Charmed baryon experiment at the J-PARC high-momentum beam line

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for the J-PARC E50 collaboration

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KEK理論センター JPARC分室、JAEA先端基礎研究センター共催研究会
「チャームハドロンの構造と相互作用」

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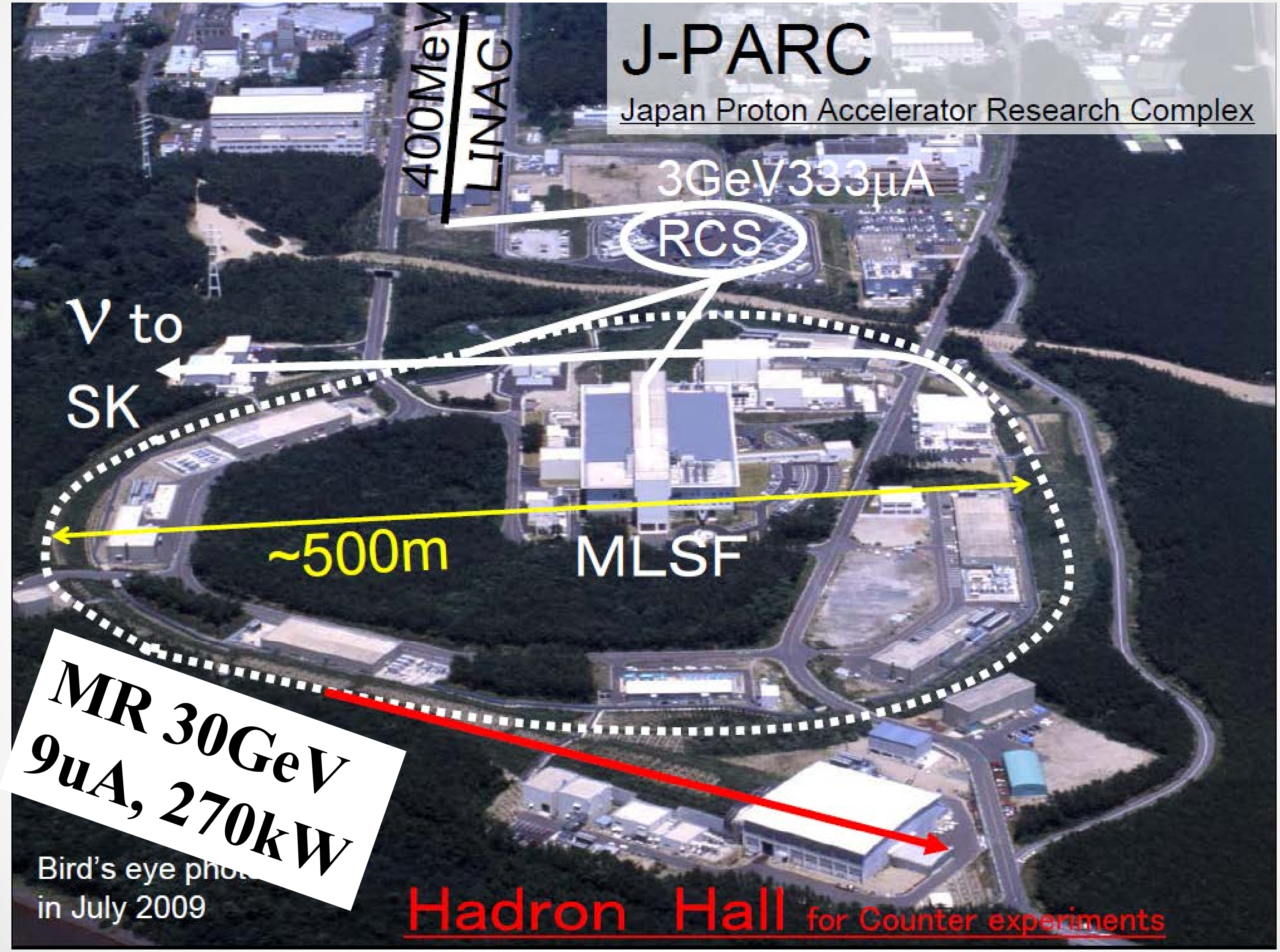
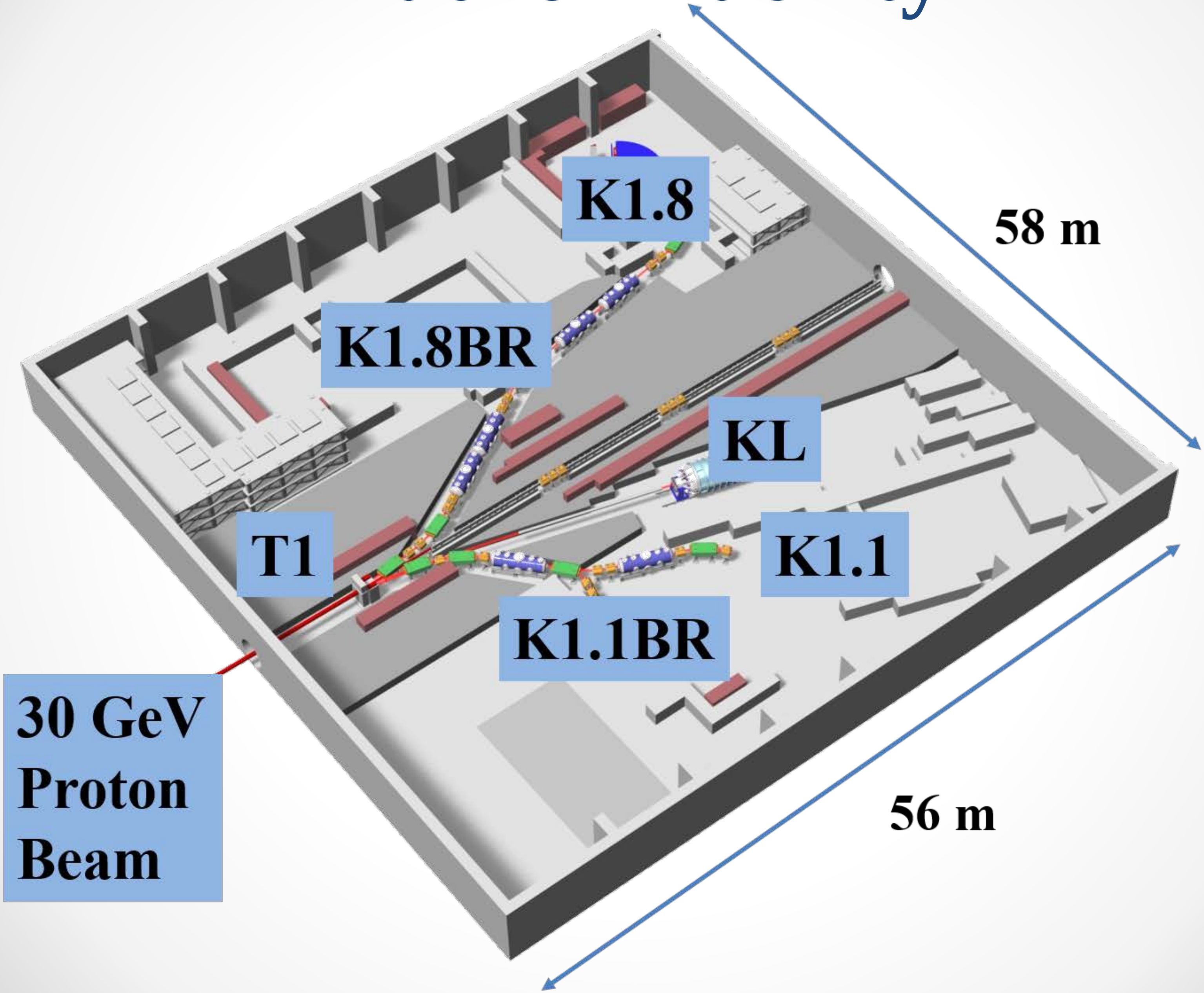
J-PARC & Hadron Facility

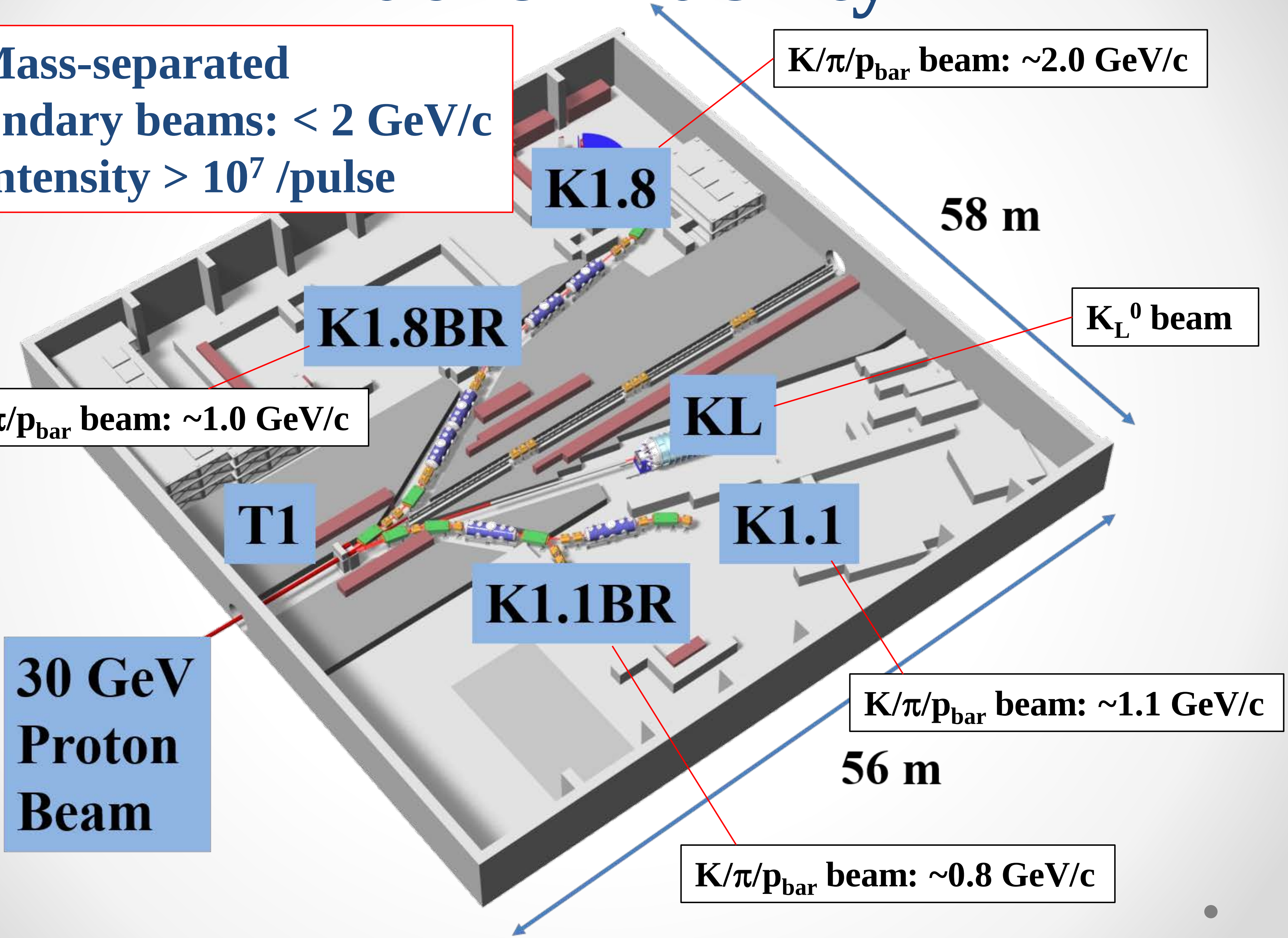


Hadron Facility



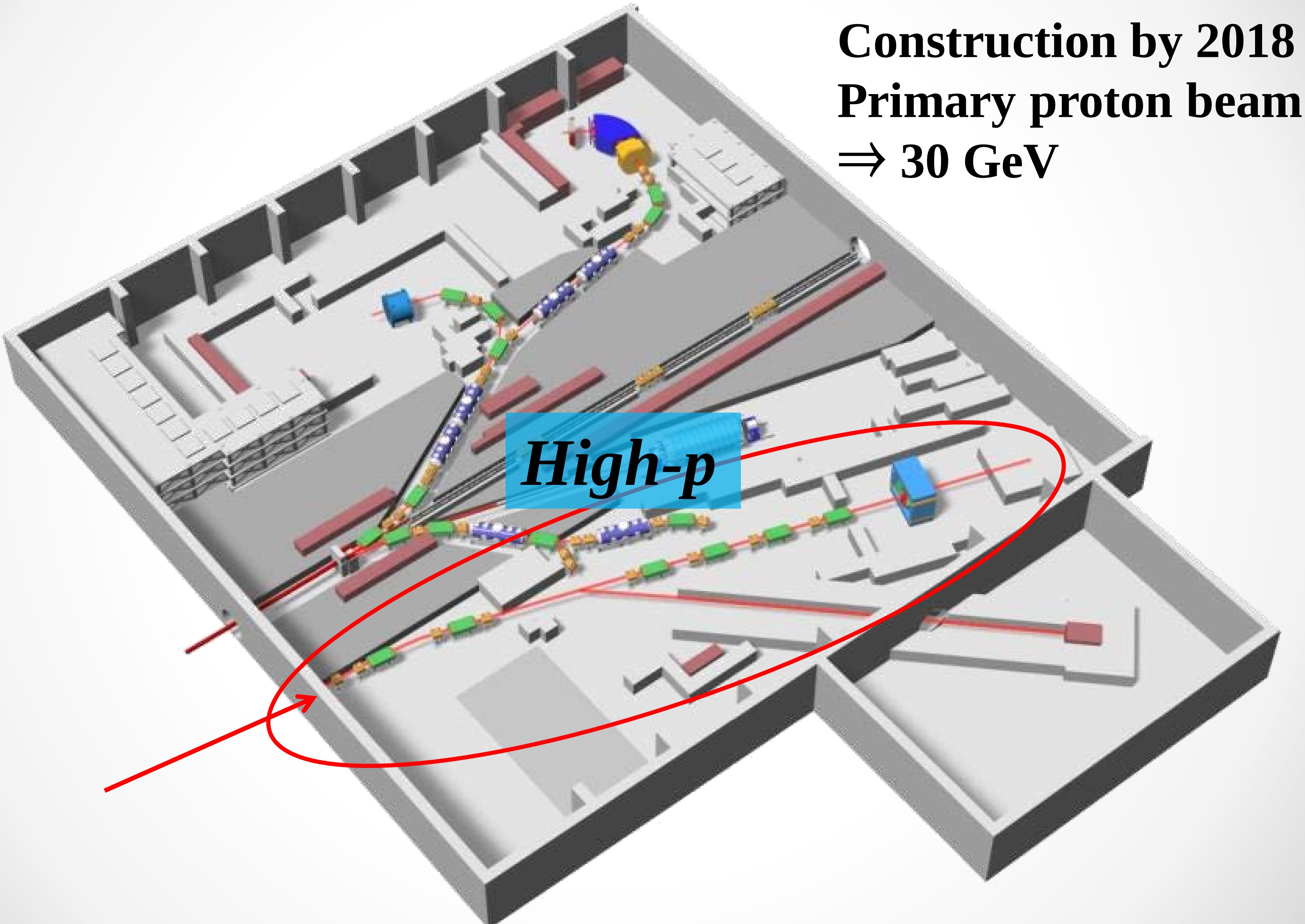
Hadron Facility

- Mass-separated secondary beams: < 2 GeV/c
- Intensity > 10^7 /pulse



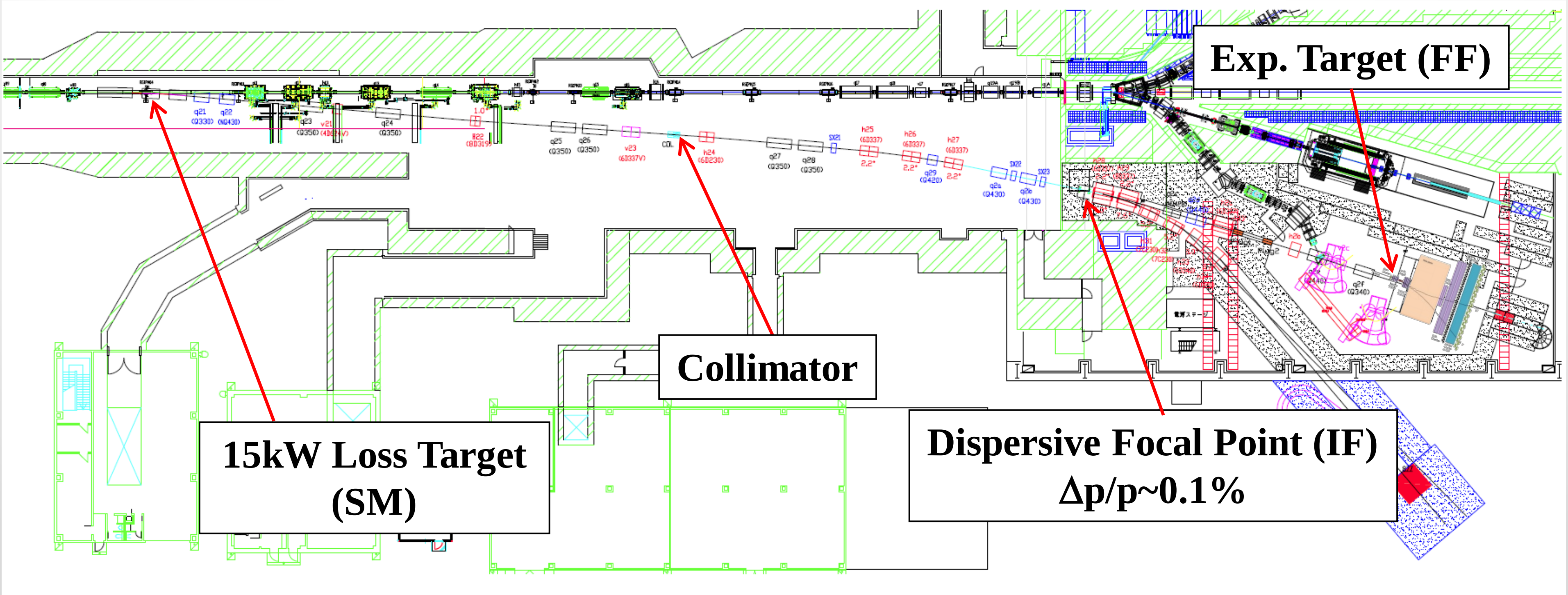
High-momentum beam line

Construction by 2018
Primary proton beam
⇒ 30 GeV



High-momentum beam line for 2ndary beam

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



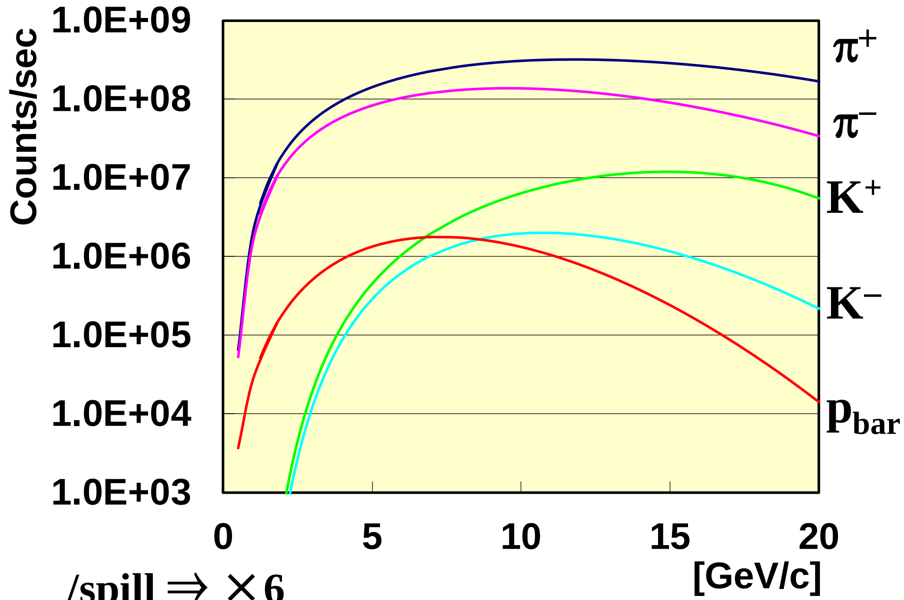
High-momentum beam line for 2ndary beam

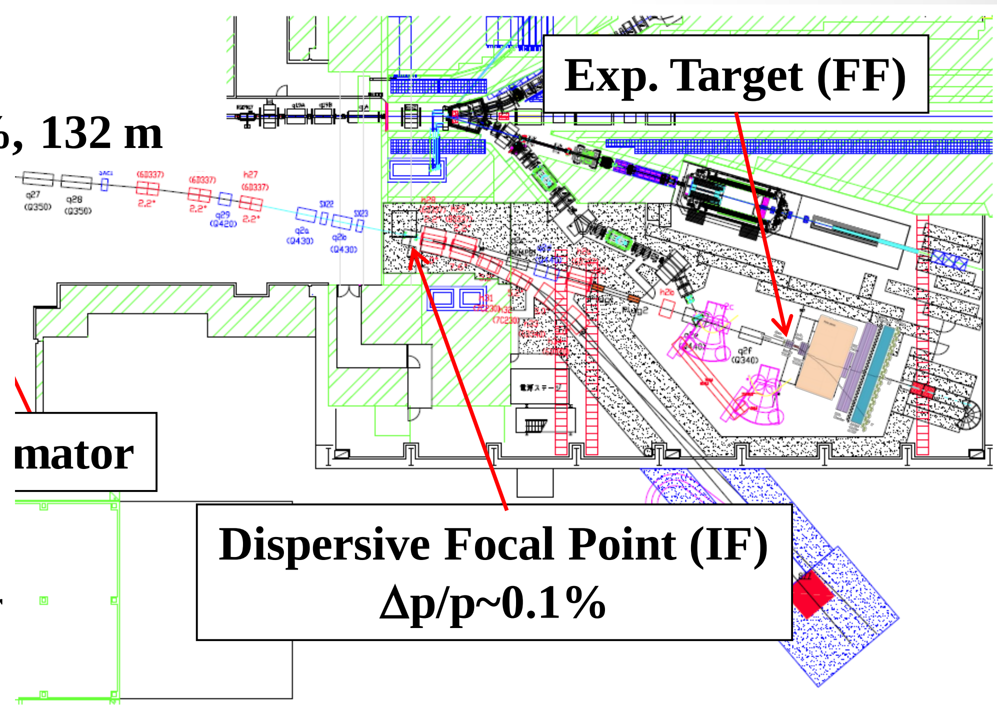
- **High-intensity beam: > 1.0×10^7 Hz π (< 20 GeV/c)**
  - **Unseparated beam**
- **High-resolution beam: Δp/p ~ 0.1%(rms)**
  - **Momentum dispersive optics method**

Sanford-Wang

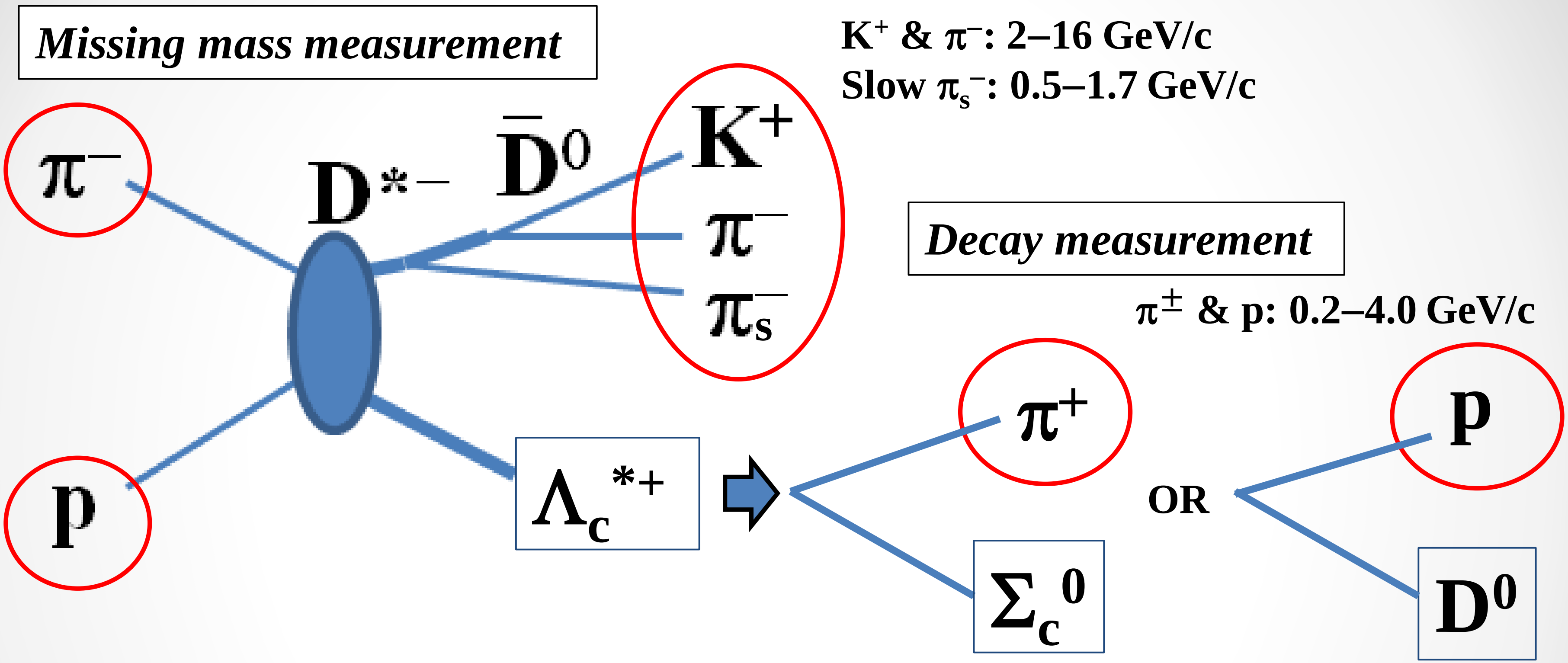
Prod. Angle =0 degrees

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





Experiment



$\pi^- + p \rightarrow Y_c^{*+} + D^{*-}$ 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%)

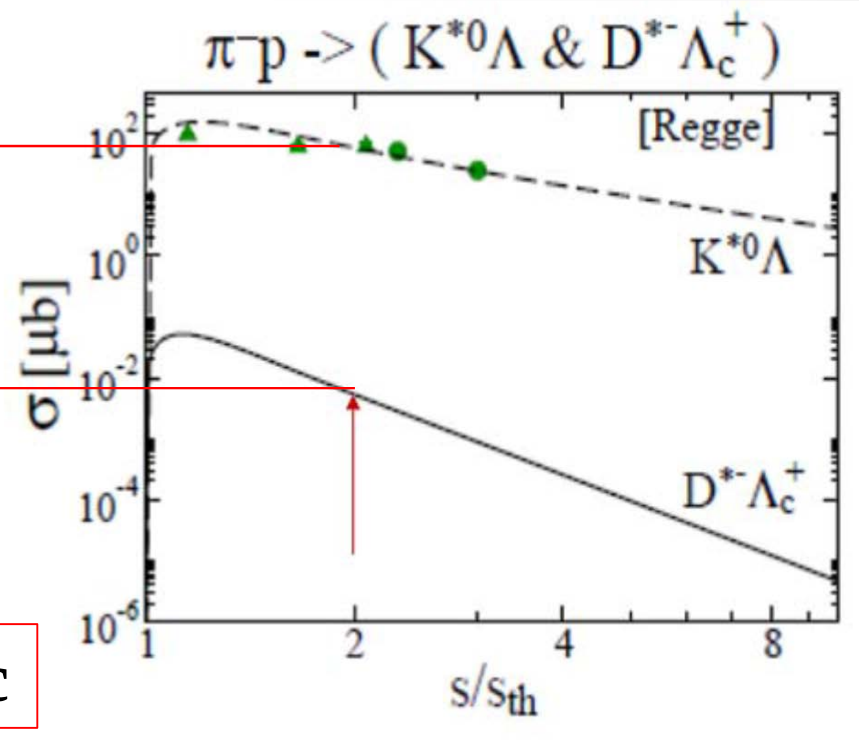
2) Decay measurement

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

Production cross section

High energy 2-body reaction based on the Regge theory

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

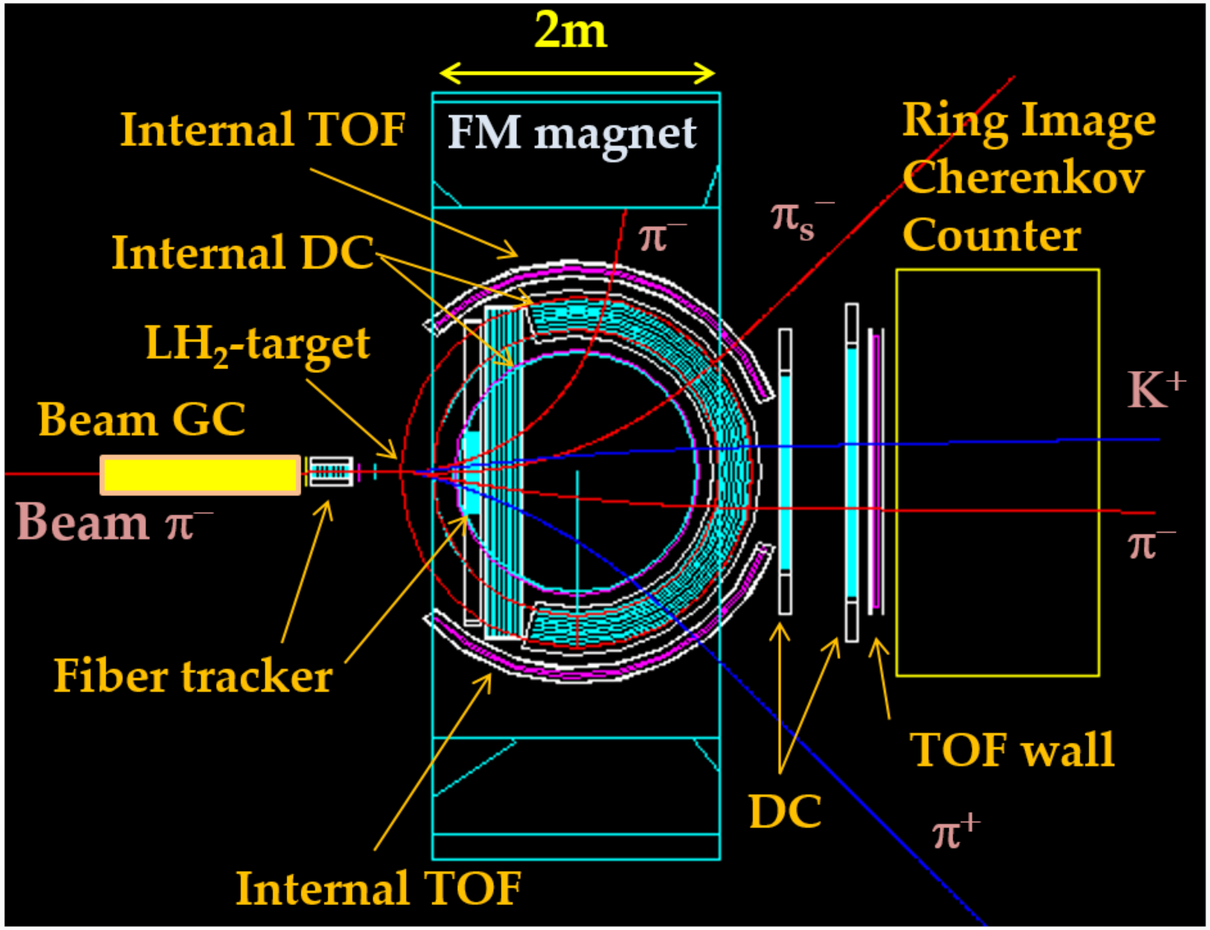


No old data @ 10-20 GeV/c

✱ **Assumed production cross section: σ ~ 1 nb**
- **$\pi^- + p \rightarrow \Lambda_c^+ + D^{*-}$ reaction @ 13 GeV/c: σ < 7 nb (BNL data)**

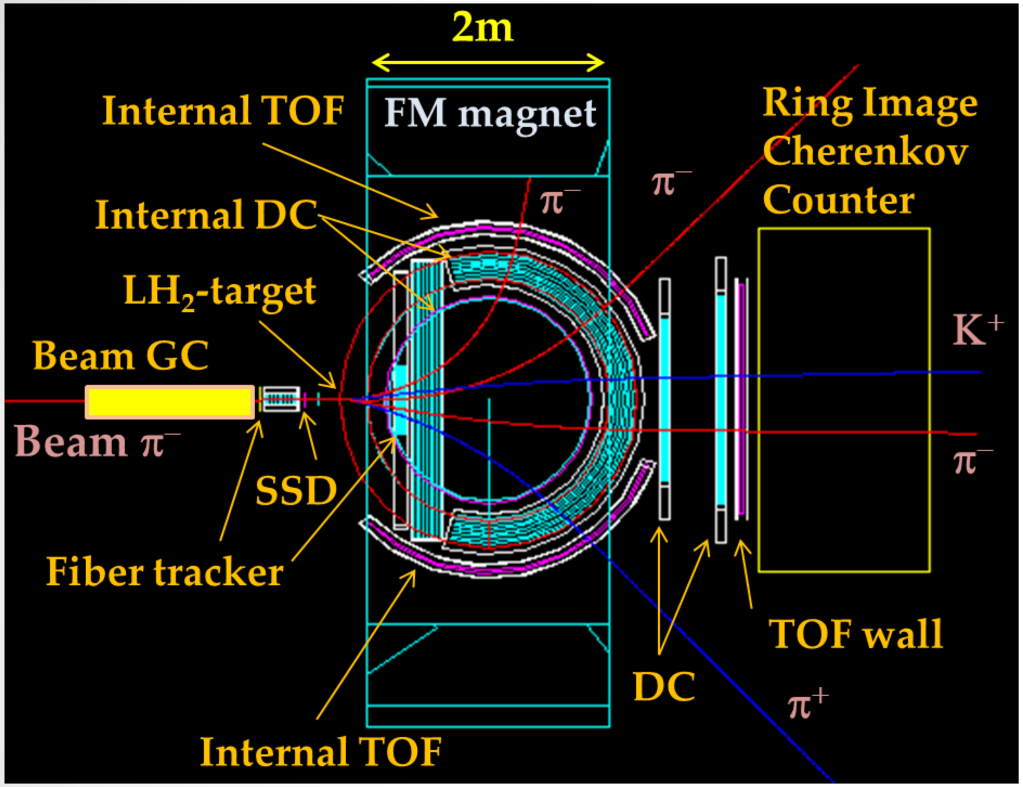
- **High-rate beam & High-rate detector system**
  - **Beam intensity: 6×10^7 /2.0 sec spill (~1 MHz/mm)**

Charmed baryon spectrometer



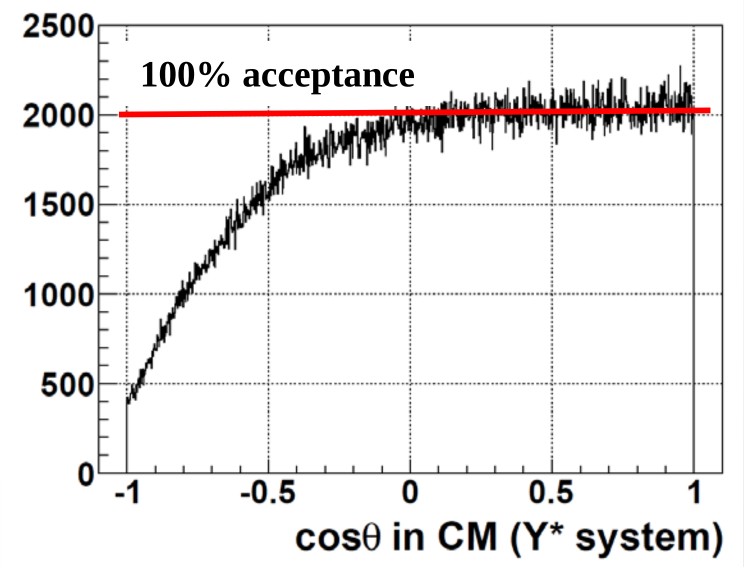
Large Acceptance Multi-Particle Spectrometer

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



High-speed DAQ system

∗ On-line event reconstruction by using PC cluster

- **Momentum analysis by DCs and fiber tracker**

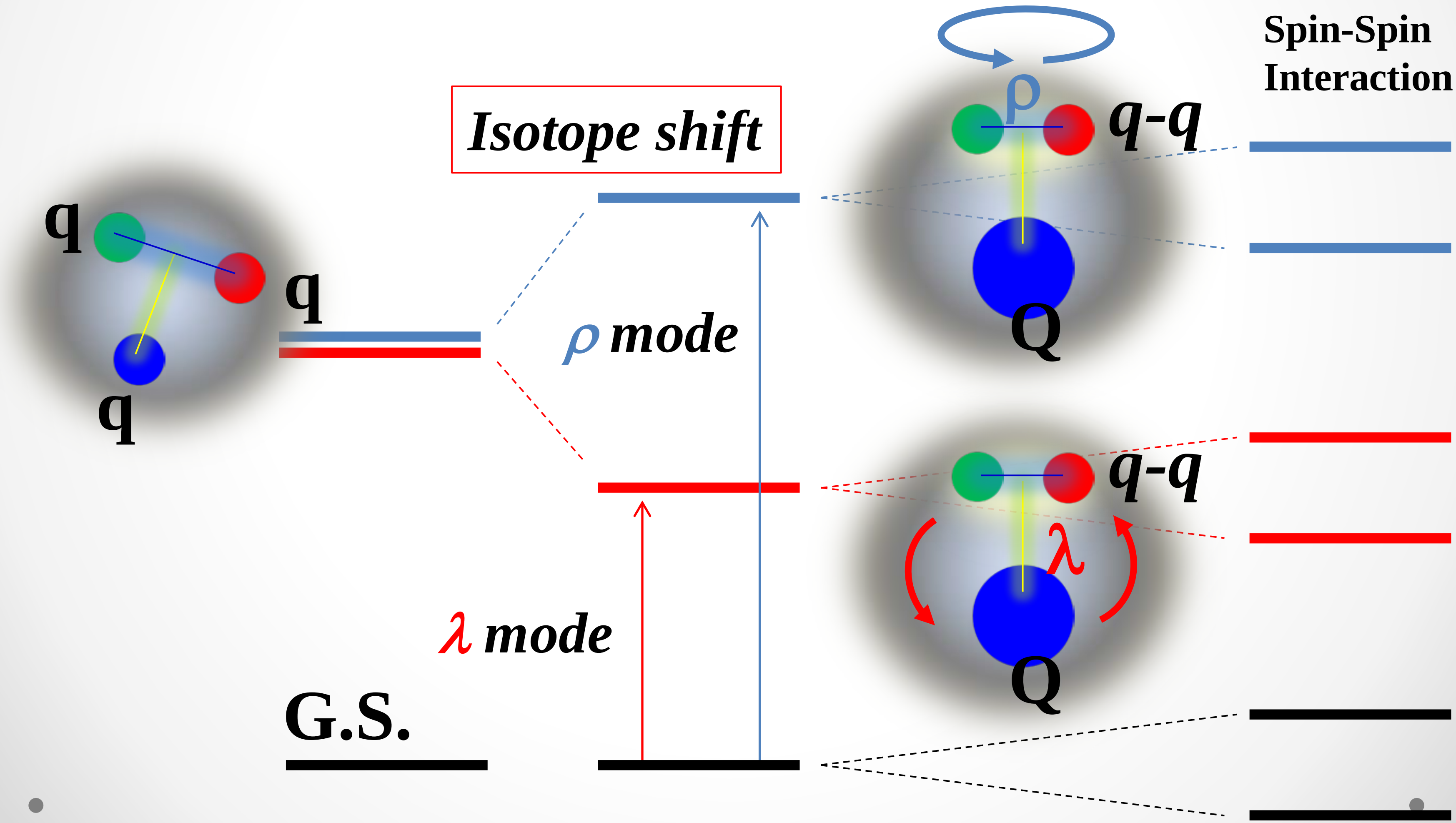
Physics motivation

Charmed baryon

Charmed baryon spectrum: "Excitation Mode"

Heavy Quark: **Weak color-magnetic interaction**

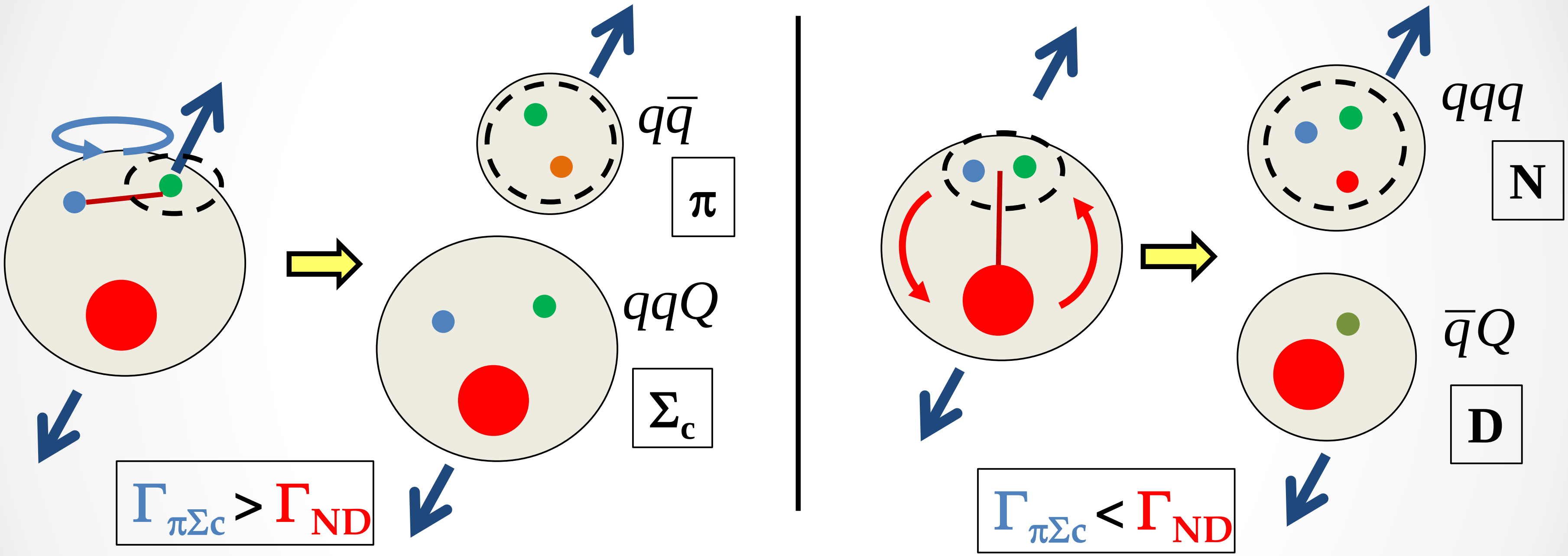
⇒"*q-q*" isolated and developed: "q-q + Q"



Decay property

ρ-mode decay: $qqQ + qq_{bar}$

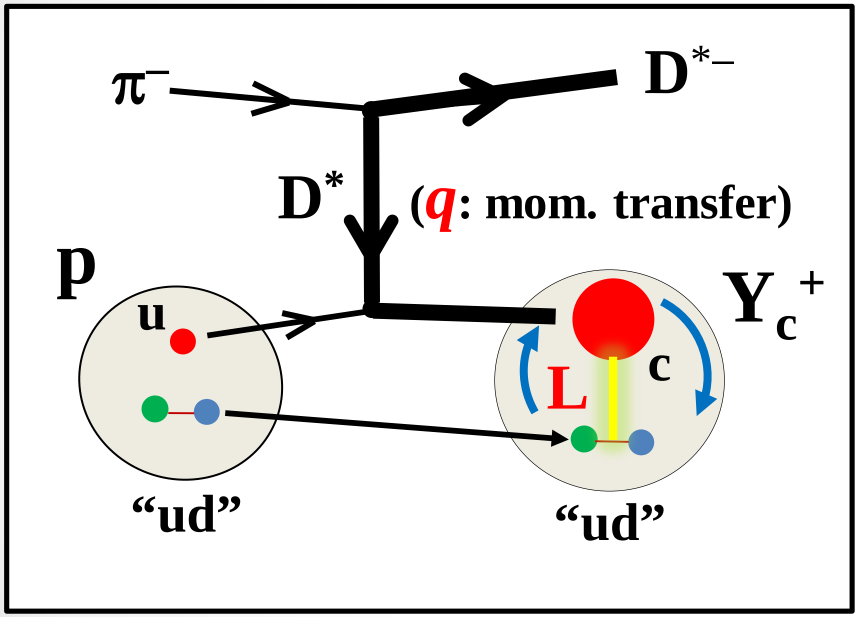
λ-mode decay: $qqq + Qq_{bar}$



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

Production cross section

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})

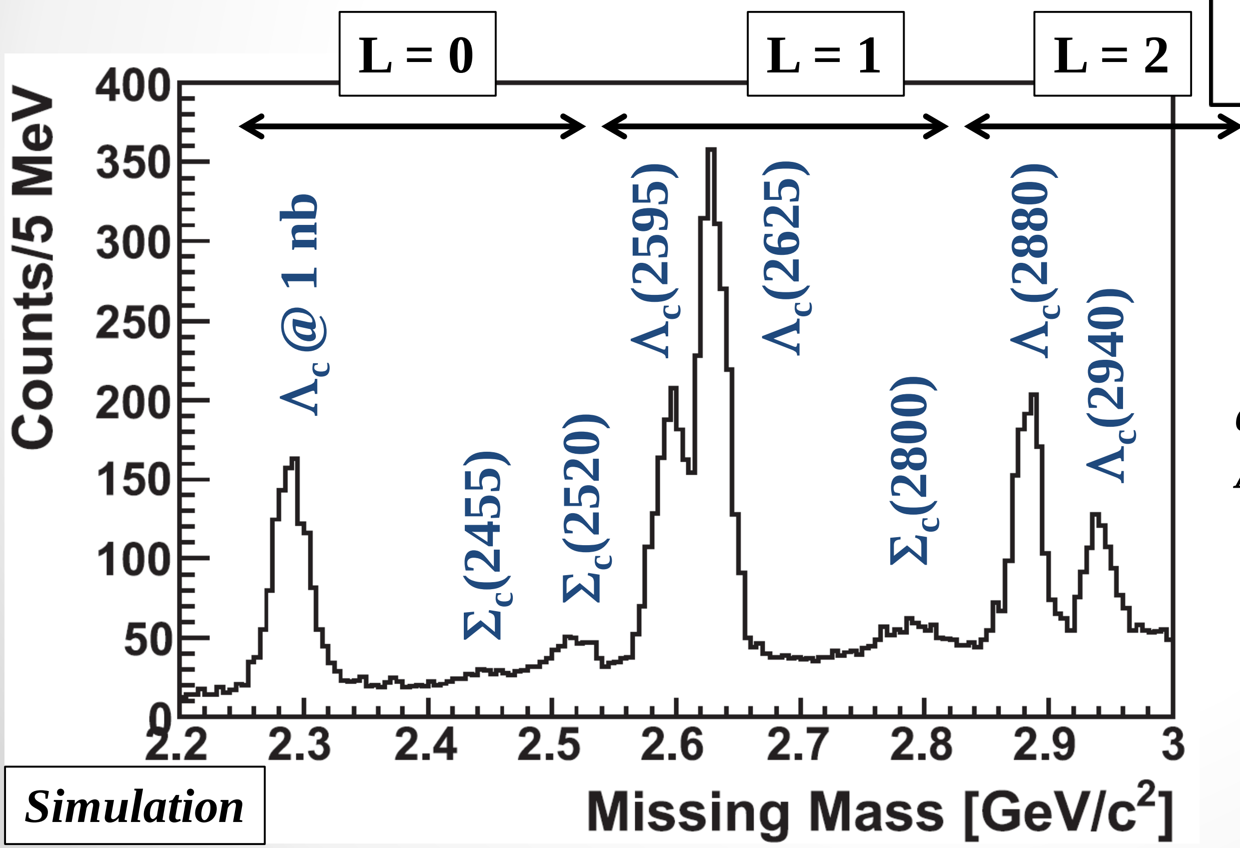
$$I_L \sim (q_{eff}/A)^L \exp(-q_{eff}^2/2A^2)$$

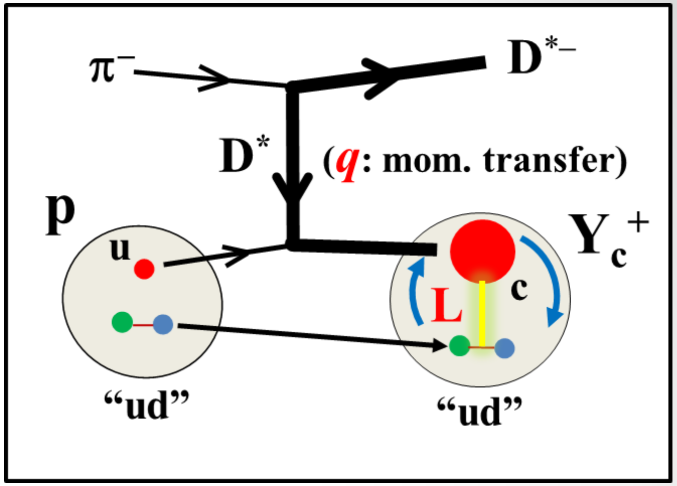
A: (baryon size parameter)$^{-1}$

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

Production cross section

- **∗ Production rates ⇔ Excitation mode**
  - Forward angles: λ mode
  - Spin/parity of Y_c^*
- ⇒ Study from ***"Reaction dynamics"***

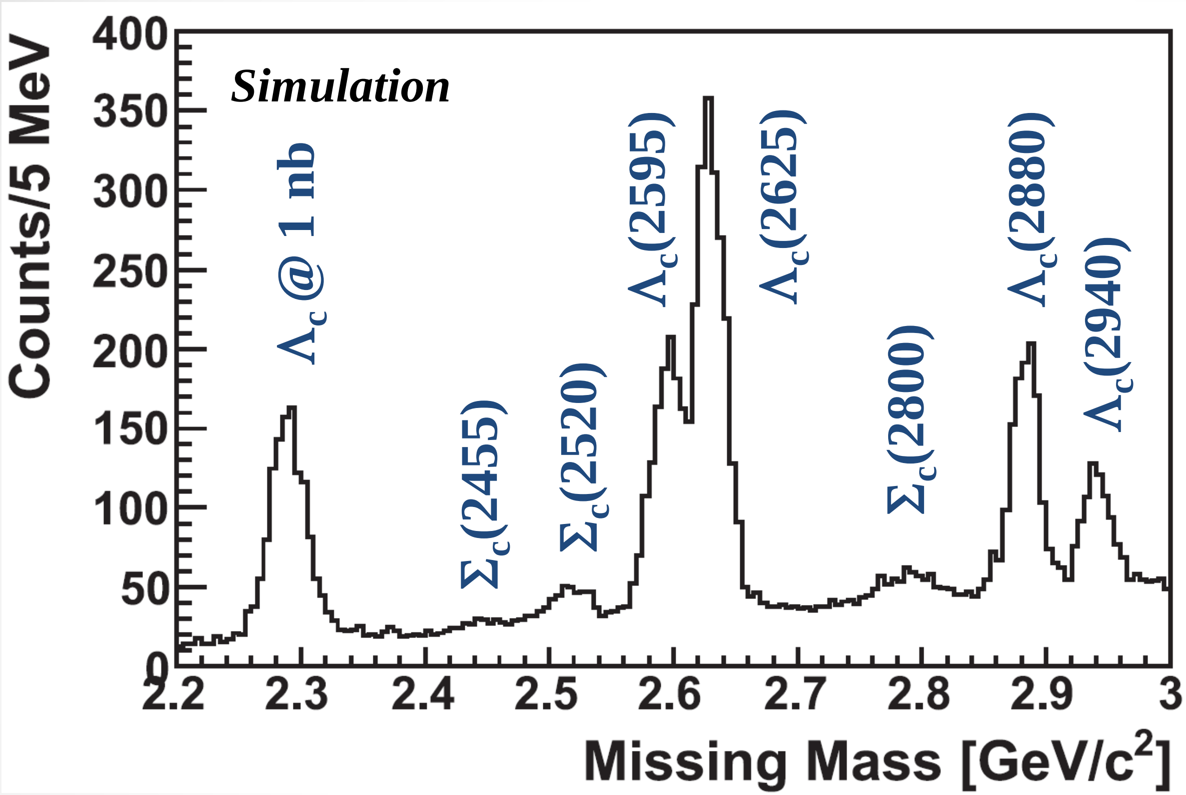




$$I_L / I_{g.s.} \sim (q_{eff}/A)^L$$

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

Expected spectra



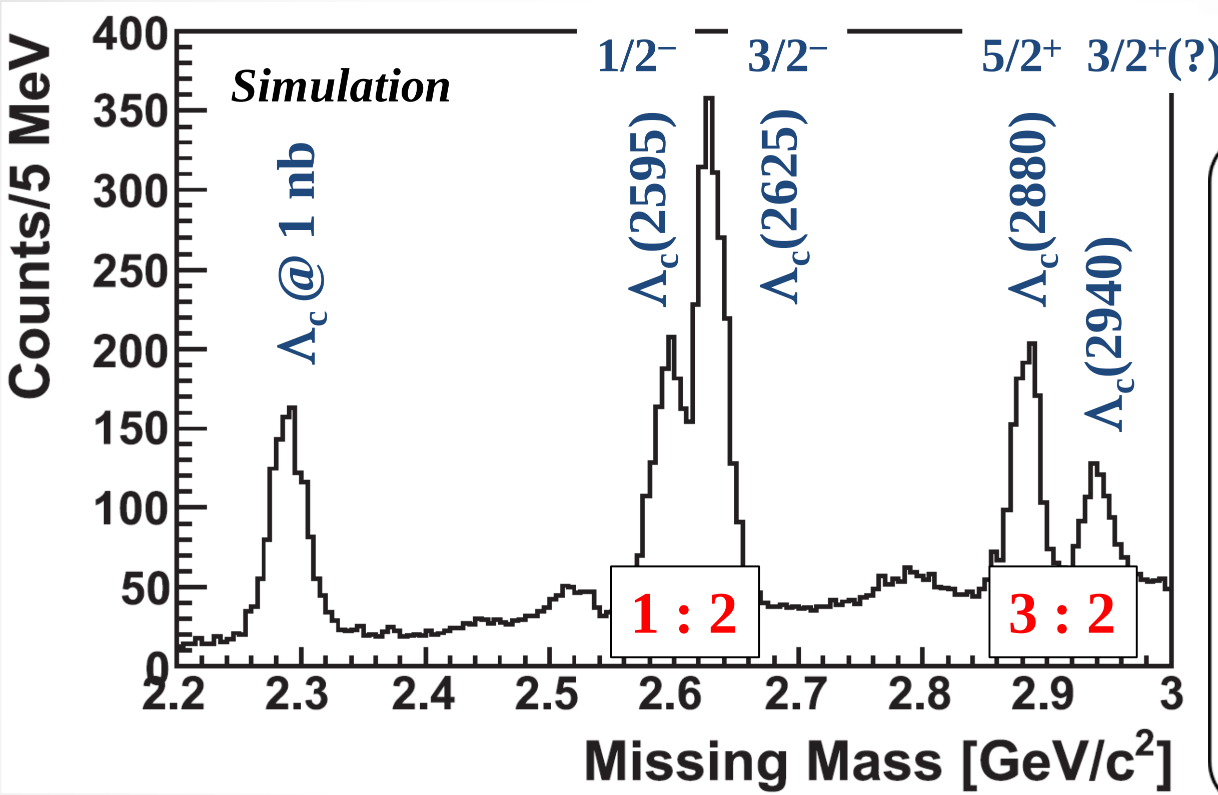
Known Mass & Width in PDG

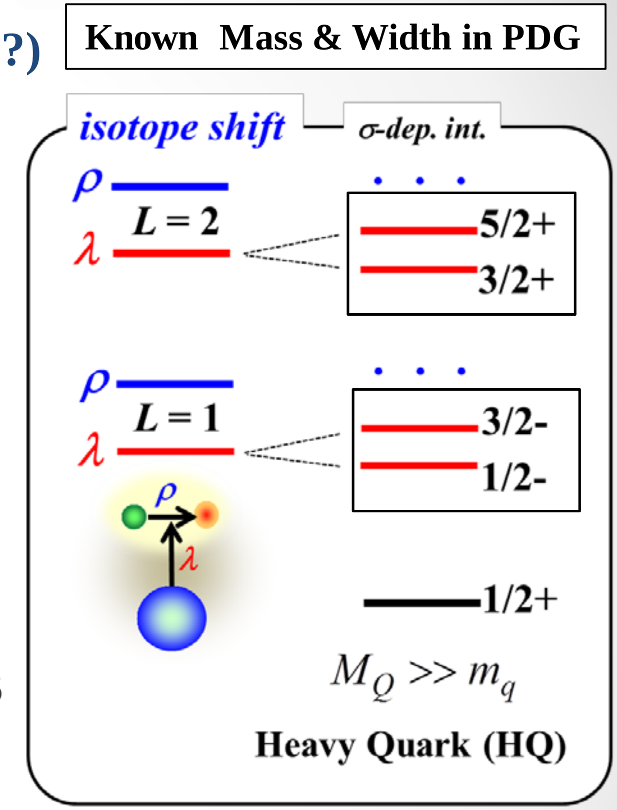
1800 counts @ N_{pot} = 8.64 × 10^{13} (100 days, ε_{total} = 0.5)

- **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, Γ < 100 MeV)

Expected spectra





- λ-mode excitation doublets: Production enhanced

HQ doublet

⇒ Internal structure of charmed baryon

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

∗Diquark correlation: Excitation mode

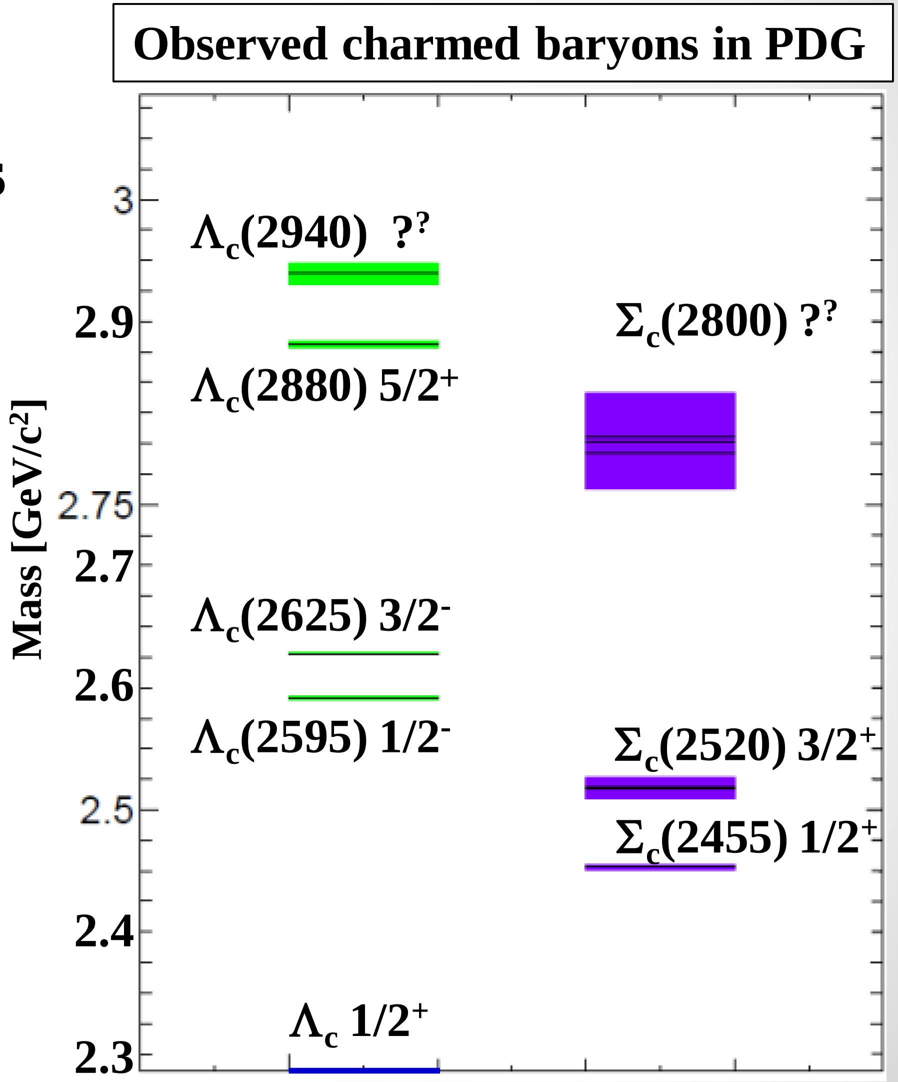
Charmed baryon spectroscopy

J-PARC E50 experiment

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

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

⇒ **Diquark correlation**
  - Excitation mode



Effective degree of freedom

- **1st level: Quark**
  - **Bare quark**

Lattice QCD

- **2nd level: Constituent**
  - **Constituent quark, diquark, hadron molecule**
    - **Colored Quasi-Particle: CQP**

⇒Need pictures of constituents for understanding

Effective theory

- **3rd level: Hadron**
  - **Objects which we can observe.**

Effective degree of freedom

- 1st level: Quark
  - Bare quark

↓ Lattice QCD: How to establish CQP ?

- 2nd level: Constituent
  - Constituent quark, diquark, hadron molecule
    - Colored Quasi-Particle: CQP

⇒Need pictures of constituents for understanding

↓ Effective theory: How to describe by CQP ?

- 3rd level: Hadron
  - Objects which we can observe.

Systematic study

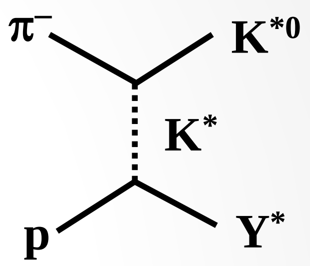
Charm and Strange

Strangeness baryons

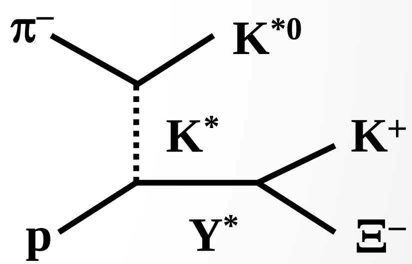
✱ Yield: ~10^5 /day @ 1 μb

- $4\ g/cm^2$, 6×10^7/spill, 50% acceptance, 50% efficiency (DAQ, PID, Analysis)

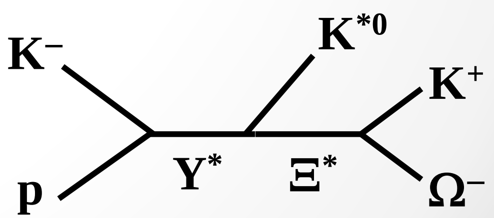
- Λ, Σ^0 baryons: $\sigma \sim 1\text{–}100\ \mu b$
  - $\pi^- + p \rightarrow \Lambda^*, \Sigma^{*0} + K_S^0$, $(K_S^0 \rightarrow \pi^+ + \pi^-)$
  - $\pi^- + p \rightarrow \Lambda^*, \Sigma^{*0} + K^{*0}$, $(K^{*0} \rightarrow K^+ + \pi^-)$
  - $\pi^+ + p \rightarrow \Sigma^{*+} + K^{*+}$, $(K^{*+} \rightarrow K_S^0 + \pi^+)$



- Ξ^- baryons: $\sigma \sim 0.1\text{–}10\ \mu b$
  - $K^- + p \rightarrow \Xi^* + K^+, K^{*0}$
  - $\pi^- + p \rightarrow \Xi^* + K^+ + K^{*0}$, $(K^{*0} \rightarrow K^+ + \pi^-)$
    - Strangeness tagging ⇒ K* detection



- Ω^- baryons: $\sigma \sim 0.01\text{–}1\ \mu b$
  - $K^- + p \rightarrow \Omega^* + K^{*0} + K^+$, $(K^{*0} \rightarrow K^+ + \pi^-)$
    - Strangeness tagging ⇒ K* detection

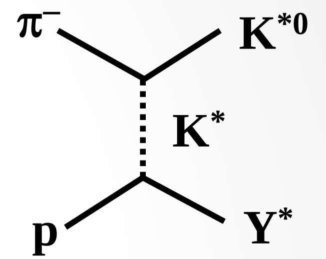


✱ Ξ and Ω data are very poor !

Strangeness baryons

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

- **Λ, Σ^0 baryons: σ ~ 1–100 μb**
  - $\pi^- + p \rightarrow \Lambda^*, \Sigma^{*0} + K_S^0$, $(K_S^0 \rightarrow \pi^+ + \pi^-)$
  - $\pi^- + p \rightarrow \Lambda^*, \Sigma^{*0} + K^{*0}$, $(K^{*0} \rightarrow K^+ + \pi^-)$
  - $\pi^+ + p \rightarrow \Sigma^{*+} + K^{*+}$, $(K^{*+} \rightarrow K_S^0 + \pi^+)$



- **Ξ^- baryons: σ ~ 0.1–10 μb**
  - $K^- + p \rightarrow \Xi^* + K^+, K^{*0}$
  - $\pi^- + p \rightarrow \Xi^* + K^+ + K^{*0}$, $(K^{*0} \rightarrow K^+ + \pi^-)$
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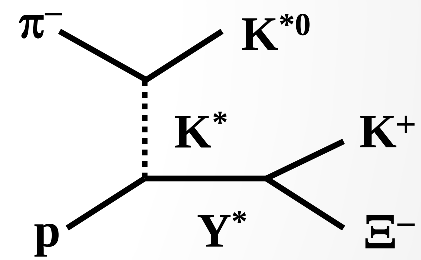
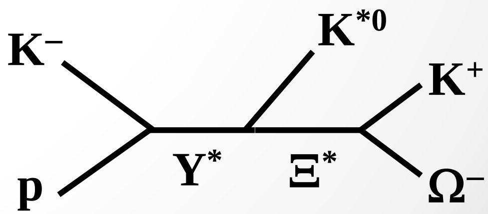


- **Ω^- baryons: σ ~ 0.01–1 μb**
  - $K^- + p \rightarrow \Omega^* + K^{*0} + K^+$, $(K^{*0} \rightarrow K^+ + \pi^-)$
    - Strangeness tagging ⇒ K* detection



- **Ξ and Ω data are very poor !**

Strangeness sector

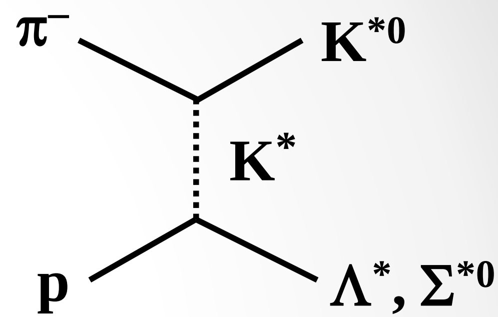
Hyperons: Λ^*, Σ^* states

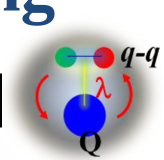
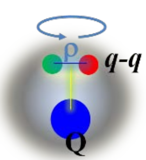
- $\pi^- + p \rightarrow \Lambda^*, \Sigma^{*0} + K^{*0}$
- $\pi^+ + p \rightarrow \Sigma^{*+} + K^{*+}$

✱ Missing mass & decay analysis

- $\Gamma_{\pi\Sigma} \Leftrightarrow \Gamma_{KN}$

π-induced Y* production

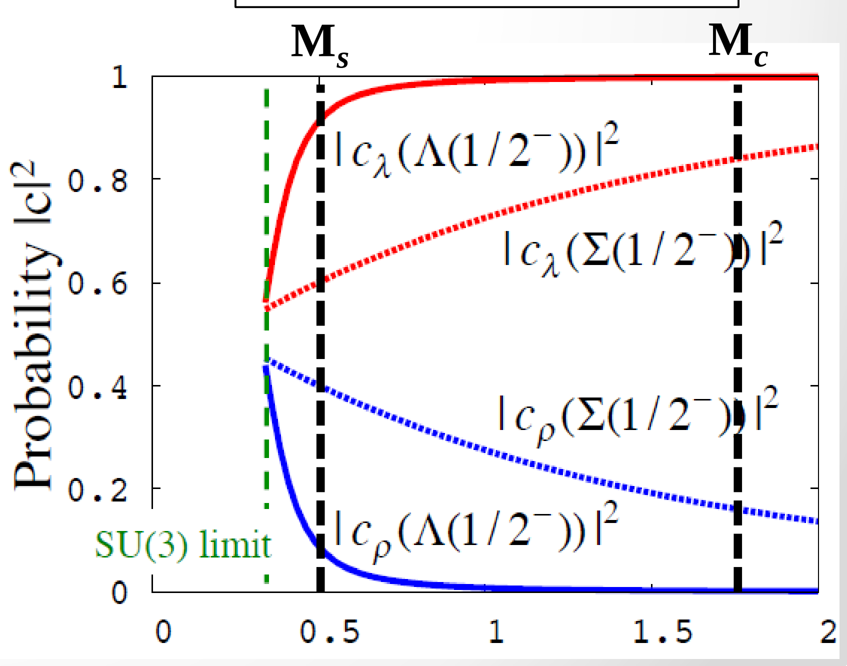


- **M_Q dependence of "q-q + Q"**
  - Y_c^* and Y^*
- **λ/ρ mixing**
  - $\Psi = C_\lambda$ |  > + C_ρ |  >
  - Production rate of Y*

⇒ Favor λ mode

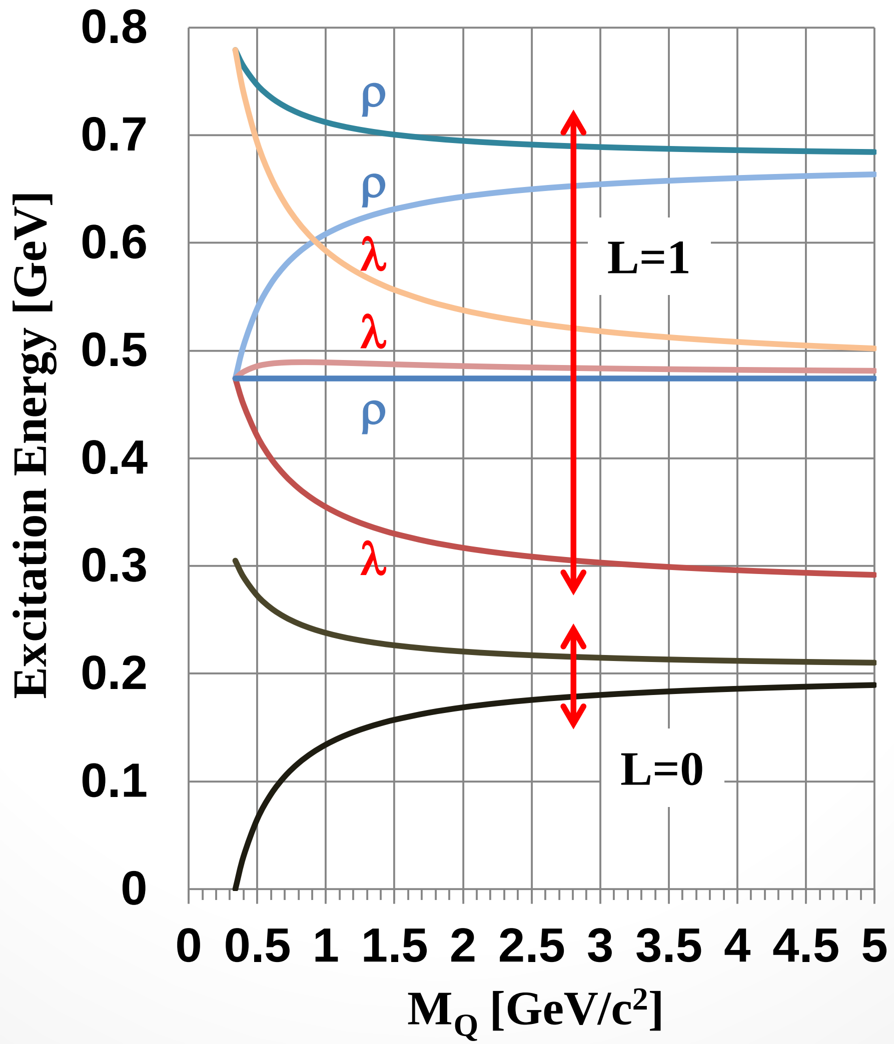
⇔ ρ mode through λ/ρ mixing

λ/ρ mixing probability



Excitation spectrum

- **L=1 excited states: Confinement & spin-spin interaction**



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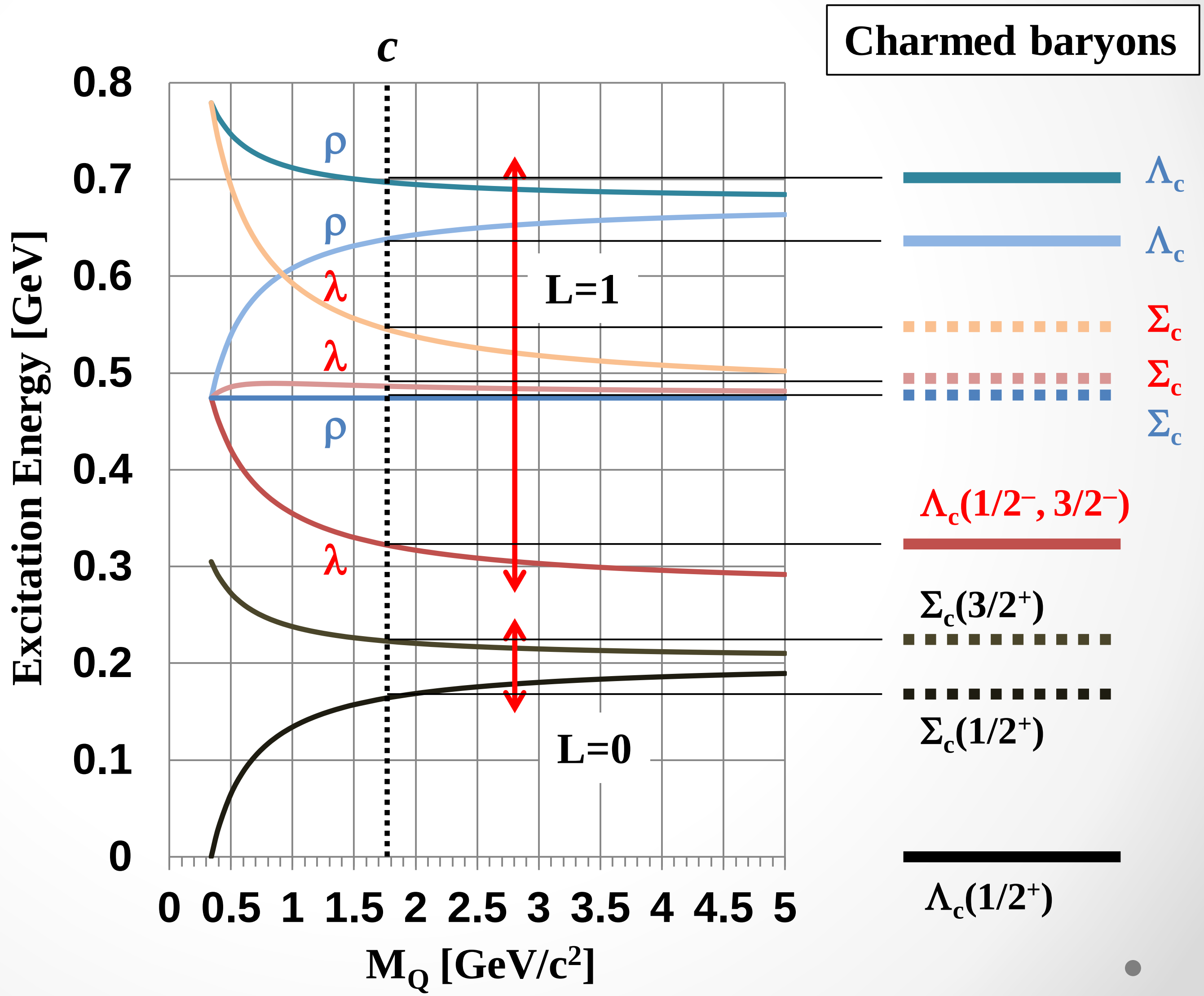

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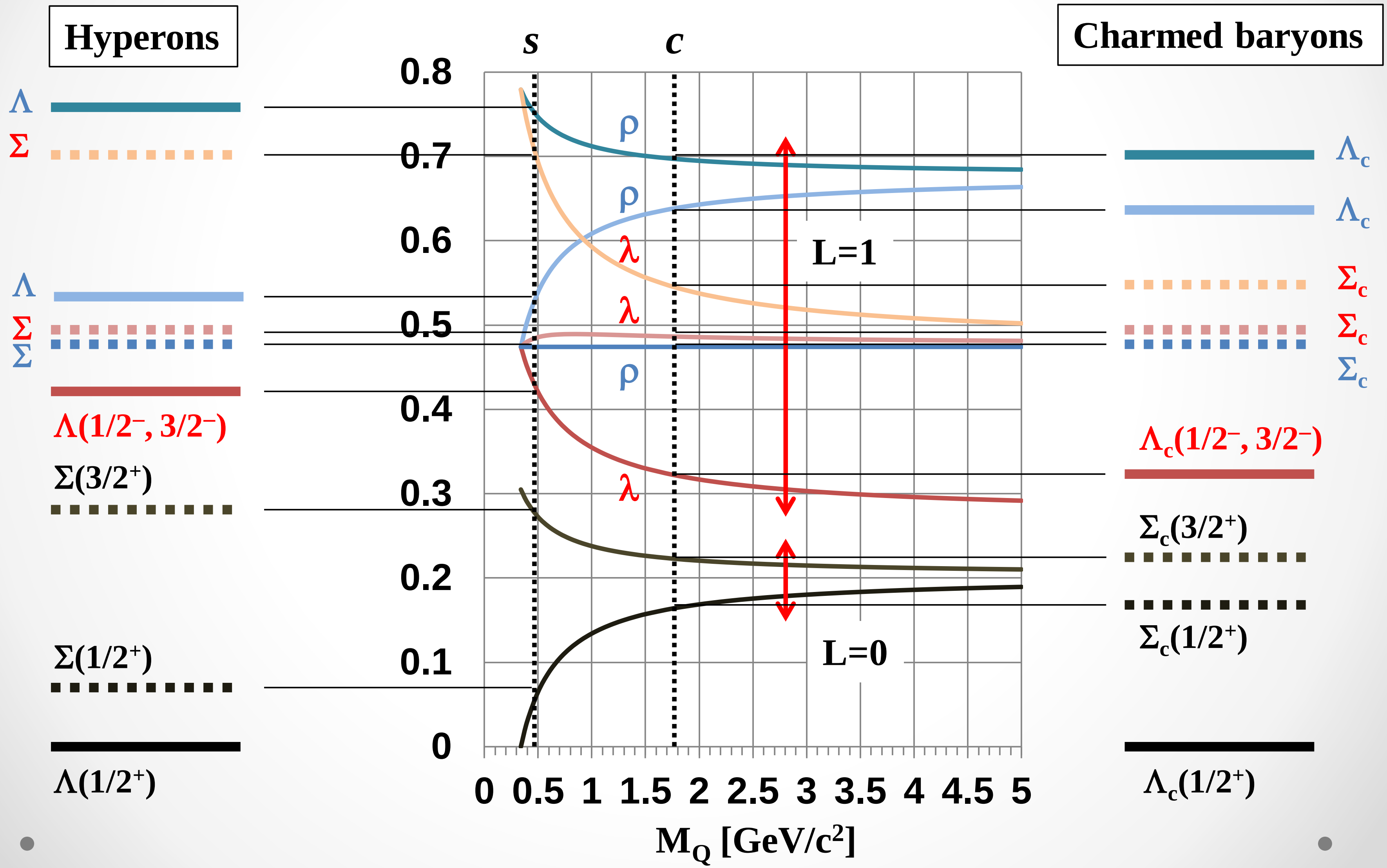
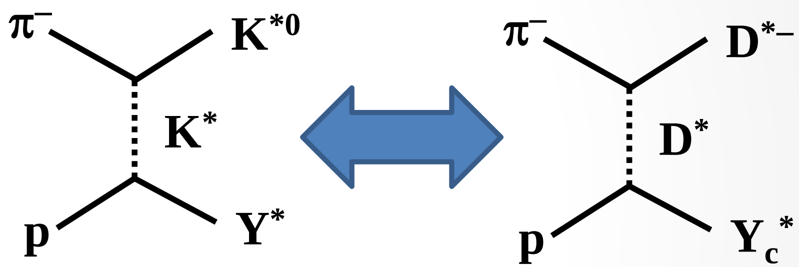


From experiments

- **Information of λ/ρ mixing probability**
  - **Production ratio**
- **Decay branching ratio**
  - **$\Gamma(NK_{bar})/\Gamma(\pi\Sigma)$**
- **Reaction systematics**
  - **t-channel production**
    - **KN ⇔ DN vertex**
  - **Production ratio**
    - **Reflect q-q**



- **Ξ: q + QQ system**
  - **Almost no information for excited states**
  - **πΞ–KY molecule: M = 1.6–1.7 GeV ?**
- **Ω: QQQ system**
  - **Almost no information for excited states**
  - **Much simpler system ?**
  - **ππΩ–KΞ molecule: M = 1.8–1.9 GeV ?**

Other channels

Pentaquark state

Other channels

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

Automatically taken by experimental conditions

- Exotic channels
  - $\pi^- + p \rightarrow D_{bar}N\ (c_{bar}d\ udd) + D^{*+}$
  - $\pi^- + p \rightarrow \beta^{++}(cs_{bar}\,uud) + D^{*-} + K^-$
    - $\pi^- + p \rightarrow \beta^+(cs_{bar}\,udd) + D_S^-\ (\phi\pi^- \rightarrow K^+K^-\pi^-$, 4.5%)

Charge inversed reactions

- P_c baryons
  - $\pi^- + p \rightarrow P_c^0$

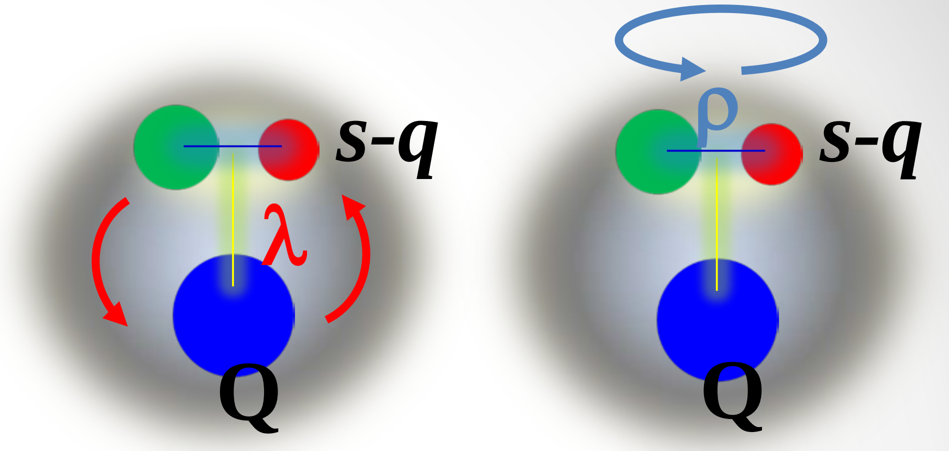
$Y_c^{*+} + D^{*-}$ channels and J/ψ detection

- Drell-Yan channels
  - $\pi^- + p \rightarrow n + \mu^+ + \mu^-$
  - $K^- + p \rightarrow Y^0 + \mu^+ + \mu^-$

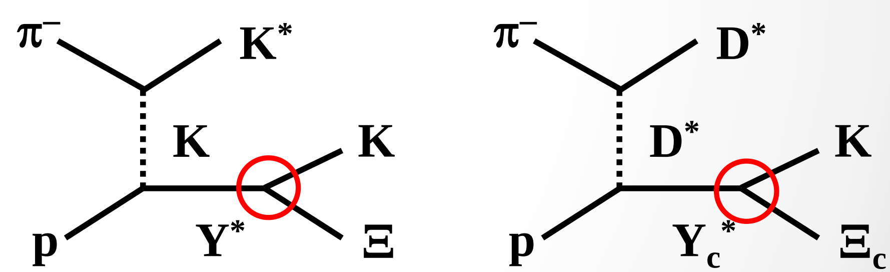
Exclusive DY production
$\Rightarrow$ GPD of N^*, Δ^*, Y^*

Ξ_c production

- **Diquark correlation: s-q**
  - Weak diquark
  - q-q can be applicable ?
    - q-Q-*Q* system ?
  - How about Belle data ?



- **Production mechanism**
  - Completely unknown
  - Complicated ?
    - c-c_{bar} + s-s_{bar} production
  - From Y^*(Y_c^*) ?
    - qqs → qss + s_{bar}q
    - qqc → qcs + s_{bar}q
  - ✱ ss_{bar} production from q-q
  - ⇒ Information of q-q correlation ?
    - Decay study of Y^* and Y_c^*



- **Absolute decay branching ratio of Ξ_c**
  - Basic information

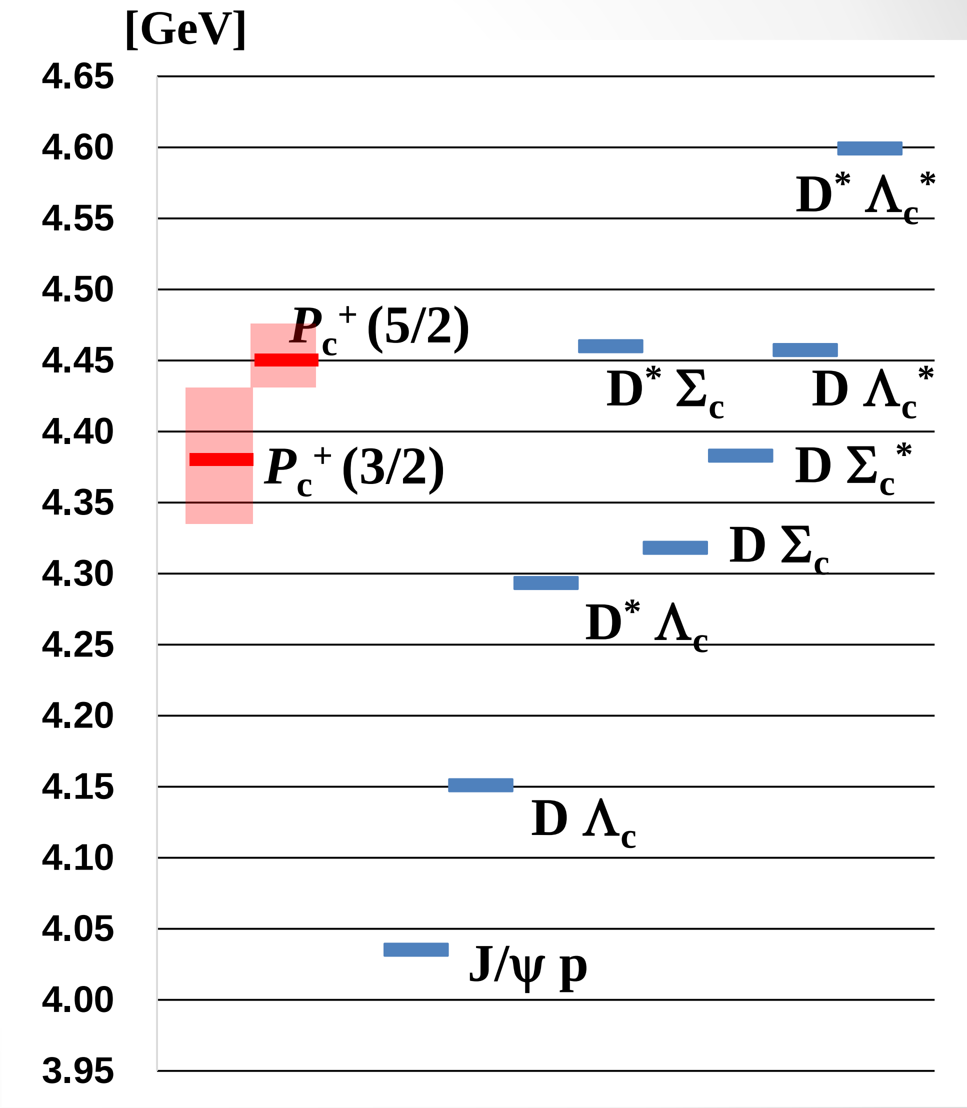
Pentaquark states

P_c^+ (cc_{bar} uud): $(M, \Gamma)(J^P)$ = (4380, 205)(3/2⁻?) & (4450, 40)(5/2⁺?)

- P_c prediction
  - $\sqrt{s}$ ~ 4.4 GeV ⇒ p_π ~ 10 GeV/c
- $\pi^- + p \rightarrow P_c^0$ (cc_{bar} udd)
  - $\pi^- + p \rightarrow P_c^0 \rightarrow J/\psi + n$
  - $\pi^- + p \rightarrow P_c^0 \rightarrow Y_c^{*+} + D^{*-}$
- Production information
  - Cross section
- Decay channel
  - $\Gamma(J/\psi N) \Leftrightarrow \Gamma(Y_c^* D^*)$

  ✱Hidden charm ⇔ Open charm
- Nuclear medium effect
  - W/ nuclear target
- Analogue states: P_s^0 (ss_{bar} udd)
  - ϕ + n (>1.96) ⇔ Y^* + K^* (>2.01)

✱What can we understand from those measurements ?



Summary

- **Experiment at the J-PARC high-p beam line**
  - **Inclusive measurements by missing mass spectroscopy with multi-purpose spectrometer system**

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

- **Systematic study of baryons at J-PARC**
  - **Excitation energy, production, decay**
    - **With strangeness sector: q-q + Q, q + Q-Q, QQQ**

- **Other study channels**
  - **Ξ_c, exotic and DY channels**
  - **Pentaquark w/ cc_{bar}**