Experimental study of di-quark correlation by charmed baryon spectroscopy at J-PARC high-momentum secondary beam line

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- J-PARC E50 experiment
  (Charmed baryon spectroscopy at J-PARC)
- Beam line
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Internal structure of hadron

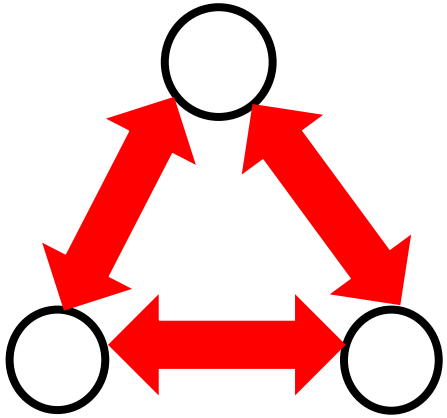
- The origin of matter is an essential problem in physics.
- How hadrons are made up of quarks?
  -It is difficult to calculate due to the non-perturbative behavior of low energy QCD.

- Hints of the internal structure of hadrons can be obtained through experiments.
  -Discoveries of exotic hadrons stimulate studies of substructure of hadrons.
- Di-quark correlation is a candidate which describes exotic hadrons.
  Ex.) Pc+(4380) and Pc+(4450) as $\bar{c}[cq][qq]$.

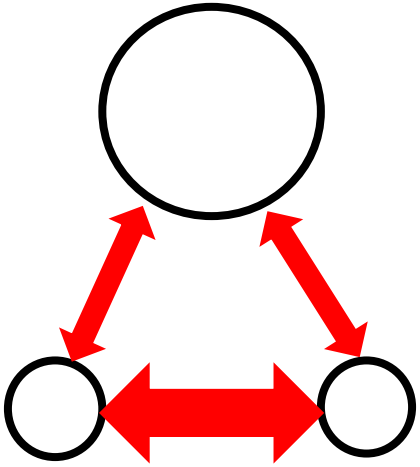
  L. Maiani, A.D. Polosa, and V. Riquer, Phys. Lett. B 749 (2015) 289

We want to know the role of di-quark correlation in hadrons!

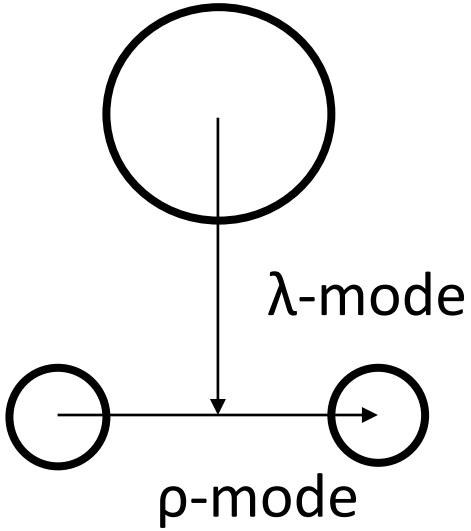
Di-quark correlation in charmed baryon



Strengths of interaction are equivalent.

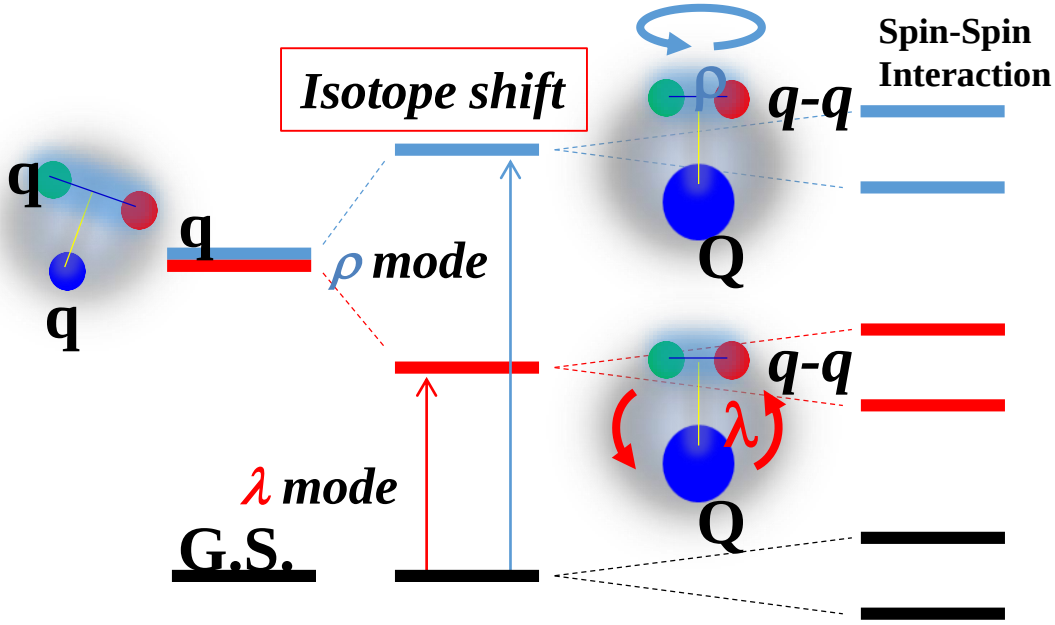


Interactions between qQ are suppressed.



Color-magnetic interaction is proportional to $\frac{1}{m_i m_j}$ and suppressed with heavy quark.

- ✓ Di-quark motion is separated by replacing one light quark with a charm quark.
  - Collective motion of di-quark (λ-mode)
  - Relative motion of light quarks (ρ-mode)
- ✓ Energy levels, production rate and decay channel depend on λ-mode and ρ-mode.



Harmonic oscillator model

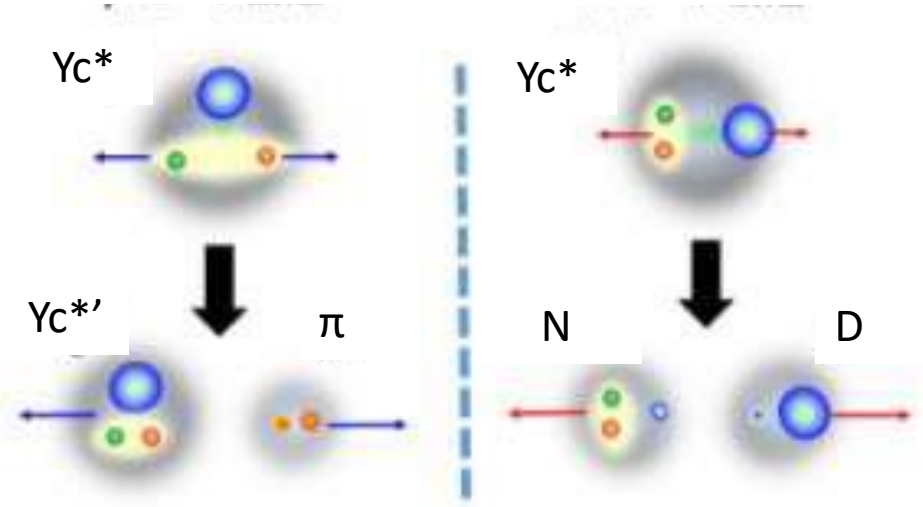
$$\omega_\lambda = \sqrt{\frac{M+2m}{M}}\omega$$

$$\omega_\rho = \sqrt{3}\omega \quad (\omega = \sqrt{\frac{k}{m}})$$

Kinematically, $\omega_\lambda < \omega\rho$

In charmed baryon, energy levels of λ-mode and ρ-mode are well separated.

ρ mode excitation **λ mode excitation**



Decay mode of charmed baryon also depends on ρ/λ mode.

What is the effect from other than valence quark ($q\bar{q}$ pair creation) for higher excited states?? Need data.

Heavy quark spin symmetry

Spin of heavy quark is conserved when $m_Q \to \infty$.

$J = 1/2$ HQS singlet

$J = j \pm 1/2$ HQS doublet

j : total spin of light degrees freedom

HQS doublet?
If so, j=2 or 3?

*Not measured.

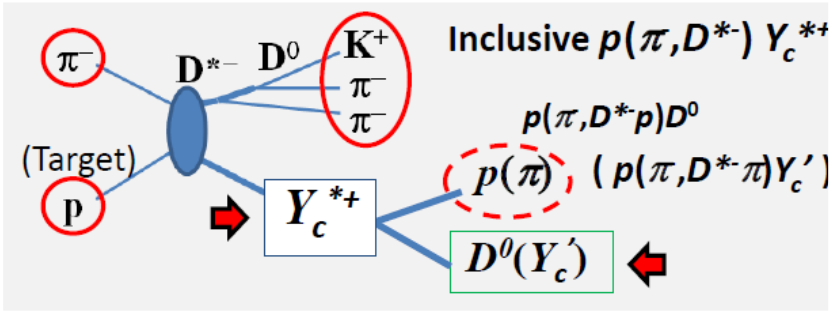
	Λc(1/2+)	Λc(1/2-)	Λc(3/2-*)	Λc(5/2+)	Λc(3/2+*)
	j=0	j=1	j=1	j=2	j=2
Mass [MeV/c2]	2286	2595	2625	2880	2940
Relative production rate	1	0.93	1.75	0.86	0.49

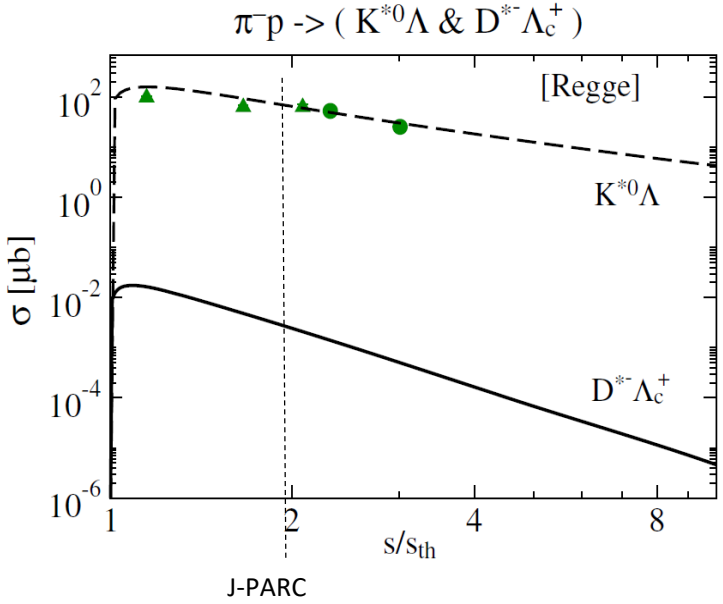
- Ratios of production rates of spin partners are predictedby A. Hosaka et al. Nucl. Phys. A 954 (2016) 341. π+N→D*+Yc at π energy of 20 GeV is assumed.
- j=3 for Λc(5/2+) is favored by H. Nagahiro et al. Phys. Rev. D 95 014023 (2017).
  If so, where is j=2 λ-mode excited state? J^P of Λc(2940) is 7/2+?
  Partial decay width is important information.

Measure energy levels , production rates and branching ratios systematically
→ **Missing mass method**!

J-PARC E50 experiment

- Charmed baryon spectroscopy provides us rich information about internal structure of hadrons, especially di-quark correlation.
- π induced reaction was once studied with beam momentum of 13 GeV/c in 1985.
  J. H. Christenson et al., Phys. Rev. Lett. 55 154(1985).
- Production cross section is estimated as several nb.
  (~10^{-4} of strangeness production).
- Measure charmed baryon of excitation energy
  ~1 GeV/c^2 systematically.
  → Missing mass method using (π, D*⁻) reaction.





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

Need high-momentum, high-intensity and high-resolution π beam!

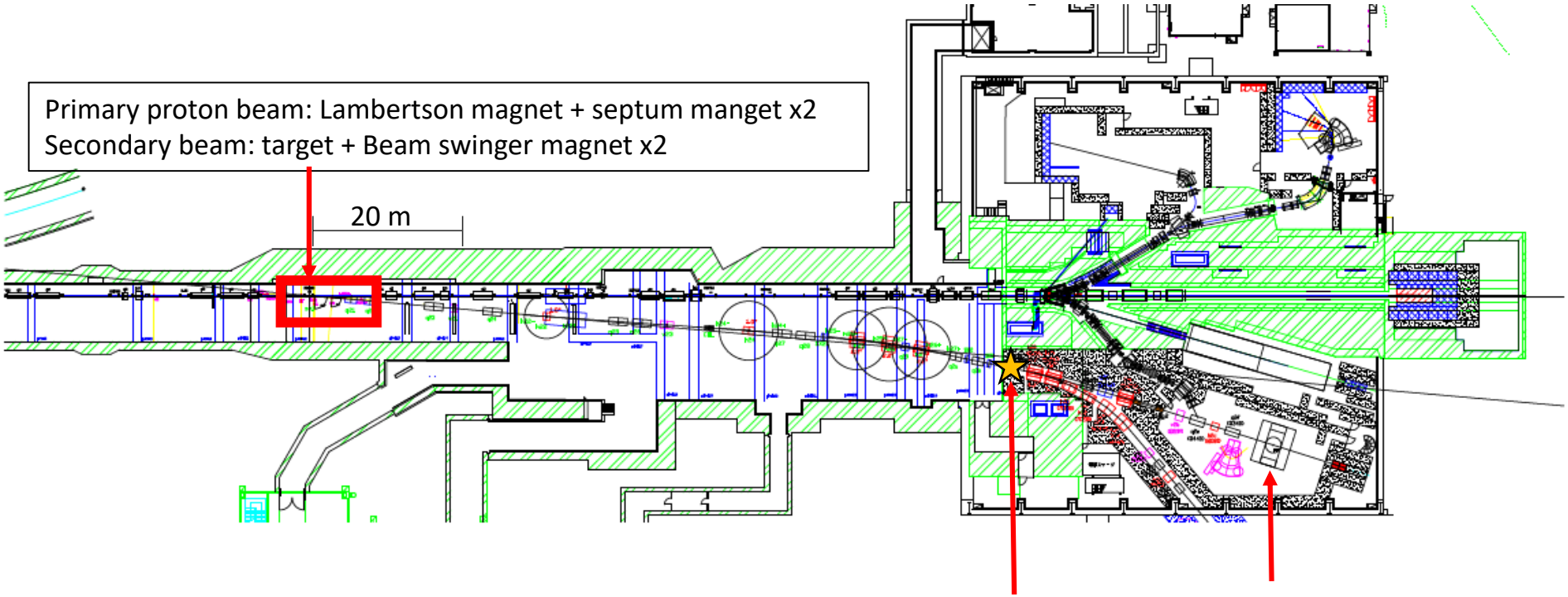
⇒ New experiment at J-PARC high-momentum beam line:

J-PARC E50 experiment (stage-1 approved.)

J-PARC High-momentum beam line

- 0.1% of primary proton beam is branched and used for experiment.

- By setting production target in switch yard, high momentum and high intensity secondary beams are extracted.
  High momentum resolution $\Delta p/p \sim 0.1\%$ is achieved with dispersive focal plane.



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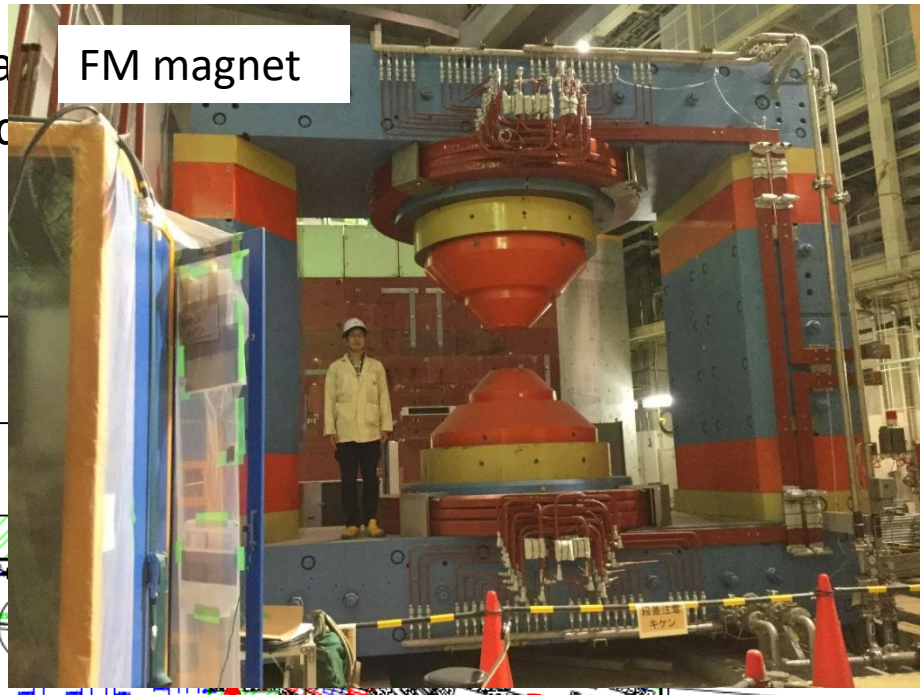
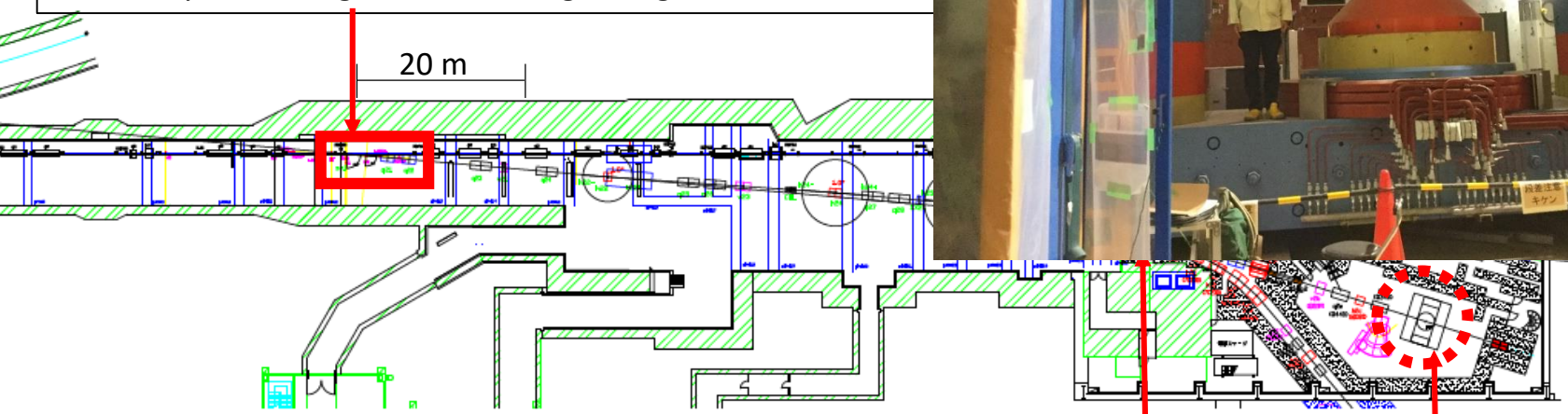


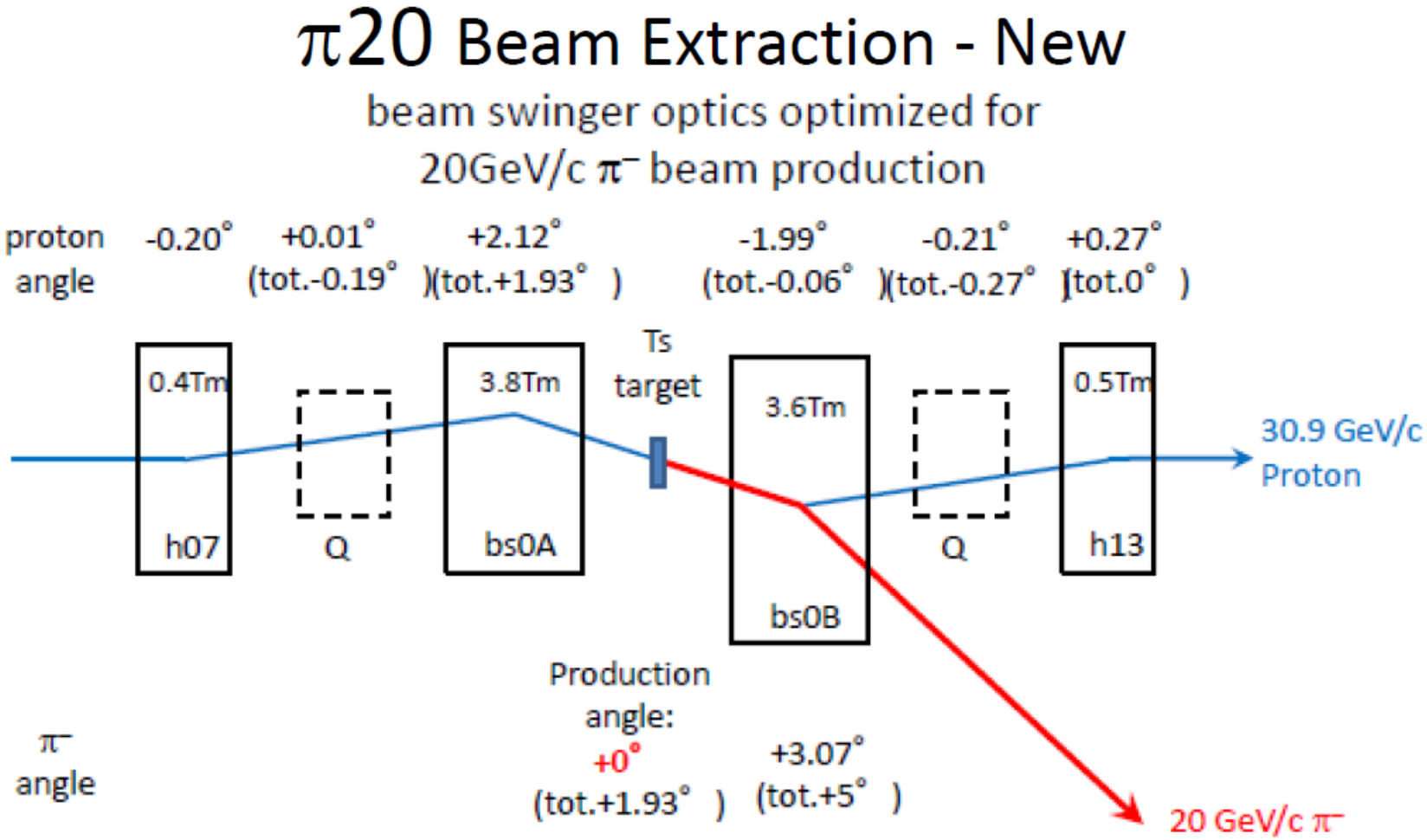


Dispersive focal plane

Spectrometer

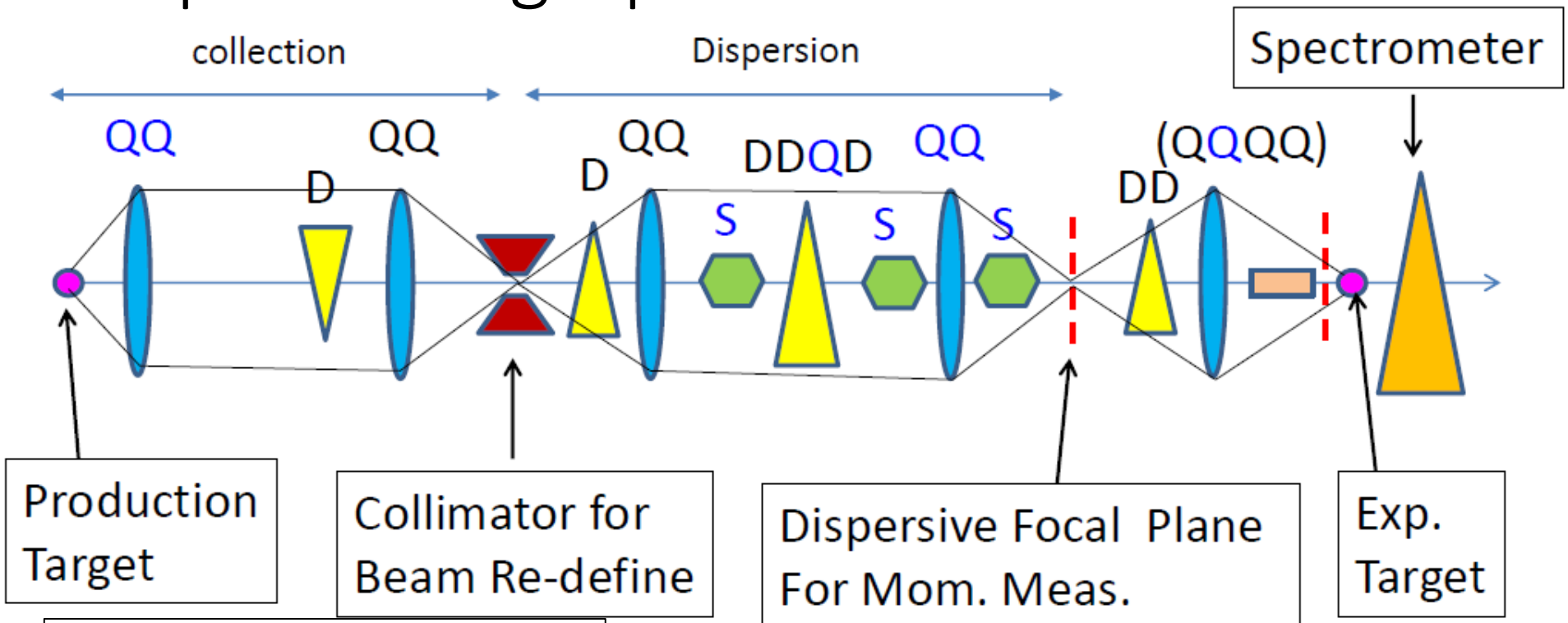
Construction is going well for the 1st beam in Jan 2020!

Beam swinger optics

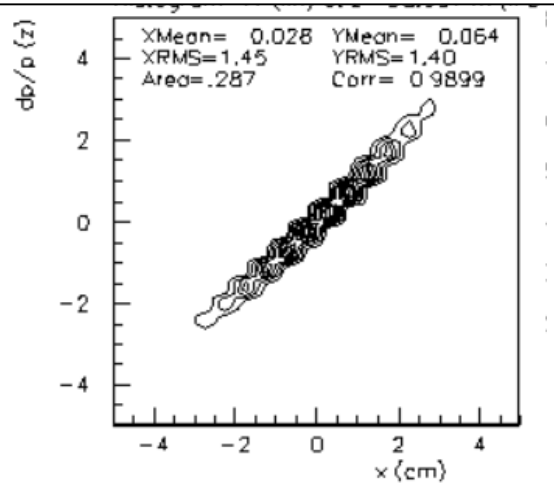


From H. Takahashi's slide

Optics in high-p line



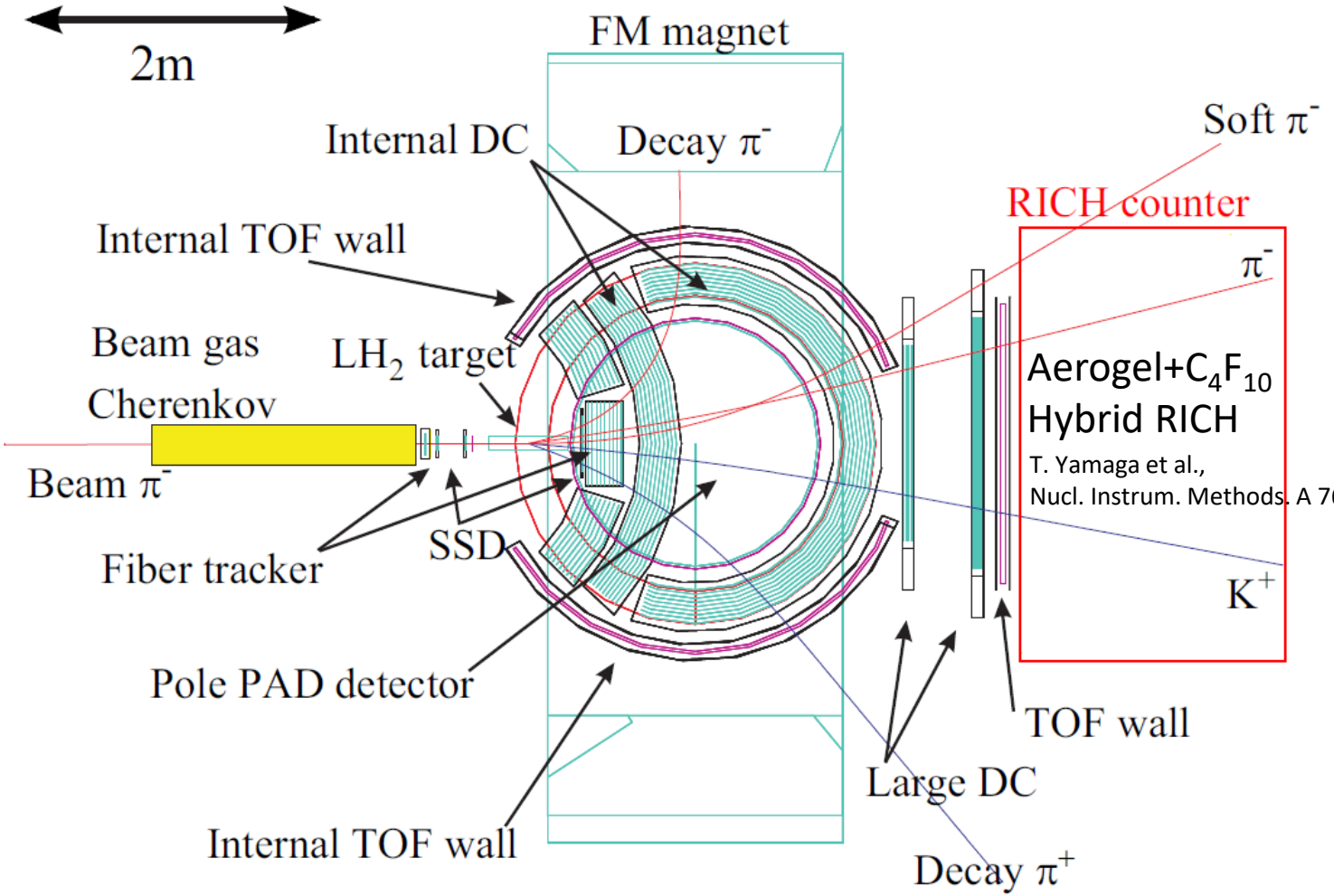
Correlation of Δp/p vs x at DP.



1 mm resolution of horizontal beam position

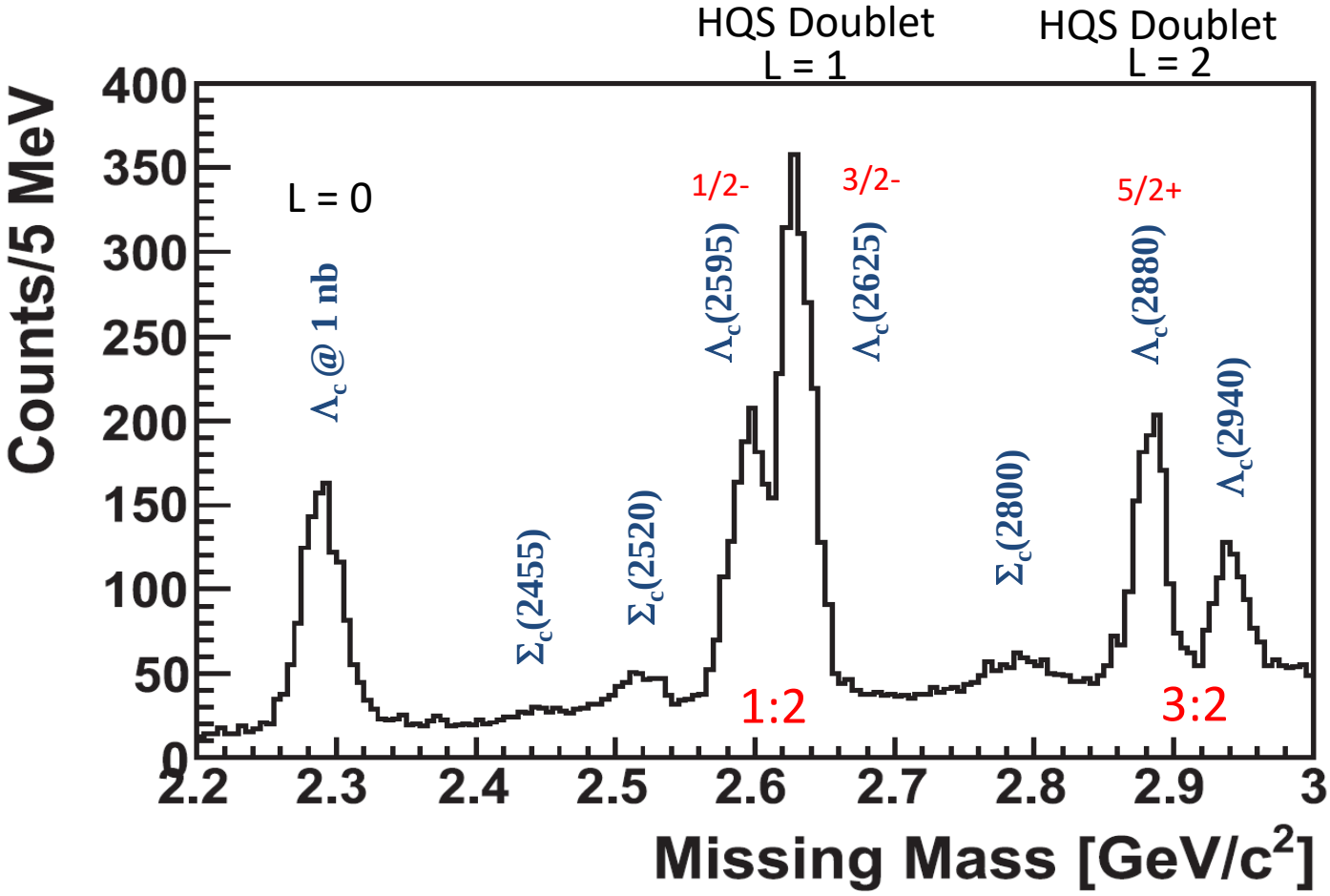
⇒ 0.1% resolution of beam momentum

Spectrometer



- Multipurpose spectrometer
- Backward detector: soft π^- from $D^0 \rightarrow \pi^- + K^+$
- Forward detector: $D^- \rightarrow \pi^- + D^0$
- Acceptance of D^- is more than 15% for forward peak angular distribution.
- Mass resolution is better than 10 MeV/c^2.
- Triggerless DAQ is used.

Expected spectrum



- ~1000 Λc(2280) are collected for 100 days beam time.
- Production cross section will be compared with calculation.

- Production cross section ∝ $(q_{eff}/A)^L e^{-(q_{eff}/A)^2}$
  Production rate takes maximum at L~1.8.
- Ratio of production rates of λ-mode doublet is predicted.
- Decay widths $\Gamma_{\pi\Sigma_c}, \Gamma_{ND}$ are also measured.

q_{eff}: Momentum transfer **~1.3 GeV**
A: (baryon size parameter)$^{-1}$ **~2.5 fm^{-1}**

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

$$R(\frac{\frac{3}{2}^-}{\frac{1}{2}^-}) \sim 2 \quad R(\frac{\frac{5}{2}^+}{\frac{3}{2}^+}) \sim \frac{3}{2}$$

Summary

- We want to understand how hadrons are made up of quarks.
  Baryon containing one heavy quark is an interesting system to study di-quark correlation.

- The experiment for Charmed baryon spectroscopy is proposed at J-PARC high-momentum beam line.
  "**J-PARC E50 experiment**"

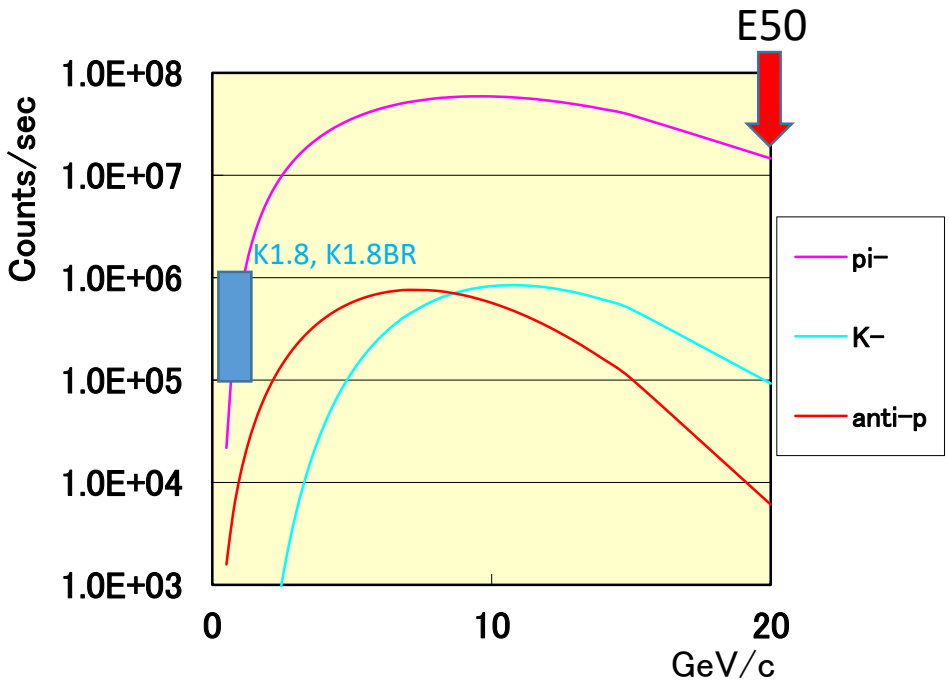
- Excited states of ~1GeV from G.S. are measured systematically by missing mass method.
  -Energy levels
  -Production rate
  -Decay branching ratios

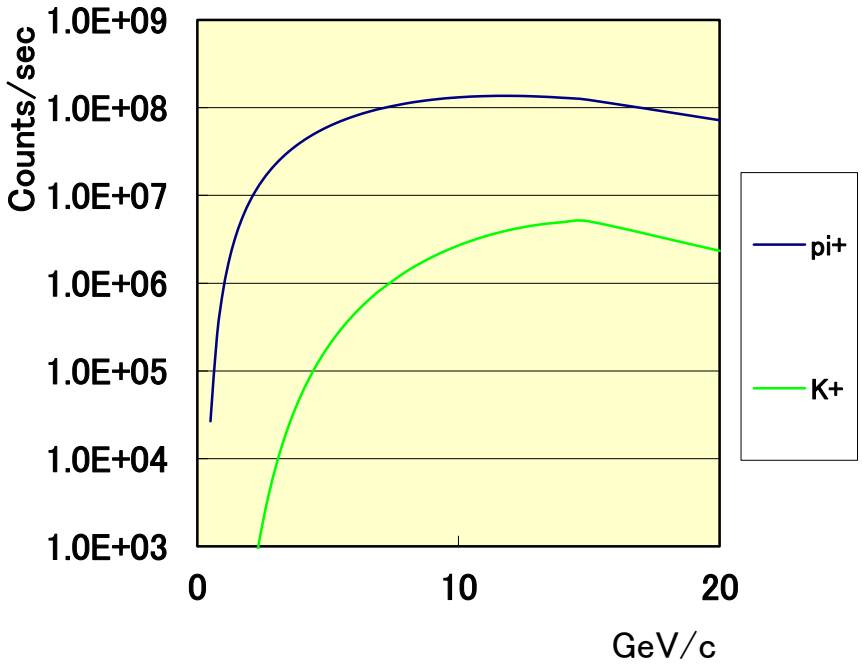
- Feasibility of the experiment is evaluated and stage-1 approved.
  -Beam line is designed to extract high momentum, high intensity and high momentum resolution secondary beam.
  -Detectors are developed to achieve good mass resolution and good PID performance.

Back up

Intensity (15 kW loss)

Momentum dependence of beam intensity for each charged particle



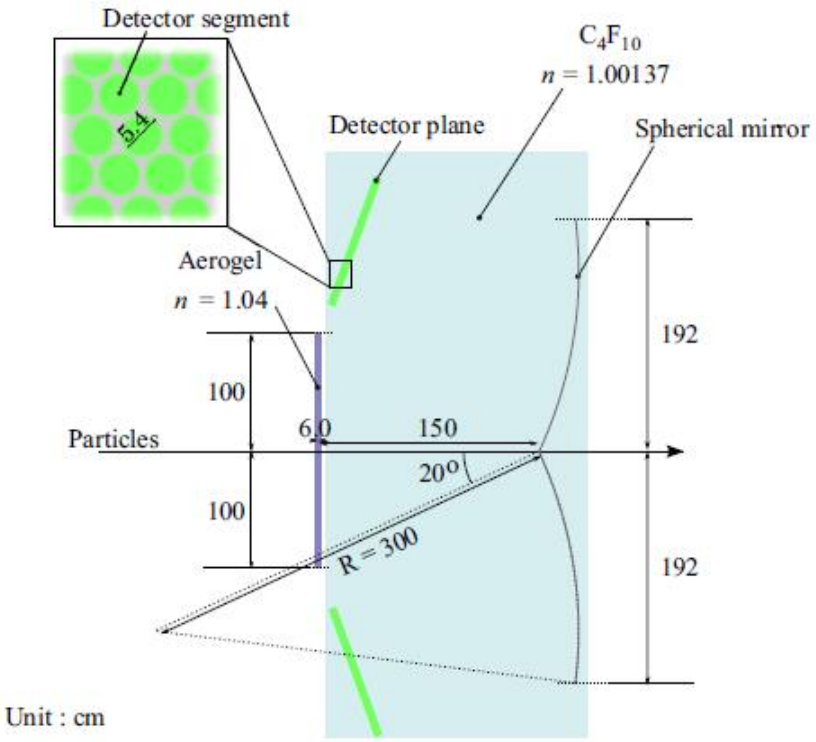


High momentum and high intensity secondary beams are available.

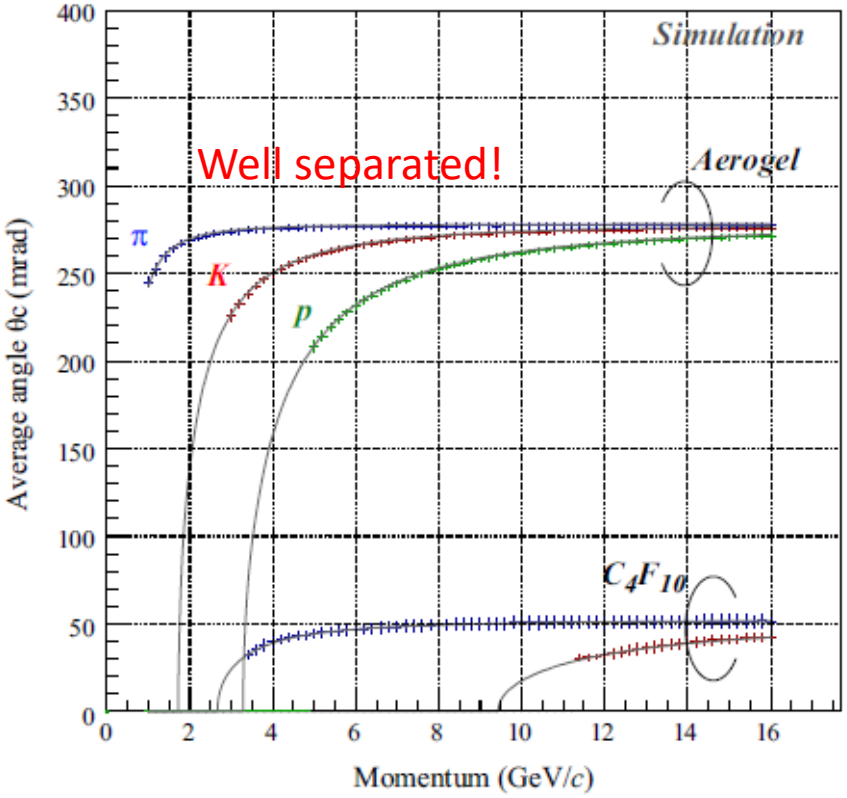
Hybrid RICH

T. Yamaga et al., Nucl. Instrum. Methods. A 766, (2014) 36

Particle identification of π and K.



GEANT simulation



< ~3 GeV/c, π and K are separated by Aerogel

>~3 GeV/c, p and π/K is separated by Aerogel and π and K are separated by C4F10.

Mis-identification efficiency of π and p to K is evaluated as only 0.1% and 0.14%.

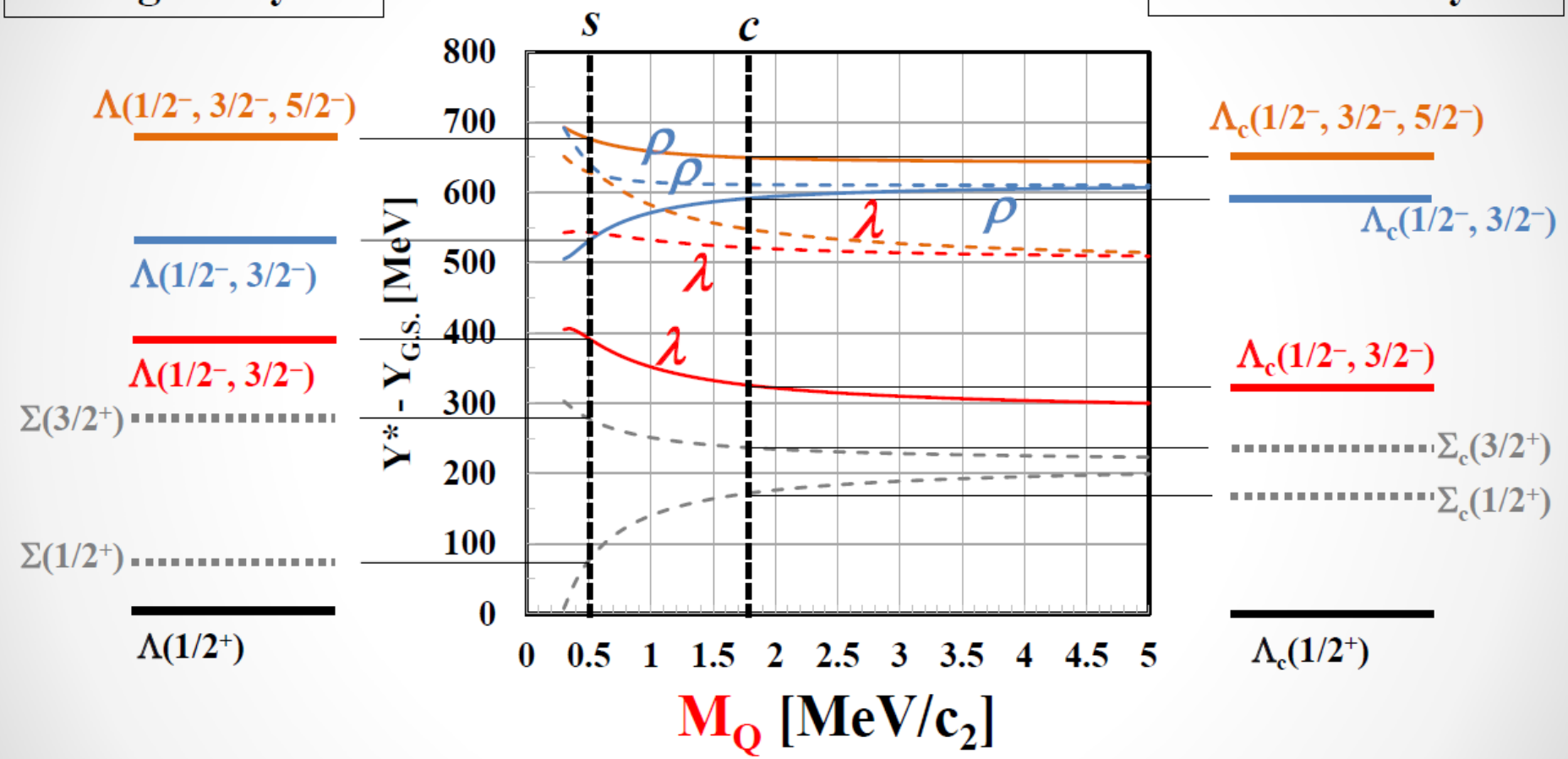
Background from mis-identification in p(π-, D*-) spectrum is only 5%.

Excitation spectrum: q-q + Q system

Strange baryons

P-wave states

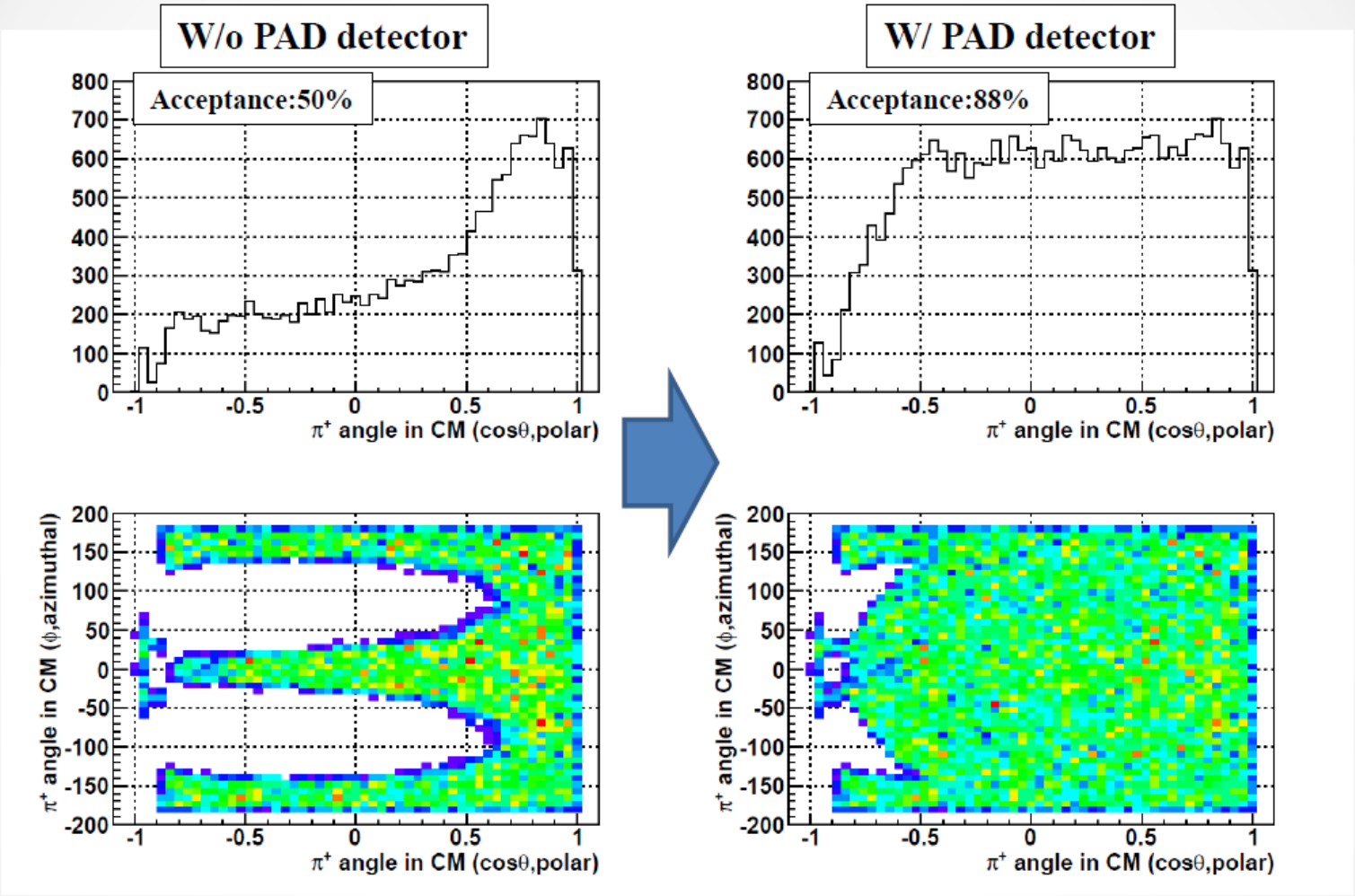
Charmed baryons



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

(cal. By T. Yoshida, Nucl.Phys. A954 (2016) 341)

Acceptance of Σ_c π event



- Enough acceptance by using Pole face detector

∗ Total acceptance: 50% ⇒ 85%

Flat acceptance: $\cos\theta > -0.5$

- Same angular acceptance for p D^0 decay channel