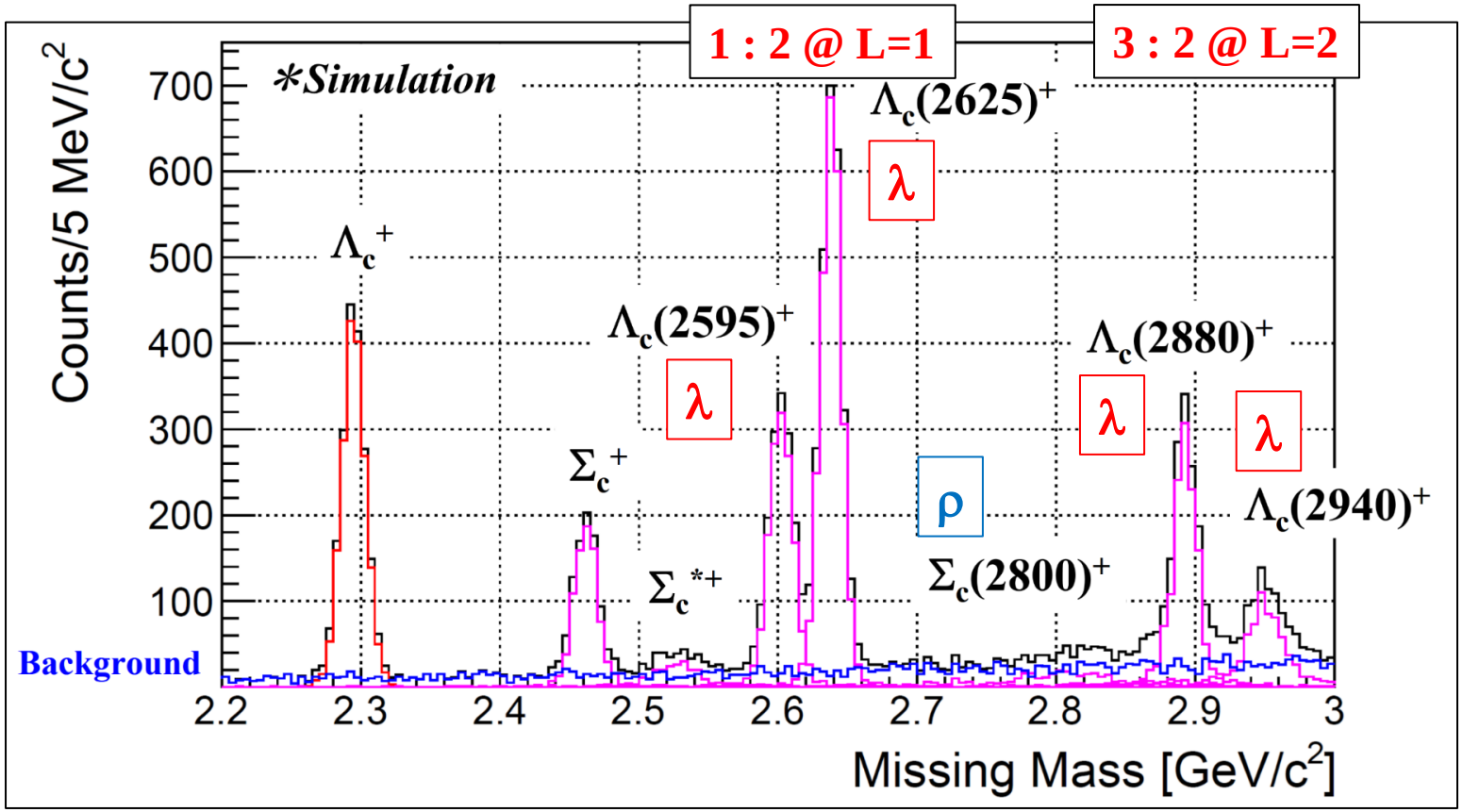
B.R.: Assumed

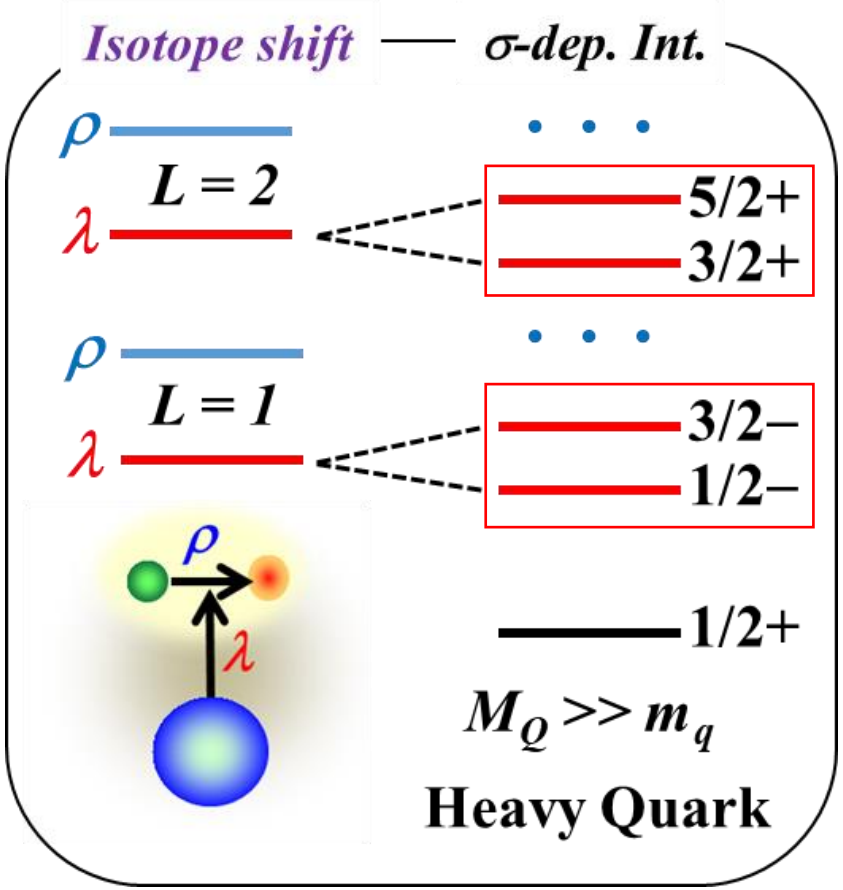
W/ $\Lambda_c^+ \pi^+ \pi^-$ selected

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

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

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





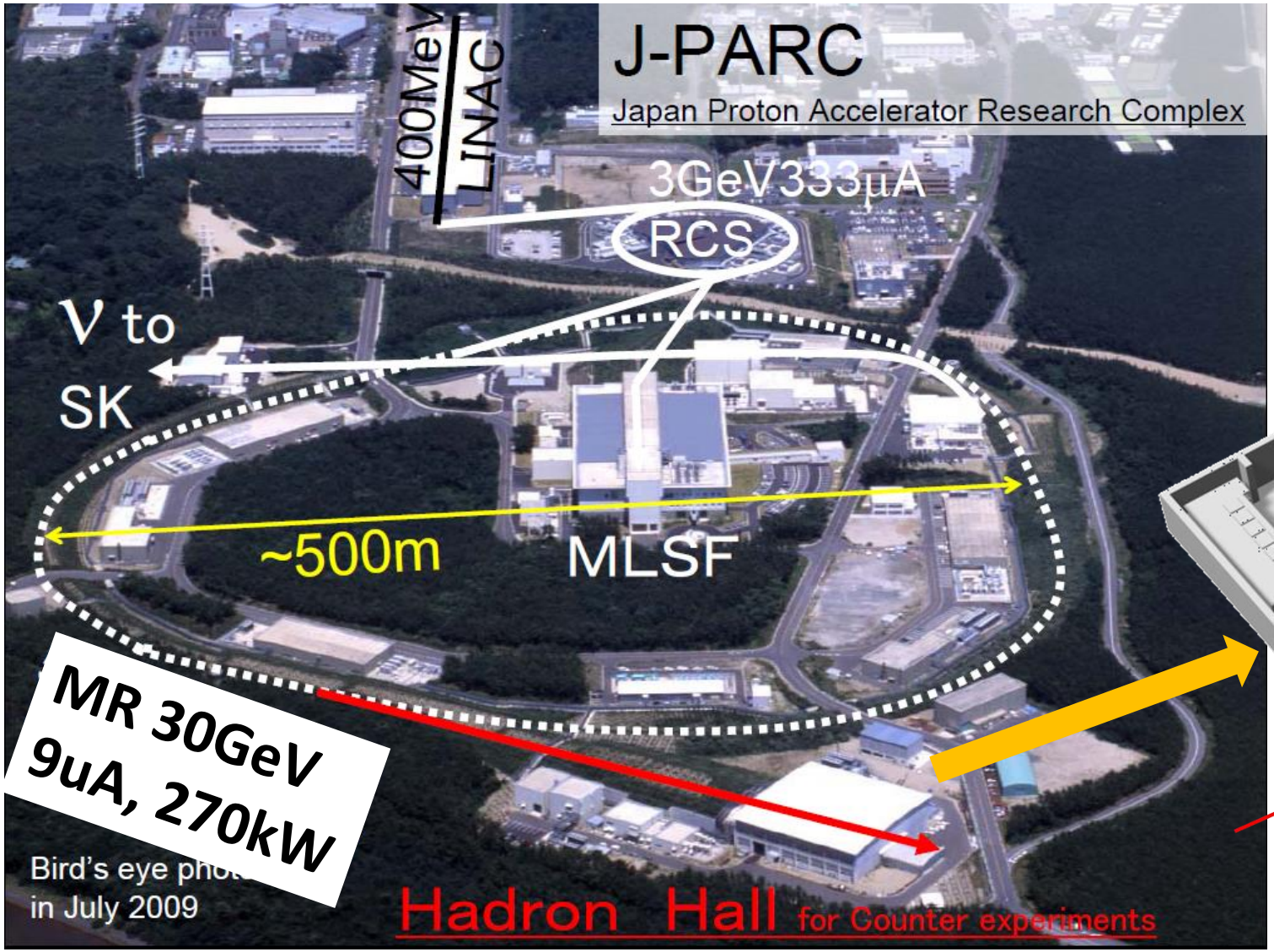
- **Dynamical information: Production rates & Absolute decay branching ratios**

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

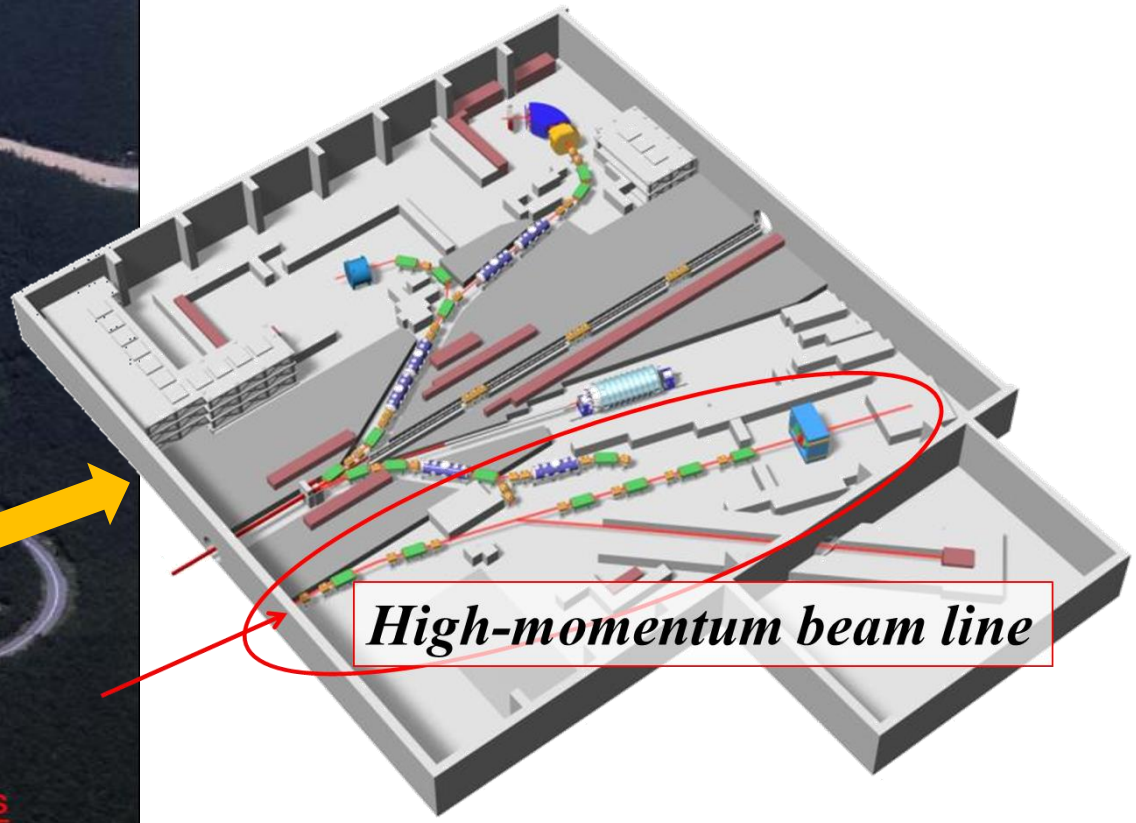
Beam line and Spectrometer system

Construction staus

J-PARC & Hadron Experimental Facility



Hadron Experimental Facility



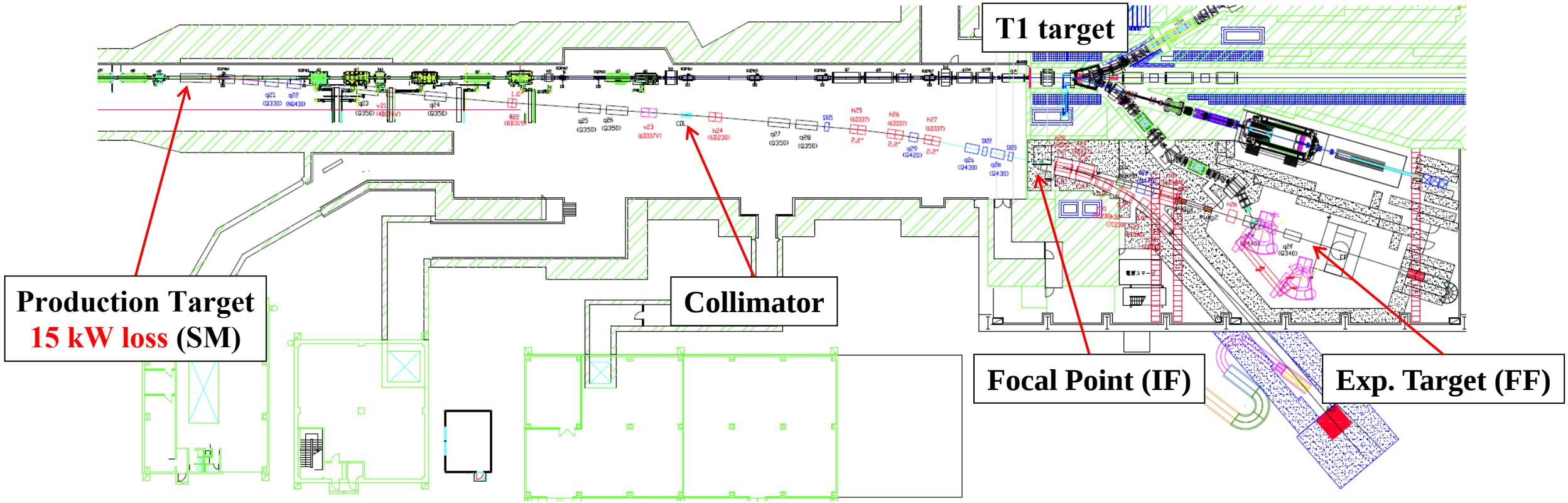
World's highest level intensity proton beam

High-p beam line for 2ndary beam: π20

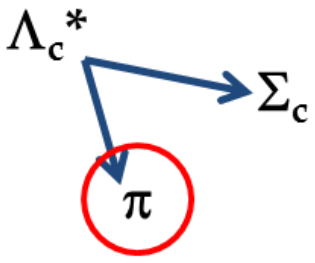
∗ High-p: 2ndary beam can be provided from the primary proton beam.

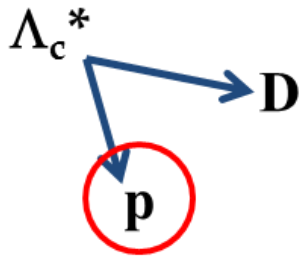
- High intensity: >10^7 /spill for $\pi^{\pm}$, p (>10^5 /spill for K^-, p_{bar}) up to 20 GeV/c
- High momentum-resolution: $\Delta p/p = 0.1\%(\sigma)$

- E50: High-intensity π^- beam: 6.0×10^7 /spill @ 20 GeV/c
  - 30 MHz ⇒ 1 MHz/1 mm (2.0 sec. extract. / 5.2 sec. cycle)



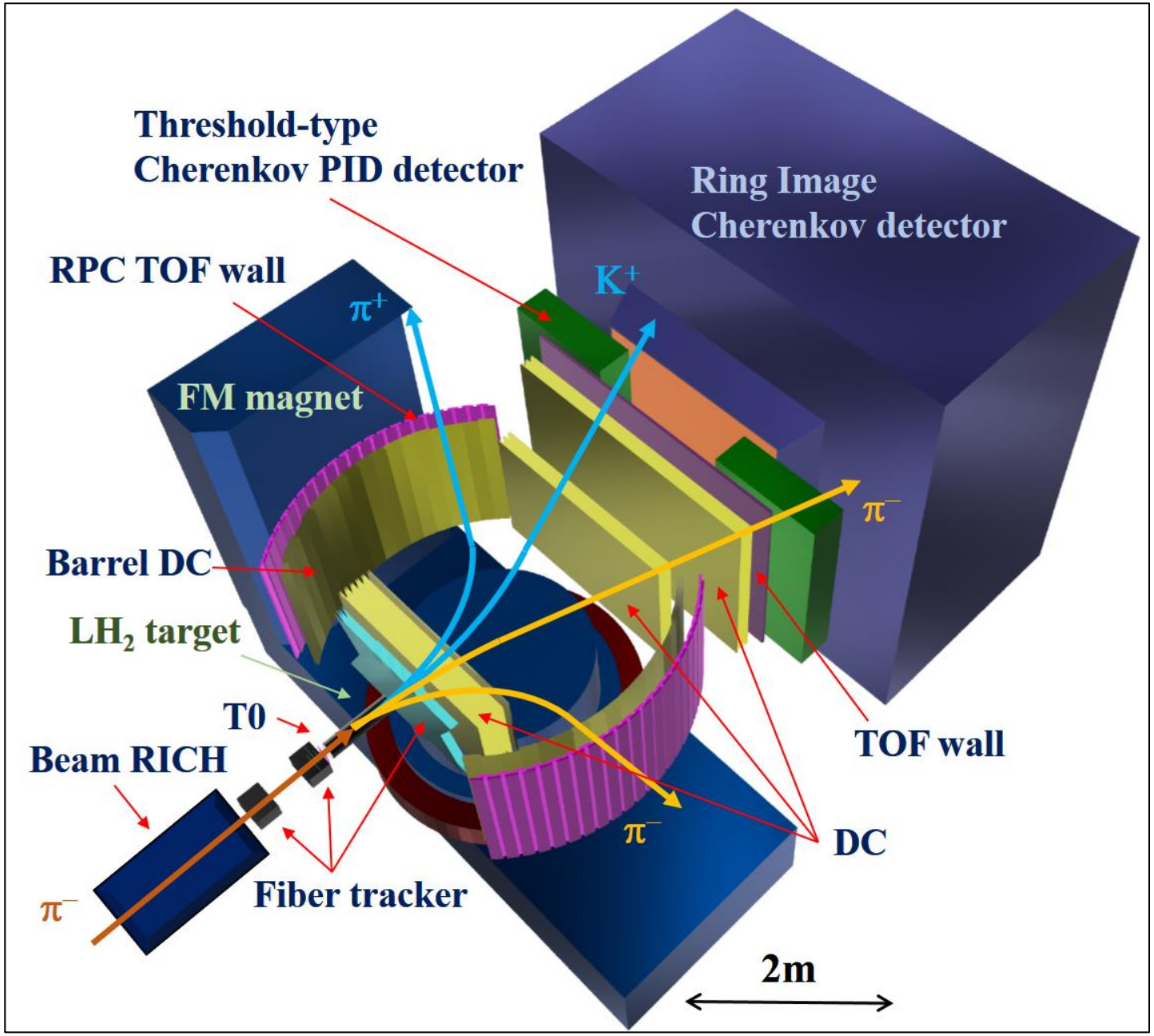
Spectrometer for charmed baryon spectroscopy

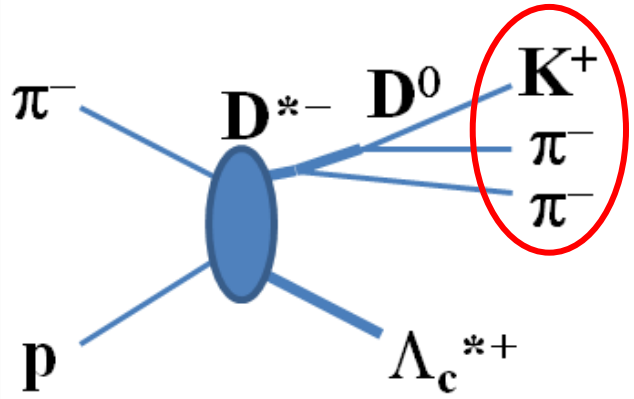




Decay measurement
∗ Branching ratios

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

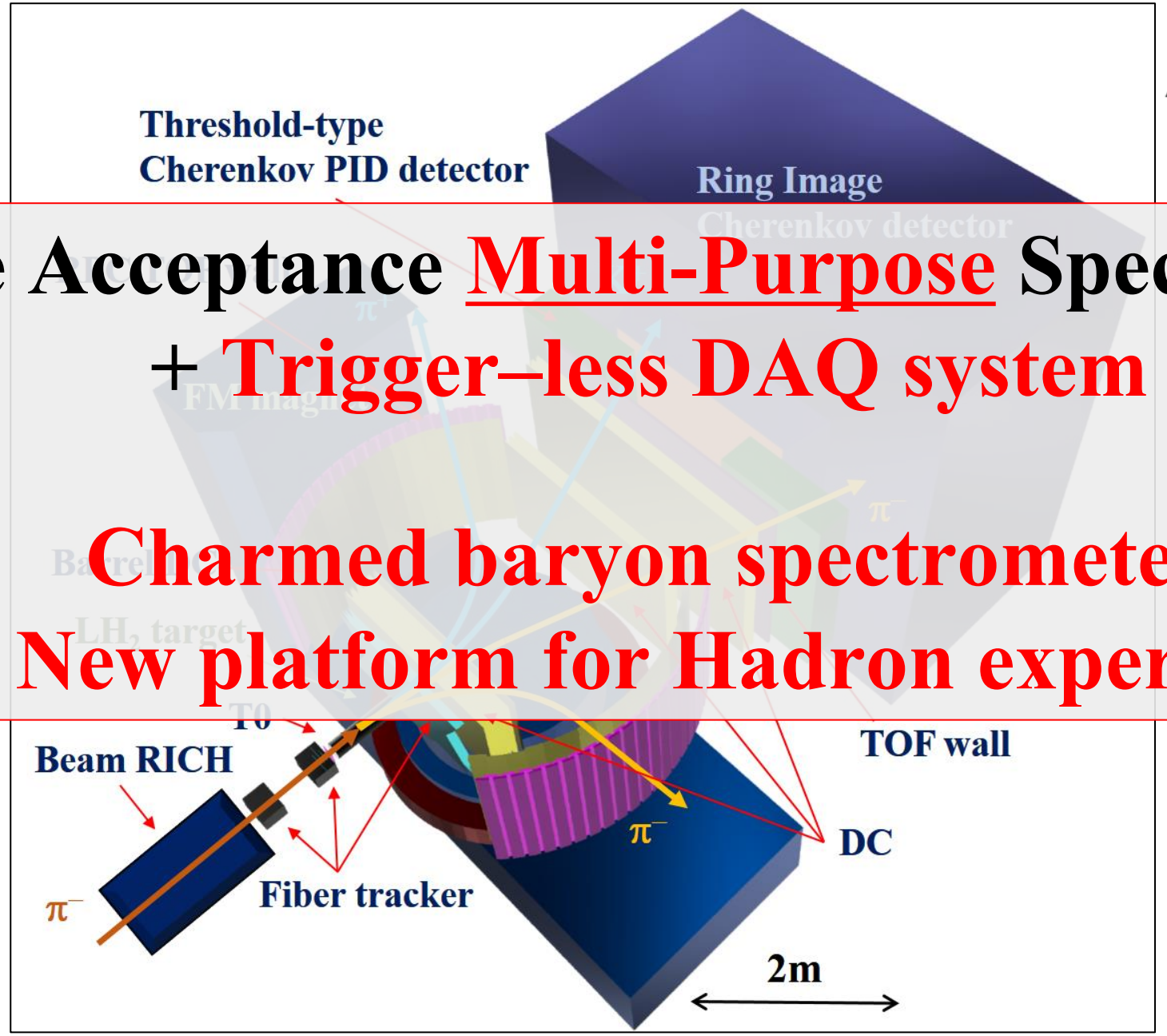




Missing mass measurement
∗ Production rate

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

Spectrometer for charmed baryon spectroscopy



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

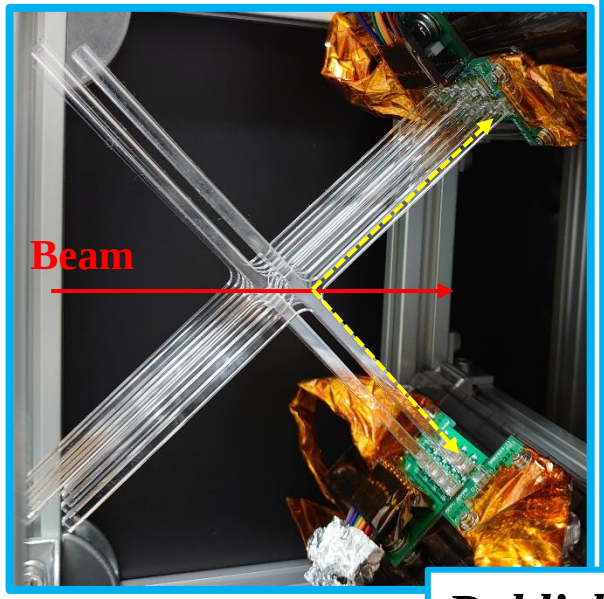
Charmed baryon spectrometer
⇒ New platform for Hadron experiment

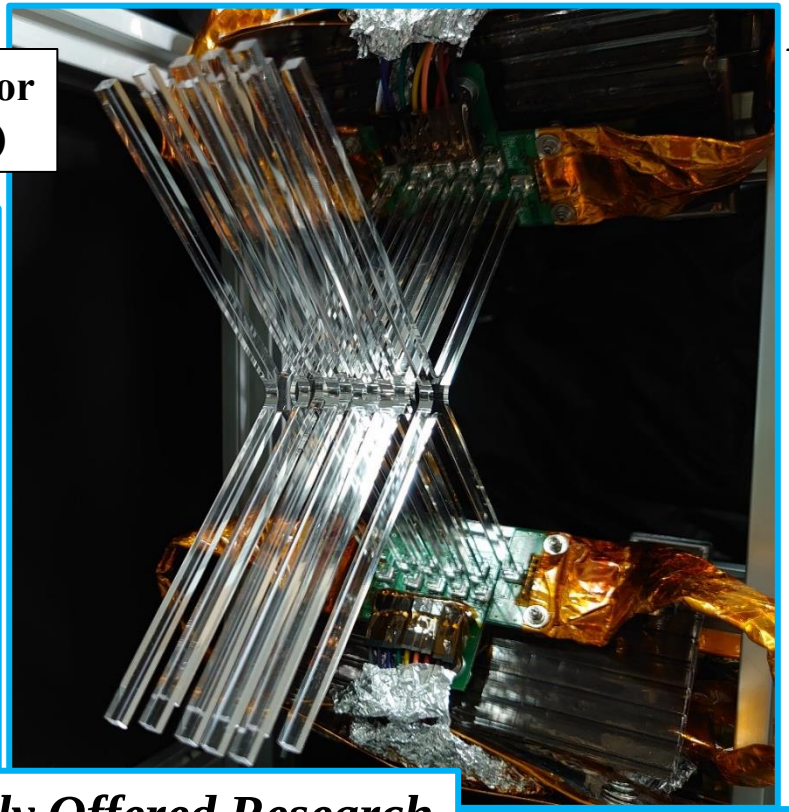
High-rate detectors

Beam Fiber Tracker
(ϕ0.5 mm fiber)

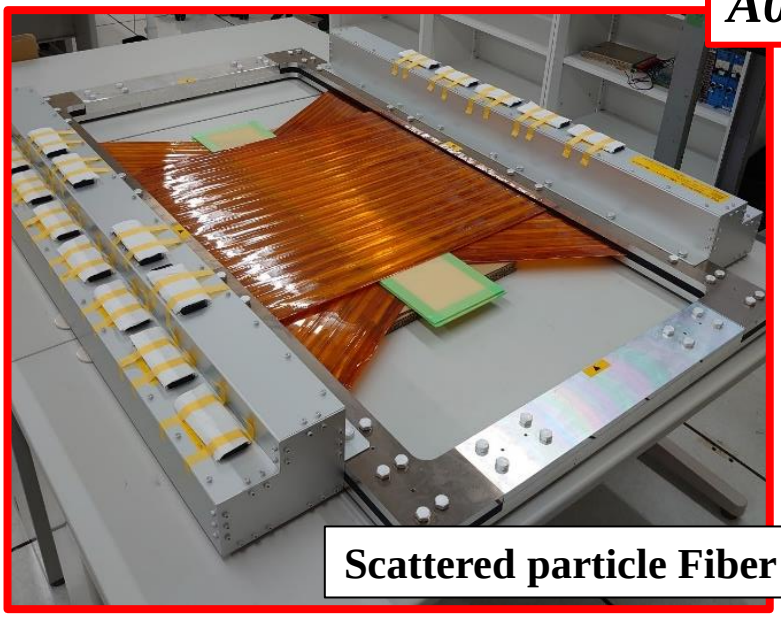
Focal plane Fiber Tracker
(ϕ1.0 mm fiber)

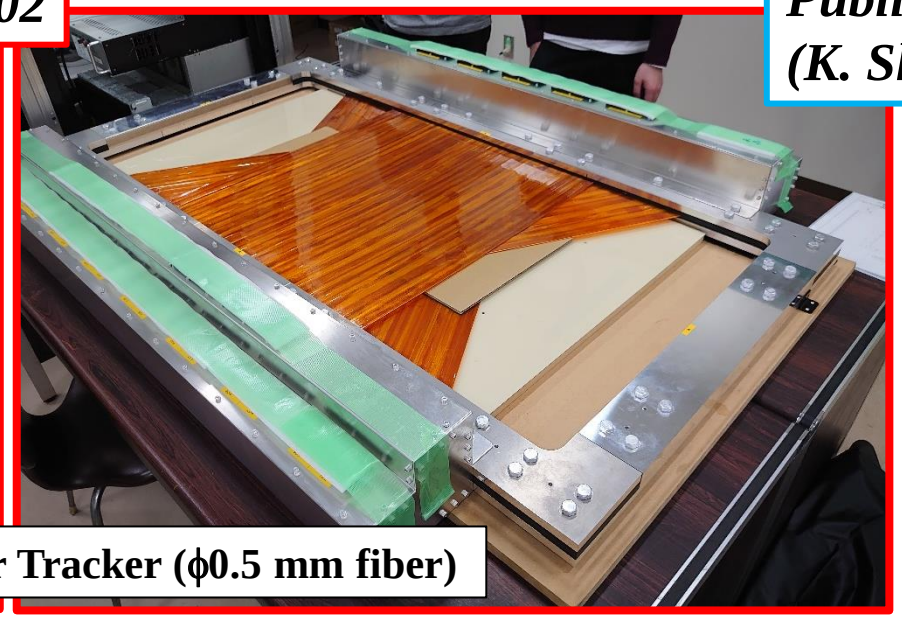
Time-Zero detector
(for EMPHATIC)





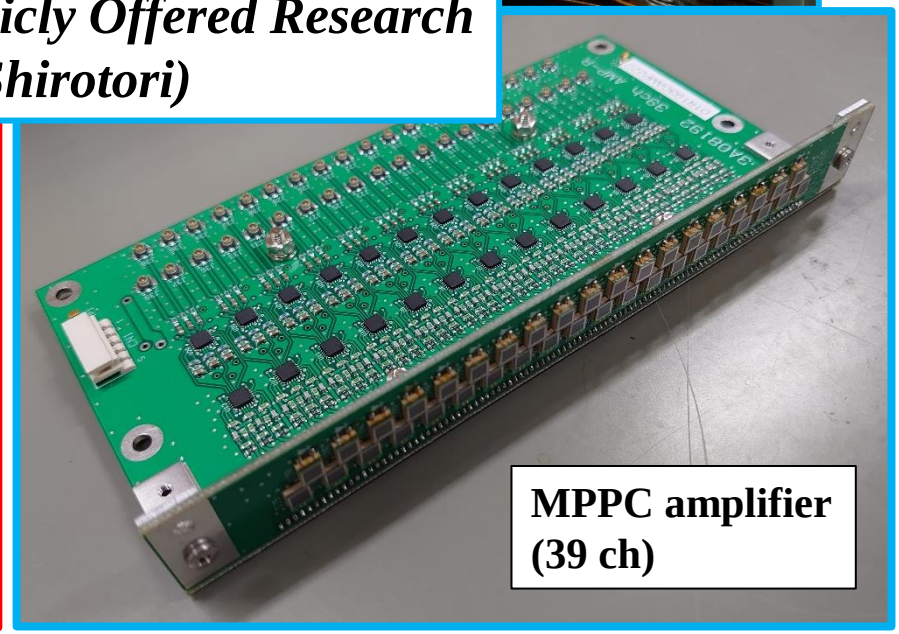
A02





Scattered particle Fiber Tracker (ϕ0.5 mm fiber)

Publicly Offered Research
(K. Shirotori)

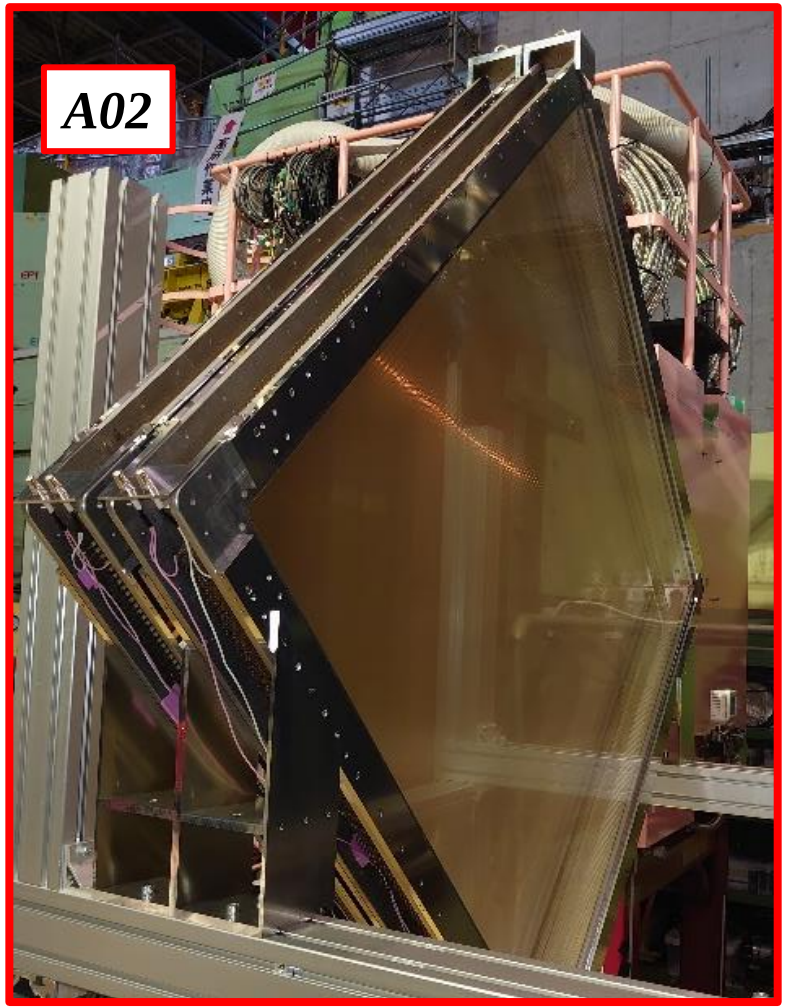


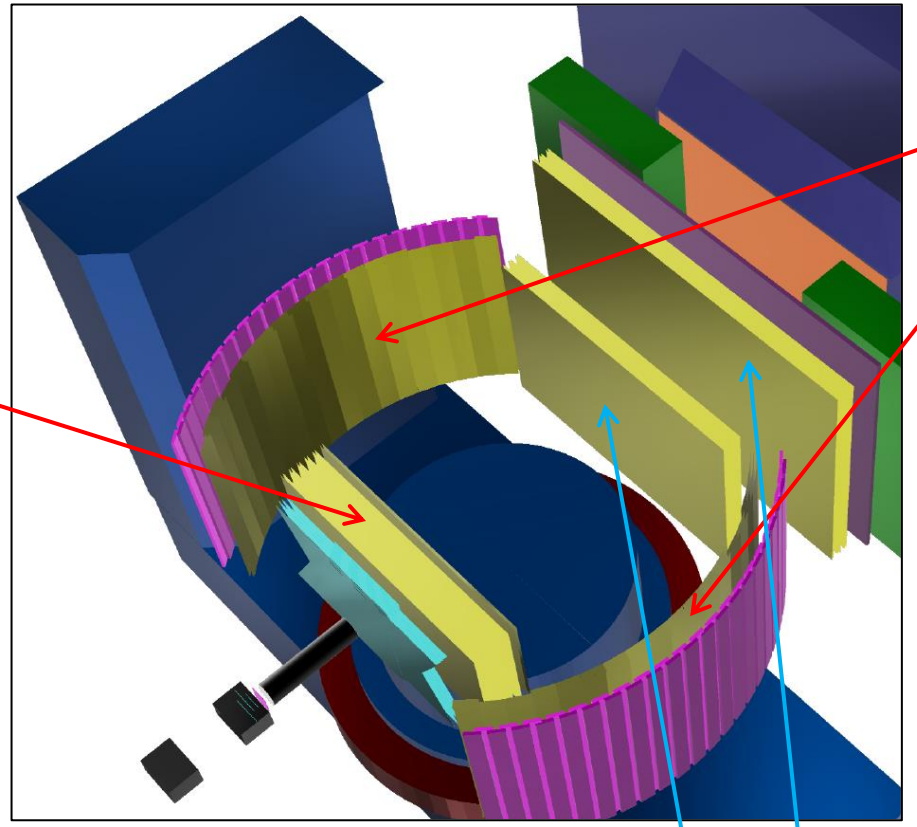
MPPC amplifier
(39 ch)

Drift Chambers

- 6 large drift chambers
- ASAGI ASD card

Target downstream DC





Internal DC

ASAGI ASD card
SPADI Alliance taskforce
* Conversion gain: 0.06–32 V/pC

- Large DC: 3.6 m×2.5 m (Outer size)

⇒ Production in FY2023

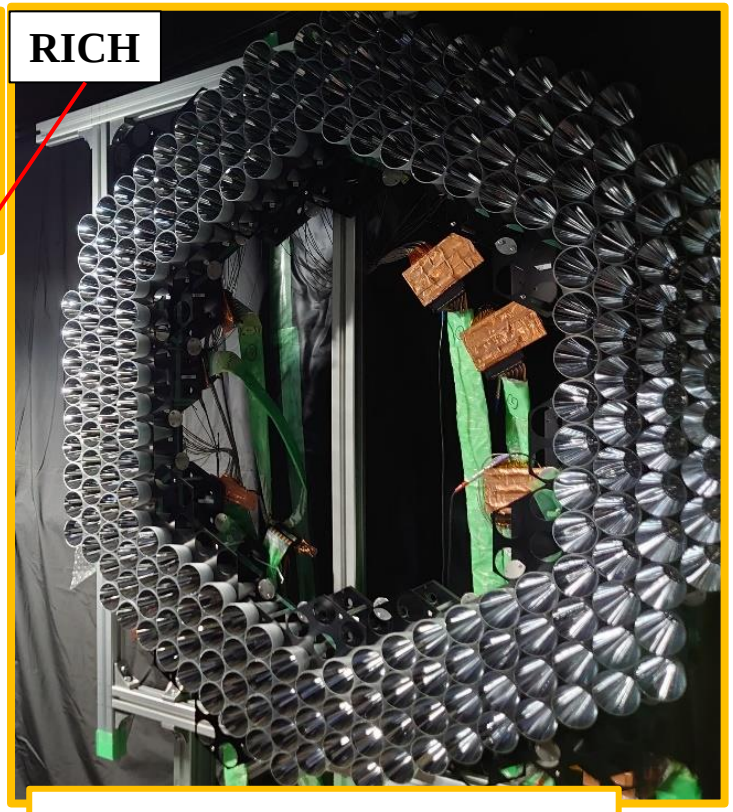
- Magnet downstream DC

⇒ To be prepared

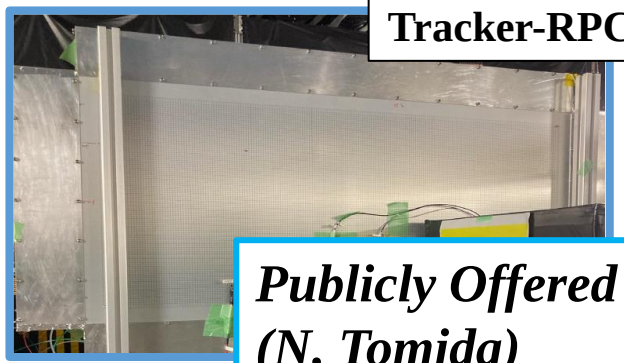
* Detector preparation and test
  - Evaluation by ASAGI ASD card

PID detectors

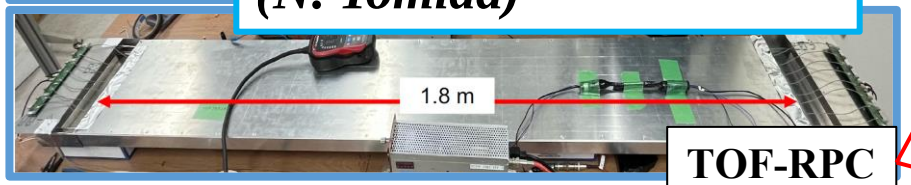
- Time-Of-Flight: RPC, Plastic scintillator
- Ring-Imaging Cherenkov (RICH)
- Threshold-type Cherenkov (VthAC)

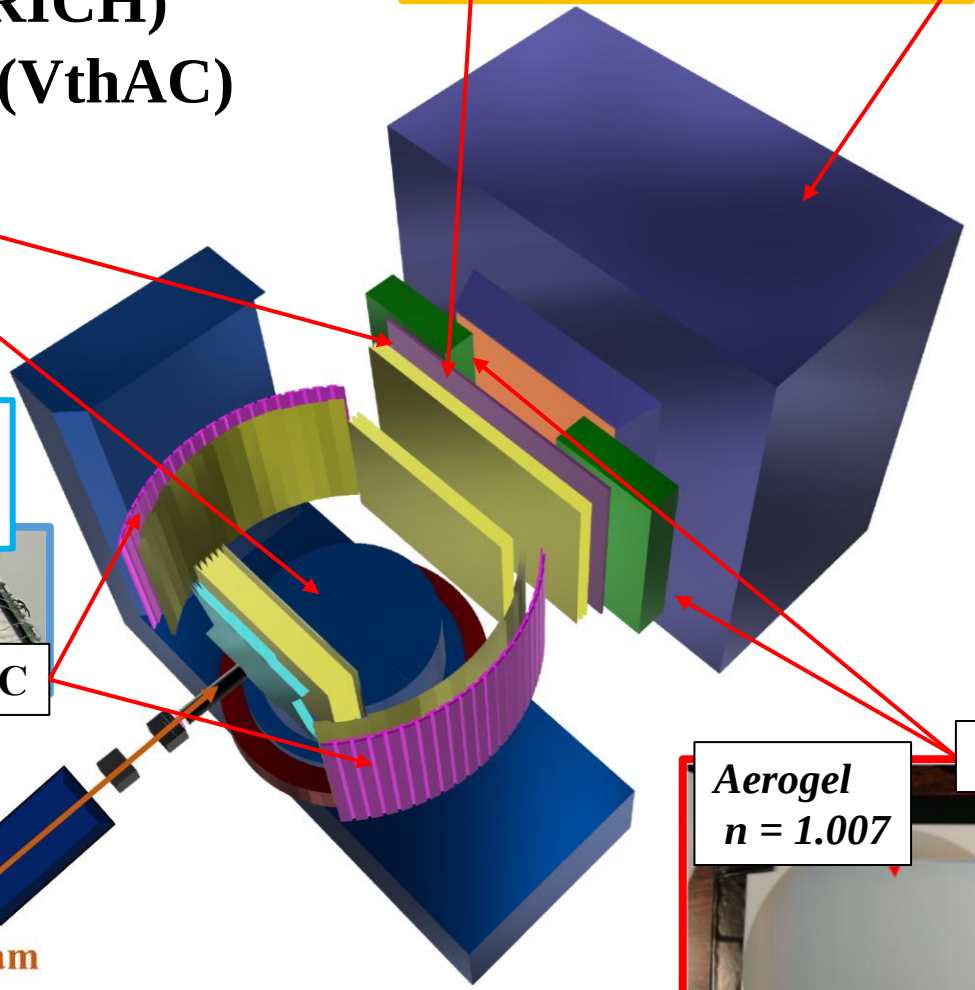


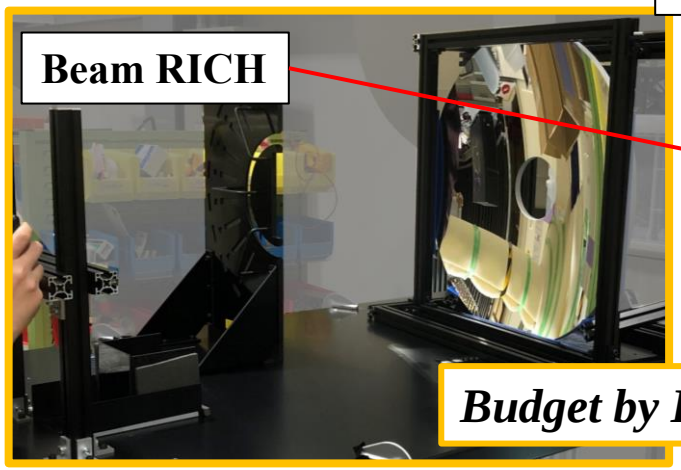
Budget by E50 collaborator (K. Shirotori)



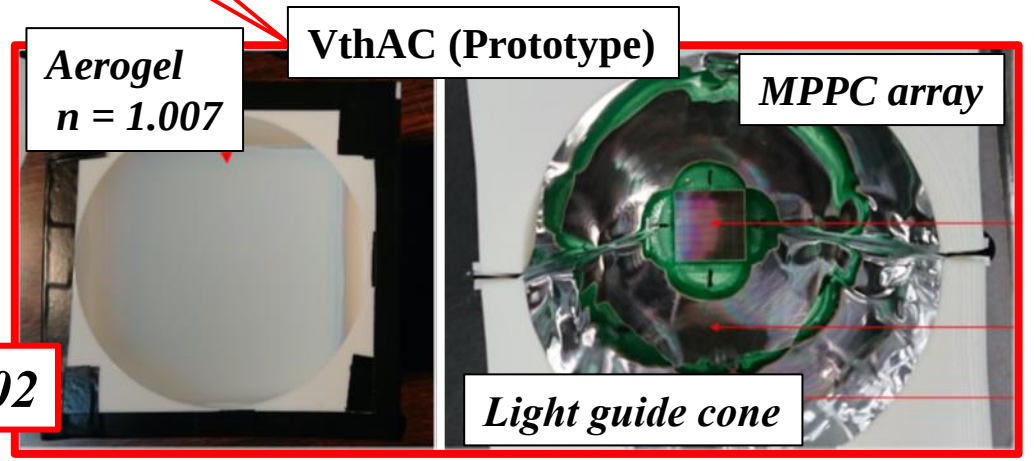
Publicly Offered Research (N. Tomida)







Budget by E50 collaborator



A02

RICH R&D

- **RICH (Ring Image Cherenkov detector)**

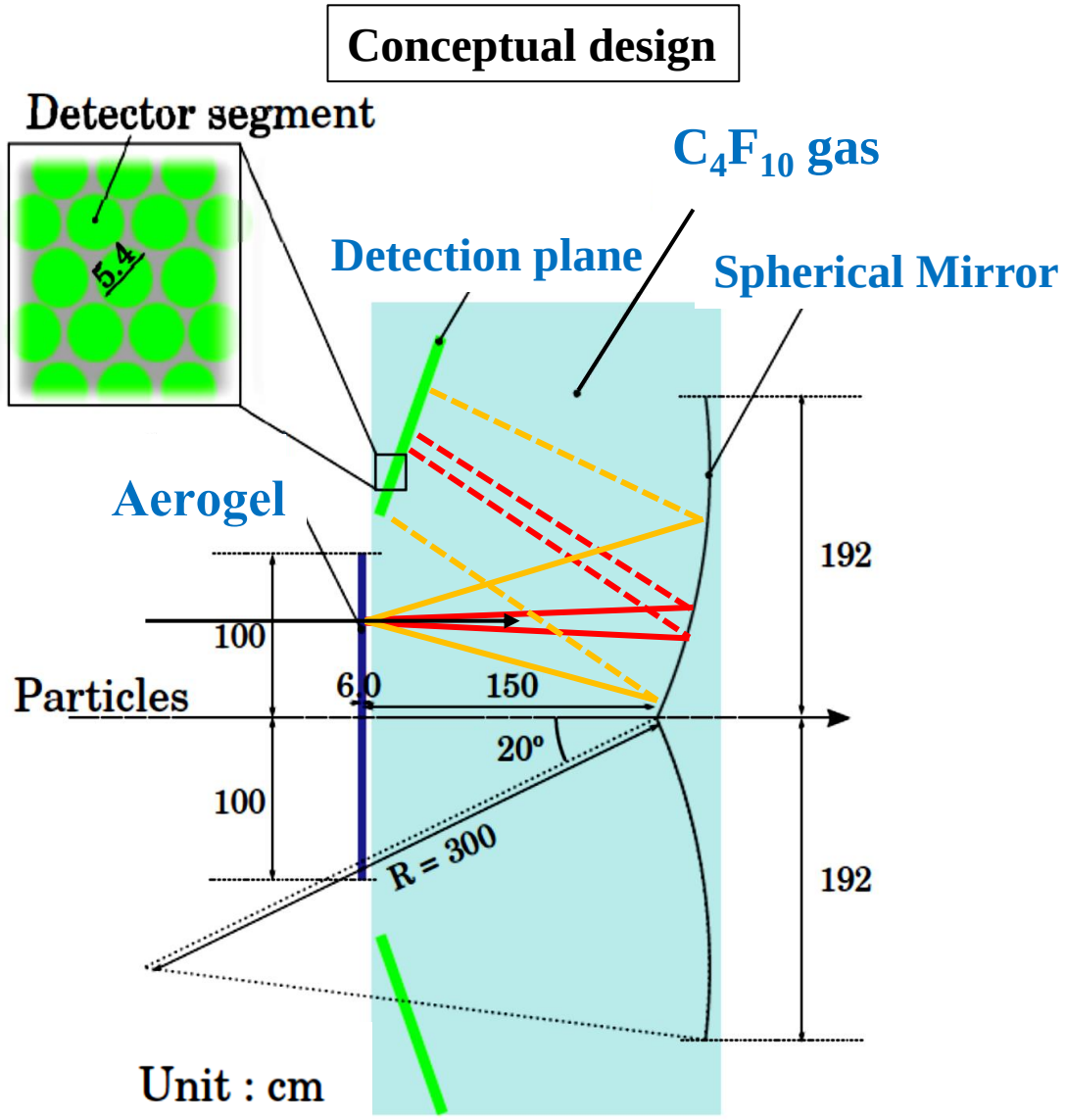
⇒ **PID by Cherenkov angle: $\cos\theta_c = \frac{1}{n\beta}$**

  - **Momentum(p) + Velocity(β)**

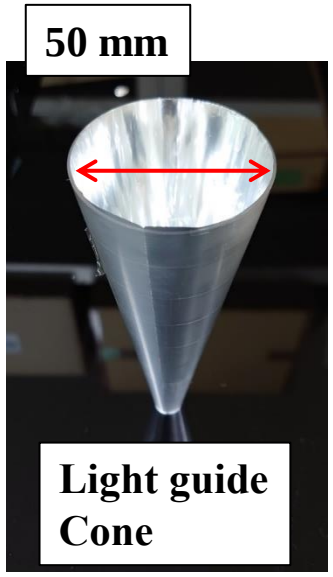
- **Simulated PID performance: $\pi^{\pm}/K^{\pm}/p(p_{bar})$**
  - **Efficiency: ~99%**
  - **Wrong PID: ~0.20%**

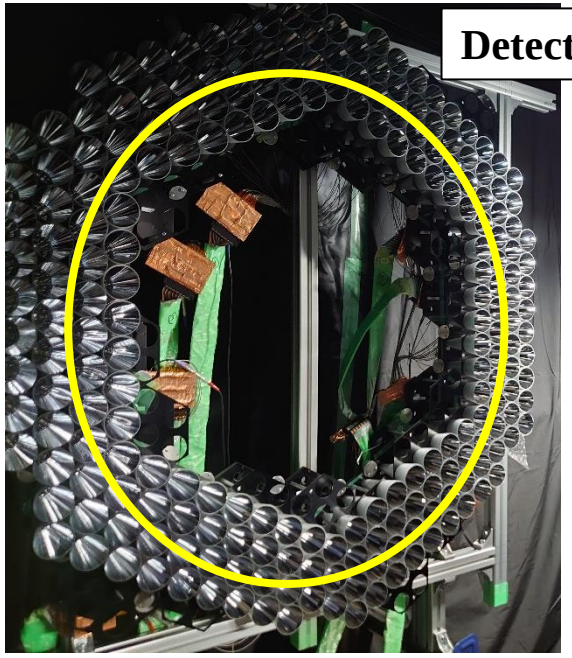
- **Specification**
  - **Aerogel (n=1.04) + C_4F_{10} gas (n=1.00137)**
  - **Detector plane: (top & bottom)**
    - **MPPC + Light guide cone**
  - **Spherical mirror: R~3 m**

- **Prototype detector test for finalizing R&D**
  - **Consisting of actual detector elements**
    - **Aerogel, Mirror, MPPC + light guide cone**

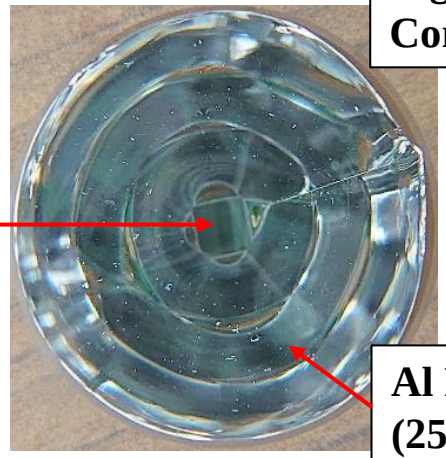


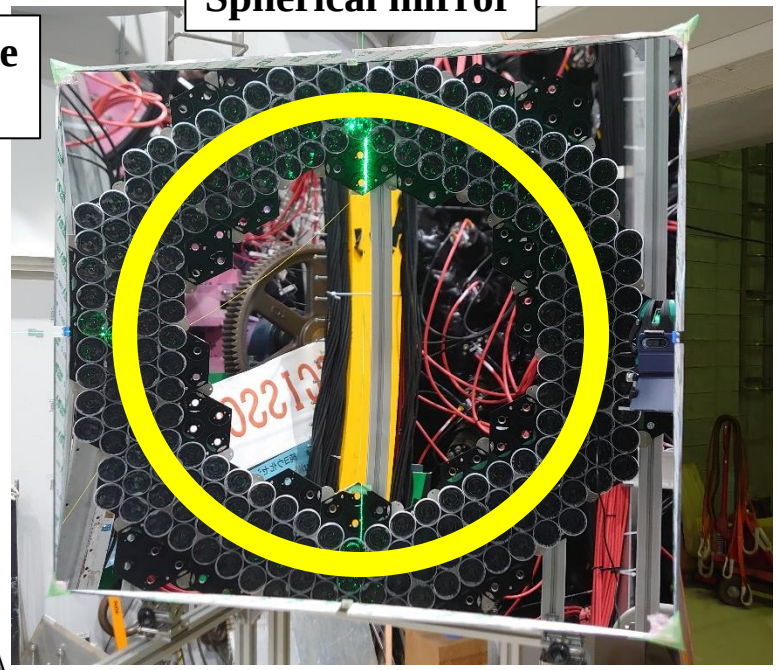
RICH test experiment @ ELPH





MPPC
(6 × 6 mm²)





Top view

Detection plane
1000 mm × 1000 mm

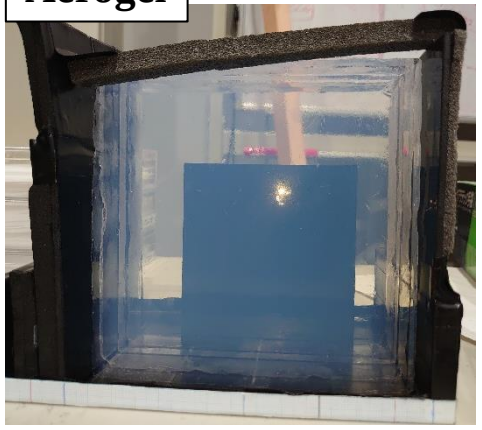
Trigger counter
10 mm × 10 mm

e⁺ beam
800 MeV

1500 mm

20°

Aerogel



Aerogel: n = 1.04
150 mm × 10–60 mm(t)

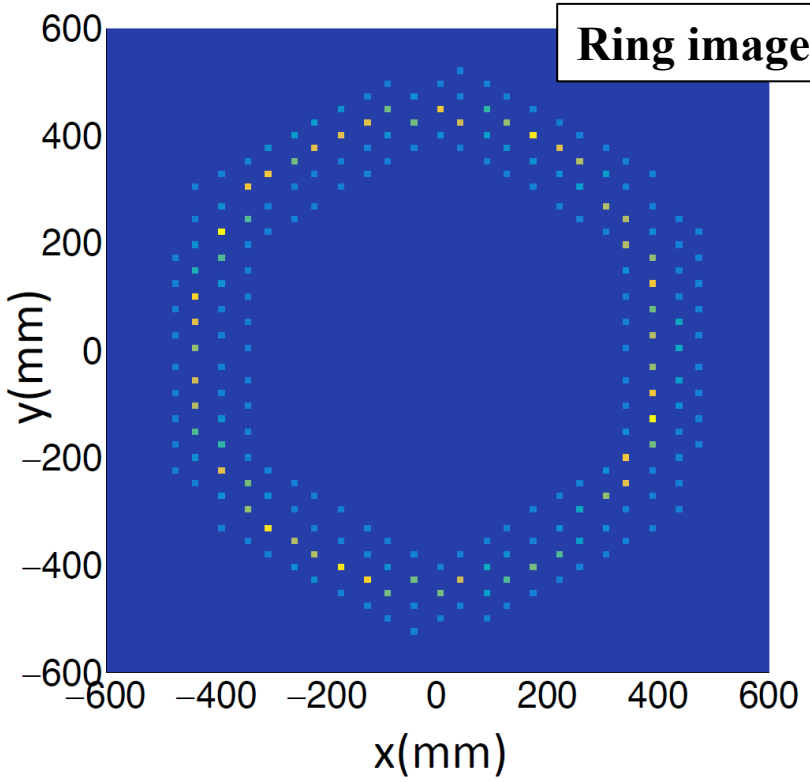
1500 mm

Spherical mirror
1080 mm(X) × 900 mm(Y)
× 6.2 mm(t) (ρ = 3000 mm)

$n = 1.04$
$\Lambda_T = 5.1$ cm
150 × 150 × 25 mm³

Test experiment results

Ring image (data)

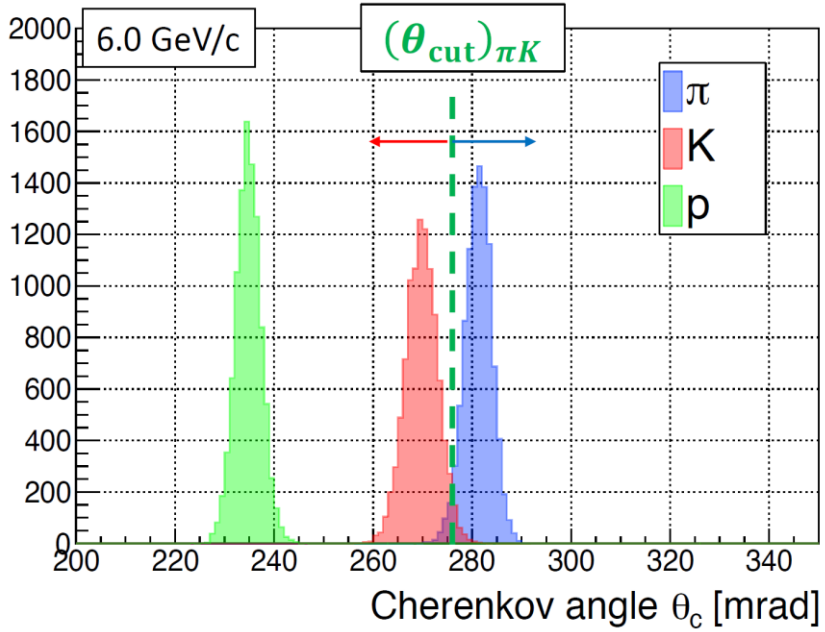


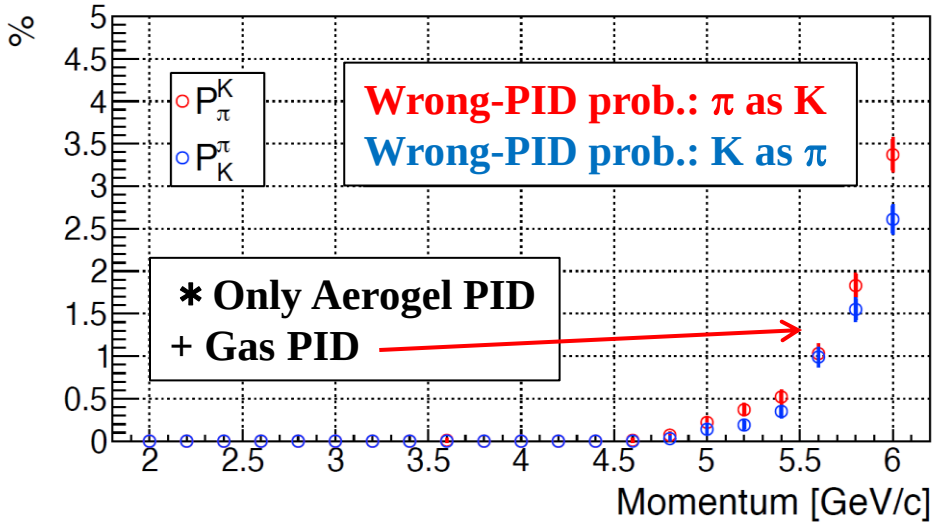
Data ⇒ Simulation

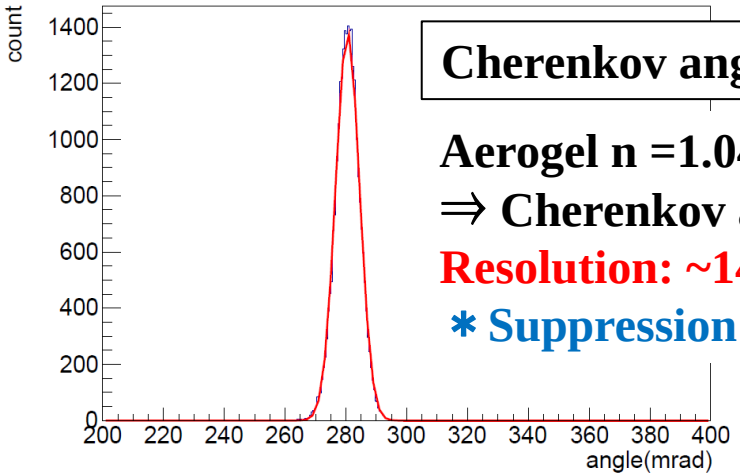
Input from data
- Aerogel property
- Mirror property
- MPPC property
- Light guide cone performance
- Dark current rate
- Hit pattern (Geometry)

+ Selection of Ring-Image region

Cherenkov angle (Simulation)







Cherenkov angle (data)

Aerogel n =1.04

⇒ Cherenkov angle: 278 mrad

Resolution: ~14 mrad(σ) > 10 mrad (design)

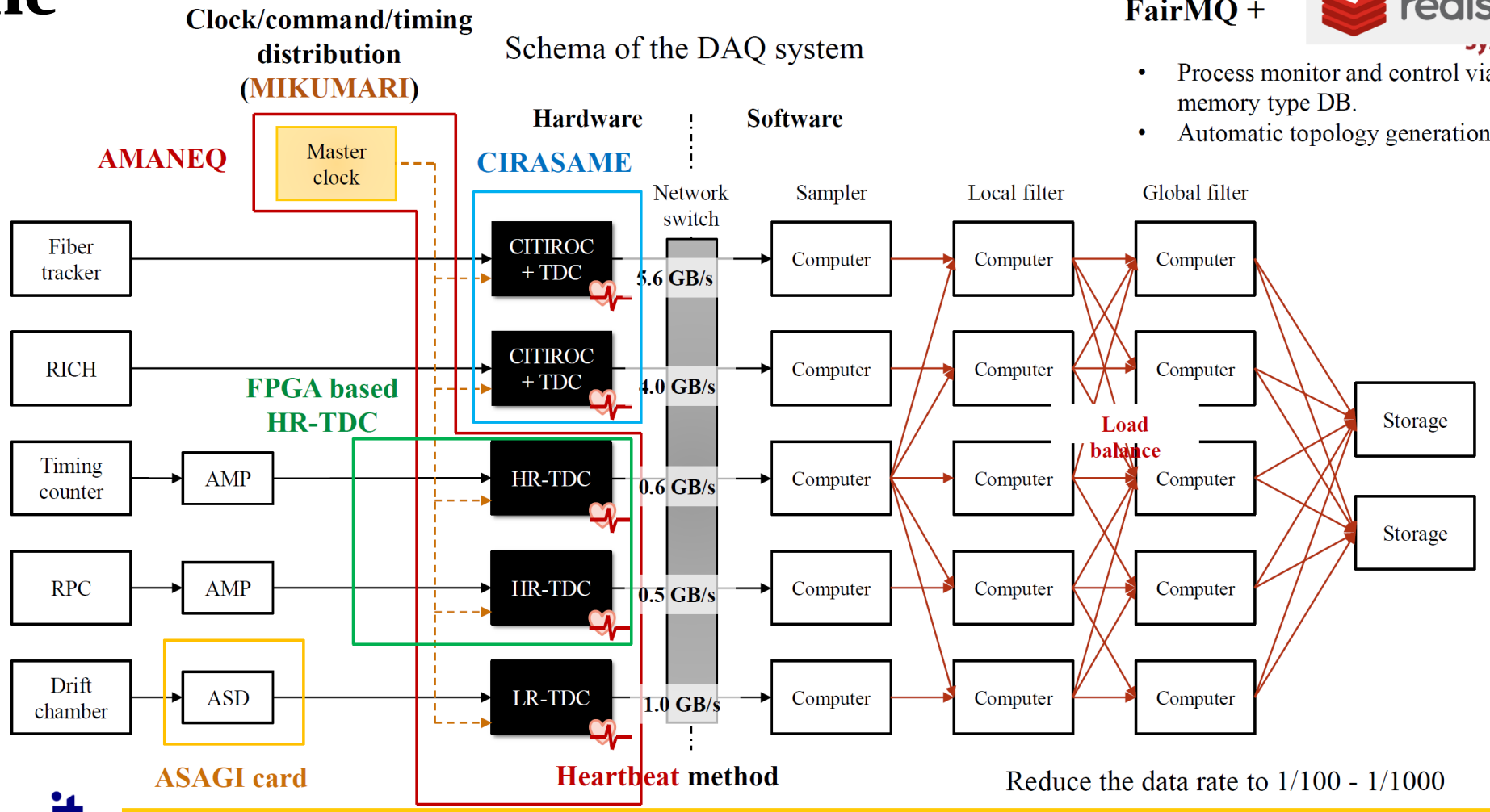
∗ Suppression of dark current effect

∗ Efficiency ~99% & Wrong PID < 1%

⇒ Actual detector fabrication

DAQ scheme

Trigger-less data-streaming-type DAQ system



FairMQ +

- Process monitor and control via in-memory type DB.
- Automatic topology generation

Total data rate: ~12 GB/s (25 GB/spill) (E50 case)

- **Trigger-less DAQ with data-streaming method**
  - **Front-end modules: AMANEQ, CIRASAME**
  - **Clock synchronization: MIKUMARI**

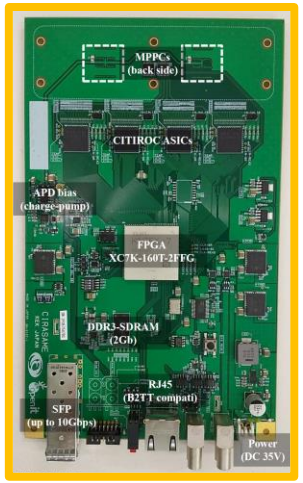
*** Basic perfromances established: R. Honda *et al.*, PTEP2021, 123H01 (2021).**

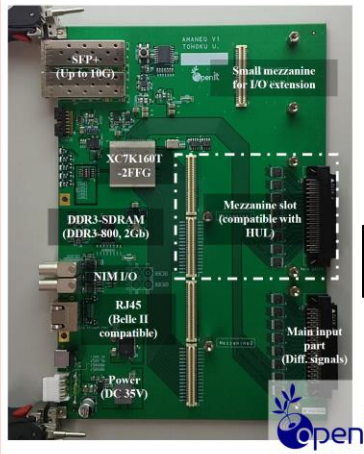
DAQ scheme

Trigger-less data-streaming-type DAQ system

Publicly Offered Research (R. Honda)

CIRASAME (MPPC readout)



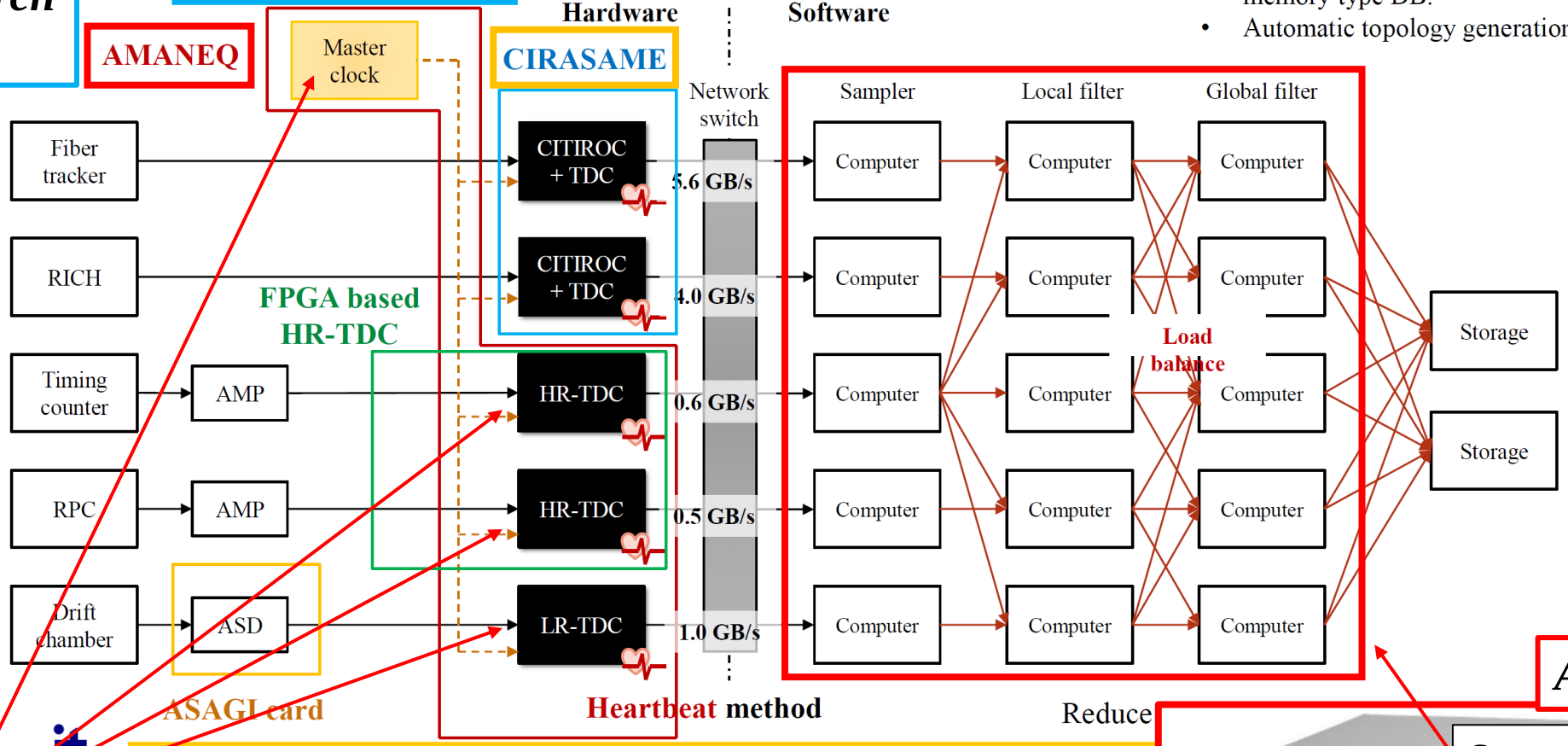


AMANEQ

A02

Clock/command/timing distribution (MIKUMARI)

Schema of the DAQ system



FairMQ +

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A02

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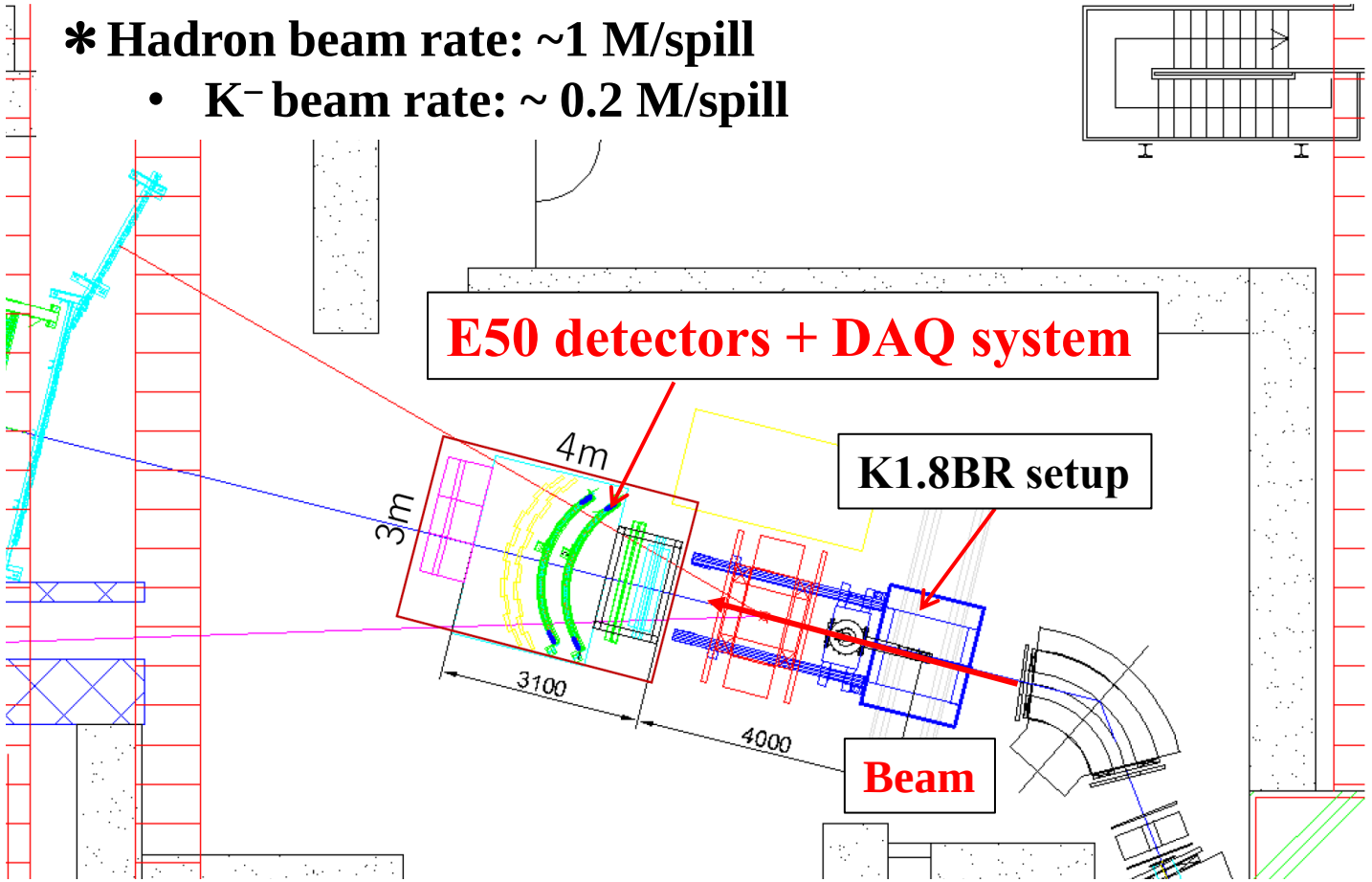
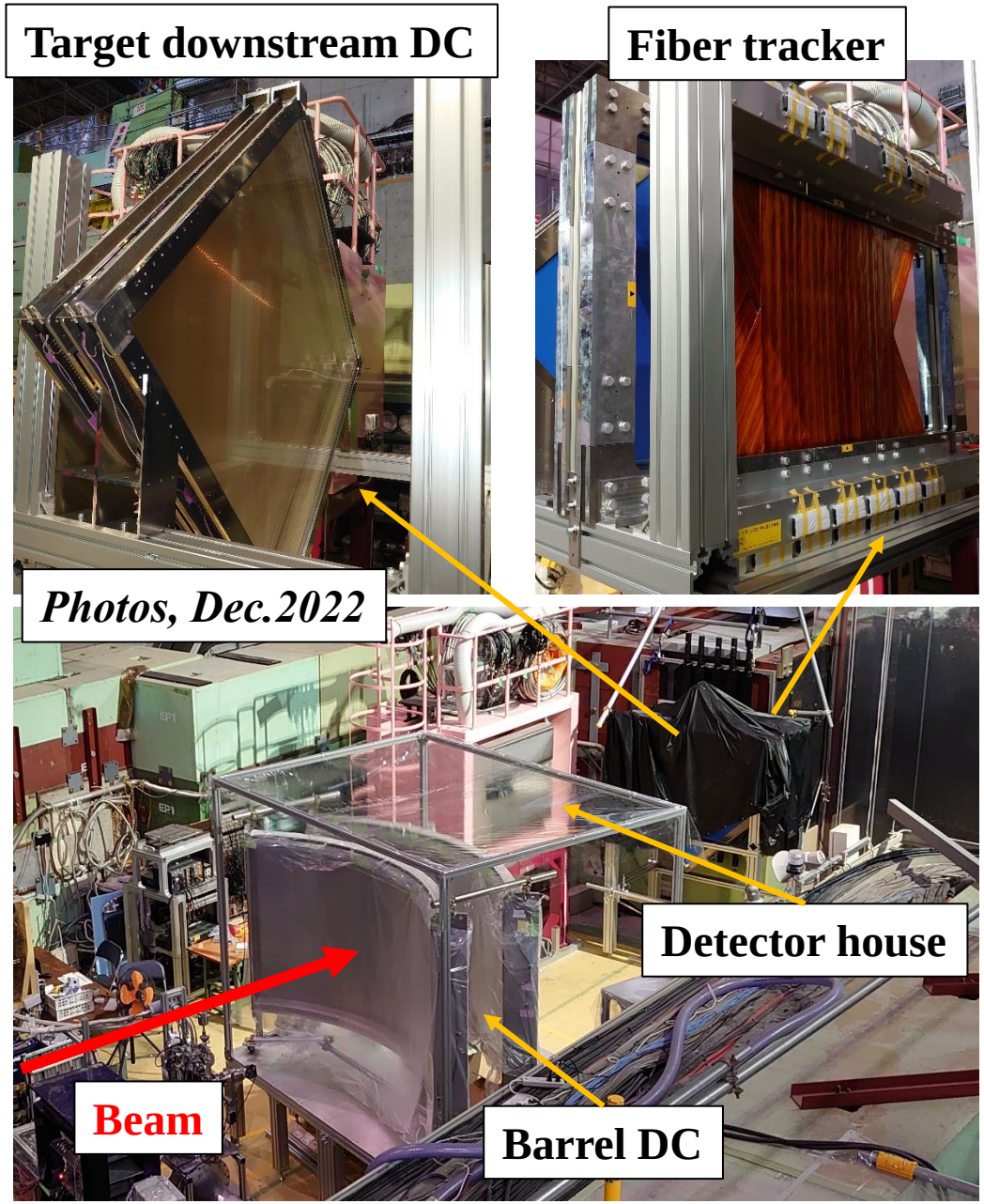
E50 test bench @ J-PARC K1.8BR beam line

- Hadron beam rate: ~1 M/spill
  - K^- beam rate: ~ 0.2 M/spill





- Streaming DAQ evaluation
  - Filtering (software trigger) test with E50 detectors

⇒ Next generation DAQ R&D (SPADI Alliance)
  - RCNP Grand Raiden test experiment

Summary

- **How quarks build hadrons ?**
  - **Effective degrees of freedom for hadron: Diquark correlation**

- **Investigation 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**

- **Experiment at J-PARC Hadron Experimental Facility**
  - **High-intensity & High-momentum hadron beam by π20 beam line**
  - **Charmed baryon spectrometer constriction**
    - **High-rate detectors, Large size drift chambers and various PID detectors**
    - **Trigger-less DAQ with data-streaming method: Demonstration at K1.8BR and Grand Raiden**

∗ Charmed Baryon spectroscopy experiment at J-PARC (E50) provides a unique opportunity for reveling effective degrees of freedom.