A series of “Extended Hadron Experimental Facility at J-PARC”

- 10/NOV/2021

  “Spectroscopy of charmed and strange baryons at the π20 and K10 beam lines” by Hiroyuki Noumi (RCNP/IPNS)

- 17/NOV/2021

  “Λp scattering experiment with a polarized Λ beam at the K1.1 beam line” by Koji Miwa (Tohoku U.)

- 24/NOV/2021

  “Precise spectroscopy of Lambda hypernuclei at High Intensity High Resolution beamline” by Satoshi N. Nakamura (Tohoku U.)

arXiv:2110.04462

Extension of the J-PARC Hadron Experimental Facility

- Third White Paper -

Taskforce on the extension of the Hadron Experimental Facility,

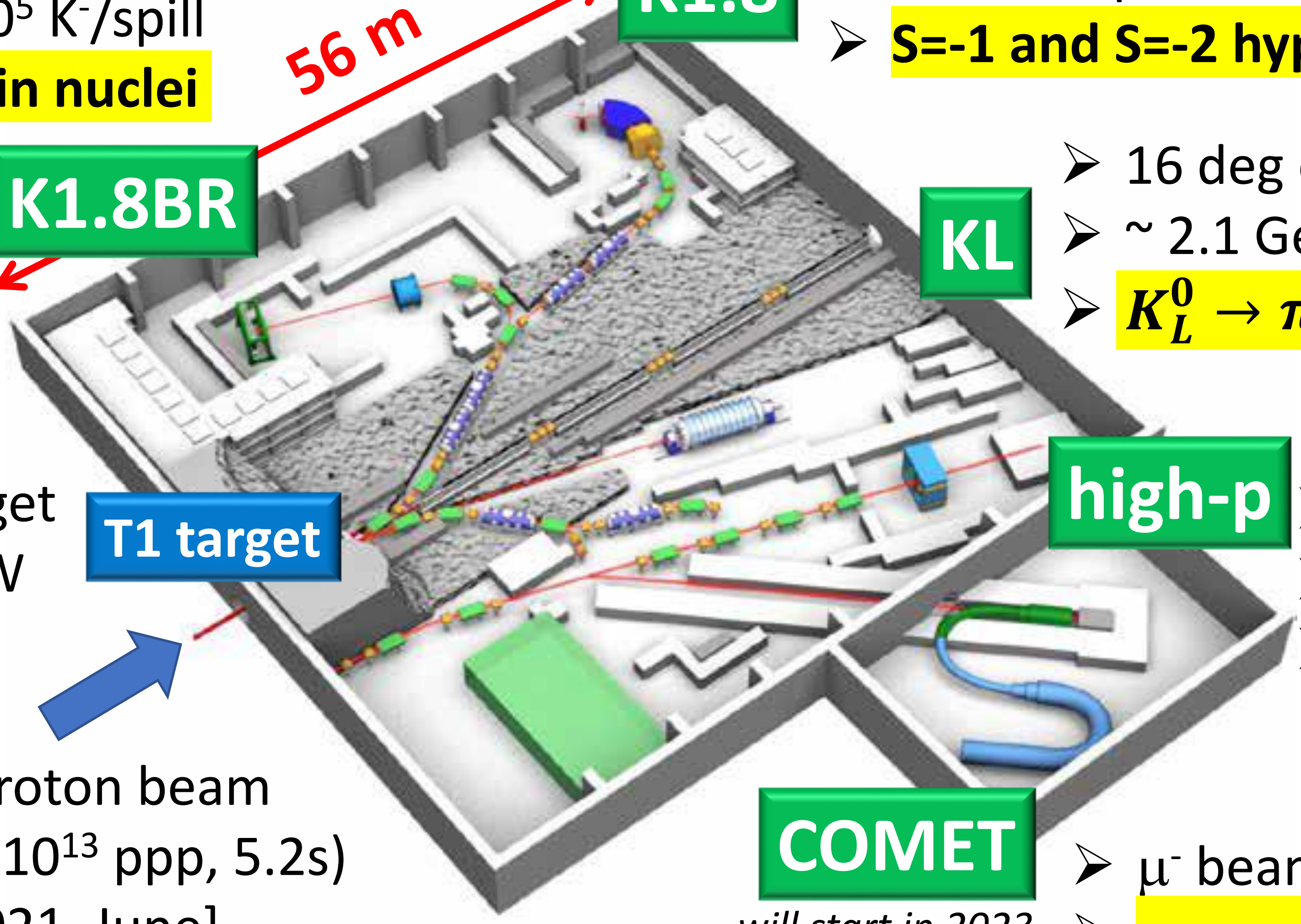
Contents


J-PARC
Linac
RCS
Pacific Ocean
ν
MLF
Main Ring
Hadron Exp. Facility
Extension

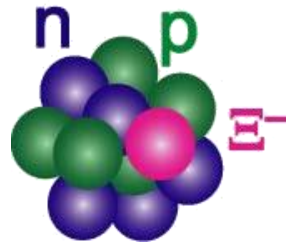
West

East

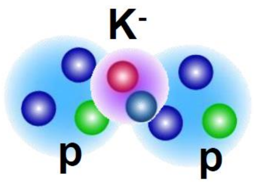
Present Hadron Experimental Facility (HEF)



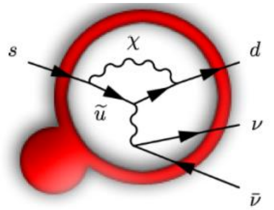
K1.8
- < 2.0 GeV/c
- ~ 10^6 K^-/spill
- **S=-1 and S=-2 hypernuclei**



K1.8BR
- < 1.1 GeV/c
- ~ 5×10^5 K^-/spill
- **Kaon in nuclei**

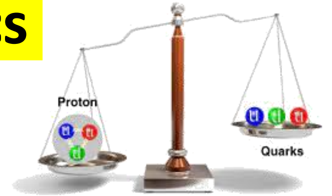


KL
- 16 deg extraction
- ~ 2.1 GeV/c ~ 10^7 K^0_L/spill
- $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$



high-p

launched in 2020
- 30 GeV proton ~ 10^{10}
- < 31 GeV/c unsepa. π ~ 10^7
- **Hadron physics**



T1 target
- Au Target
- < 95 kW

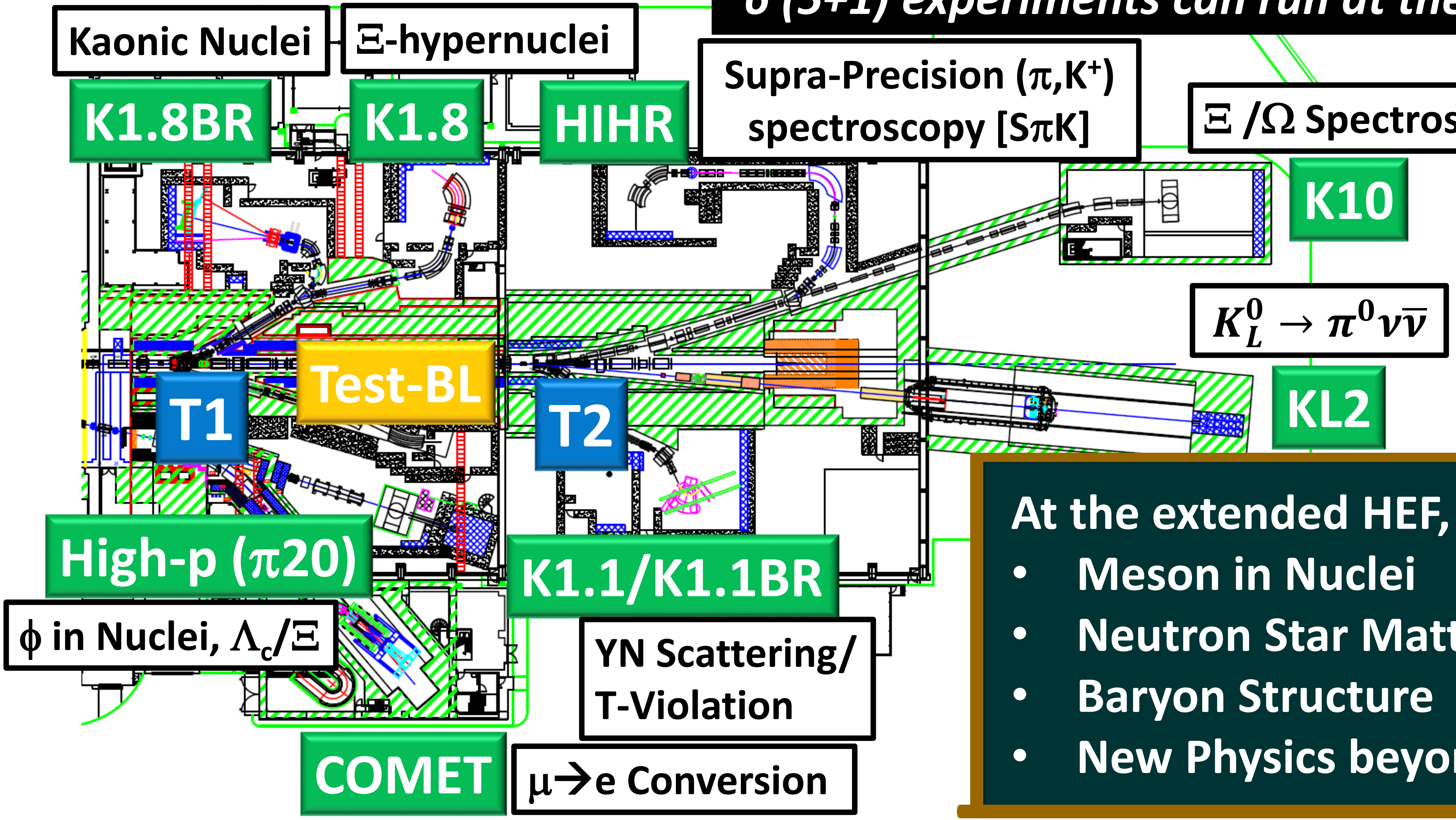
- 30 GeV proton beam
- 65kW (7×10^{13} ppp, 5.2s)
  [as of 2021, June]

COMET

will start in 2023
- μ^- beam
- **μ-e conversion**

Extend Physics Capability

6 (5+1) experiments can run at the same time



At the extended HEF, we attack:

- Meson in Nuclei
- Neutron Star Matter
- Baryon Structure
- New Physics beyond the SM

Origin & Evolution of Matter

Matter in Extreme Conditions

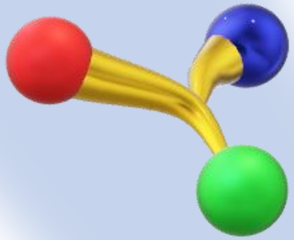
hyperon puzzle in neutron stars

flavor symmetry breaking
hadron interaction
formation of a nucleus

Hypernuclei spectroscopy
YN scattering

Matter Evolution

fundamental structure of matter



chiral symmetry breaking
quark interaction

Hadron spectroscopy
Meson in nuclei

Birth of Matter

matter dominated universe

CP symmetry violation
weak interaction

Kaon decays

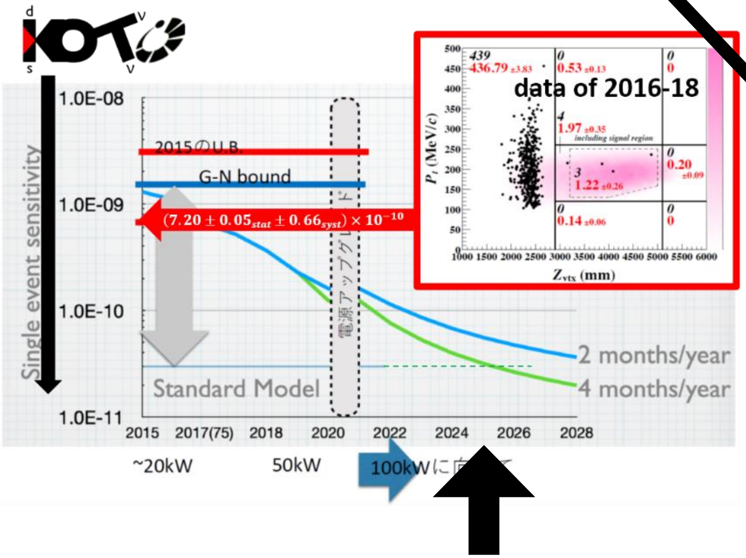
Toward New Physics

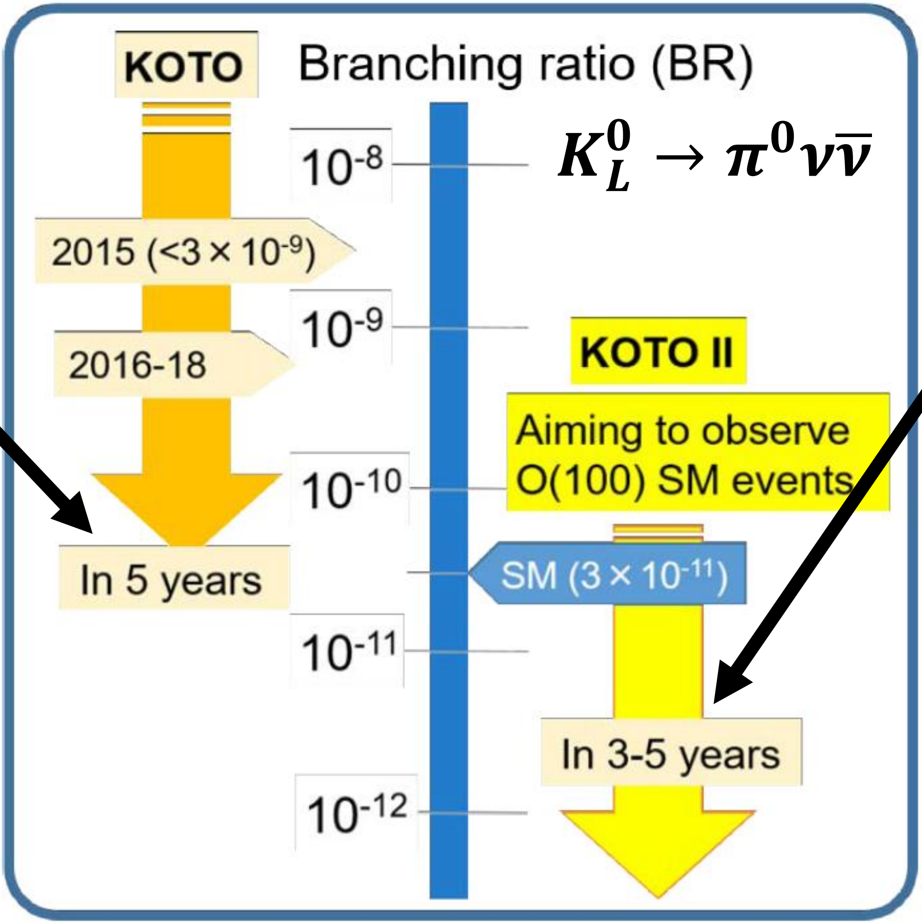
- So far, no evidence of new physics beyond the SM from direct searches
- **Flavor physics in intensity frontier** plays an important role more and more

@ present HEF

KOTO:

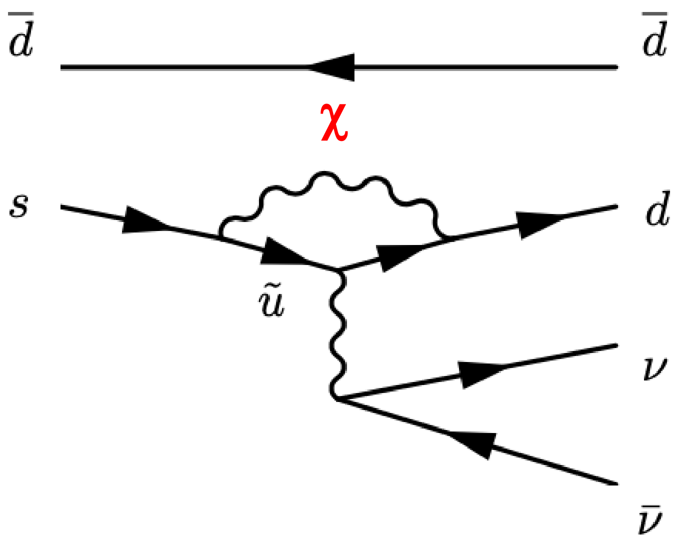
- Will reach the sensitivity of <$O(10^{-10})$ around FY2025





KOTO Step2:

- Will explore the region beyond the SM



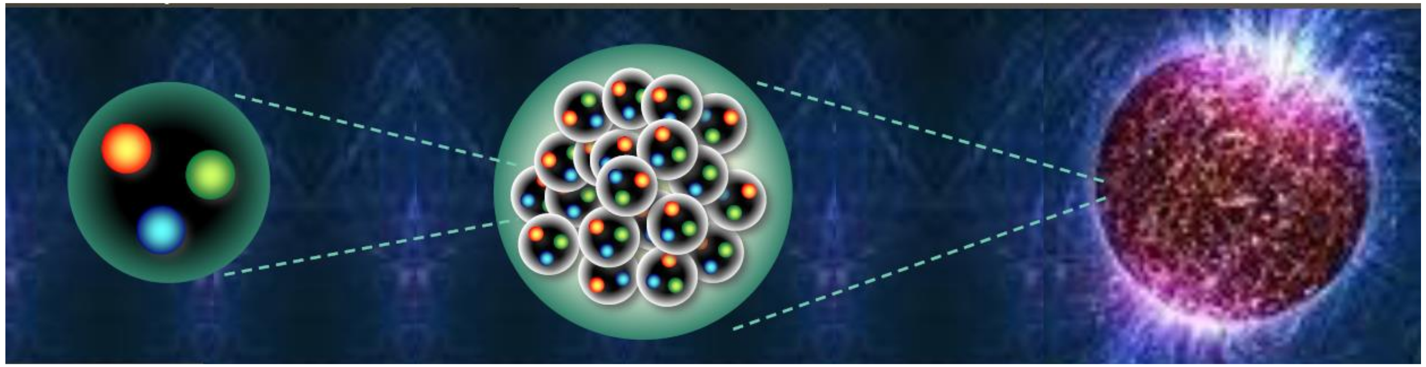
Nuclear & Hadron Physics

= Study of quantum many-body system governed by QCD

Baryon

Nucleus

Neutron Star
= “Giant Nucleus”



10^{-15} m

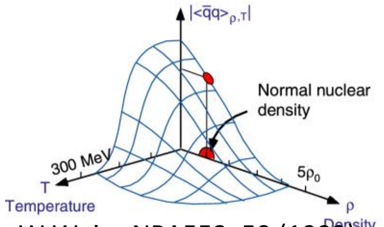
10^{4} m

The ultimate goal:

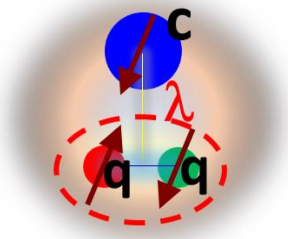
to reveal formation and evolution of the matter based on QCD, widely ranging from hadrons to neutron stars

Nuclear & Hadron Physics **at ~GeV Region**

= Study of quantum many-body system governed by QCD



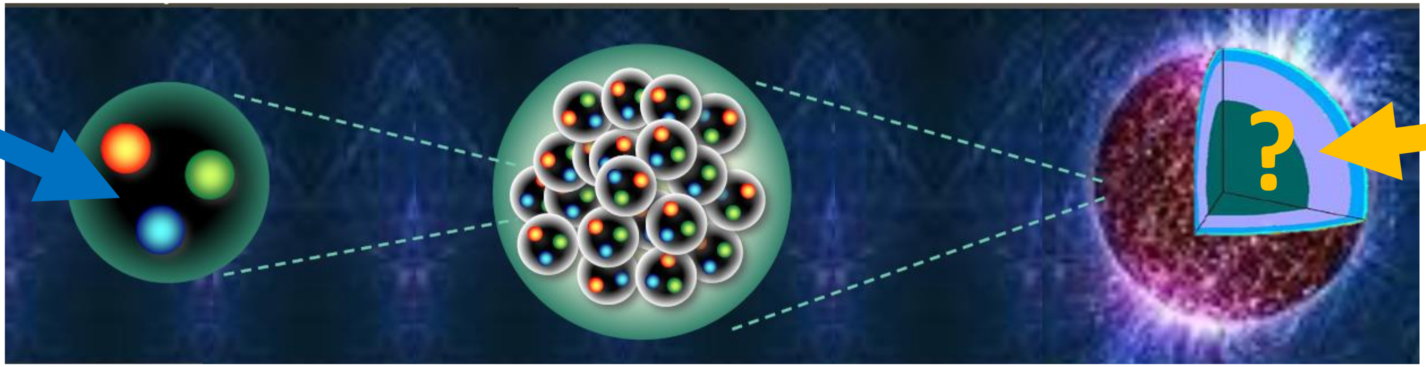
W.Weise NPA553, 59 (1993).



Baryon

Nucleus

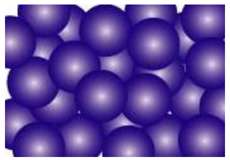
Neutron Star
= "Giant Nucleus"



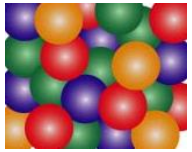
10^{-15} m

10^{4} m

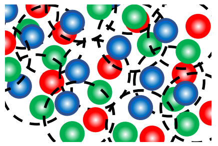
neutron matter?



hyperon matter?



quark matter?



How quarks and gluons build hadrons?

<u>Key:</u> χ-sym. breaking, *q-g* dynamics

<u>Approaches:</u> meson in nuclei, quark correlation in baryon

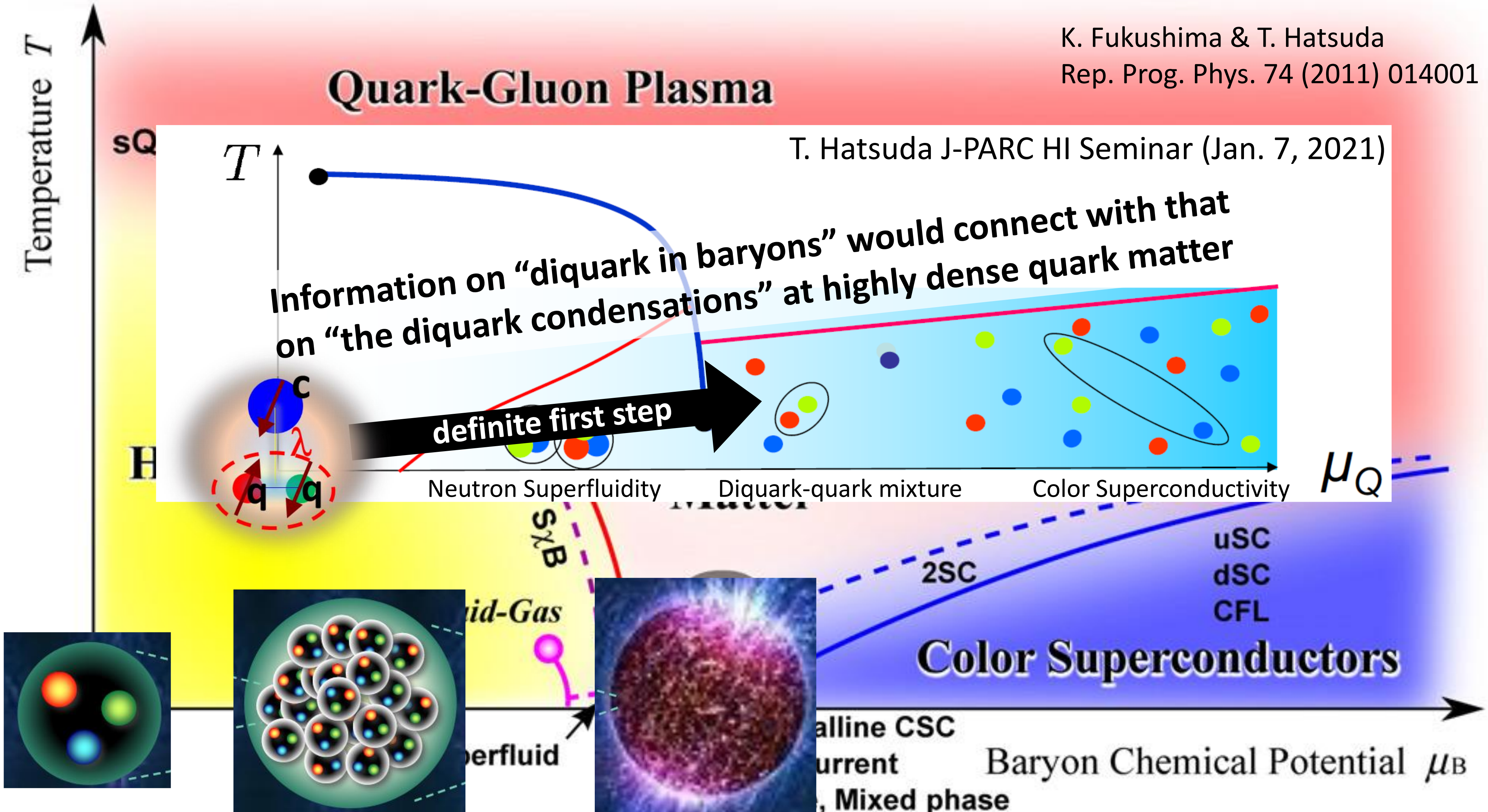
The properties of dense nuclear matter?

<u>Key:</u> role of hyperons

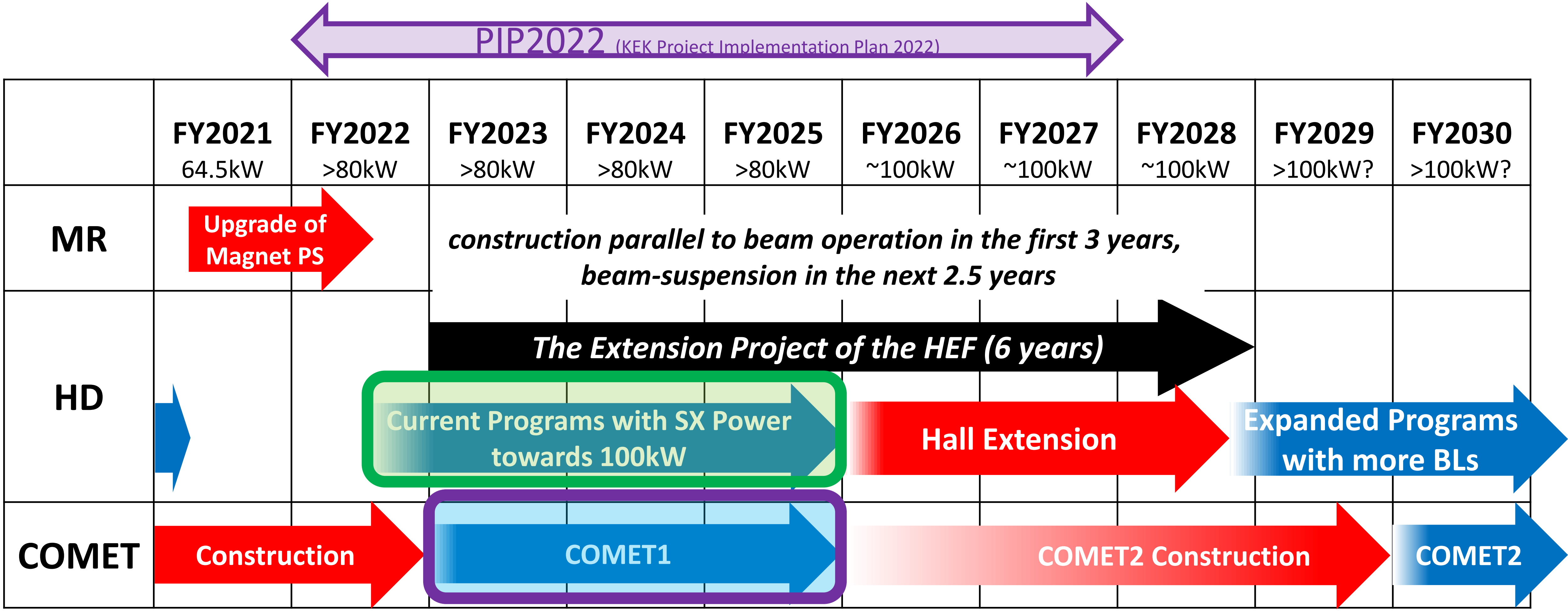
<u>Approaches:</u> precise & density-dependent BB interaction (incl. Y)

Nuclear & Hadron Physics **at ~GeV Region**

= Study of quantum many-body system governed by QCD

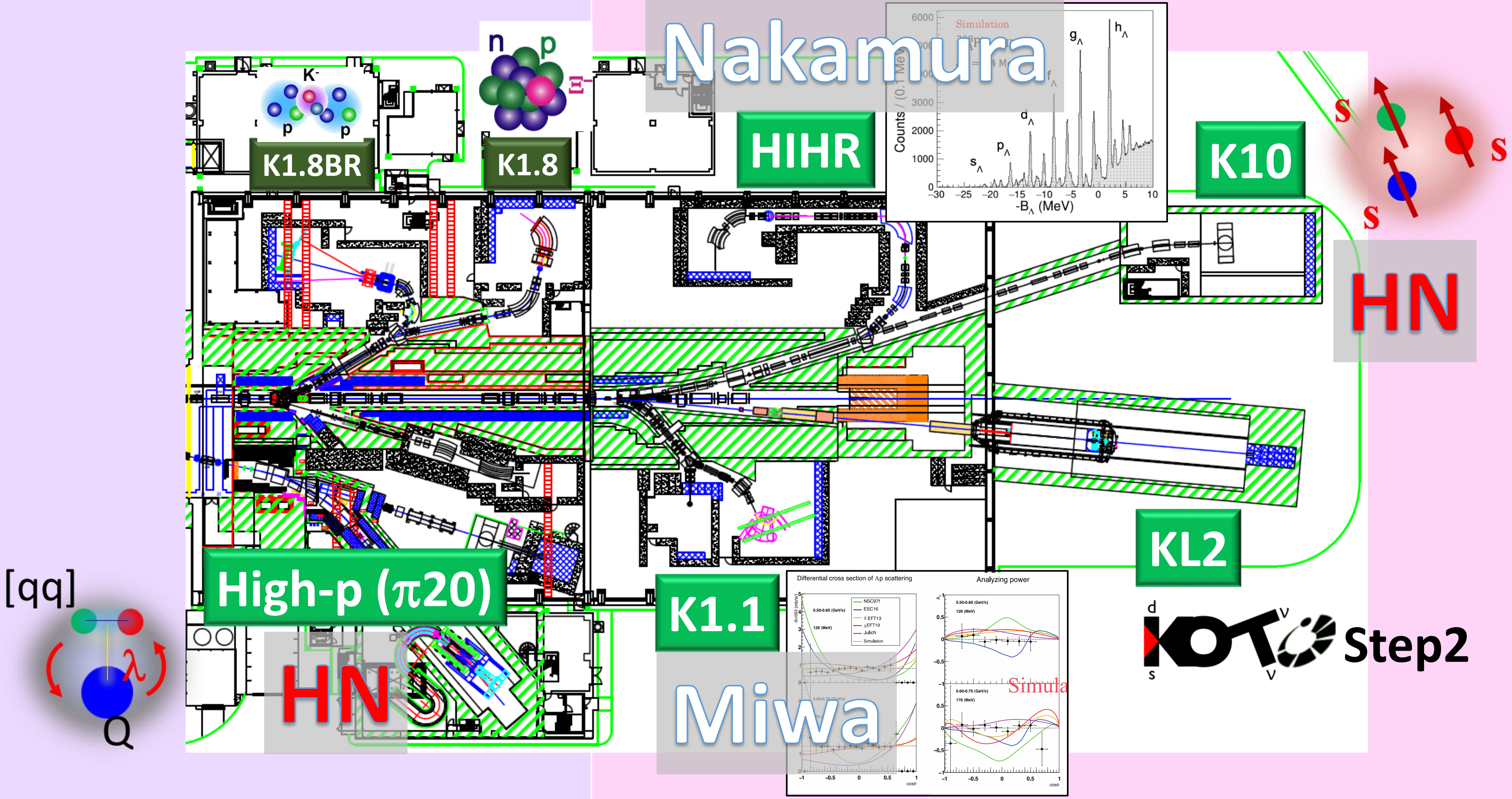


Timeline with the current programs



- **We would like to start the project from FY2023**
  - **4 years operation before beam suspension (except for COMET)**
  - **3 years operation for COMET (Beamline completion in FY2022)**

Extended Hadron Experimental Facility



Spectroscopy of charmed and strange baryons at the π20 and K10 beam lines

10 November, 2021

Hiroyuki NOUMI for K10TF
Research Center for Nuclear Physics, Osaka University
Institute of Particle and Nuclear Studies, KEK

White Paper III – Section 3 –

arXiv:2110.04462

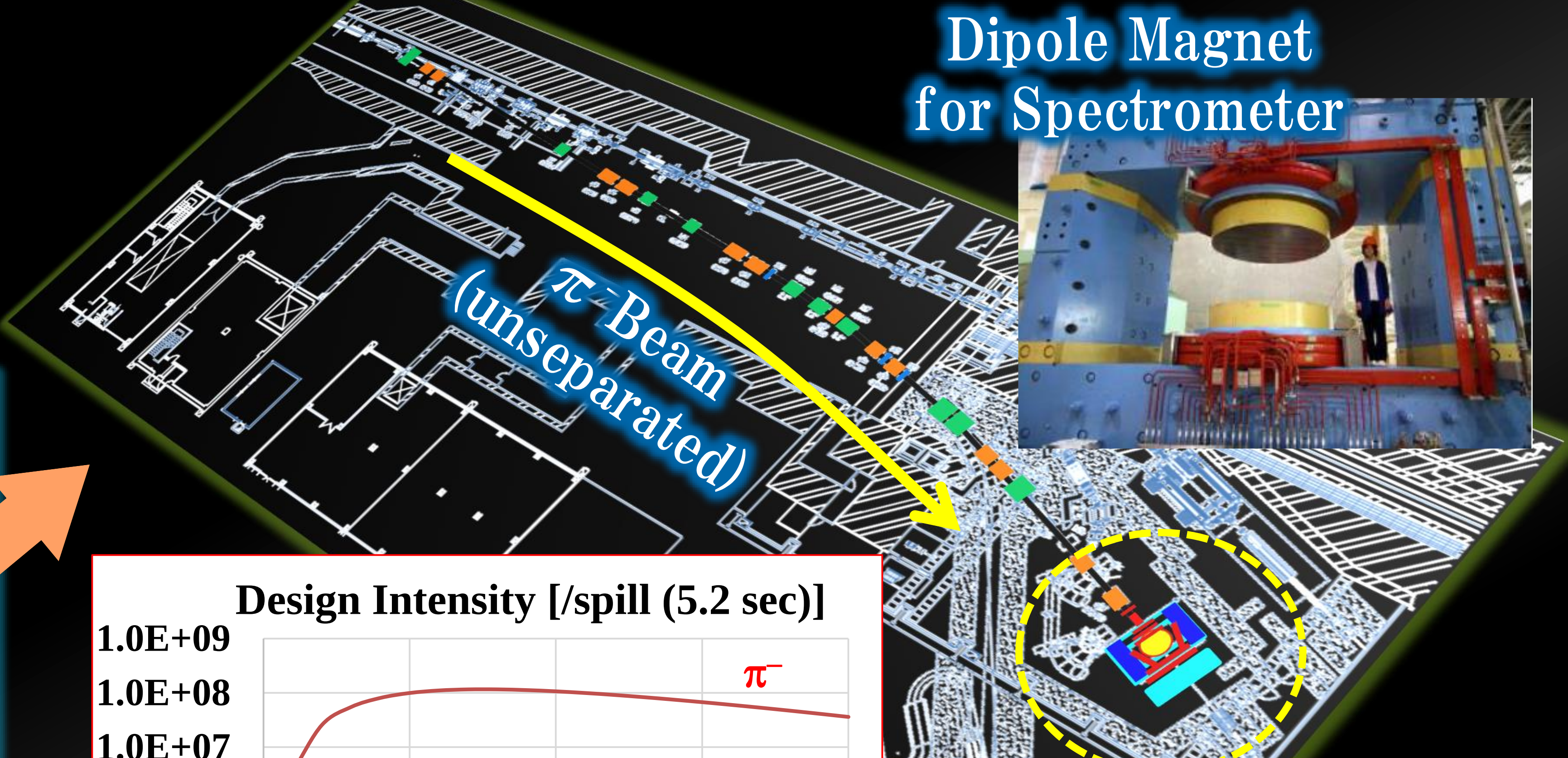
3 Physics Objectives at π20 and K10 Beam Lines

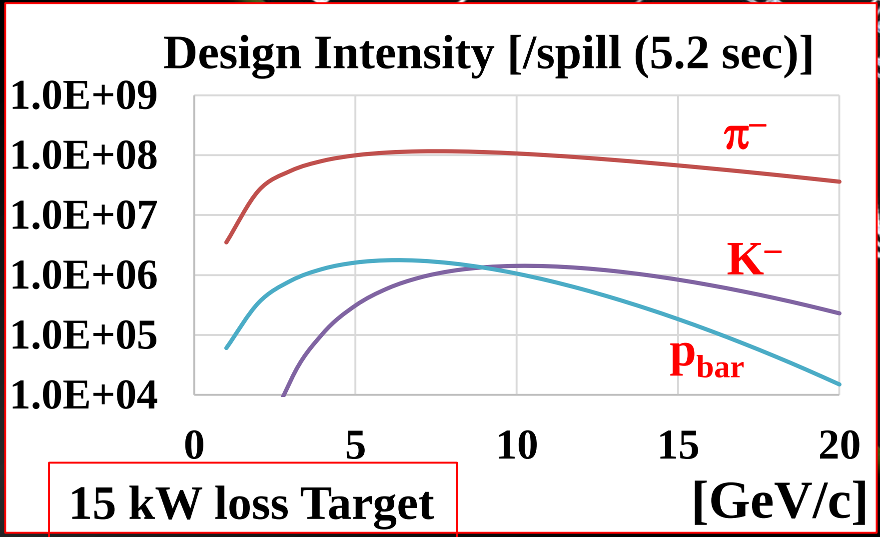
K. Aoki, Y. Hidaka, A. Hosaka, N. Ishii, T. Ishikawa, Y. Komatsu, Y. Morino, M. Naruki, H. Nemura, H. Noumi, H. Ohnishi, K. Ozawa, F. Sakuma, T. Sekihara, S. I. Shim, K. Shirotori, H. Takahashi, S. Takeuchi, and M. Takizawa

Charmed Baryon Spectroscopy at π20

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

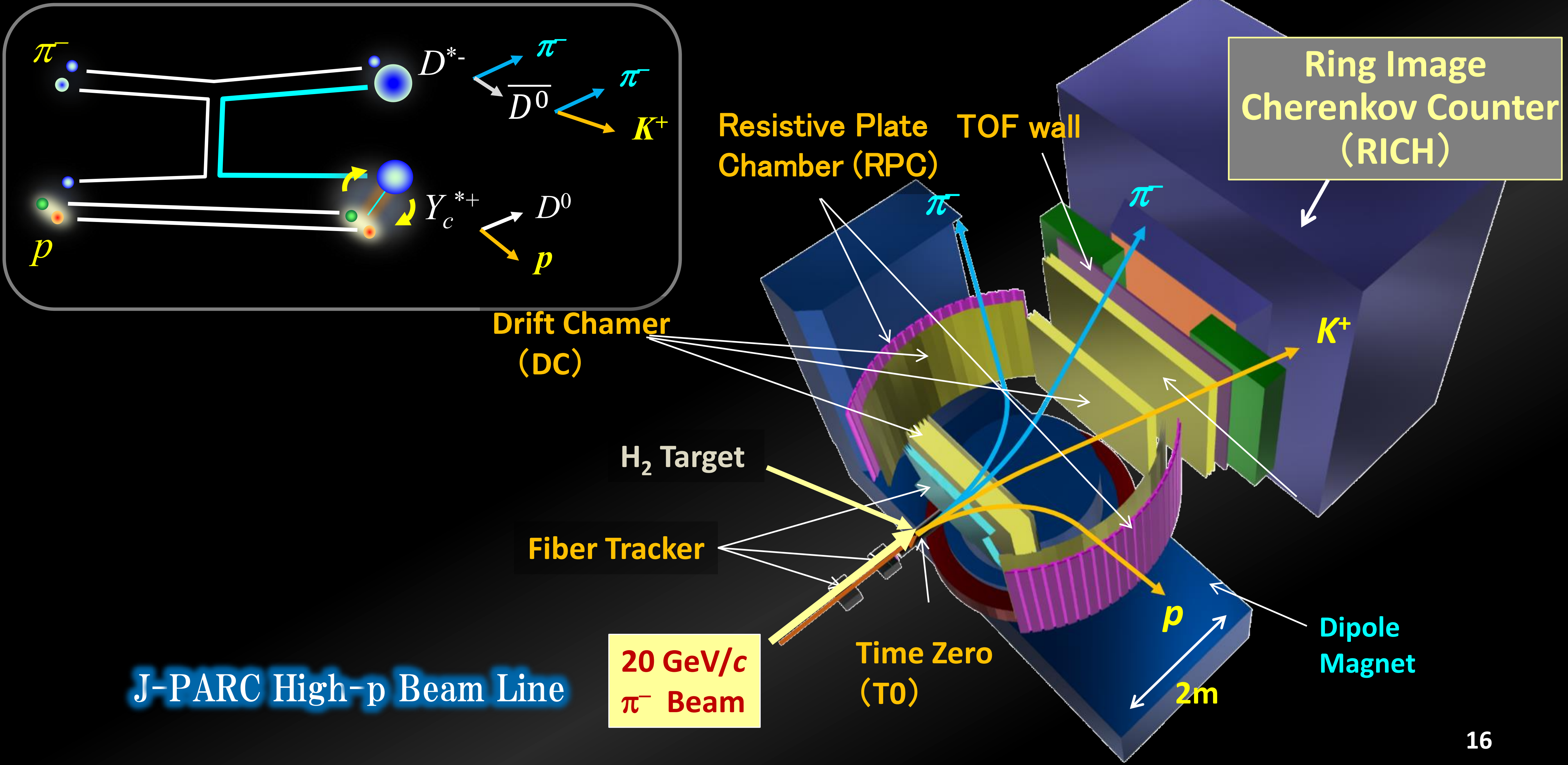
- 20 GeV/c π-
- Intensity >10^7 /s
- Δp/p~ 1/1000





Spectrometer System：

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

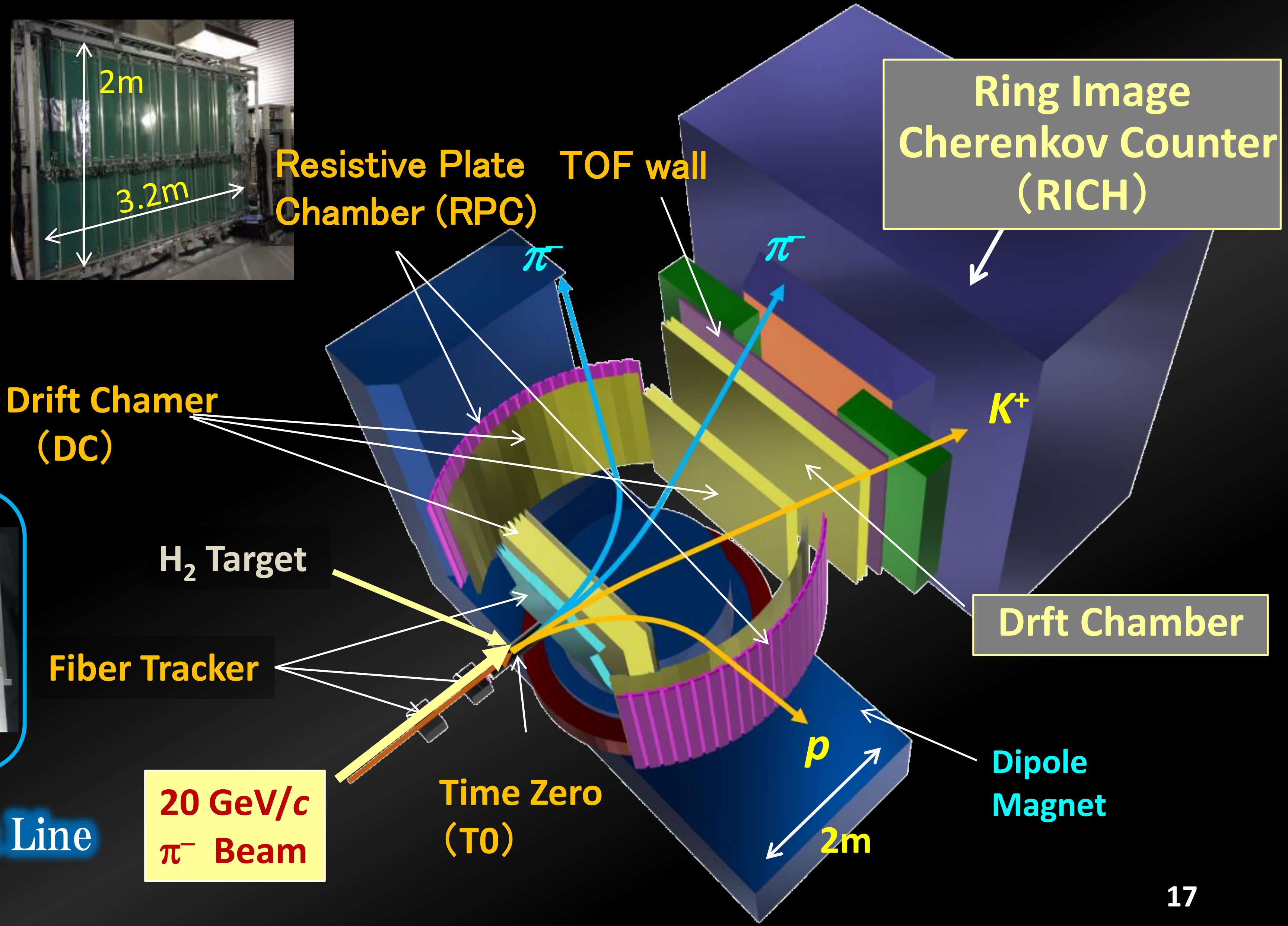


Spectrometer System :

Acceptance: ~ 60% for D^*, ~ 80% for decay π^+

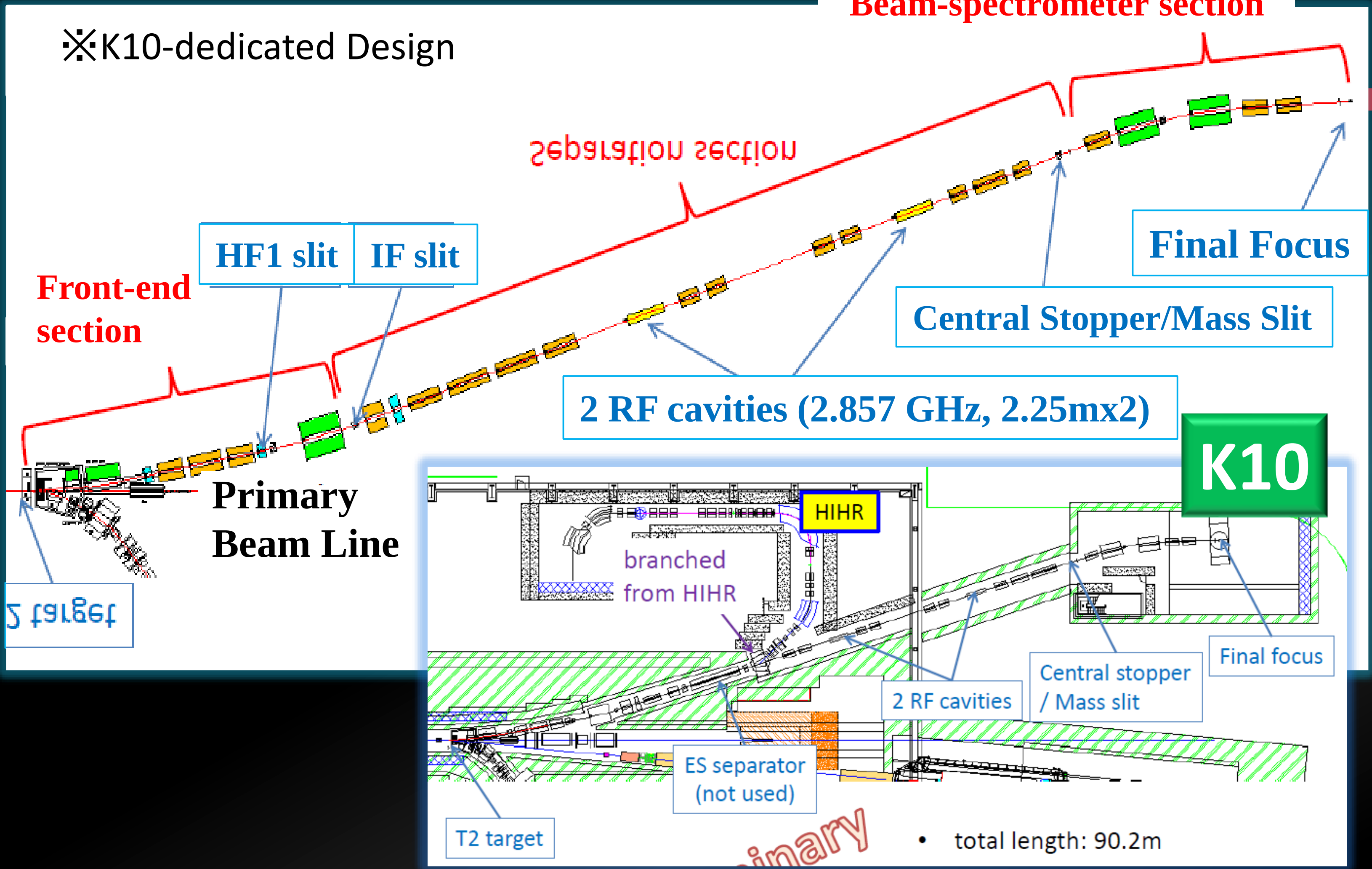
Resolution: $\Delta p/p$~0.2% at ~5 GeV/c (Rigidity: ~2.1 Tm)

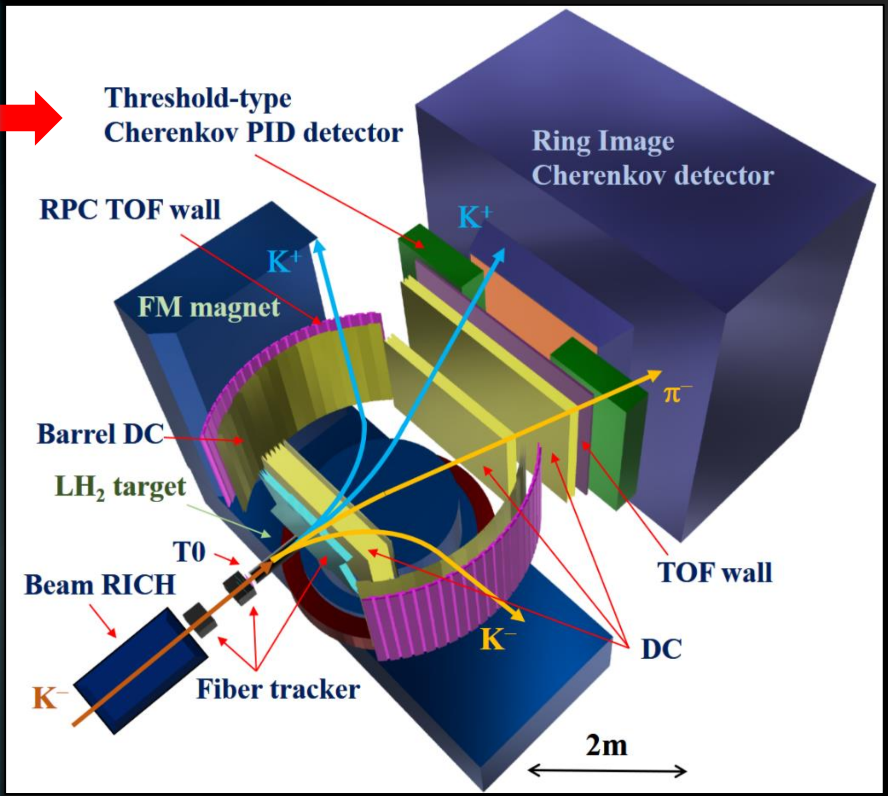
J-PARC High-p Beam Line



Xi/Omega Baryon Spectroscopy at K10

- Intense Kaon Beam: K- 7.9M/spill@8 GeV/c (50-kW p on T2 [Au 66mm])
- RF-separated Kaon Beam: $K^-/\pi^- \sim$ 1:2.1@8 GeV/c (1:2.5@10 GeV/c)





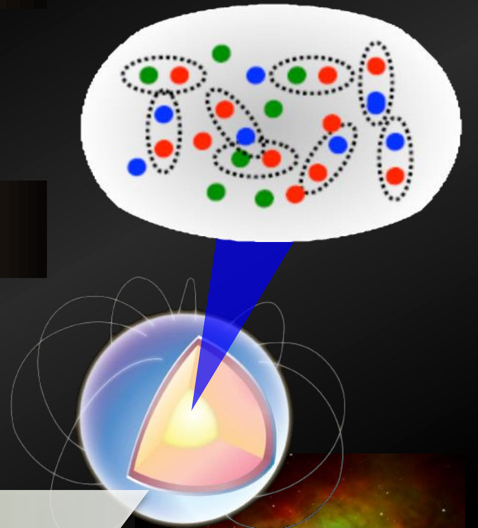
※Design to share upstream w/ HIRH is in progress

Hierarchy of Matter in the Universe

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

How QCD works in Hadron? ⇐ **We attack here.**

Quark Matter?



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

Quark

Effective DoF

Hadron

BB Int.（2BF, 3BF）

Nucleus

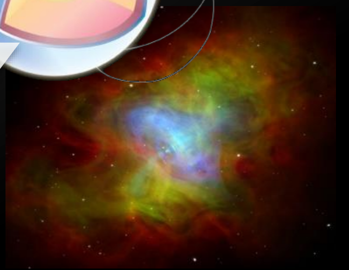
Hypernuclei

How are nuclei formed?

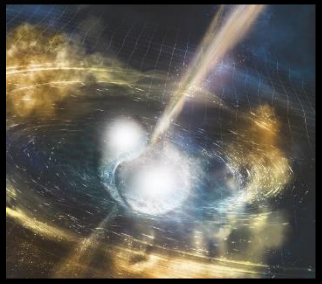
- **Extended Nuclear Force：Baryon-Baryon Int.**
- **Stability of Heavy Neutron Stars (EoS)**

Dense Nucl. Matter

Hypron Matter？



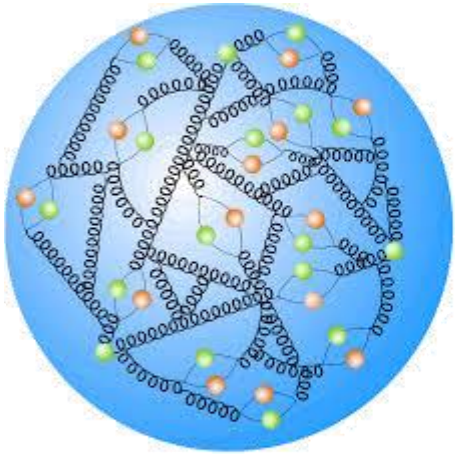
Mystery of Neutron Star



Atom→Molecule→Material,Human,Star,Galaxy

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

perturbative
High E

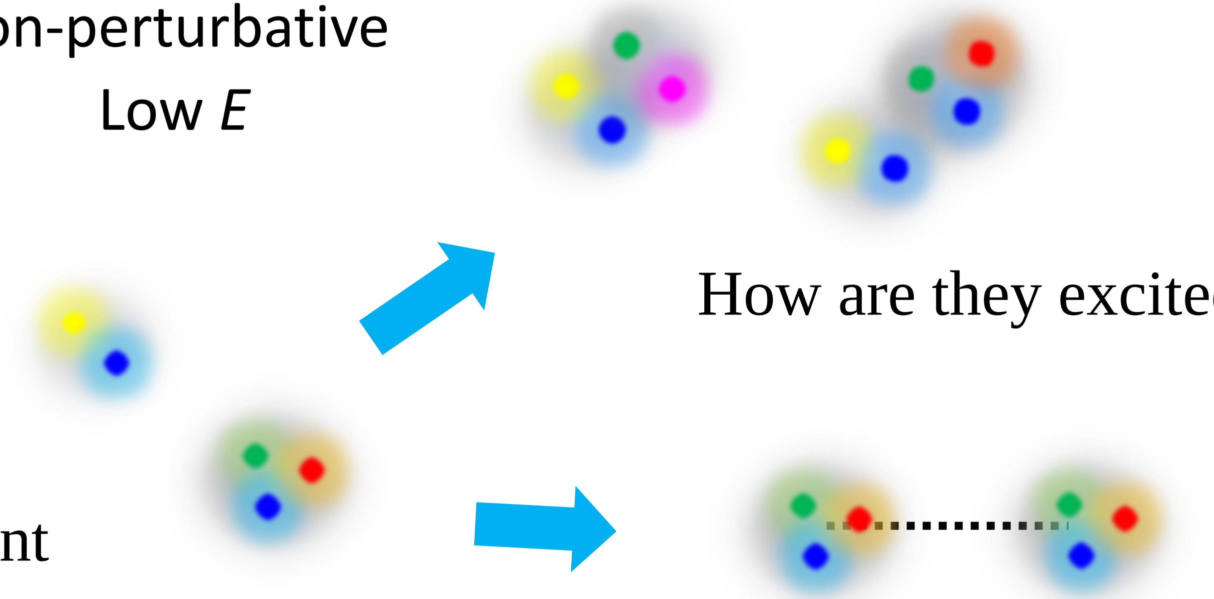


http://ppssh.phys.sci.kobeu.ac.jp/~yamazaki/lectures/07/modernphys-yamazaki07.pdf

$\alpha_s = \infty$
at Λ_{QCD}

Confinement

non-perturbative
Low E



Effective DoF

How are they excited ?

How do they interact ?

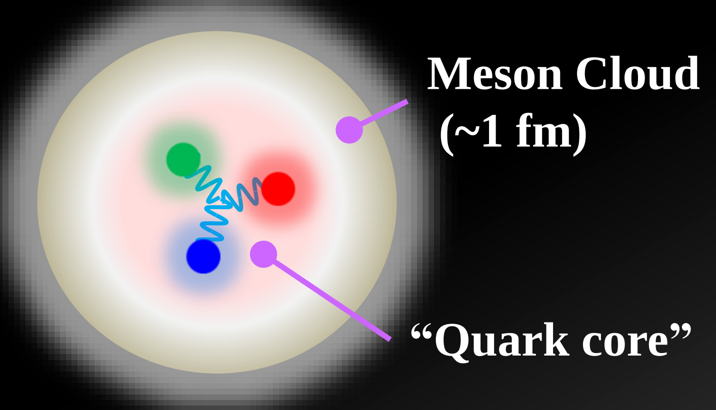
QCD ←------------→ Hadron Spectroscopy

Lattice (HAL)

w/ physics picture

Observation / Effective theory

Non-trivial QCD vacuum in Baryon



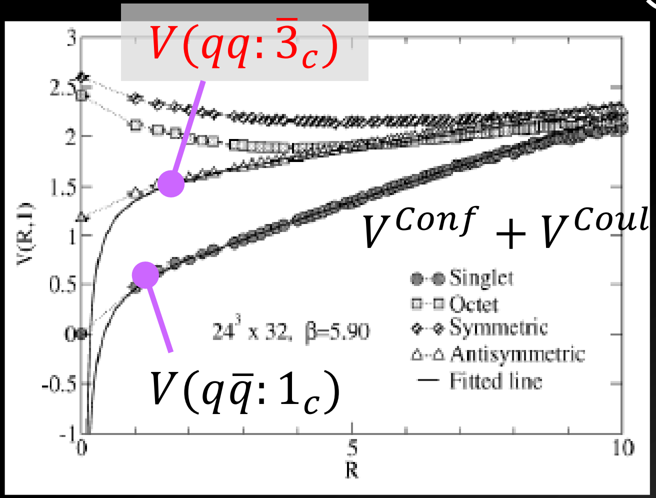
- Non-trivial gluon field ⇒ $\langle \bar{q}q \rangle$, $U_A(1)$ anomaly

  "massive" constituent q, NG boson as Eff. DoF

- Dynamics of Effective DoF
  - Confinement (~1 fm)
  - "Short-range" int. (<0.5 fm)
    - One-Gluon Exchange (OGE)
    - Instanton-Induced Int. (III)

      Kobayashi-Maskawa-t'Hooft (KMT) int.

$$H = K + V^{Conf} + \underbrace{V^{Coul} + V^{SS} + V^{LS} + \cdots}_{\text{"short-range" int.}}$$



qLQCD, Nakamura, Saito
PLB621(2005)171

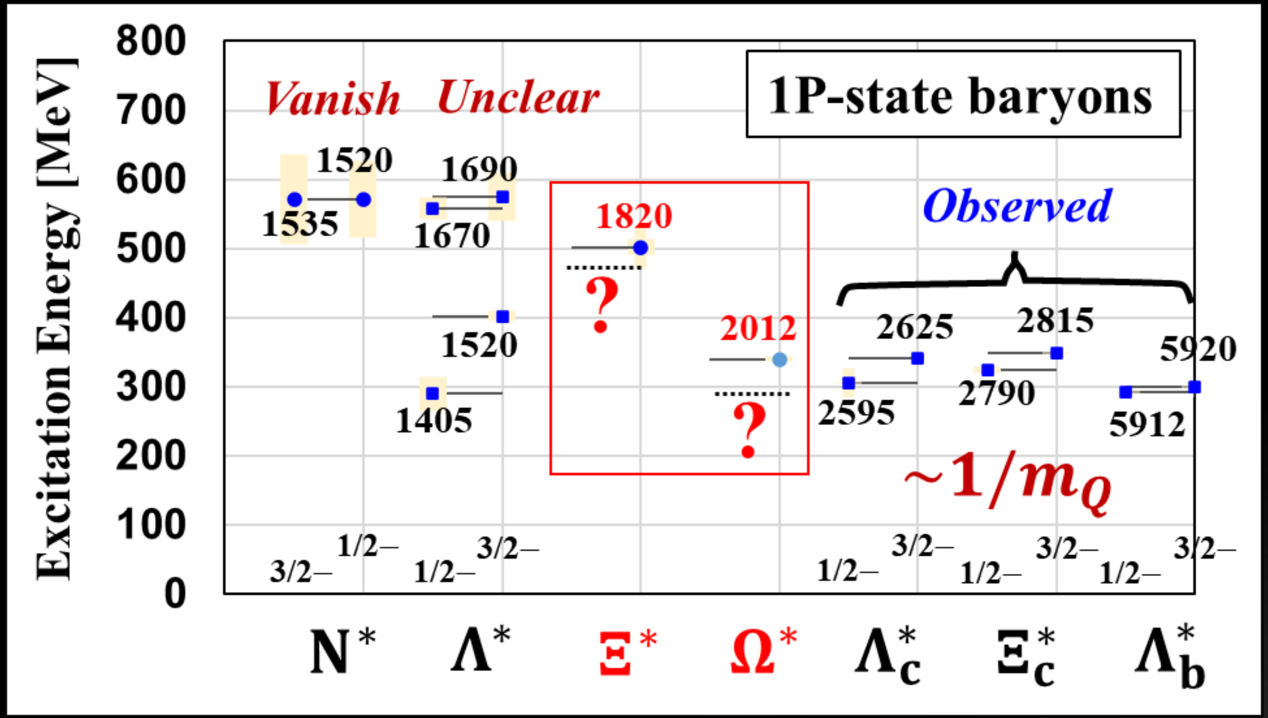
- Issues (not so straight-forward to solve)
  - Mechanism of confinement
    - Size of "cloud"/"core"
  - Origin of spin-dep't int. (SS/LS)

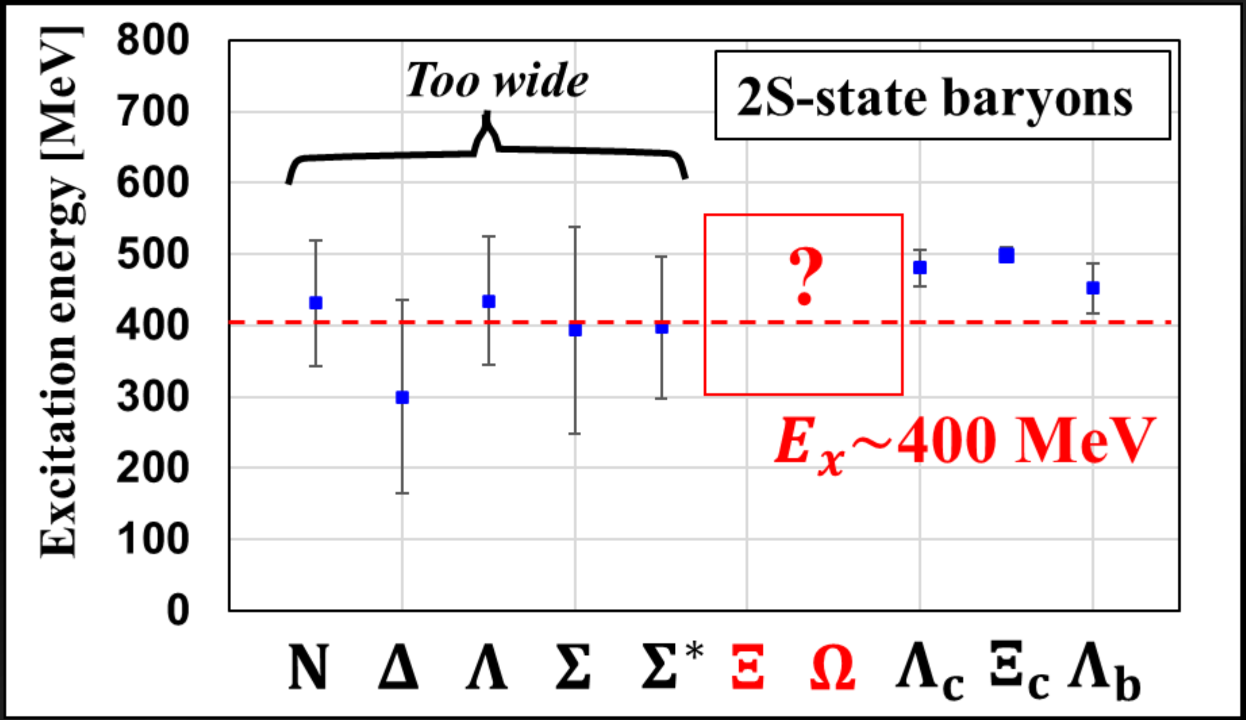
✓ *Diquark correlation*
  - source of $\langle qq \rangle$ in highly dense quark matter

✓ *Systematics of SS/LS forces*
  - OGE vs III, else

✓ *Quark motions*
  - Decay width, Form Factor (dσ/dt)

Systematic behaviors in Excited Baryons





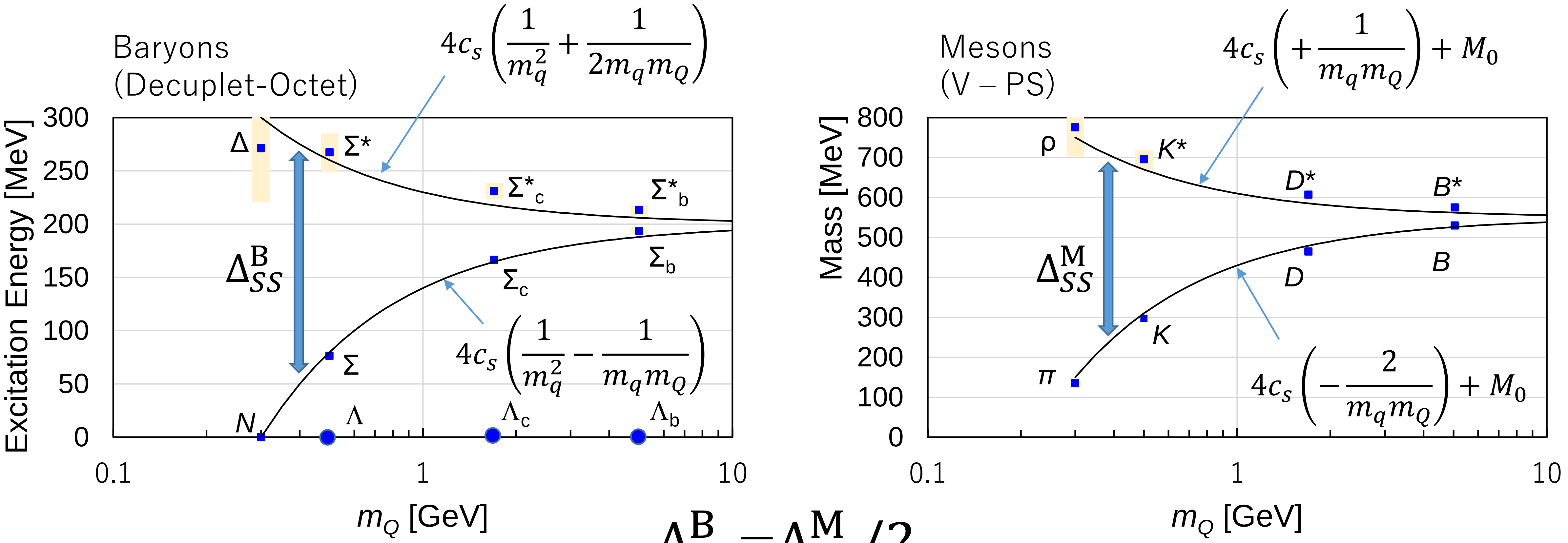
※Origin of LS forces:
Vanished in Light System
Observed in Heavy System

※Universality of “Roper Like” states:
By chance or Mechanism behind them?

Systematic behavior of Spin-Spin(SS) Int.

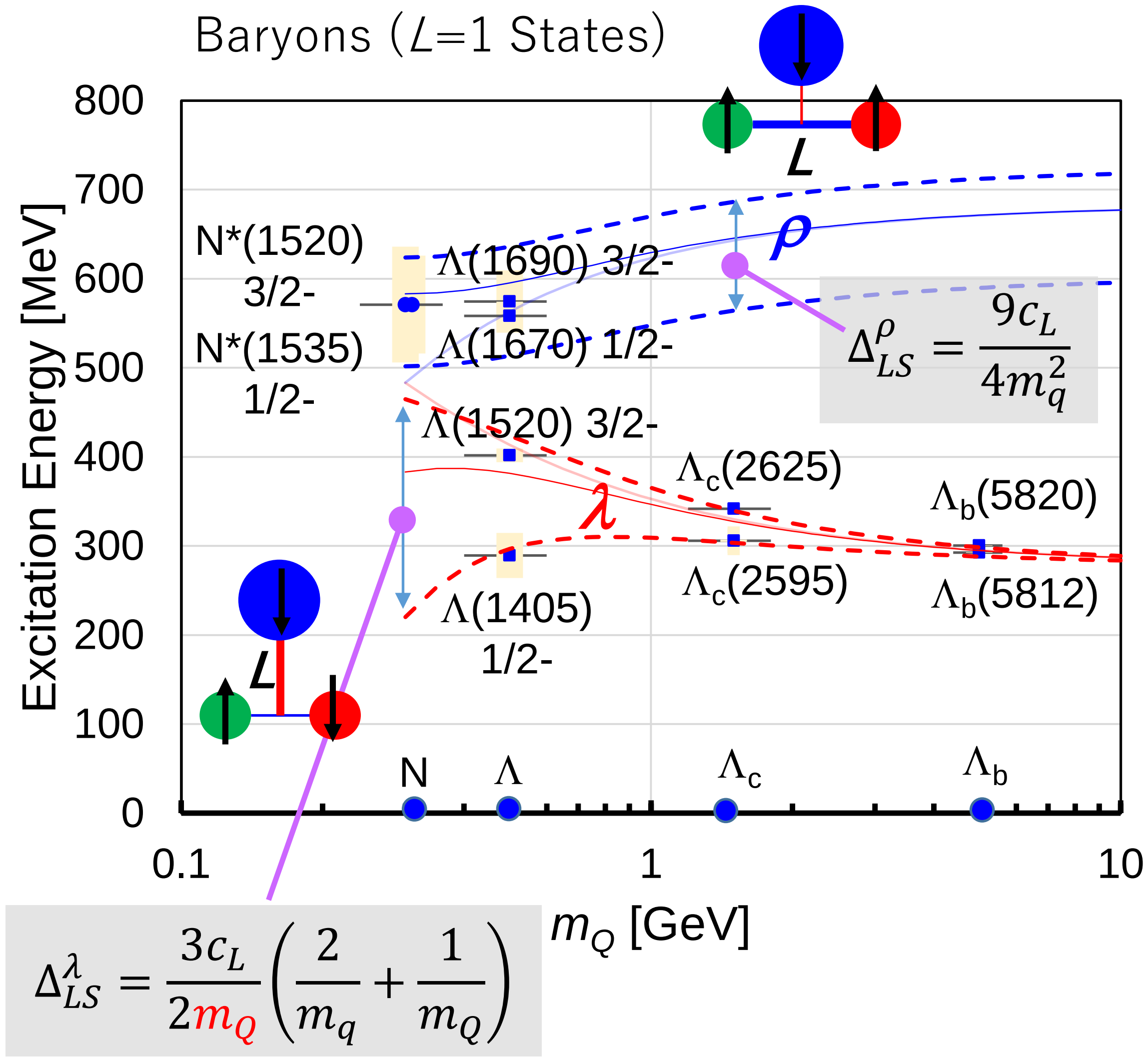
$$V^{SS} = \sum_{i<j} \alpha_S^{SS} \frac{16\pi}{9m_i m_j} \delta(r_{ij}) \vec{s_i} \cdot \vec{s_j}$$

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



$$\Delta^{B}_{SS} = \Delta^{M}_{SS}/2$$

Systematic behavior of Spin-Orbit(LS) Int.



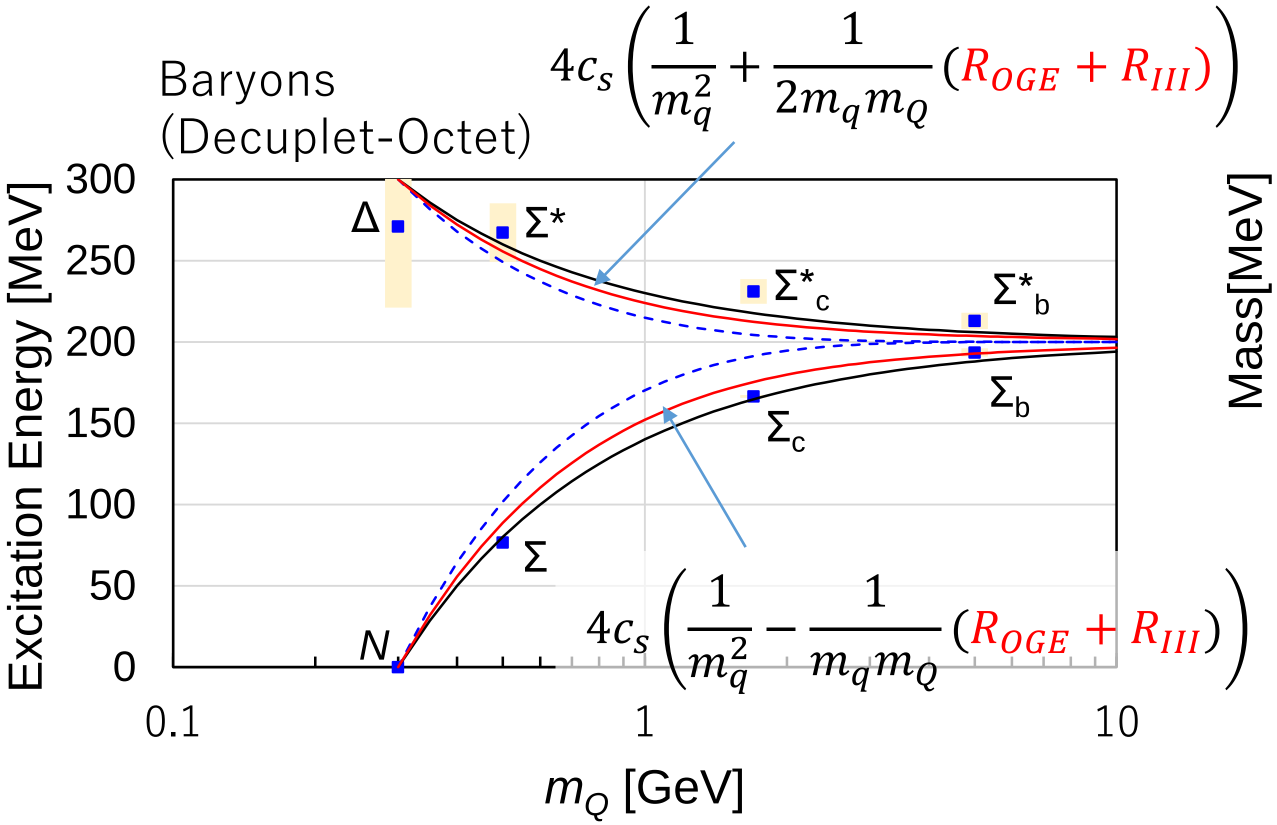
- LS splitting vanishes in light baryons.
  - CQM, which suggests Δ^{ρ}_{LS}~100 MeV, does not reproduce the LS splitting.
- Cancellation mechanism exists?
  - Instanton Induced Interaction (III)

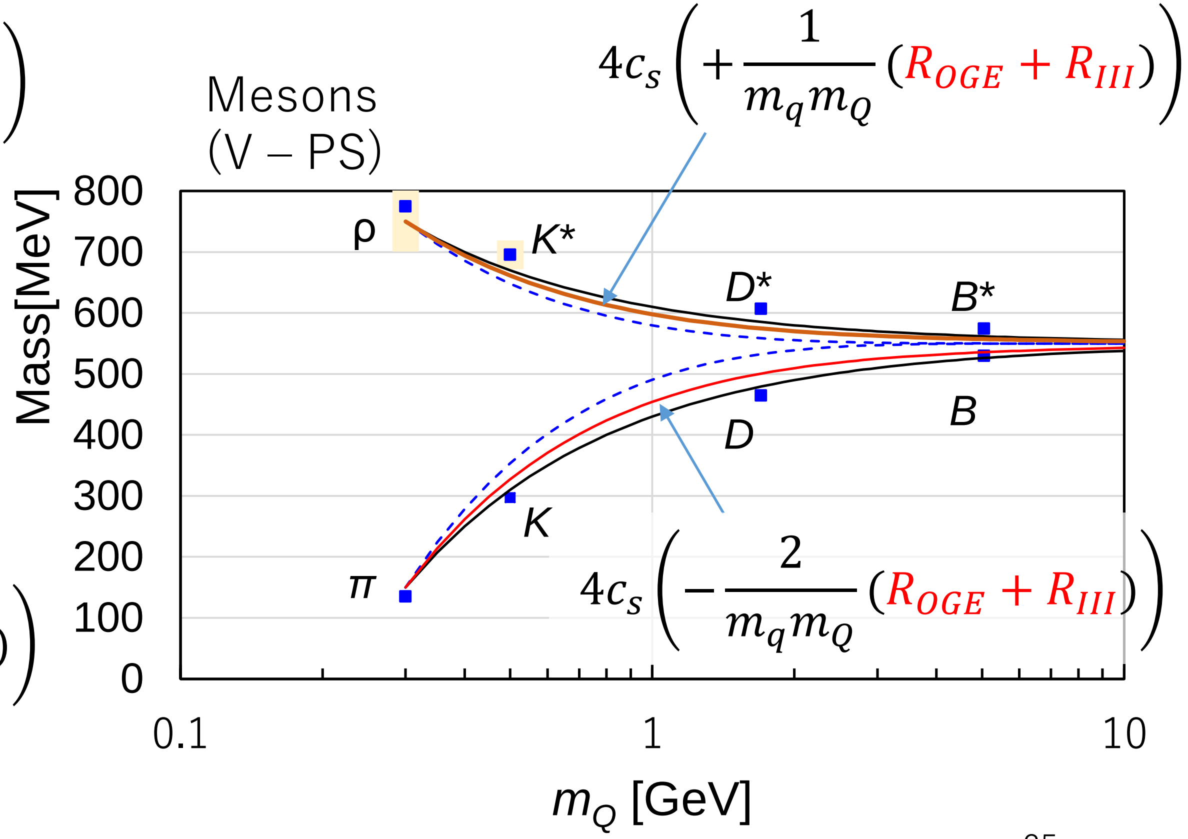
Systematic behavior of Spin-Spin(SS) Int.

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

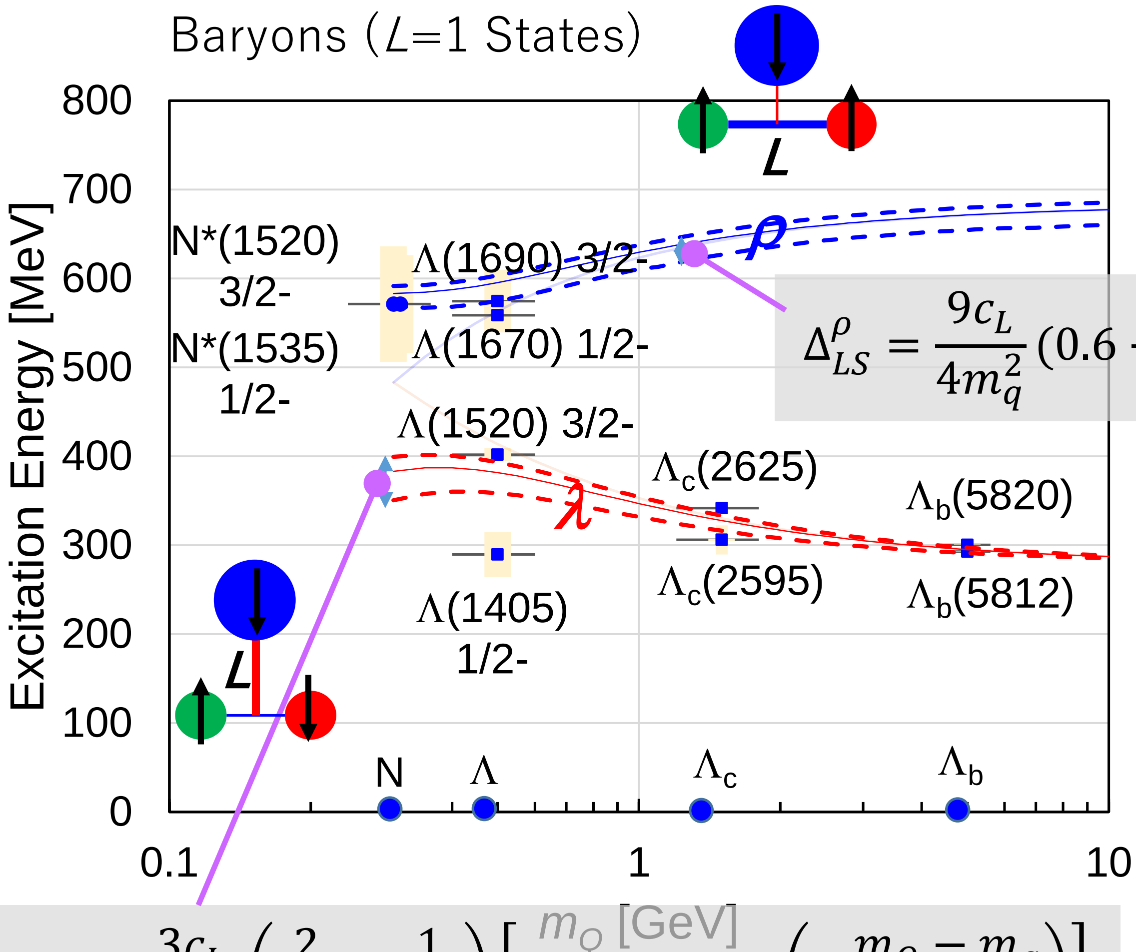
Constructive for SS

- **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 Δ_{LS}^{ρ}~100 MeV, does not reproduce the LS splitting.
- Cancellation mechanism exists?
  - Instanton Induced Interaction (III)

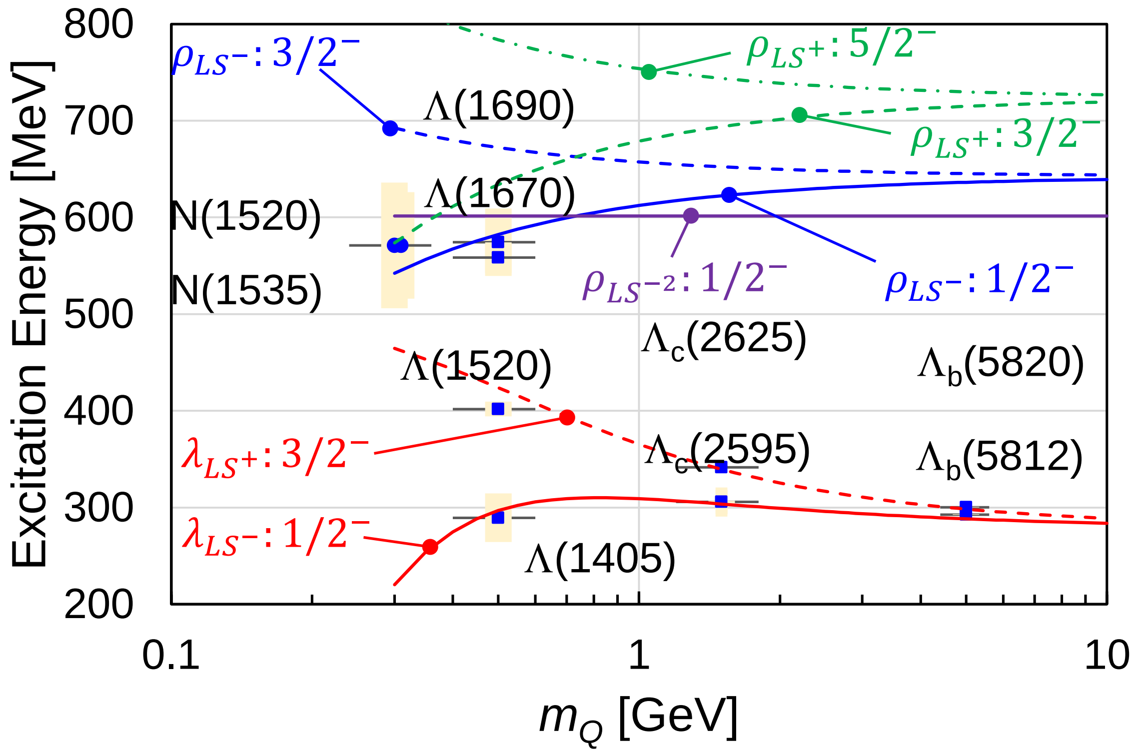
$$V^{LS} \sim (R_{OGE} - R_{III})\Delta$$

Destructive for LS

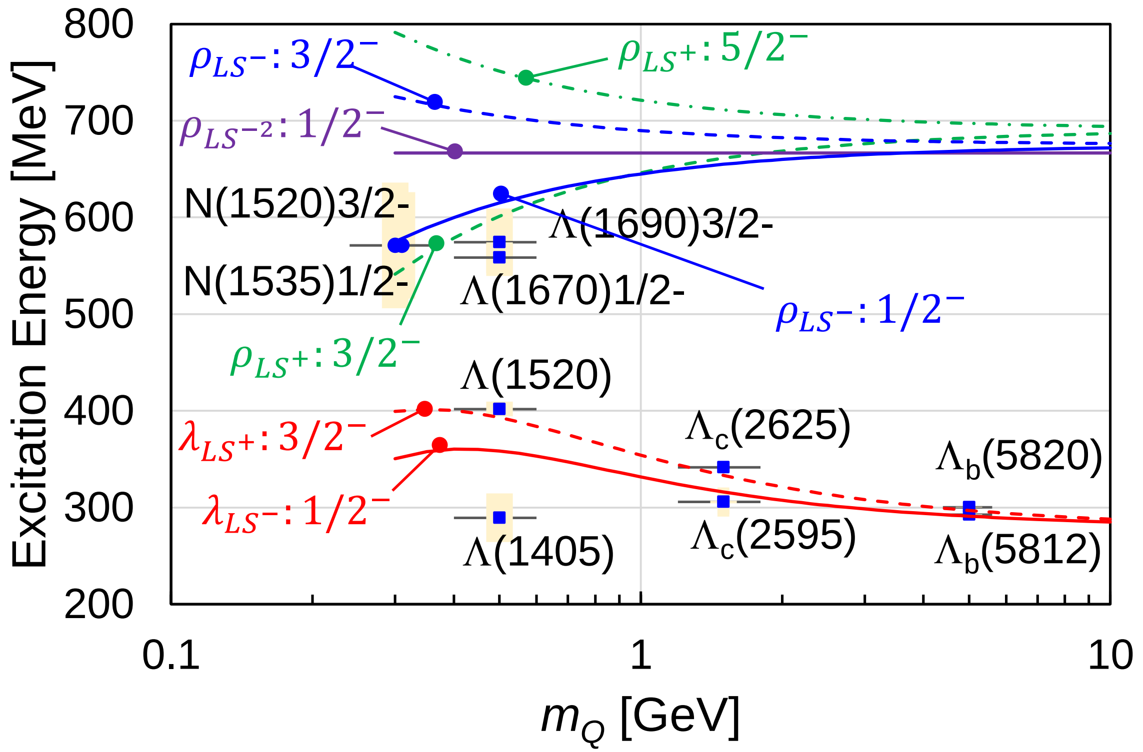
- LS splitting in heavier systems are to be investigated with identifying if they are λ/ρ-mode excitations

P-wave *Qqq* (*I*=0)Baryons – m_Q dependence

OGE only



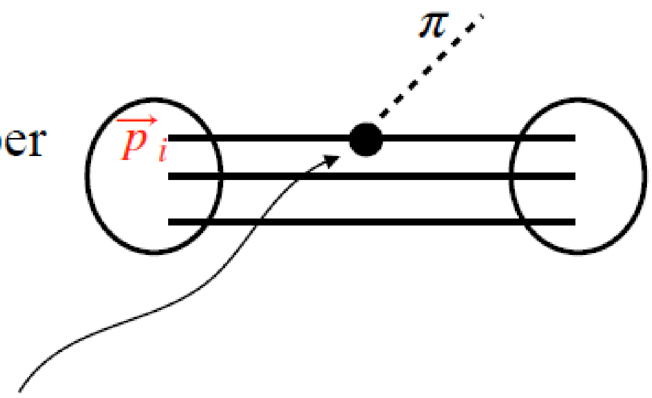
LS cancellation (OGE(0.6)+III(0.4))



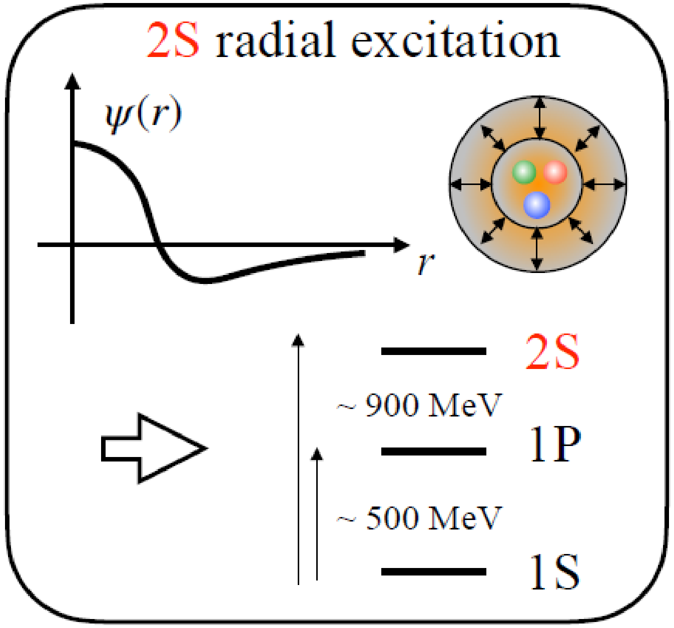
(3) The Roper like states

Another method to look at the internal quark motion

Decay of Roper like stats



G.S.



NR expansion of ME

$$\langle \text{Roper} | \mathcal{O} | \text{G.S.} \rangle \sim \langle \vec{\sigma} \cdot \vec{q} \rangle (\not{a}_0 + a_2 \vec{p}_i^{\,2} + \cdots)$$

Leading order (LO) suppressed
Unique for radial excitations

Next to leading order (NLO)

$$\langle p_i^2 \rangle \sim \frac{1}{\langle r^2 \rangle} \quad \sim \text{Size}$$

Arifi et al, *PRD* 103 (2021) 9, 094003

- Previous calculations (LO): too small
- Inclusion of NLO: 50 - 100 MeV for $\Omega^*(3/2^+)$

Prof. Hosaka's slide

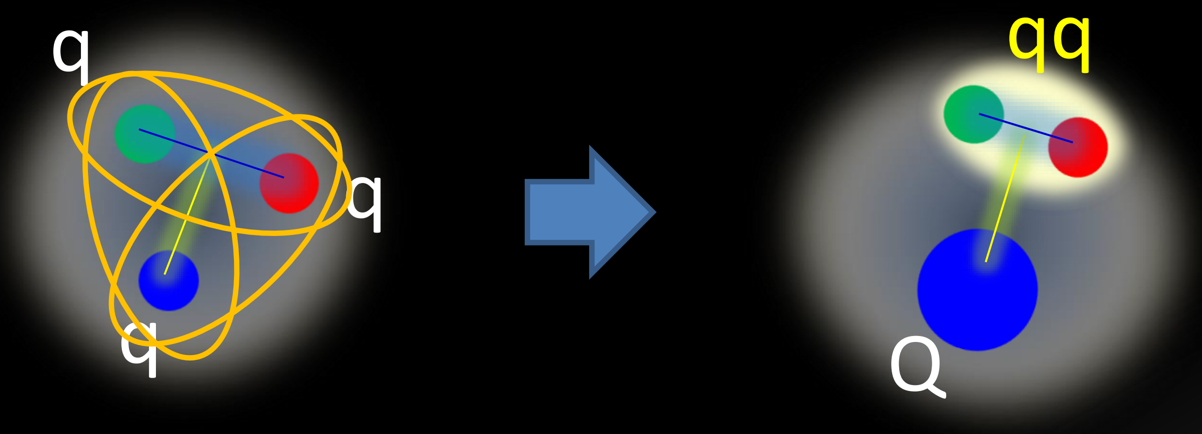
Hadrons w/ light to heavy quarks

- "Dressed" quark mass

	Light Quark					Heavy Quark	
	u	$\sim$	d	$<$	s	$\ll$	c	b
M_Q [GeV/c^2]	0.3				0.5		1.5	5

"s" sometimes works as a HQ to disentangle quark motion.

Roles of Heavy Flavors



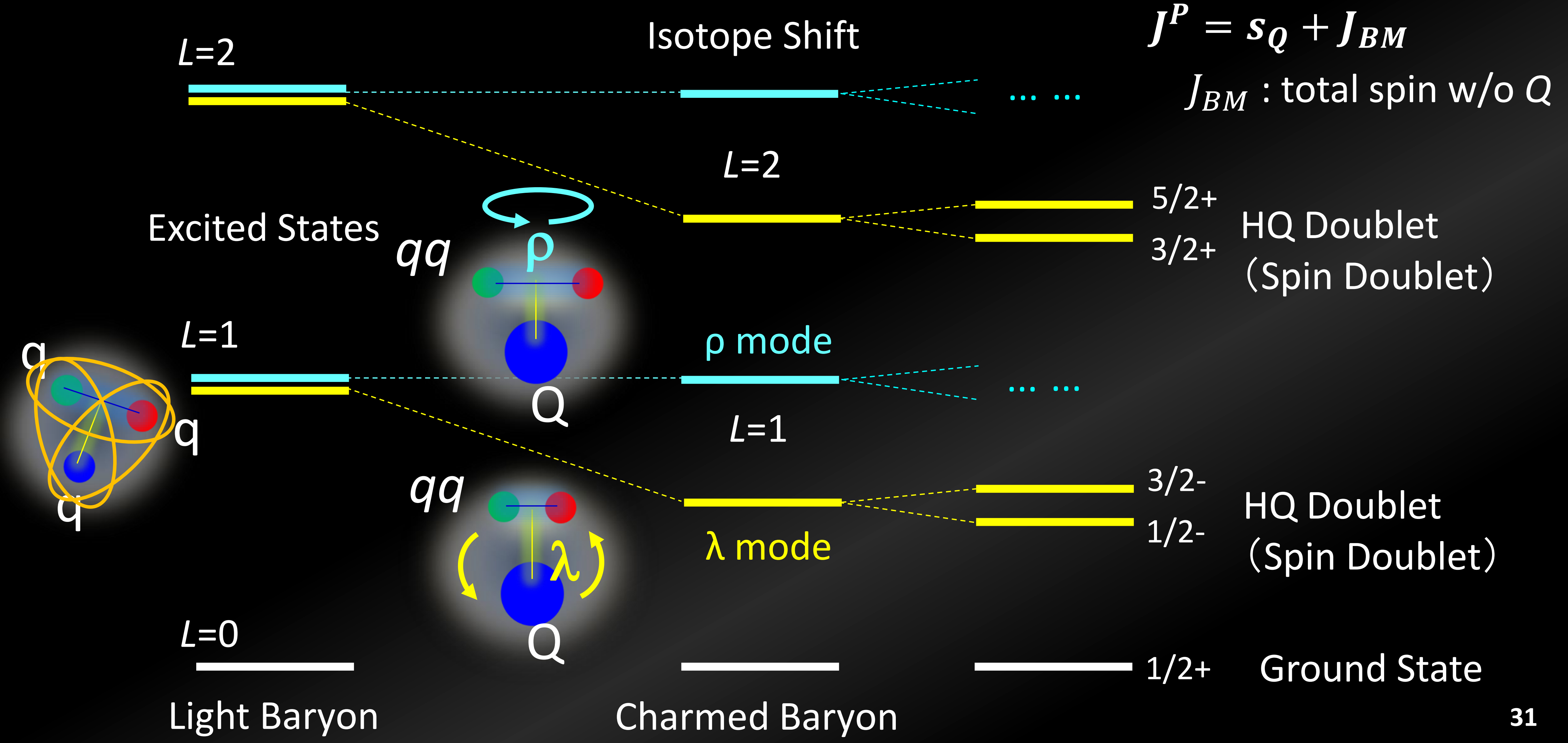
$$V_{CMI} \sim [\alpha_s/(m_i m_j)]*(\lambda_i,\lambda_j)(\sigma_i,\sigma_j)$$
$$\rightarrow 0 \text{ if } m_{i,j} \rightarrow \infty$$

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

- 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

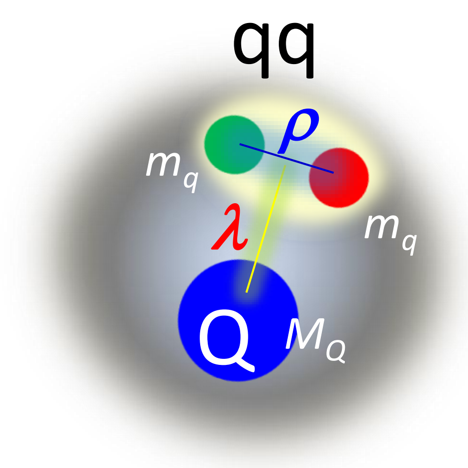


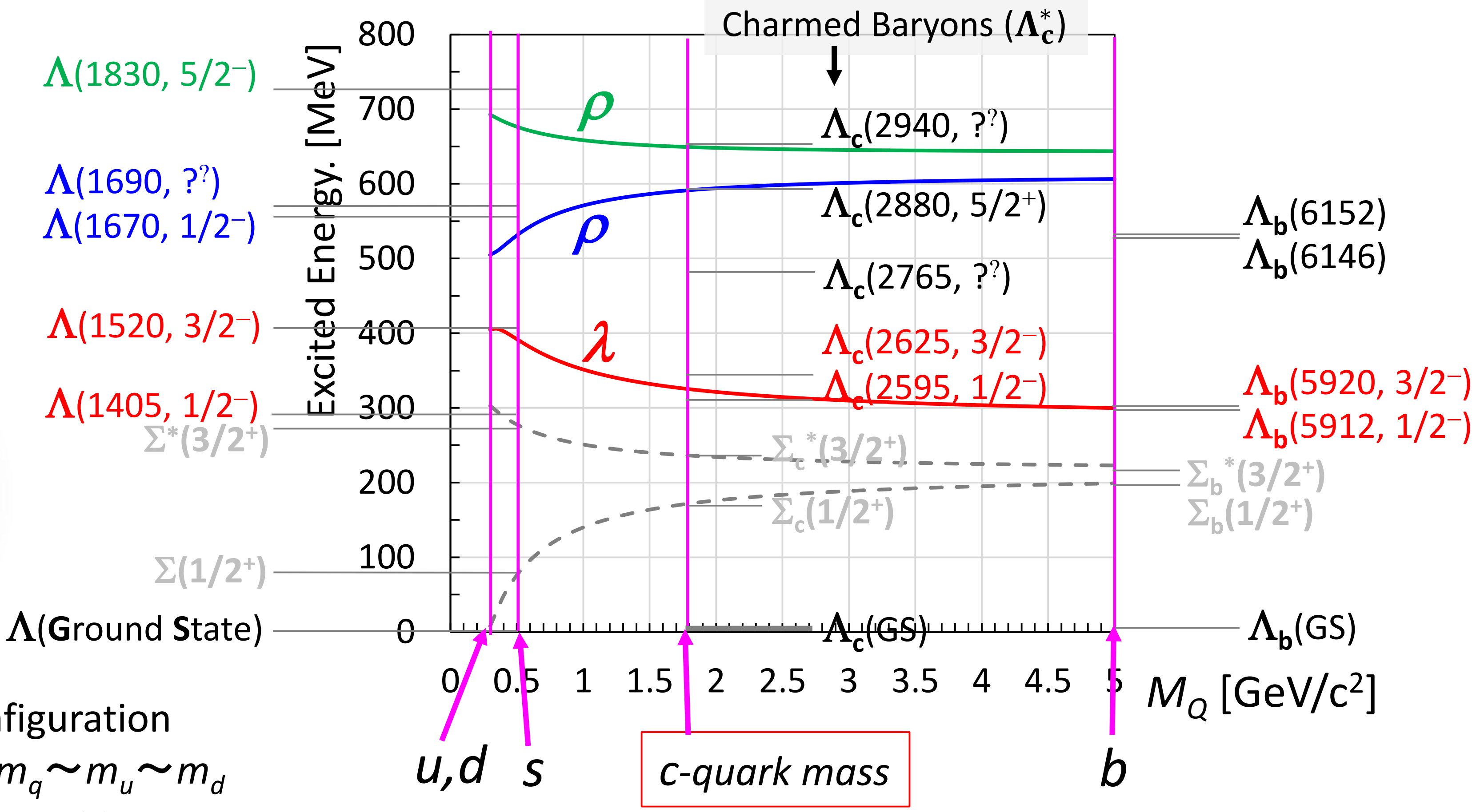
T. Yoshida, E. Hiyama, A. Hosaka, M. Oka, K. Sadato, Phys. Rev. D**92** (2015) 114029

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





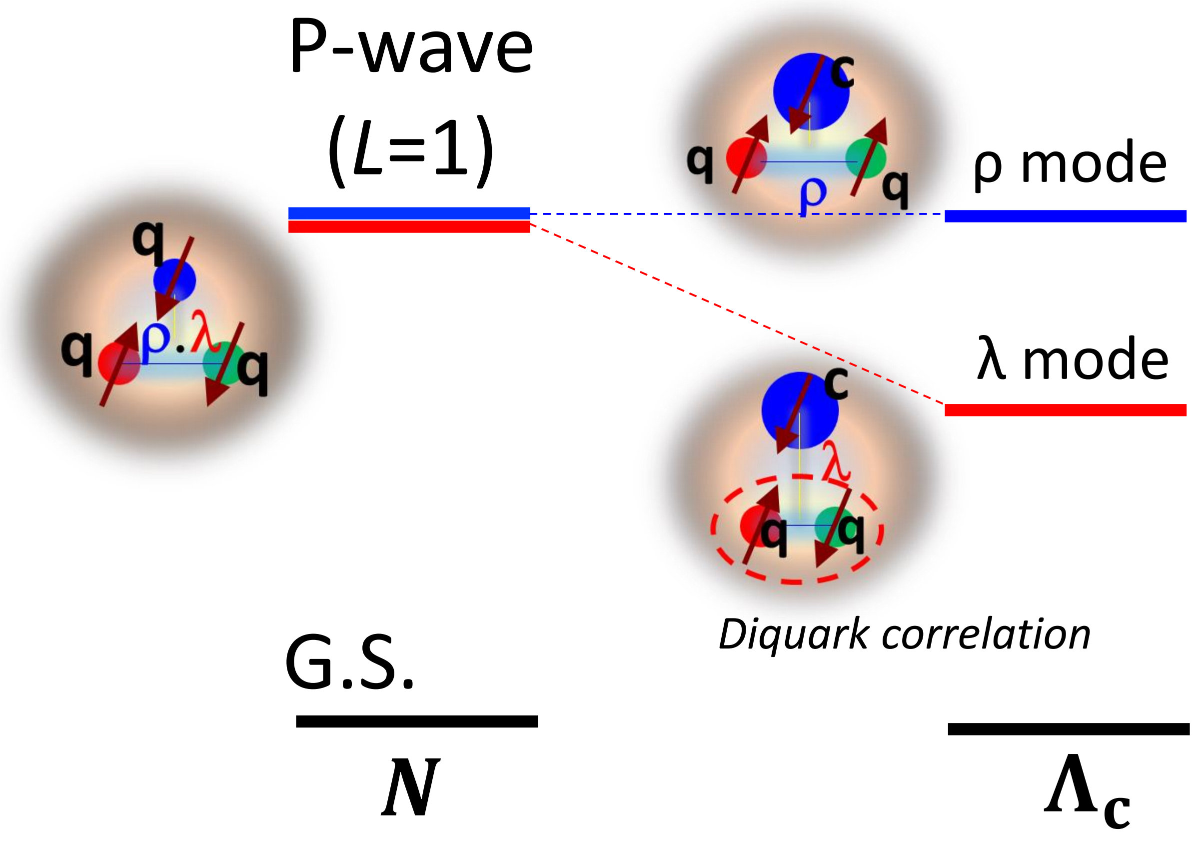
Baryon with [Qqq] configuration

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

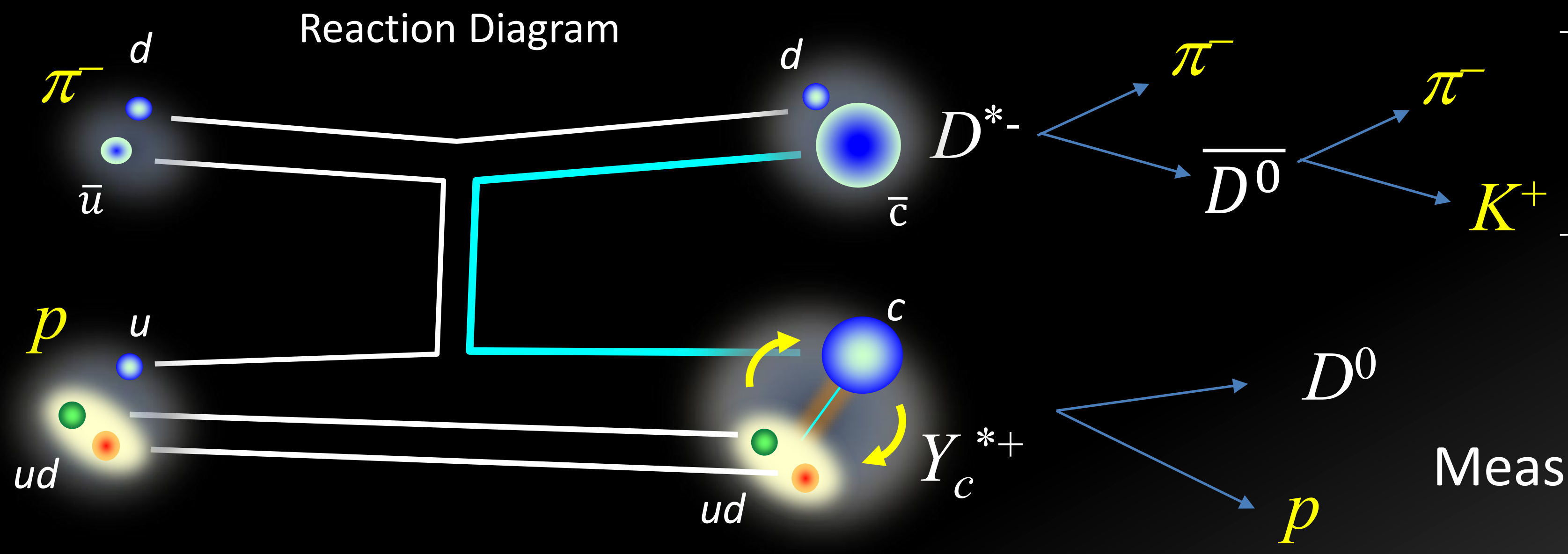
Spectroscopy of strange and charmed baryons



Disentangle "*qq*" motion
in Baryon w/ Heavy Quark

Good to study *qq* correlation
induced by Spin-Spin int.

Production and Decay of Charmed Baryons



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

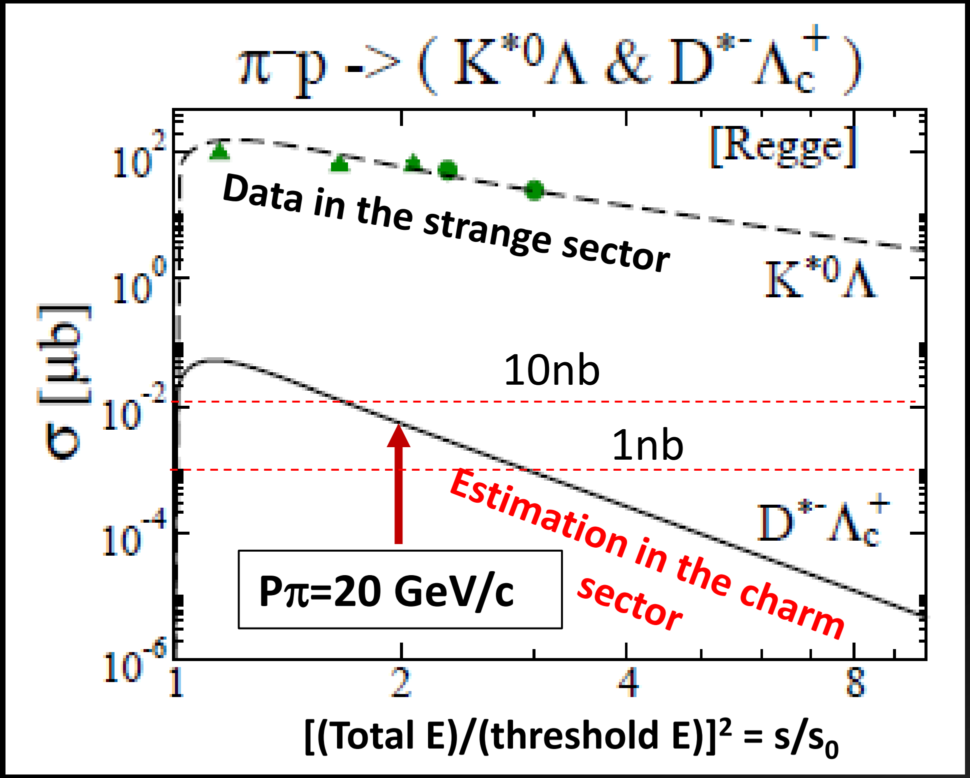
Measure Decay particles , too

- Introducing a finite orbital angular momentum *L* ⇒ favor *λ*-mode excitations
  - Establish "*ud*" diquark motion in baryon
- Production ratio of the HQ doublet to be *L*:*L*+1 ⇒ Spin, Parity
  - The ratio would be a measure of how "*ud*" is correlated.
- Production and Decay measurement ⇒ Branching Ratio (partial width)
  - Decay rates would be a measure of how "*ud*" is firmly correlated

Production of Charmed Baryons: Theoretical Study

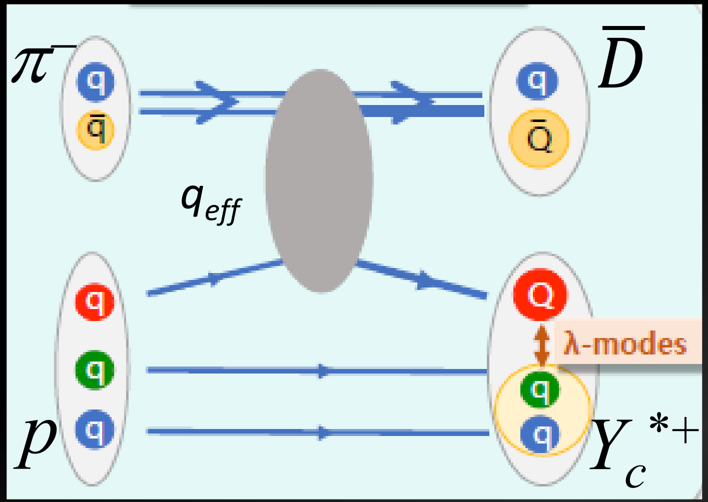
Reggeon Exchange Model in 2-body reaction

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

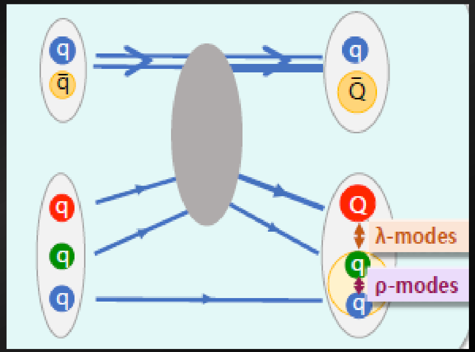


※no data available is in the charm sector.

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

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

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

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

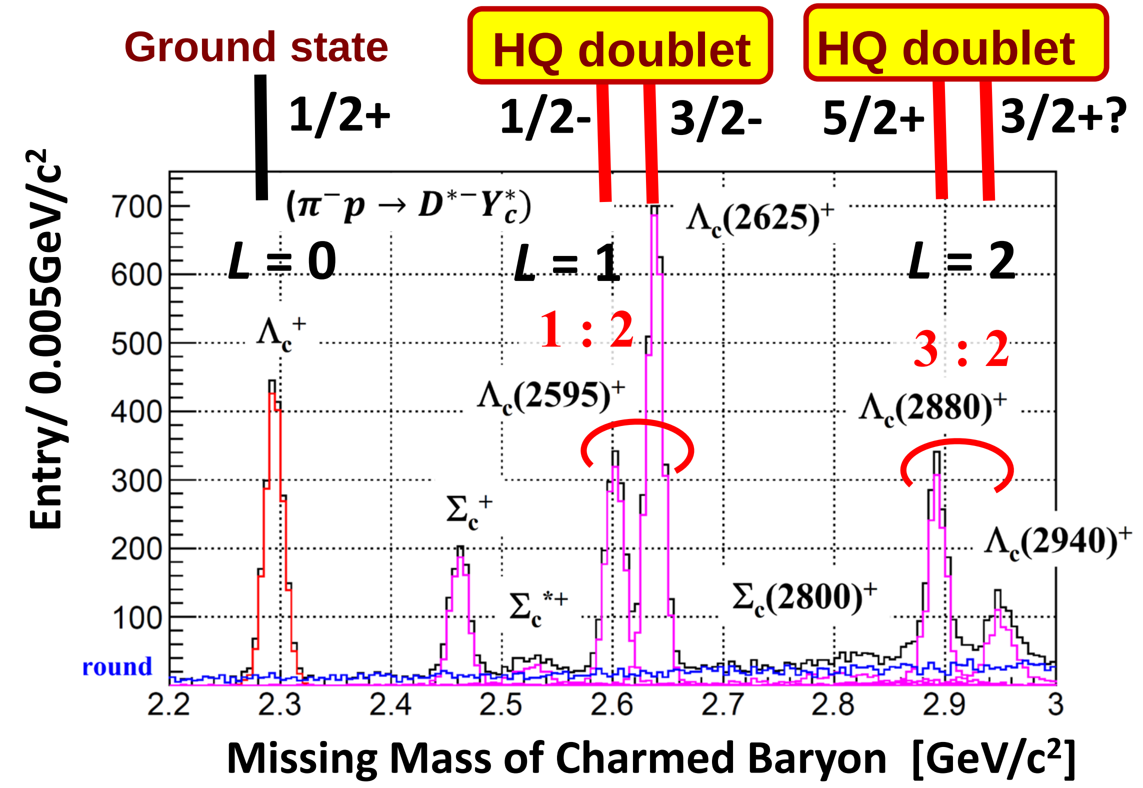
※favor λ-mode
excited state with finite L is populated by factor $(q_{\rm eff}/\alpha)^L$

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

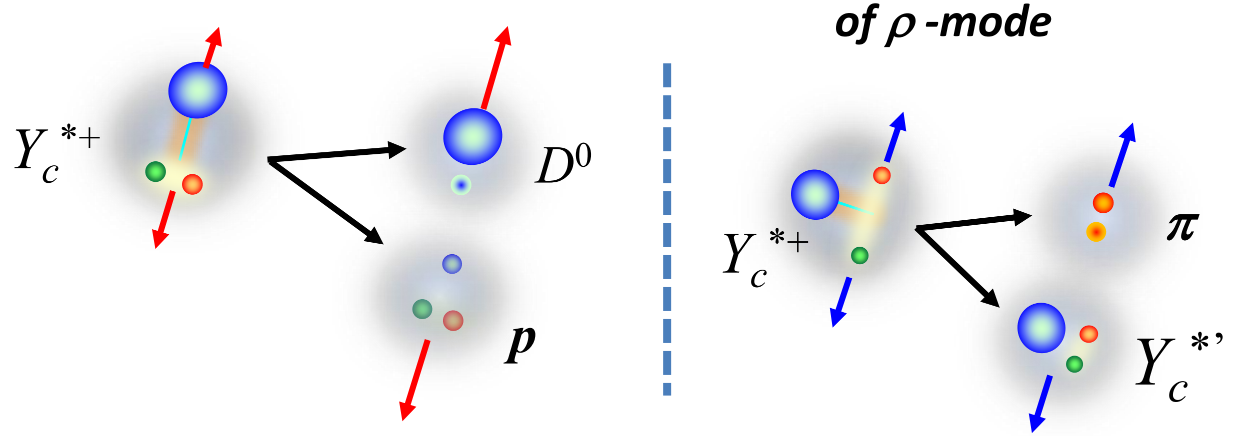
※excite ρ-mode, giving how much the two-quark process contributes.

Expected Mass Spectrum (Simulation)

Simulation (100 days) ***λ-mode excitation***



Decay pattern of λ mode ***Decay pattern of ρ-mode***



※Simulation with assuming known states

- 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 from the prod. ratios (*L*:*L*+1 for λ mode doublet)

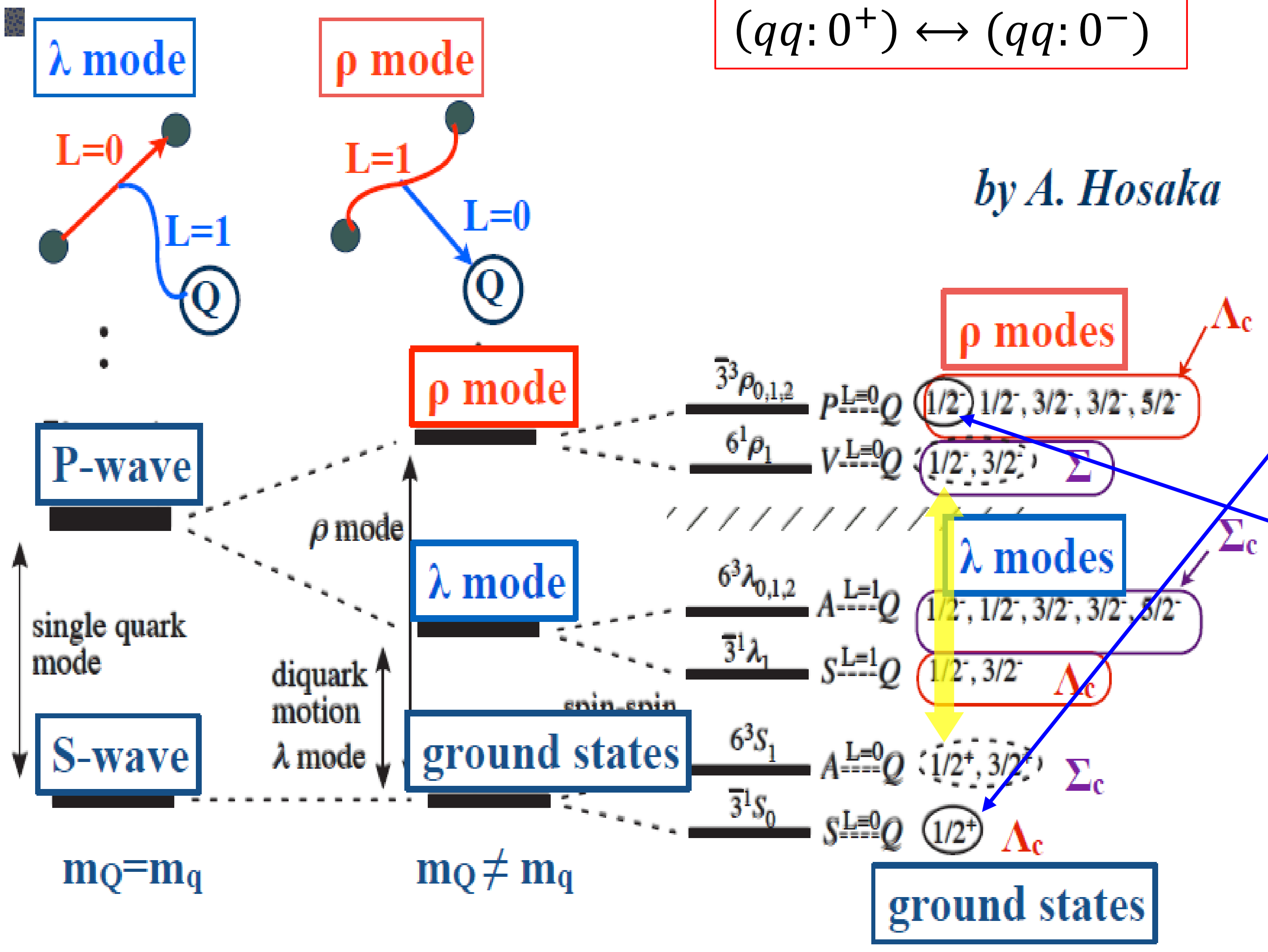
Identify λ/ρ mode

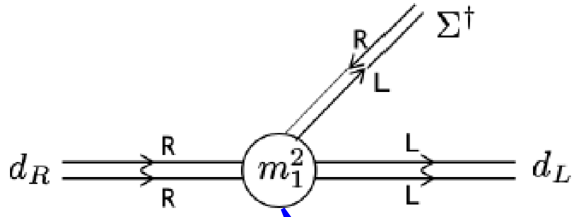
- Establish diquark correlations in λ modes

Diquark in Heavy Baryons

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

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





by M. Oka

Scalar diquark

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

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

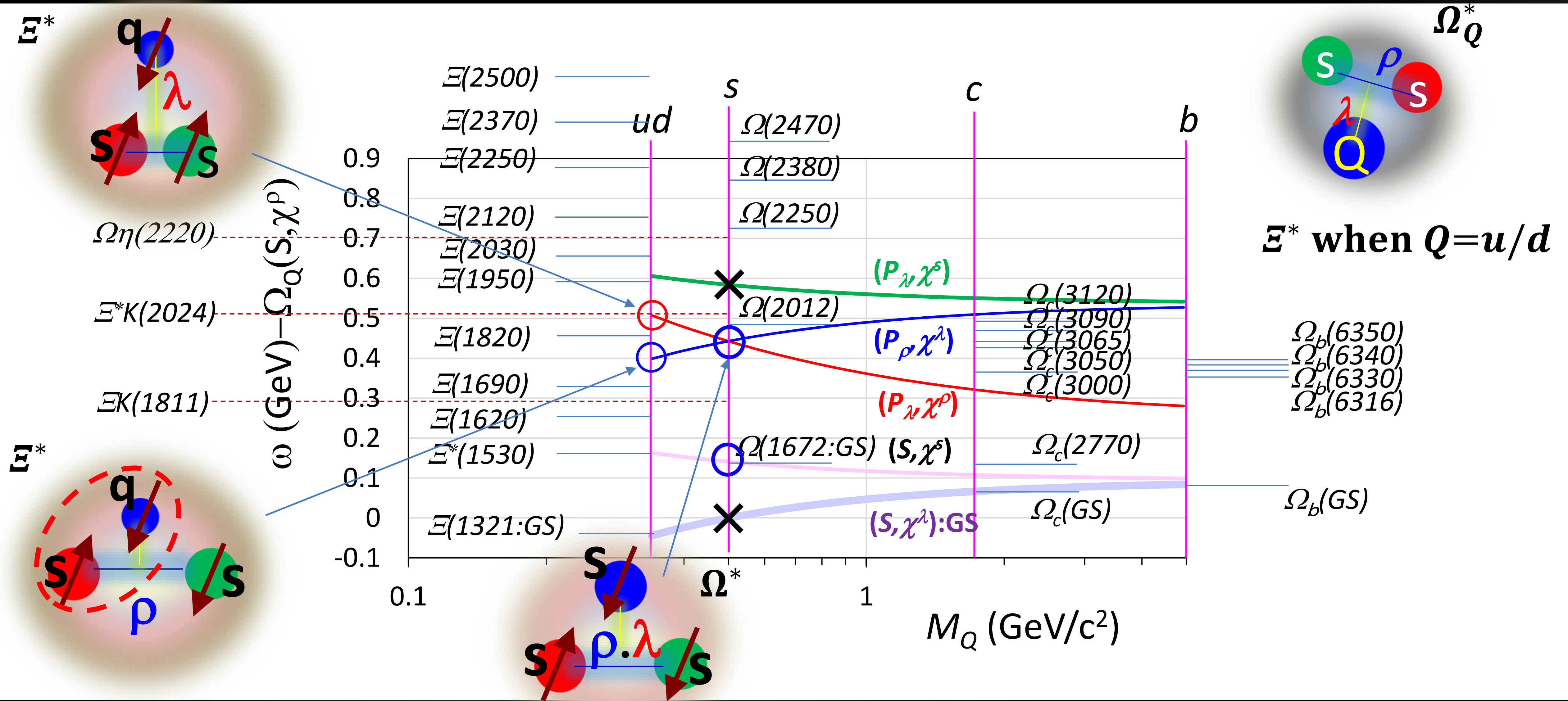
Pseudo-scalar diquark

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

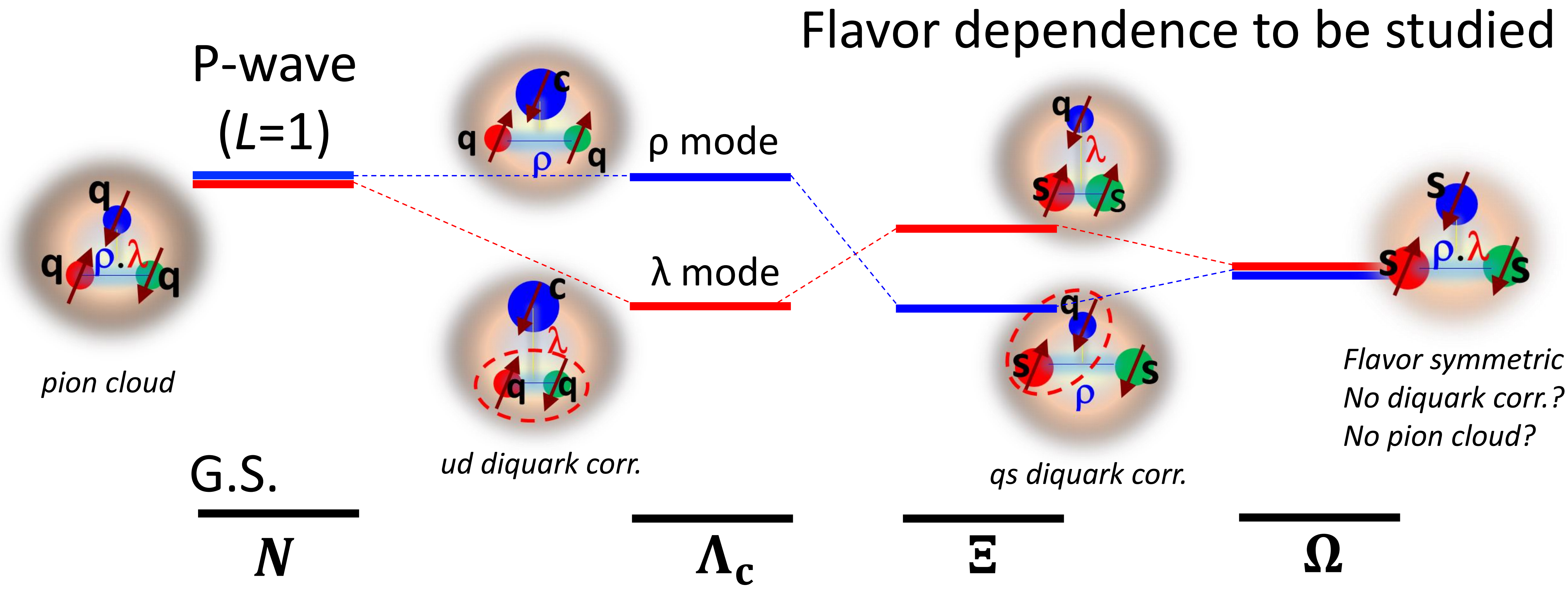
$$\longrightarrow M(0^-) = \sqrt{m_0^2 + m_1^2 + m_2^2},$$

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

Systematics of Qss Baryons – Ξ and Ω –

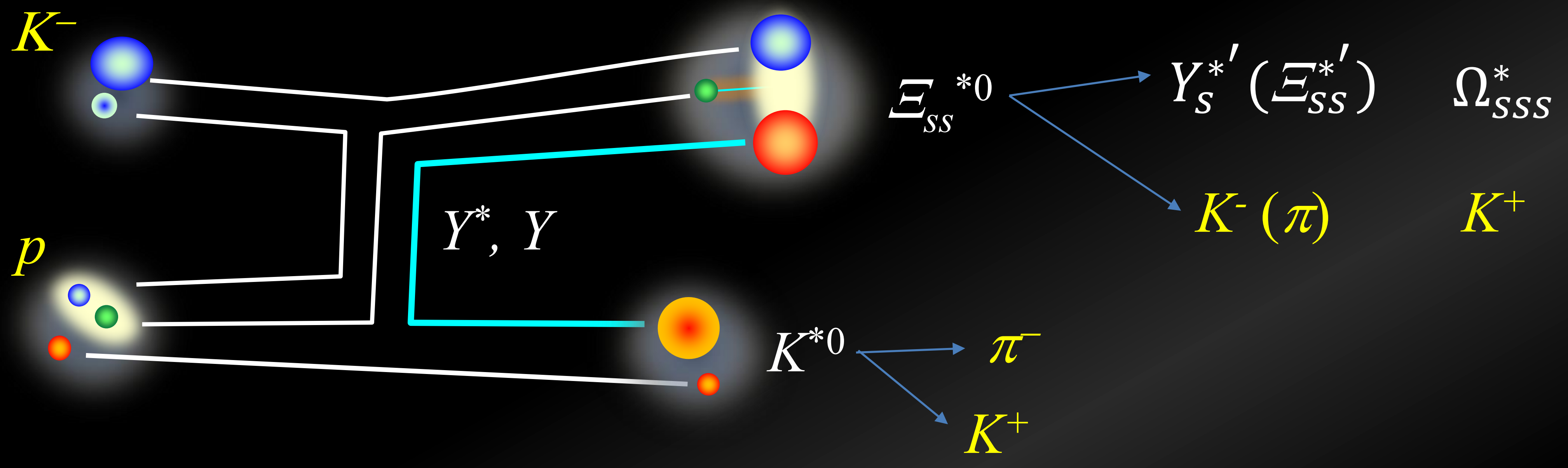


Spectroscopy of strange and charmed baryons



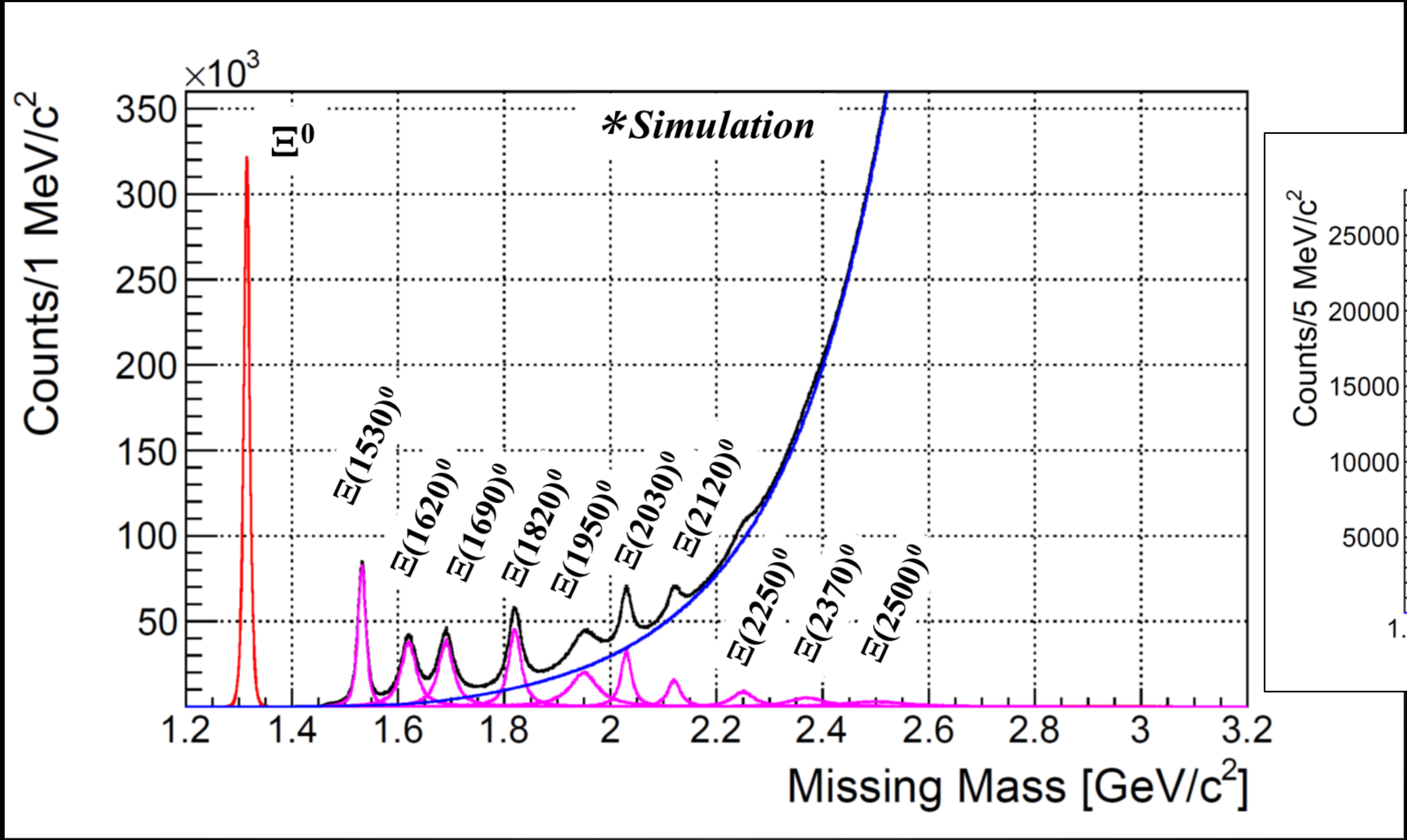
Multi-Strangeness Baryon Spectroscopy Using Missing Mass Techniques

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

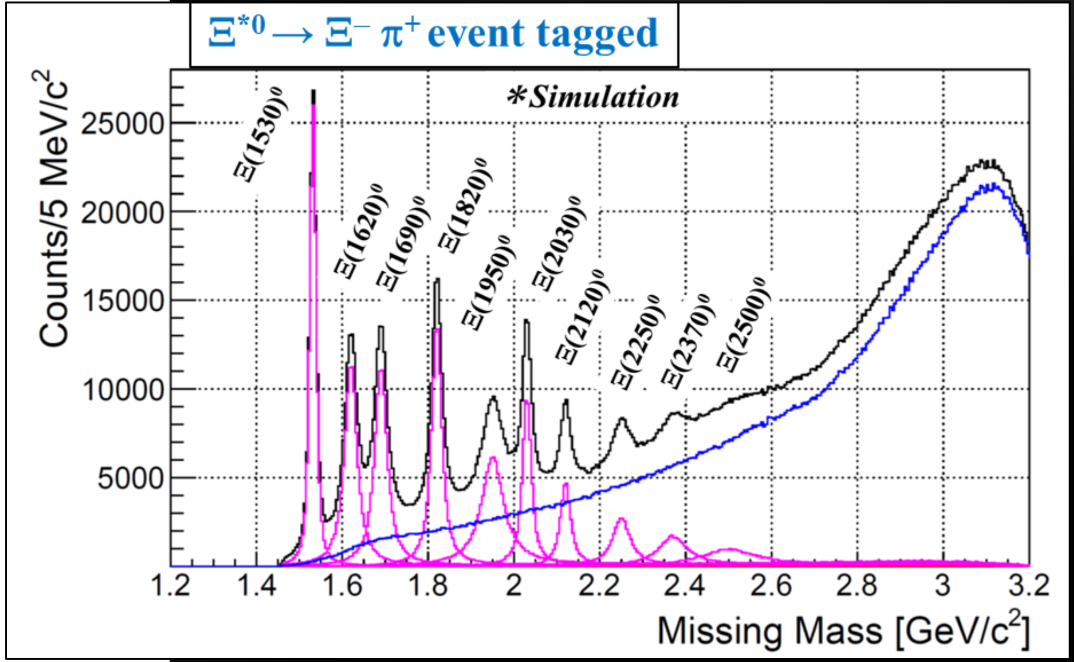


- ✓ Production and Decay reflect [QQ] correlation
- ✓ *Two-quark-involved reaction →Both ρ/λ mode excitations*
- ✓ *Doorway channel to Ω* production* (*via* $\Xi_{ss}^* \rightarrow \Omega_{sss}^* + K^+$)

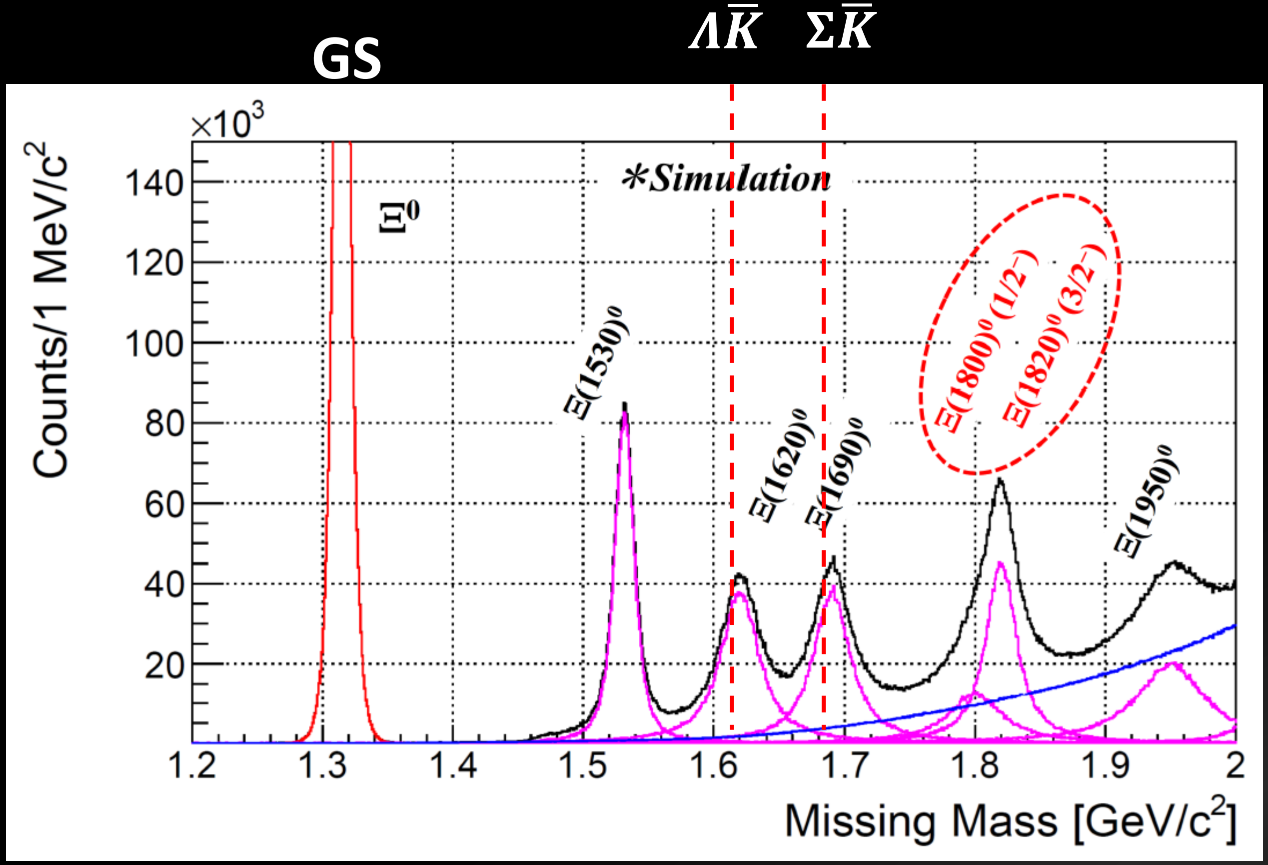
Expected Spectra in $K^- p \rightarrow K^{*0} \Xi^{*0}$ at 8 GeV/c



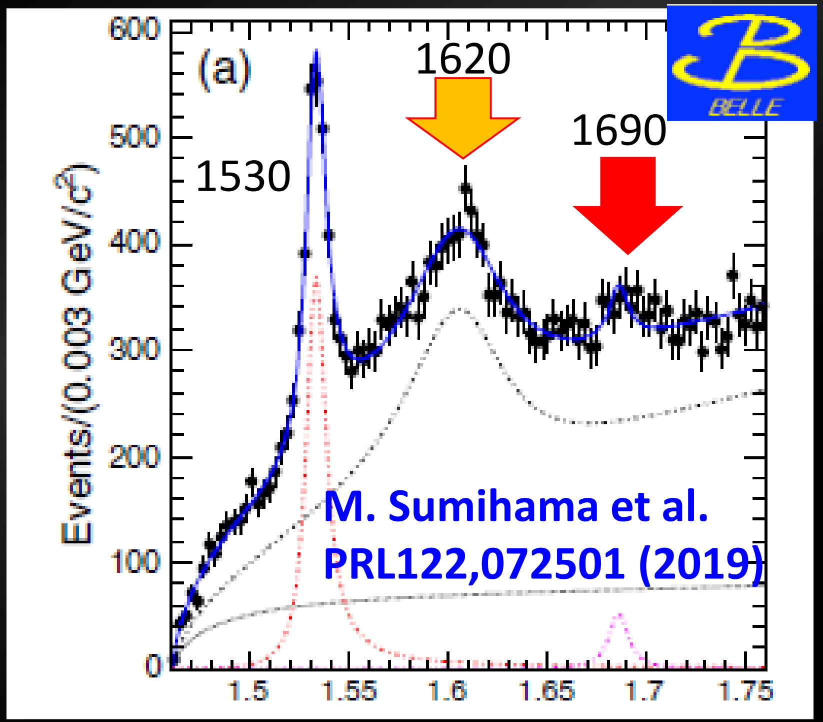
Tagged spectrum showing BG reduction.



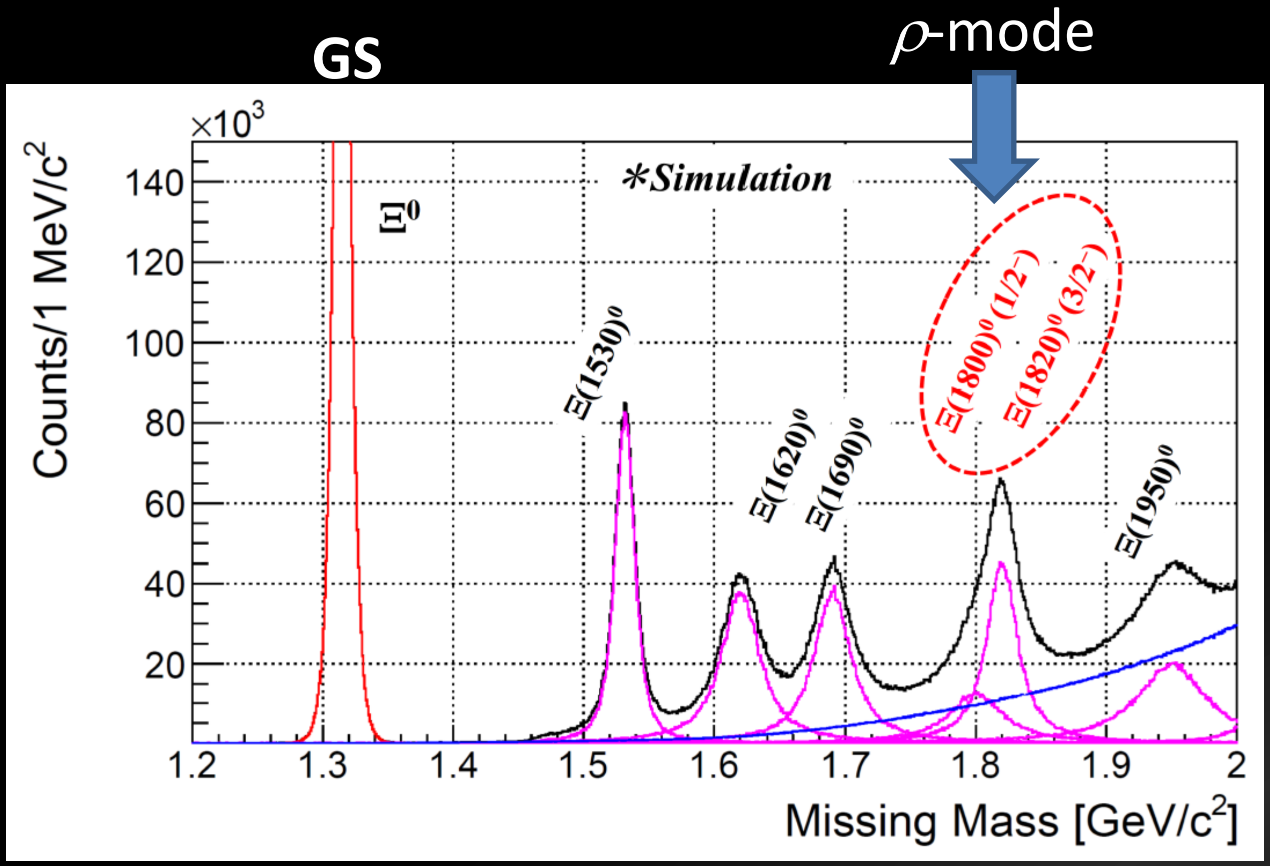
Closed-up the low-lying Ξ states



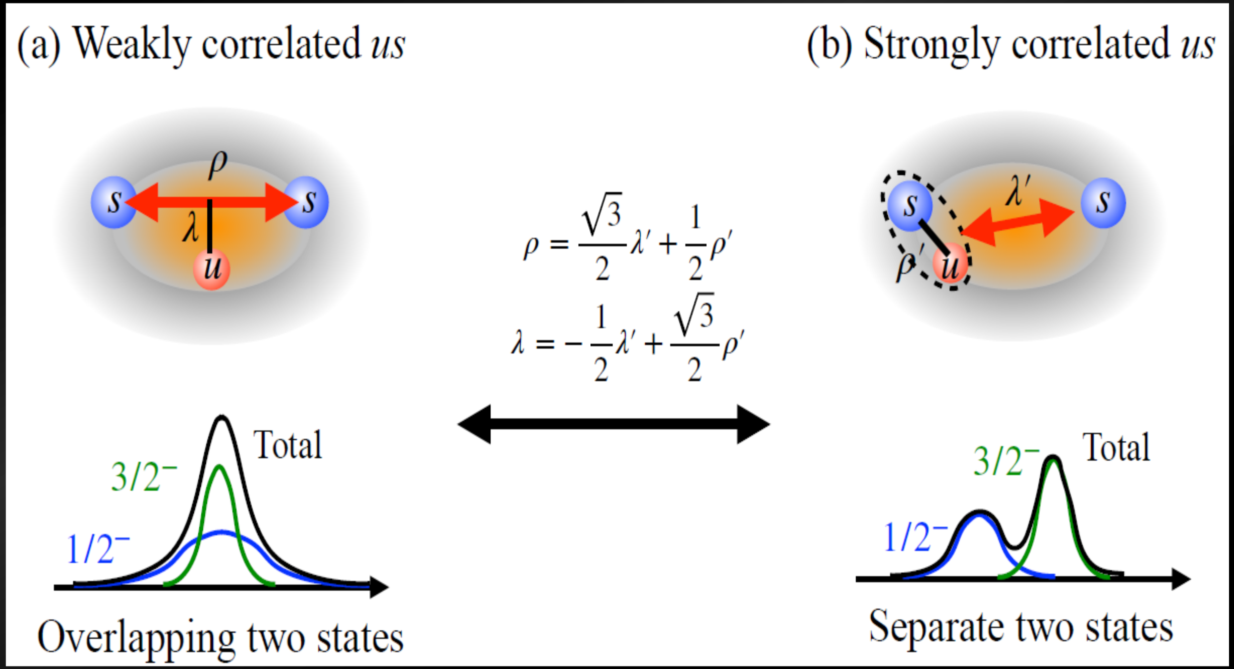
- Unexpected states in CQM?
  - Ξ(1620) nearby $\Lambda\bar{K}$ threshold
  - Ξ(1690) nearby $\Sigma\bar{K}$ threshold
- $Y\bar{K}$ molecular state or casp?
  - Prod. rates would be reduced.



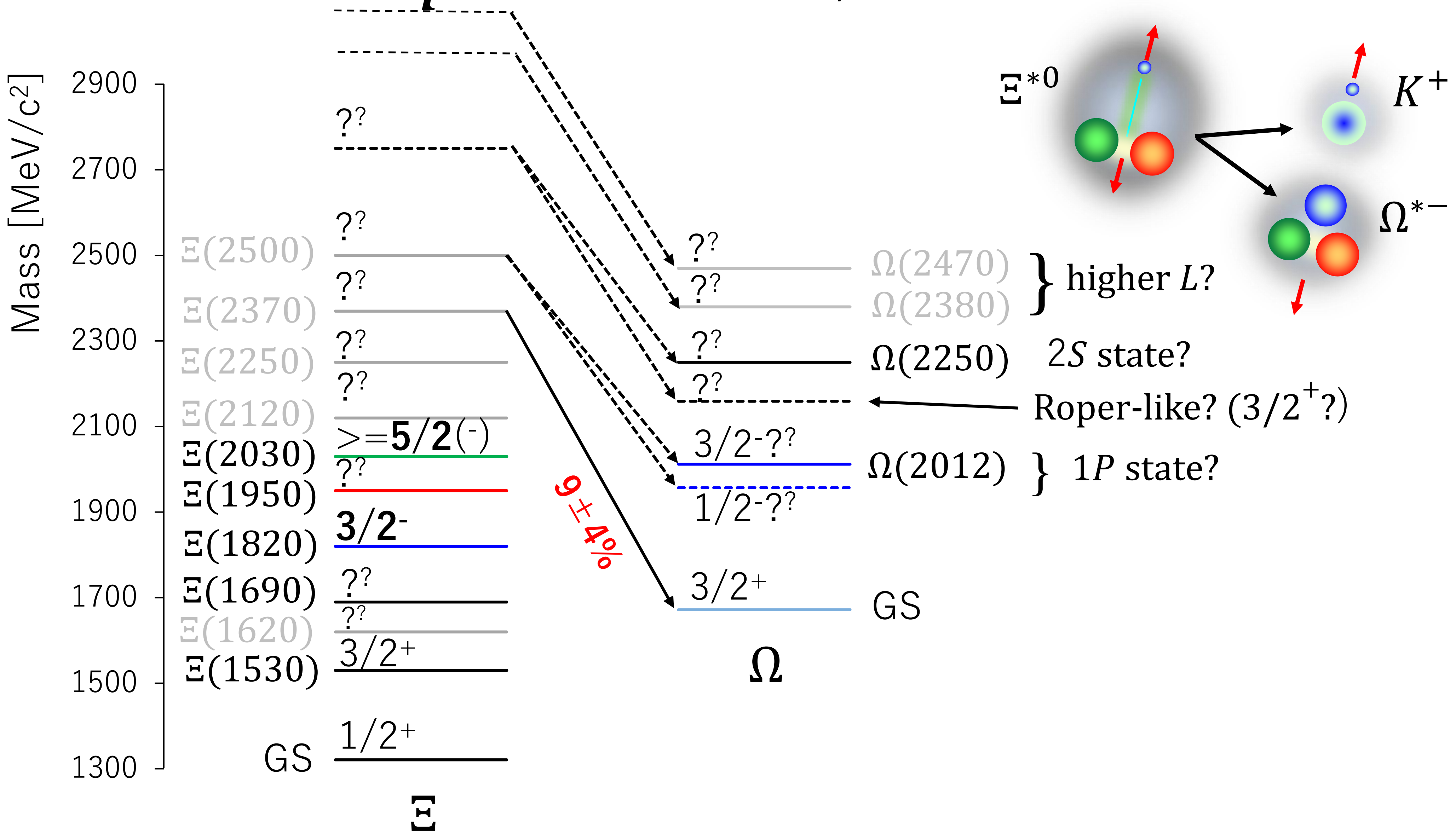
Closed-up the low-lying Ξ states



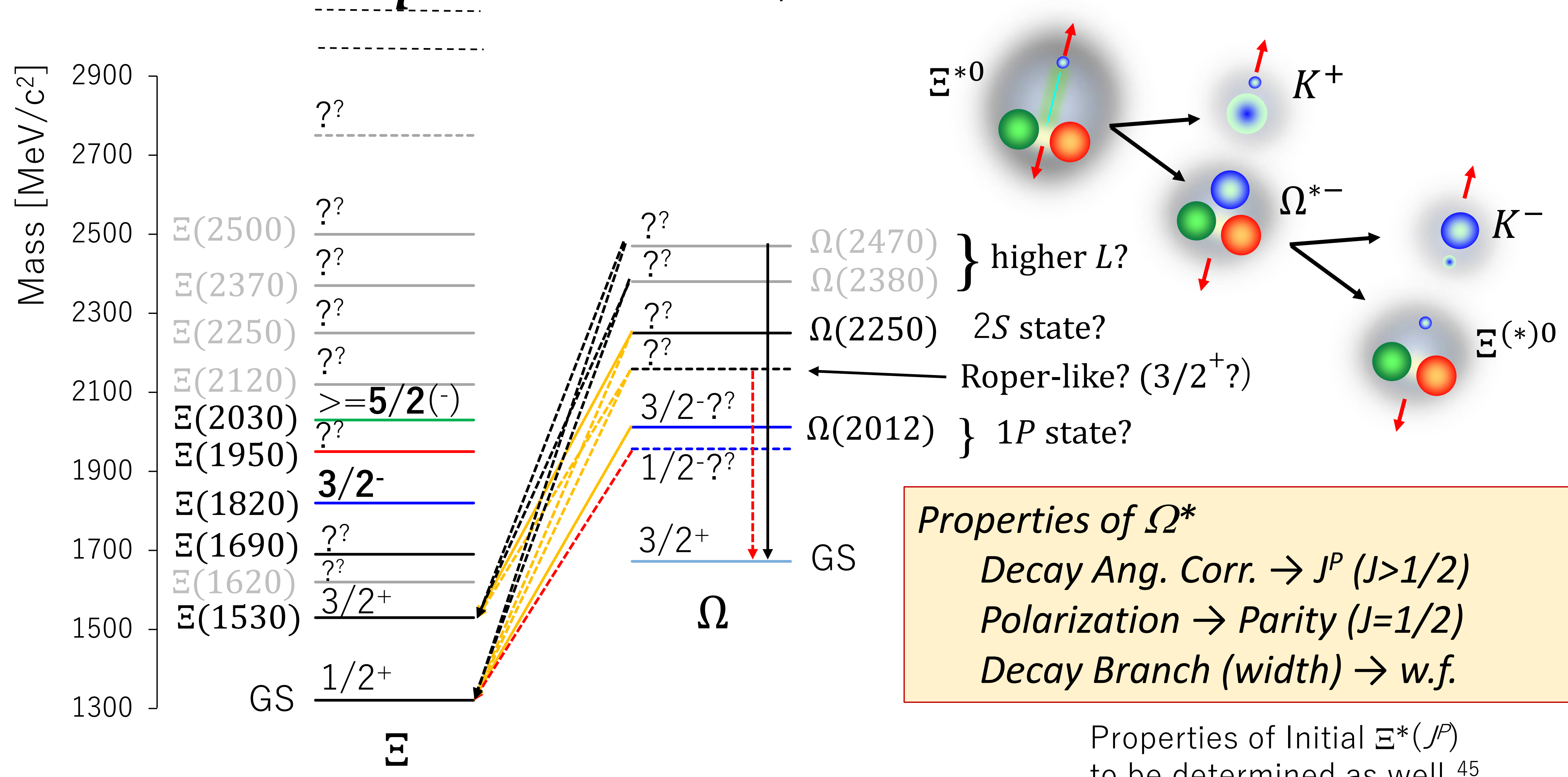
- Interest of ρ-mode excited states
  - Ξ(1820)3/2- to be confirmed
  - *LS* partner (1/2-) to be found
  - Reveal *us*-diquark correlation



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



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



*Properties of Ω**

Decay Ang. Corr. → J^P (J>1/2)

Polarization → Parity (J=1/2)

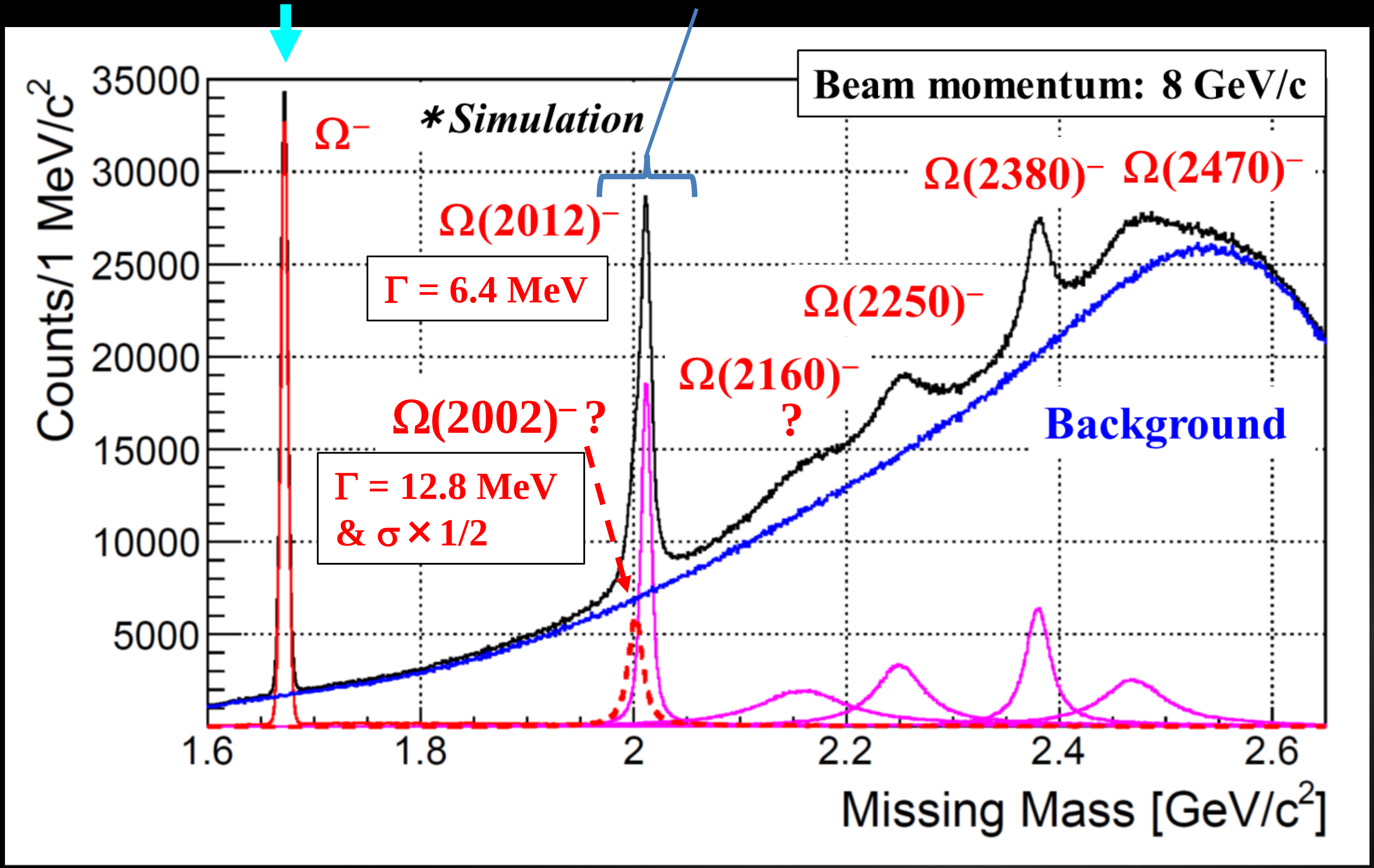
Decay Branch (width) → w.f.

Properties of Initial Ξ*(J^P) to be determined as well

Expected Spectra in $K^- p \rightarrow K^{*0} K^+ \Omega^{*-}$ at 8 GeV/c

63 nb assumed

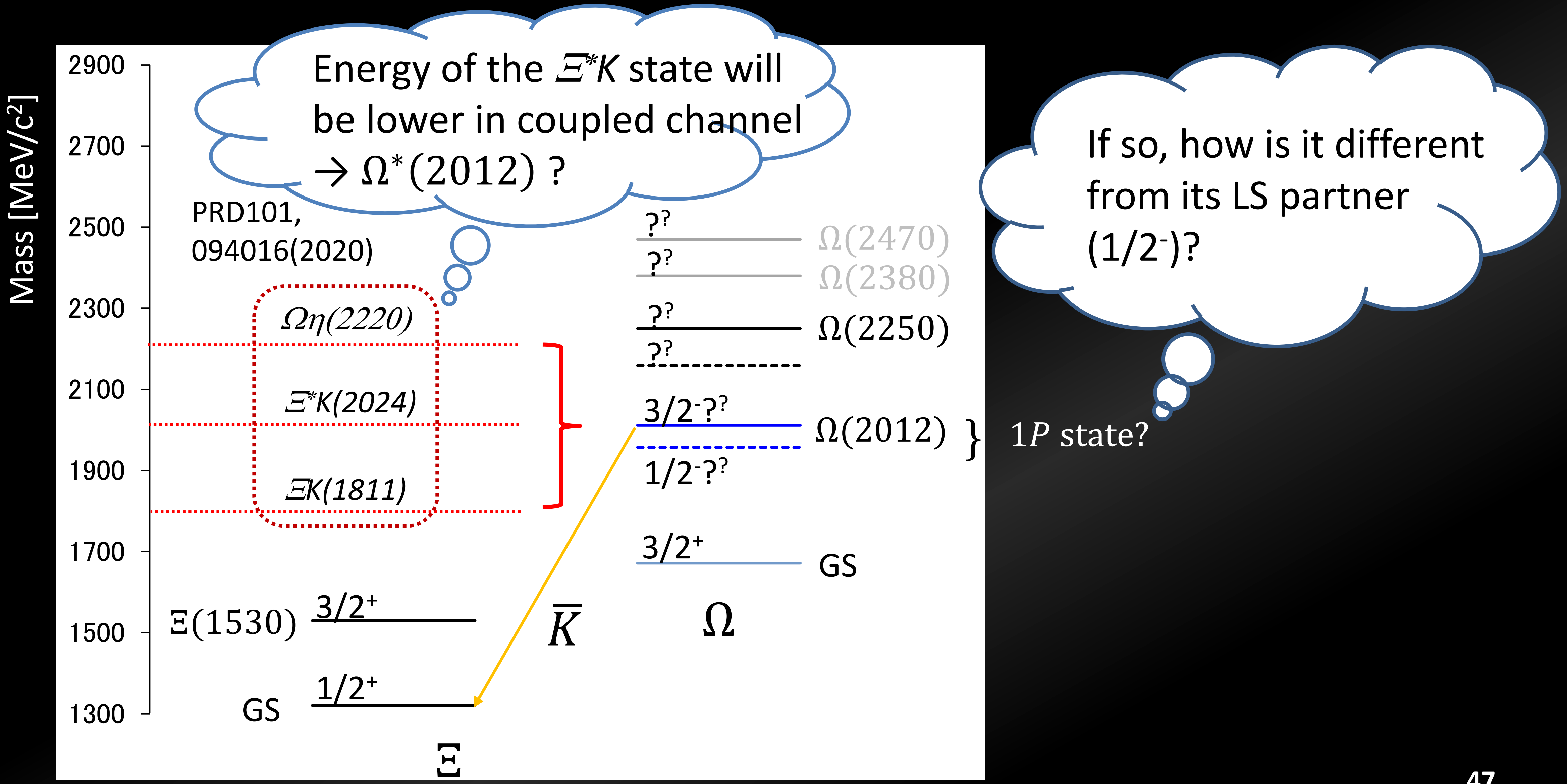
1P states?



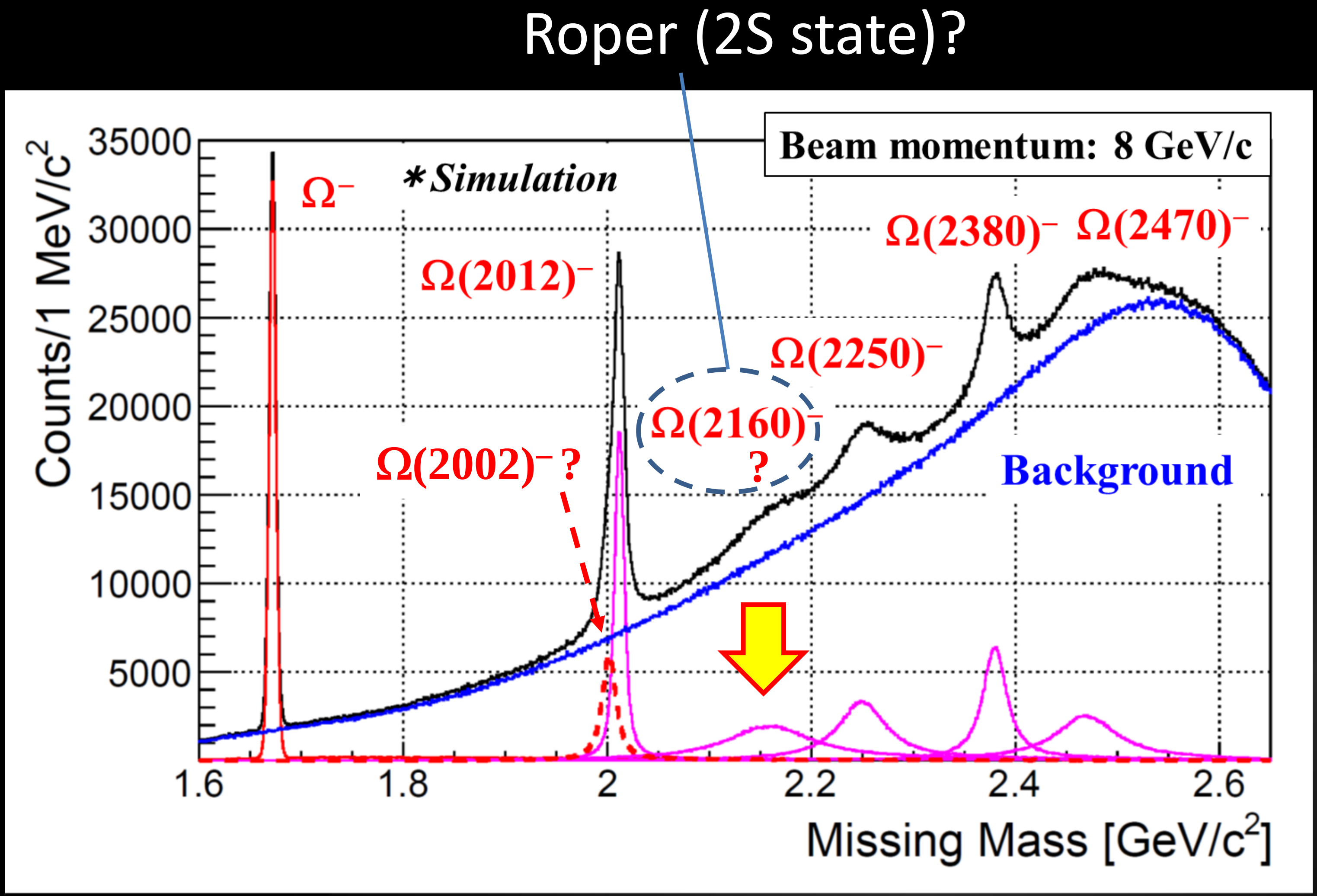
Physics Highlight

- 1P excited states
  - $\Omega(2012)$ J^P to be measured
    - 3/2-?
  - *LS* partner (1/2-) to be found
    - No LS splitting by CQM due to flavor symmetry
  - If a Finite *LS* splitting, Relativistic effect in confinement force?
- Is $\Omega(2012)$: $\Xi^* \bar{K}$ Molecular?
  - PRD101, 094016(2020)

$\Omega^*(2012)$: a Molecular State?



Expected Spectra in $K^{-}p \rightarrow K^{*0}K^{+}\Omega^{*-}$ at 8 GeV/c



Physics Highlight

- 2S excited states
  - Radial excitation
  - So-called Roper-like state, yet to be found
    - $\Omega(2160), \Gamma \sim 100$ MeV assumed
  - The width related to its size.
    - In relativistic correction term <p^2> is a main term.

Summary

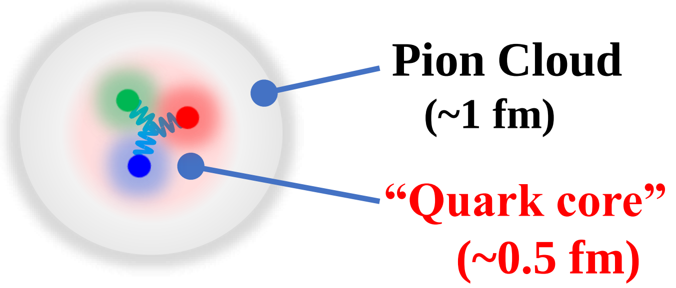
- A heavy quark plays an inert particle in a hadron and is quite helpful to investigate internal motions and/or correlations of quarks.
  - Systematics meas. of Excitation Energy, Production Rate, and Decay (Partial) Width
- Understanding of quark interactions in Baryons is important since it provides fundamental information to understand baryon interactions in nuclear systems and highly-dense hadronic/quark matter.
- We conduct strange and charmed baryon spectroscopy by means of missing mass technique at pi20 and K10, where intense pions and kaons up to 20 and 10 GeV/c, respectively, will be delivered.
  - New platform of hadron physics will be covered owing to the general purpose spectrometer

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)

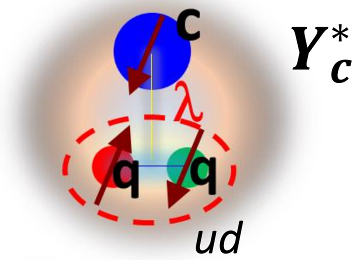
⇒ Constituent q and NG boson (effective DoF).

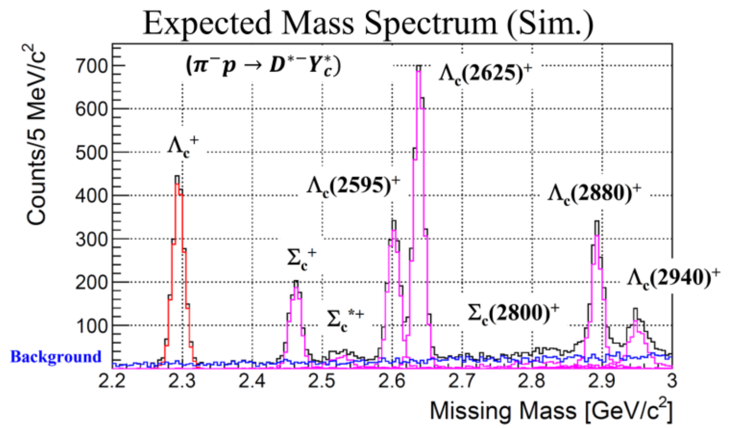


s- and c-baryon spectroscopy → qq correlation in baryons

- **Charm Baryon[$Y_c^*(cqq)$] @ High-p (π20)**

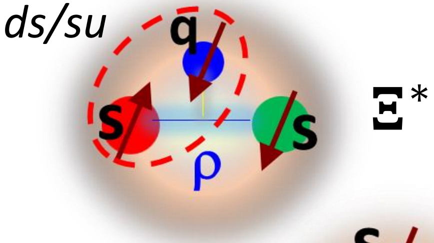
> Disentangle the diquark correlation
> → λ/ρ mode assignment

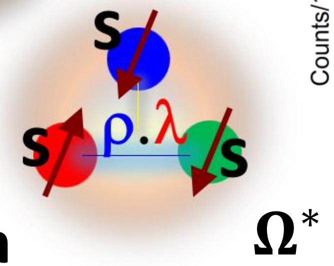


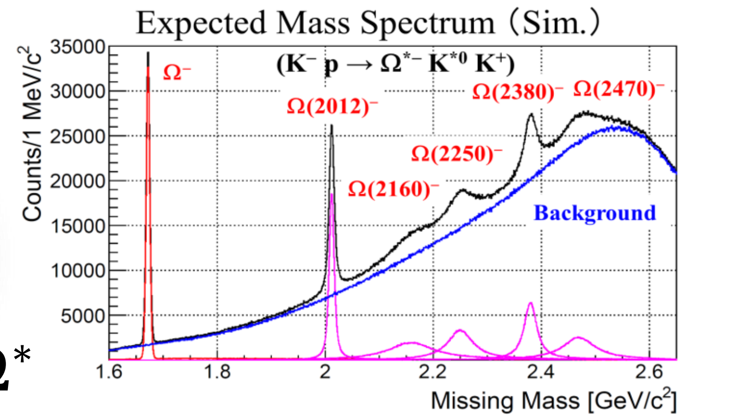


- **$\Xi^*(qss)$、$\Omega^*(sss)$ Baryon @ K10**

> Ξ^*: *ds/su diquark correlation*
> → ρ/λ mode assignment
> Ω^*: the simplest *sss* system
> → NO diquark corr. (ρ/λ degenerated)





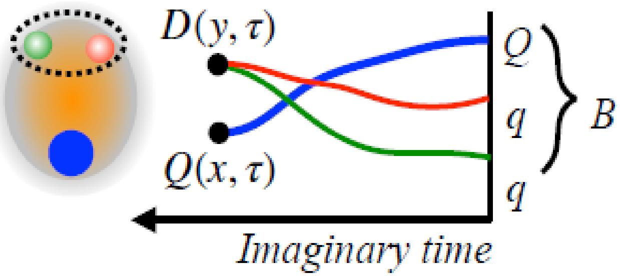


Systematic measurements of "total CS" and "Br ratio" will provide the *internal structure* of the excited baryon

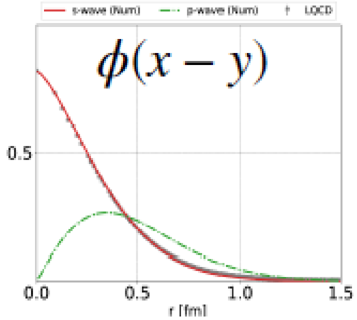
Strategy

https://zukan.com/fish/internal33

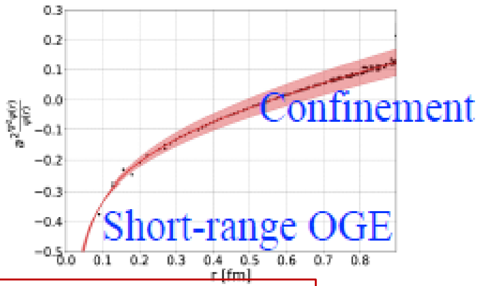
$$\phi(x-y) \sim \langle 0 | D(y,\tau) Q(x,\tau) B^{\dagger}(\tau=0) | 0 \rangle$$
$$\sim qq$$



Watanabe and Ishii e-Print: 2105.07969 [hep-lat]



$V(r) \sim$ *Effective Hamiltonian*



A Q-DQ model set up in LQCD
to examine various diquark correlations

Effective theory

Constituent quarks and pions

Instantons

High Temp Matter

QCD

SSB of χ symm.

Confinement

Excited states

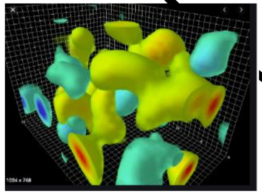
Quarks

Hadrons@π20/K10

Extension to various strongly interacting systems

Ground states

※



Various correlators

Baryon-Baryon Int.

High Density Matter

Lattice QCD

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