Spectroscopy of charmed baryon at the J-PARC high-momentum beam line

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for the J-PARC E50 collaboration

Research Center for Nuclear Physics (RCNP)
Osaka University

International workshop on J-PARC hadron physics in 2016
3 Mar 2016

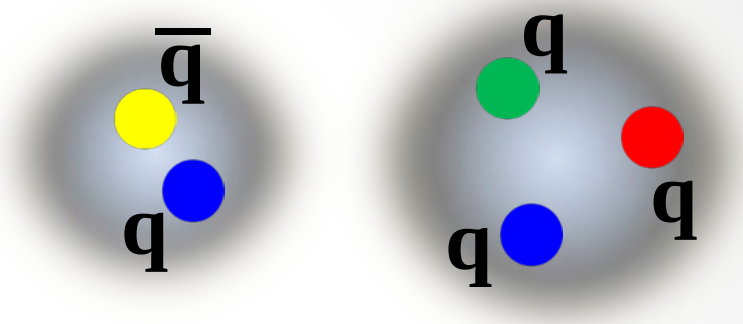
Contents

Physics motivation

...

What is an essential degree of freedom ?

Constituent Quark



- **Hadrons**
  - **Baryon: qqq**
  - **Meson: $q\bar{q}$**

⇒ Constituent Quark model

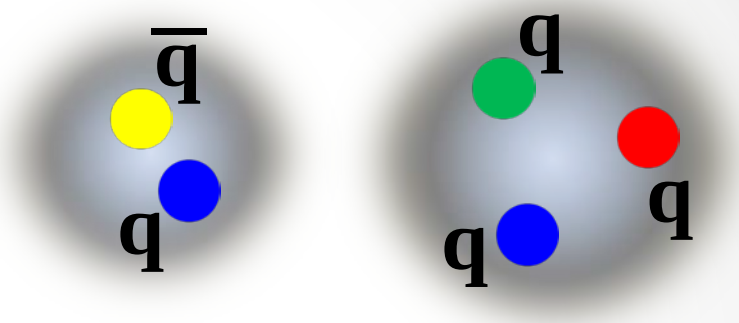
  - **c.f. Mass and Magnetic moment of Ground States**

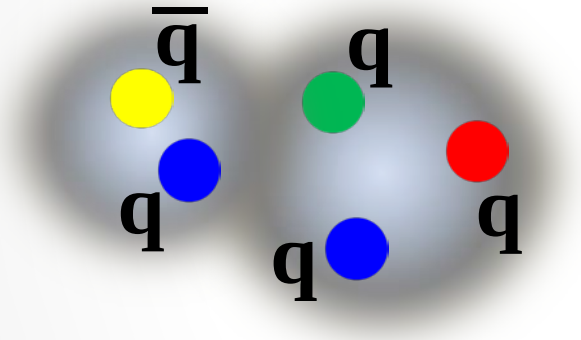
However, we cannot understand…

- **Missing states**
- **Exotic hadrons**

What is an essential degree of freedom ?

Constituent Quark



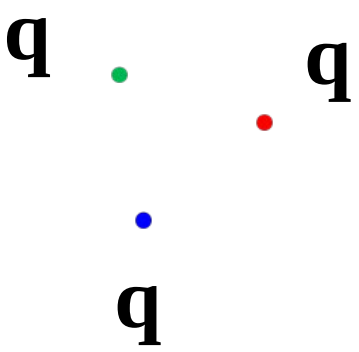


Exotic hadron

- **Hadron molecular & Multi-quark states**
  - **$\Lambda(1405)$: $\bar{K}$ + Nucleon**
  - **X, Y, Z, Z_b particle**
  - **Θ^+, P_c: Pentaquark**

Bridge from quark to hadron

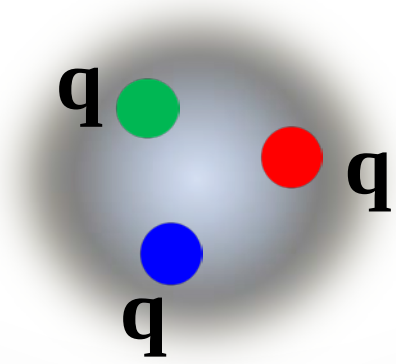
- **Quark**
  - **Bare quark**



- **Constituent**
  - **Constituent quark**

⇒ Need constituent pictures for understanding

- **Hadron**
  - **Observables**



Bridge from quark to hadron

- **Quark**
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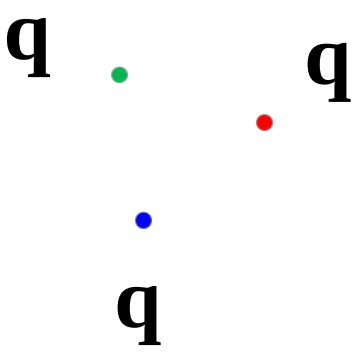
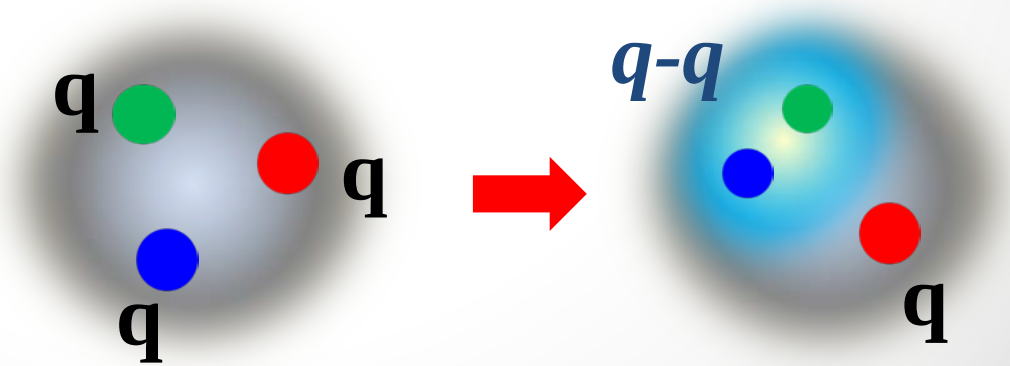


- **Constituent**
  - **Constituent quark, diquark correlation, hadron molecule**

  ⇒ Need constituent pictures for understanding

- **Hadron**
  - **Observables**

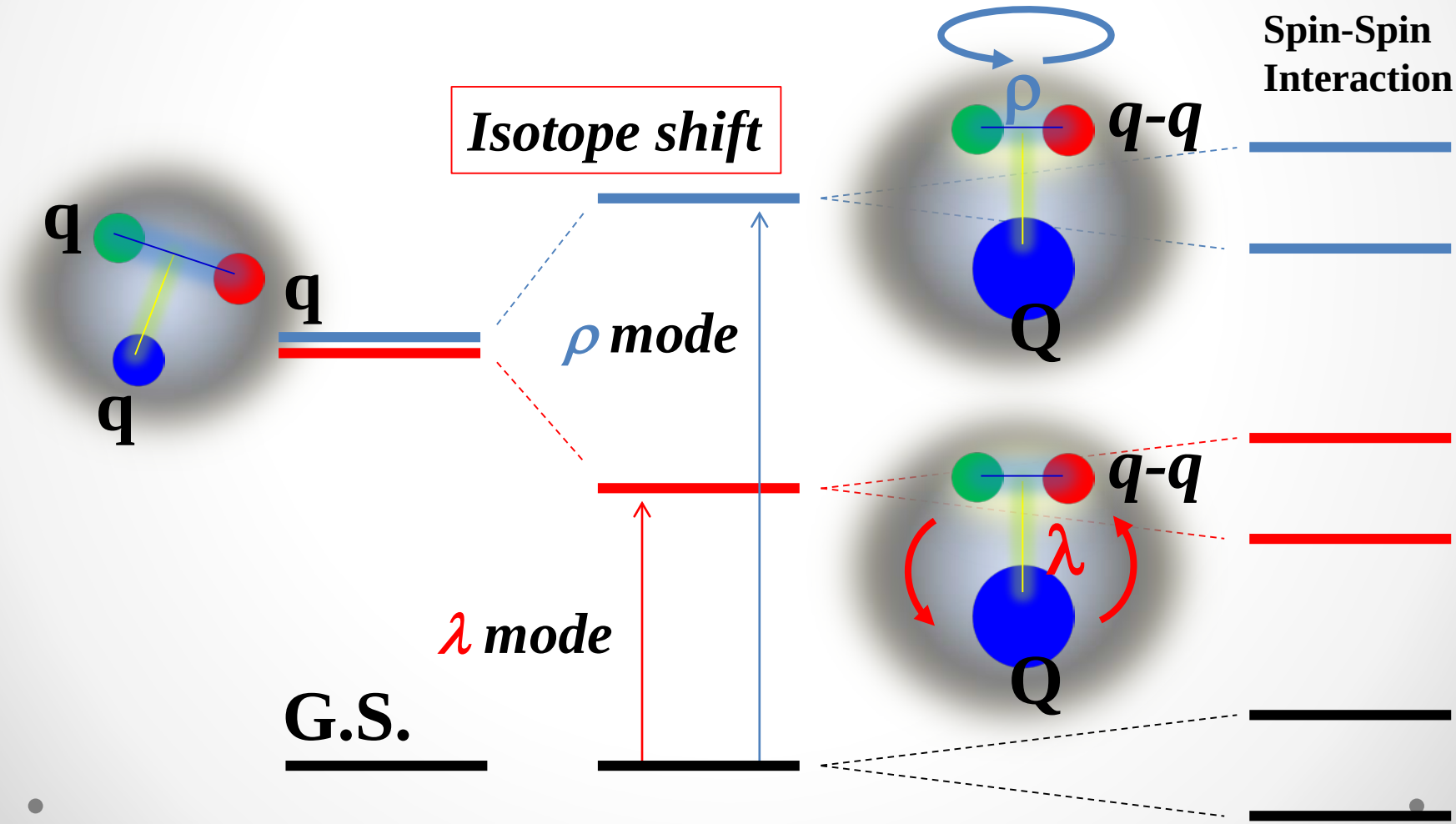
  ⇒ Exotic hadrons



Charmed baryon spectrum: "Excitation Mode"

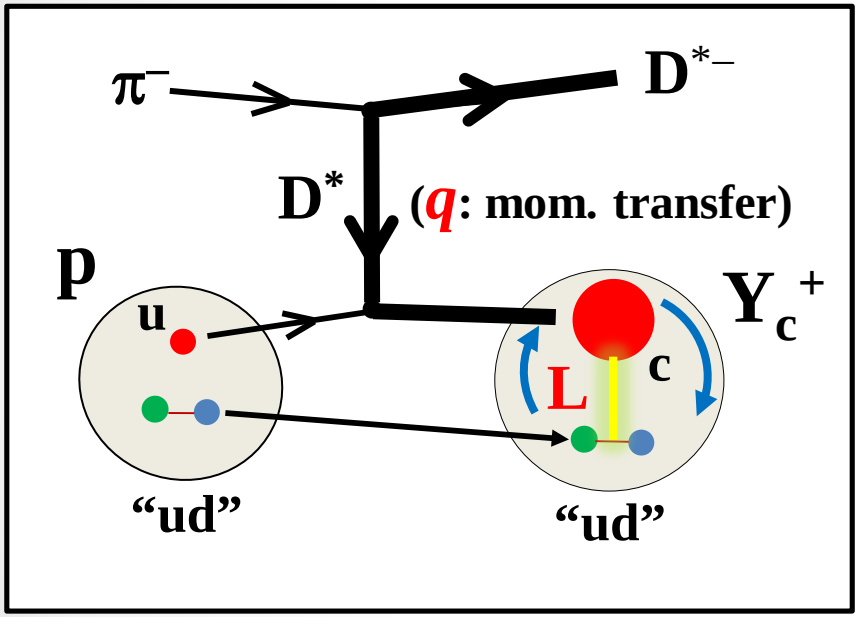
Heavy Quark: Weak color-magnetic interaction

⇒"*q-q*" isolated and developed: "q-q + Q"



Production by hadron beam

Hadronic production: $\pi^- + p \rightarrow Y_c^{*+} + D^{*-}$



D^* exchange at a forward angle

Production cross section

⇒ **Overlap of wave function**

∗ **charm and *q*-*q* (spectator)**

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

1. Spin/Parity of Y_c^*

2. Momentum transfer (q_{eff})

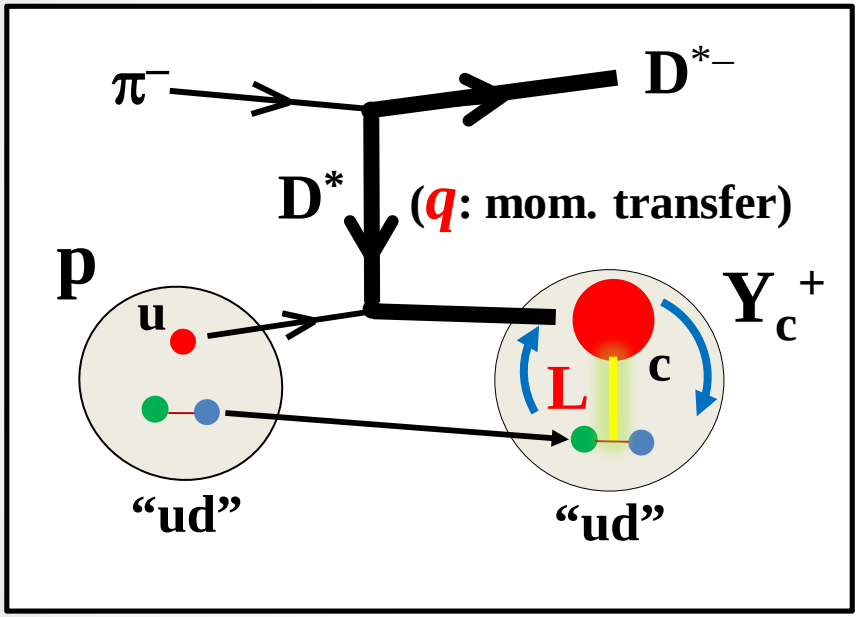
$$I_L \sim (q_{eff}/A)^L \, exp(-q_{eff}^2/2A^2)$$

***A*: (baryon size parameter)$^{-1}$**

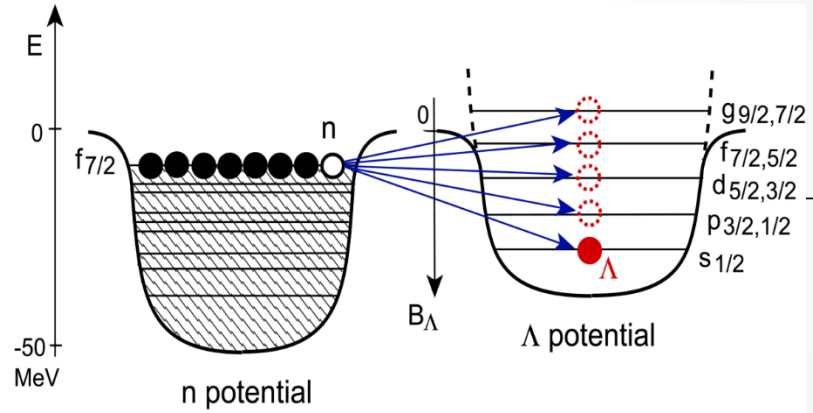
S.H. Kim, A. Hosaka, H.C. Kim, H. Noumi, K. Shirotori
Prog. Theor. Exp. Phys. 103D01 (2014).

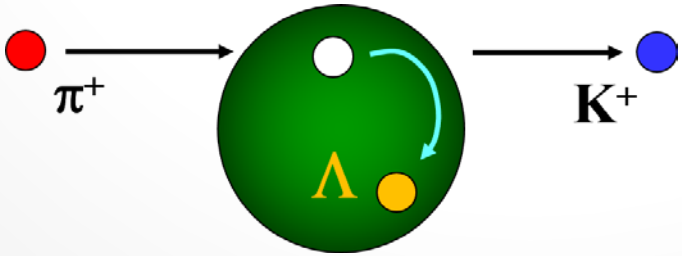
Production by hadron beam

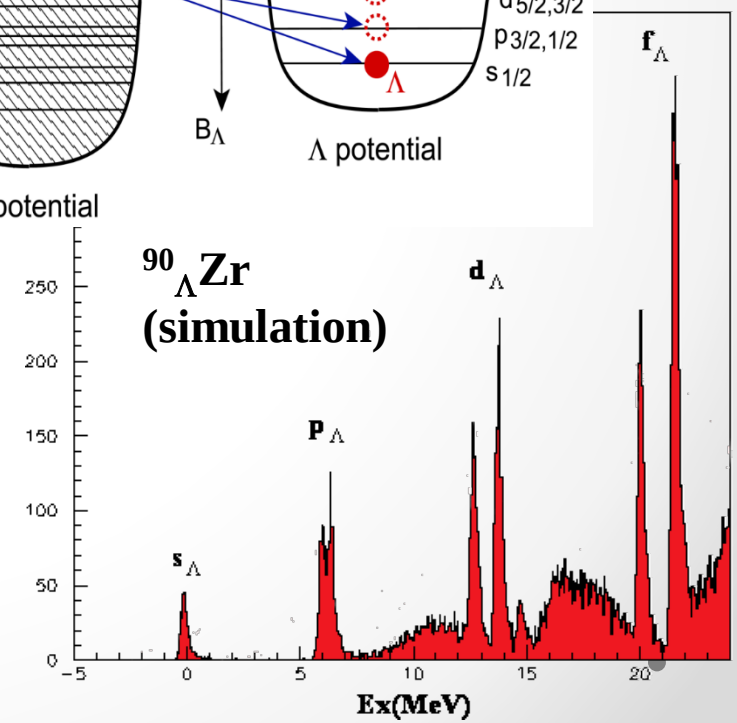
Hadronic production: $\pi^- + p \rightarrow Y_c^{*+} + D^{*-}$



Similar mechanism to
$\pi^+ + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + K^+$ **reaction**



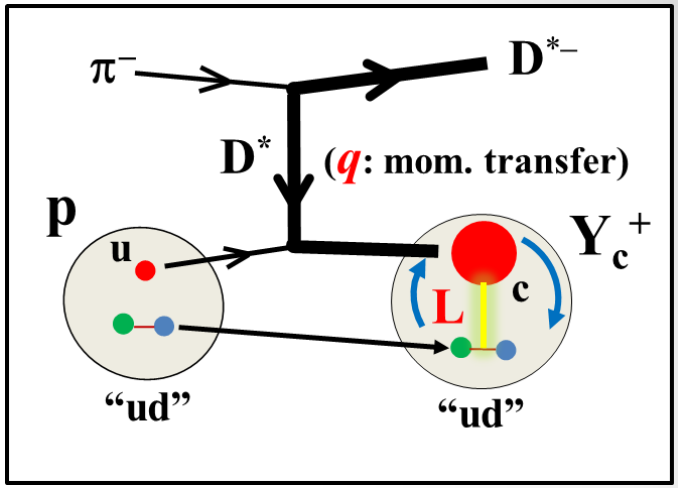


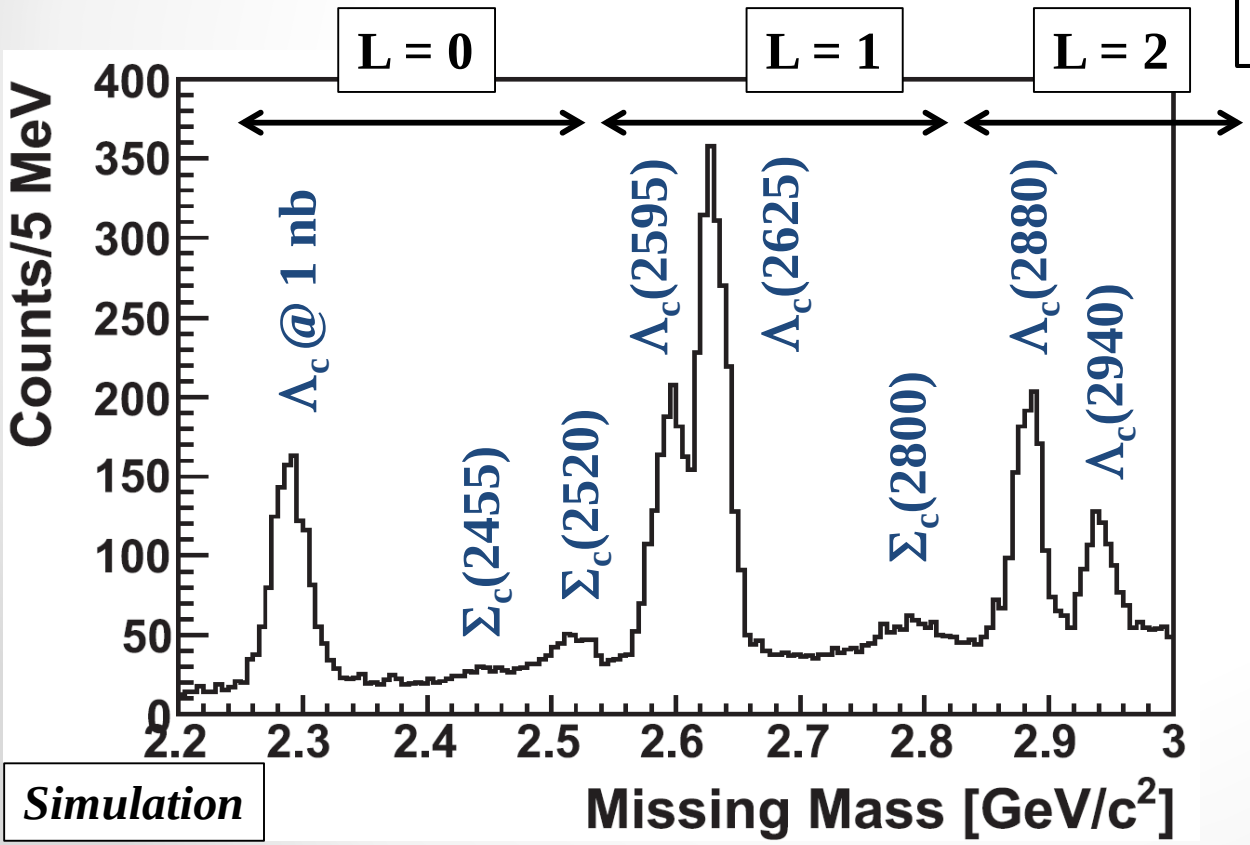


Production by hadron beam

- ✱ Production rates ⇔ Excitation mode
  - Forward angles: λ mode
  - Angular distribution: λ/ρ modes
  - Spin/parity of Y_c^*

⇒ Study from *"Production"*





$$I_L / I_{g.s.} \sim (q_{eff}/A)^L$$

q_{eff}: Momentum transfer
A: (baryon size parameter)$^{-1}$

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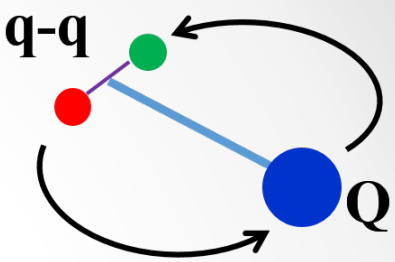
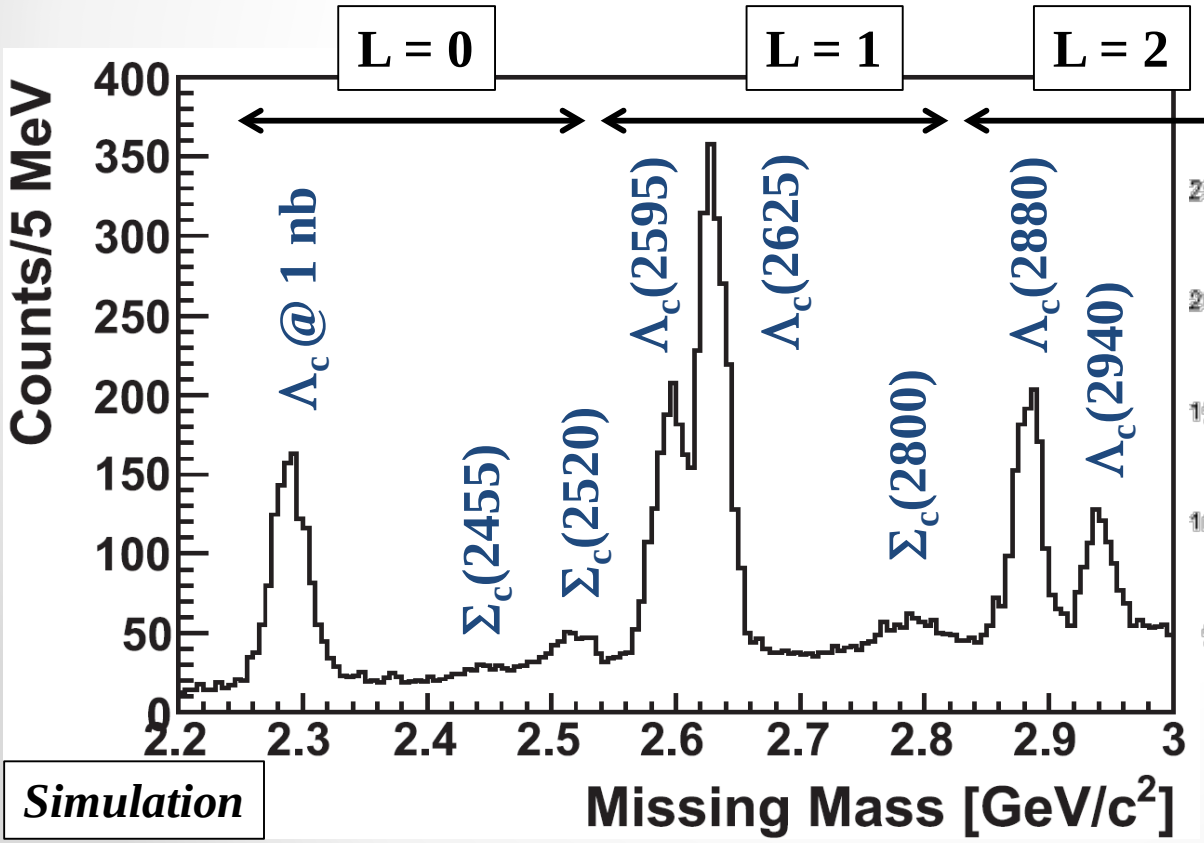
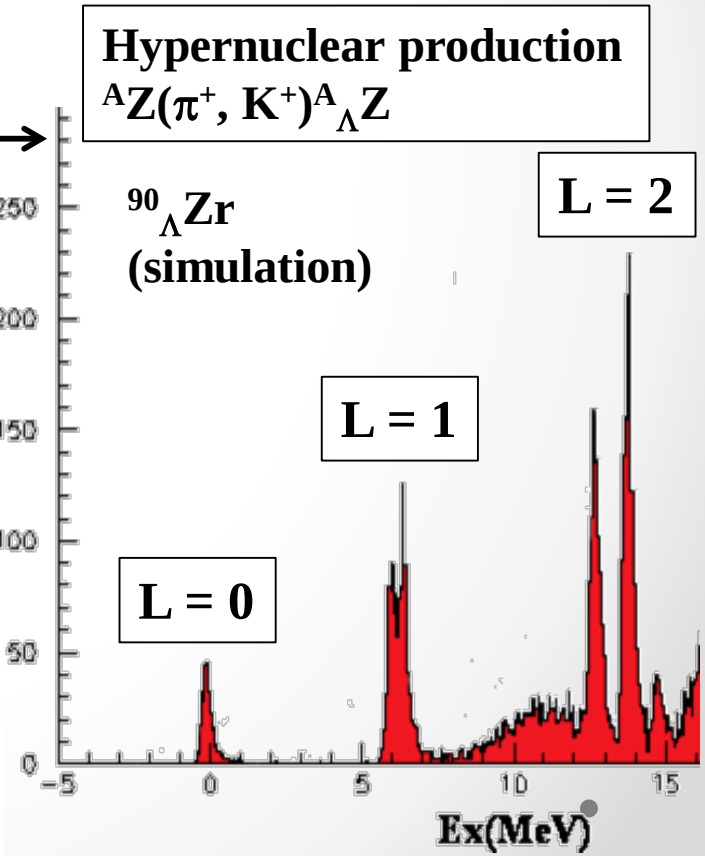


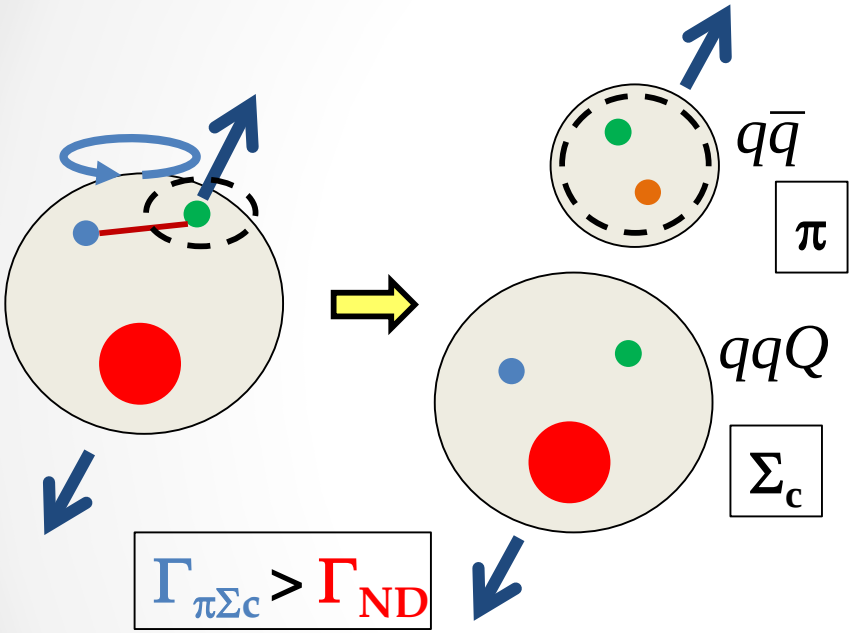
⇒ Unique approach to investigate "q-q + Q" system



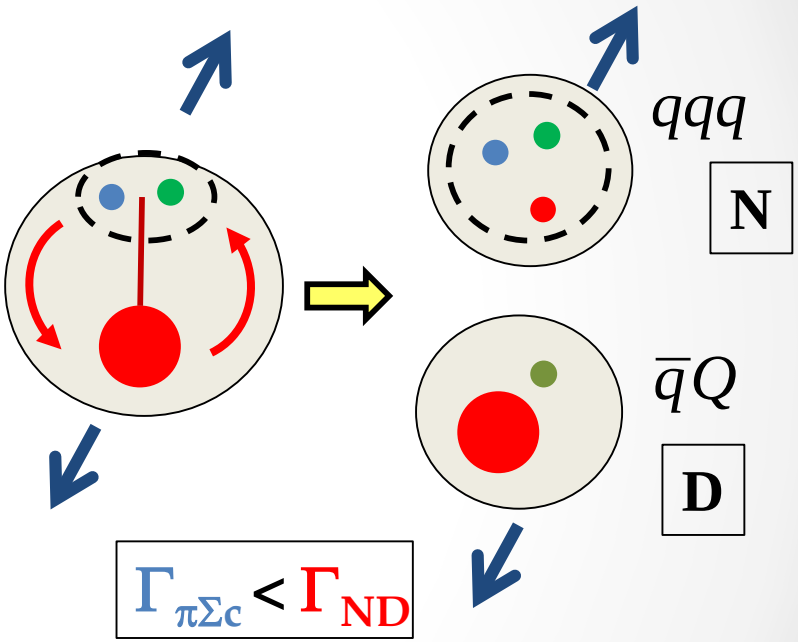


Decay property

ρ-mode decay: qqQ + qq_{bar}



λ-mode decay: qqq + Qq_{bar}



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

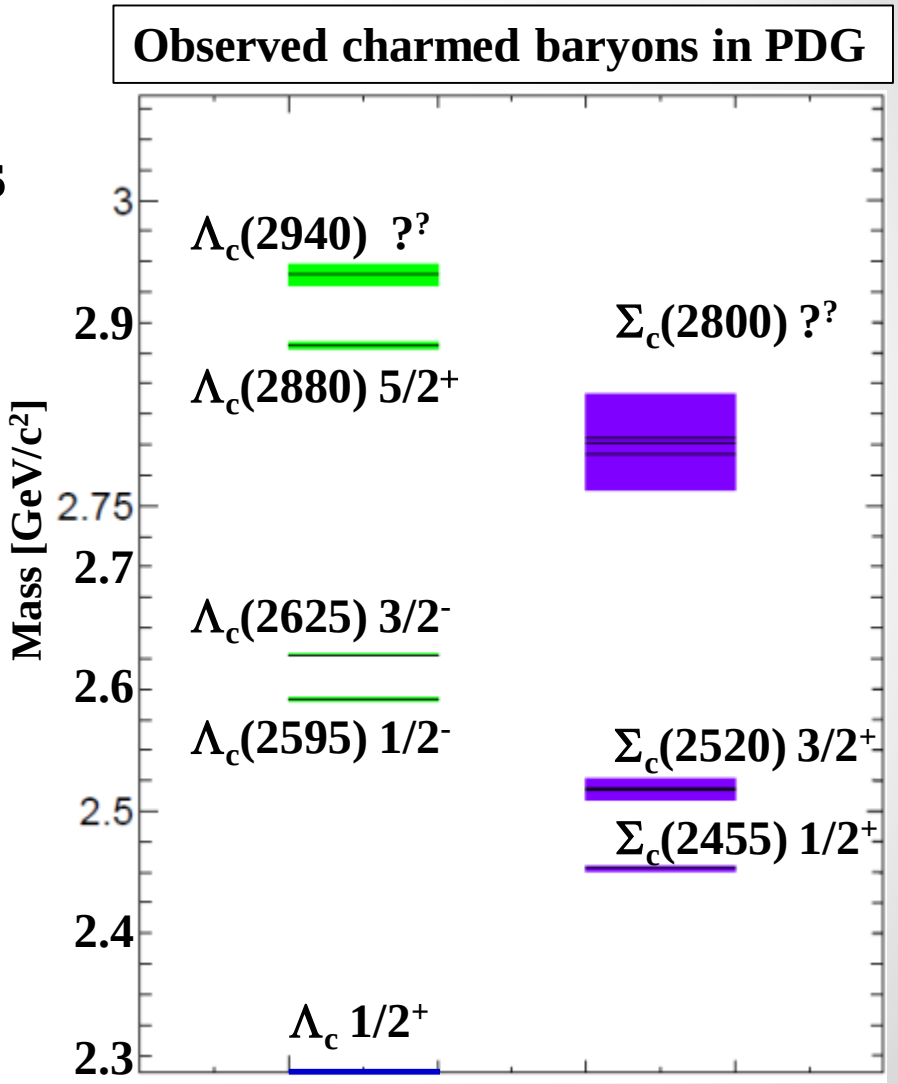
Charmed baryon spectroscopy

J-PARC E50 experiment

- **Investigate charmed baryons by Missing Mass spectroscopy**

- **Systematic measurement**
  - Excited states search
  - Excitation energy
  - Production cross section
  - Decay property

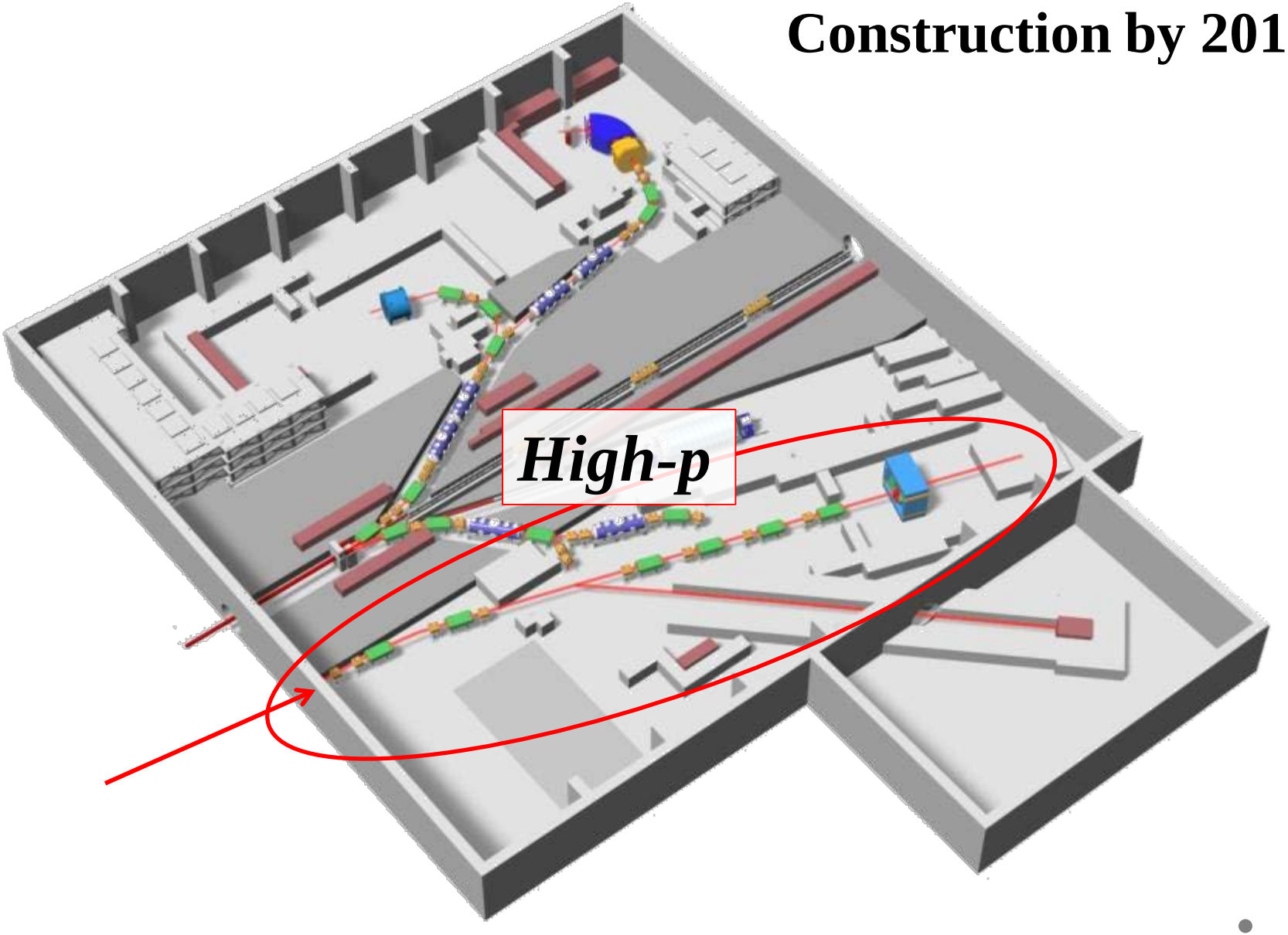
⇒ **Diquark correlation**
  - Excitation mode



Experiment

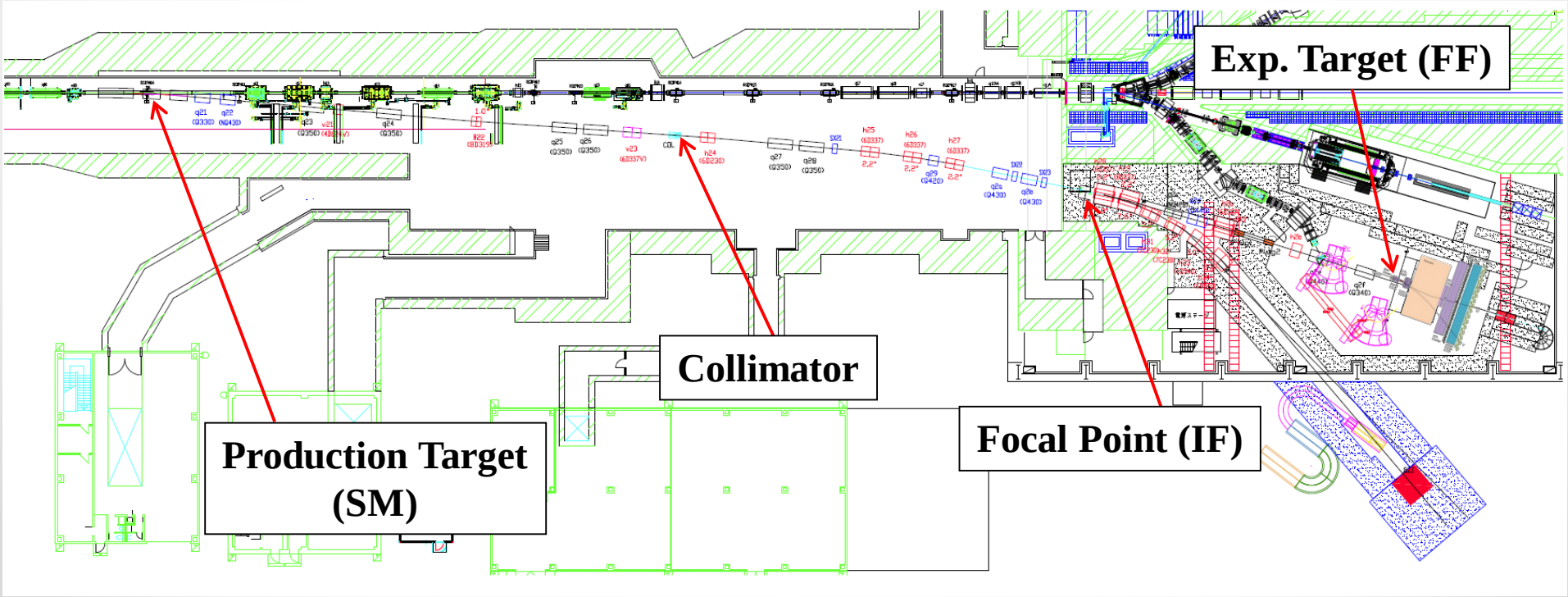
High-momentum beam line

Construction by 2018



High-momentum beam line for 2ndary beam

- **High-intensity beam:** > 1.0×10^7 Hz π (< 20 GeV/c)
  - Unseparated beam
- **High-resolution beam:** $\Delta p/p \sim 0.1\%$(rms)
  - Momentum dispersive optics method



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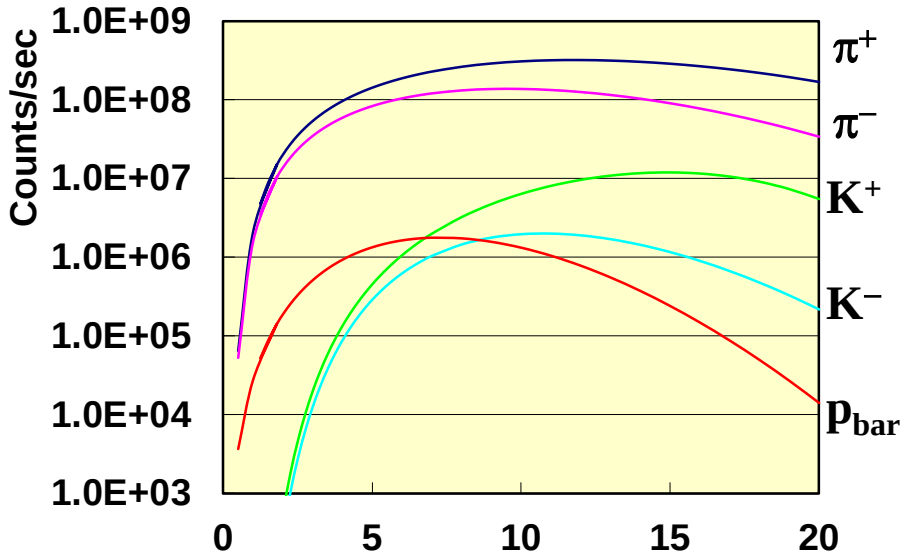
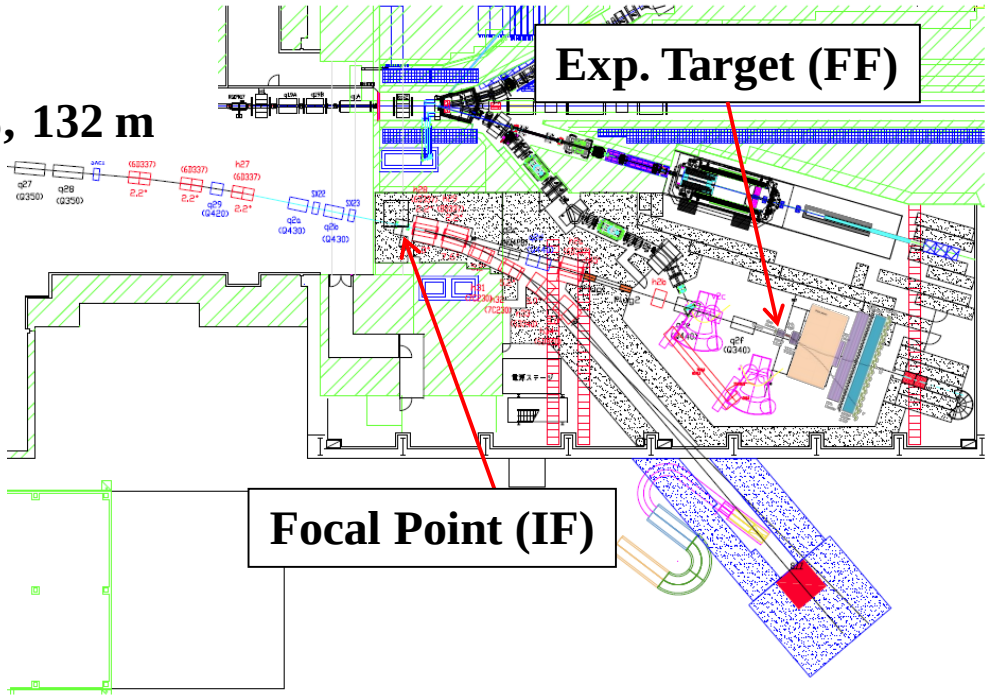
Sanford-Wang

Prod. Angle =0 degrees

15 kW Loss on Pt, Acceptance :2 msr%, 132 m



/spill ⇒ ×6



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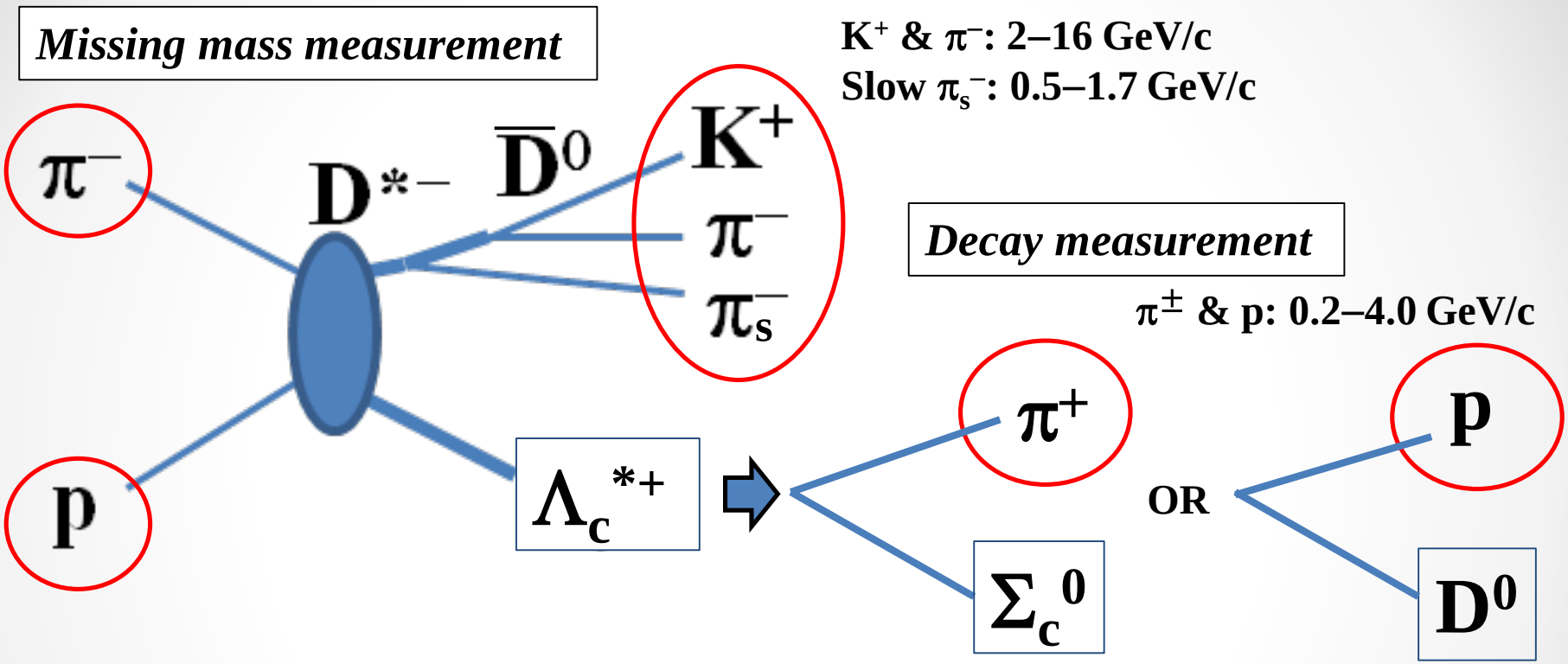


$\pi^- + p \rightarrow Y_c^{*+} + D^{*-}$ reaction @ 20 GeV/c

1) Missing mass spectroscopy

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

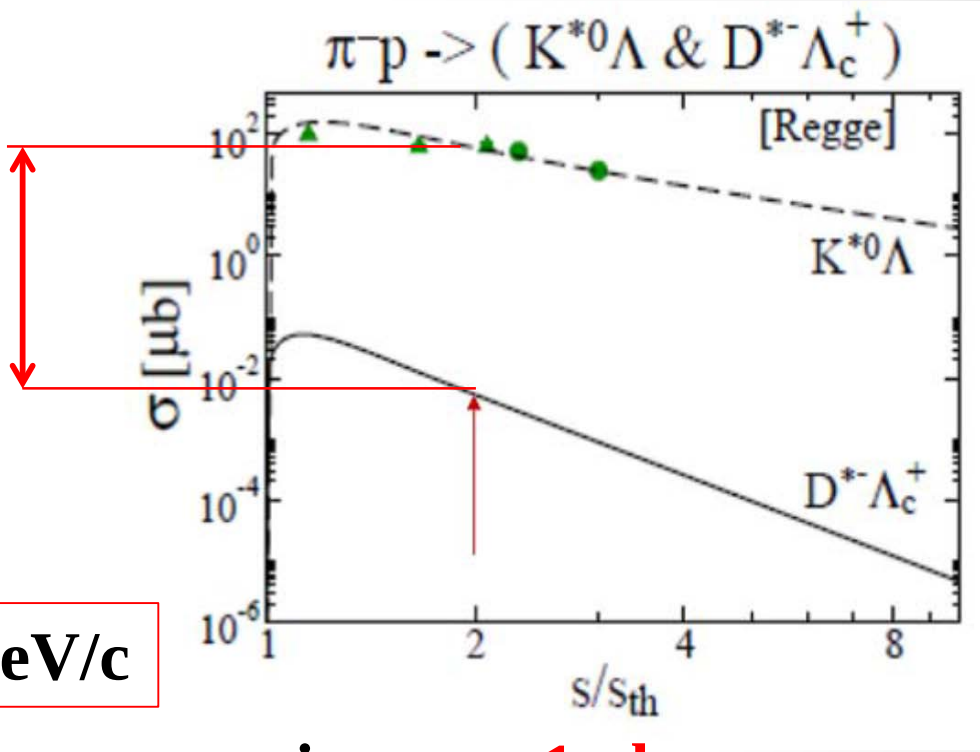
2) Decay measurement

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

Expected production cross section

High energy 2-body reaction based on the Regge theory

Normalized to strangeness production
⇒ Charm production: ~10^{-4}



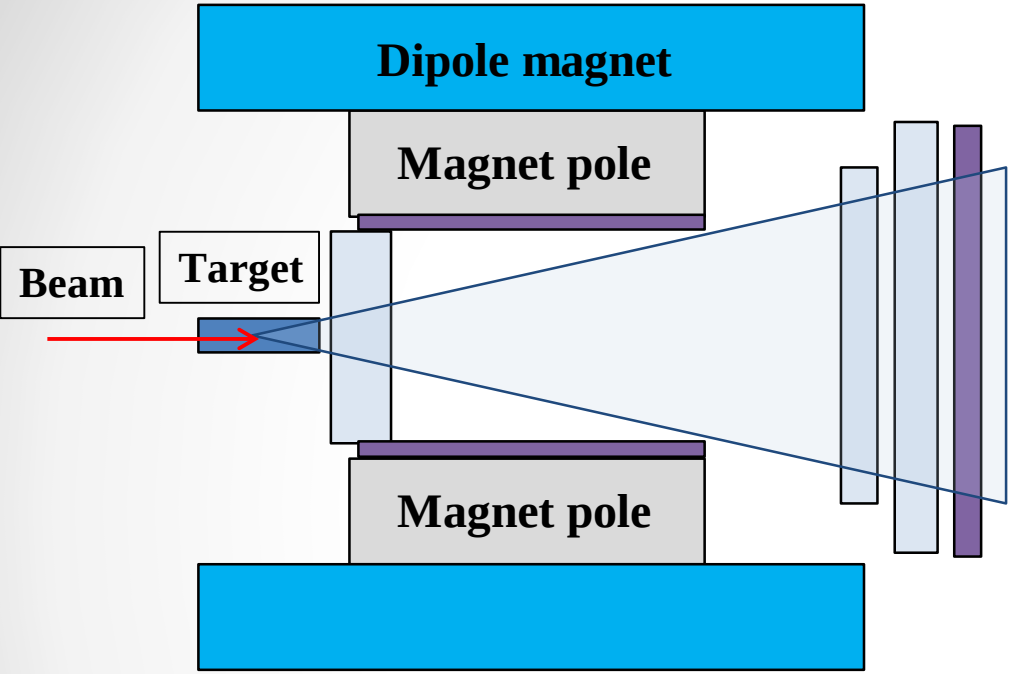
No old data @ 10-20 GeV/c

∗ **Assumed production cross section: σ ~ 1 nb**

- $\pi^- + p \rightarrow \Lambda_c^+ + D^{*-}$ reaction @ 13 GeV/c: σ < 7 nb (BNL data)

- **High-rate beam & Multi-purpose spectrometer system**
  - Beam intensity: 6×10^7 /2.0 sec spill
  - Large acceptance spectrometer

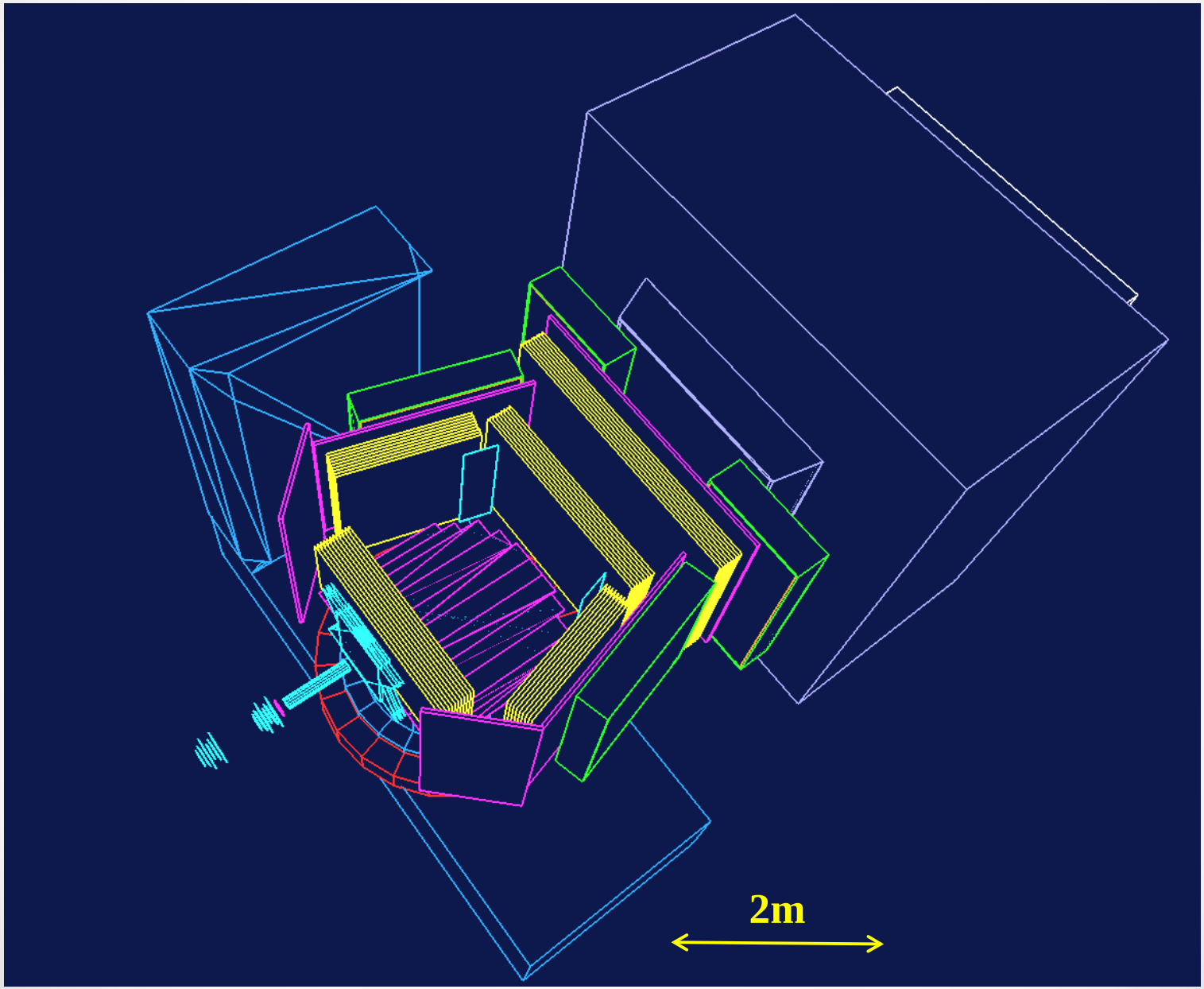
Spectrometer design



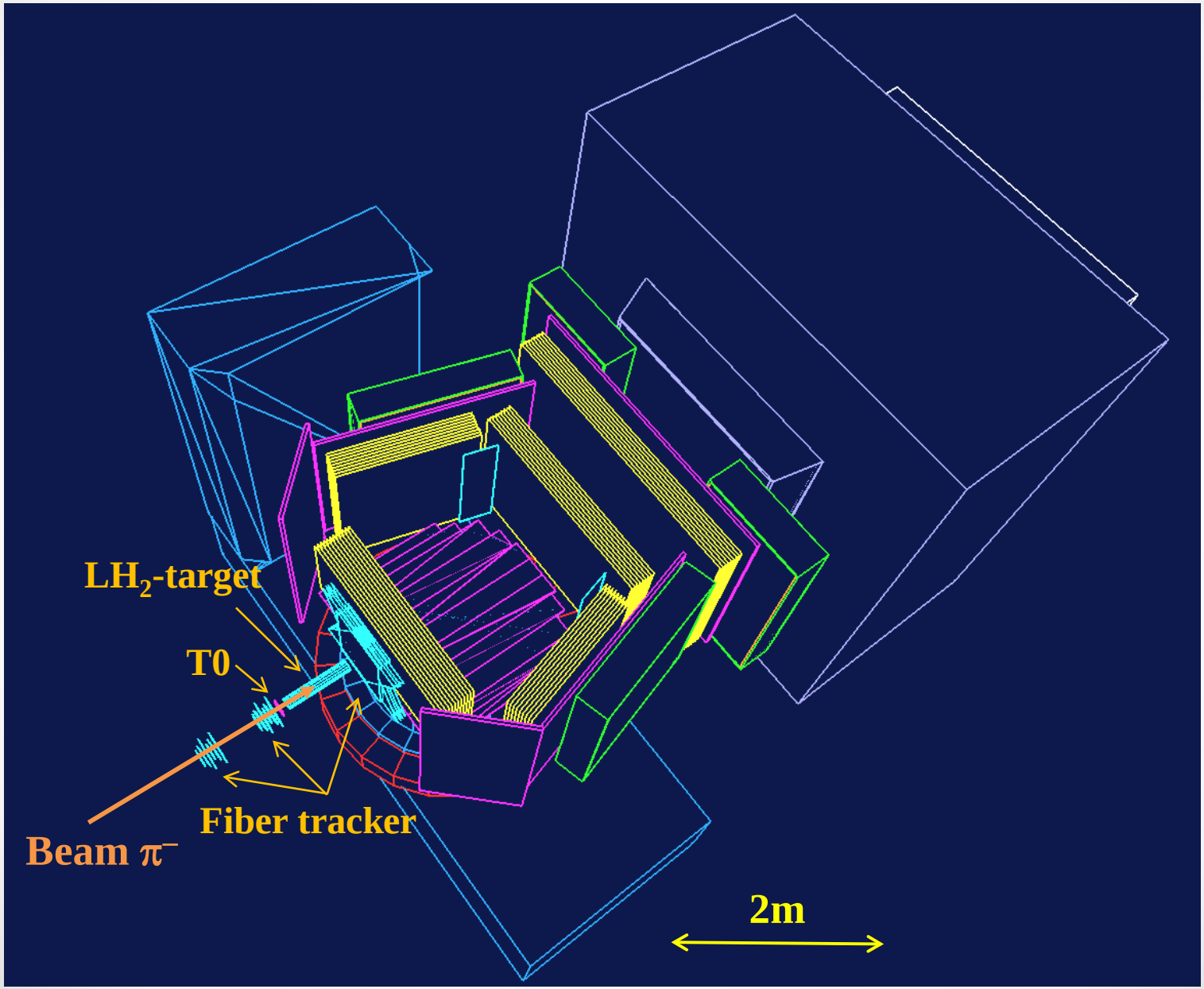
FM cyclotron magnet

- **Scattered partials: Forward direction**
  - **D^* detection by forward detectors**
  - **Y_c^* decay particle detection with wide angular range**
    - **Internal detectors in magnet gap**

Charmed baryon spectrometer



Charmed baryon spectrometer



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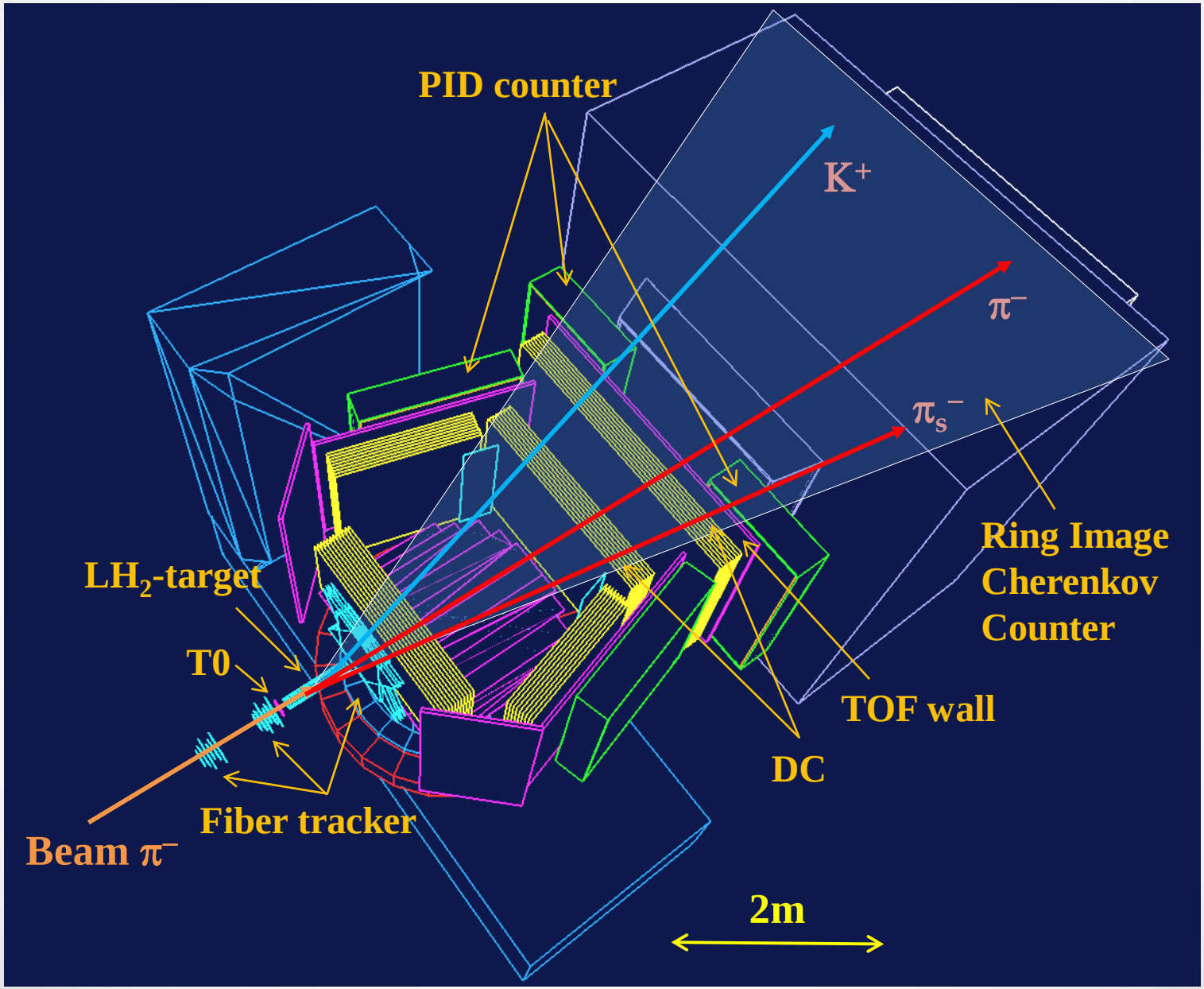

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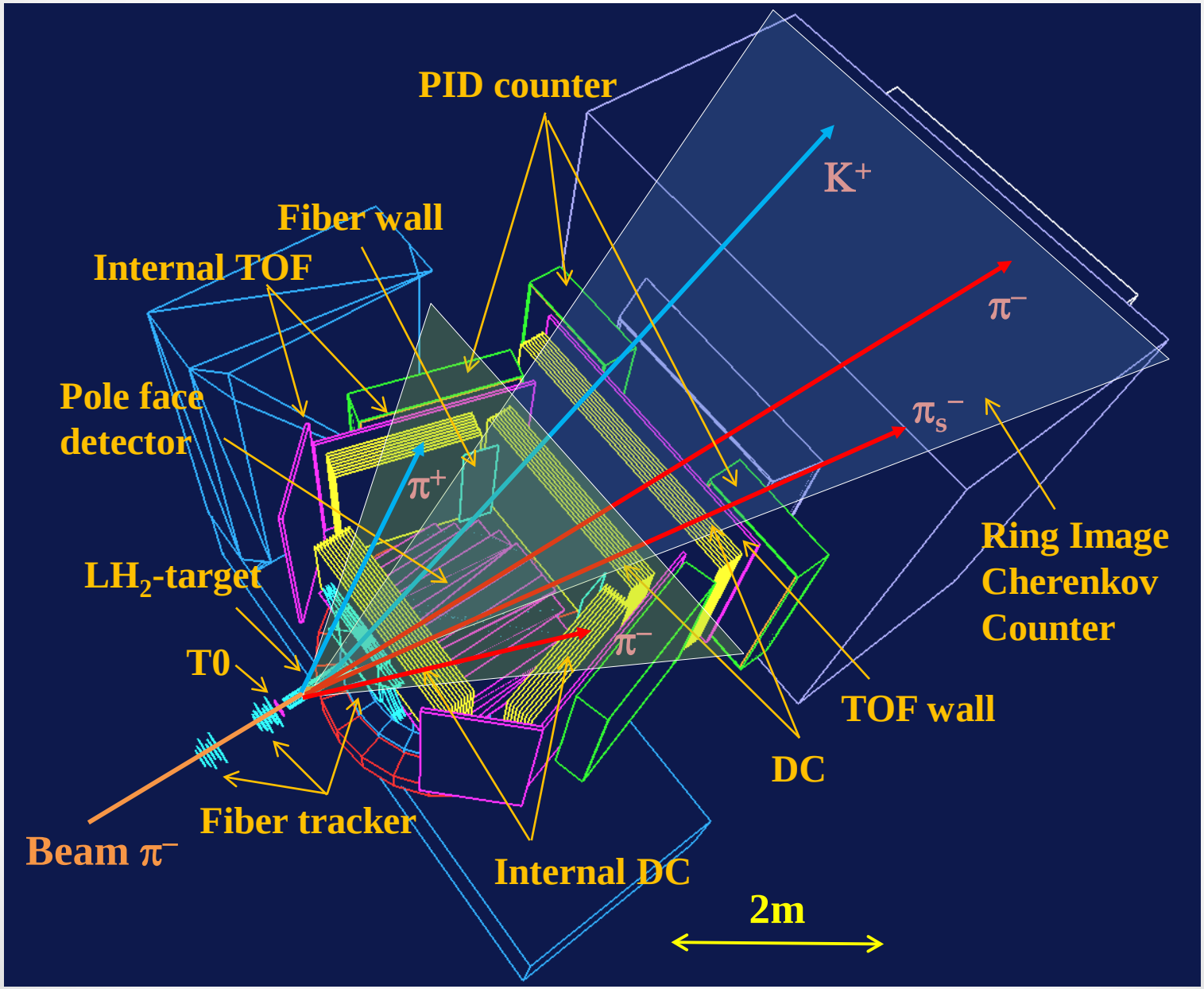
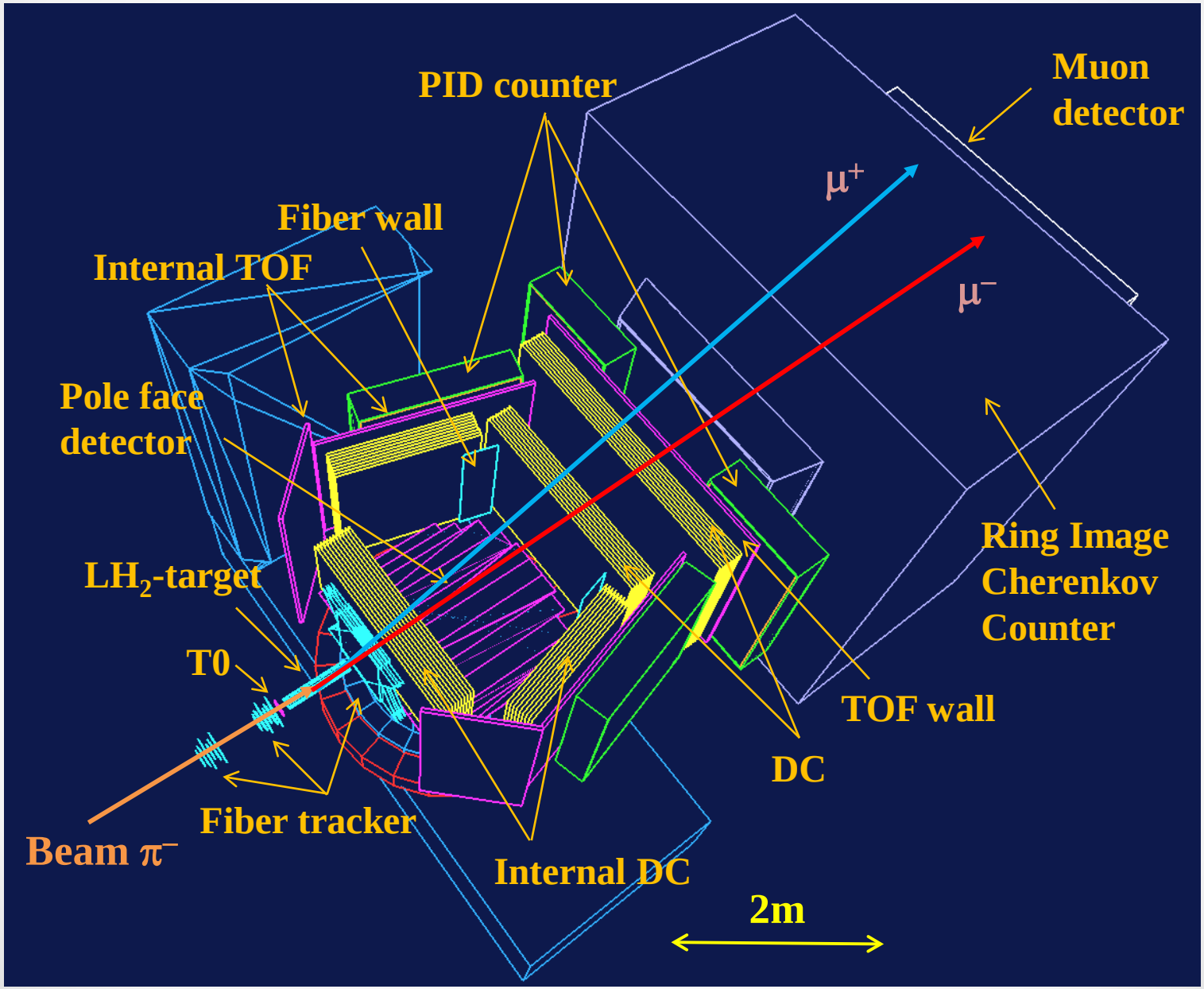
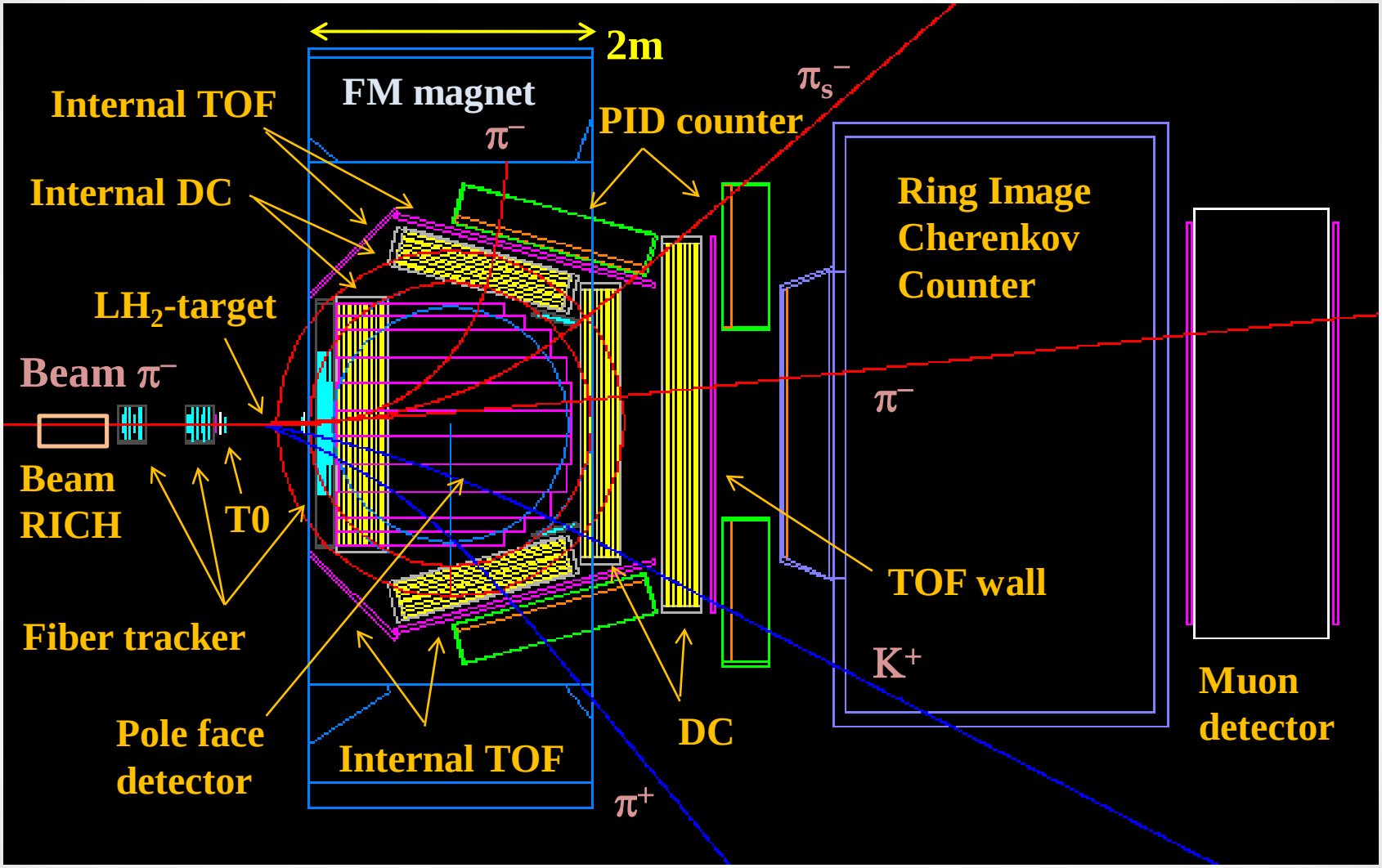


Charmed baryon spectrometer

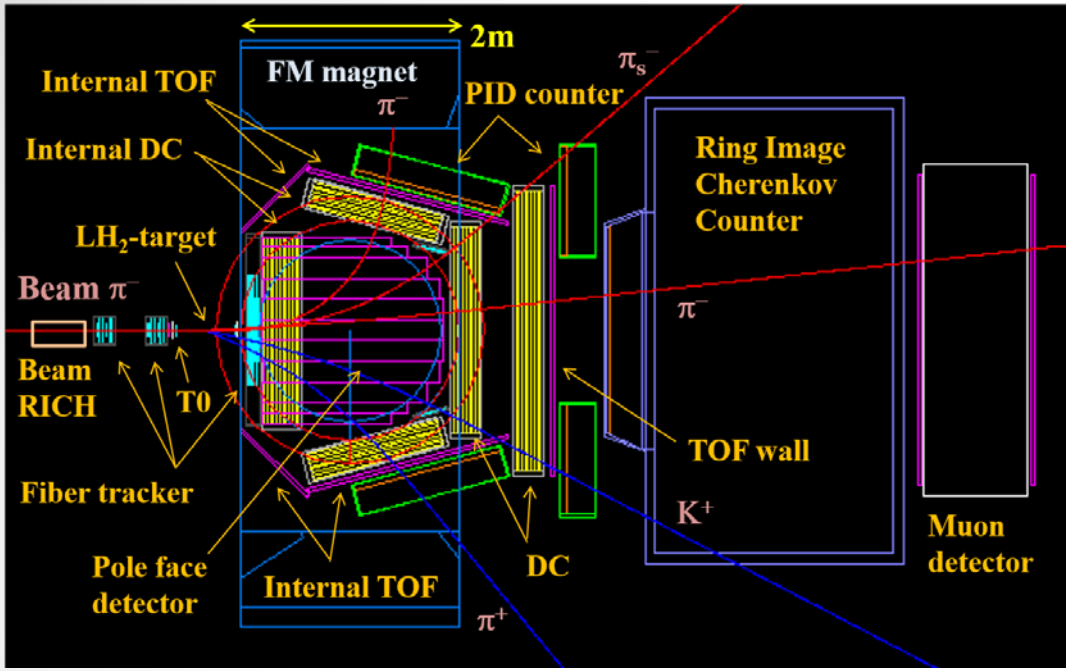


Charmed baryon spectrometer



Large Acceptance Multi-Purpose Spectrometer

Charmed baryon spectrometer

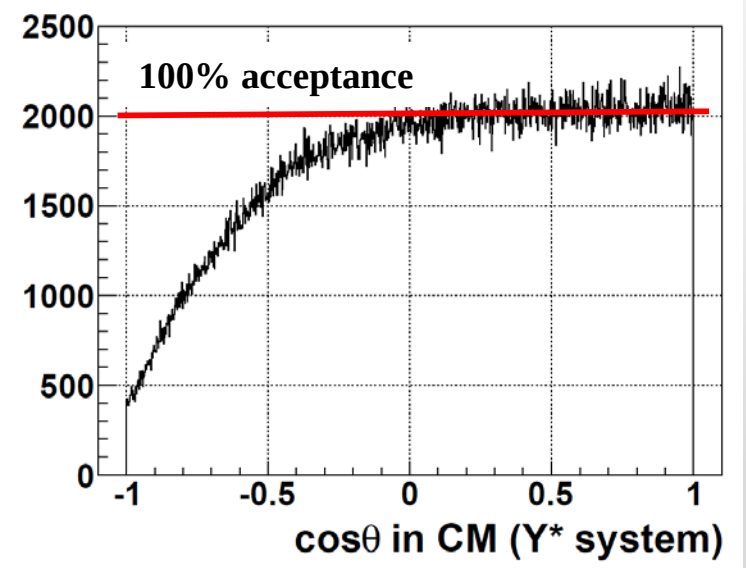


- **Acceptance**
  - **Momentum: 0.2–20 GeV/c**
  - **Angle: < 40°**

  ⇒ D*: 50–60%,

  Decay particle: ~80%
    - **Wide angular coverage**
- **Resolution**
  - **$\Delta p/p$ = 0.2% @ 5 GeV/c**
  - **$\Delta M_{\Lambda c^*}$ = 10 MeV @ 2.8 GeV/c^2**

Decay angle: $\Lambda_c(2940)^+ \rightarrow \Sigma_c(2455)^0 + \pi^+$



To be *"Multi-purpose"*

⇒ High-speed DAQ system

- **Trigger less system**

∗ On-line event reconstruction

by using PC clusters

- **Momentum & PID analysis**

DAQ: Scheme

∗ E50: Streaming DAQ system

Frontend modules

∗ **Signal digitalization**
- Self or periodic trigger
- Pipelined system
  - ~30,000 ch

Buffer PCs (~50 GB/spill)

∗ **Event accumulation**
- Several 10 GB memories
- > 10 spill data

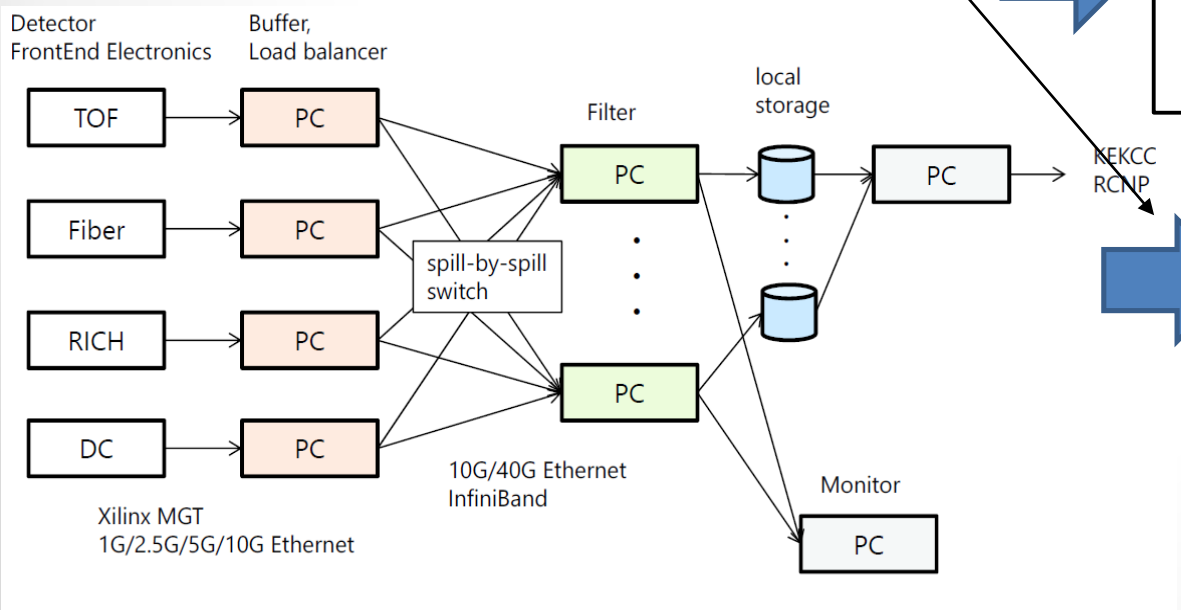
∗ **High-speed data link**

Gigabit transceivers, Ethernet

Filter PCs (~50 GB/spill)

∗ **Event reconstruction**
- Several 10 GB memories
- 100–200 CPUs

Storage (< 0.5 GB/spill)
- Local storage
- Transferred to KEKCC/RNCP



∗ **Data rate: 4 g/cm^2 target and 30 MHz beam conditions**

Data taking channels: For example

- **Charmed baryons**
  - $\pi^- + p \rightarrow Y_c^+ + D^{*-}$
- **Ξ_c baryons**
  - $\pi^- + p \rightarrow \Xi_c^0 + D^{*-} + K^+$

- **Y baryons: Yield = $Y_c \times 10^4$**
  - $\pi^- + p \rightarrow Y^0 + K_S^0$
  - $\pi^- + p \rightarrow Y^0 + K^{*0}$
  - $\pi^- + p \rightarrow Y^- + K^{*+}$
  - $\pi^- + p \rightarrow \Theta^+ + K^{*-}$
- **Ξ baryons: Yield = $Y_c \times 10^3$**
  - $K^- + p \rightarrow \Xi^0 + K^{*0}$
  - $K^- + p \rightarrow \Xi^- + K^{*+}$: $(K_S^0 + \pi^+)$
  - $\pi^- + p \rightarrow \Xi^- + K_S^0 + K^+$
  - $\pi^- + p \rightarrow \Xi^- + K^{*0} + K^+$
- **Ω baryons: Yield = $Y_c \times 10^2$**
  - $K^- + p \rightarrow \Omega^- + K_S^0 + K^+$
  - $K^- + p \rightarrow \Omega^- + K^{*0} + K^+$

∗Hyperon beams as well

- **Drell-Yan channels**
  - $\pi^- + p \rightarrow n + \mu^+ + \mu^-$ (Same as P_c^0)
  - $K^- + p \rightarrow Y^0 + \mu^+ + \mu^-$

Data taking channels: For example

- **Charmed baryons**
  - $\pi^- + p \rightarrow Y_c^+ + D^{*-}$
- Ξ_c **baryons**
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  - $K^- + p \rightarrow \Omega^- + K^{*0} + K^+$

∗ **Hyperon beams as well**

- **Drell-Yan channels**
  - $\pi^- + p \rightarrow n + \mu^+ + \mu^-$ (Same as P_c^0)
  - $K^- + p \rightarrow Y^0 + \mu^+ + \mu^-$

Main channel

Data rate: < 0.1 kHz

Data taking channels: For example

- **Charmed baryons**
  - $\pi^- + p \rightarrow Y_c^+ + D^{*-}$
- **Ξ_c baryons**
  - $\pi^- + p \rightarrow \Xi_c^0 + D^{*-} + K^+$
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  - $\pi^- + p \rightarrow Y^0 + K^{*0}$
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  - $K^- + p \rightarrow \Xi^0 + K^{*0}$
  - $K^- + p \rightarrow \Xi^- + K^{*+}$: $(K_S^0 + \pi^+)$
  - $\pi^- + p \rightarrow \Xi^- + K_S^0 + K^+$
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∗Hyperon beams as well

- **Drell-Yan channels**
  - $\pi^- + p \rightarrow n + \mu^+ + \mu^-$ (Same as P_c^0)
  - $K^- + p \rightarrow Y^0 + \mu^+ + \mu^-$

Byproducts

Event selection as you like !

∗Single scattered channels

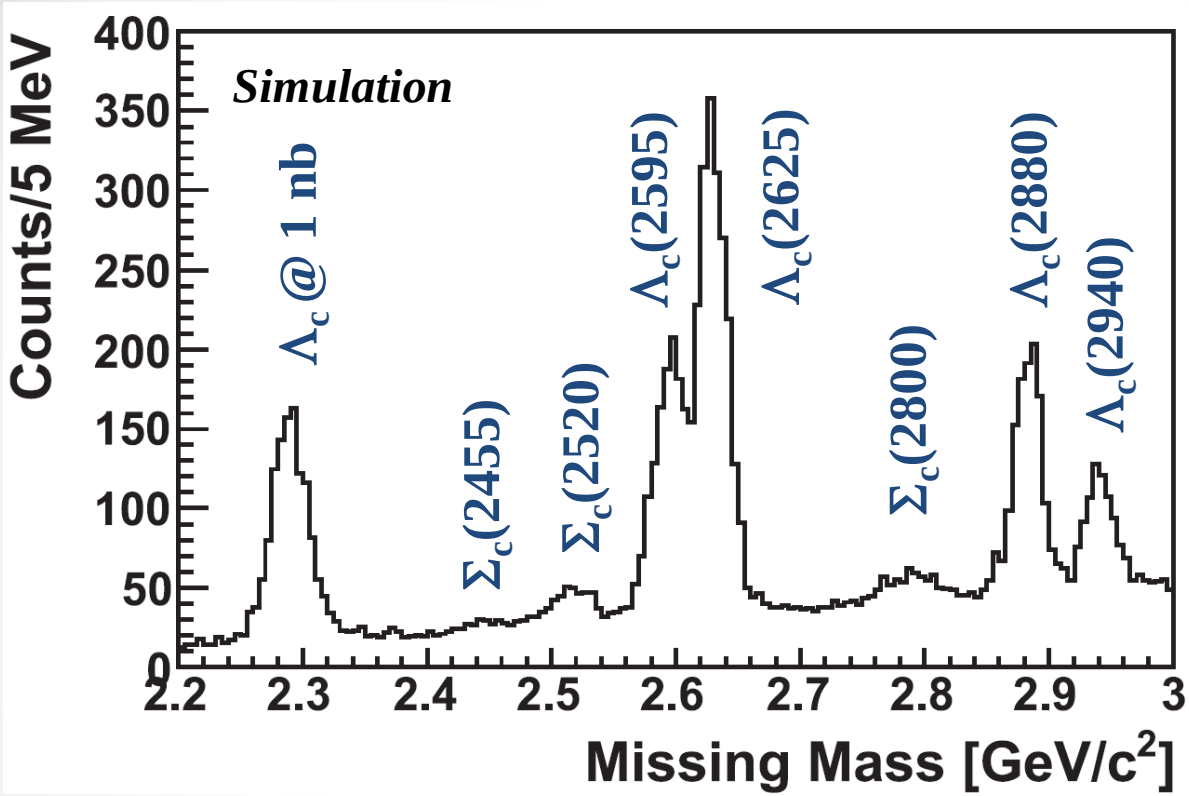
c.f. $\pi^- + p \rightarrow Y + K^+/K^0$

- **K^+/K^0 rate: ~200 kHz**

∗Kaon beam rate ~1/100

c.f. $K^- + p \rightarrow \Xi^- + K^+$

Expected spectra



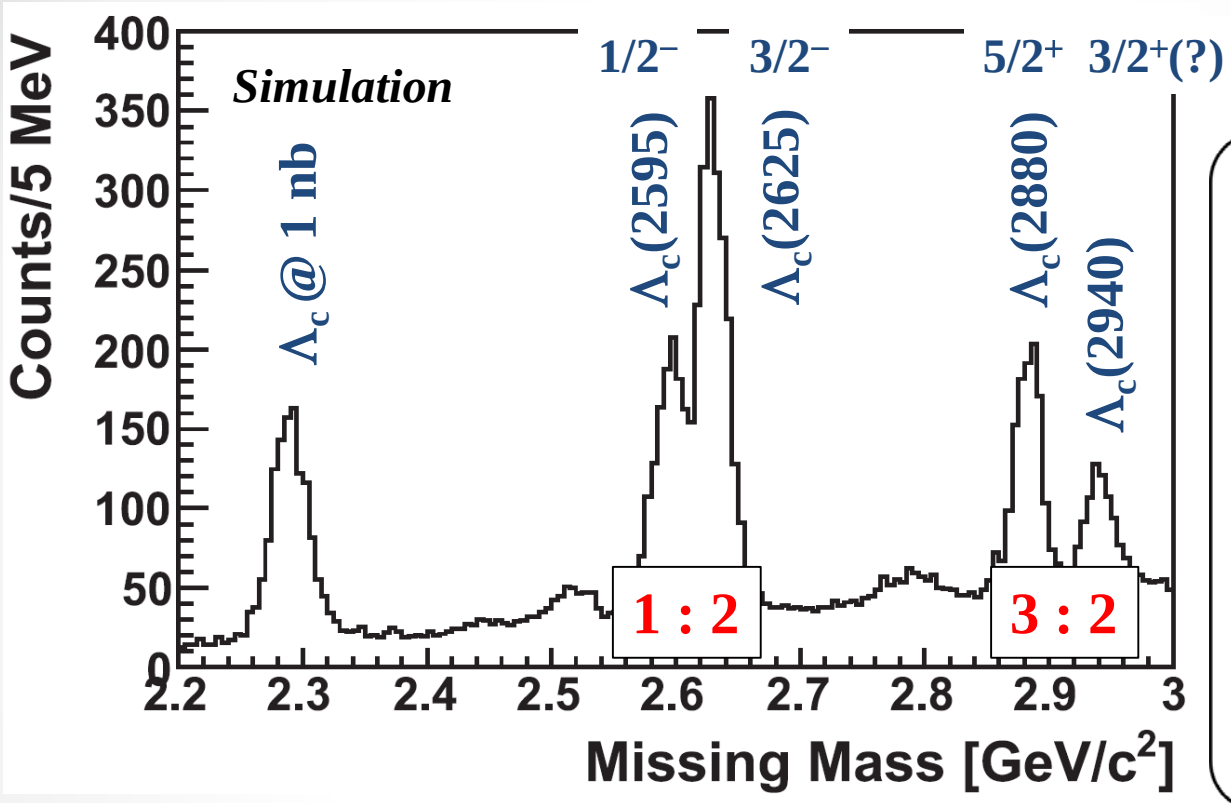
Known Mass & Width in PDG

~2000 counts @ $N_{pot} = 8.64 \times 10^{13}$ (100 days, $\varepsilon_{total} = 0.5$)

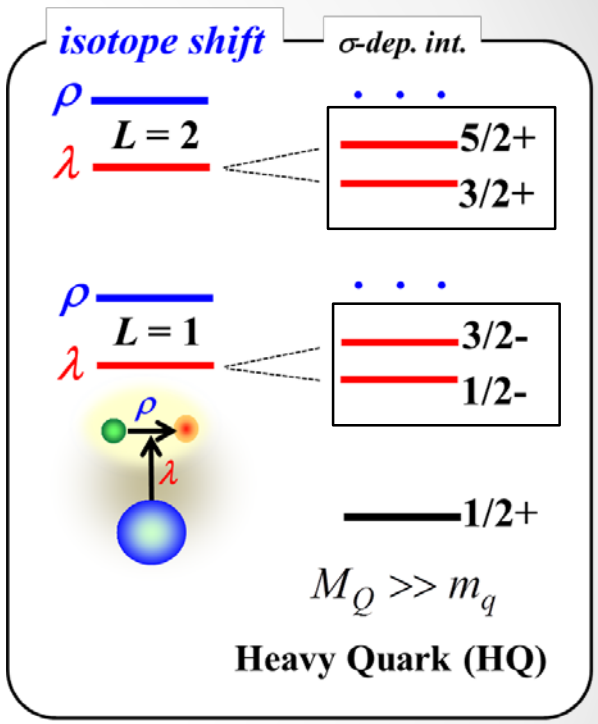
- **Λ_c(g.s.): 1 nb production cross section**
  - **Production ratio for excited states**
- **Background level and reductions were precisely studied.**

∗ Achievable sensitivity of 0.1–0.2 nb: (3σ level, $\Gamma < 100$ MeV)

Expected spectra



Known Mass & Width in PDG



- λ-mode excitation doublets: Production enhanced

HQ doublet

⇒ Internal structure of charmed baryon

- Decay measurement also performed: $\Gamma_{\pi\Sigma c} \Leftrightarrow \Gamma_{pD}$

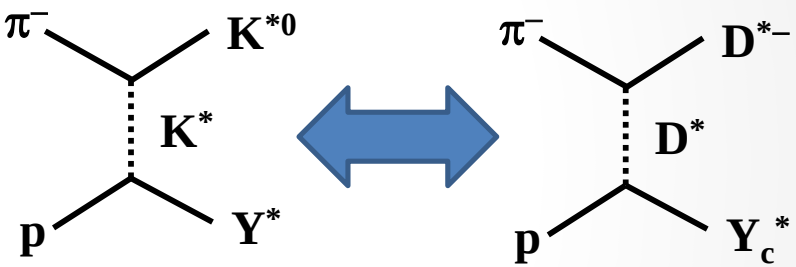
∗Diquark correlation: Excitation mode

Systematics of strangeness baryons

∗ **Yield: 10^4–10^5 /day @ 1 μb**
- 4 g/cm^2, 6×10^7 /spill (~10^6 /spill for K beam)
- 50% acceptance, 50% efficiency (DAQ, PID, Analysis)

- **Y: q-q + Q system @ Strangeness sector**

  c.f. $\pi^- + p \rightarrow Y^* + K^{*0}$ reaction
  - Production ratio
    - Reflect q-q excitation mode
  - Decay branching ratio
    - $\Gamma(NK_{bar})/\Gamma(\pi\Sigma)$



- **Ξ: q + QQ system**

  c.f. $K^- + p \rightarrow \Xi^* + K/K^*$ and $\pi^- + p \rightarrow \Xi^* + K/K^* + K$ reactions
  - Heavier diquark (q-s, s-s) system ?

- **Ω: QQQ system**

  c.f. $K^- + p \rightarrow \Omega^* + K/K^* + K$ reaction
  - Much simpler system: Diquark less system ?

Summary

- **Charmed baryon spectroscopy**
  - **Essential way to understand hadron structure**
  - **Diquark correlation: λ and ρ mode excitation**

- **Experiment at the J-PARC high-p beam line**
  - **Inclusive measurements by missing mass spectroscopy with multi-purpose spectrometer system**
    - **Unique information from the production measurement**
  - **Multi-purpose spectrometer system**
    - **Data taking of many reaction channels by high-speed DAQ**

- **Systematic study of baryons at J-PARC**
  - **Excitation energy, production, decay**

  with strangeness sector: q-q + Q, q + QQ, QQQ
    - **Pilot studies for the K10 beam line**
  - **Systematics to understand hadron structure**

J-PARC E50 collaboration

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- **RIKEN**
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- **Kyoto U**
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- **Tohoku U**
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- **Academia Sinica**
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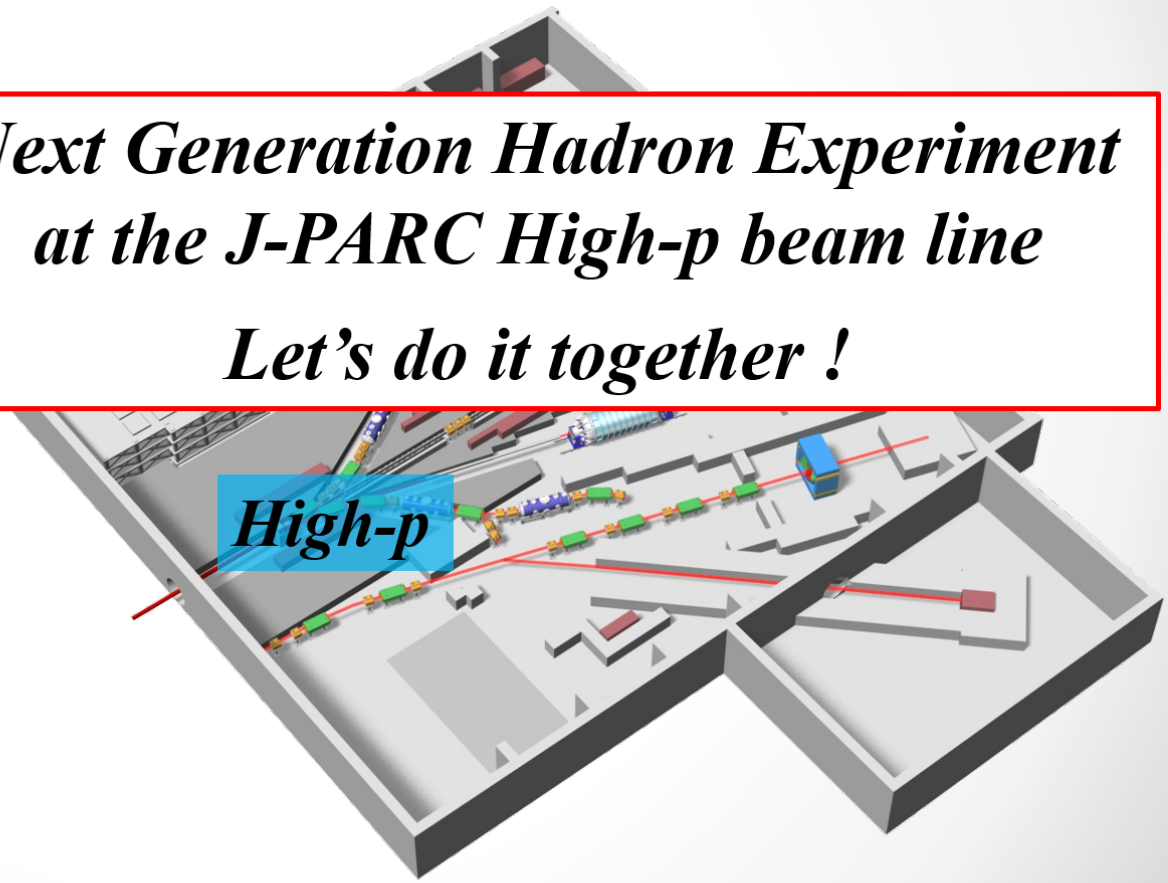
- **Korea U**
  - J.K. Ahn
- **Osaka U**
  - R. Honda
- **JLab**
  - J.T. Goetz

Next Generation Hadron Experiment at the J-PARC High-p beam line

Let's do it together !



Thank you for your attention

Joint collaboration at High-p