International Workshop on the Extension Project for the J-PARC Hadron Experimental Facility
(J-PARC HEF-ex WS)
7-9 July, 2021

Baryon Spectroscopy at J-PARC

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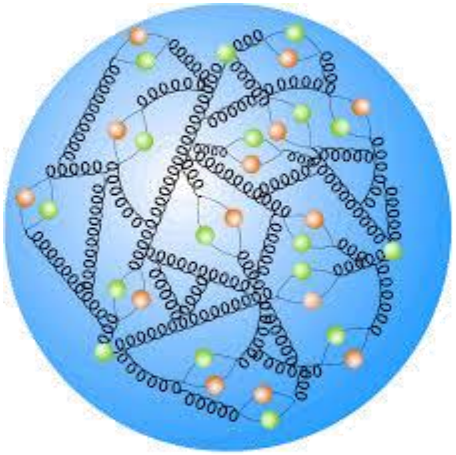
RCNP, Osaka University/IPNS, KEK

Contents:

How does QCD work in Hadrons and Hadron-Hadron Interactions ?

perturbative
High E

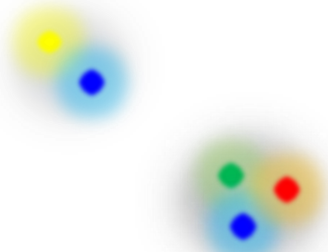


http://ppssh.phys.sci.kobeu.ac.jp/~yamazaki/lectures/07/modernphys-yamazaki07.pdf

$\alpha_s = \infty$
at Λ_{QCD}

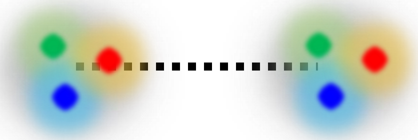
Confinement

non-perturbative
Low E



Effective DoF

How are they excited ?



How do they interact ?

QCD

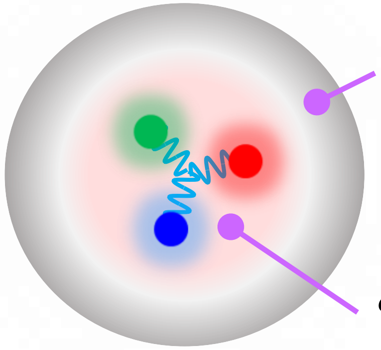
Lattice (HAL)

w/ physics picture

Hadron Spectroscopy

Observation / Effective theory

Baryon Structure



Meson Cloud (~1 fm)

“Quark core”

- Non-trivial gluon field $\Rightarrow \langle\bar{q}q\rangle$, constituent q, NG boson, $U_A(1)$ anomaly (η-η' mass diff.)

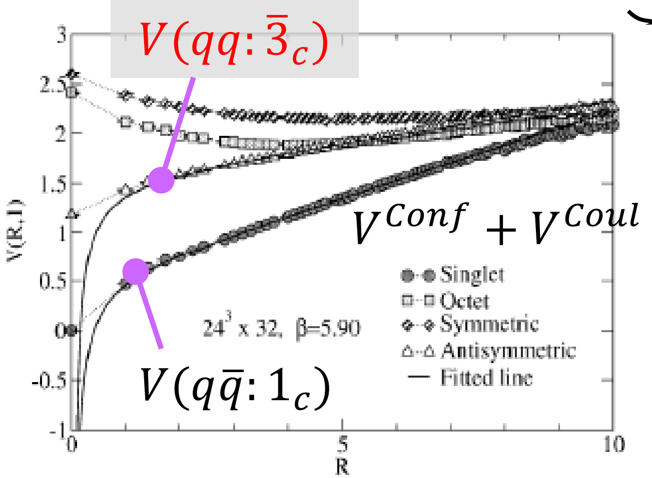
Dynamics of Effective DoF

- Confinement (~1 fm)
- One-Gluon Exchange (OGE)
  - perturbative effect
- Instanton-Induced Int. (III) (<0.5 fm)
  - Kobayashi-Maskawa-t'Hooft (KMT) int.

In baryons

- Diquark
  - $(qq: 0^+) \leftrightarrow (qq: 0^-)$ ~ $U_A(1)$ anomaly
- Origin of Spin-dep't force
  - To explain systematic behaviors of SS/LS

$$H = K + V^{Conf} + \underbrace{V^{Coul} + V^{SS} + V^{LS} + \cdots}_{\text{OGE/III/else (“short” range)}}$$



qLQCD, Nakamura, Saito PLB621(2005)171

Disentangle

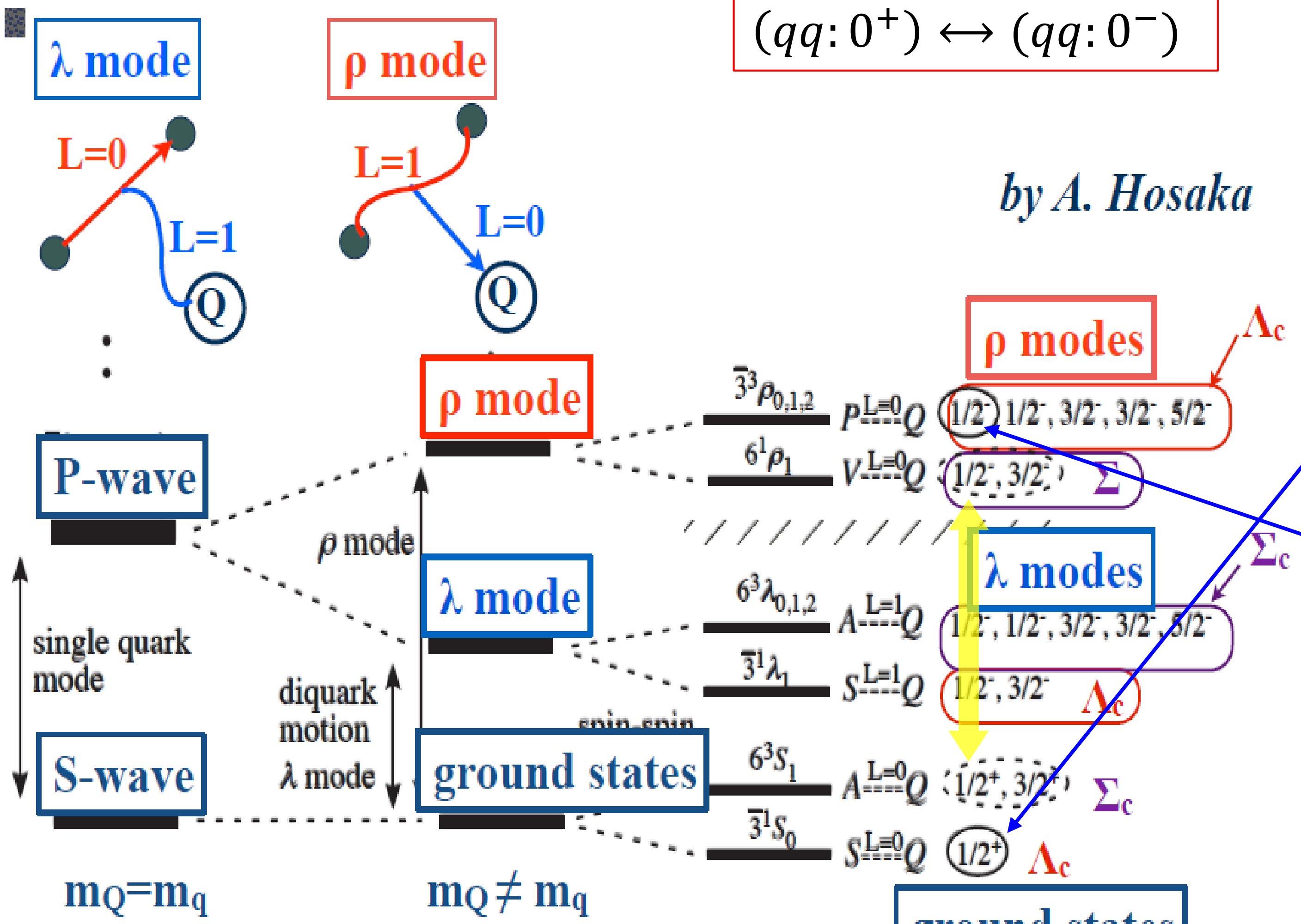
- Diquark correlation in Charmed Baryons
- OGE/III/else in Omega Baryons(*)

(*)Takizawa's and Shirotori's Talks

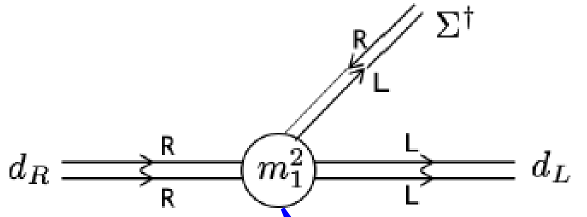
Diquark in Heavy Baryons

$U_A(1)$ anomalous singlet current
in Chiral diquark effective theory

Chiral partner
$(qq: 0^{+}) \leftrightarrow (qq: 0^{-})$



by A. Hosaka



by M. Oka

Scalar diquark

$$S_i^a = \frac{1}{\sqrt{2}}(d_{R,i}^a - d_{L,i}^a)$$

$$\longrightarrow M(0^+) = \sqrt{m_0^2 - m_1^2 - m_2^2},$$

Pseudo-scalar diquark

$$P_i^a = \frac{1}{\sqrt{2}}(d_{R,i}^a + d_{L,i}^a)$$

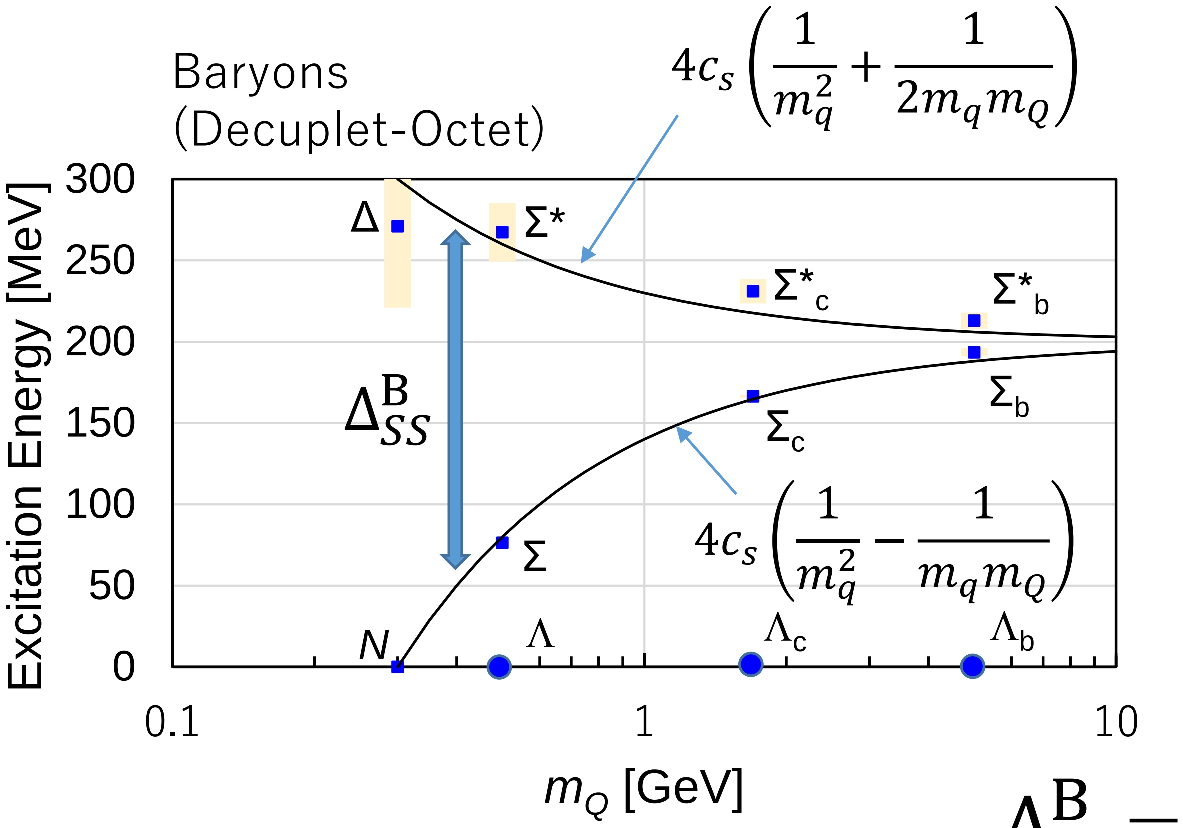
$$\longrightarrow M(0^-) = \sqrt{m_0^2 + m_1^2 + m_2^2},$$

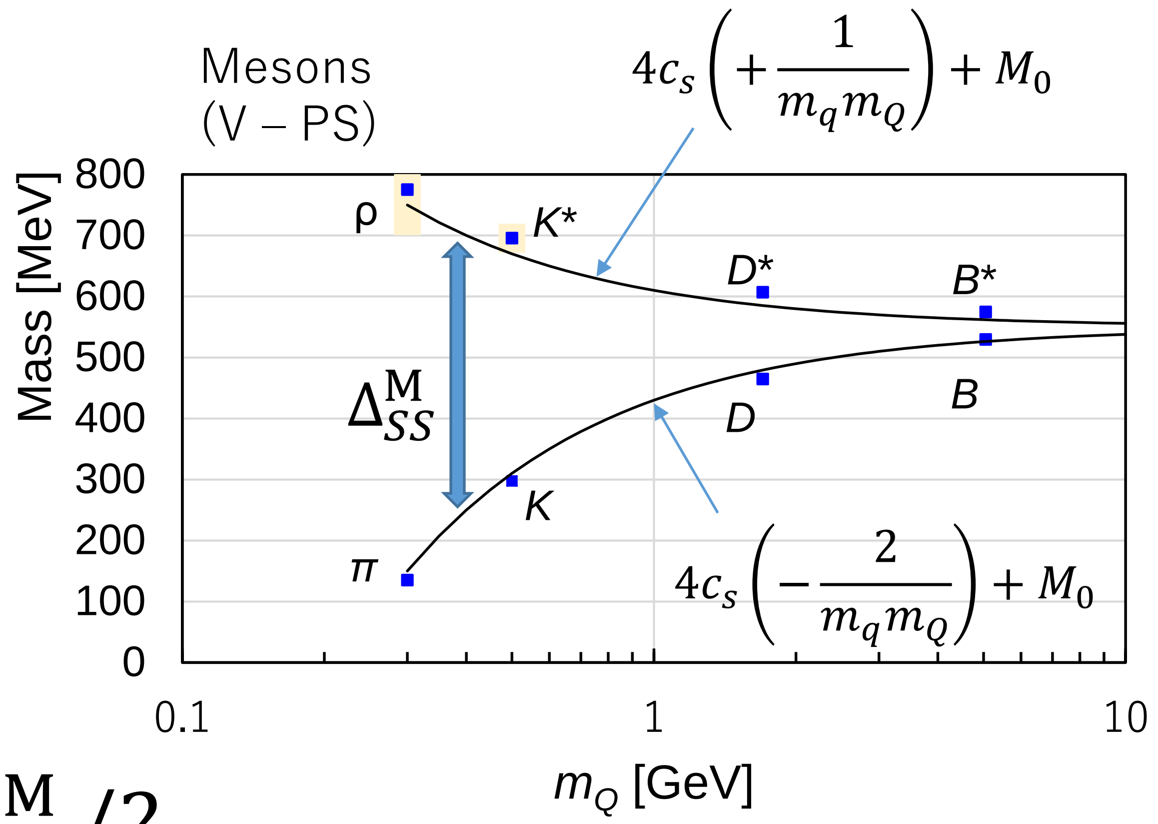
Kim et al, Phys.Rev.D 102 (2020) 014004

Systematic behavior of Spin-Spin(SS) Int.

$$V^{SS} = \sum_{i<j} \alpha_S^{SS} \frac{16\pi}{9m_i m_j} \delta(r_{ij}) \vec{s_i} \cdot \vec{s_j}$$

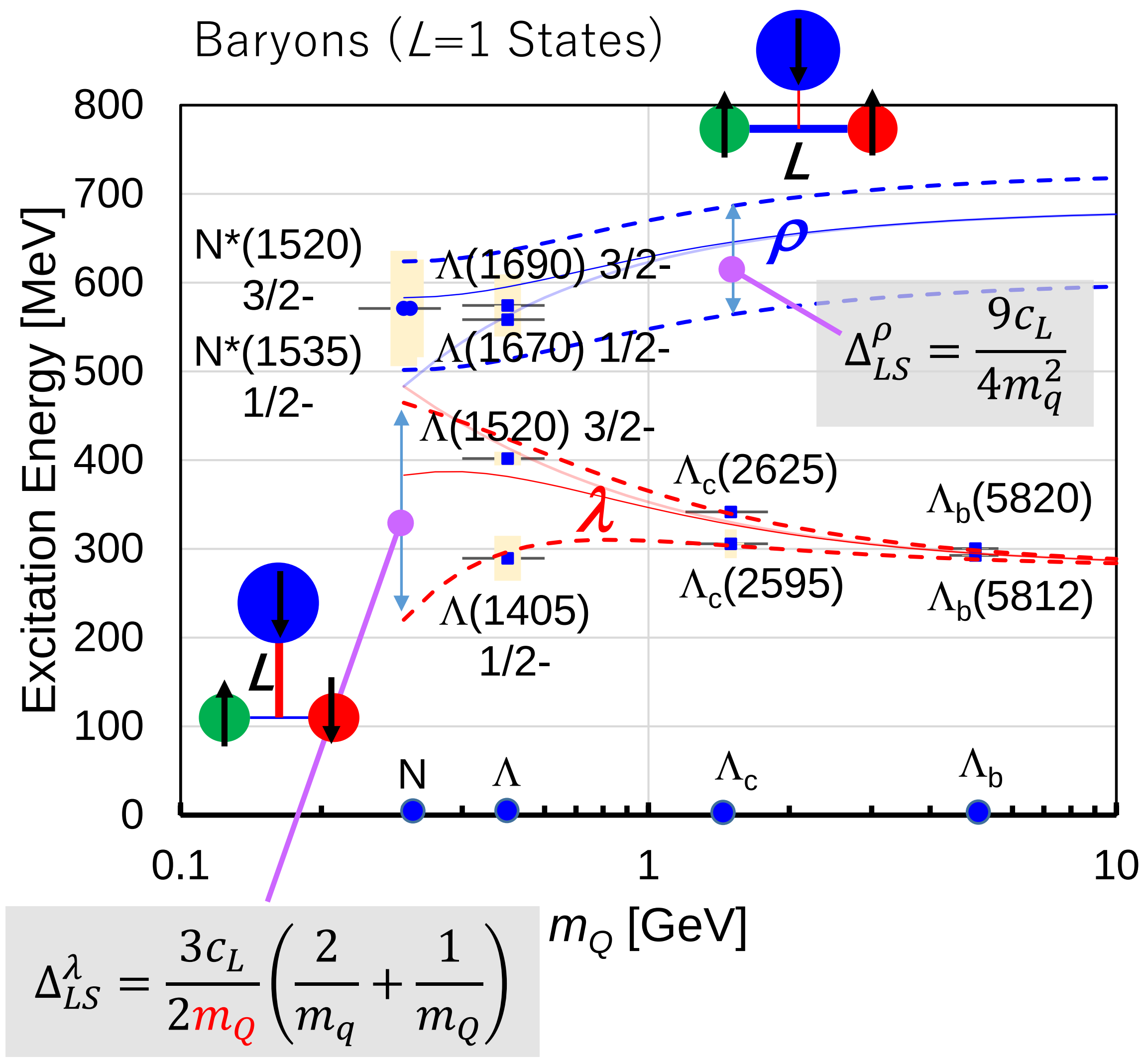
- SS int. seems well described by CQM (OGE).





$$\Delta^B_{SS} = \Delta^M_{SS}/2$$

Systematic behavior of Spin-Orbit(LS) Int.



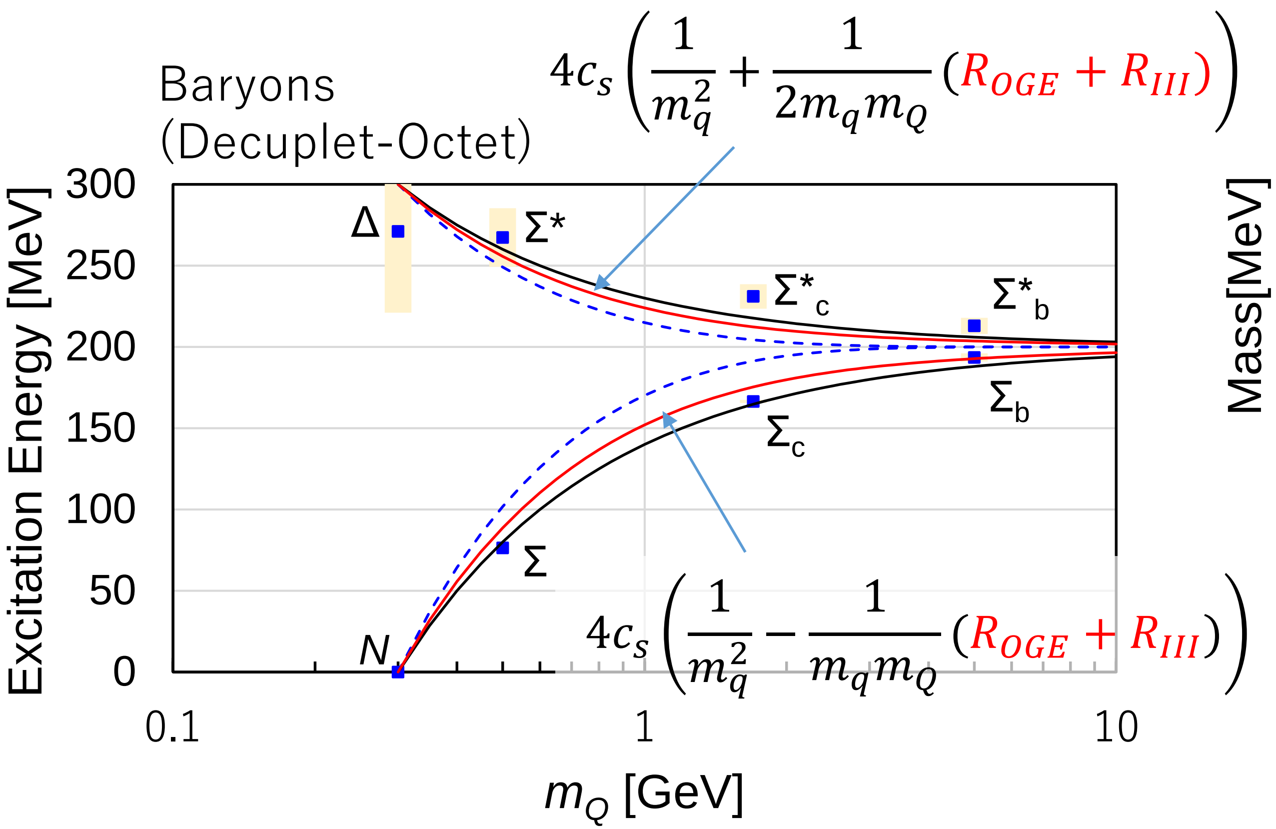
- LS splitting vanishes in light baryons.
  - CQM, which suggests $\Delta_{LS}^{\rho} \sim 100$ MeV, does not reproduce the LS splitting.
- Cancellation mechanism exists?
  - Instanton Induced Interaction (III)

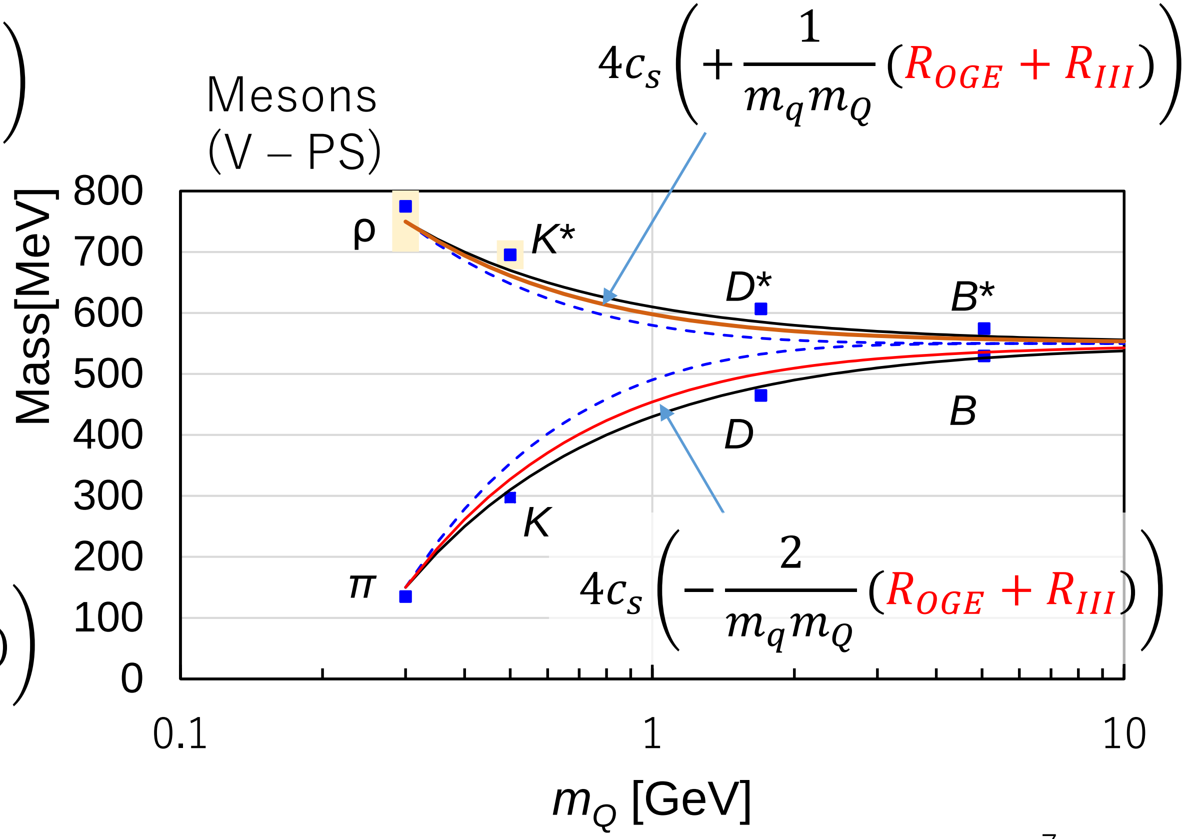
Systematic behavior of Spin-Spin(SS) Int.

$$R_{OGE} + R_{III} \sim 0.6 + 0.4\exp\left(-\frac{m_Q - m_q}{\Lambda_\chi}\right)$$

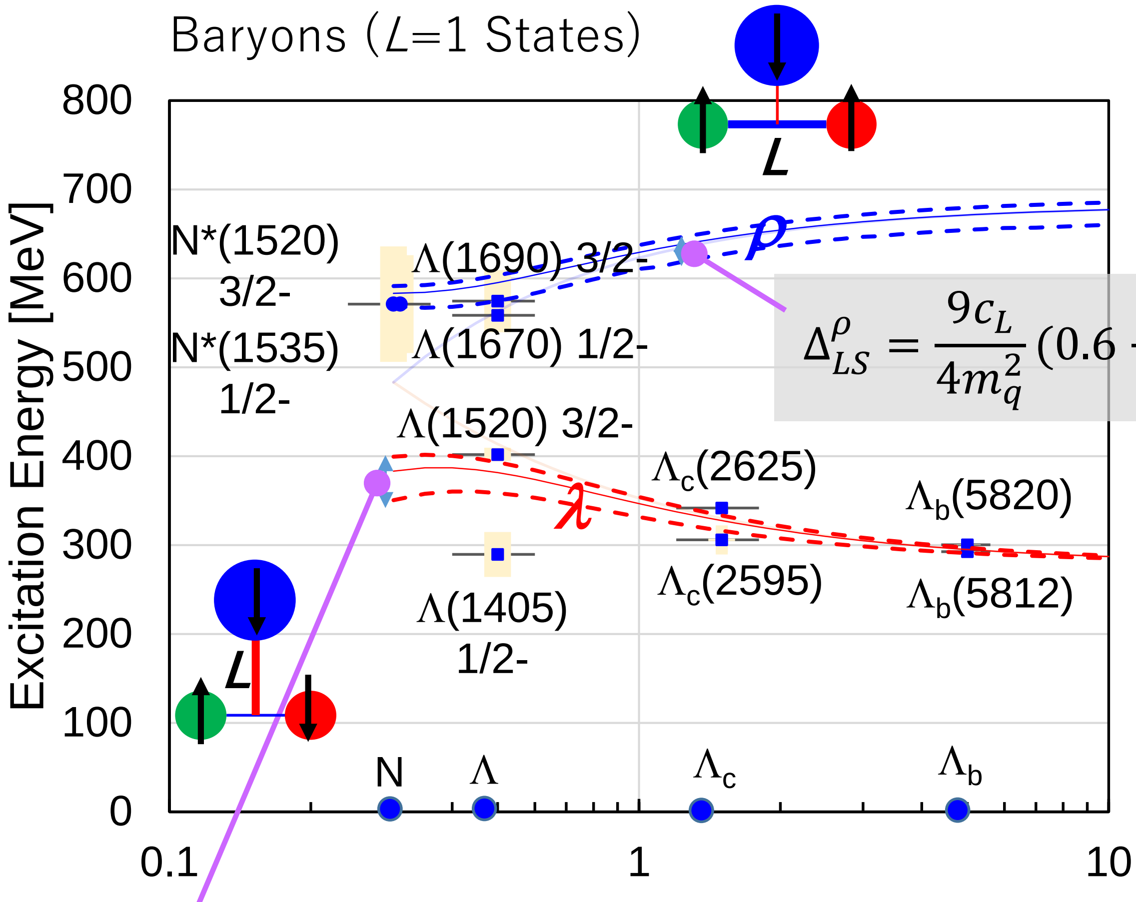
Constructive for SS

- **Very Naive demo.**: OGE + III seems work well.
  - III is comparable to OGE to explain $\eta - \eta'$ mass diff.
  - III works only in flavor-antisymmetric system in light quarks (u,d,s).





Systematic behavior of Spin-Orbit(LS) Int.



$$\Delta_{LS}^{\rho} = \frac{9c_L}{4m_q^2}(0.6 - 0.4)$$

$$\Delta_{LS}^{\lambda} = \frac{3c_L}{2m_Q}\left(\frac{2}{m_q} + \frac{1}{m_Q}\right)\left[0.6 - 0.4\exp\left(-\frac{m_Q - m_q}{\Lambda_\chi}\right)\right]$$

- LS splitting vanishes in light baryons.
  - CQM, which suggests $\Delta_{LS}^{\rho} \sim 100$ MeV, does not reproduce the LS splitting.
- Cancellation mechanism exists?
  - Instanton Induced Interaction (III)

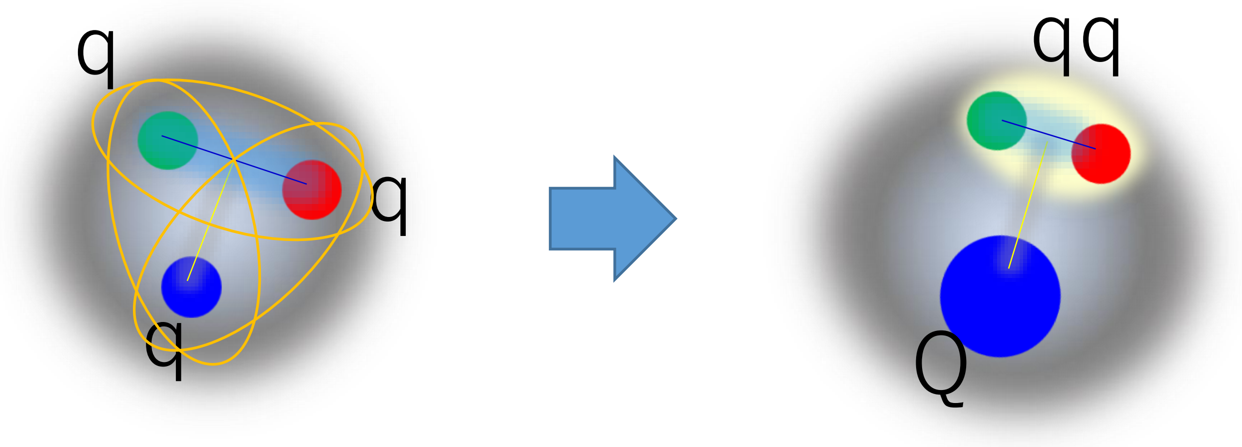
$$\boxed{V^{LS} \sim (R_{OGE} - R_{III})\Delta}$$

Destructive for LS

- LS splitting in heavier systems are to be investigated with identifying if they are λ/ρ-mode excitations

Baryon Spectroscopy at High-p 2nd (π20)
-- Charmed Baryons

Disentangle diquark correlations



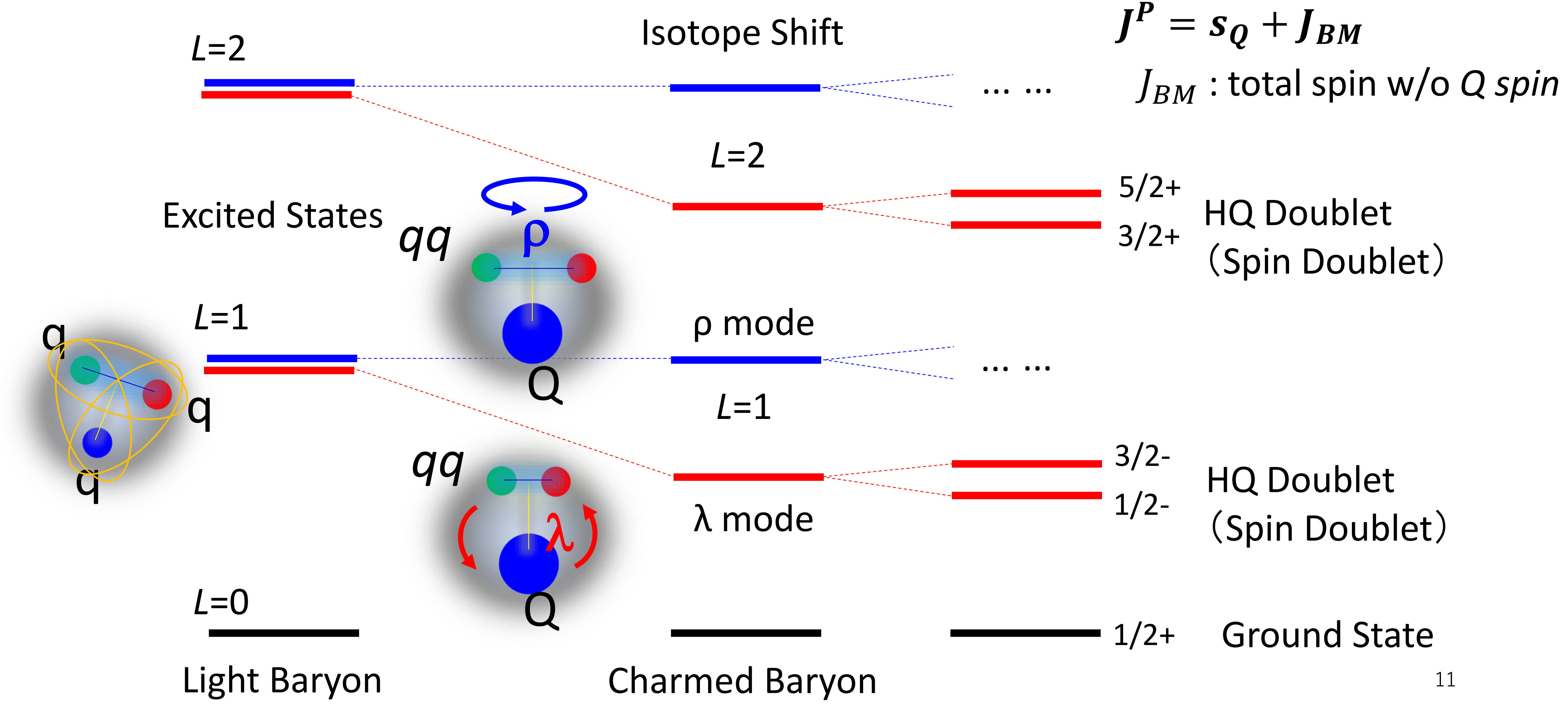
$$V_{CMI} \sim [\alpha_s/(m_i m_j)]*(\lambda_i \cdot \lambda_j)(\sigma_i \cdot \sigma_j)$$
$$\rightarrow 0 \text{ if } m_{i,j} \rightarrow \infty \text{ (HQ symm.)}$$

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

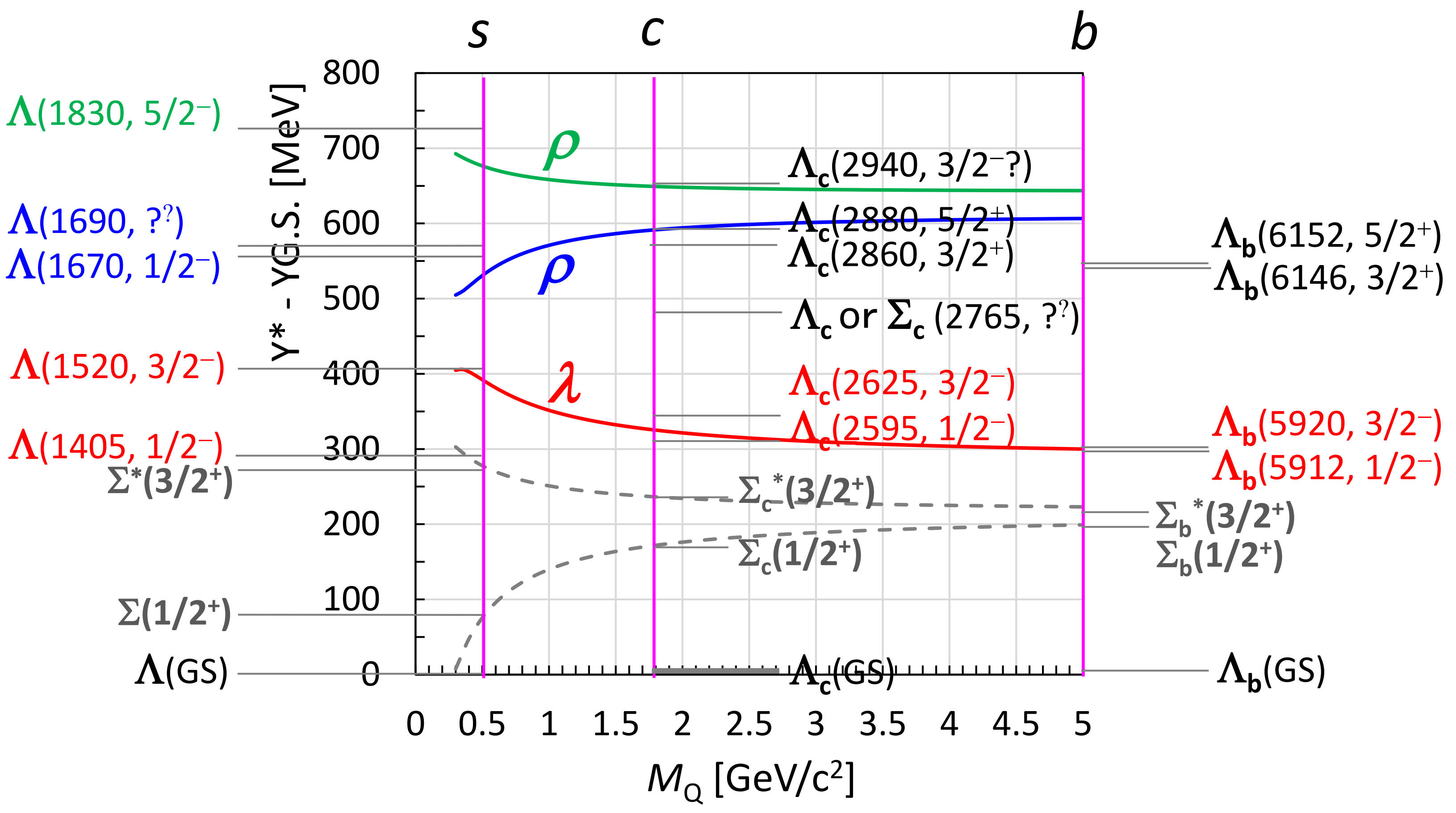
- Motion of "*qq*" is singled out by a heavy Q
  - Diquark correlation
- Level structure, Production rate, Decay properties
  - sensitive to the internal quark(diquark) WFs.
- Properties are expected to depend on a Q mass.

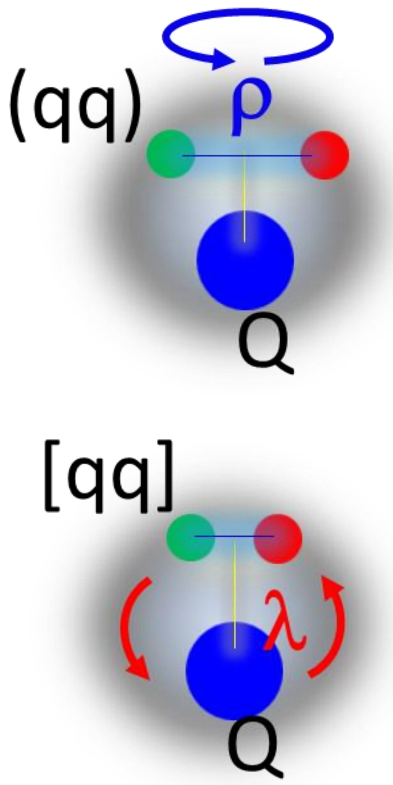
Disentangle motions of a light-quark pair w/ a heavy quark (HQ)

※Identifying λ/ρ modes -> provide internal quark motions and correlation



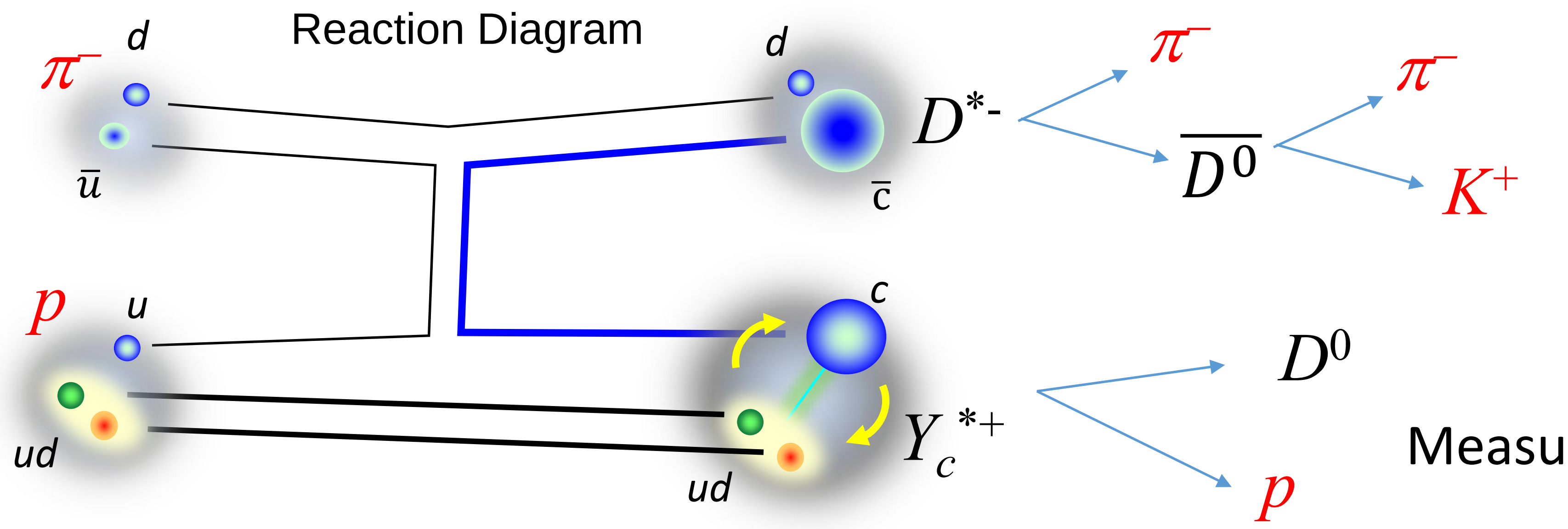
Systematic behavior of Qqq Baryons
Qqq: singly-heavy quark (Q)+ diquark (qq)





※Curves: CQM calculation by T. Yoshida, E. Hiyama, A. Hosaka, M. Oka, K. Sadato, Phys. Rev. D**92** (2015) 114029

Production and Decay of Charmed Baryons



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

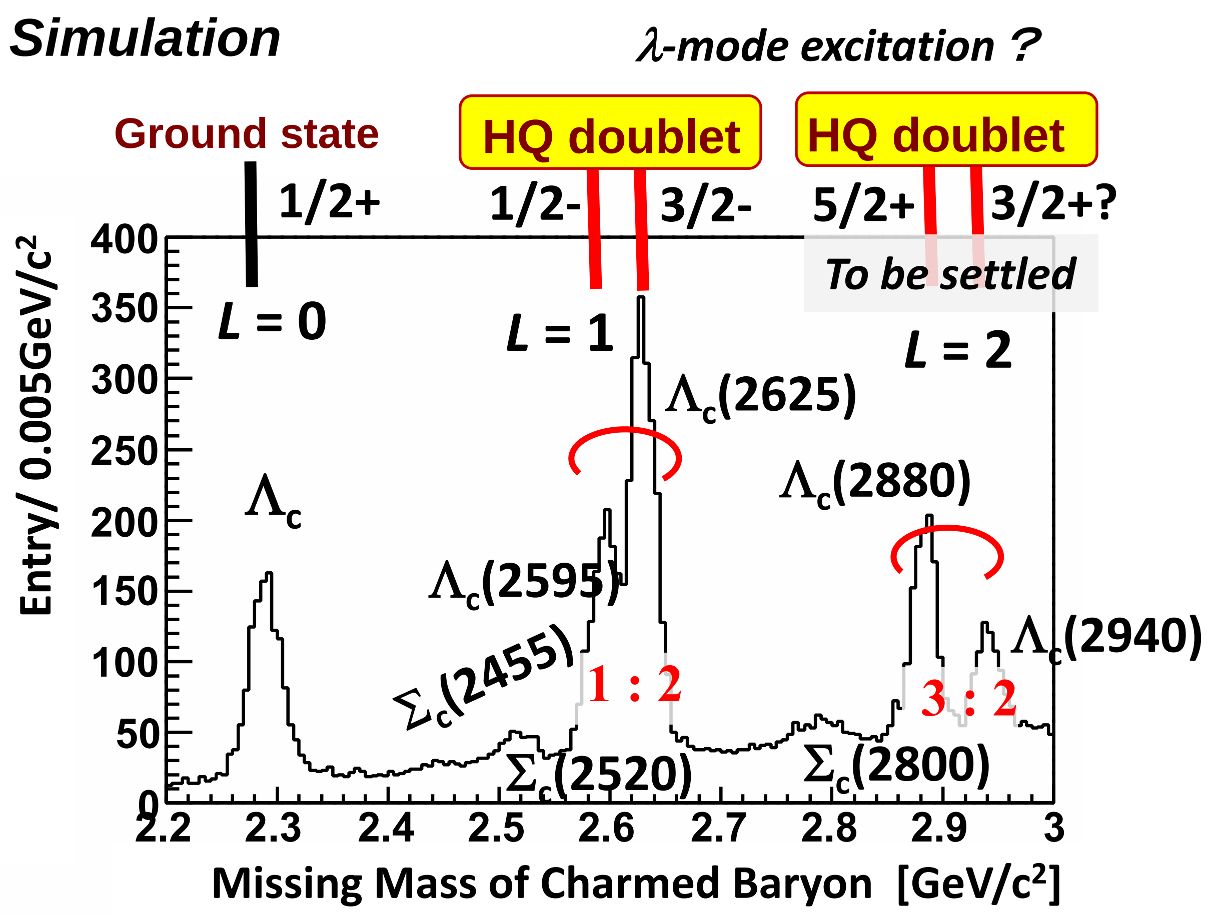
Measure D*- and Identify Y_c^{*+} in the Missing mass spectrum

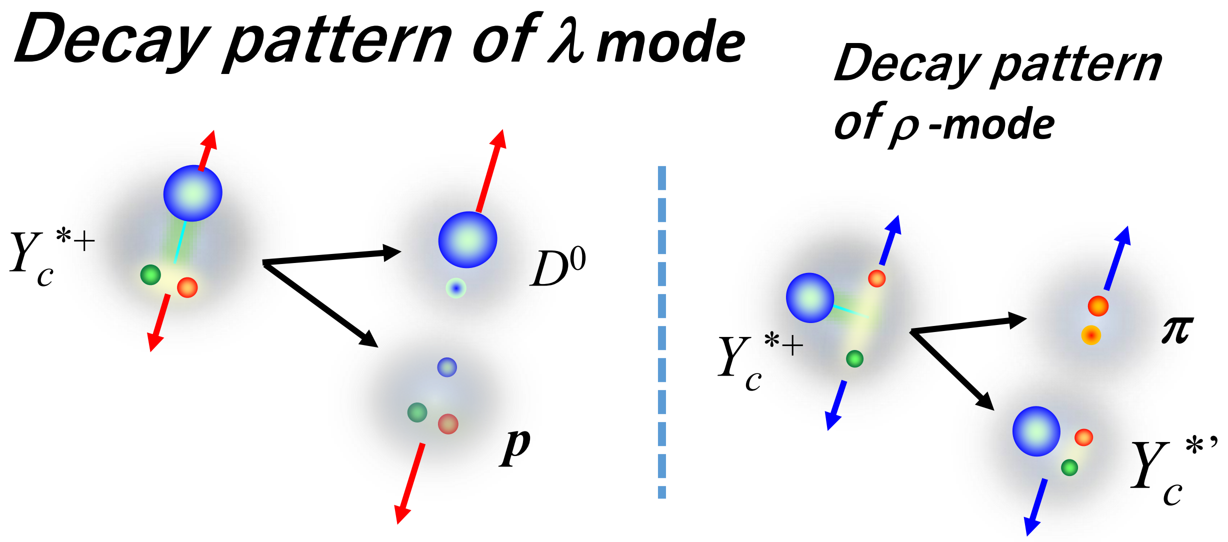
Measure Decay particles , too

Remarks

- Introducing a finite orbital angular momentum L ⇒ highly excited states
- Production ratio of the HQ doublet to be L:L+1 ⇒ Spin, Parity (J^P)
- Production and Decay measurement ⇒ Branching Ratio (partial width)

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 (J^P) is to be determined

Identify λ/ρ mode

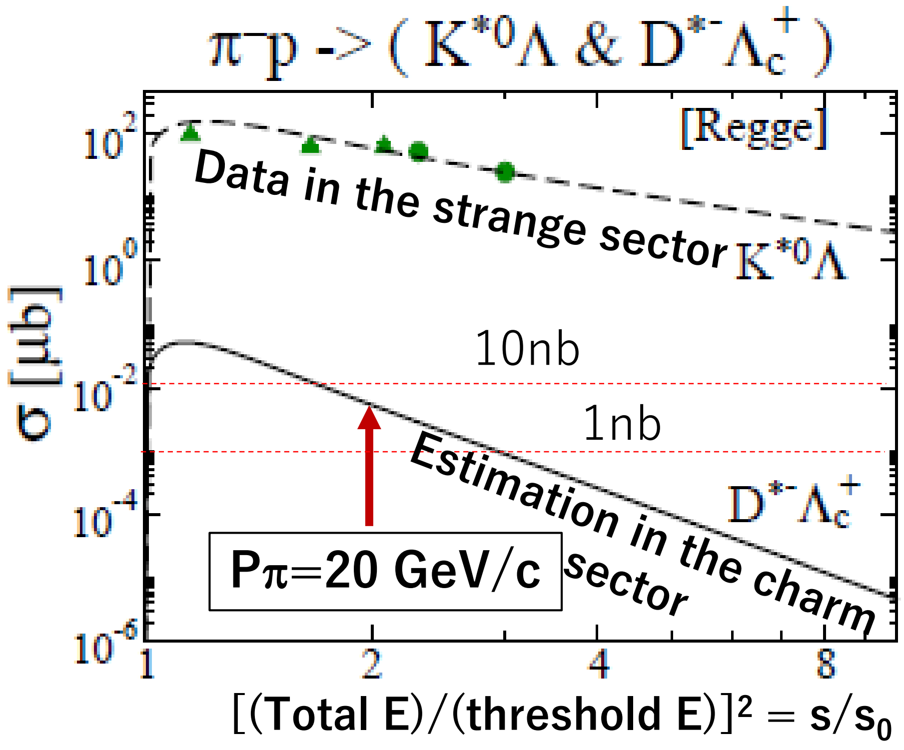
- Internal structure (wave func.)

  (*q* motion and *qq* correlation)

Production of Charmed Baryons: Theoretical Study

Reggeon Exchange Model in 2-body reaction

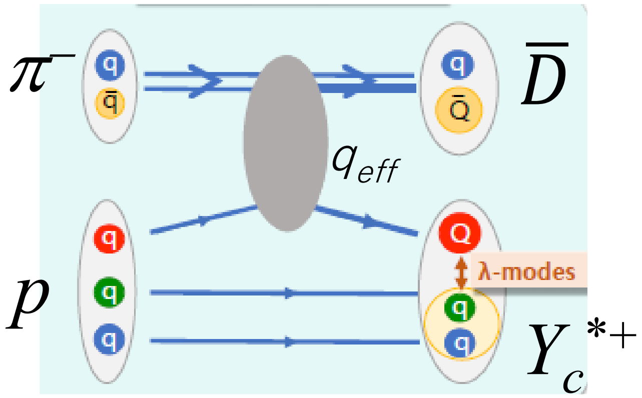
S.H. Kim, A. Hosaka, H.C. Kim, and H. Noumi PRD92 (2015) 094021



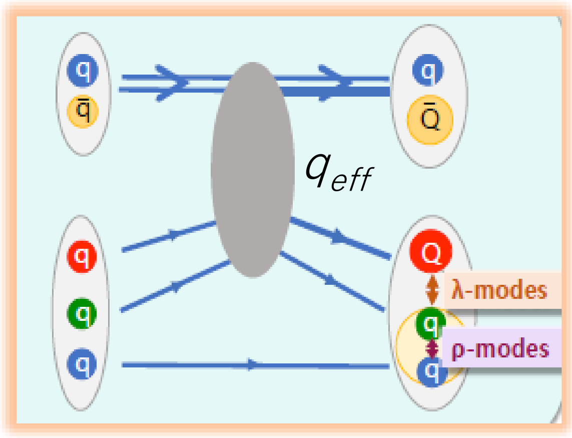
※no data available is in the charm sector.

Production rate in excited state

One-quark process



Two-quark process



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

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

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

Mom. Trans. : q_{eff}~1.4 GeV/c

α~0.4 GeV ([Baryon size]$^{-1}$)

※λ-mode states w/ finite L are populated.

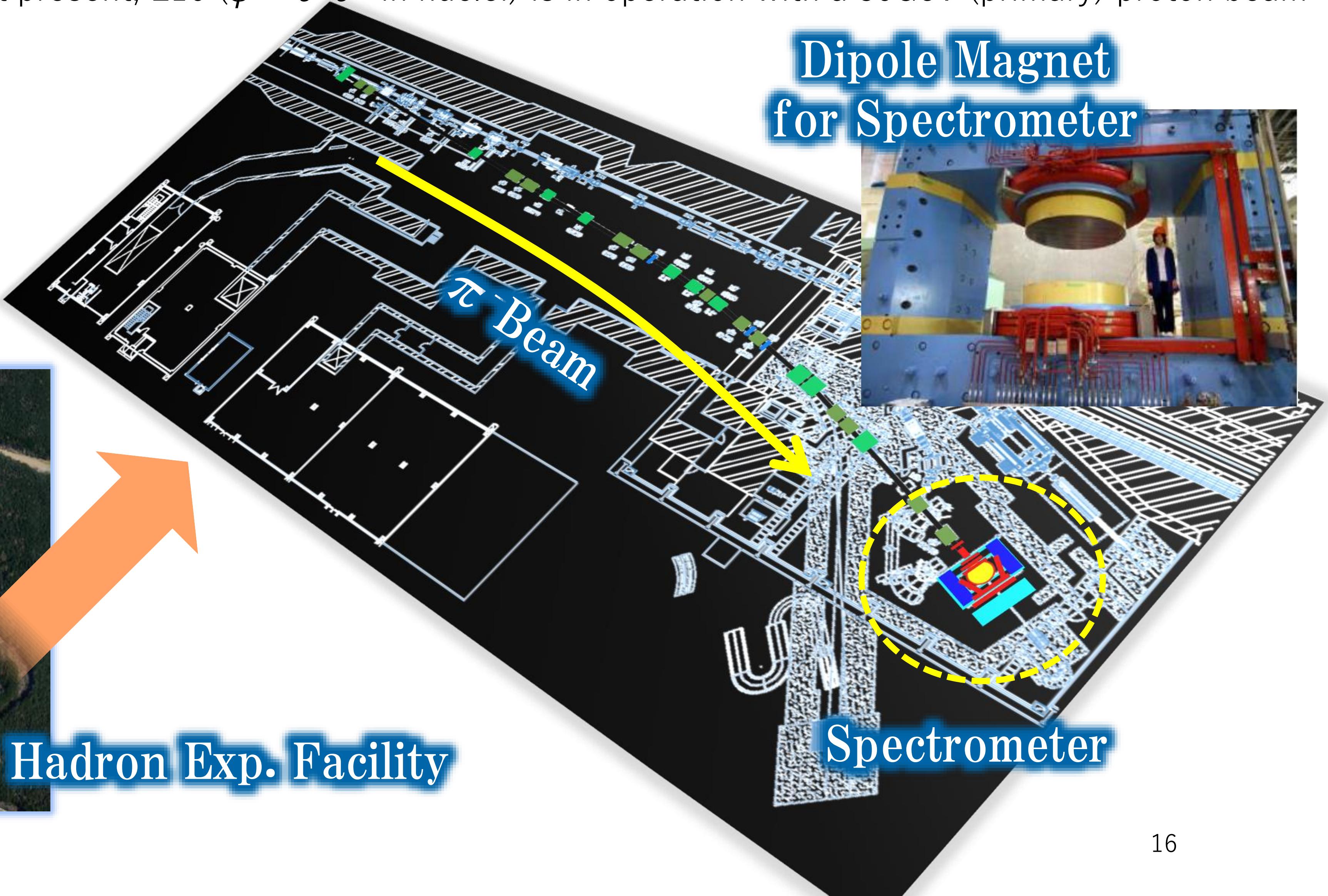
S.I. Shim, A. Hosaka, H.C. Kim, PTEP 2020, (2020) 5, 053D01

※Comparable ρ -mode excitations are expected.

Charmed Baryon Spectroscopy at J-PARC

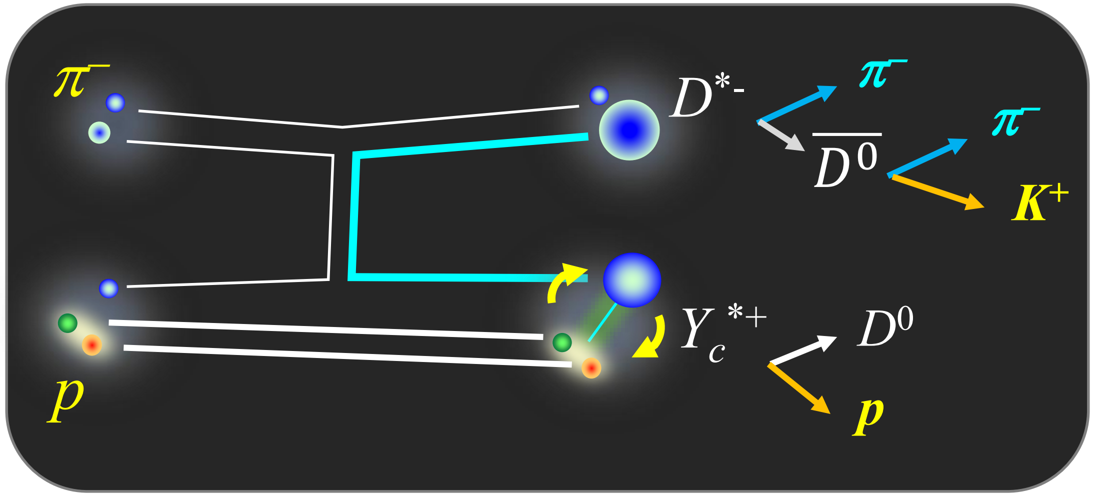
High-p Beam Line ※At present, E16 ($\phi \rightarrow e^+e^-$ in nuclei) is in operation with a 30GeV (primary) proton beam

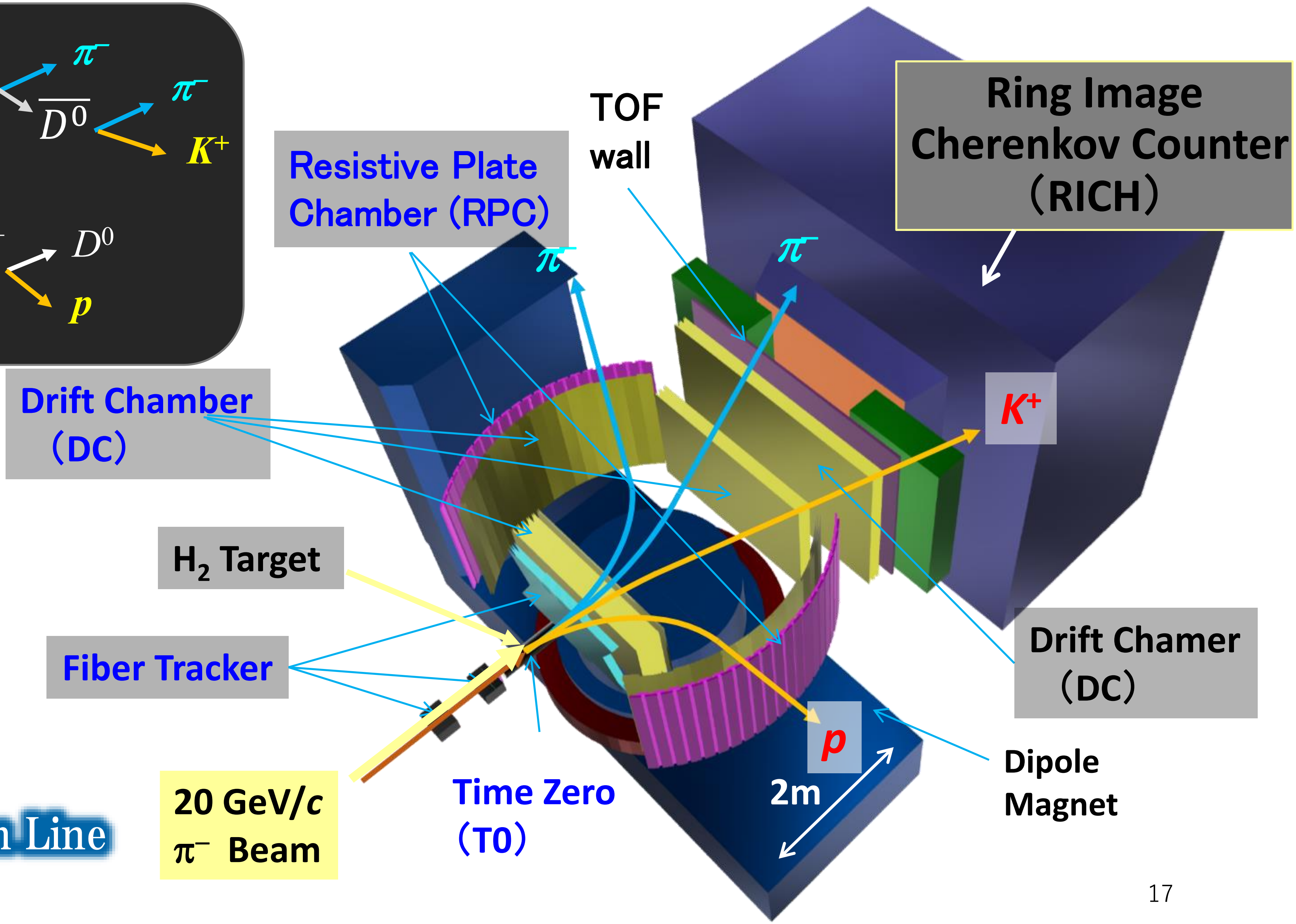
- 20 GeV/c π -
- Intensity >10^7 /s
- $\Delta p/p \sim 1/1000$



Spectrometer System

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

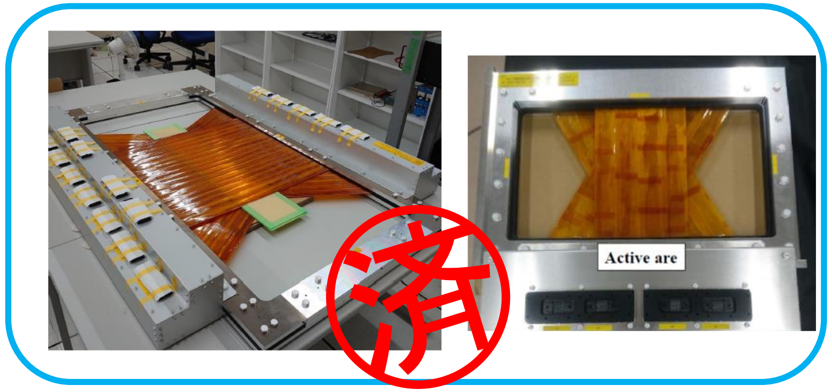




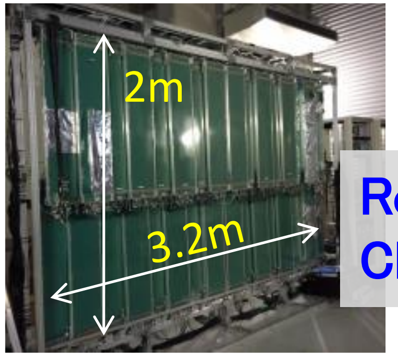
J-PARC High-p Beam Line

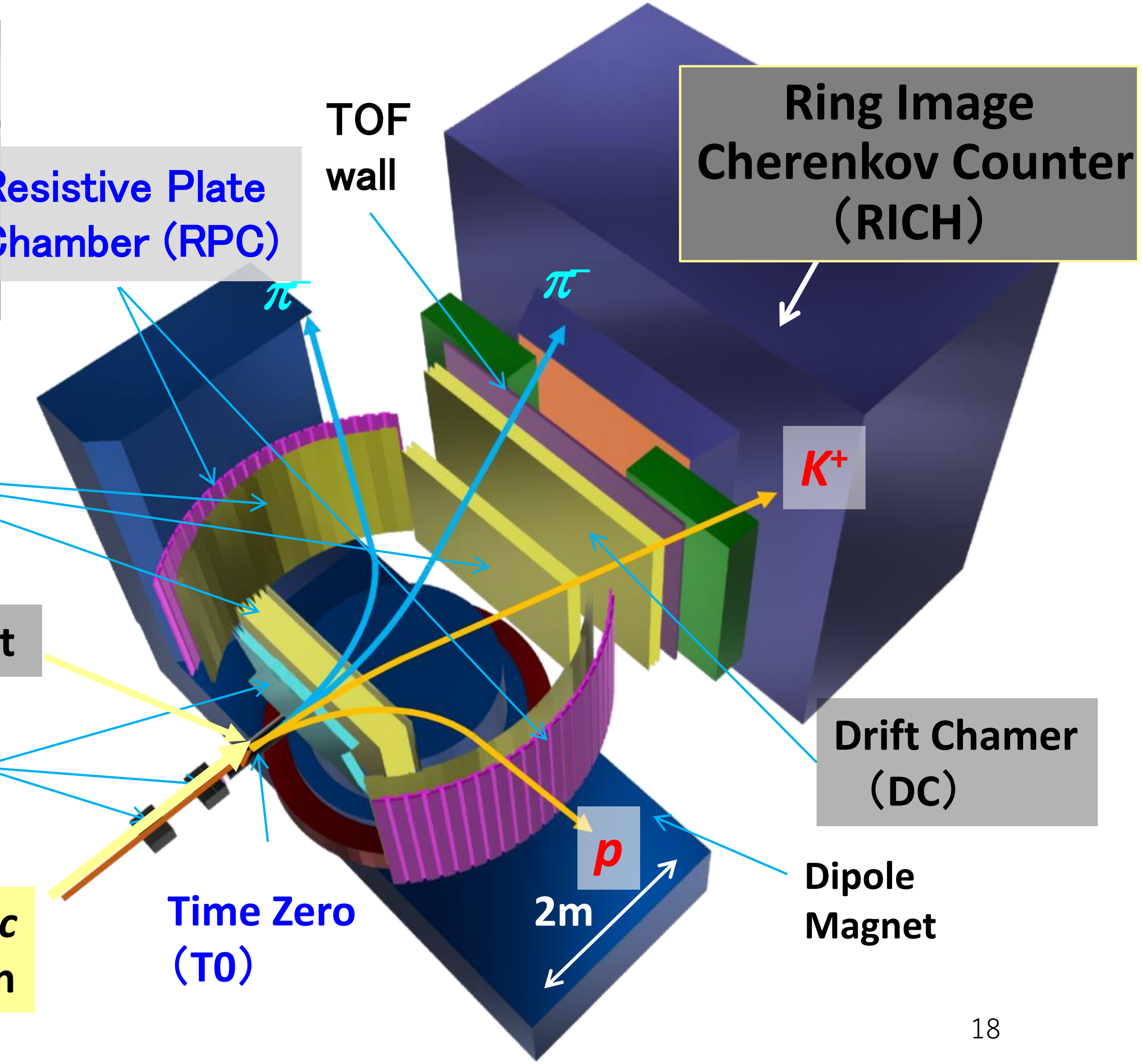
Spectrometer System

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

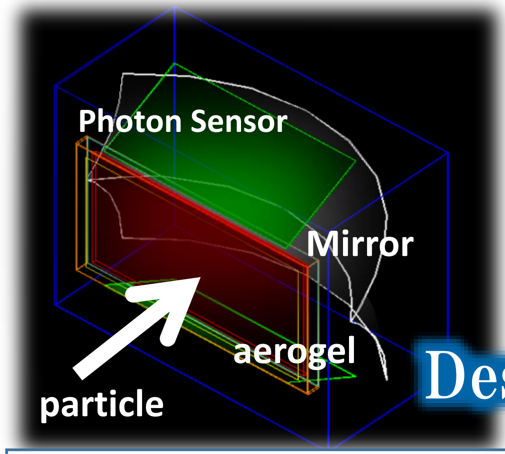




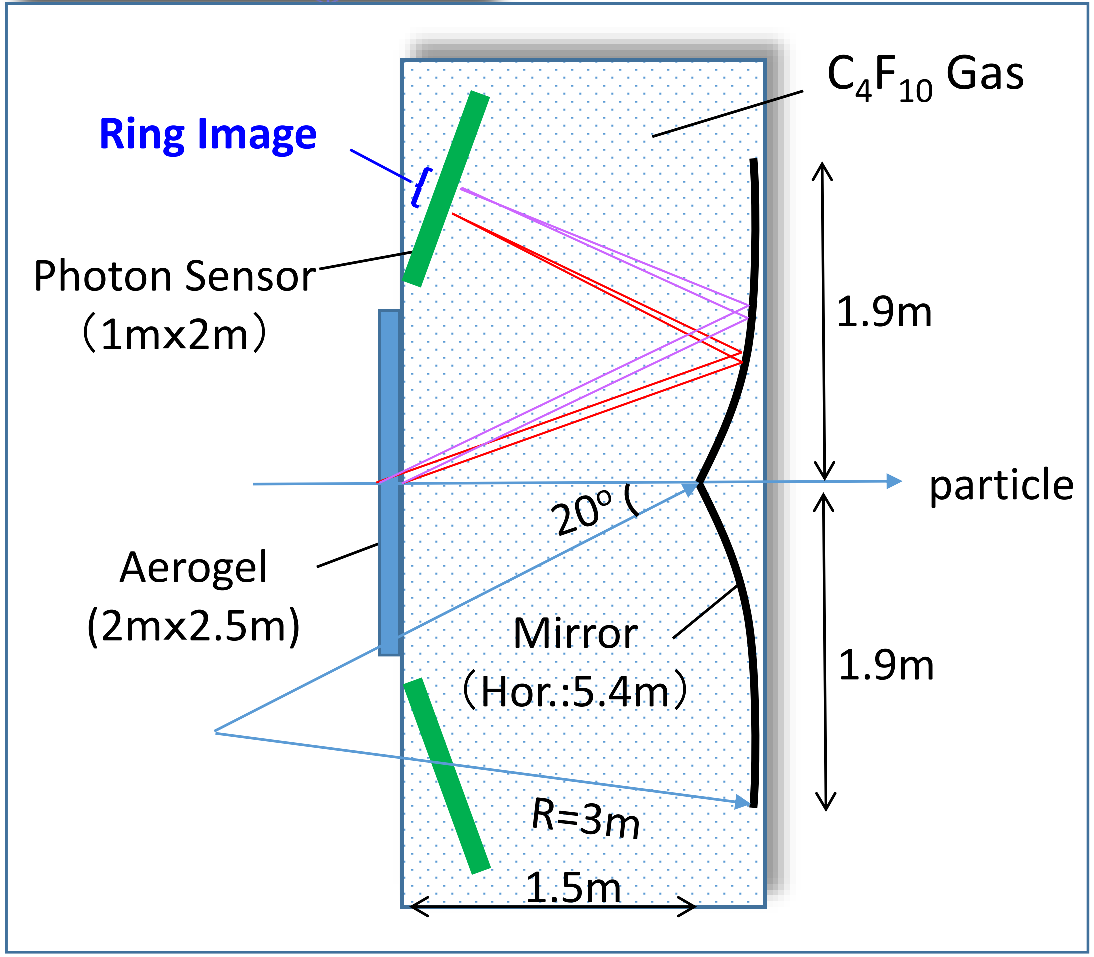
Particle Identification in a wide momentum range of 2〜16GeV/c, K-beam ID as well

Development of prototype RICH in progress

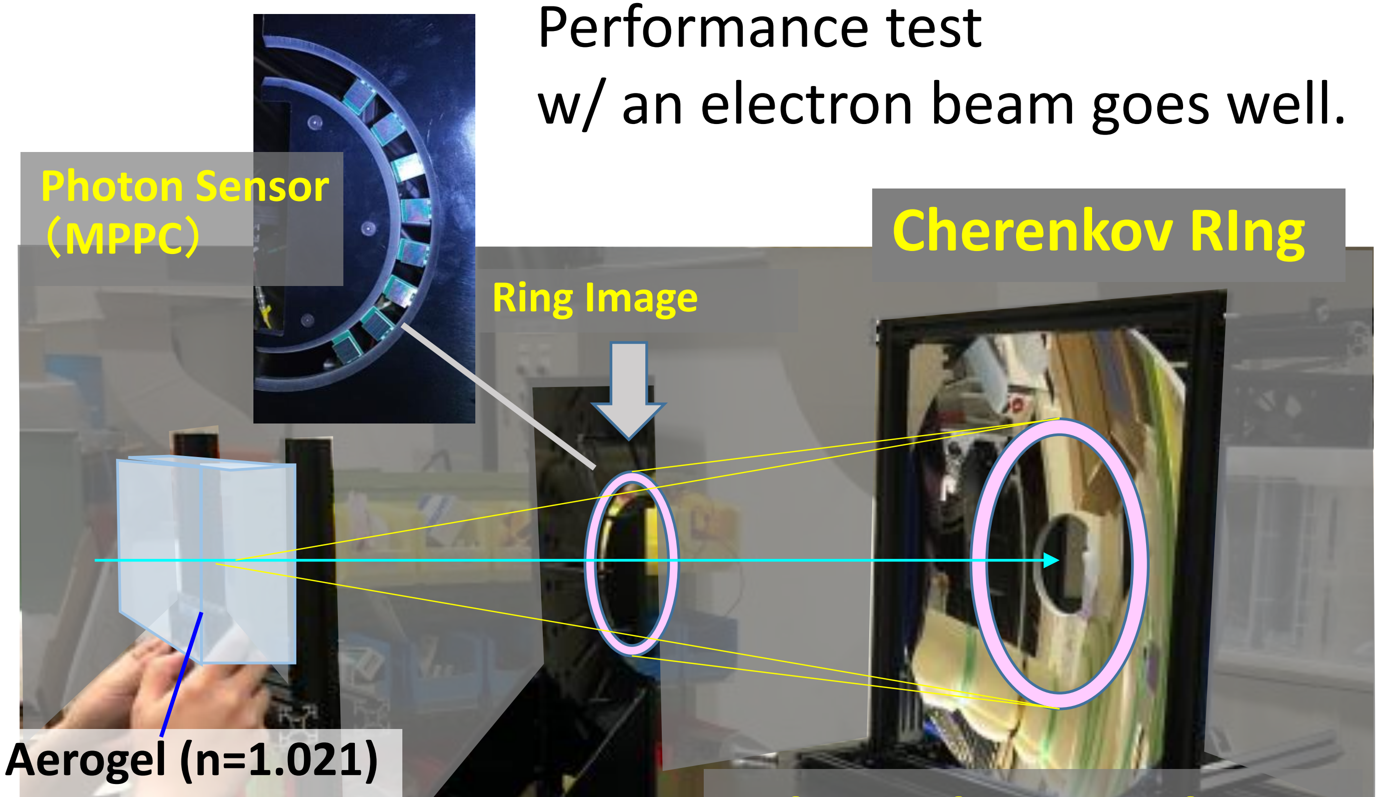
Precise Measurement of a Cherenkov radiation angle → Particle velocity

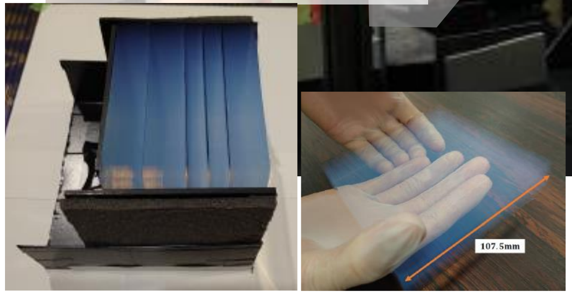


Designed RICH



Performance test
w/ an electron beam goes well.



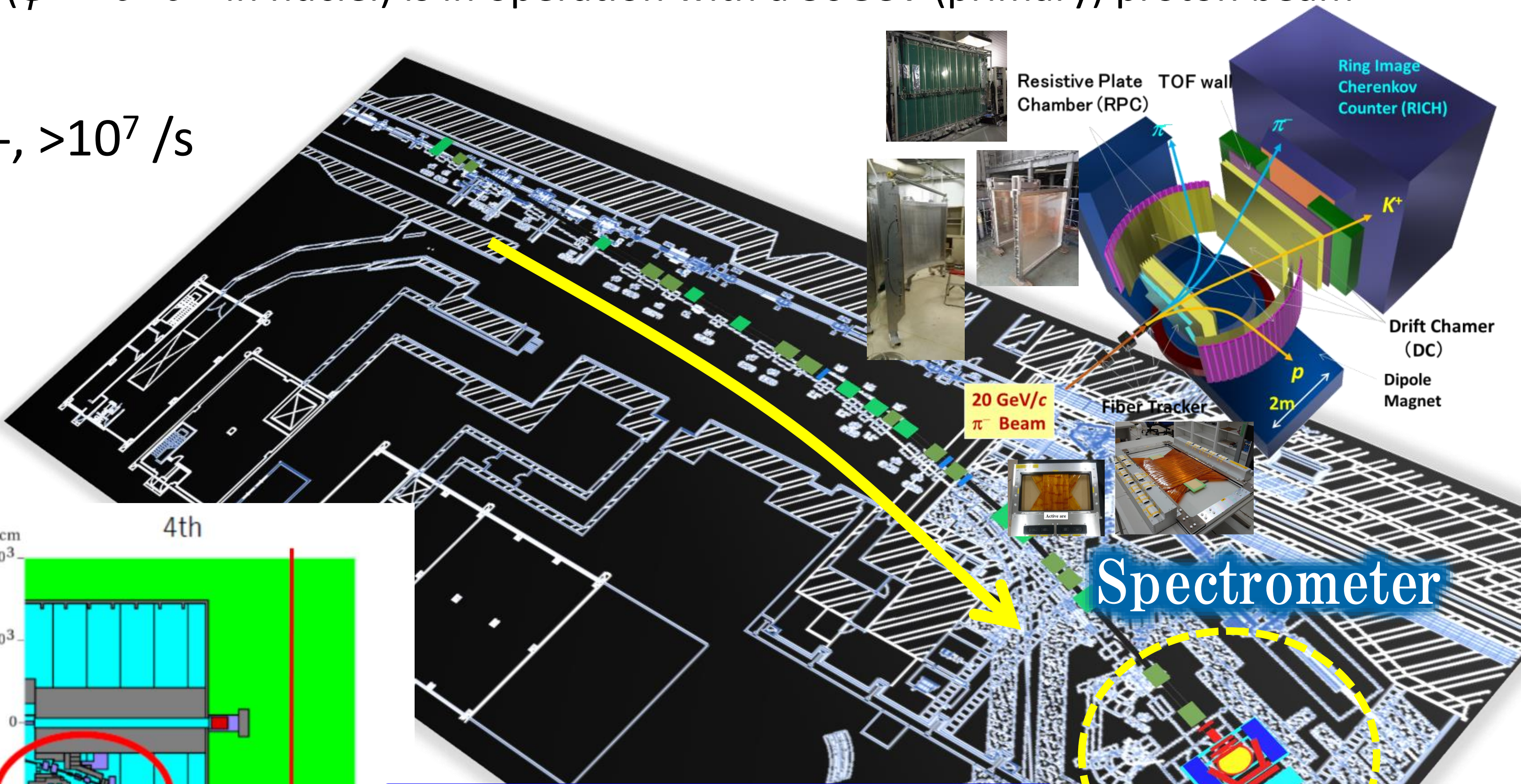


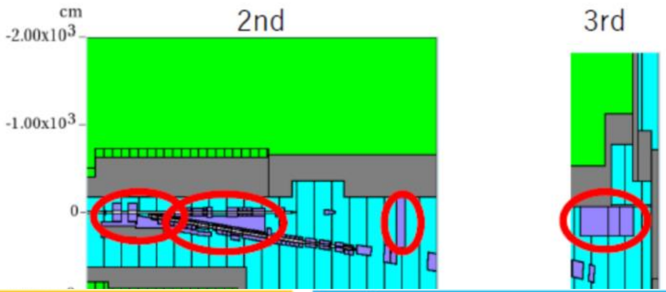
☺ angular res. 〜1.7mrad

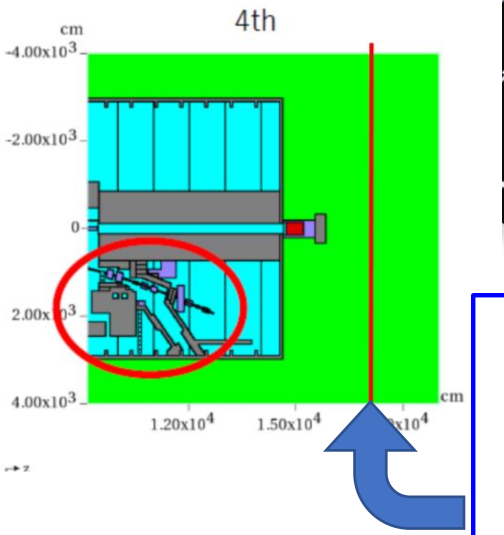
“High-p Beam Line” has taken off in a primary mode※

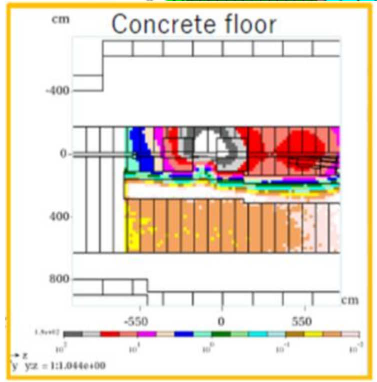
※At present, E16 ($\phi \rightarrow e^+e^-$ in nuclei) is in operation with a 30GeV (primary) proton beam

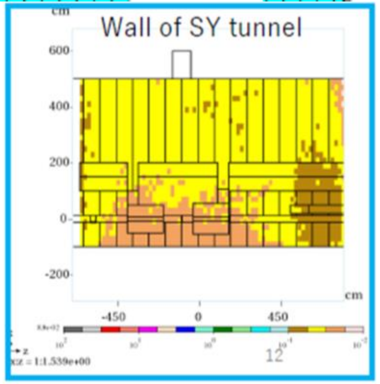
Toward “High-p 2nd”
- 15-kW loss TGT → 20 GeV/c π-, >10^7 /s
- BL Design in progress
  - Satisfy Rad. Safety regulation
  - Shielding, Air-born activity
  - Maintenance scenario
    - Residual Rad.<0.1 mSv/h

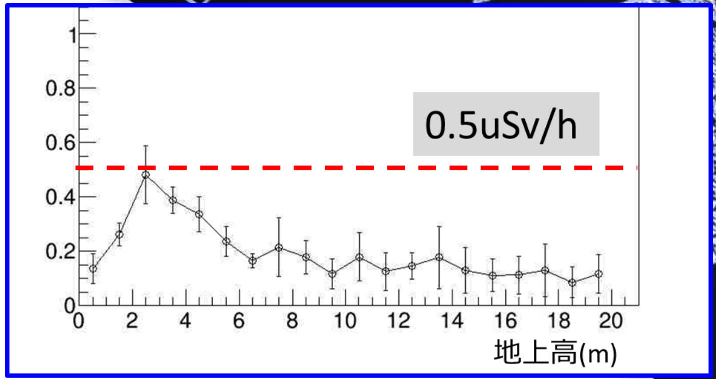






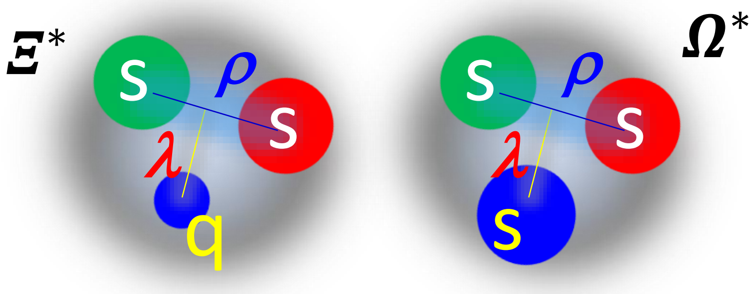


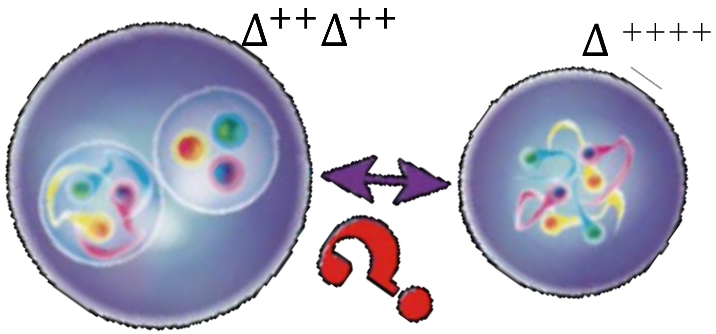


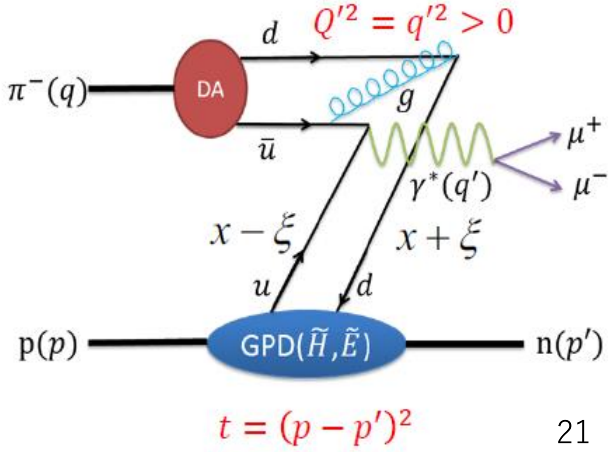


Hadron Physics at the High-p BL

- 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 (*P*-wave) Scattering for the study of high-density nuclear matter (LoI: KEK/J-PARC-PAC 2020-08)
- For Neutrino Physics
  - Hadron Production for neutrino beams



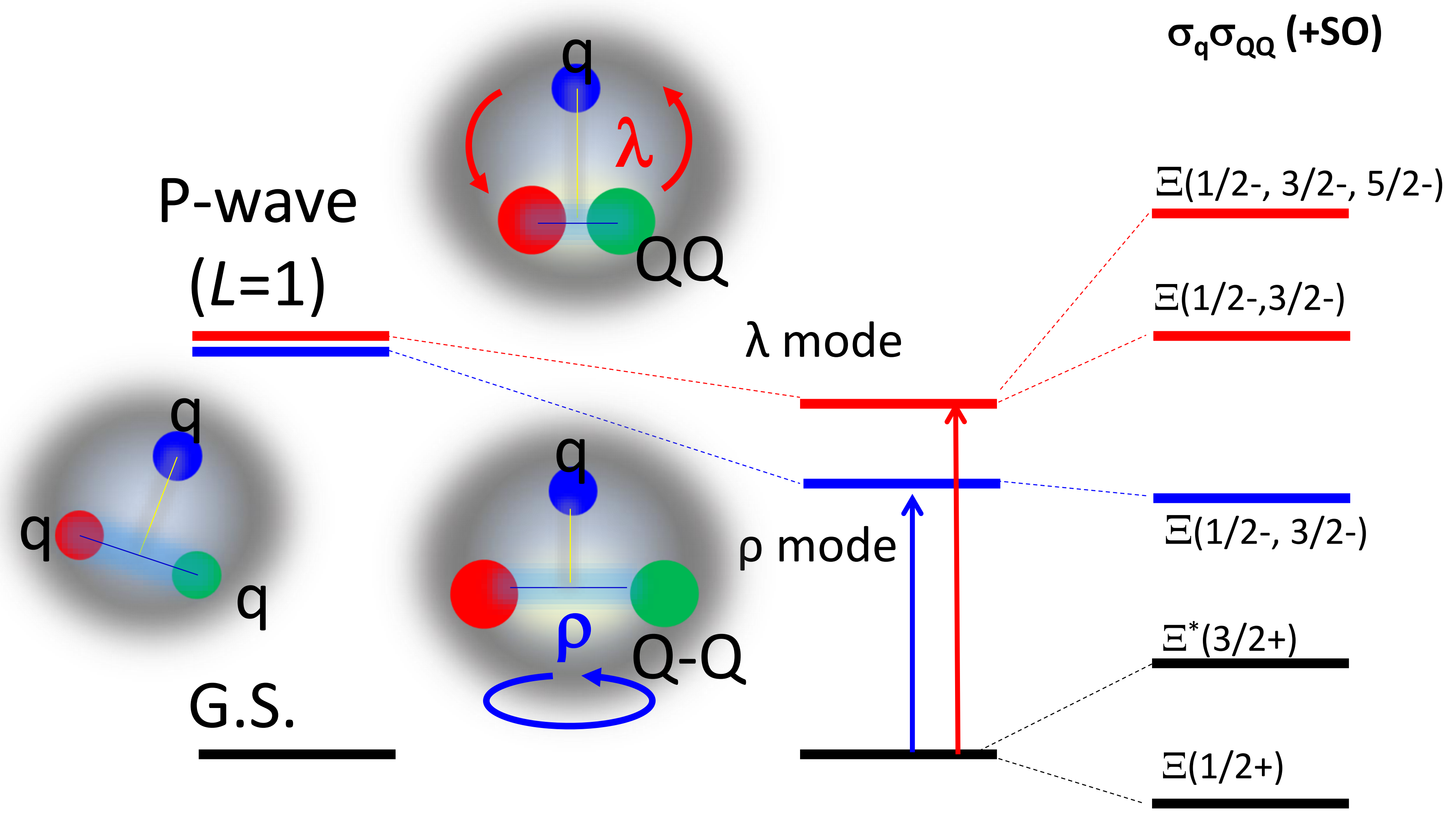




Baryon Spectroscopy at High-p 2^{nd} (π20)
-- Multi-strangeness Baryon, a bridge to K10

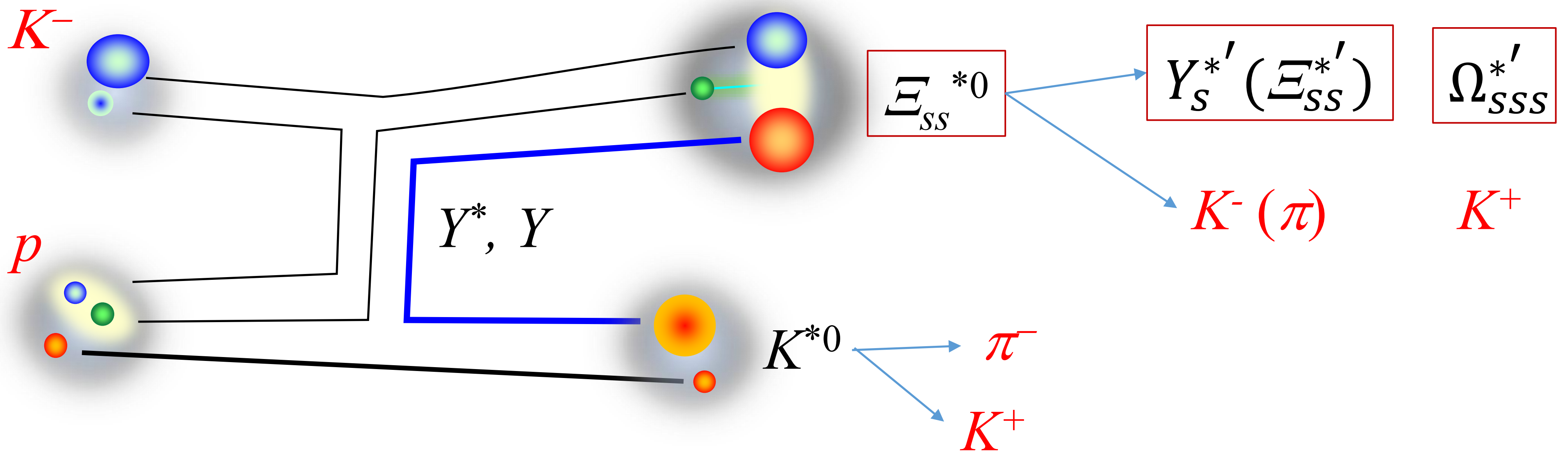
Level Structure of Double-Q baryons

- λ and ρ mode excitations interchange



Multi-Strangeness Baryon Spectroscopy Using Missing Mass Techniques

M. Naruki and K. Shirotori, LoI submitted to the 18th J-PARC PAC in May, 2014(KEK/J-PARC-PAC 2014-4)



- ✓ Production and Decay reflect [QQ] correlation
- ✓ *U-channel production may be dominant*
- ✓ *Two-quark-involved reaction →Both ρ/λ mode excitation*

Measured Ξ (PDG)

Threshold

$\Omega\bar{K}(2166)$

$\Sigma\bar{K}^*(1983)$

$\Sigma^*\bar{K}(1878)$ $\Lambda\bar{K}^*(1908)$

$\Sigma\bar{K}(1685)$

$\Xi^*\pi(1665)$

$\Lambda\bar{K}(1610)$

$\Xi\pi(1450)$

	JP	rating	Width [MeV]	→Ξπ [%]	→ΛK [%]	→ΣK [%]	
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	Why ΣK?
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			

- ✓ *Most of spins/parities have NOT been determined yet.*
- ✓ *Why the Ξ* -> $\pi\Xi$* decay seems to be suppressed?
  - ✓ expected to reflect QQq configuration.

Ξ Baryon Spectroscopy w/ the High-p Secondary Beam

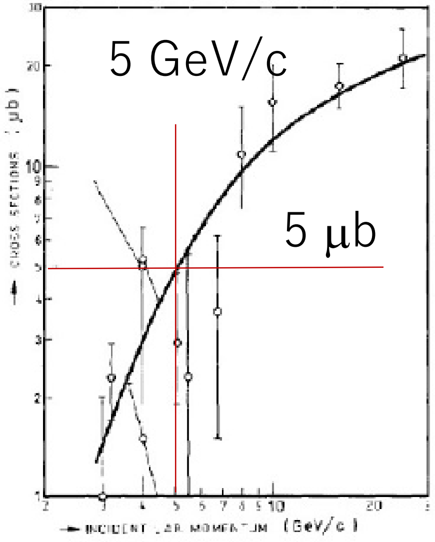
LoI submitted by M. Naruki and K. Shirotori

- Sizable yields are expected for a month.

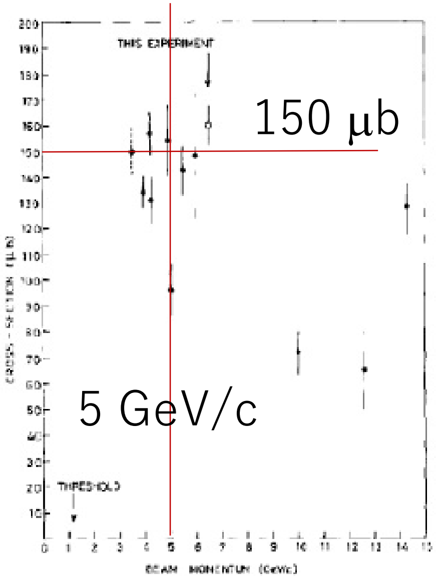
Reaction	σ [μb]	Beam [/spill]	B.R.	Acceptance [%]	Y_{Total}	$Y_{Decay/bin}$
$K^-p \to \Xi^{*-}K^+$	1.0	10^6	1.0	50	3.1×10^5	2500
$K^-p \to \Xi^{*-}K^{*+}$	1.0	10^6	0.23	50	0.7×10^5	580
$K^-p \to \Xi^{*0}K^{*0}$	1.0	10^6	0.67	50	2.1×10^5	1700
$\pi^-p \to \Xi^{*-}K^{*0}K^+$	0.1	10^7	0.67	50	3.1×10^5	2500

- Past exp.

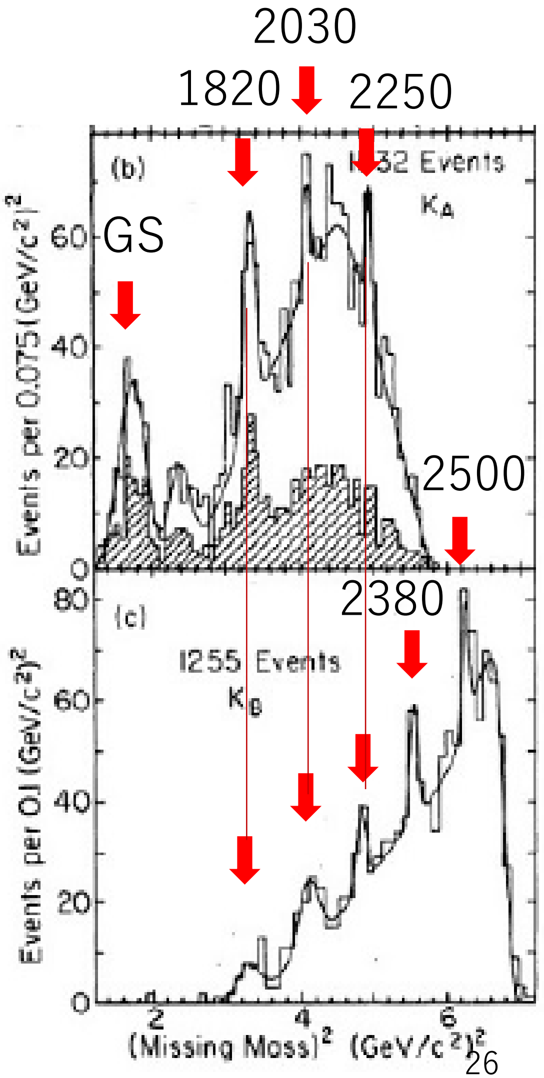
Inclusive Ξ prod in πp



Inclusive Ξ prod. in K$^-$p



Kaon beams: productive in Ξ*



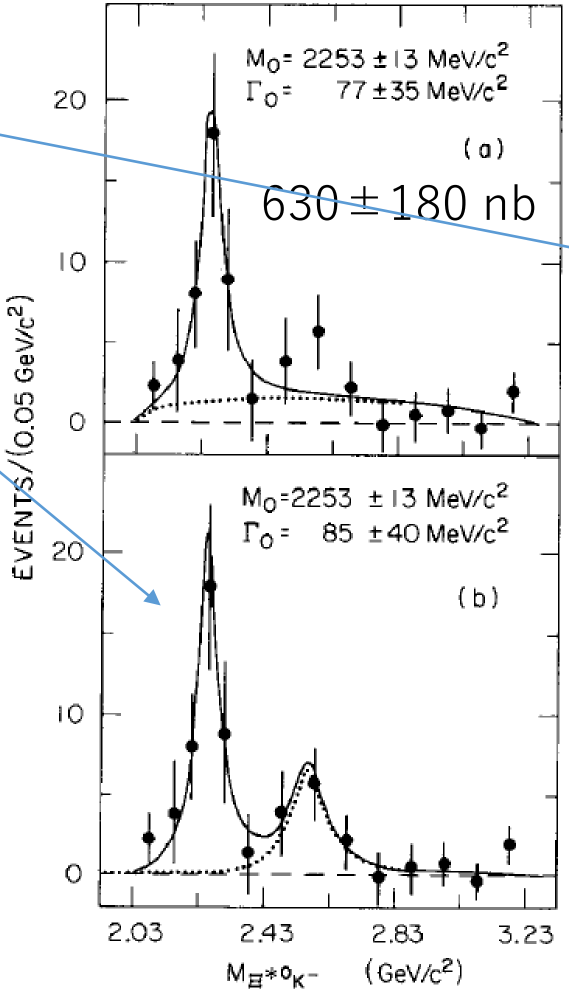
p(K$^-$,K$^+$) spectra
C.M. Jenkins et al., PRL51, 951(1983)

Omega*: Productive Kaon Beams

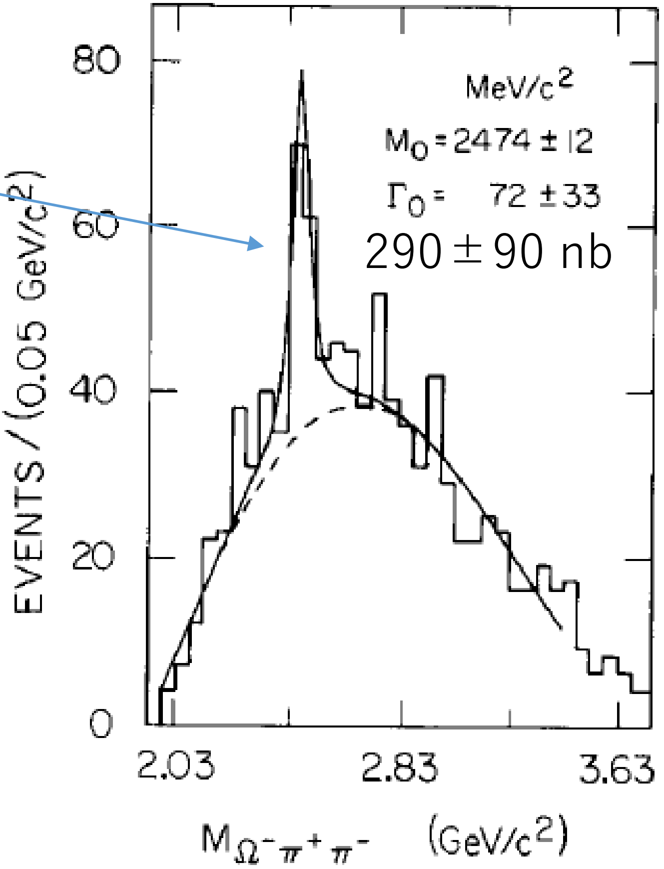
	J^P	
Ω(2470)	??	**
Ω(2380)	??	**
Ω(2250)	??	***
Ω(2012)	?-	***
Ω(GS)	3/2+	****

Pilot Exp. for Omega*
at High-p 2nd (π20)

PLB194,574(1987)
11 GeV/c K-



PLB215,799(1989)
11 GeV/c K-



Measured Ω (PDG)

Threshold

ΞK*- 2109

Ξ0*K- 2024

Ξ0K-π0 1956

Ωπ0π0 1942

Ξ0K- 1811

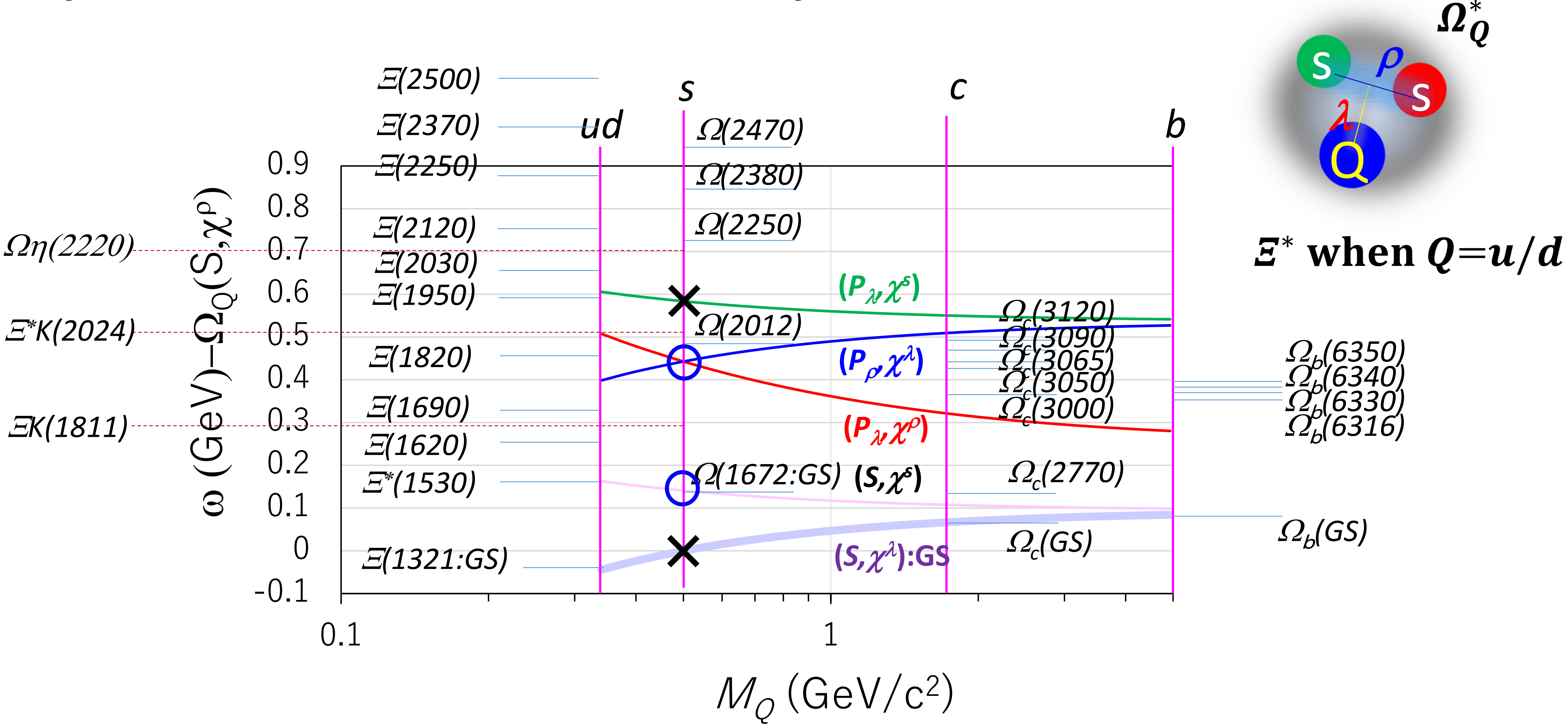
(Ωπ0 1807)

	JP	rating	Width [MeV]	→ΞK (1)	→Ξ*K (2)	→ΞK* (3)	→ΞKπ (4)	→Ωππ (5)	
Ω(2470)	??	2*	72+-33					seen	LASS (113MK-,11GeV/c) (290+-90)/(5) nb
Ω(2380)	??	2*	26+-23		<0.44 to (4)	0.5+-0.3 to (4)			Xi Beam
Ω(2250)	??	3*	55+-18		0.7+-0.2 to (4)		Seen		Xi Beam LASS (113MK-, 11GeV/c) (630+-180)/(2) nb
Ω(2012)	?-	3*	$6.4^{+2.5}_{-2.0}$ +-1.6	1.2+-0.3 (=X0/X-)	<0.119 /(1)				->Ξ*K dominant if Ξ*K mol?
Ω(1672)	3/2+	4*	-						

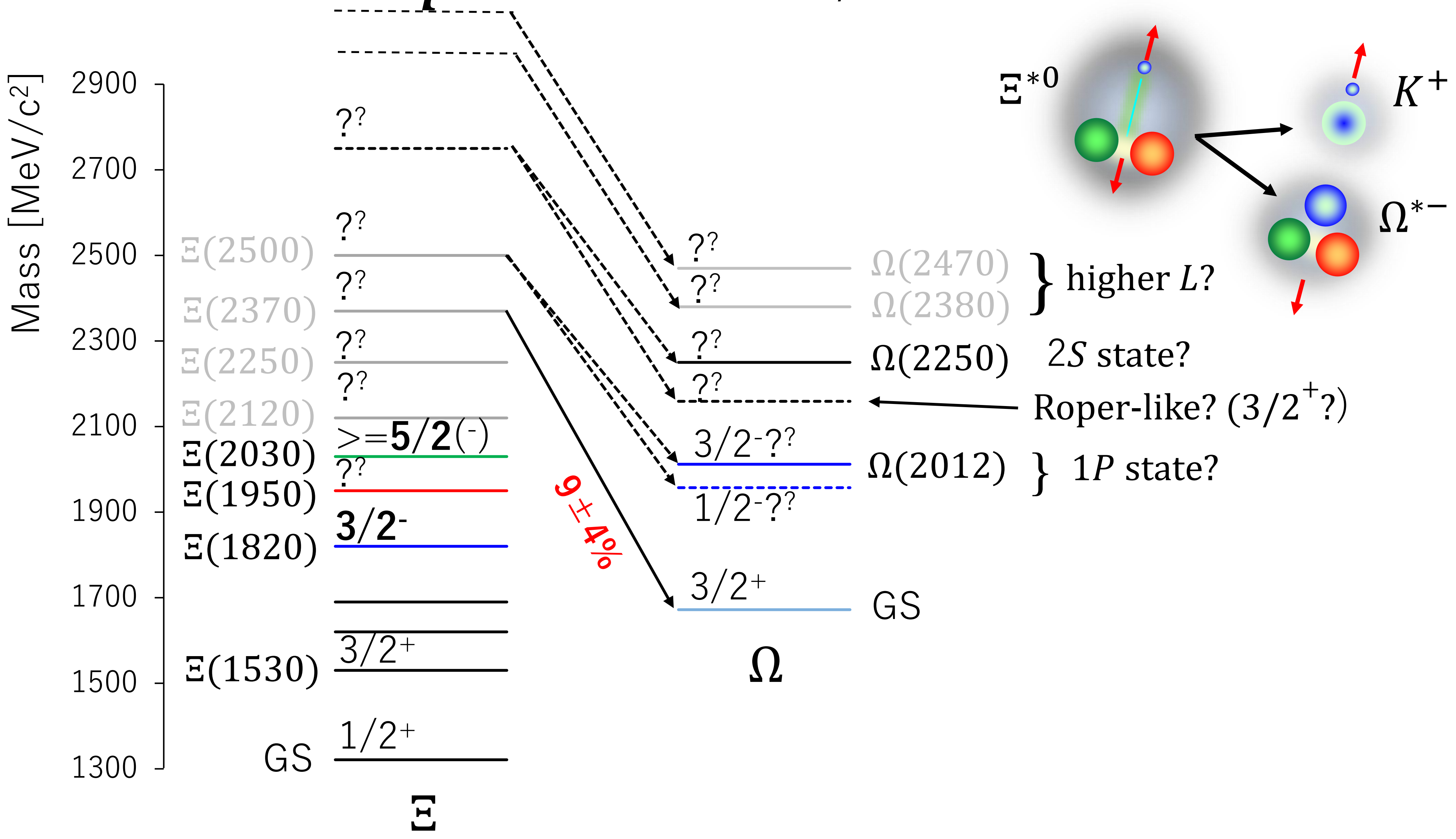
✓*Most of spins/parities/decay branches have yet to be determined.*

✓*What the production Ξ* -> Ω*K and Ω* decay modes tell us Ω*'s internal structure*

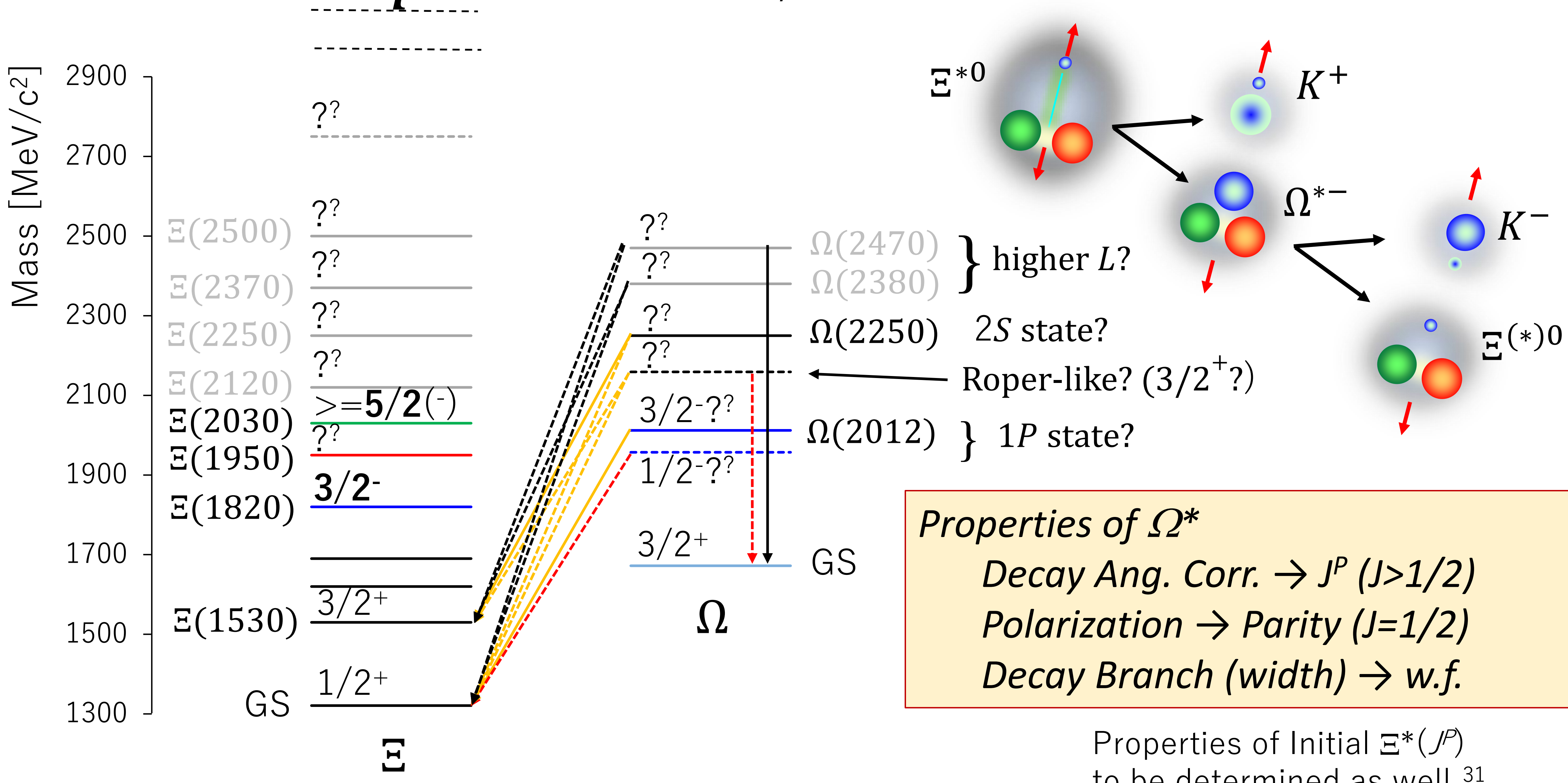
Systematics of Qss Baryons – Ξ and Ω –



$K^- p \rightarrow K^{*0}\Xi^{*0}, \quad \Xi^{*0} \rightarrow \Omega^{*-}K^+$



$$K^- p \to K^{*0}\Xi^{*0},\quad \Xi^{*0} \to \Omega^{*-}K^+$$



*Properties of Ω**

Decay Ang. Corr. → J^P (J>1/2)

Polarization → Parity (J=1/2)

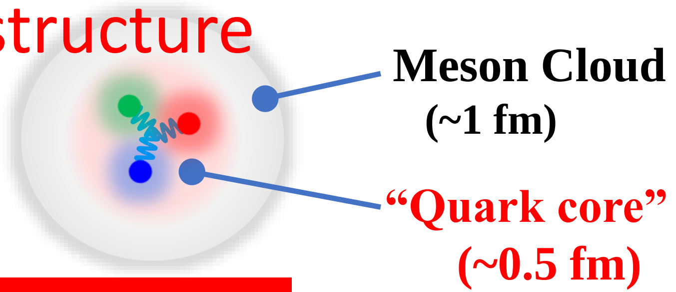
Decay Branch (width) → w.f.

Properties of Initial $\Xi^*(J^P)$ to be determined as well

In Summary…

How quarks build hadrons?

Dynamics of non-trivial QCD vacuum in baryon structure

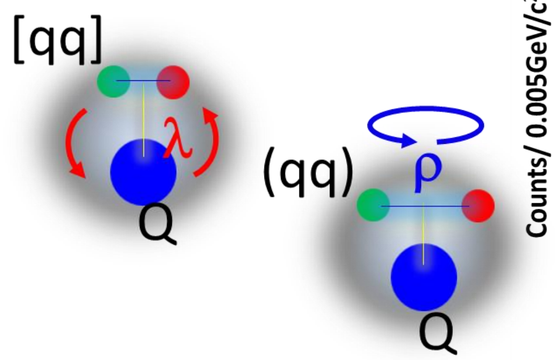


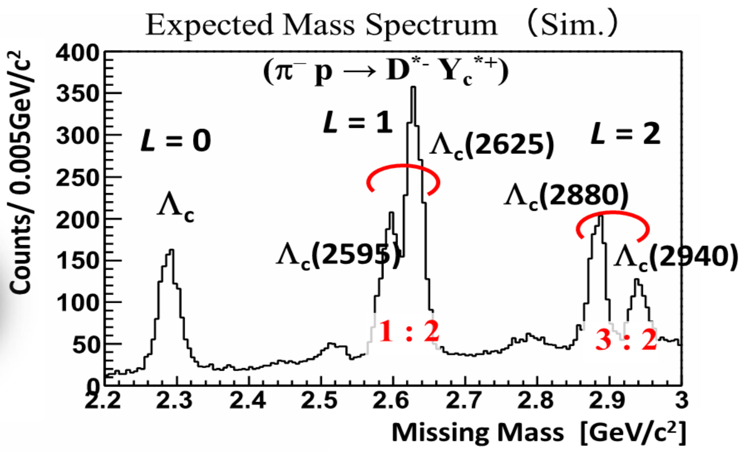
※Chiral condensate $\langle \bar{q}q \rangle \neq 0$, $U_A(1)$ anomaly
⇒ Constituent q and NG boson (effective DoF).

s- and c-baryon spectroscopy: q correlation and spin-dep. force

- Charmed Baryon (High-p)

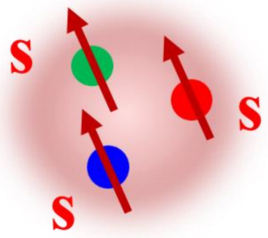
Disentangle the diquark correlation
→ λ/ρ mode assignment
→ $U_A(1)$ anomaly: $[qq](0^+) \leftrightarrow (qq)(0^-)$

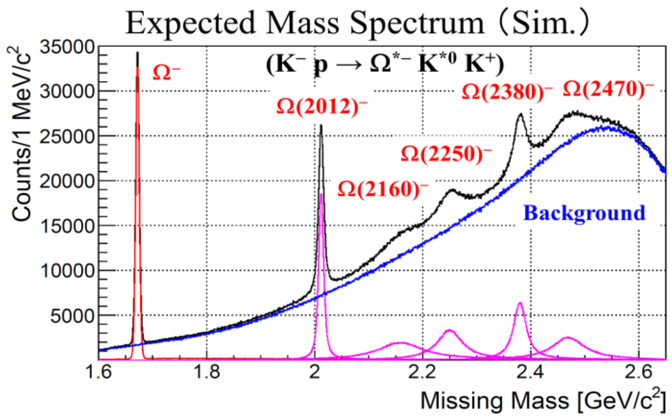




- Ω^* (sss) Baryon (K10)

Single-flavored (Flavor-symmetric) system
Free from pion cloud
→Spin-orbit Force (One Gluon Exchange)
→Roper-like (2S, 3/2+) states("quark core" size)





How quarks build hadrons?

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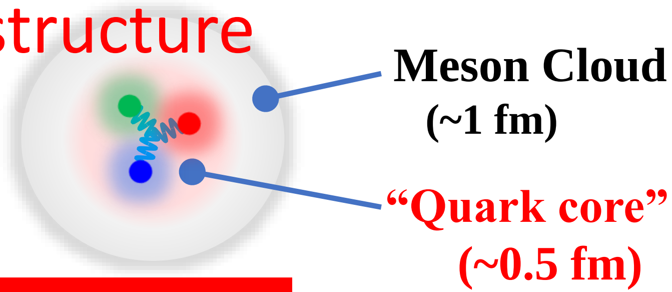

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