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

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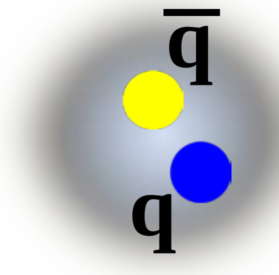
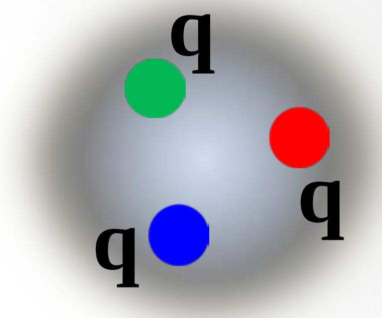
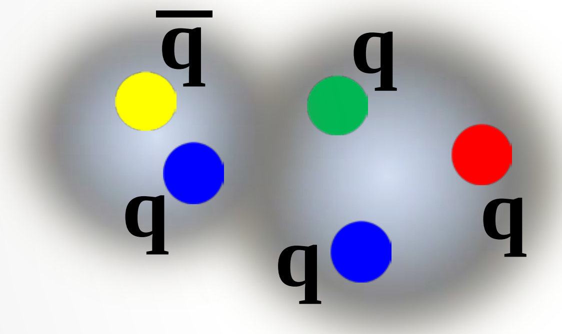
Physics motivation

What is a building block of hadrons ?

Constituent Quark

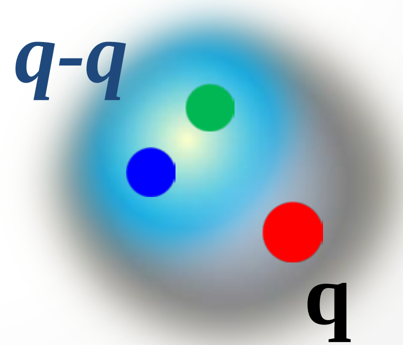






Exotic hadron

q-q correlation (diquark)

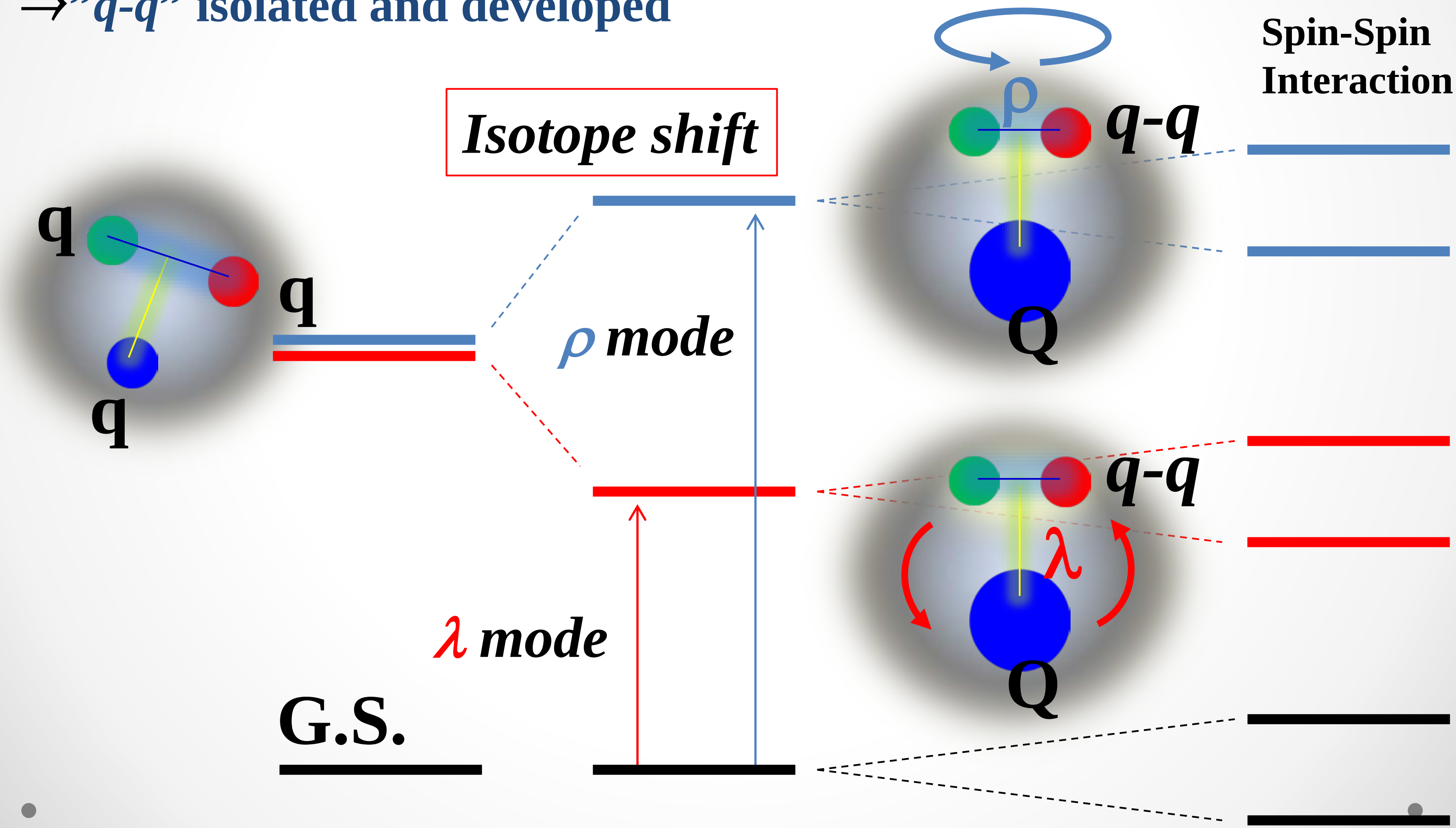


Charmed baryon spectrum: "Excitation Mode"

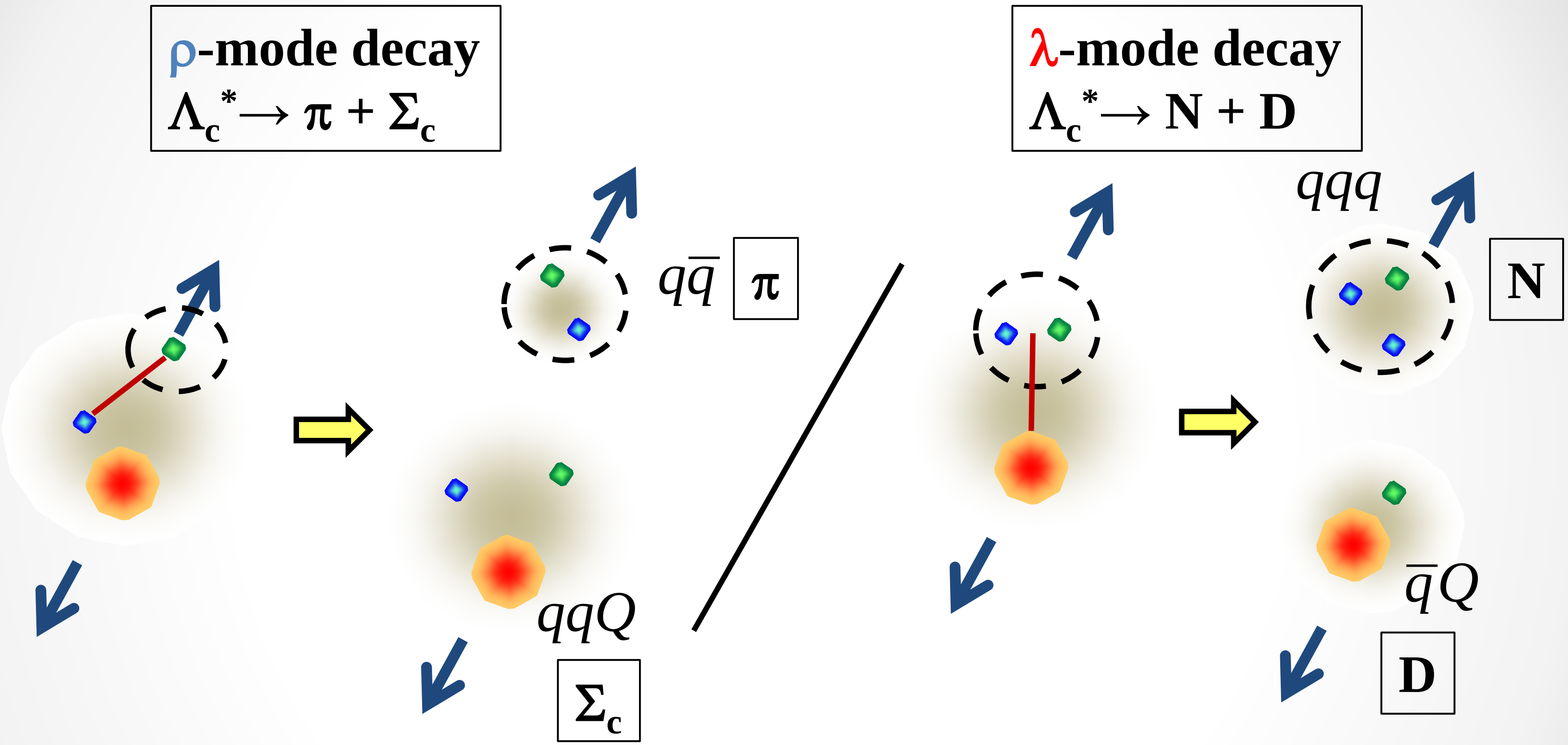
Heavy Quark: Weak color-magnetic interaction

- $V_{CMI} \sim [\alpha_s/(m_i m_j)] \times (\lambda_i, \lambda_j)(\sigma_i, \sigma_j)$

⇒**"*q-q*" isolated and developed**



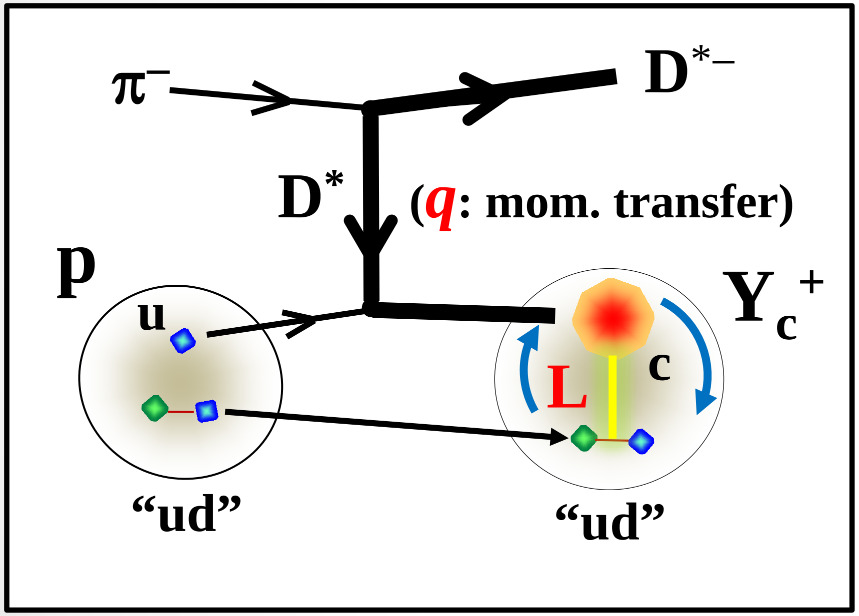
Decay property



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

Production cross section

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



D* **exchange at a forward angle**

Production cross section

⇒ **Overlap of wave function**

✱ **charm and *q-q* (spectator)**

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

1. Spin/Parity of Y_c^*

2. Momentum transfer (q_{eff})

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

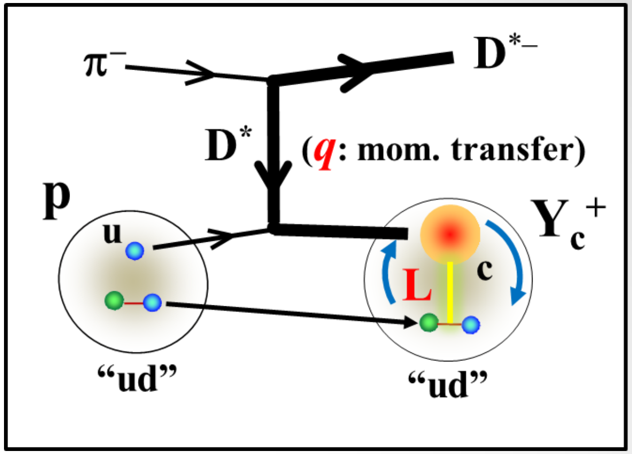
***A*: (baryon size parameter)$^{-1}$**

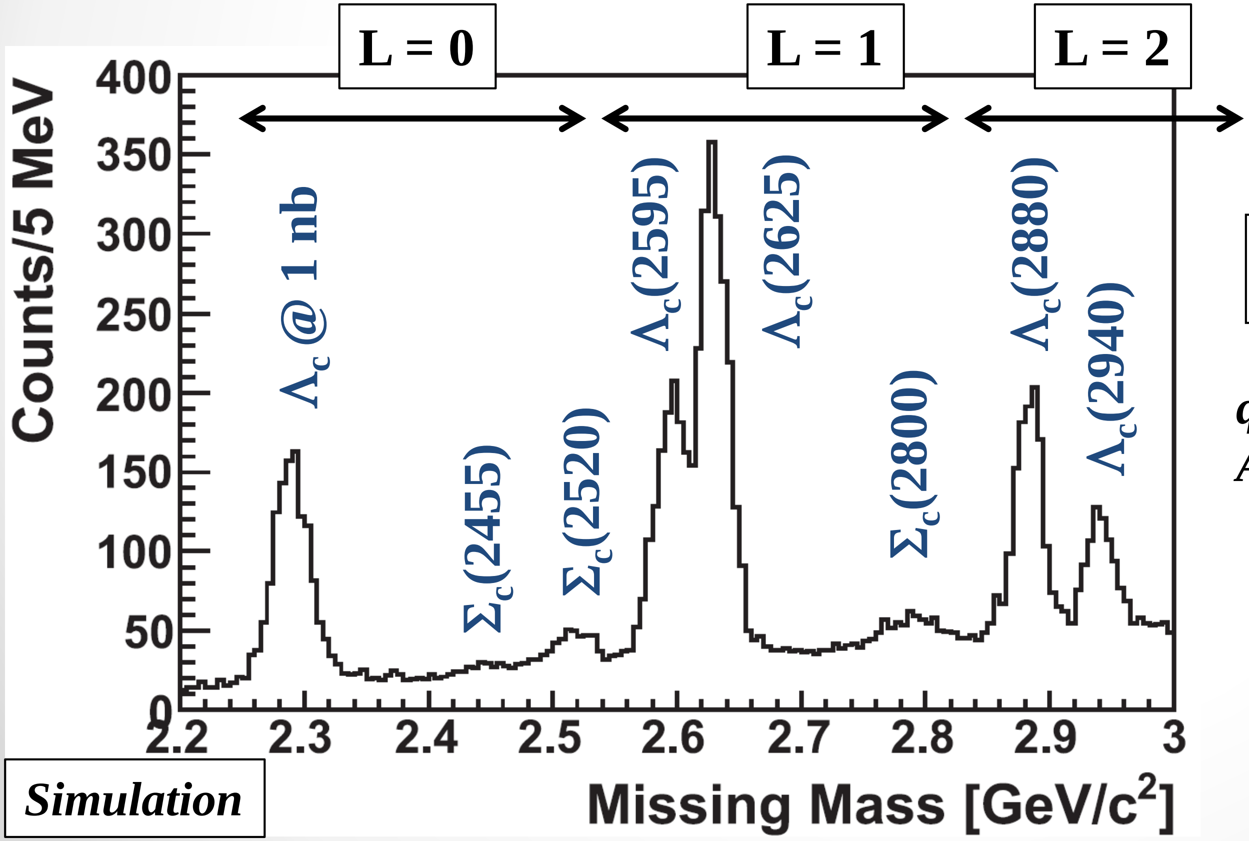
S.H. Kim, A. Hosaka, H.C. Kim, H. Noumi, K. Shirotori, arXiv:1405.3445.

Production cross section

Production rate: Excitation mode

- Forward (0°): λ mode
  - ○ ρ mode excitation: Under discussing





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

q_{eff}: Momentum transfer

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

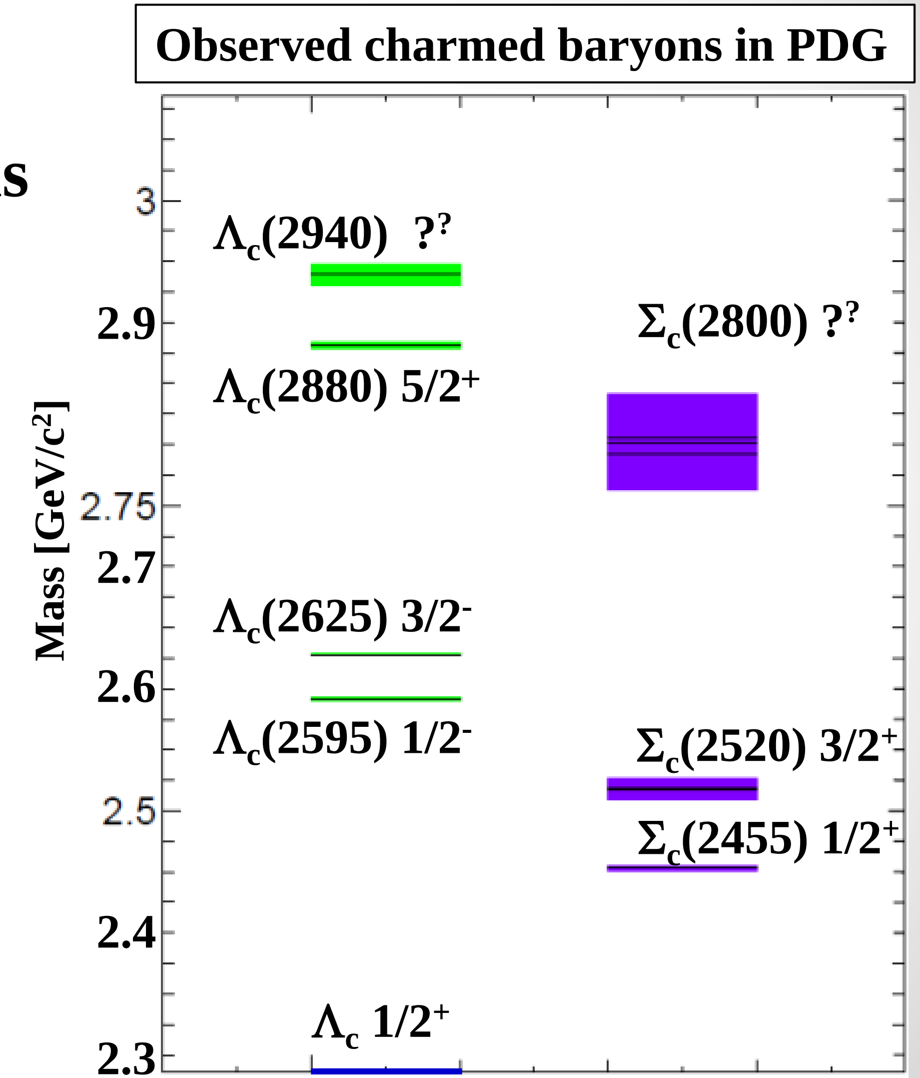
Charmed baryon spectroscopy

Propose

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

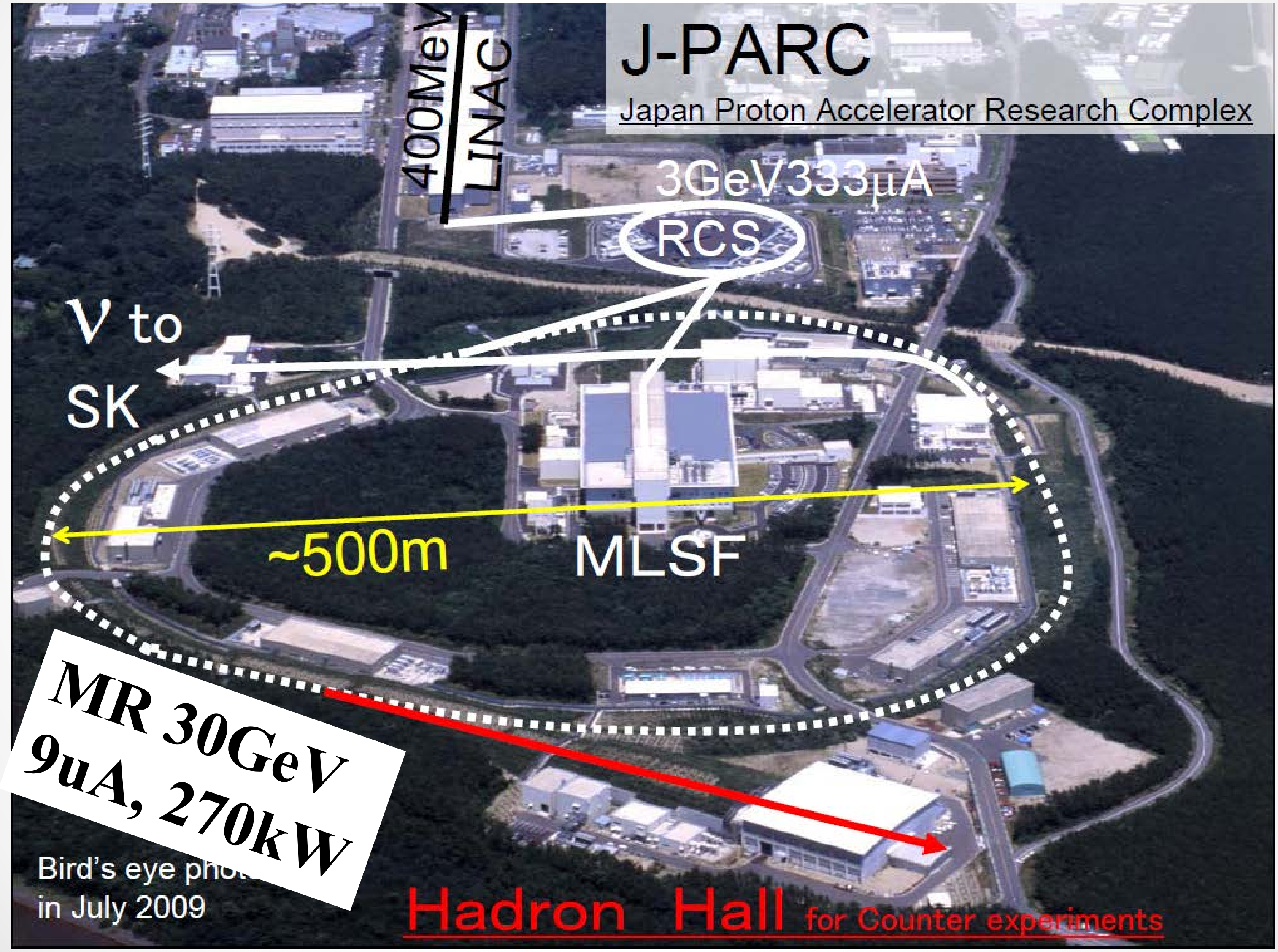
- **Systematic measurement**
  - Excited states search
  - Excitation energy
  - Decay property
  - Production cross section

⇒ **Diquark correlation**
  - Excitation mode

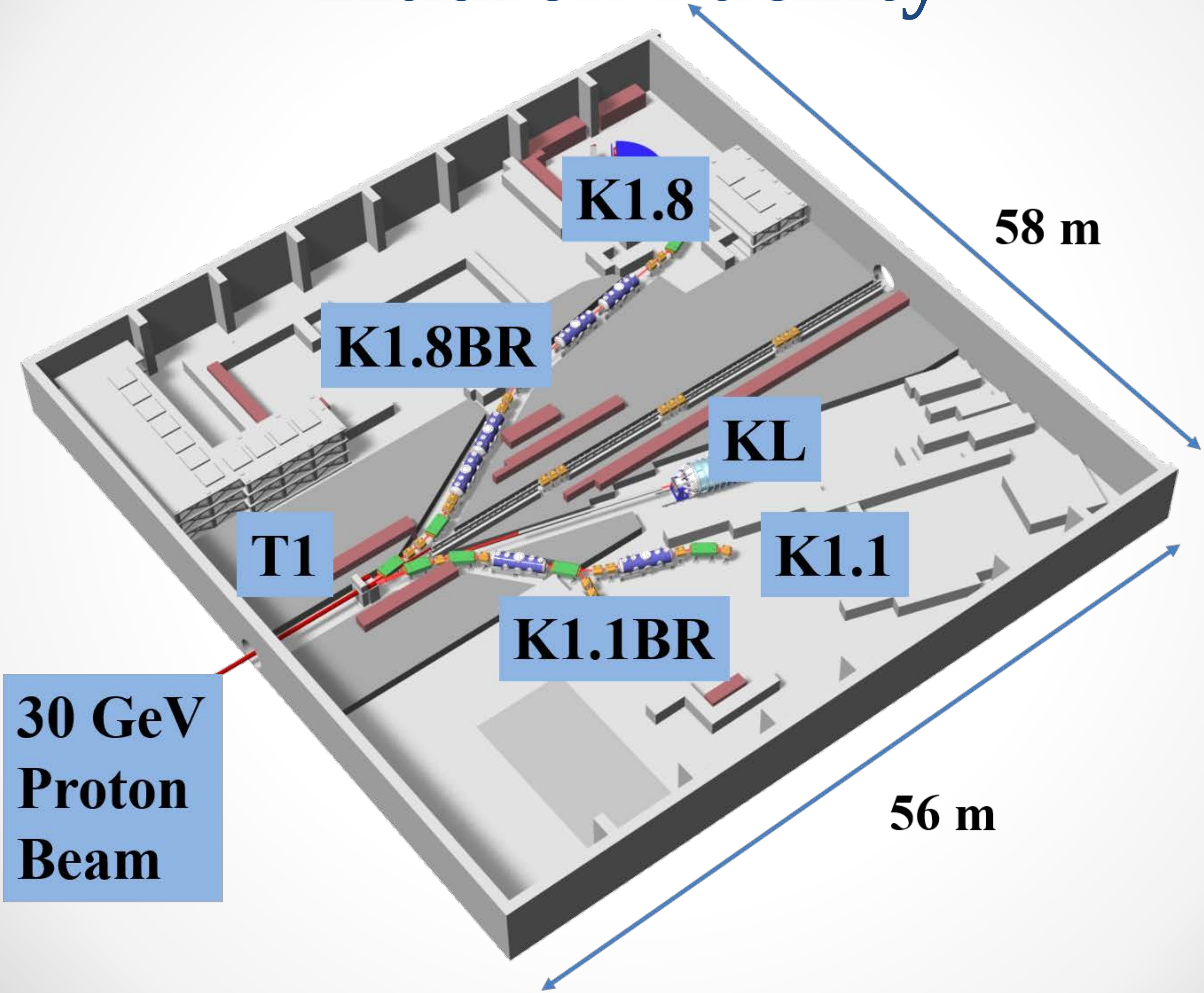


Experiment

J-PARC & Hadron Facility

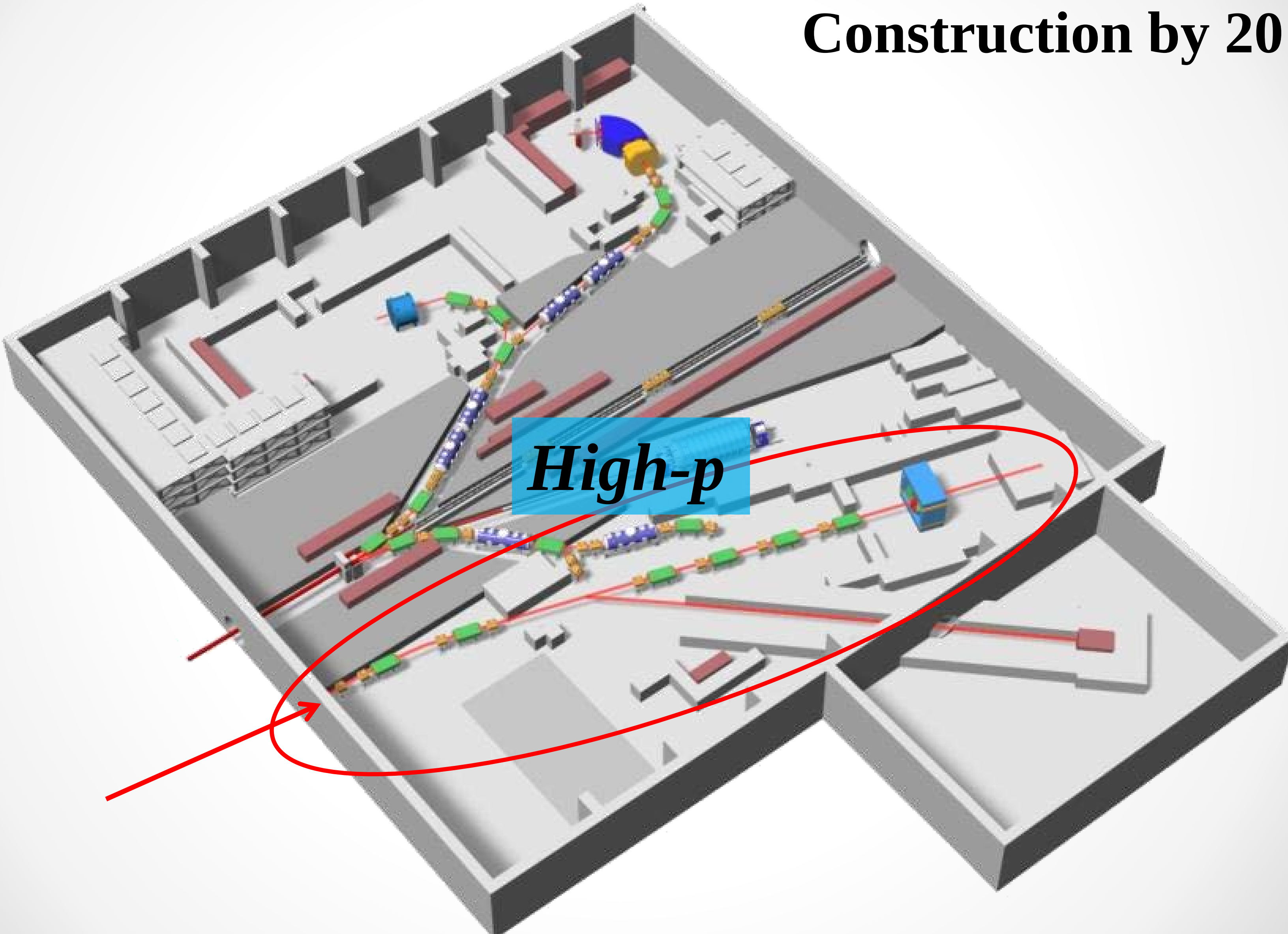


Hadron Facility



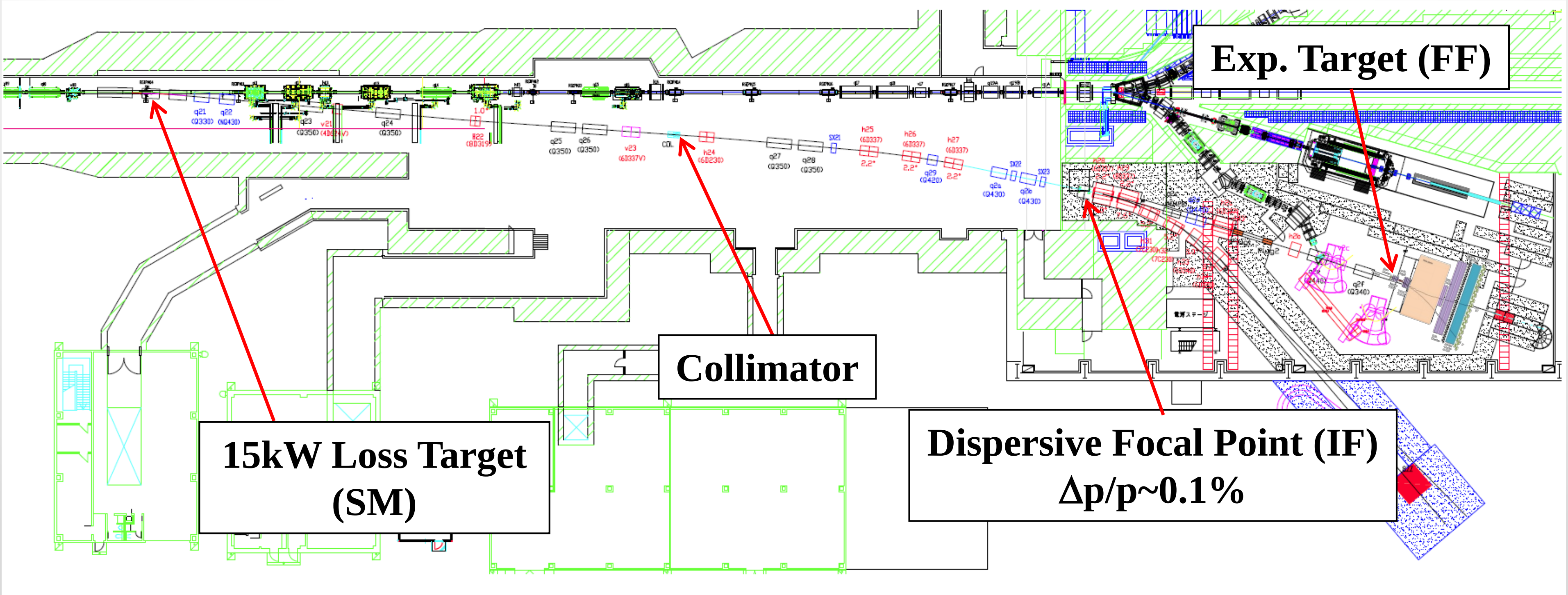
High-momentum beam line

Construction by 2016

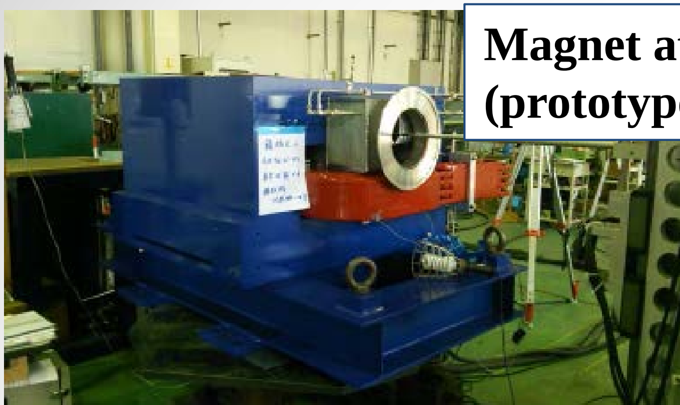


High-momentum beam line for 2^{ndary} beam

- **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**

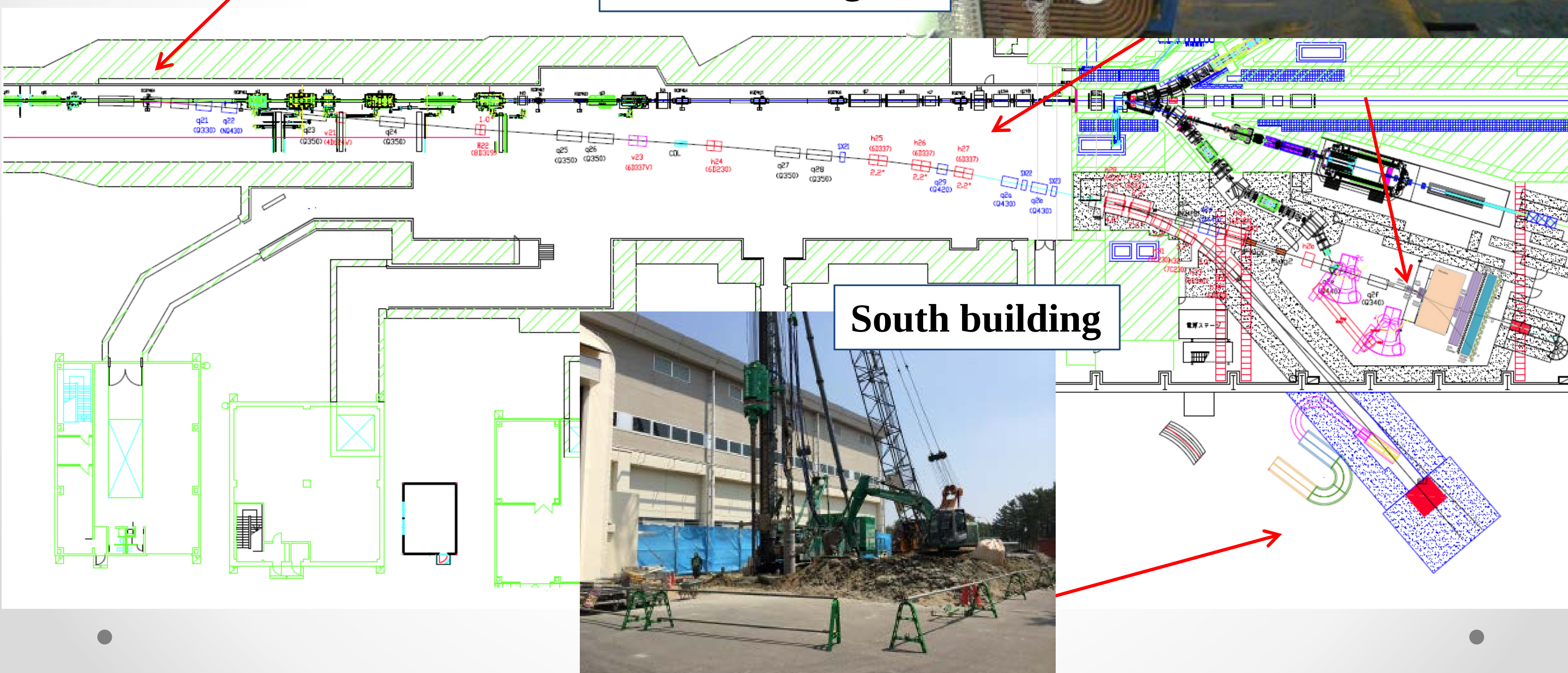


High-momentum beam line for 2^{ndary} beam



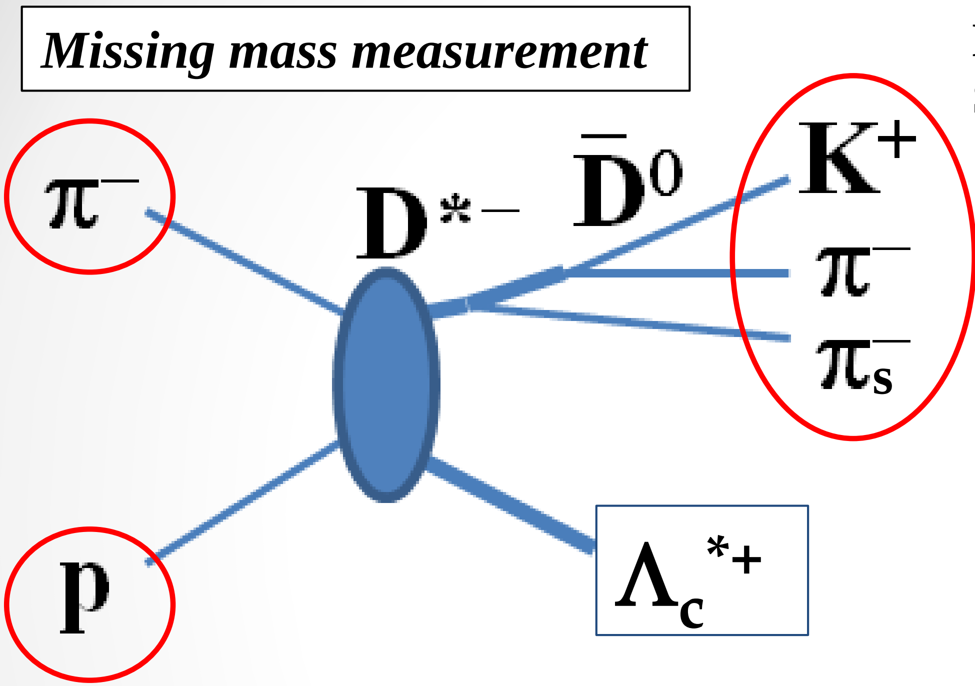
Magnet at extraction point (prototype)

High-p beam line magnets



South building

Experiment



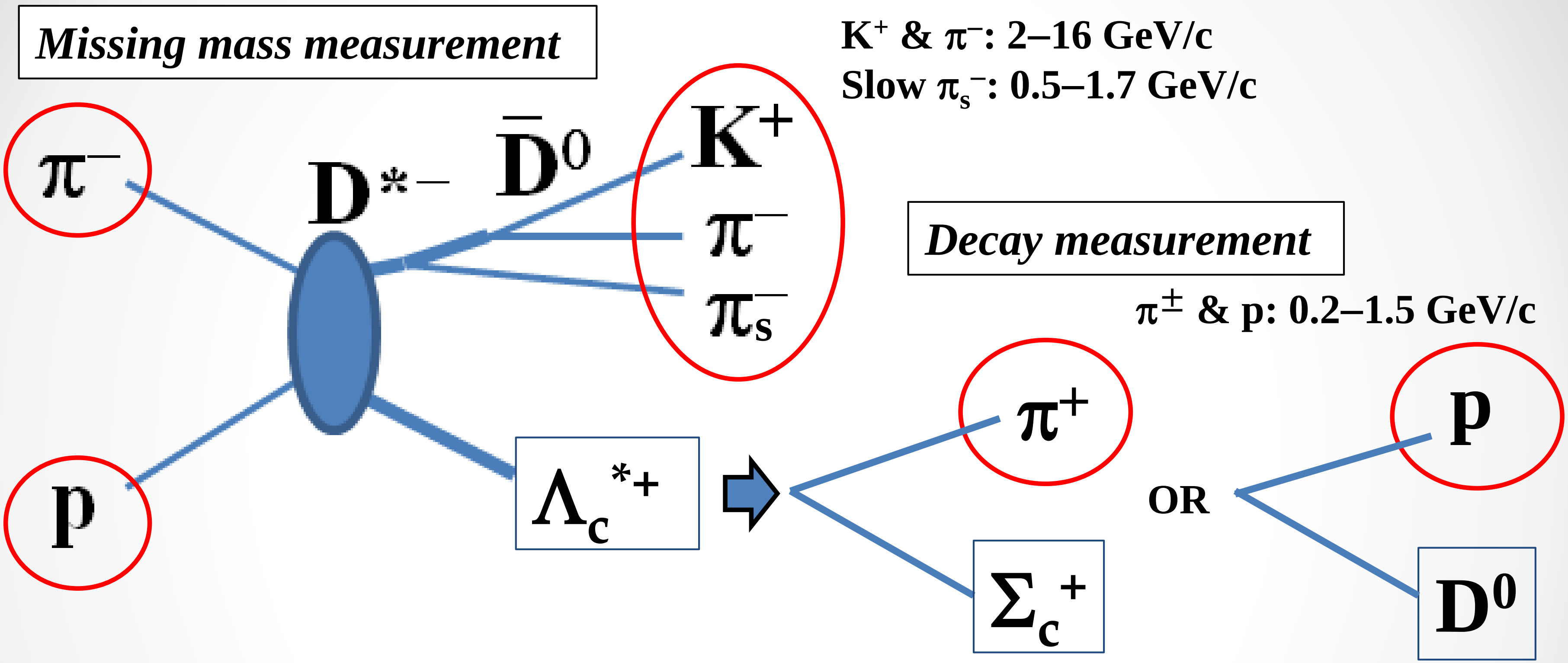
K^+ & π^-: 2–16 GeV/c
Slow π_s^-: 0.5–1.7 GeV/c

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

Experiment



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

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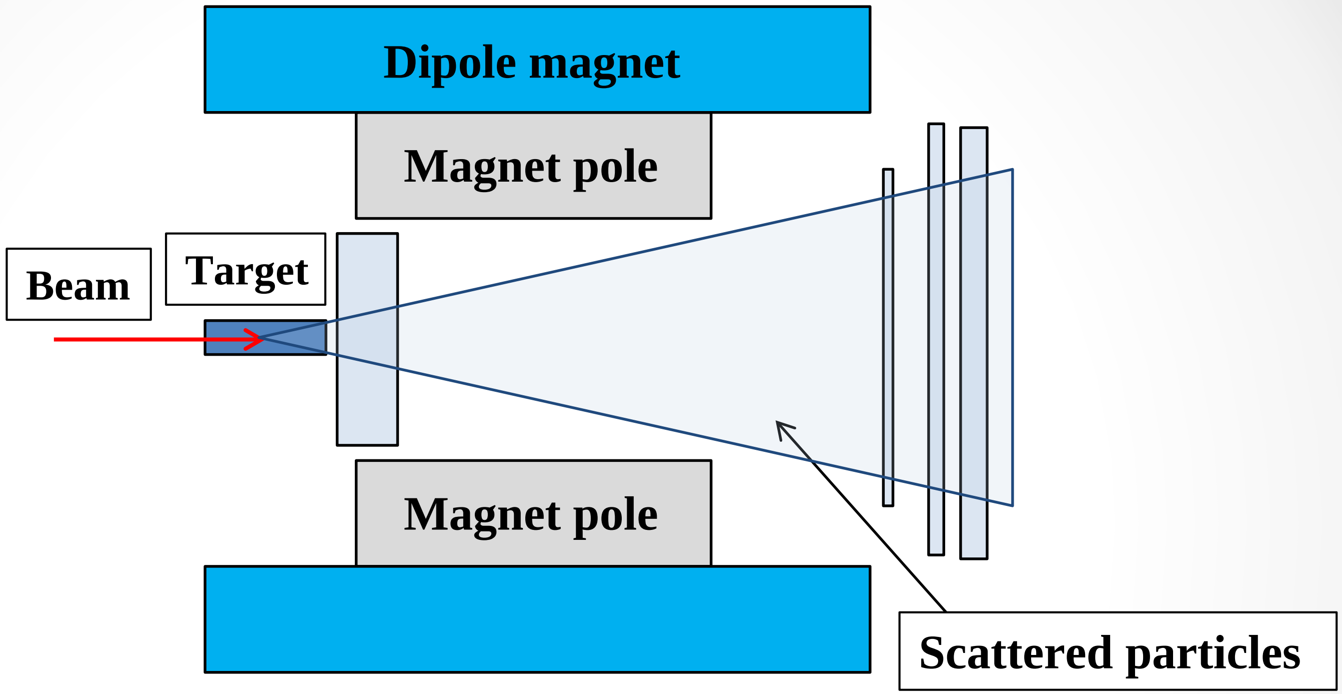
2) Decay measurement

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

Experimental design

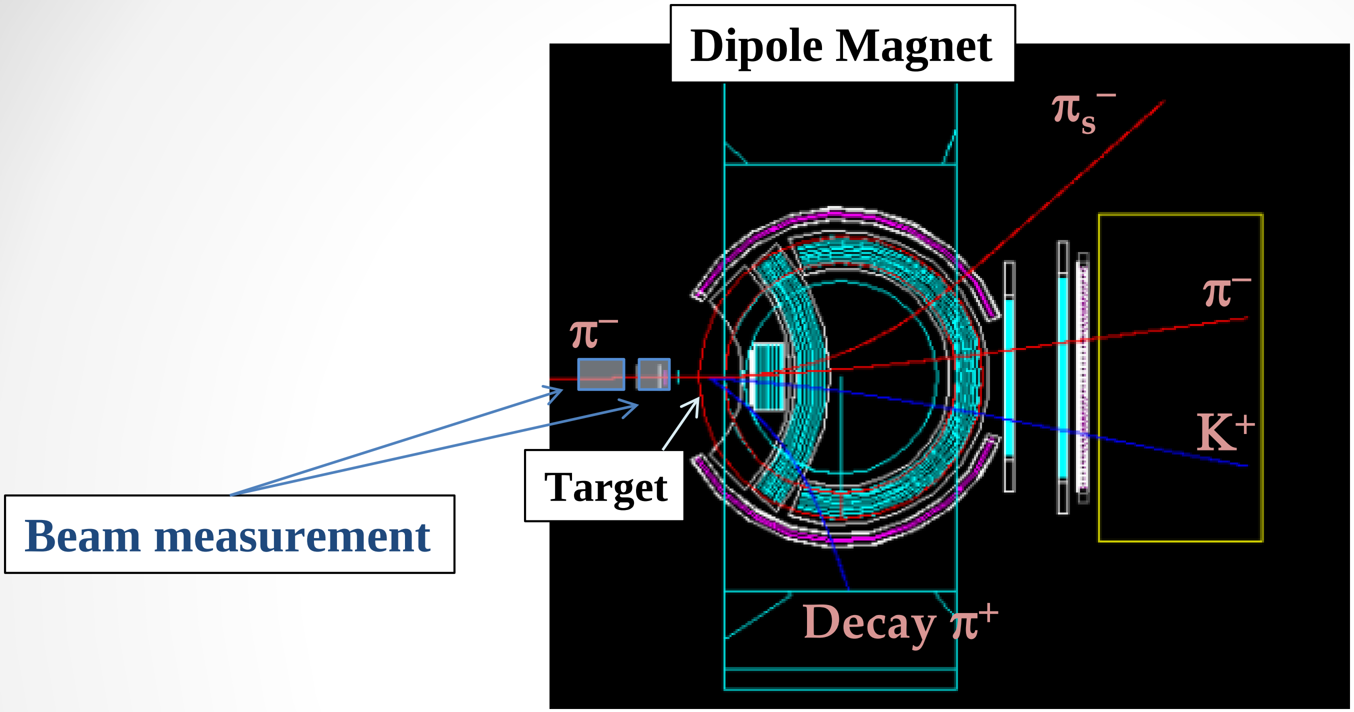


✱ **Assumed production cross section: $\sigma \sim 1$ nb**

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

- **Dipole-magnet spectrometer**
- **High-rate beam & High-rate detector system**

Experimental design



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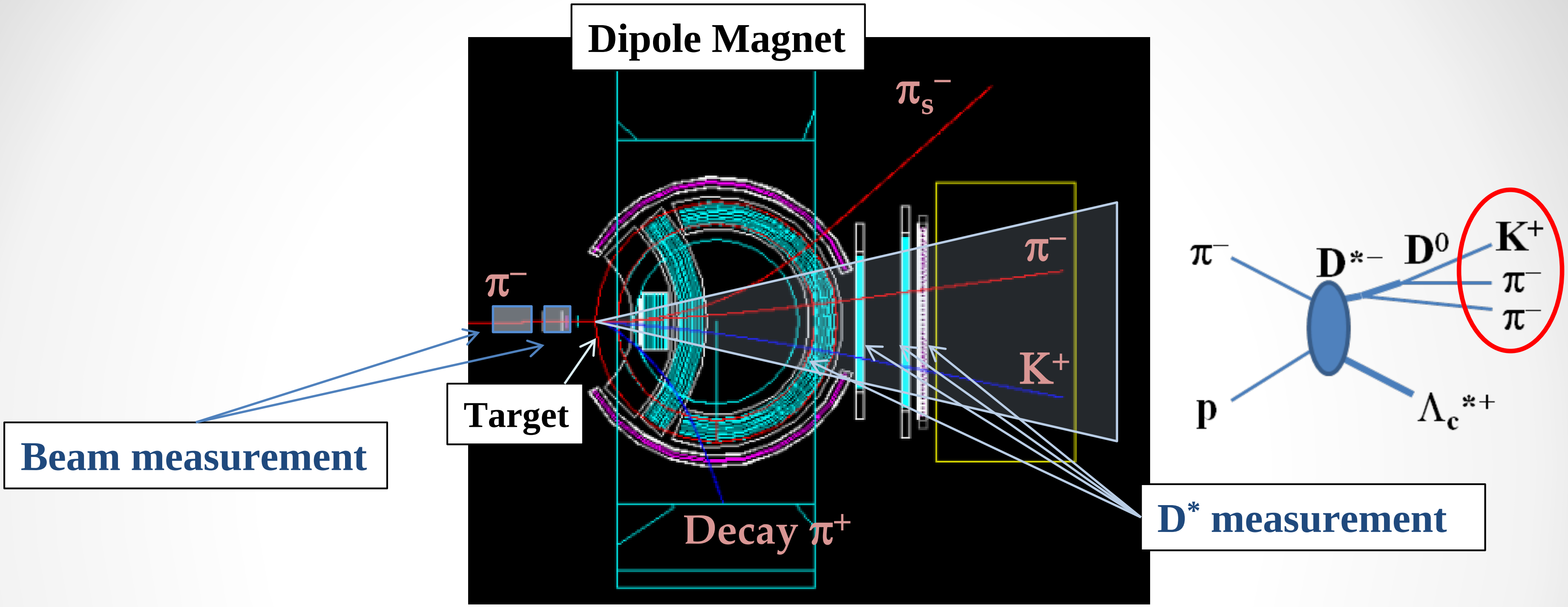

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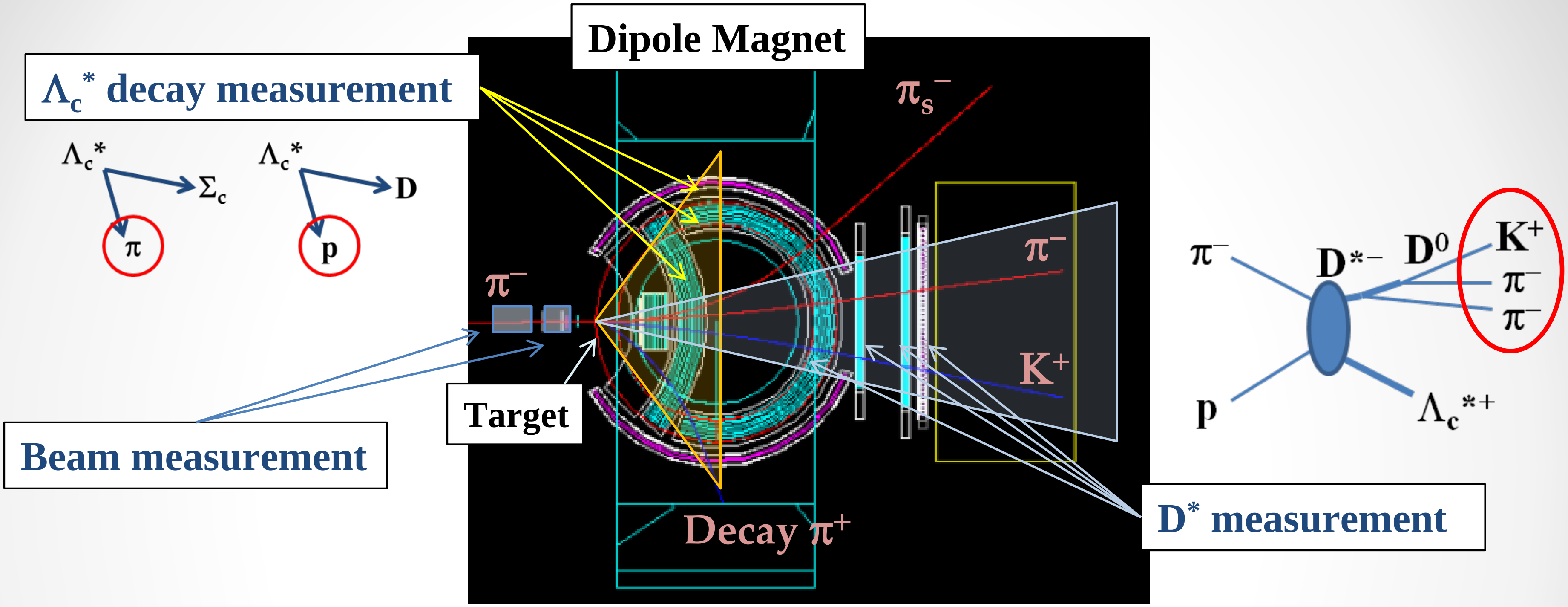

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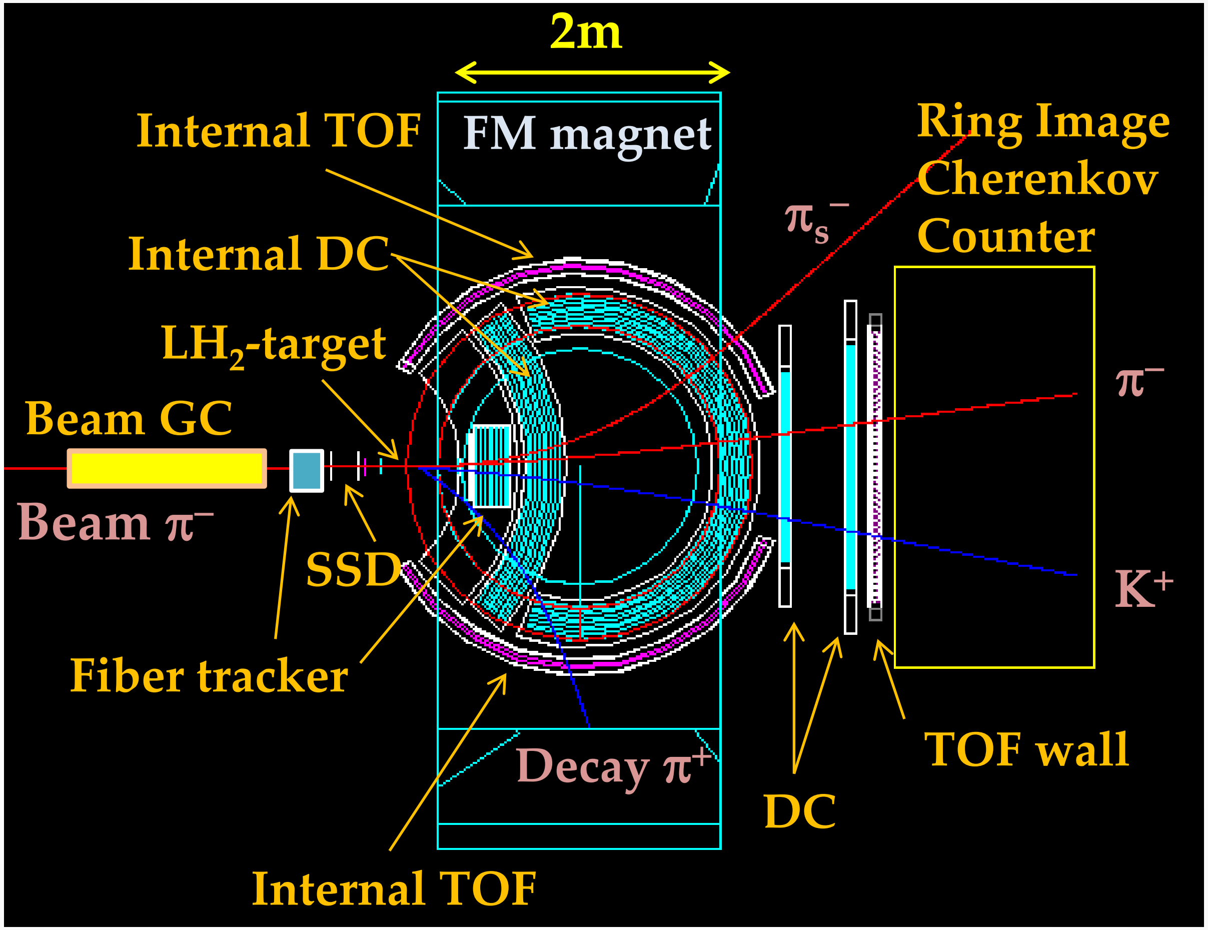
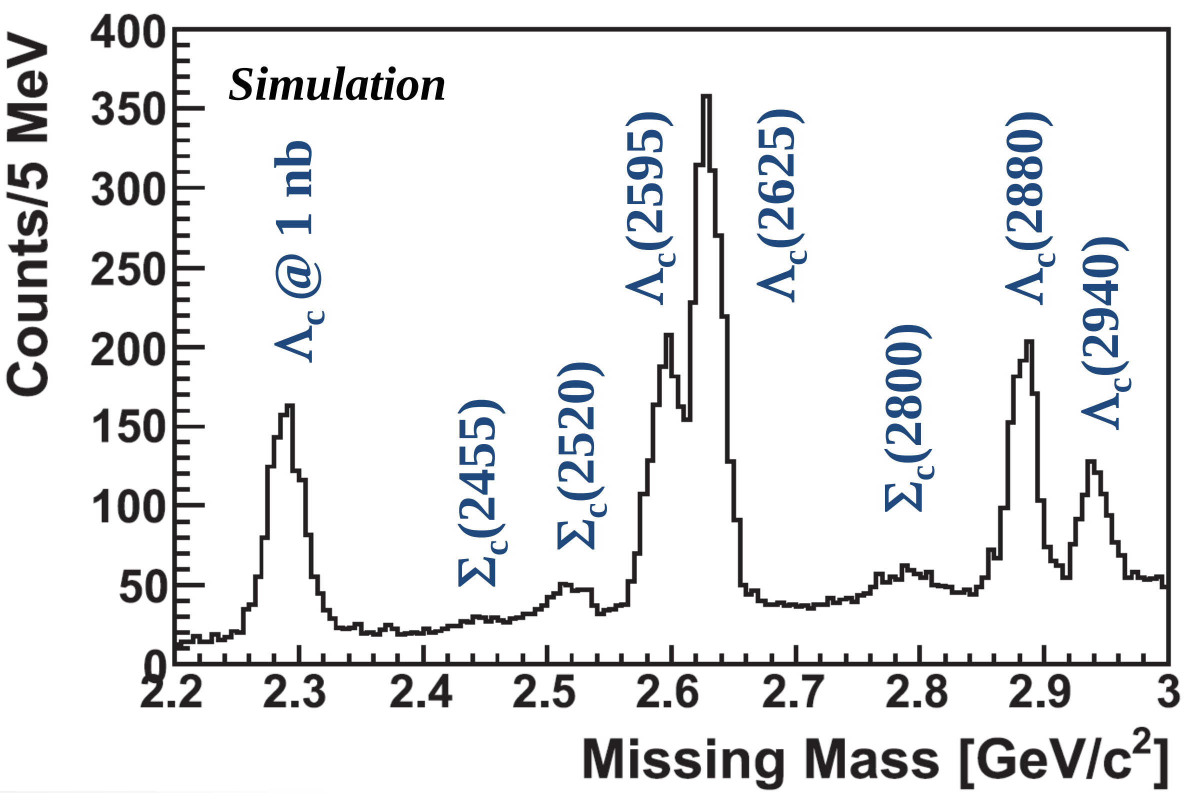
Charmed baryon spectrometer



Large Acceptance Multi-Particle Spectrometer

- **Acceptance: ~50% for D***
- **Mass resolution: $M_{\Lambda c^*}$ = 10 MeV(rms) @ 2.7 GeV/c^2**

Expected spectra



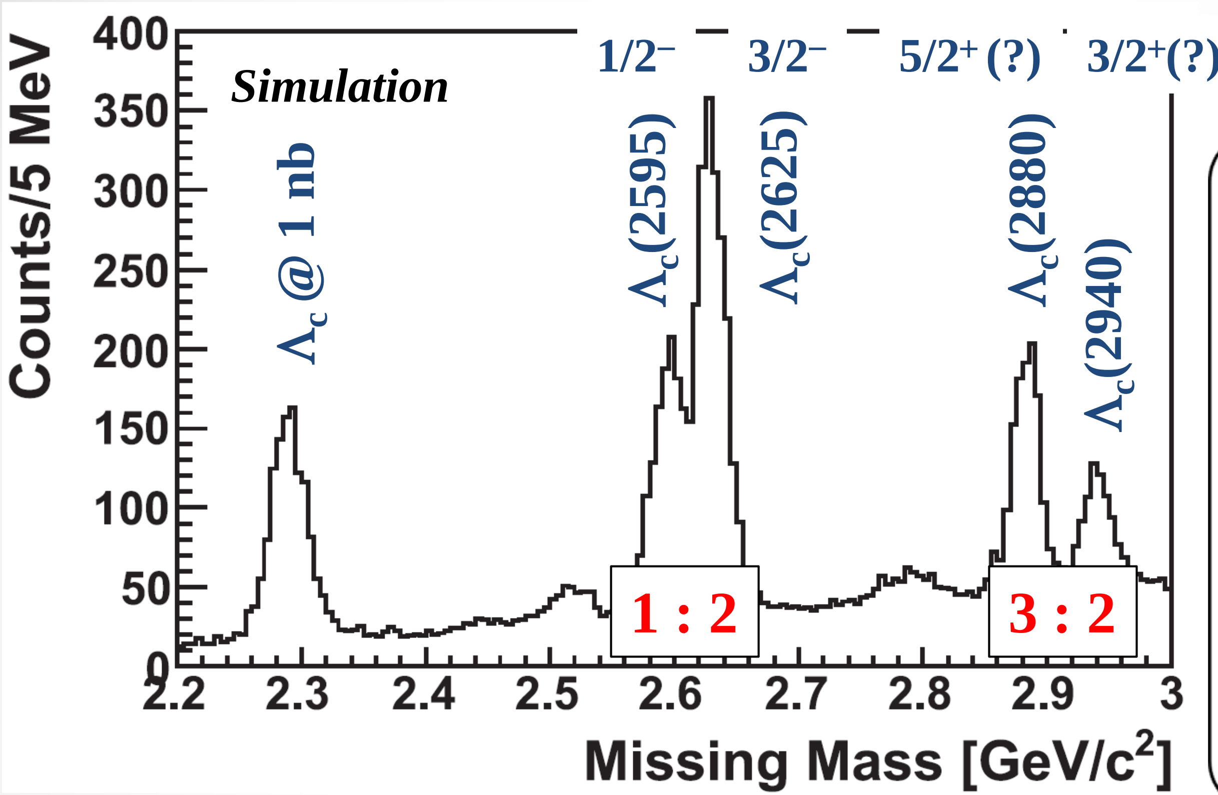
Known Mass & Width in PDG

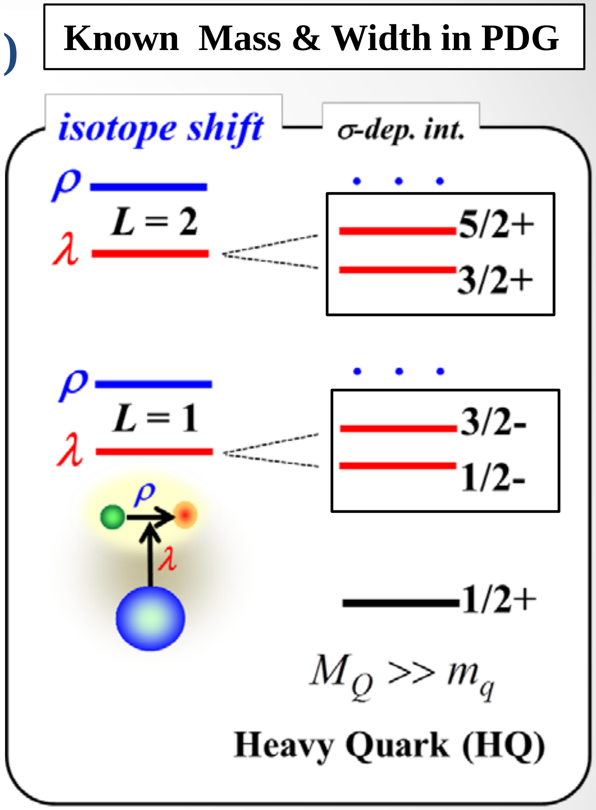
- **Background generated by the hadronic reaction code**

⇒ Reductions of background were precisely studied.

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

Expected spectra





HQ doublet

- **HQ doublets: Enhanced & Ratios (0°)**

⇔ Internal structure of charmed baryons

∗Diquark correlation: λ-mode excitation

Systematic study

Charm and Strange

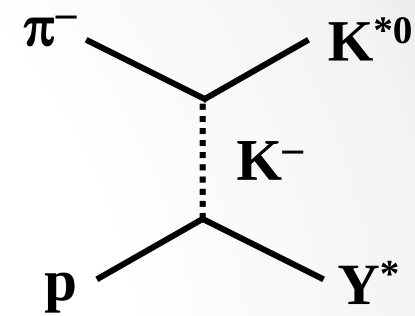
Strangeness sector

Hyperons: Λ^*, Σ^* states

- $\pi^- + p \rightarrow \Lambda^*(\Sigma^{*0}) + K^{*0}$: $\sigma \sim$ 1–10 μb
- $\pi^+ + p \rightarrow \Sigma^{*+} + K^{*+}$: $\sigma \sim$ 1–10 μb

✱ **Missing mass & decay analysis**

π-induced Y* production



Strangeness sector

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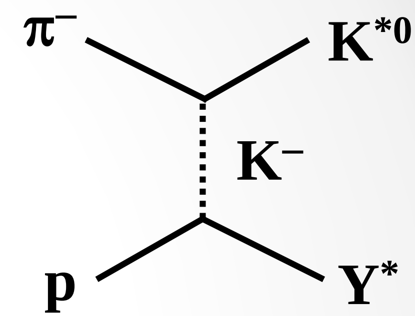
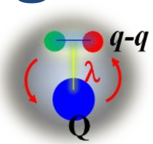
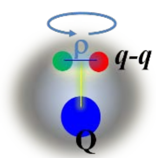
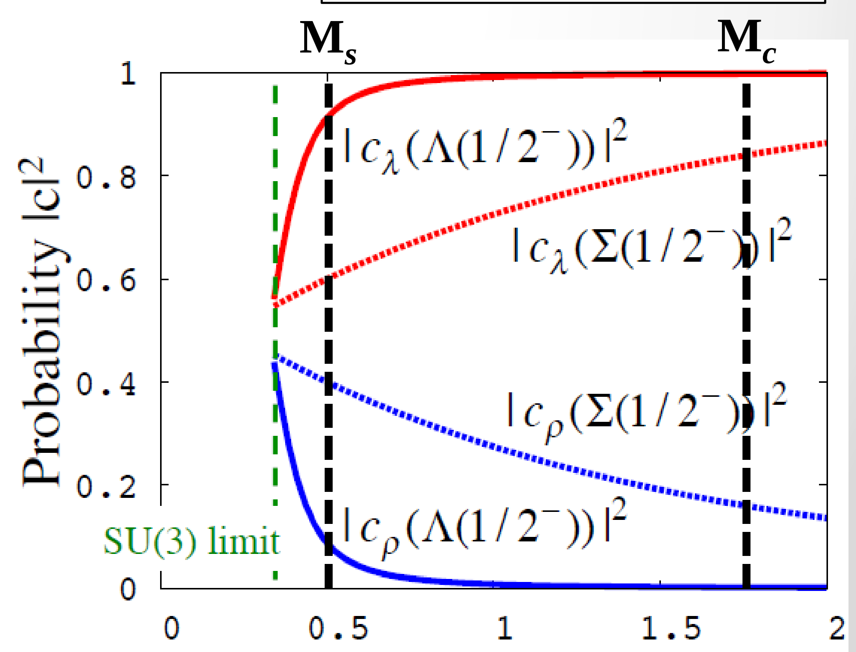


- **M_Q dependence of excitation energy**
  - Y_c*and Y*
- **λ/ρ mixing**
  - $\Psi = C_\lambda\,|$  $> + \, C_\rho\,|$  $>$
  - Production rate of Y*

⇒ Favor λ mode

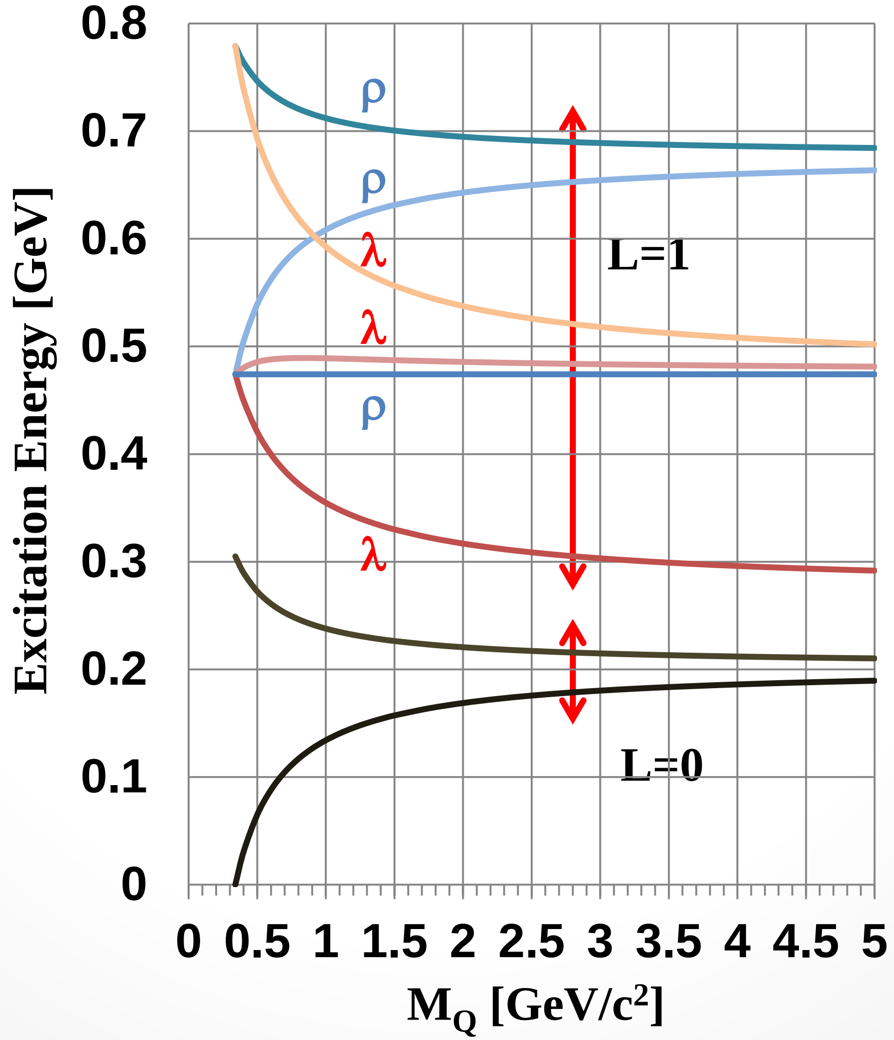
⇔ ρ mode through λ/ρ mixing

λ/ρ mixing probability



Excitation spectrum

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



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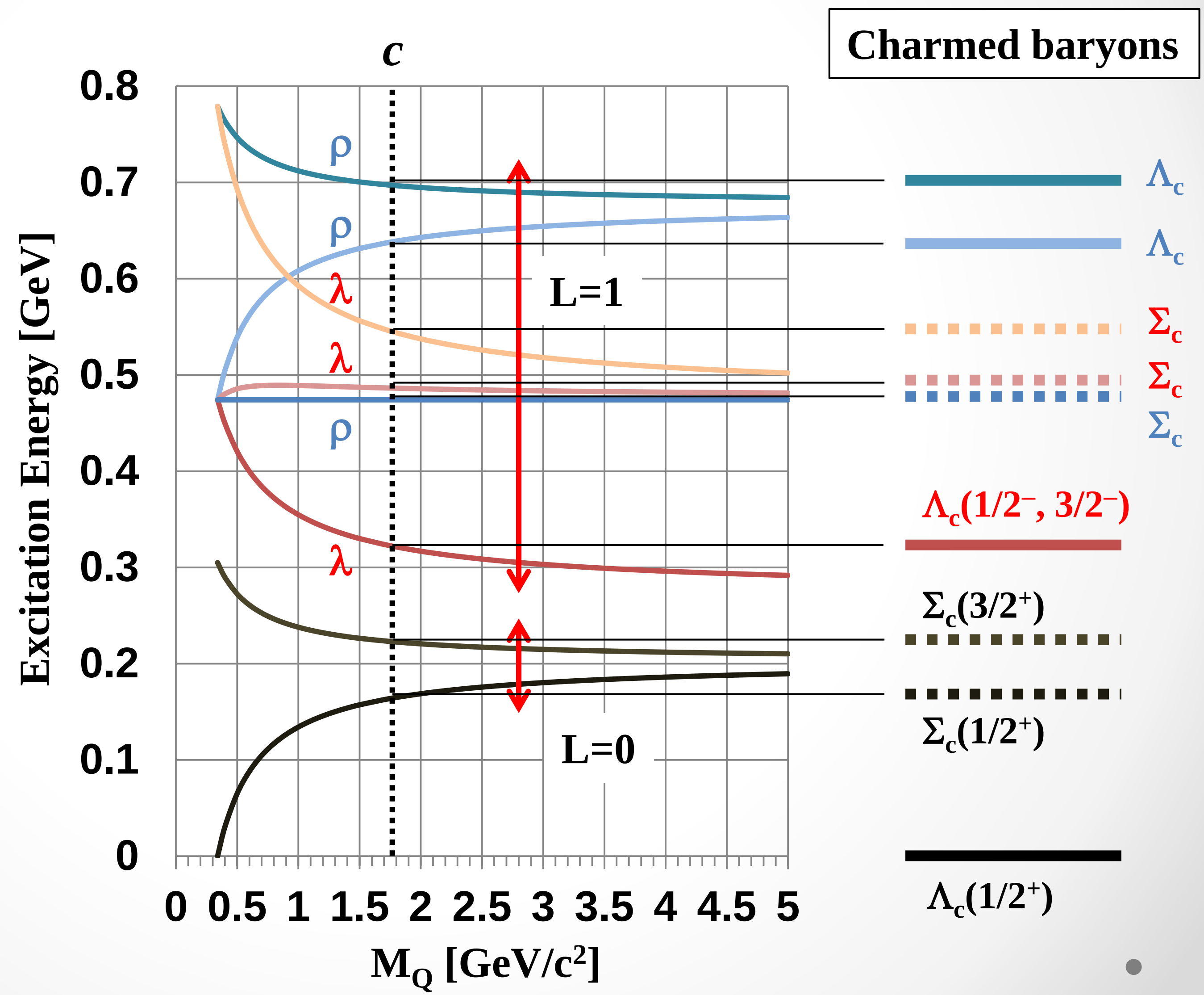

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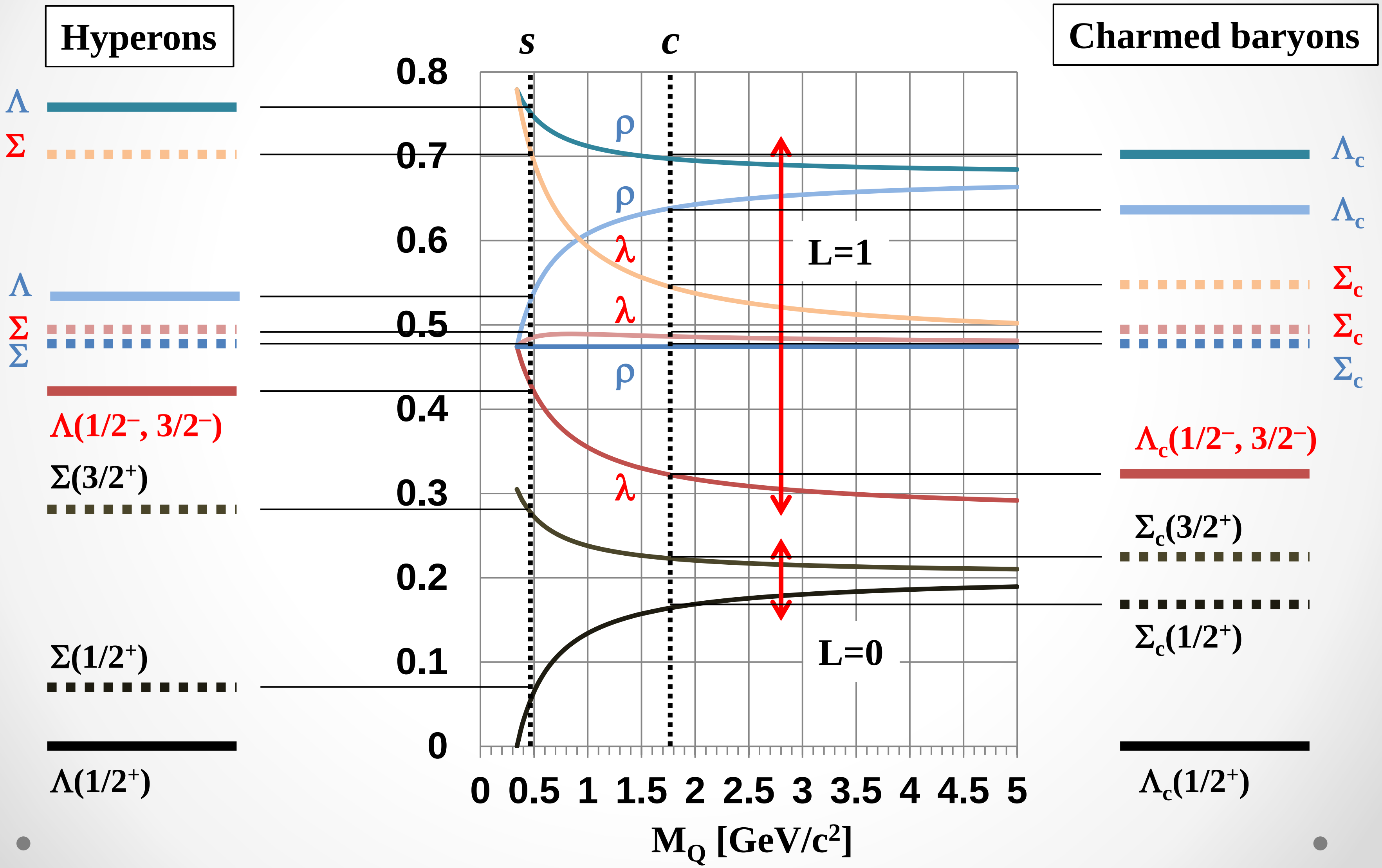


Systematic study

- **Excited state measurements**

Hyperons

- **Decay property: $\pi\Sigma/K_{bar}N$**
- **Production rate**

⇒ Known states measured

Production rate: λ mode

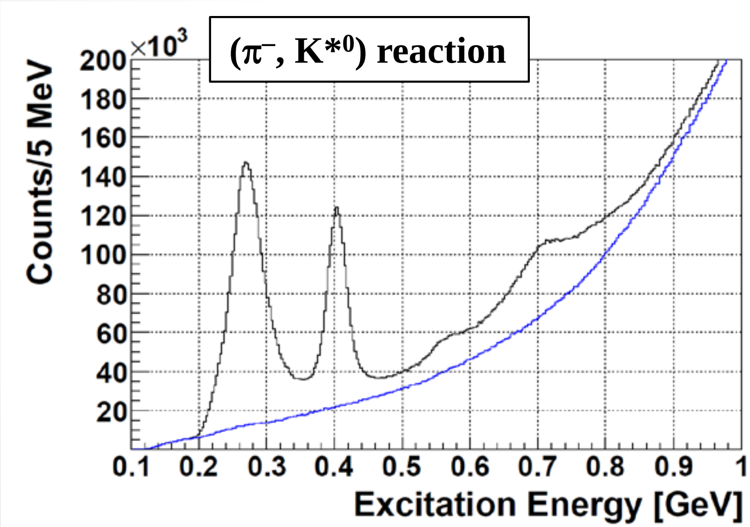
✱ ρ mode through λ/ρ mixing

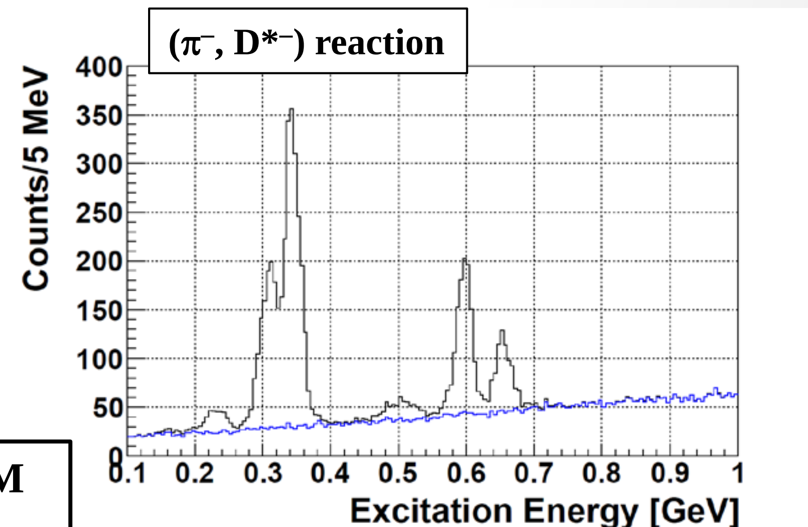
Charmed baryons

- **Decay property: $\pi\Sigma_c/DN$**
- **Production rate**

⇒ Systematic measurement

✱ Clear distinction of λ and ρ excitation modes





Systematic study

- **Excited state measurements**

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- **Decay property: $\pi\Sigma/K_{bar}N$**
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Production rate: λ mode
✱ρ mode through λ/ρ mixing

Charmed baryons

- **Decay property: $\pi\Sigma_c/DN$**
- **Production rate**

⇒ Systematic measurement
✱Clear distinction of λ and ρ excitation modes

Proper degree of freedom to understand structure

- **Connection to QCD**
- **Diquark: Just correlation between two constituent quarks ? or Quasi-particle object of two quarks ?**

✱ Essential step to understand low energy QCD nature

Summary

- Charmed baryon spectroscopy
  - Diquark correlation: λ and ρ mode excitation
  - Inclusive measurements by missing mass spectroscopy

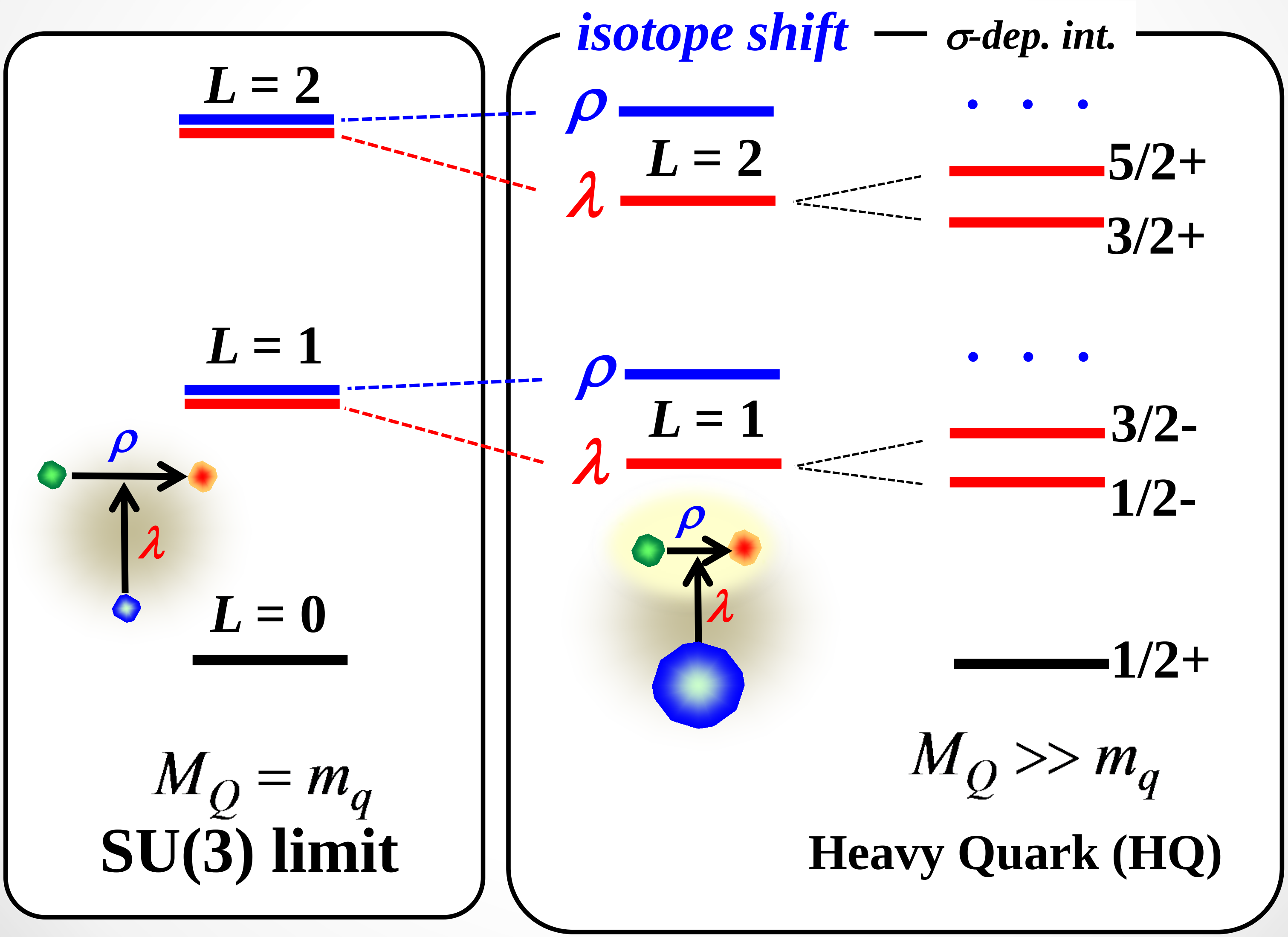
- Experiment at the J-PARC high-p beam line
  - Spectrometer
    - High resolution & Lager acceptance spectrometer
  - Experimental feasibility being checked by simulation
    - Mass resolution
    - Background study
    - Decay measurement to help missing mass measurement

- Systematic study of charmed baryons at J-PARC
  - Excitation energy, production, decay
    - With strangeness sector

Backup

A heavy quark differentiates diquark motions

λ and ρ modes are distinct ~ *isotope shift*



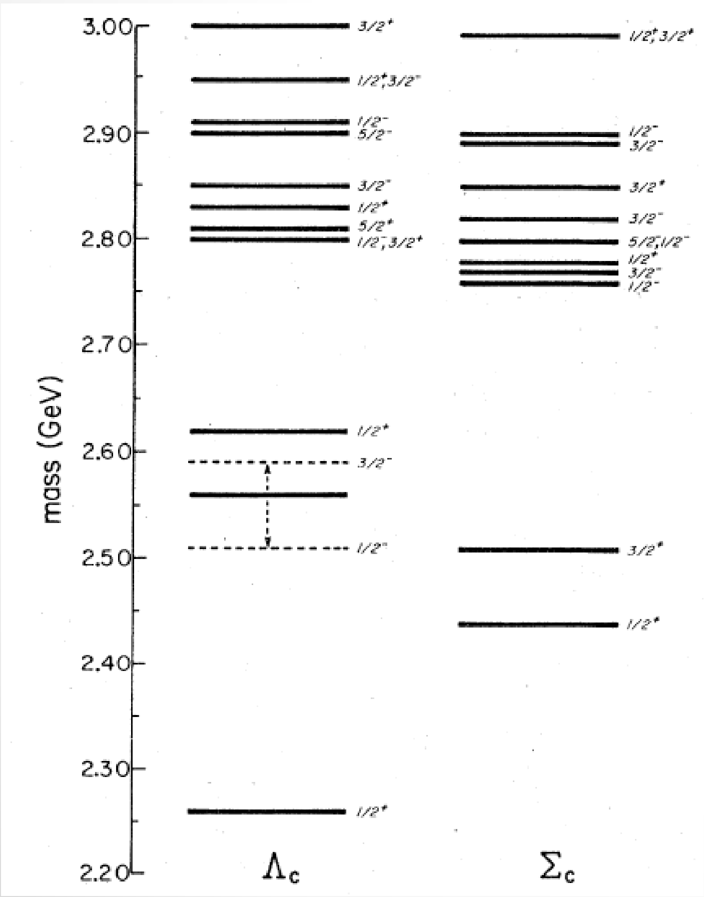
Charmed baryons: Observed

- Excited charmed baryons above 0.4 GeV

⇒ Search & Study are needed.

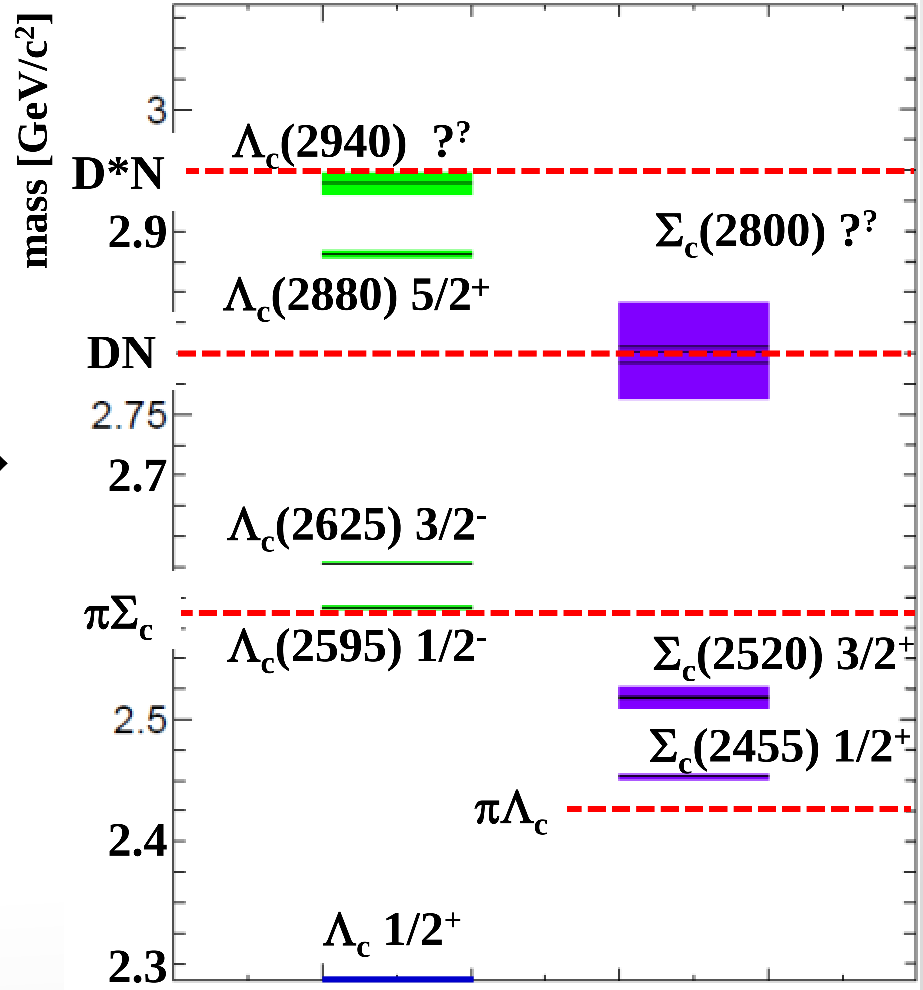
Predicted states using a quark model

(L.A. Copley et. al, Phys. Rev. D 20 (1979) 768)



⇔

Observed charmed baryons

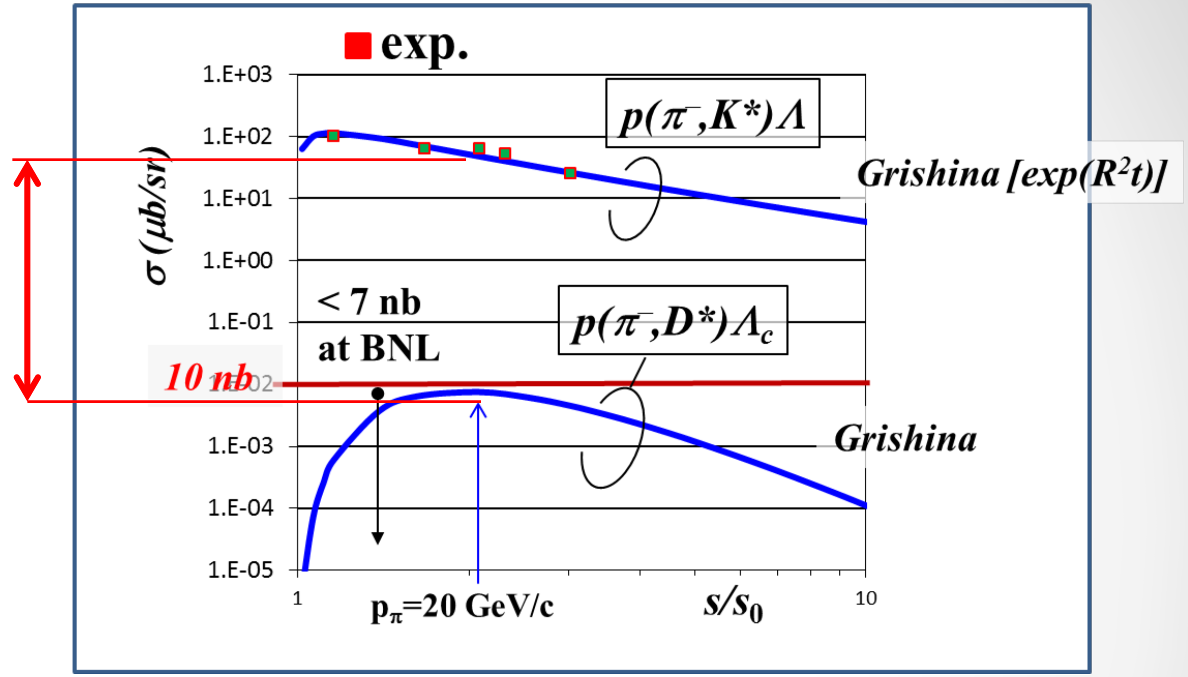


Experimental requirements

High energy 2-body reaction based on the Regge theory

Normalized to strangeness production

⇒ Charm production: ~10^{-4}

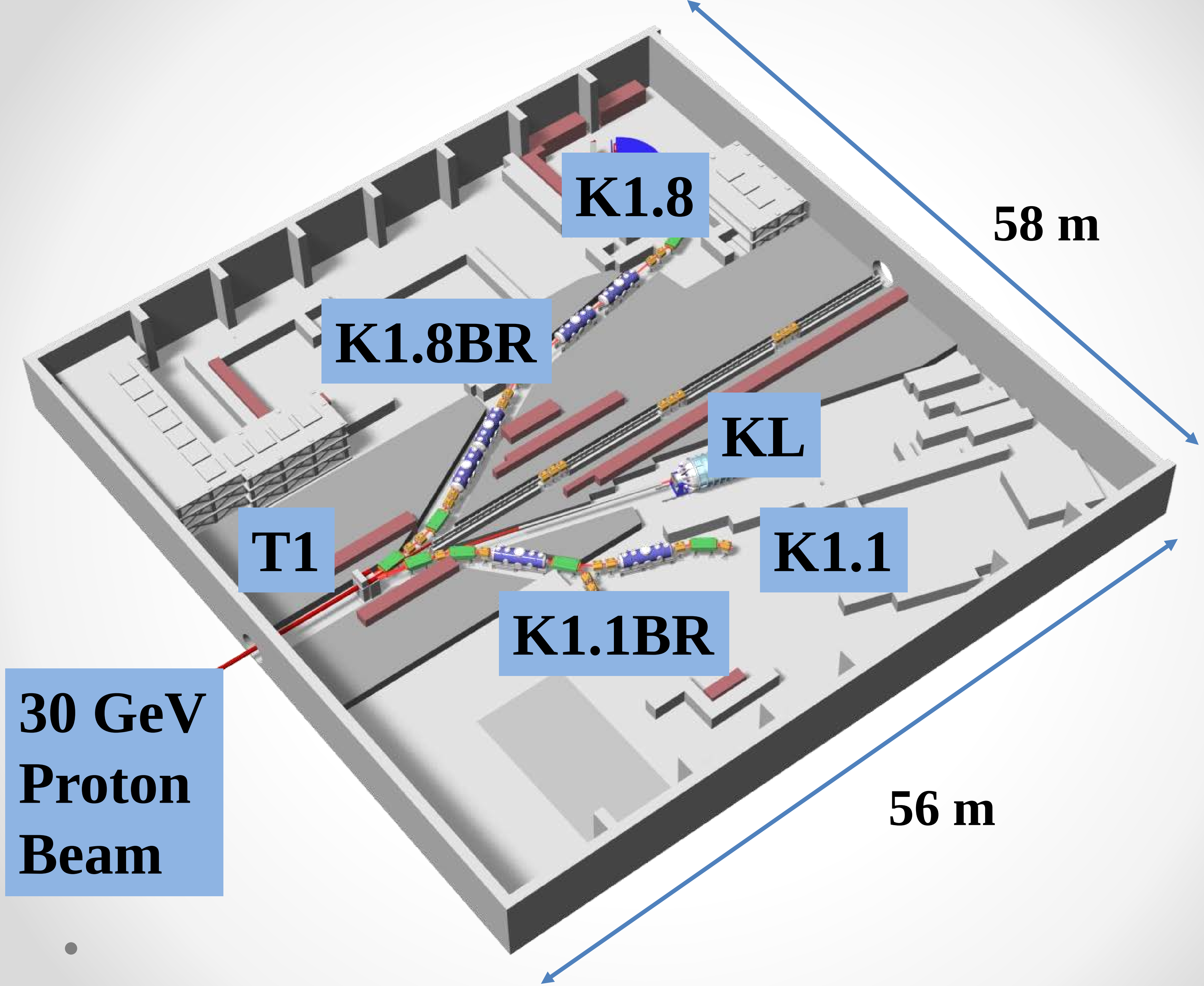


✱ Assumed production cross section: σ ~ 1 nb

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

Calculated production rates

	p_π=20 GeV/c	Mass (GeV/c)	"ud" isospin factor	Y_c^* Spin factor	q_{eff} (GeV/c)	Rate (Relative)
L=0	$\Lambda_c^{1/2+}$	2286	1/2	1	1.34	1
	$\Sigma_c^{1/2+}$	2455	1/6	1/9	1.44	0.03
	$\Sigma_c^{3/2+}$	2520	1/6	8/9	1.45	0.17
L=1	$\Lambda_c^{1/2-}$	2595	1/2	1/3	1.38	0.93
	$\Lambda_c^{3/2-}$	2625	1/2	2/3	1.38	1.75
	$\Sigma_c^{1/2-}$	2750	1/6	1/27	1.49	0.02
	$\Sigma_c^{3/2-}$	2820	1/6	2/27	1.50	0.04
	$\Sigma_c^{1/2-'}$	2750	1/6	2/27	1.49	0.05
	$\Sigma_c^{3/2-'}$	2820	1/6	56/135	1.51	0.21
	$\Sigma_c^{5/2-'}$	2820	1/6	2/5	1.51	0.21
L=2	$\Lambda_c^{3/2+}$	2940	1/2	2/5	1.43	0.49
	$\Lambda_c^{5/2+}$	2880	1/2	3/5	1.42	0.86



K1.8
58 m
K1.8BR
KL
T1
K1.1
K1.1BR
30 GeV
Proton
Beam
56 m

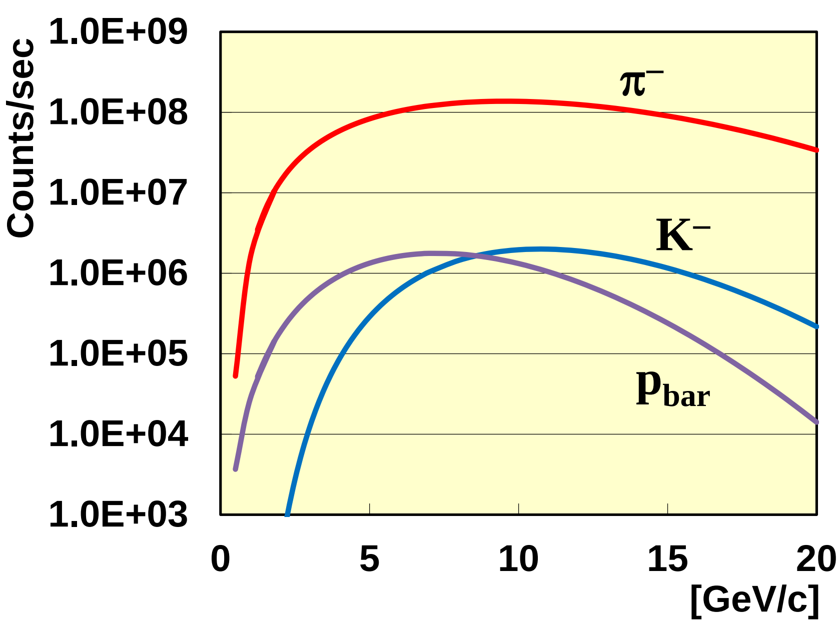
Beam intensity

- **Calculated by Sanford-Wang**
  - **15 kW loss on Pt (30 kW on 6 cm length)**
  - **Acceptance :1.5 msr%, 133.2 m**

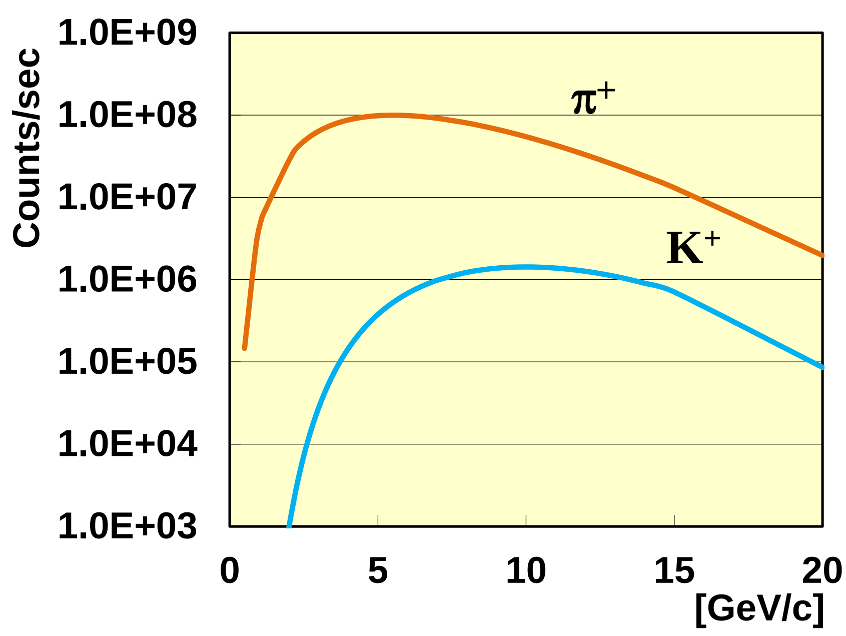
⇒ High-rate π beam available: > 10^7 /spill

- **K^- and p_{bar} beam: > 10^5 /spill**

Negative: **Prod. Angle = 0 degrees**



Positive: **Prod. Angle = 3.1 degrees**



Backgrounds

1. **Main background**
   - **Strangeness production: (K^+, π^-, π_s^-) in final state**
   - **10^6 time higher than charmed baryon production**

2. **Wrong particle identification**
   - **Dominant cases: (π^+, π^-, π_s^-), (p, π^-, π_s^-)**
     - **Miss-identification of K^+**

3. **Associated charm production: D^{*-}**
   - **Highly excited D***
   - **DD_{bar} pair**
   - **Charmonium**

Backgrounds

1. **Main background**
   - **Strangeness production: (K^+, π^-, π_s^-) in final state**
   - **10^6 time higher than charmed baryon production**

2. **Wrong particle identification: 6% of Main BG**
   - **Dominant cases: (π^+, π^-, π_s^-), (p, π^-, π_s^-)**
     - **Miss-identification of K^+**

3. **Associated charm production: D^{*-}**
   - **Highly excited D^***
   - **DD_{bar} pair**
   - **Charmonium**

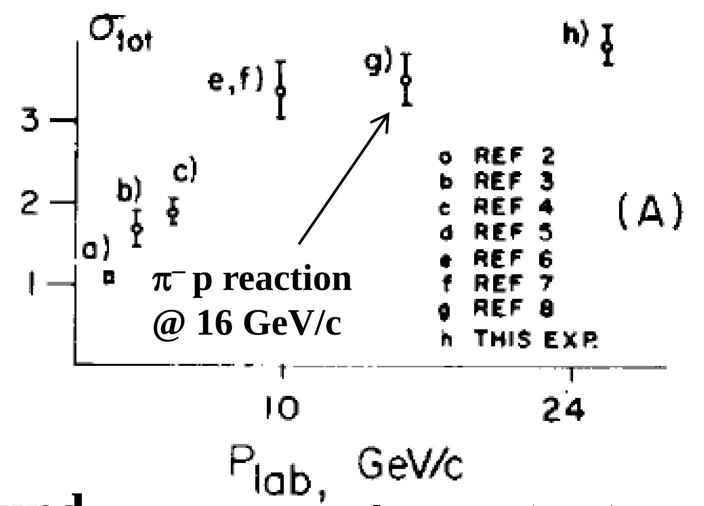
   Contribution (peaking or not) checked by analysis

Main background

All events including K^+, π^-, π^-

∗ σ_{Total} of $\pi^- p$ @ 16 GeV/c : 25.7 mb
⇔ Strangeness production: 3.4 mb

Strangeness production C.S.



- **Background source**
  - $K^{*0}(\rightarrow K^+, \pi^-) + \pi^-$
  - KK_{bar} $(K^*K^*_{bar})$ production + π^-
  - $Y K^+ + \pi^-$
  - Non-resonant multi-meson production

  ∗ No special channel contribute to background J. W. Waters et al, NPB17 (1970) 445

- **Background generation** Y. Nara et.al. Phys. Rev. C61 (2000) 024901
  - JAM (Jet AA Microscopic transport model)
    - Include many elementary processes in low-high energy
    - Use K^+ and π^- distribution from $\pi^- p$ reaction at 20 GeV/c
      - σ = 2.4 mb for (K^+, π^-, π^-)
    - ss_{bar} production multiplicity: ~1 (2 K^+event: ~3%)

Charged track multiplicity

of charged track $\pi^- p \to X$ @ 16 GeV/c

Track数	2T [mb]	4T [mb]	6T [mb]	8T [mb]	10T [mb]	Total [mb]
Data	9.78	9.02	4.85	1.37	0.2	25.22
JAM	8.03	8.81	6.17	1.42	0.08	24.51
PYTHIA	8.84	9.72	5.21	0.79	0.03	24.59

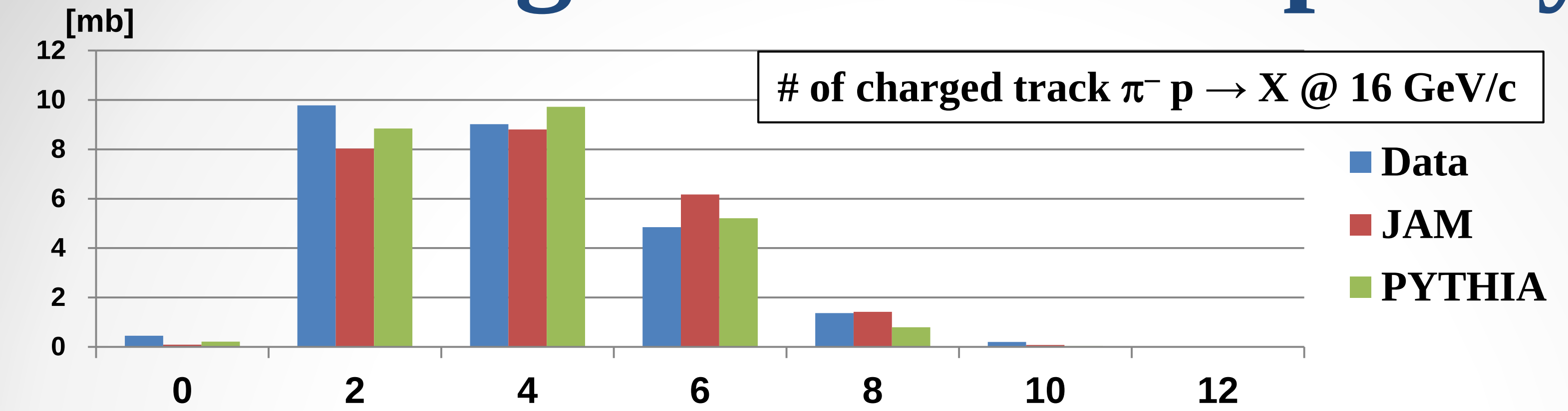
# of charged track $\pi^- p \to \Lambda + X$ @ 15 GeV/c

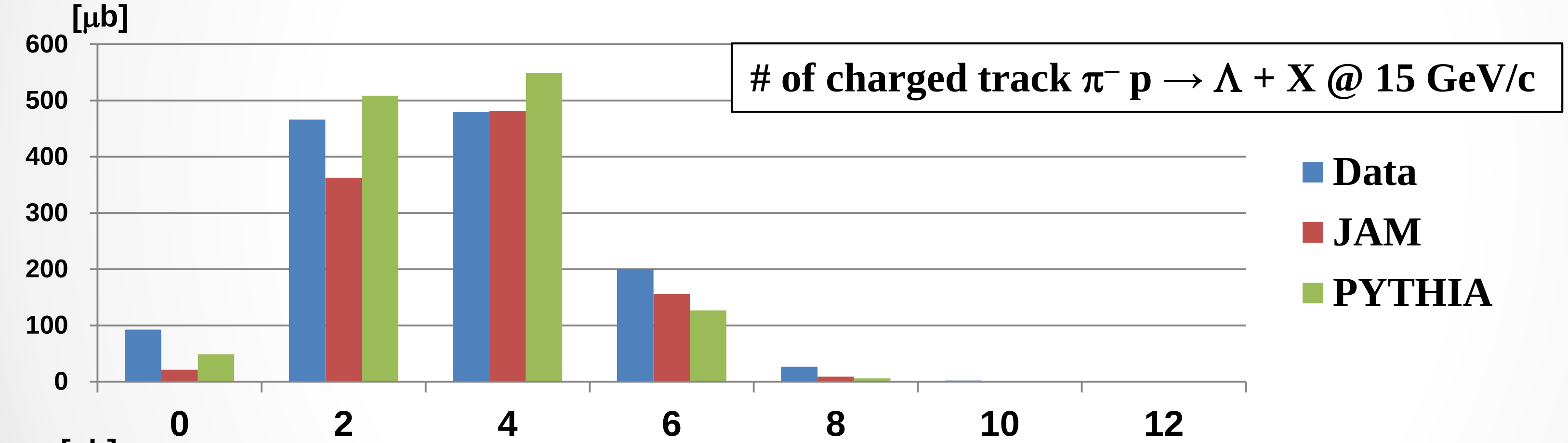
Track数	2T [μb]	4T [μb]	6T [μb]	8T [μb]	10T [μb]	Total [μb]
Data	466	480	200	26.6	1.8	1174
JAM	363	482	155	9.00	0.02	1009
PYTHIA	509	549	127	5.84	0.05	1191

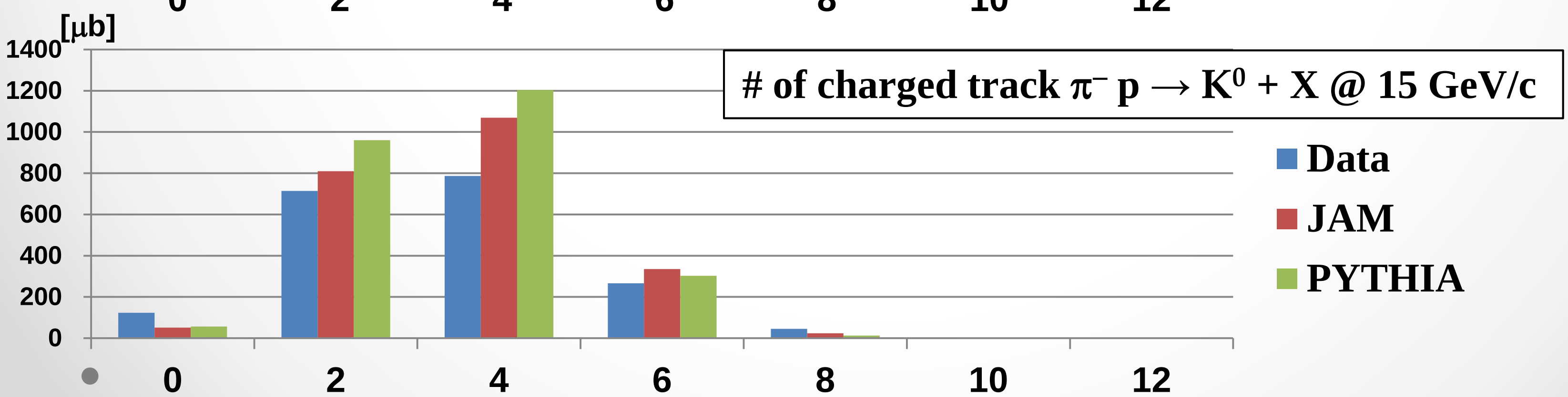
# of charged track $\pi^- p \to K^0 + X$ @ 15 GeV/c

Track数	2T [μb]	4T [μb]	6T [μb]	8T [μb]	10T [μb]	Total [μb]
Data	714	787	266	45.2	2.4	1815
JAM	810	1069	345	23.8	0.2	2248
PYTHIA	960	1203	302	13.1	0.1	2478

Charged track multiplicity

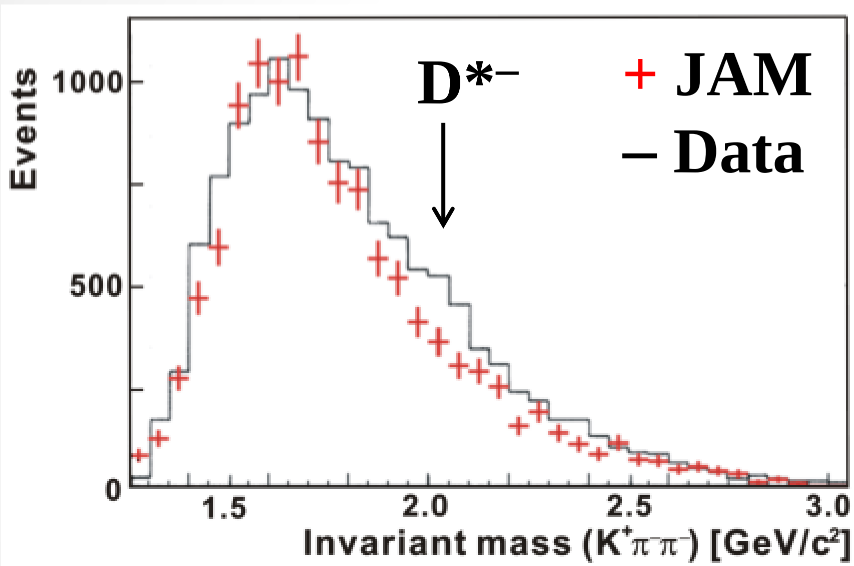




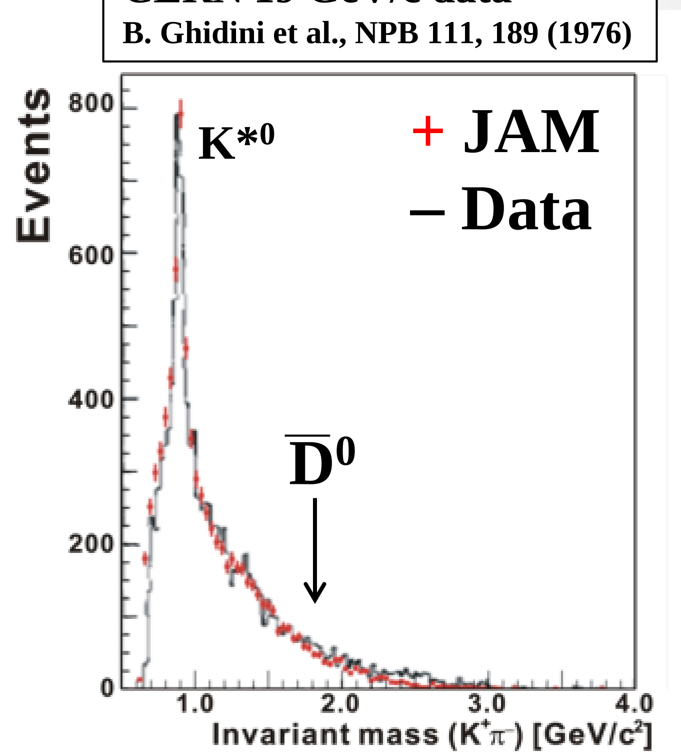


Reliability of the BG simulation

BNL 13 GeV/c data
J.H. Christenson et al., PRL 55, 154 (1985)



CERN 19 GeV/c data
B. Ghidini et al., NPB 111, 189 (1976)



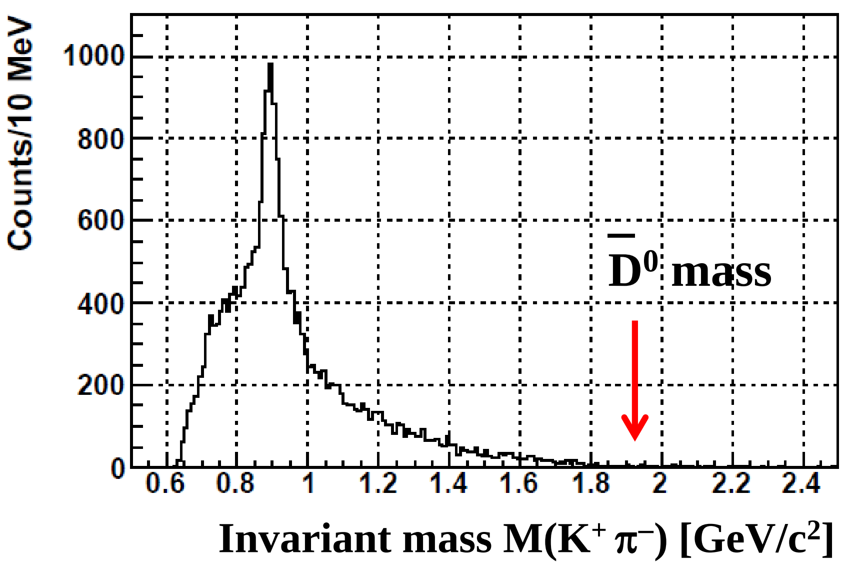
- **Background simulation by JAM (PYTHIA)**

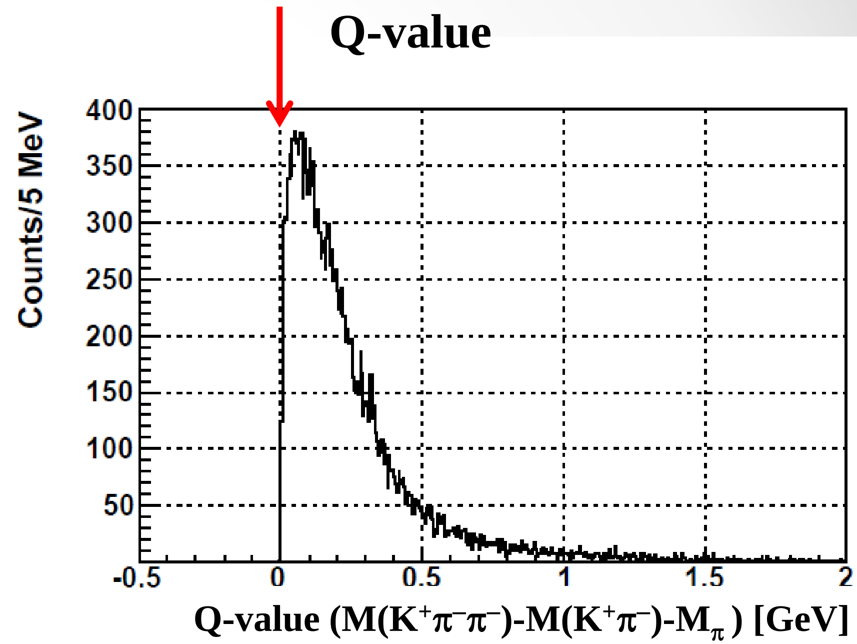
⇒ Shapes and yields were well reproduced.

-Event counts in D* mass and K^{*0} cross section: ~30% ambiguity

Y. Nara et.al., Phys. Rev. C61 (2000) 024901

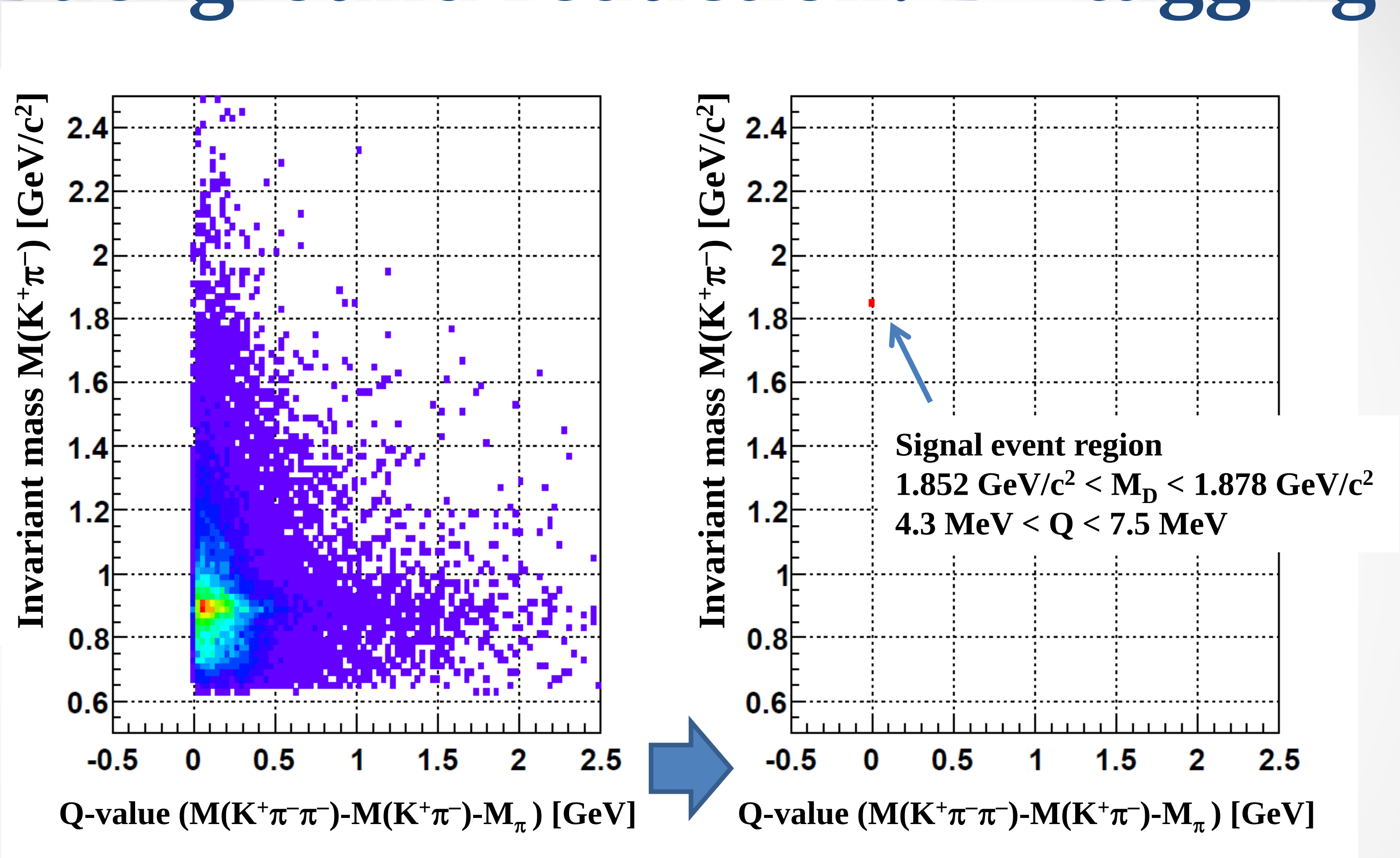
Background spectra





- Events around $\overline{D}^0$ and D* mass (Q-value) region selected
  - $\overline{D}^0$ mass(1.865): 1.852-1.878 GeV/c^2 (26 MeV)
  - Q-value(5.9) ($Q = M(K^+\pi^-\pi^-)-M(K^+\pi^-)-M_\pi$): 4.3-7.5 MeV (3.2 MeV)
    - For removing momentum resolution of p_K and p_π

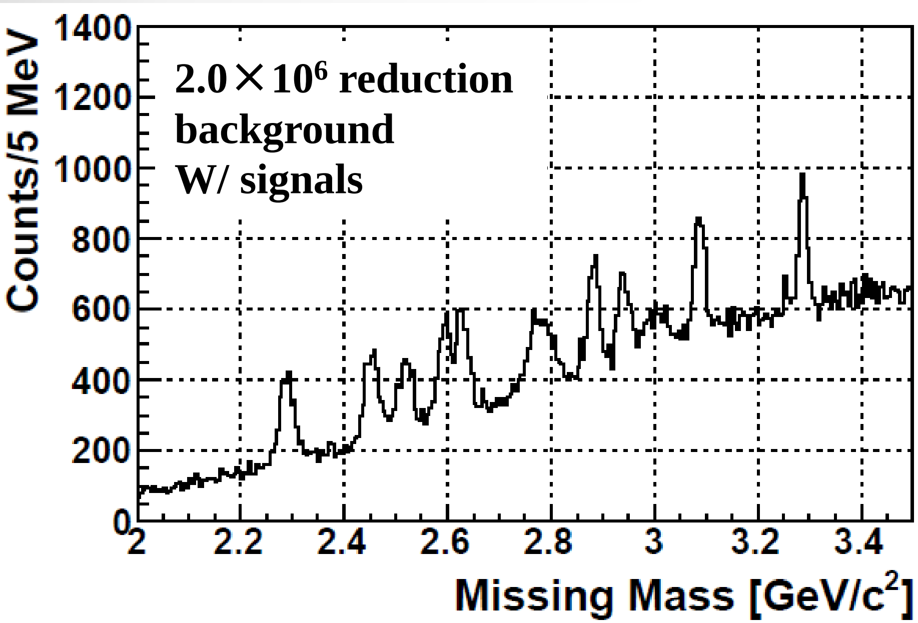
Background reduction: D* tagging



∗ Both $\overline{D}^0$ mass and Q-value region selected by narrow gate

⇒ More than 10^6 reduction for background events

Background reduction

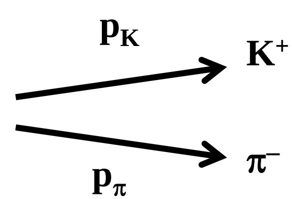


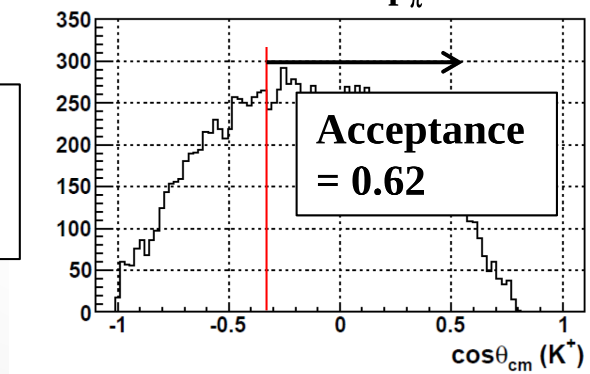
S/N improvement

- **D* tagging**
  - Mass resolution: × 4
- **Event selections**
  - Decay angle cut: ×2
  - Production angle cut ×4 (depends on $d\sigma/dt$)

Signal

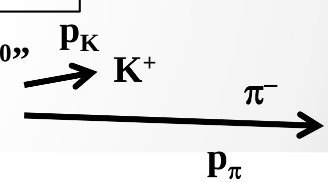
"True D^0" mass

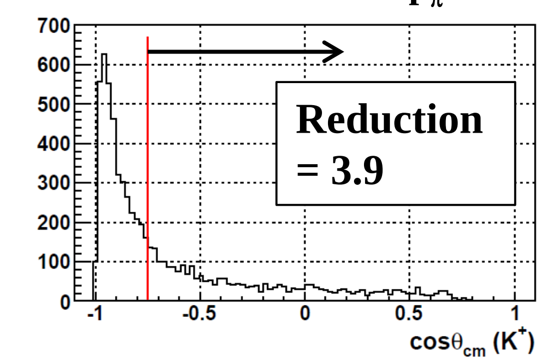




Background

"Fake D^0" mass

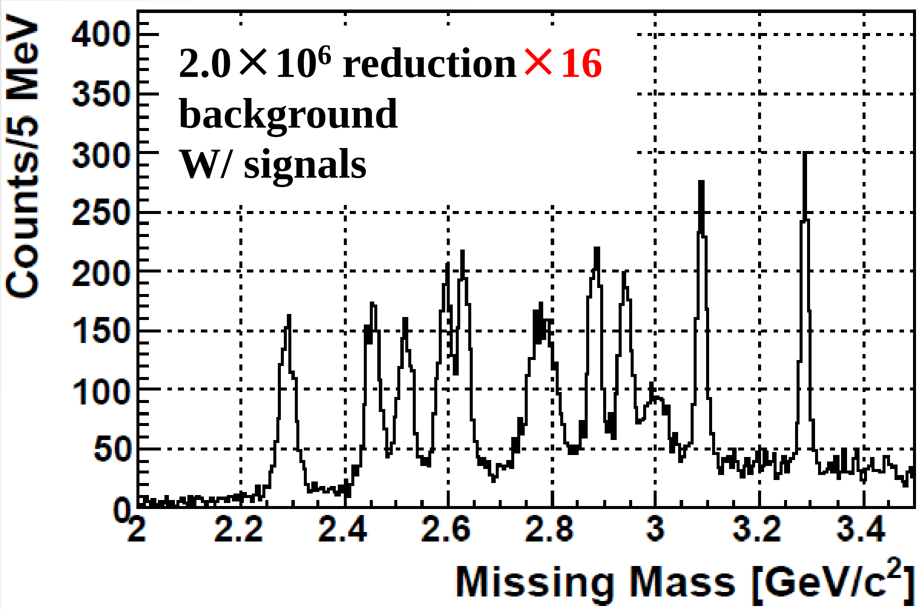




K^+ scattering angel in CM
- Simulation

w/ spectrometer acceptance

Background reduction



S/N improvement

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  - Decay angle cut: ×2
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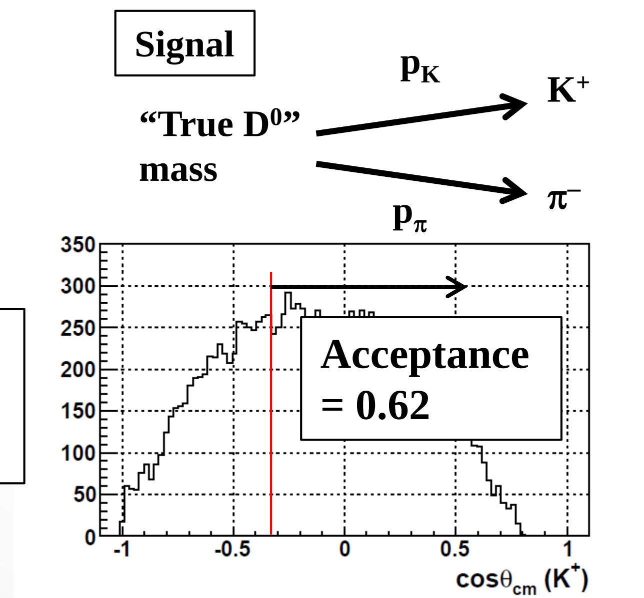
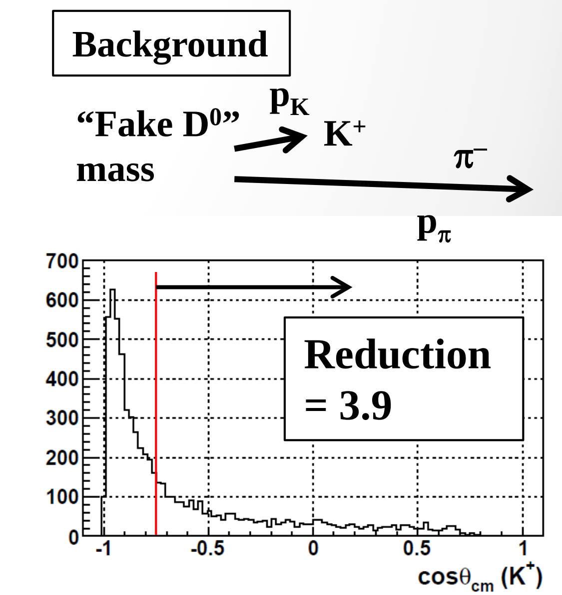




K^+ scattering angel in CM
- Simulation

w/ spectrometer acceptance

Background reduction

Total cross section @ 20 GeV/c: 25.1 mb

- **(K^+, π^-, π^-) final state: 2.43 mb**
- **D^0 mass region (1.852–1.878 GeV/c^2): 21.7 μb (1/112)**
- **D^{*-} tagging (Q = 4.3–7.5 MeV): 50.2 nb (1/434)**
  - **Old experiment: 1/100 by 4 time worse resolution**
- **Acceptance: 1.2 nb (1/43)**
  - **Detector: 50% for D* tagged events**
  - **Momentum cut (p_{K+} & $p_{\pi-}$ > 2.0 GeV/c, Soft π^- = 0.5–1.7 GeV/c)**

- **Total reduction: $112 \times 434 \times 43 \sim 2 \times 10^6$**

S/N ratio

Background reduction

- **Total reduction: 112×434×43 ~ 2×10^6**
- **Event selection: 16**

- **Signal: 12 nb (1 nb×12 states)**
  - **B.R.×0.026 ⇒ 0.312 nb**
  - **Event selection×1/2 ⇒ 0.156 nb**
- **BG: 2.43 mb ((K^+, π^-, π^-) final state)**
  - **0.081 nb**

⇒ S/N = 2.1 for D^0 and D* mass region

S/N estimation

- **Signal: 12×1000 = 12000 counts**
- **BG: 12000/2.1 = 5700 counts**

⇒ Mass region: 2.2-3.4 GeV ⇒ ~5 counts/MeV

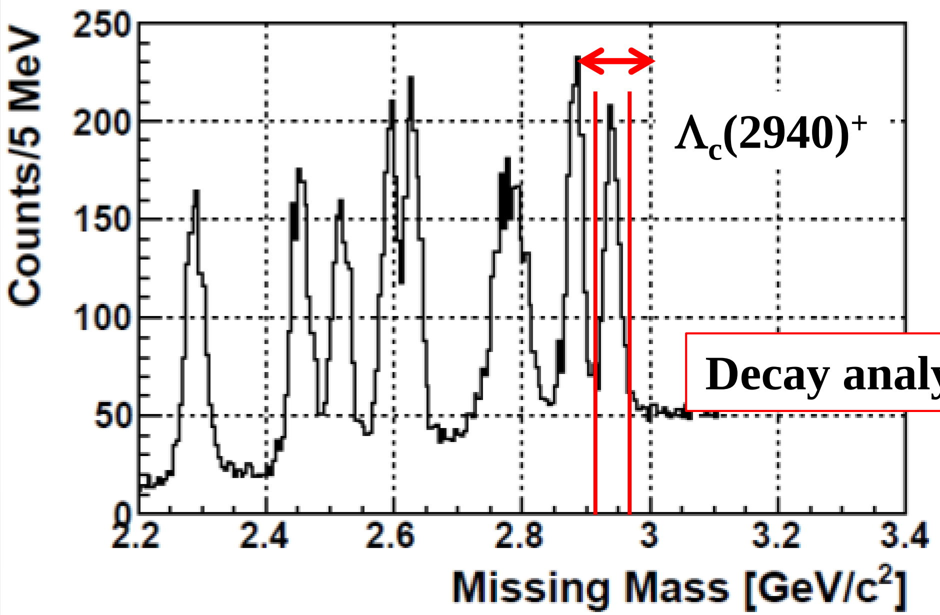
⇒ S/N = 1000/150 ~ 7

  - **30 MeV region: 150 counts**

- **$S/\sqrt{N}$ = $100/\sqrt{1000}$ ~ 3**
  - **Signal: σ= 0.1 nb, Γ = 100 MeV: ⇒ 100 counts**
  - **BG: 200 MeV region ⇒ 1000 counts**

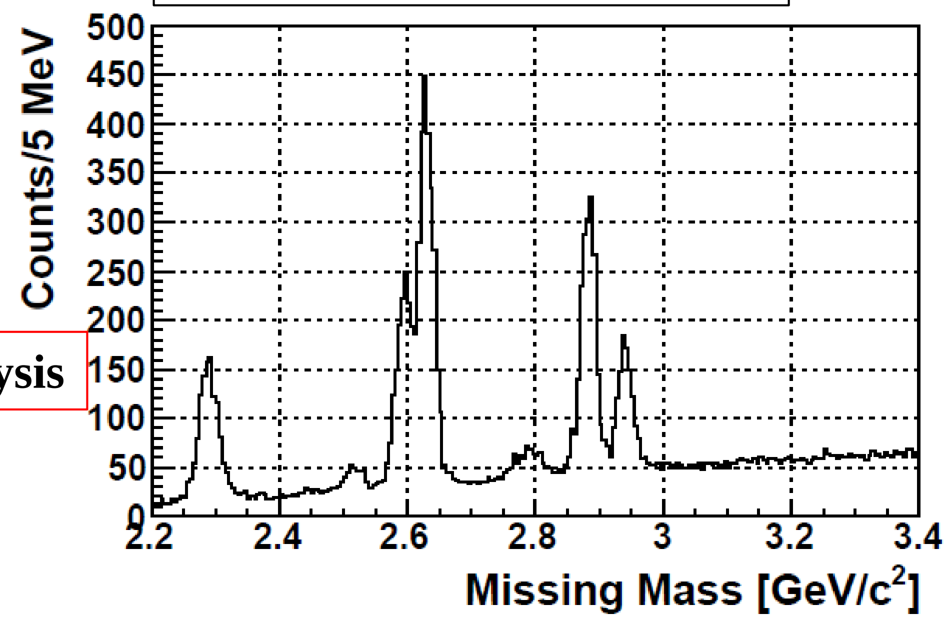
Expected spectra: σ = 1 nb

σ = 1 nb case for each state



Decay analysis

G.S. = 1 nb & production ratio



Known Mass & Width in PDG

- Background study by the JAM code

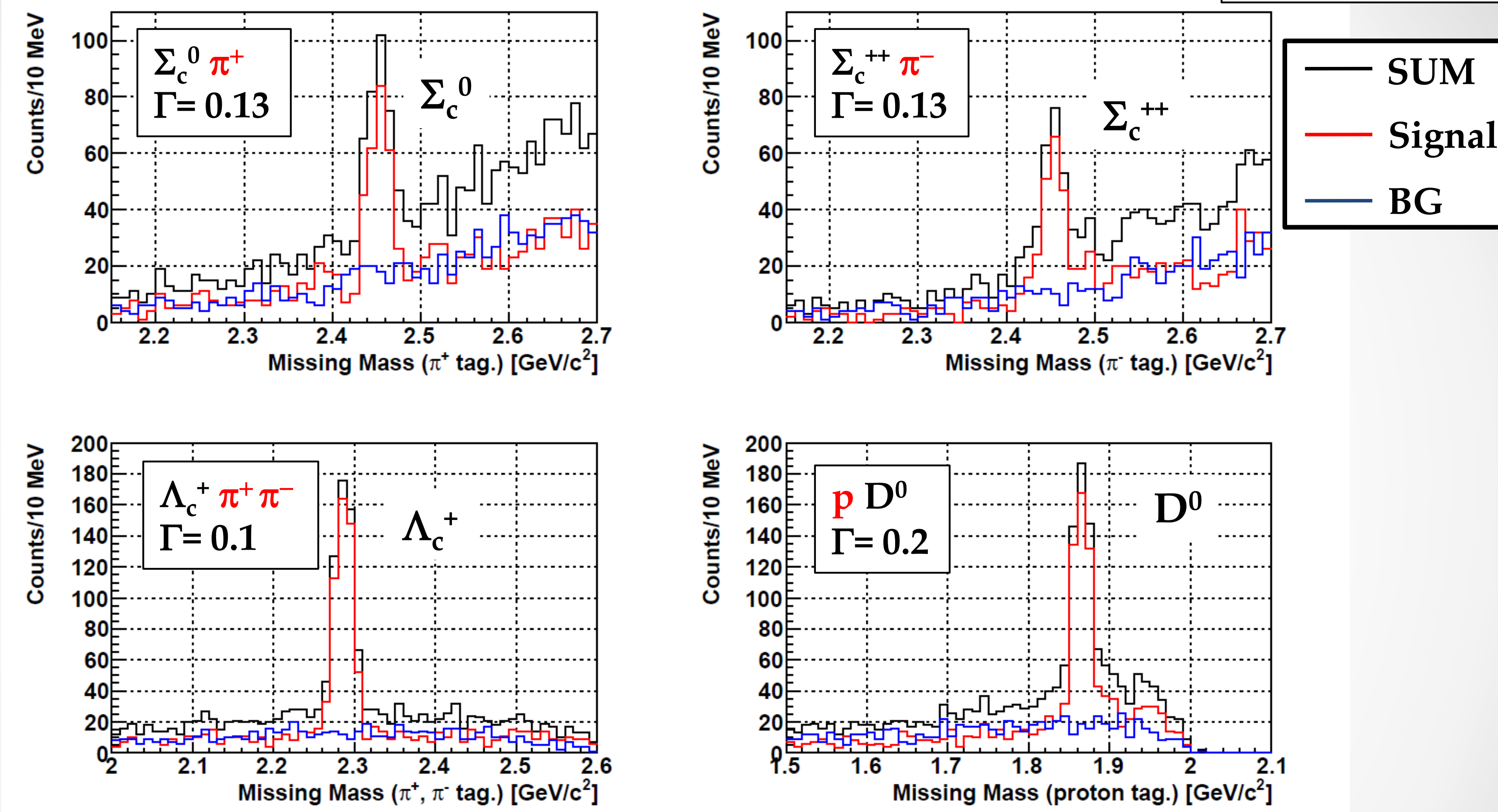
⇒ Reduction by D* tagging + Event selections

- $D^0 \rightarrow K^+ \pi^-$ decay angle cut, production angle cut

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

Decay measurement

B.R.: Assumed



Decay measurement strongly assists the missing mass spectroscopy.

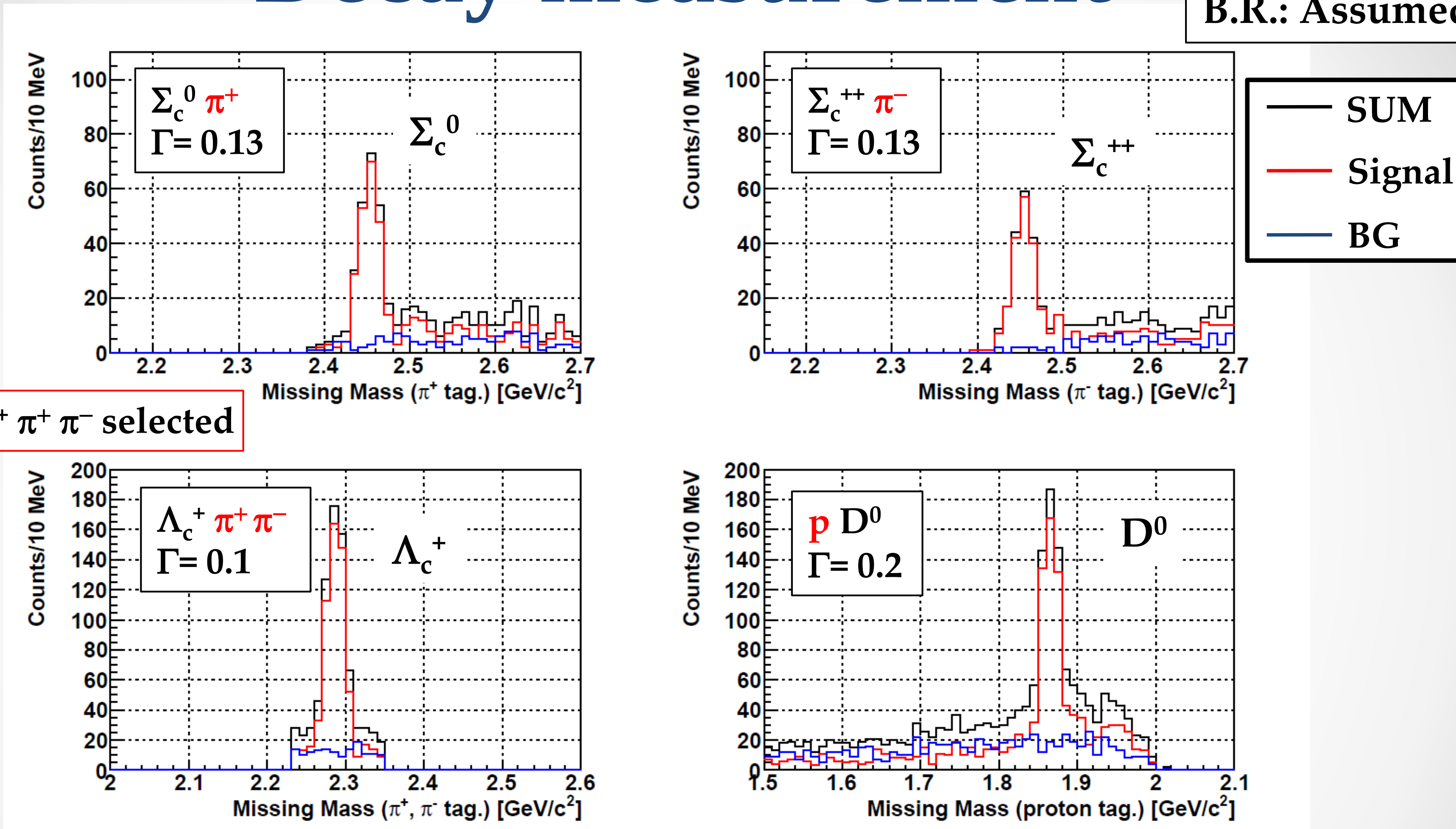
- **Branching ratios: $\Gamma(\Lambda_c^* \to p\,D)/\Gamma(\Lambda_c^* \to \Sigma_c\,\pi)$**
- **Angular distribution**

✱ $D^0 \to K^+\pi^-$ (3.88%), $D^0 \to K^+\pi^-\pi^+\pi^-$ (8.07%), $D^0 \to K_S^0\pi^+\pi^-$ (2.82%) can be used.

Decay measurement

B.R.: Assumed

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



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Old experiments

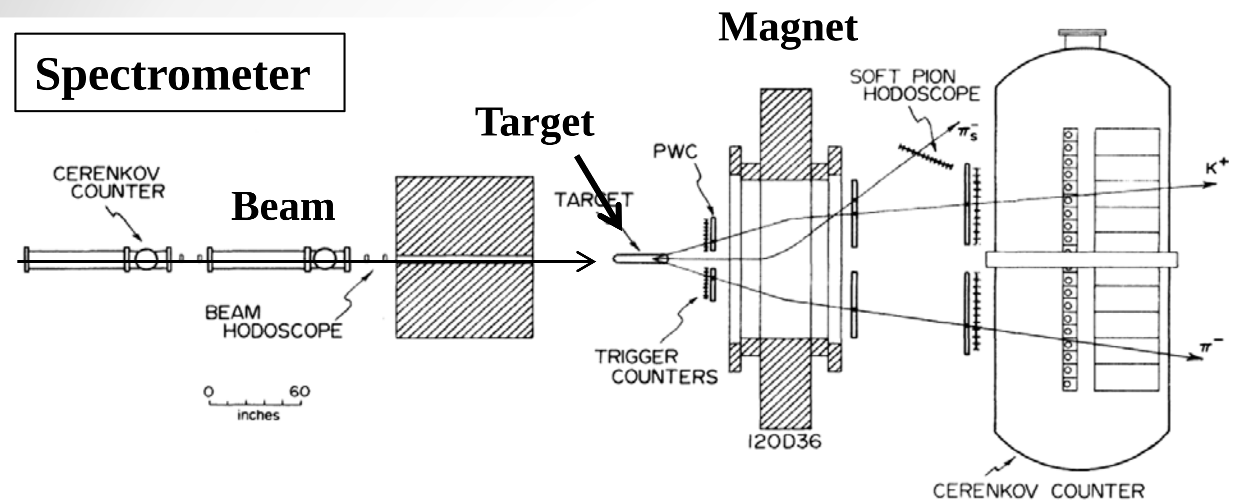
Reference	Method	Beam [GeV/c]	Reaction channels	Upper Limit ×BR [μb] (95% C.L.)
C. Baltay et al. PRL 34, 1118 (1975)	SLAC Bubble	15	$\pi^+ p \rightarrow \Sigma_c^{++} \overline{D}^0$ (Exclusive)	3.0 (M_Σ: 1.5-4.0 GeV/c^2)
B. Ghidini et al. NPB 111, 189 (1976)	CERN PS Spectroscopy	19	$\pi^- p \rightarrow \Lambda_c^+ D^-$ $\pi^- p \rightarrow \Sigma_c^0 \overline{D}^0$ (Exclusive)	0.08 0.07 $M_D > 1.5$ GeV/c^2 $M_C > 2.0$ GeV/c^2
S.U. Chung et al. PRL 48, 785 (1982)	BNL Spectroscopy	16	$\pi^- p \rightarrow \Lambda_c^+ D^{*-}$ (Inclusive)	0.13 (D* inclusive) 0.07 (Ch. exclusive)
J.H. Christenson et al. PRL 55, 154 (1985)	BNL Spectroscopy	13	$\pi^- p \rightarrow \Lambda_c^+ D^{*-}$ $\pi^- p \rightarrow \Sigma_c^+ D^{*-}$ (Inclusive)	7 nb (σ) M_{D*} : 1.99-2.03 GeV/c^2, Λ_c^+,Σ_c^+ mass region

No old experiment observed charmed baryons.

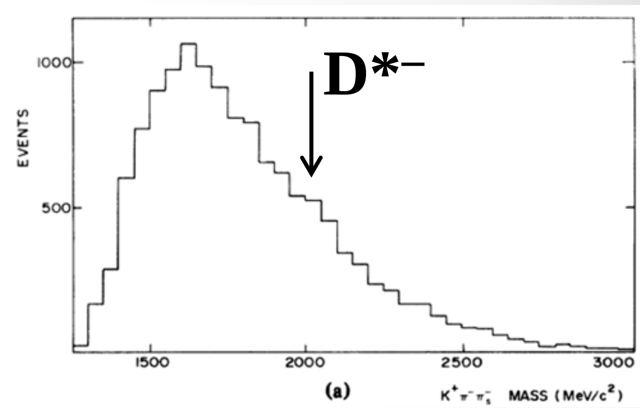
- **Beam momentum: 10–20 GeV/c region**

Old experiments

Spectrometer



$K^+\pi^-\pi_s^-$ invariant mass



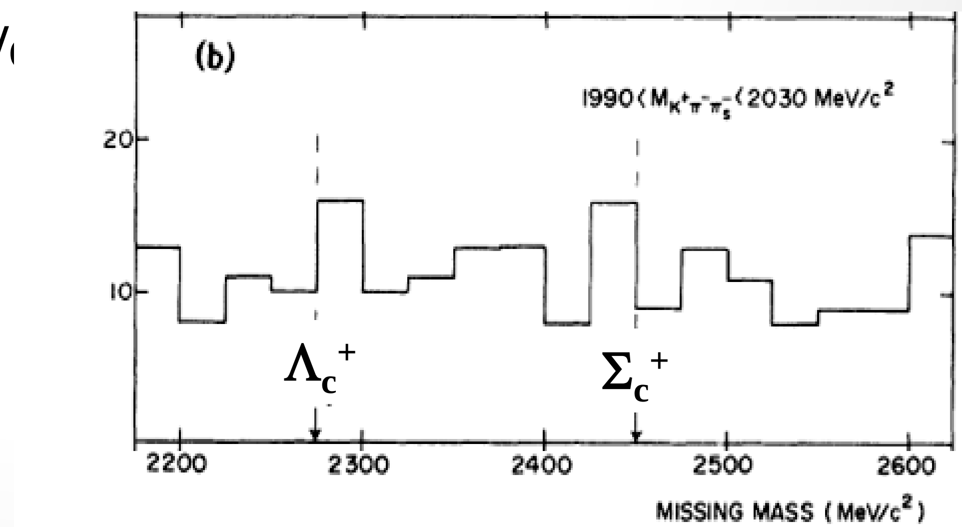
BNL experiment in 1983

- $\pi^- p \rightarrow \Lambda_c^+ D^{*-}$ @ 13 GeV/
  - $N_\pi = 3\times10^{12}$
  - $\Delta M = 20$ MeV

✱No peak structure

⇒Upper limit: σ = 7 nb

Missing mass spectrum



Old experiments

	Beam [GeV/c]	Beam [/spill]	PoT	Acceptance	High rate	HS DAQ	PID	Beam Resol.	Mass Resol.	D* detection	S/N method
J-PARC	15–20	○	○	○	○	○	○	○	○	○	○
BNL 1	13	○	△	×	×	×	×	○	○	○	×
BNL 2	16	×	×	○	×	×	×	×	△	○	×
CERN 1	19	×	×	○	×	×	×	×	×	×	×

- Yield ⇔ Cross section: level of nb
  - Both beam & acceptance
  - High-rate detectors & High-speed DAQ
  - High performance PID system

- Experimental techniques
  - Beam & D mass resolution
  - Background reduction: D* detection
  - Study for good S/N

✱Design of experiment with proper conditions needed

Comparison with old experiments

	Beam [GeV/c]	Target [g/cm^2]	PoT [T]	Accep. $\times \varepsilon_{eff}$ [%]	$\Delta P_B/P_B$ [%]	ΔM_D [MeV]	ΔM_{D*} [MeV]	ΔMM [MeV]	S/N by D mass resol.	Counts for 1 nb
J-PARC	20	4.0	86.4	35	0.1	5.0	0.6	10	3.3 $\times$8	> 2000
BNL 1	13	7.1	3.0	1	0.25	~10	~1	25	1	2
BNL 2	16	4.2	< 1	2	?	~10	~1	45	1	< 1

BNL: J.H. Christenson et al. PRL 55, 154 (1985)

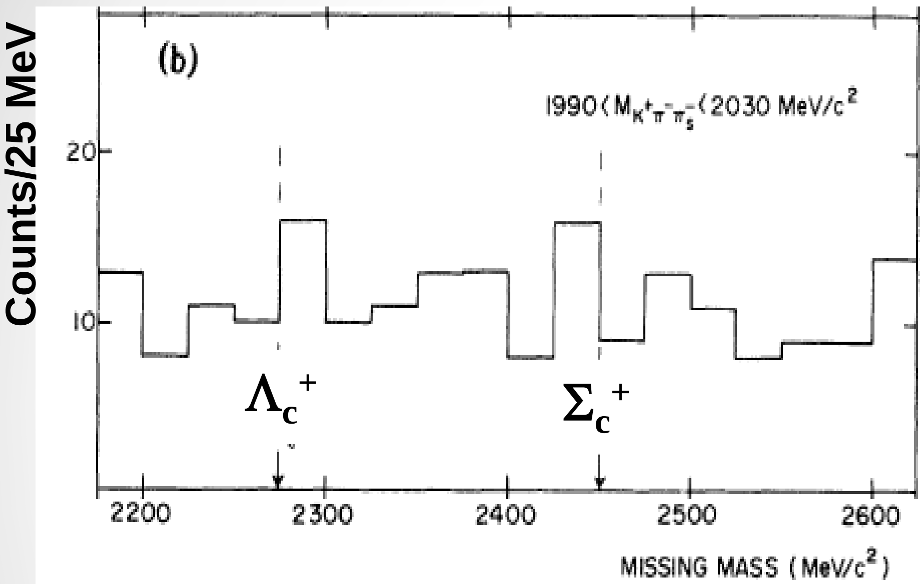
- 13 GeV/c , Acceptance: $\pi^- p \rightarrow \Lambda_c + D^{*-}$, exp(bt) distribution: b = 2.0 GeV^{-2}
- D* tagging was used.

*** Experimental qualities drastically improved.**

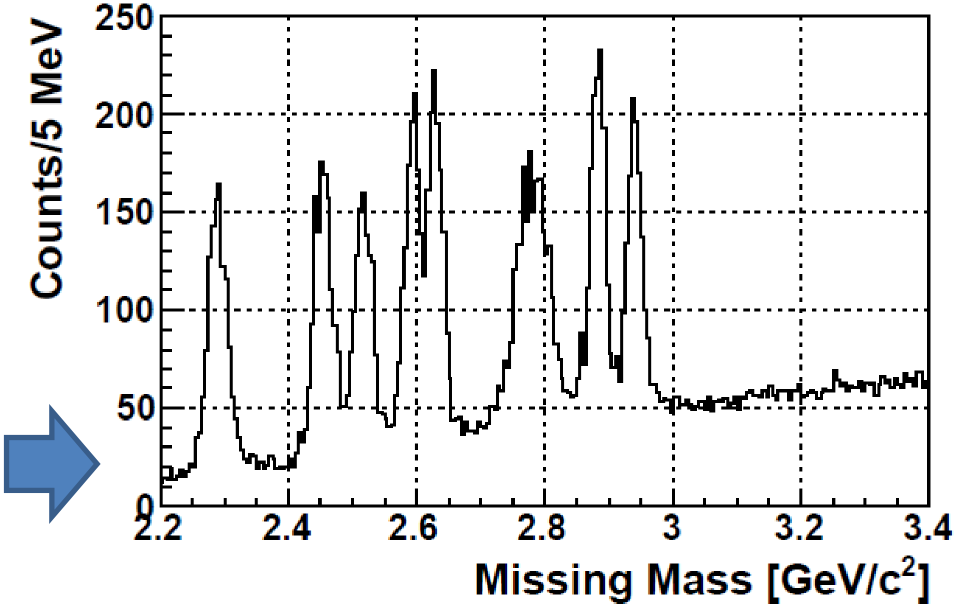
- Yield: 30(beam)$\times$35(acceptance & ε_{eff}) = 1050
- S/N: 3.3(resolution)$\times$8(event selection) = 26

Expected spectrum: Comparison

Old experiment @ BNL



σ = 1 nb case @ J-PARC



D* tagging + Event selections

- **$D^0 \rightarrow K^+ \pi^-$ decay angle cut, production angle cut**

⇒ S/N improvement: 50–100

- **Mass resolution × ~3.3, event selections × ~8, PID × 2–4**

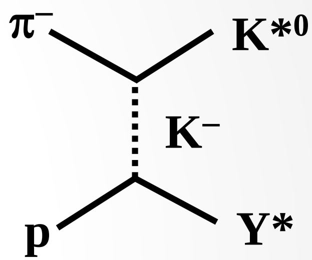
∗ Yield: 30(beam) × 35(acceptance & ε_{eff}) = 1050

Strangeness baryons

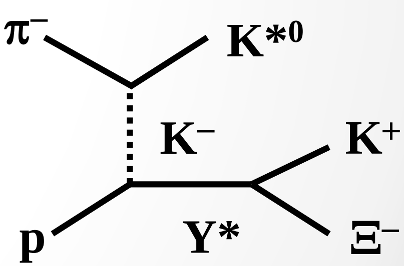
✱ Yield: ~5.0×10^5 /day @ 1 μb

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

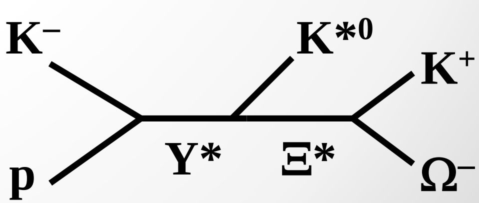
- Λ, Σ^0 baryons: σ ~ 1–100 μb
  - $\pi^- + p \rightarrow \Lambda^* + K_S^0$, $K_S^0 \rightarrow \pi^+ + \pi^-$
    - Yield: $\sigma \times 0.5 \times 0.70$
    - K^0_{bar} background & 10 times higher pion production rate
  - $\pi^- + p \rightarrow \Lambda^* + K^{*0}$, $K^{*0} \rightarrow K^+ + \pi^-$
    - Yield: $\sigma \times 0.67$ (0.4 cross section compared with K^0 production channel)
    - Strangeness tagged: Smaller background from K^0 channel
    - Mass resolution: 20–40 MeV @ 20 GeV/c beam



- Ξ^- baryons: σ ~ 0.1–10 μb
  - $\pi^- + p \rightarrow \Xi^* + K^{*0} + K^+$, $K^{*0} \rightarrow K^+ + \pi^-$
    - Inclusive Ξ^- production: 20–30 μb @ 15-20 GeV/c π^- p reaction
    - Strangeness tagged: Small multi-strangeness production background
    - Same trigger scheme: By-products in charm experiment
    - Mass resolution: 10–20 MeV @ 20 GeV/c beam



- Ω^- baryons: σ ~ 0.01–1 μb
  - $K^- + p \rightarrow \Omega^* + K^{*0} + K^+$, $K^{*0} \rightarrow K^+ + \pi^-$
    - Ω production: ~1 μb @ 4 GeV/c $K^- p \rightarrow \Omega^- K^0 K^+$ reaction
    - Same trigger scheme: By-products in charm experiment
    - Mass resolution: 10–20 MeV @ 20 GeV/c beam

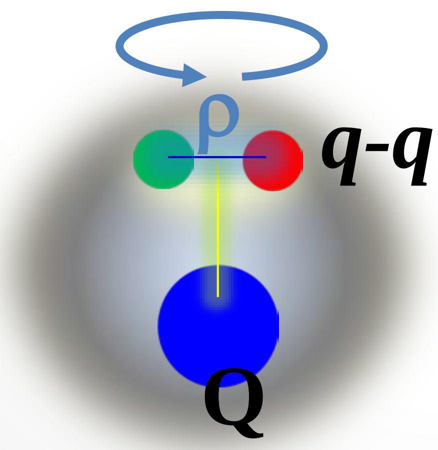


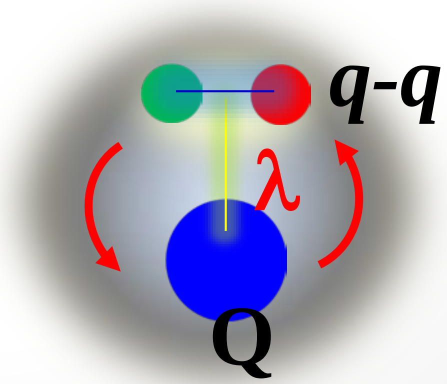
Excitation mode

- Heavy Q: λ and ρ-mode

⇒ M_Q dependence of excitation spectrum
  - Charmed baryons: Y_c*
  - Hyperons: Y*

✱ spin-spin: $H = H_0 + V_c + V_{ss}$
  - $V_c = k/2 \sum r_i^2$
  - $V_{ss} = c_s \sum \frac{\sigma_i \cdot \sigma_j}{m_i m_j} \delta(r_{ij})$





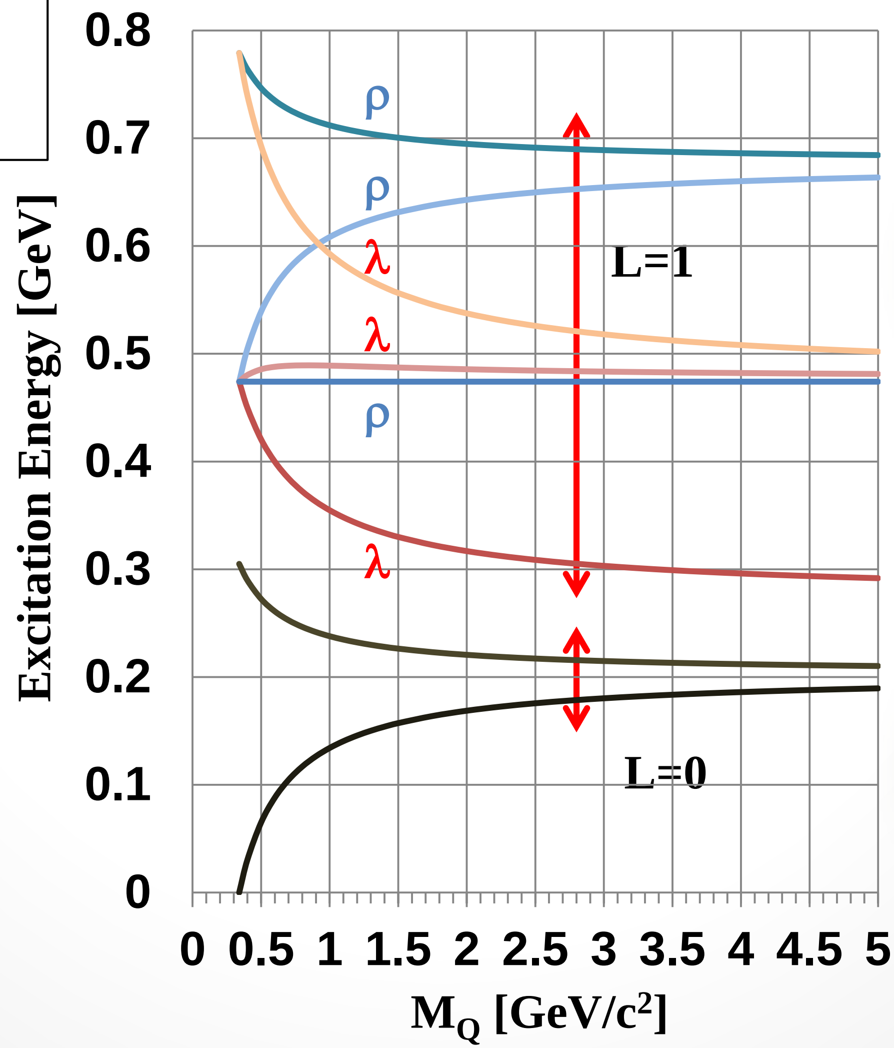
Excitation spectrum

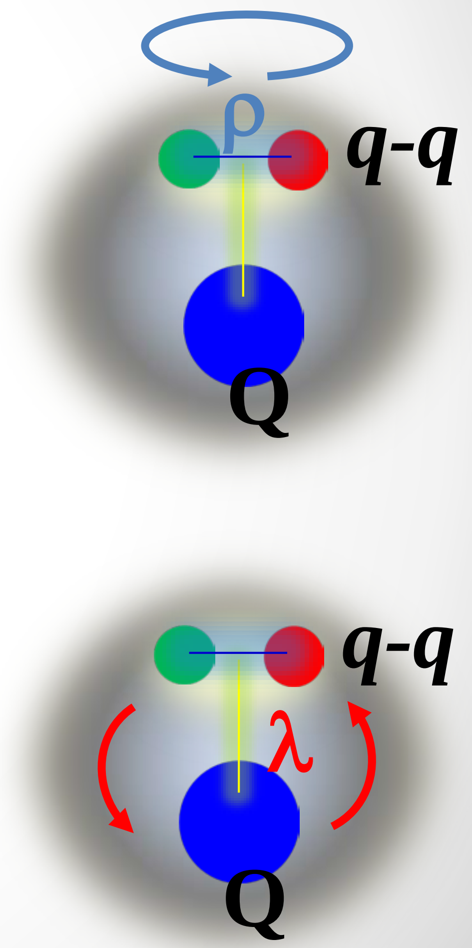
- **L=1 excited states: Confinement & spin-spin interaction**

✻Confinement & spin-spin:

$H = H_0 + V_c + V_{ss}$

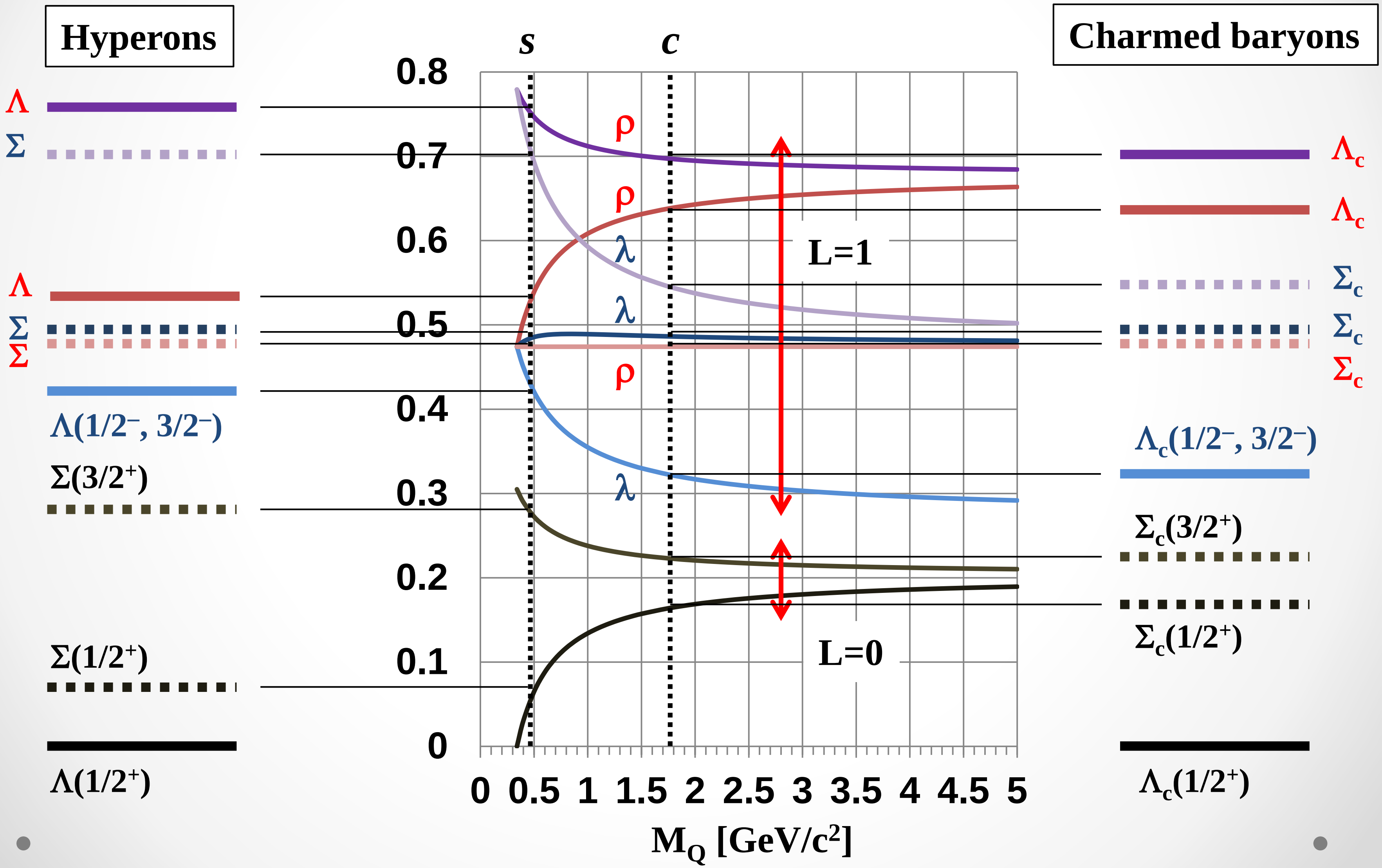
- $V_c = k/2 \sum r_i^2$
- $V_{ss} = c_s \sum \frac{\sigma_i \cdot \sigma_j}{m_i m_j} \delta(r_{ij})$





Excitation spectrum

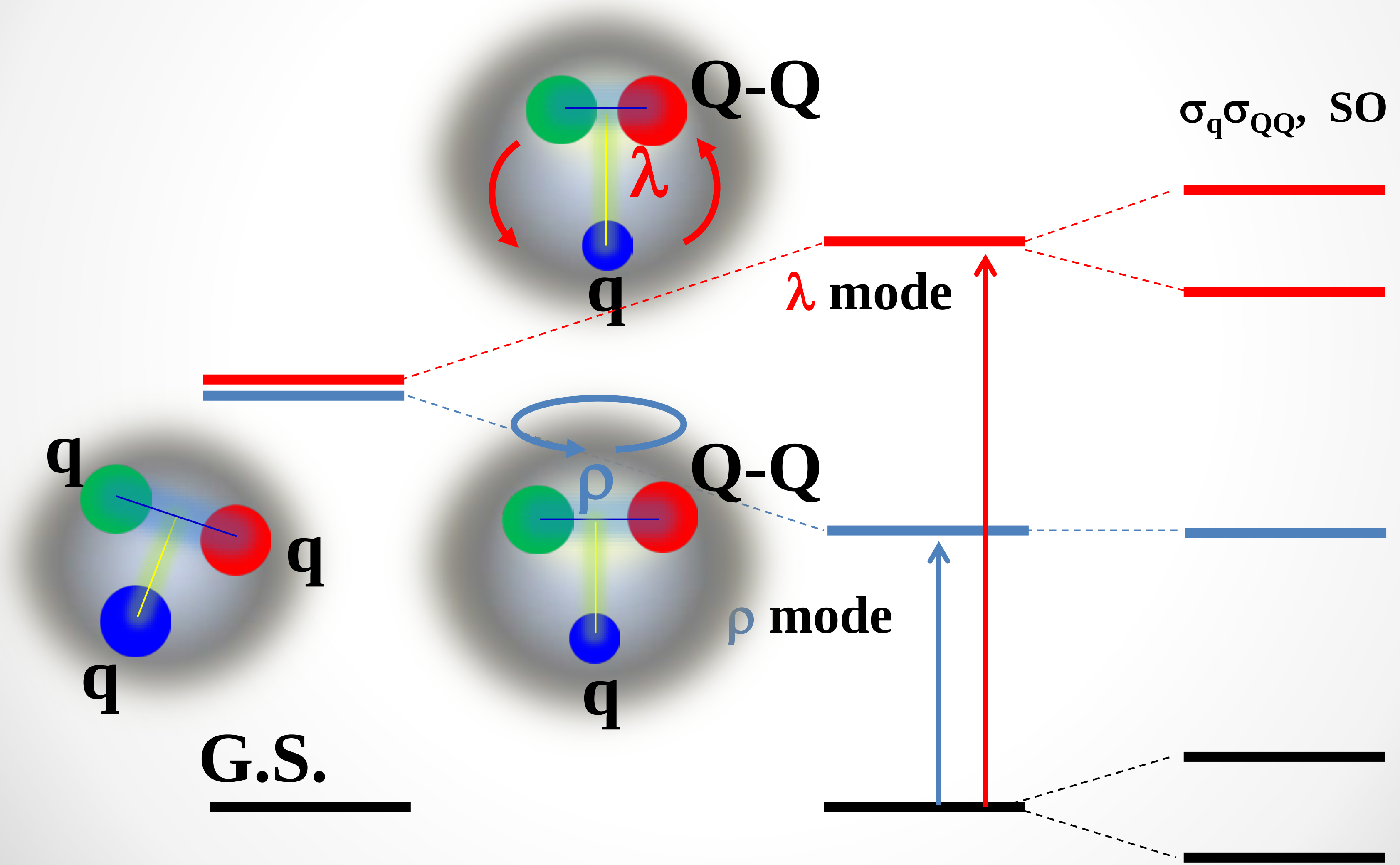
- L=1 excited states: Confinement & spin-spin interaction



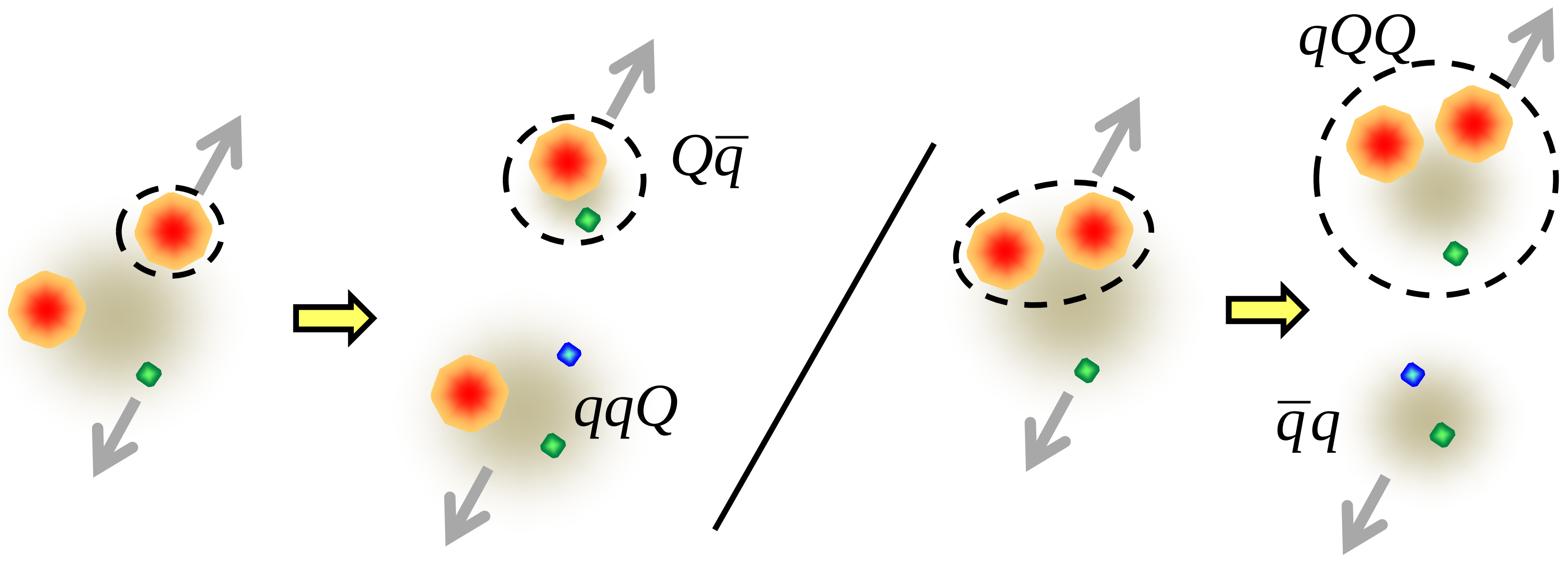
Threshold			JP	rat in g	Width [MeV]	→NK [%]	→Λπ [%]	→Σπ [%]	
		Σ(1940)	3/2–	4*	220	<20	seen	Seen	
		Σ(1915)	5/2+	3*	120	5-15	seen	Seen	
	Λ(1890)		3/2+	4*	95	20~35		3~10	
		Σ(1880)	1/2+	2*	220?				
K*N(1830)		Σ(1840)	3/2+	1*	120?				
	Λ(1830)		5/2–	4*	95	3~10	35~75		
	Λ(1820)		5/2+	4*	80	55~65	8~14		
	Λ(1810)		1/2+	3*	150	20~50	10~40		
	Λ(1800)		1/2–	3*	300	25~40	Seen		
		Σ(1775)	5/2–	4*	120	37~43	16-25		
Ση(1740)		Σ(1750)	1/2–	3*	90	10~40	?		(Ση)15~55
		Σ(1690)	??	2*	?	?	?		
	Λ(1690)		3/2–	4*	60	20~30	20~40		
Λη(1663)		Σ(1670)	3/2–	4*	60	7~13	35~75		
KN(1432)	Λ(1670)		1/2–	4*	35	20~30	25~55		
Σπ(1330)		Σ(1620)	1/2–	1*	?	?	?		
Σ*π(1520)		Σ(1580)	3/2–	1*	?	?	?		
	Λ(1520)			4*	[illegible]	45±1	42±1		

Level Structure of double-strange baryons

- λ and ρ mode excitations interchanged



Decay property



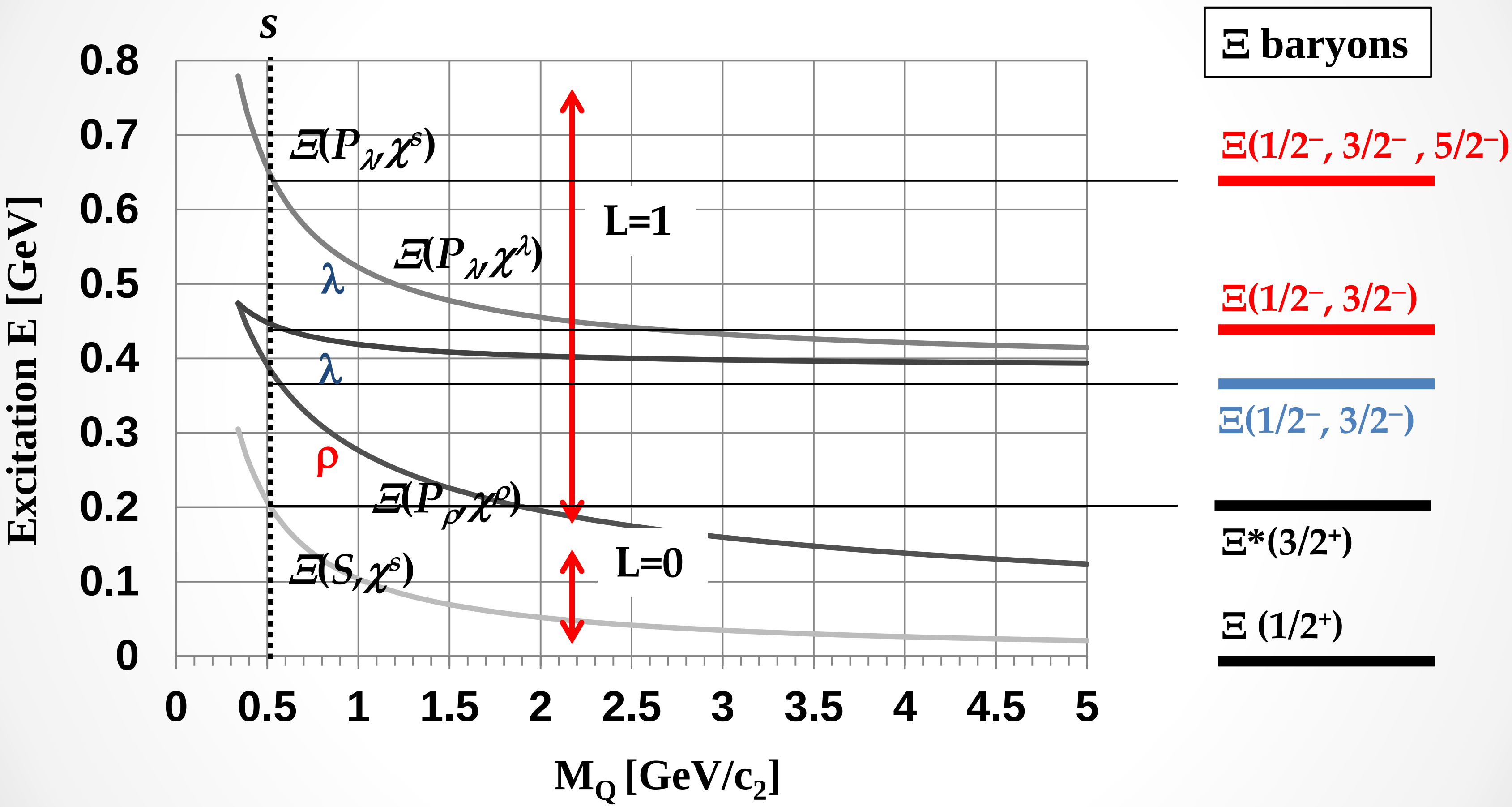
ρ mode (QQ)

$\Xi^* \to \Lambda\, K$

λ mode [QQ]

$\Xi^* \to \Xi\, \pi$

Ξ (ρ, λ-mode excitations w/ Vss)



Ξ in PDG

	JP	rating	Width [MeV]	Ξπ [%]	Λ K [%]	Σ K [%]	
Ξ(2500)	??	1*	150?				
Ξ(2370)	??	2*	80?				ΩK~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*	19	100			

ΩK(2166)

ΣK∗(1983)
Σ∗K(1878)
ΛK∗(1908)

ΣK(1685)

Ξ∗π(1665)

ΛK(1610)

Ξπ(1450)