Heavy-quark Baryons

Hiroyuki NOUMI
Research Center for Nuclear Physics, Osaka University
Institute of Particle and Nuclear Studies, KEK

Contents:

I. Baryon Structure with Heavy Quarks
II. Charmed Baryon Spectroscopy
III. New Platform of Hadron Physics at J-PARC

Hierarchy of Matter in the Universe

Matter Evolution from Quark to Hadron, Nucleus, and Neutron Star

How QCD works in Hadron?

- **Effective DoF (building blocks) to describe hadrons**
- **Change of Hadron Properties in High-T and High-ρ Matter**

We attack here.

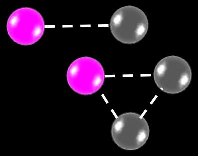
Quark

Effective DoF

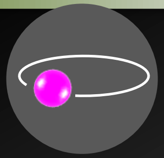
Q Q Q

Hadron

BB Int.（2BF, 3BF）



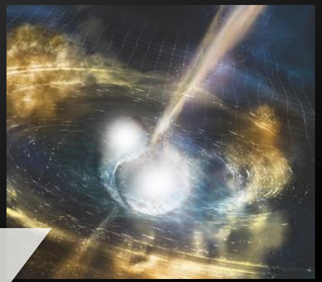
Nucleus



Hypernuclei

How are nuclei formed?

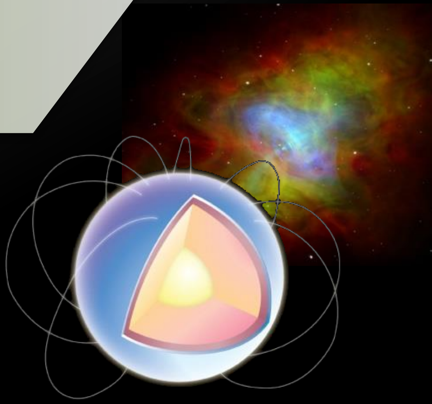
- **Extended Nuclear Force：Baryon-Baryon Int.**
- **Stability of Heavy Neutron Stars (EoS)**



Dense Nucl. Matter

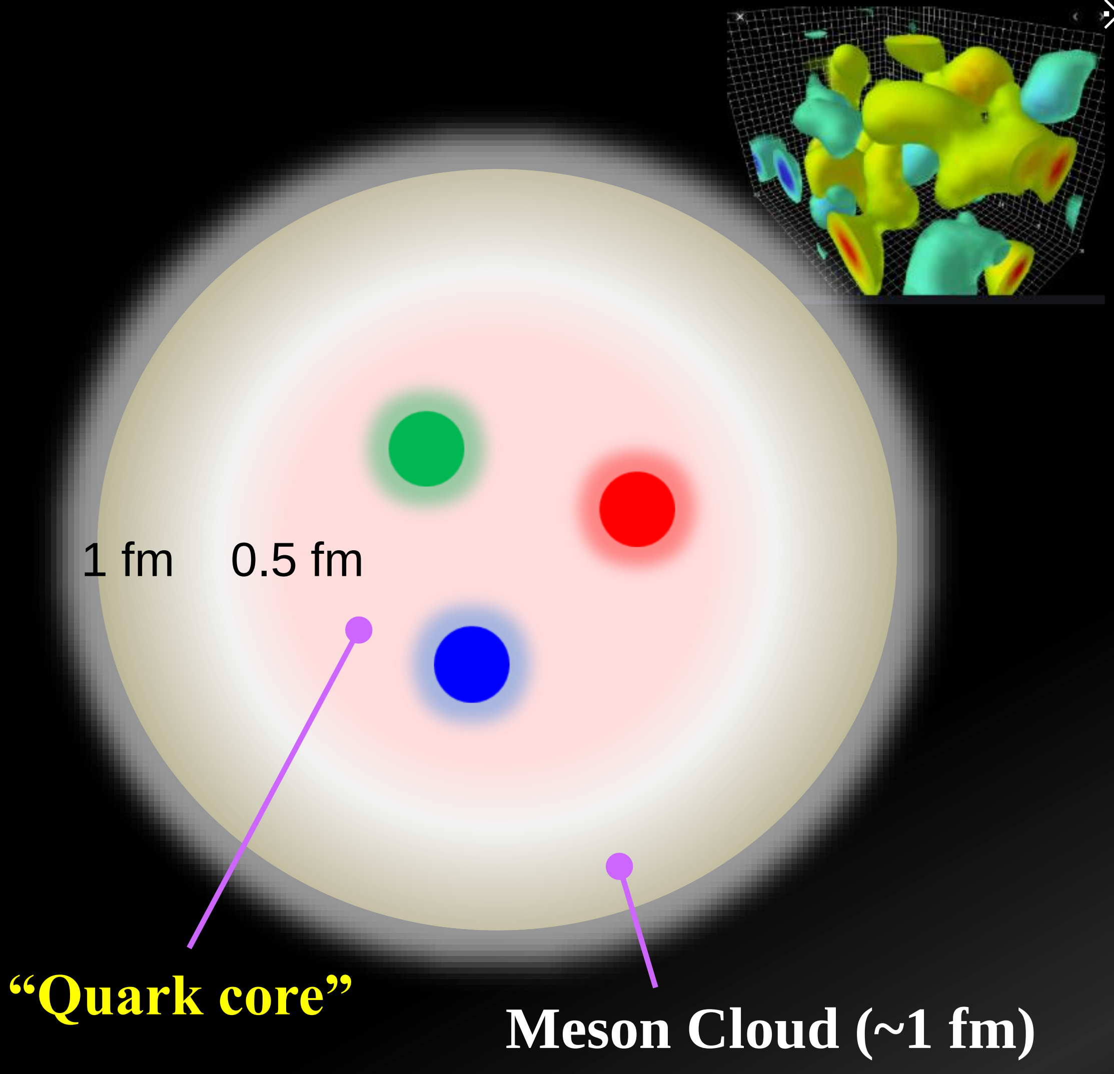
Hypron Matter？

Mystery of Neutron Star



Atom→Molecule→Material,Human,Star,Galaxy

Non-trivial QCD vacuum in Baryon Structure



※Derek Leinweber, 2003, 2004
http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/index.html

- Non-trivial gluon field ⇒ $\langle \bar{q}q \rangle$

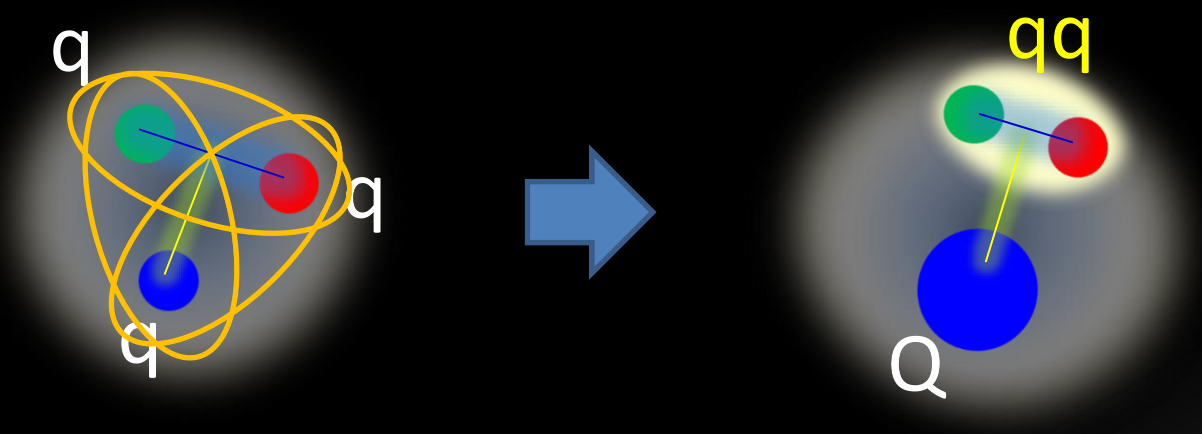
  "massive" constituent q, NG boson

  ($U_A(1)$ anomaly)
- Dynamics of Effective DoF
  - OGE (as a residual int.)/Instanton Induced Int.
    - Too large α_S in Spin-Spin Int.
  - Meson Cloud

Short-range *qq* spin correlation
⇒ Origin of Spin Dependent force

※WS on Physics of Omega Baryons at J-PARC K10: https://indico.rcnp.osaka-u.ac.jp/event/1689/

Roles of Heavy Flavors



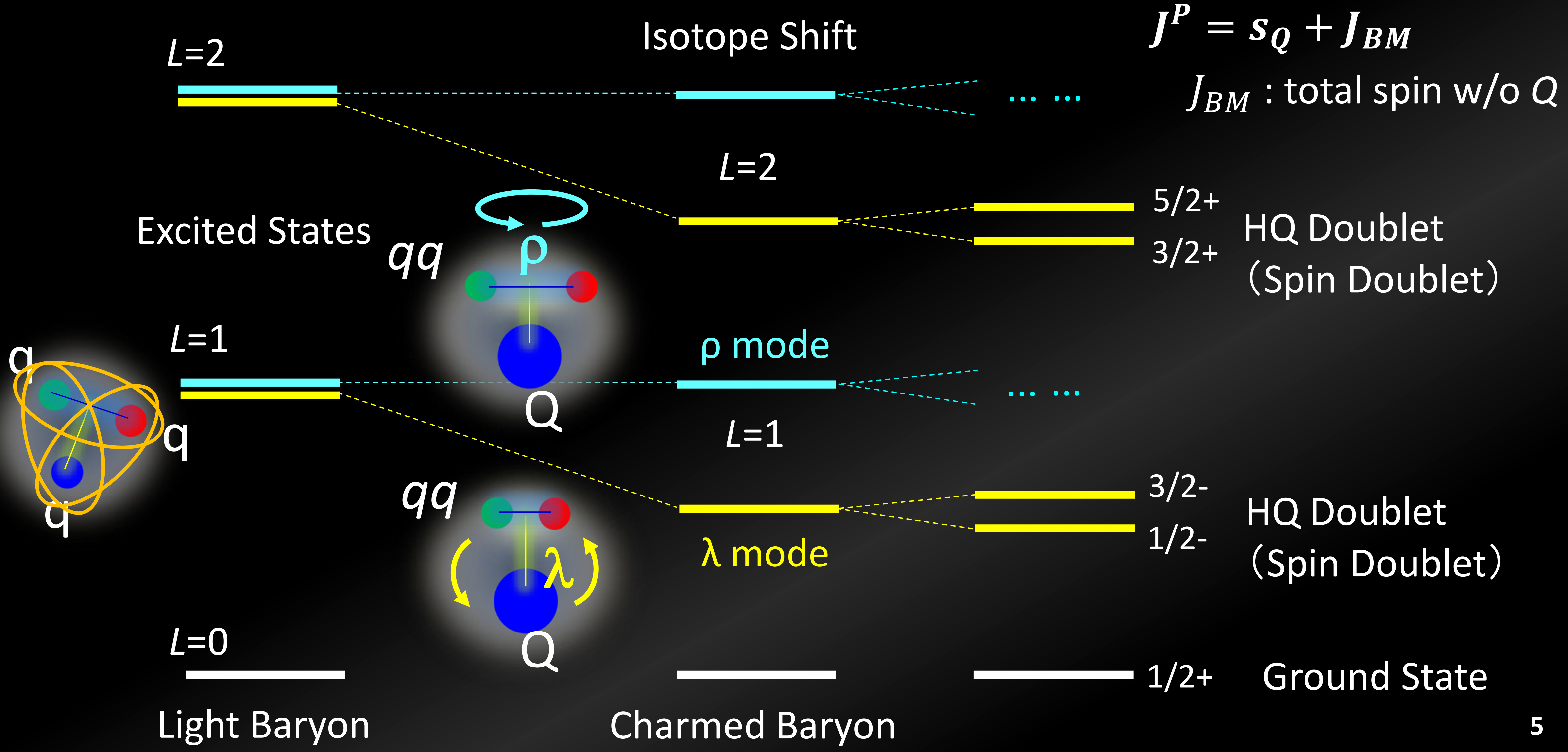
$$V_{CMI} \sim [\alpha_s/(m_i m_j)]*(\lambda_i,\lambda_j)(\sigma_i,\sigma_j)$$
$$\to 0 \text{ if } m_{i,j} \to \infty$$

$$\underset{[qq]}{V_{CMI}({}^1S_0, \bar{3}_c)} = 1/2 * \underset{[\bar{q}q]}{V_{CMI}({}^1S_0, 1_c)}$$

- Motion of "*qq*" is singled out by a heavy Q
  - Diquark correlation
- Level structure, Production rate, Decay properties
  - sensitive to the internal quark(diquark) WFs.
- Properties are expected to depend on a Q mass.

Disentangle motions of a light-quark pair w/ a heavy quark (HQ)

※Identifying l/r modes -> provide internal quark motions and correlation

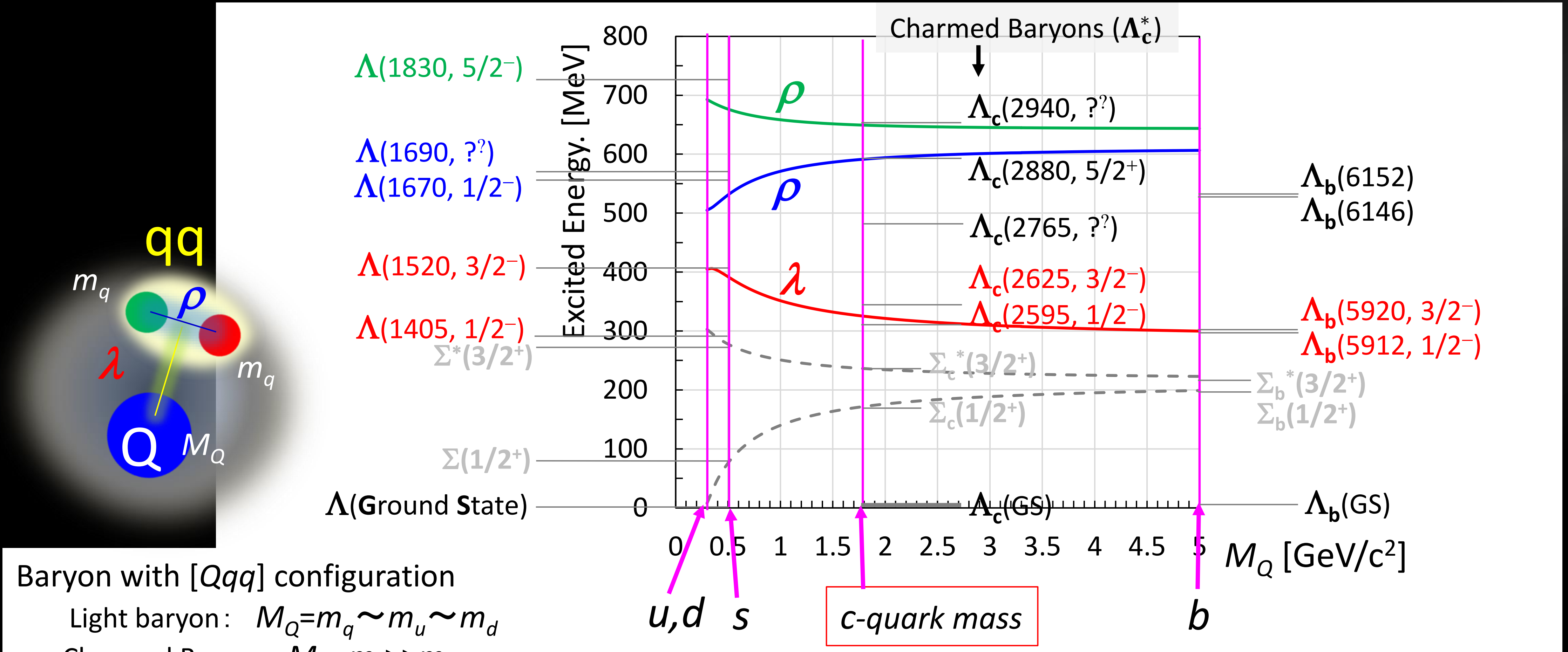


T. Yoshida, E. Hiyama, A. Hosaka, M. Oka, K. Sadato, Phys. Rev. D**92** (2015) 114029

Effect of the Isotope Shift

Quark Model Calculation (curves) for Excitation Energy Spectra as a function of Heavy quark mass (M_Q)

※Mass/spin/parity of Λ, Λ_c, Λ_b observed so far are shown below : Their excitation modes (internal structure) to be clarified



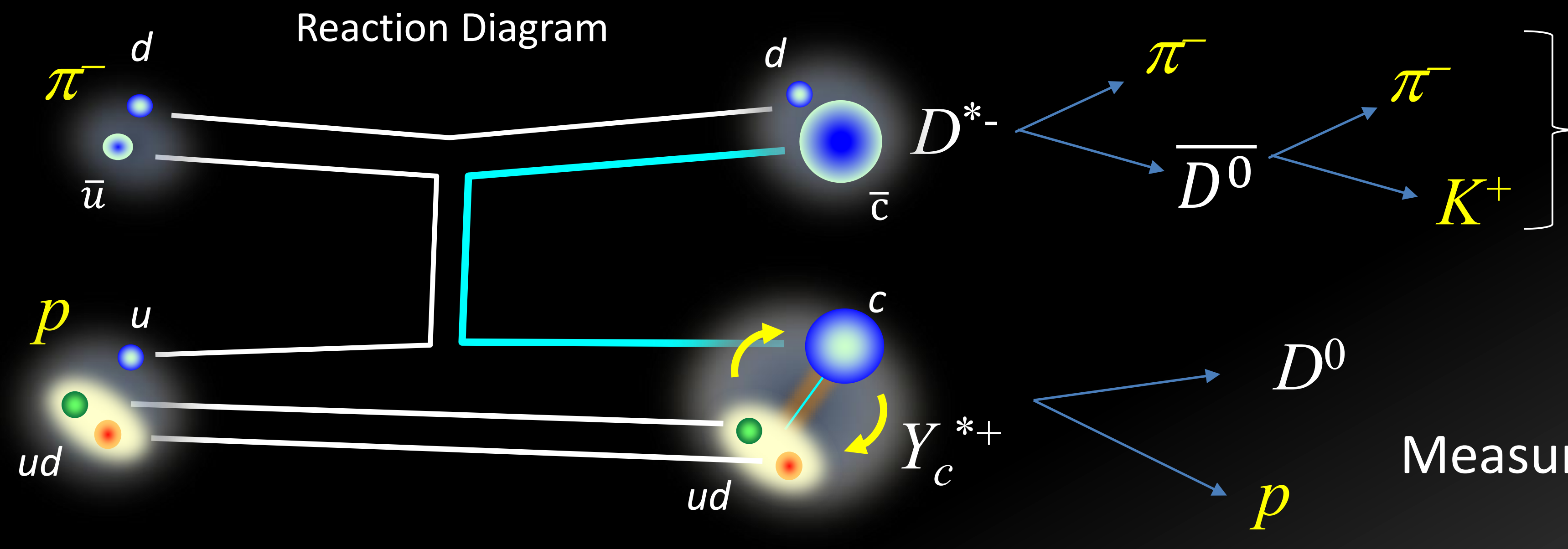
Baryon with [Qqq] configuration

Light baryon : $M_Q = m_q \sim m_u \sim m_d$

Charmed Baryon : $M_Q = m_c >> m_q$

※Further understanding of baryon structure though systematic change of the excitation modes in different flavors

Production and Decay of Charmed Baryons



Measure D*- and Identify Y_c^{*+}) in the Missing mass spectrum

Measure Decay particles , too

Replacing *u*-quark in a proton into *c*-quark

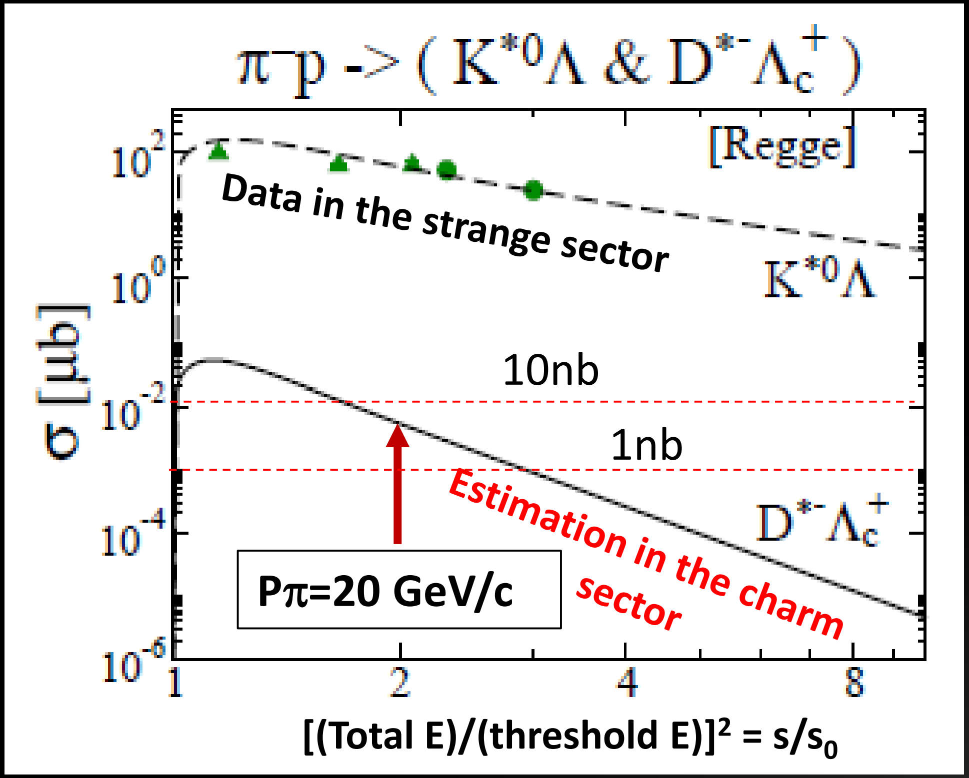
Remarks

- Introducing a finite orbital angular momentum *L* ⇒ favor λ-mode excitations
- Production ratio of the HQ doublet to be *L*:*L*+1 ⇒ Spin, Parity
- Production and Decay measurement ⇒ Branching Ratio (partial width)

Production of Charmed Baryons: Theoretical Study

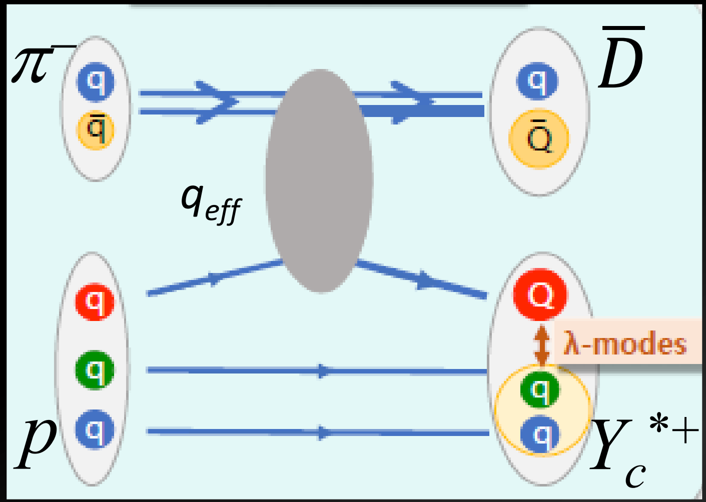
Reggeon Exchange Model in 2-body reaction

S.H. Kim, A. Hosaka, H.C. Kim, and H. Noumi
PRD92 (2015) 094021

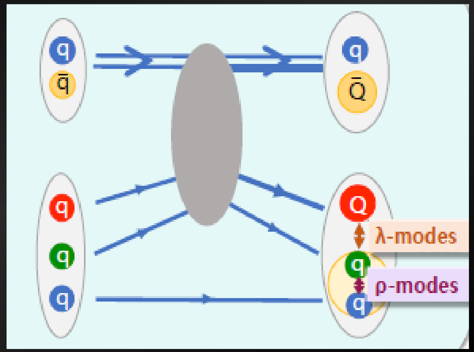


※no data available is in the charm sector.

One-quark process



Two-quark process



Production rate in excited state

S.H. Kim, A. Hosaka, H.C. Kim, and H. Noumi,
PTEP 2014 (2014) 103D01

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

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

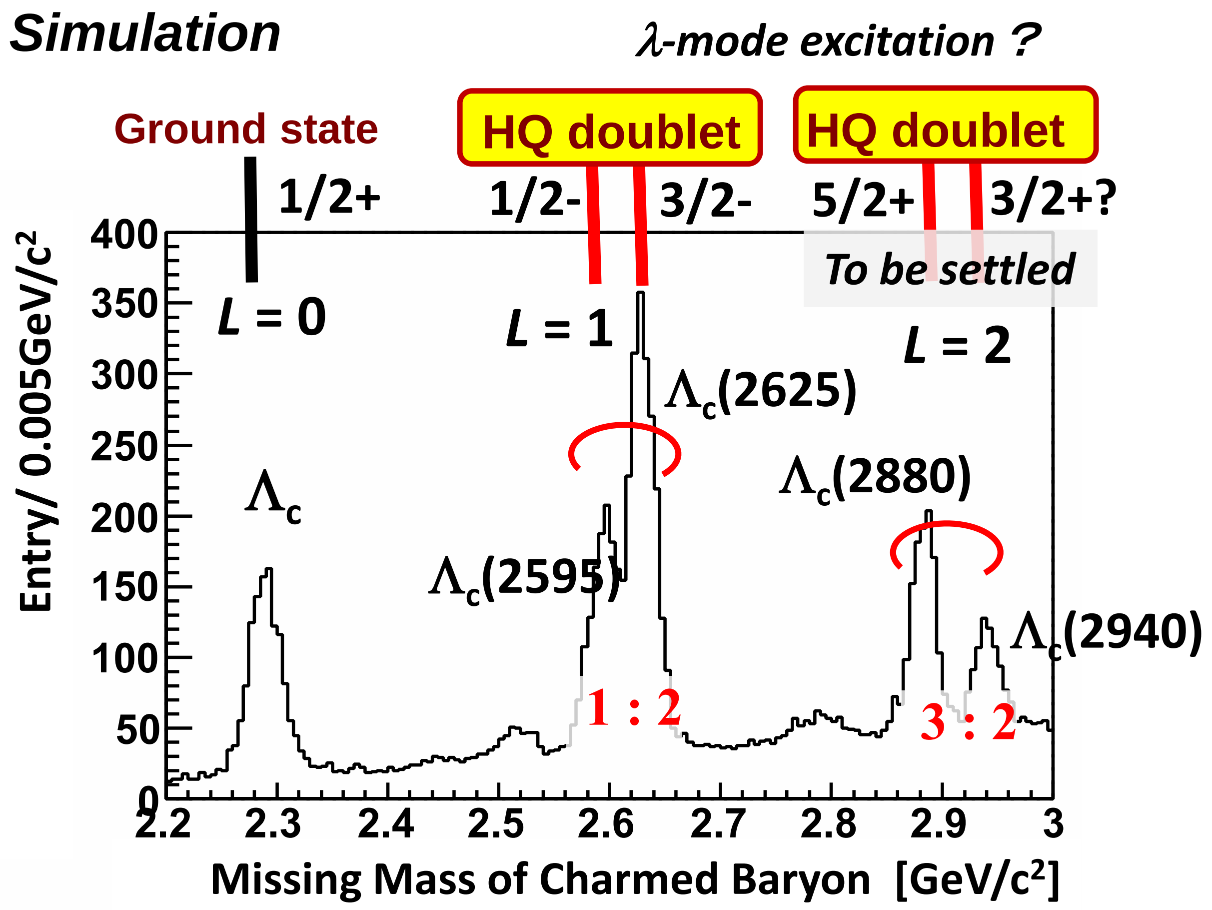
Mom. Trans. : $q_{eff} \sim 1.4$ GeV/c
$\alpha \sim 0.4$ GeV ([Baryon size]$^{-1}$)

※favor λ-mode
excited state with finite L is
populated by factor $(q_{\mathrm{eff}}/\alpha)^L$

S.I. Shim, A. Hosaka, H.C. Kim,
PTEP 2020, (2020) 5, 053D01

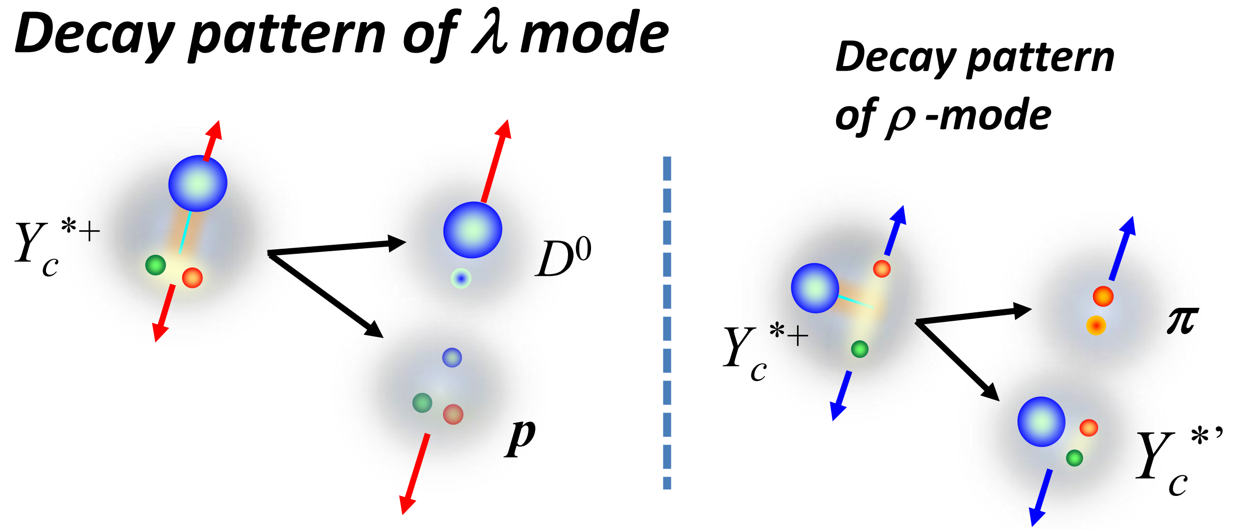
※excite ρ-mode, giving how much the two-quark process contributes.

Expected Mass Spectrum (Simulation)



※Simulation with know states assuming

- λ/ρ and Spin-Parity
- cross sections estimated by theoretical model
- background due to particle miss-identification



※Prod. Rates and Decay Pattern

- Specify a pair of the HQ doublet
  ※unexpected pair may be identified.
- Spin-parity is to be determined

Identify λ/ρ mode

- Internal structure (wave func.) (q motion and qq correlation)

Unsettled Problem: Expected "LS" Pattern

OGE: One Gluon Exchange, III: Instanton Induced Interaction
A, B = finite numbers (flavor dependent)

	Ω^-		N*		Λ_c^*		Λ_b^*		Δ		Λ	
	P-state	D-state	P	D	P	D	P	D	P	D	P	D
OGE	–	+*A*	+*A*	+*A*	+*A*	+*A*	+*A*	+*A*	–	+*A*	+*A*	+*A*
III	–	–	-*B*	-*B*	–	–	–	–	–	–	-*B*	-*B*
Sum	0	*A*	~ 0	~ 0	*A*	*A*	*A*	*A*	0	*A*	small	small
Exp (MeV)	?	?	~ 0	~ 0	36	?	8	7	~ 65?	~ 100?	~ 20?	?

Vanished

Observed

Unclear

Yet to be measured
(in J-PARC K10 Proj.)

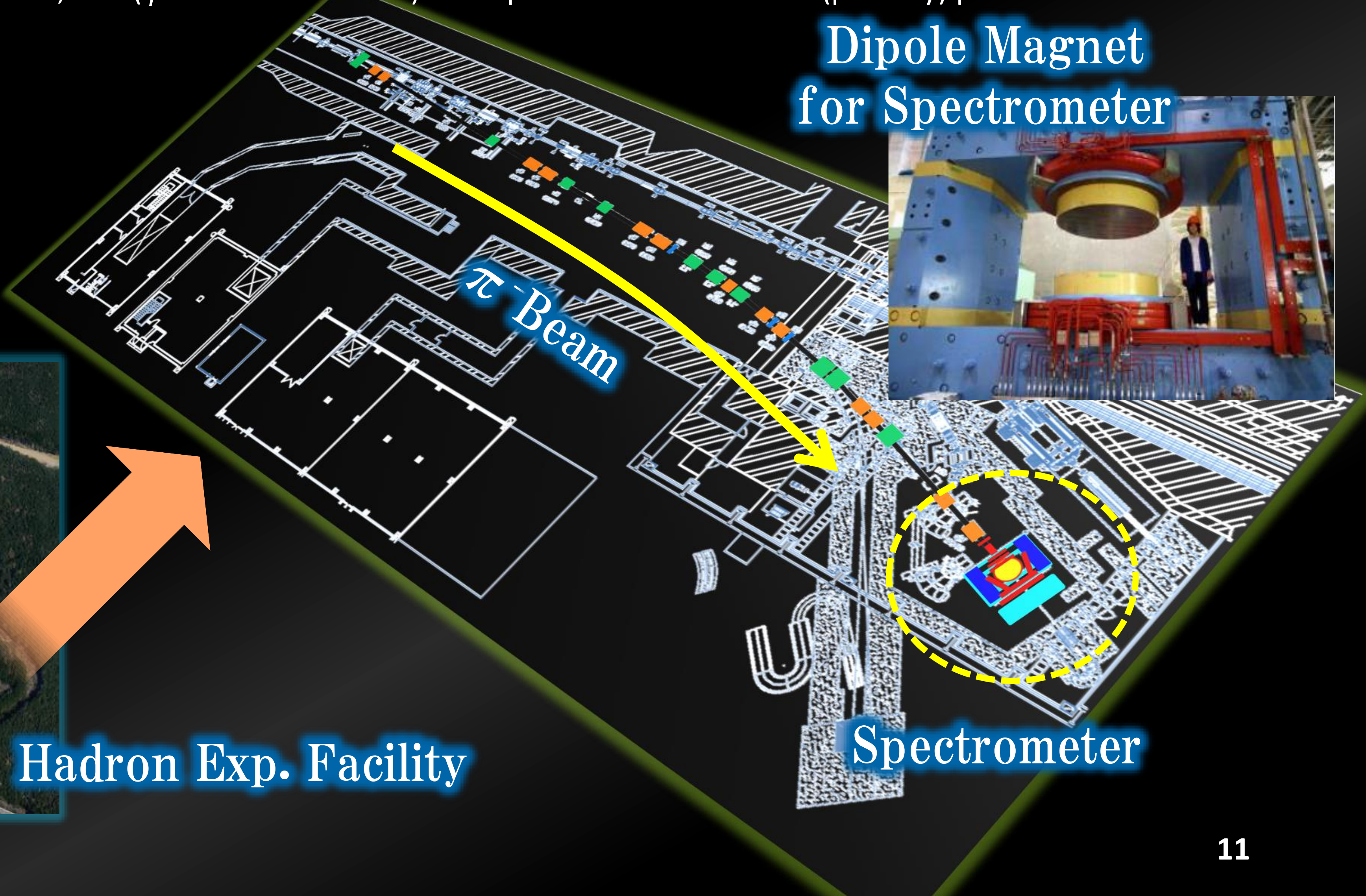
to be studied
(in J-PARC High-p)

Charmed Baryon Spectroscopy at J-PARC

High-p Beam Line ※At present, E16 ($\phi \rightarrow e^+e^-$ in nuclei) is in operation with a 30GeV (primary) proton beam

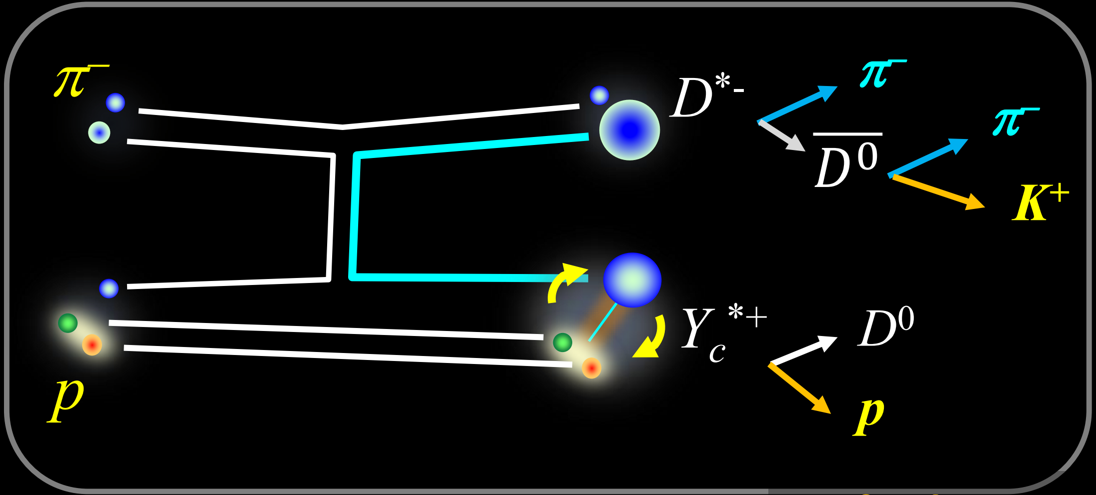
- 20 GeV/c π-
- Intensity >10^7 /s
- Δp/p~ 1/1000

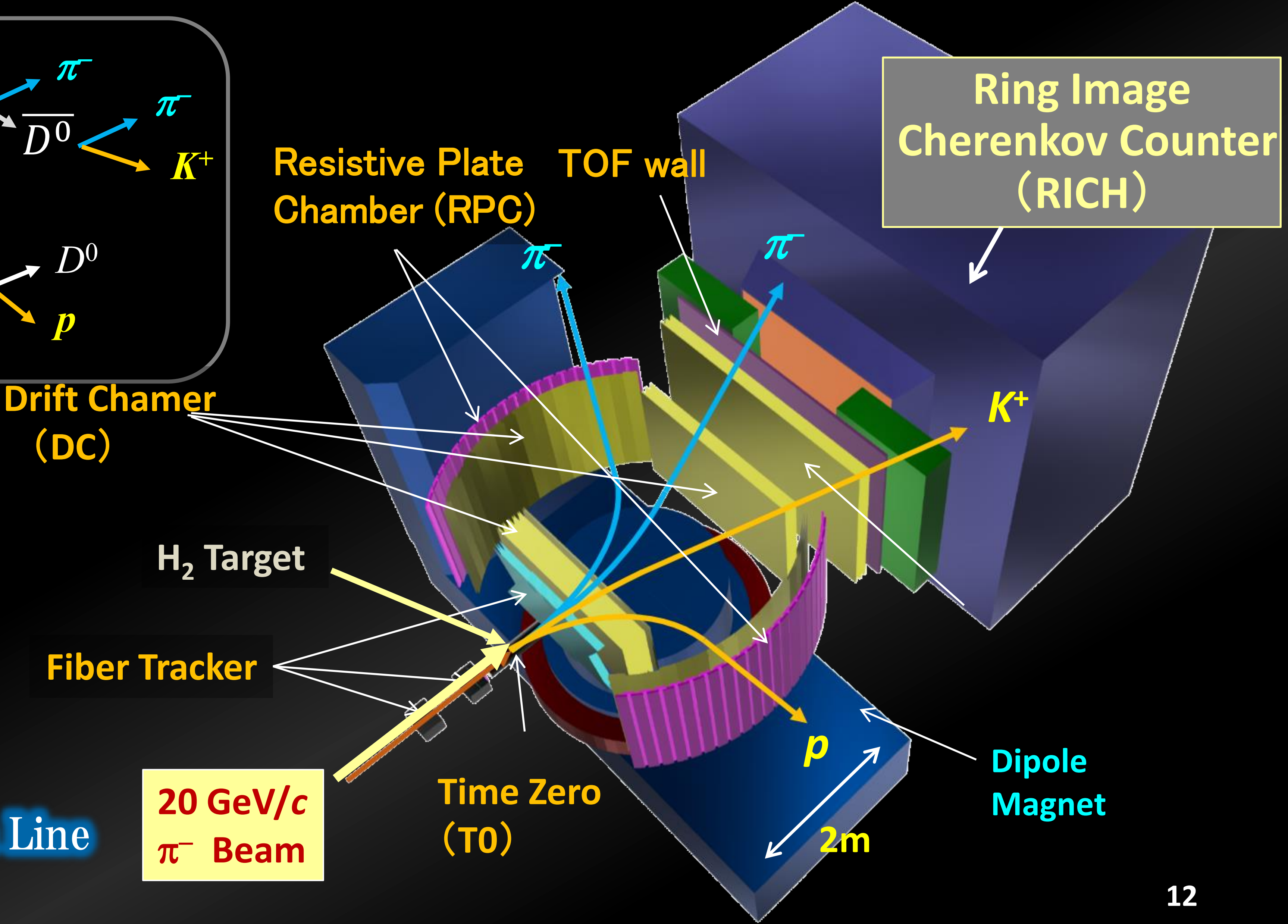
Hadron Exp. Facility



Spectrometer System：

Acceptance: ~ 60% for D^*, ~ 80% for decay π^+
Resolution: $\Delta p/p$~0.2% at ~5 GeV/c（Rigidity：~2.1 Tm)

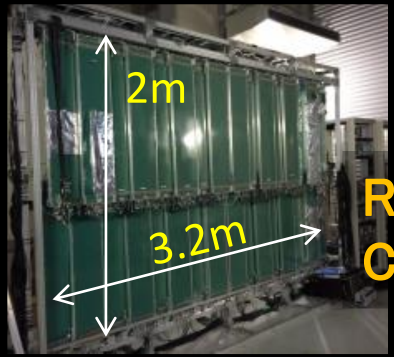




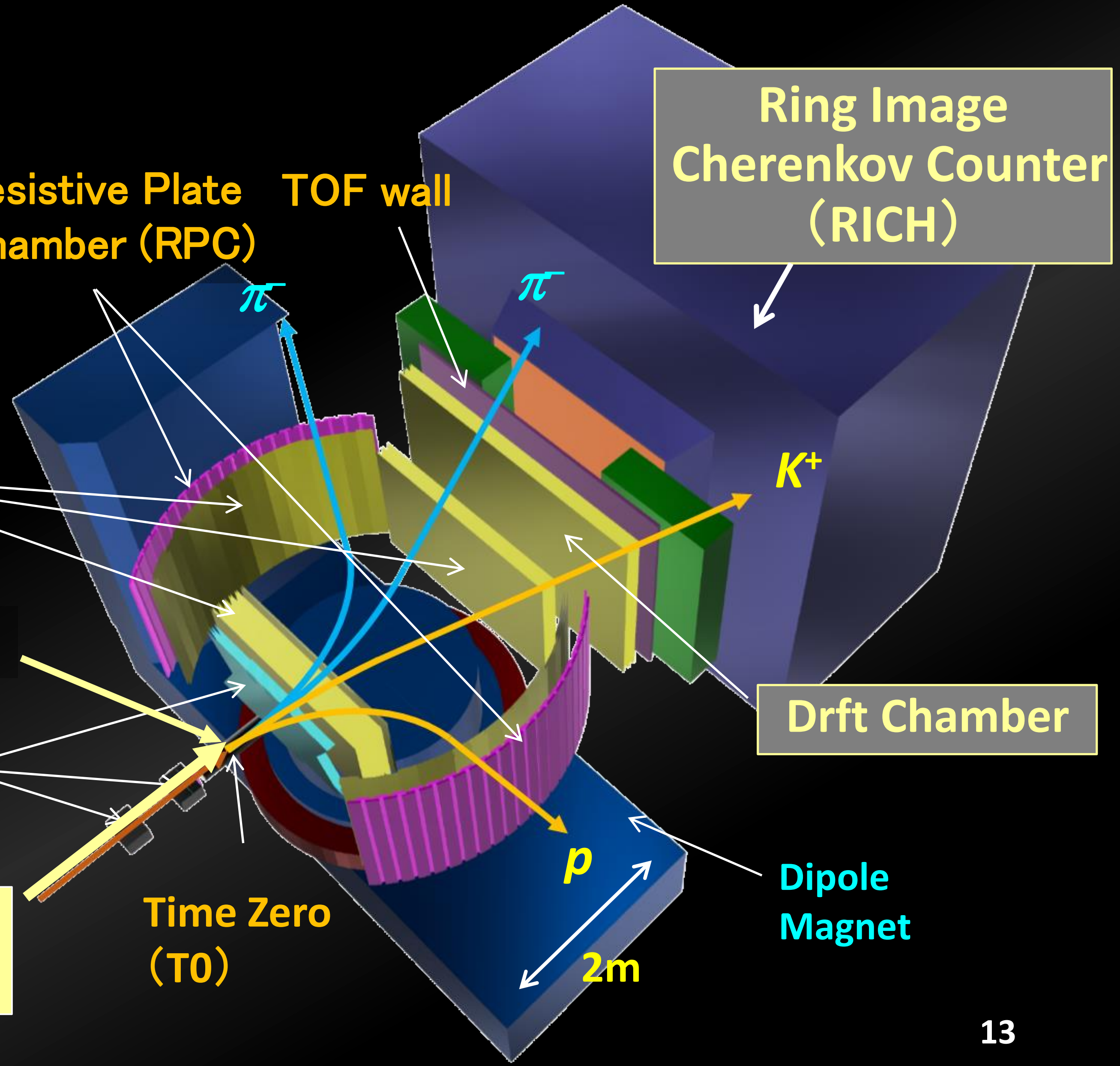
J-PARC High-p Beam Line

Spectrometer System：

Acceptance: ~ 60% for *D, ~ 80% for decay π^+**
Resolution: $\Delta p/p$~0.2% at ~5 GeV/*c*（Rigidity：~2.1 Tm)



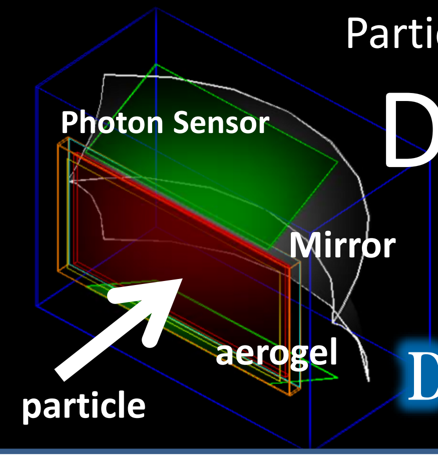
J-PARC High-p Beam Line



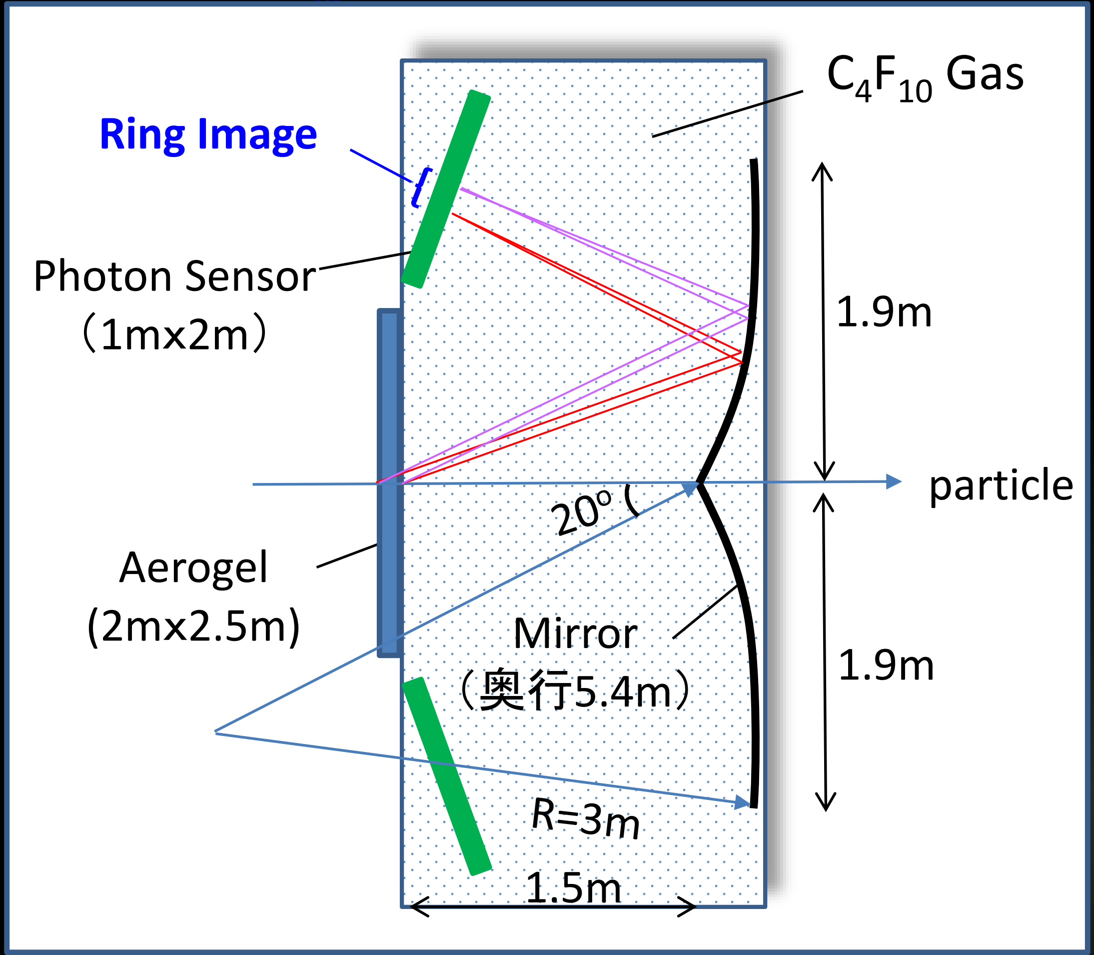
Particle Identification in wide momentum range of 2～16GeV/c

Development of prototype RICH in progress

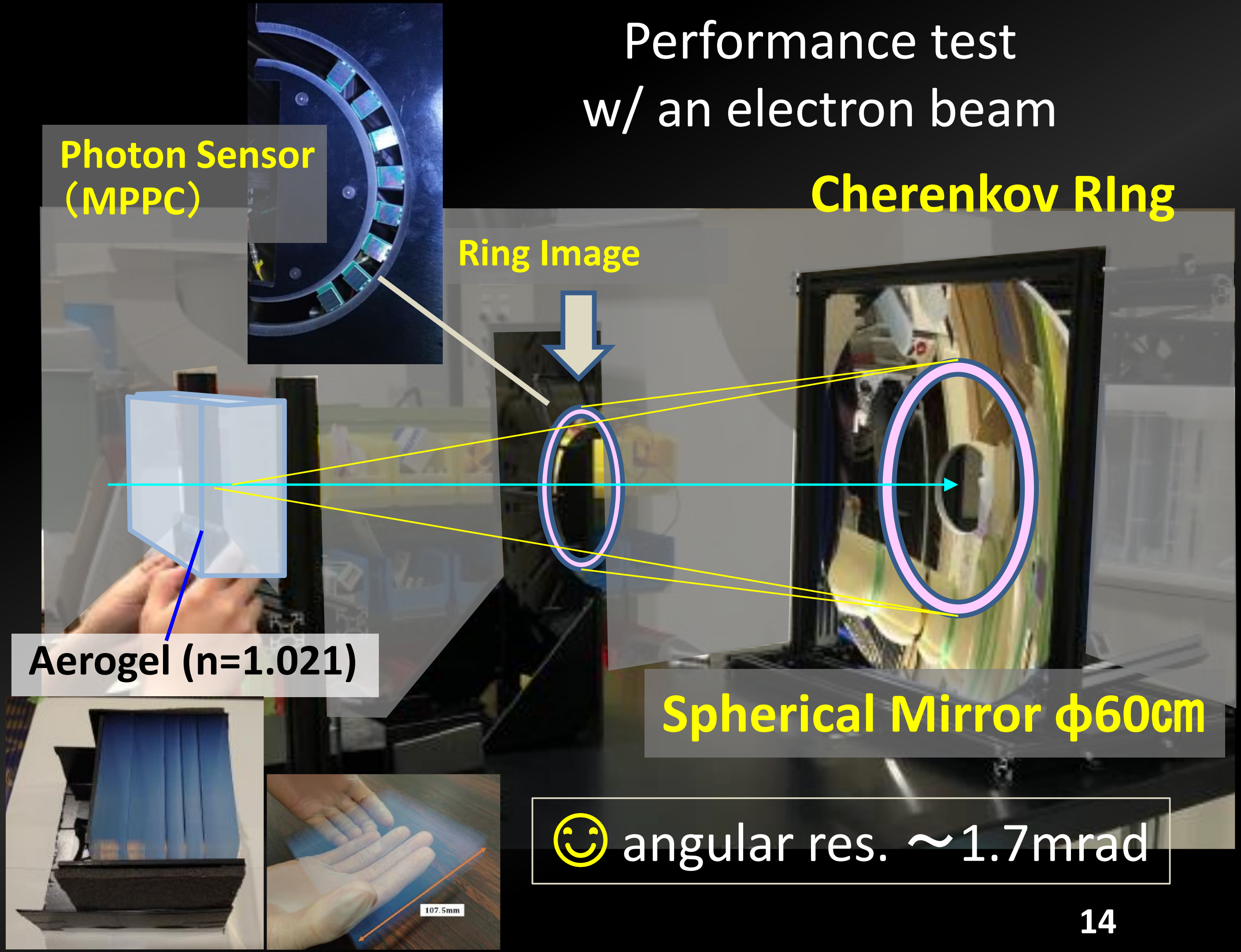
Precise Measurement of a Cherenkov radiation angle → Particle velocity



Designed RICH



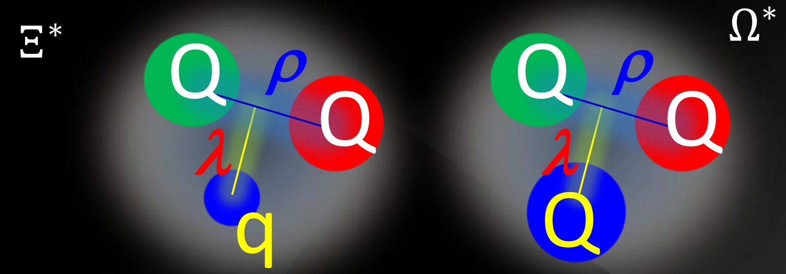
Performance test
w/ an electron beam

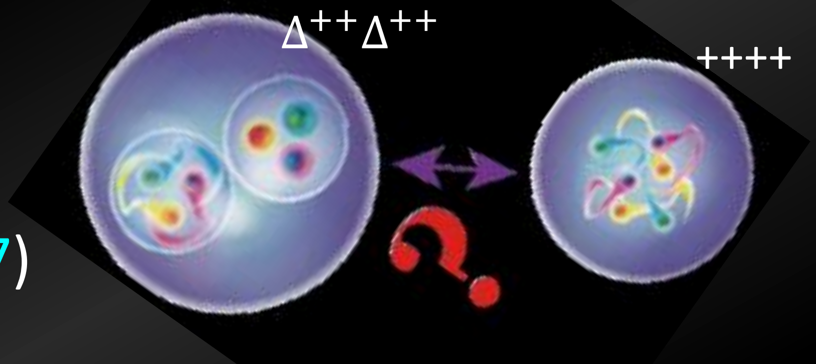


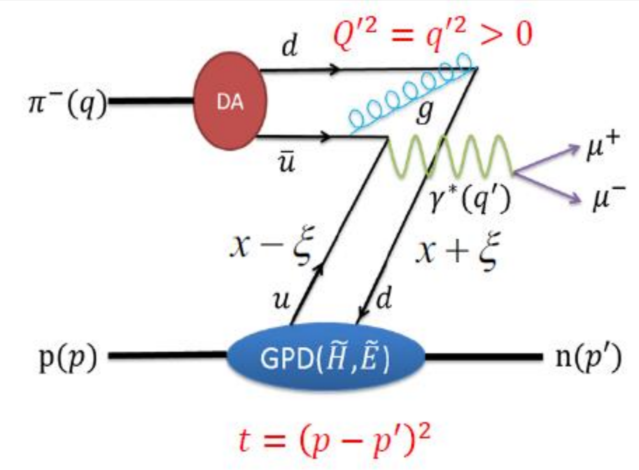
☺ angular res. ～1.7mrad

Hadron Physics at High-p BL

- Baryon Spectroscopy
  - p(π^-,D^{*-})Y$_c^*$ (E50)
  - p(K$^-$,K*)Ξ^*, p(K$^-$,K$^+$K*)Ω^* (LoI:KEK/J-PARC-PAC 2014-4)
  - Search for D_{30} Dibaryon State in $pp \rightarrow \pi^-\pi^- D_{30}$ (E79)
  - p(π^-,K*)Λ(1405) at large *s*, *t* (to be proposed)
- Hadron Tomography
  - Exclusive DY, $\pi^- p \rightarrow \mu^-\mu^+ n$ (LoI: KEK/J-PARC-PAC 2019-7)
- For Strangeness Nuclear Physics
  - Λp Scattering for the study of high-dense nuclear matter (LoI: KEK/J-PARC-PAC 2020-08)
- For Neutrino Physics
  - Hadron Production for neutrino beams







Summary

- A heavy quark plays an inert particle in a hadron and is quite helpful to investigate internal motions and/or correlations of quarks.
  - Excitation Energy, Production Rate, and Decay Branching Ratio
- We conduct charmed baryon spectroscopy by means of missing mass technique at the J-PARC high-momentum beam line, where the intense pion beams up to 20 GeV/c will be delivered.
  - New platform of hadron physics will be covered owing to the general purpose spectrometer