Light Cone 2021: Physics of Hadrons on the Light Front
29 November-4 December, 2021

Spectroscopic study of quark dynamics in baryons at J-PARC

Hiroyuki NOUMI*
for the Taskforce on the extension of the Hadron Experimental Facility

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

arXiv:2110.04462

Extension of the J-PARC Hadron Experimental Facility

- Third White Paper -

Taskforce on the extension of the Hadron Experimental Facility,

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Origin & Evolution of Matter

Matter in Extreme Conditions

hyperon puzzle in neutron stars

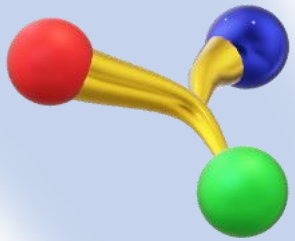
flavor symmetry breaking
hadron interaction
formation of a nucleus

HIHR/K1.1

Hypernuclei spectroscopy
YN scattering

Matter Evolution

fundamental structure of matter



chiral symmetry breaking
quark interaction

π20/K10

Hadron spectroscopy
Meson in nuclei

Birth of Matter

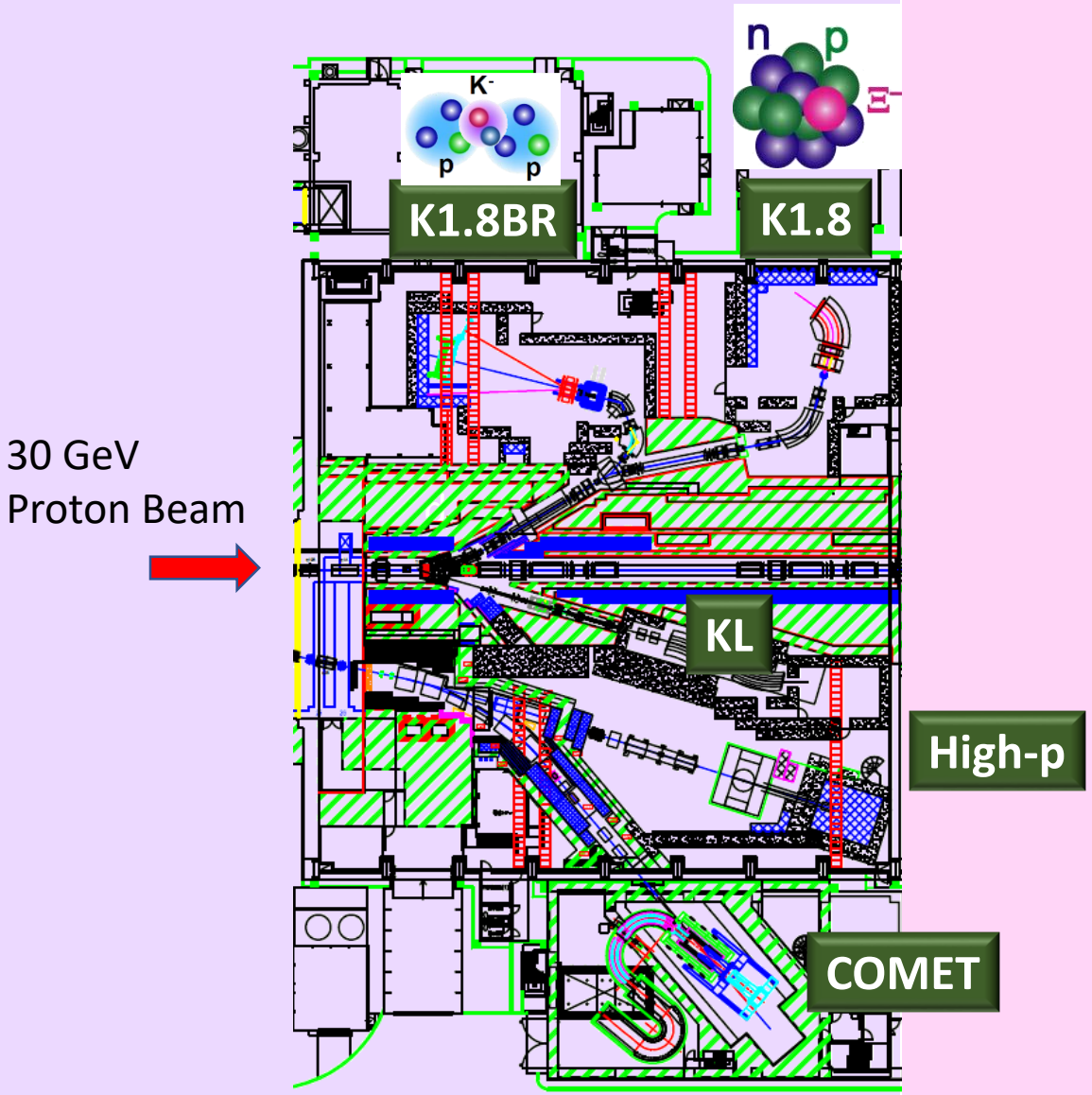
matter dominated universe

CP symmetry violation
weak interaction

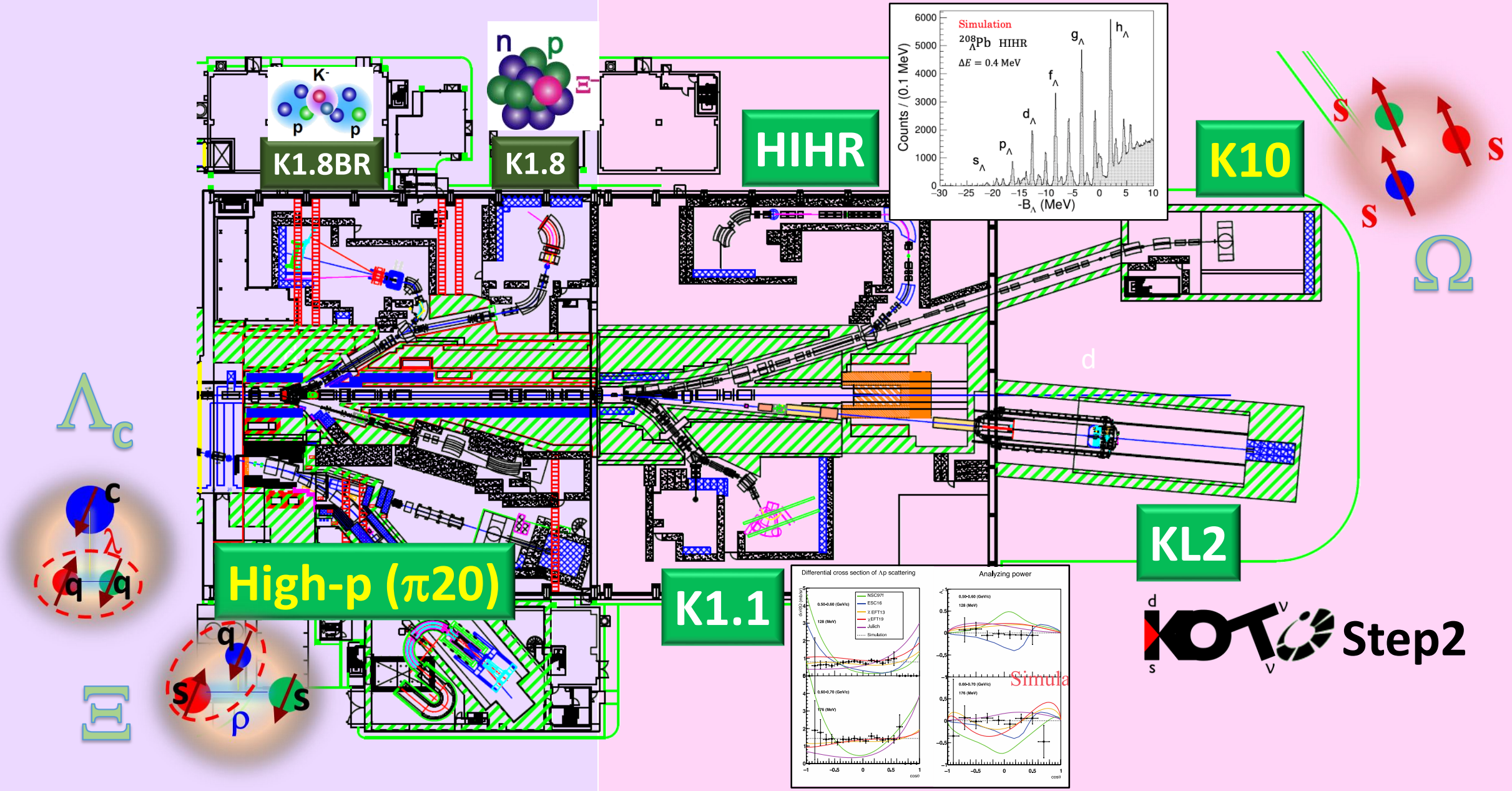
KL2

Kaon decays

Current Hadron Experimental Facility



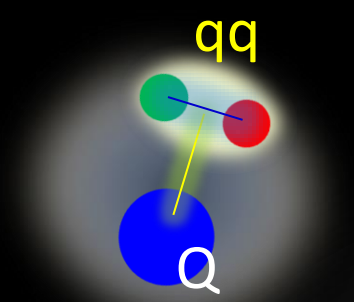
Extended Hadron Experimental Facility

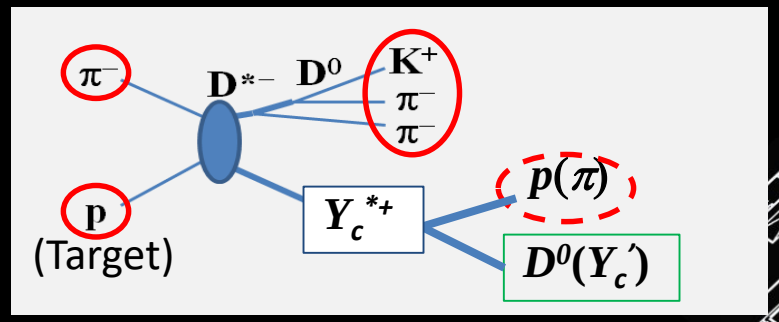


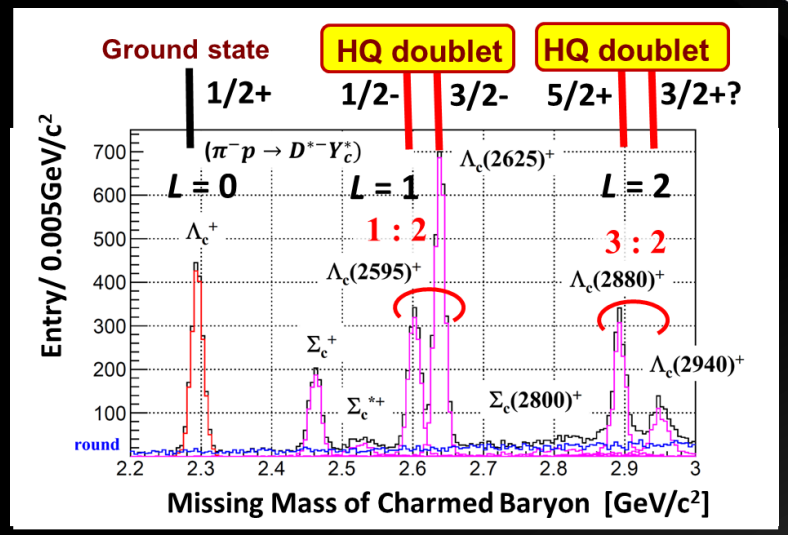
Charm Baryon Spectroscopy at High-p (π20)

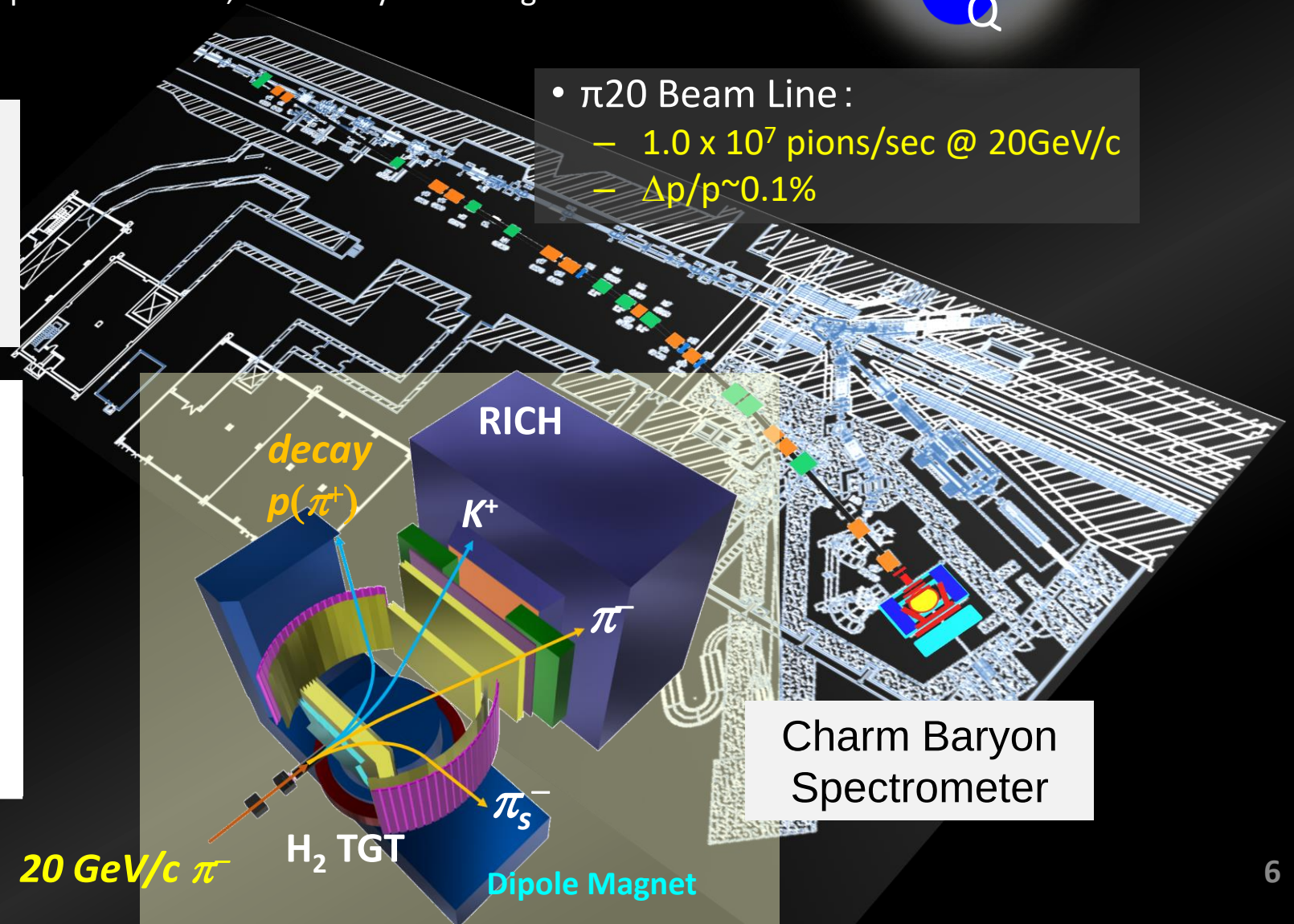
Diquark [qq]: an effective degree of freedom to describe hadrons

- [qq] would be singled out by Introducing a Heavy Quark
- Characteristic level structure, production rate, and decay branching ratio







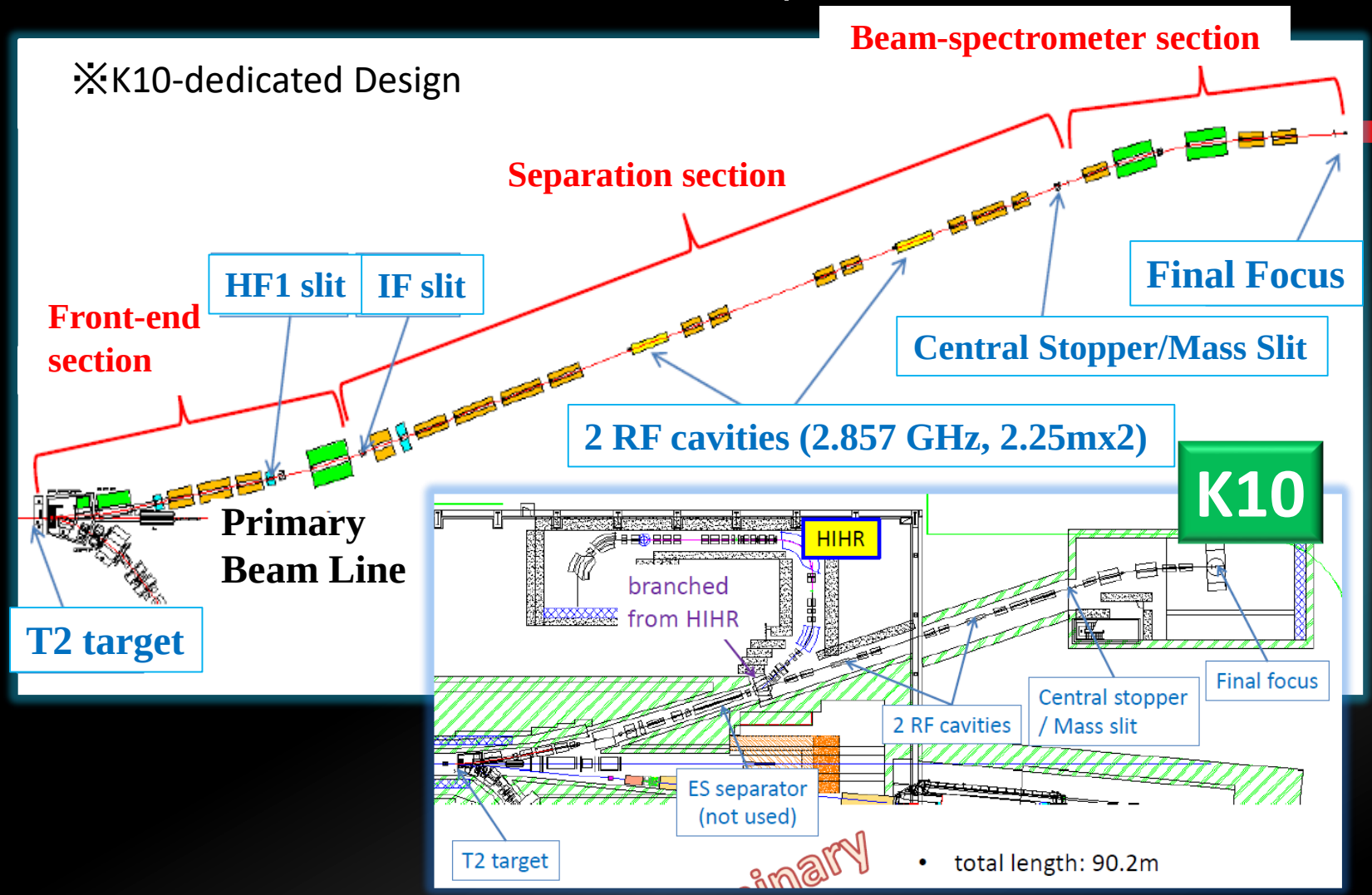


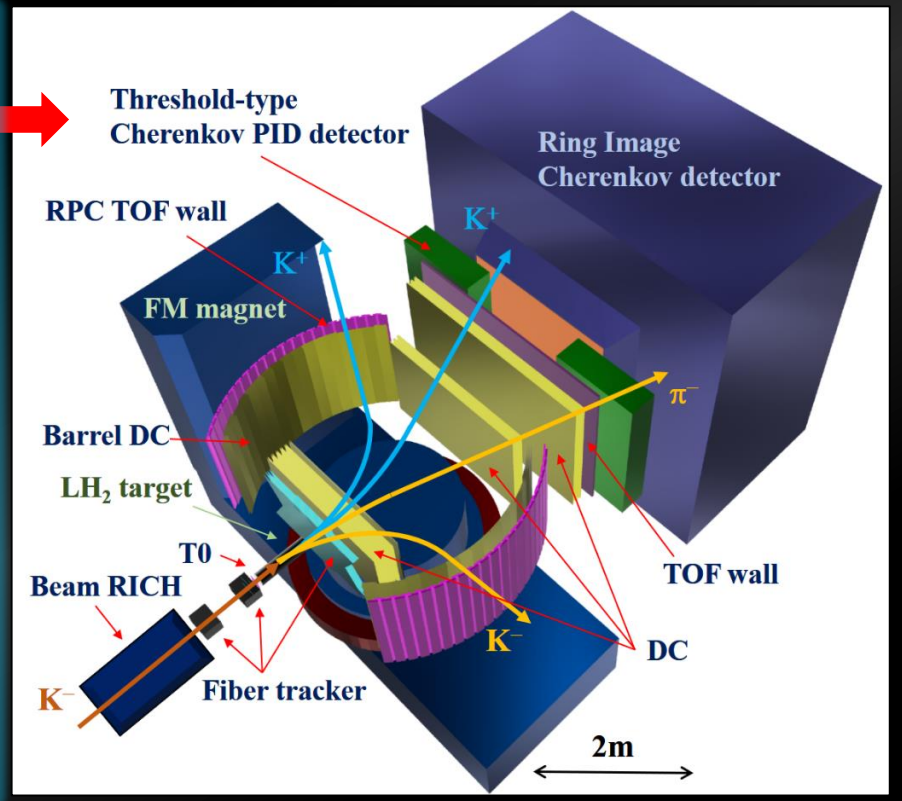
- π20 Beam Line :
  - 1.0 x 10^7 pions/sec @ 20GeV/c
  - Δp/p~0.1%

Charm Baryon Spectrometer

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)

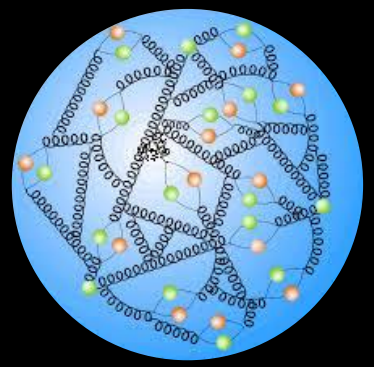




※Design to share upstream w/ HIRH is in progress

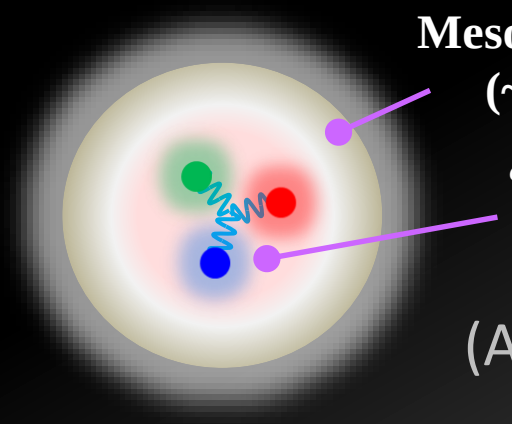
Issue: How does QCD build baryons?

High E
perturbative



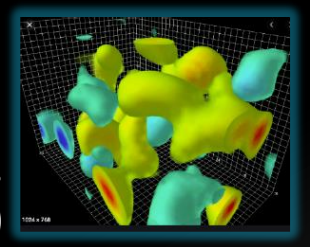
$\alpha_s = \infty$
at Λ_{QCD}

Low E
non-perturbative



(A typical figure)

Instanton
(LQCD demo.
by D. Leinweber)

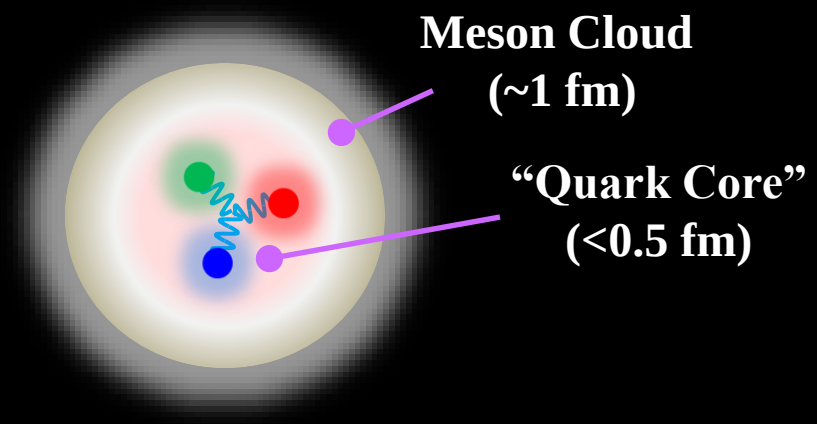


- Non-trivial gluon field
  $\Rightarrow \langle \bar{q}q \rangle$, $U_A(1)$ anomaly
- Confinement

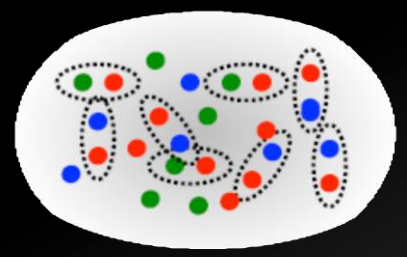
Yet to be clarified

Eff. DoF emerge:
"massive" quarks
NG bosons (pion, …)

Issue: How does QCD build baryons?



dense matter



$\langle qq \rangle$

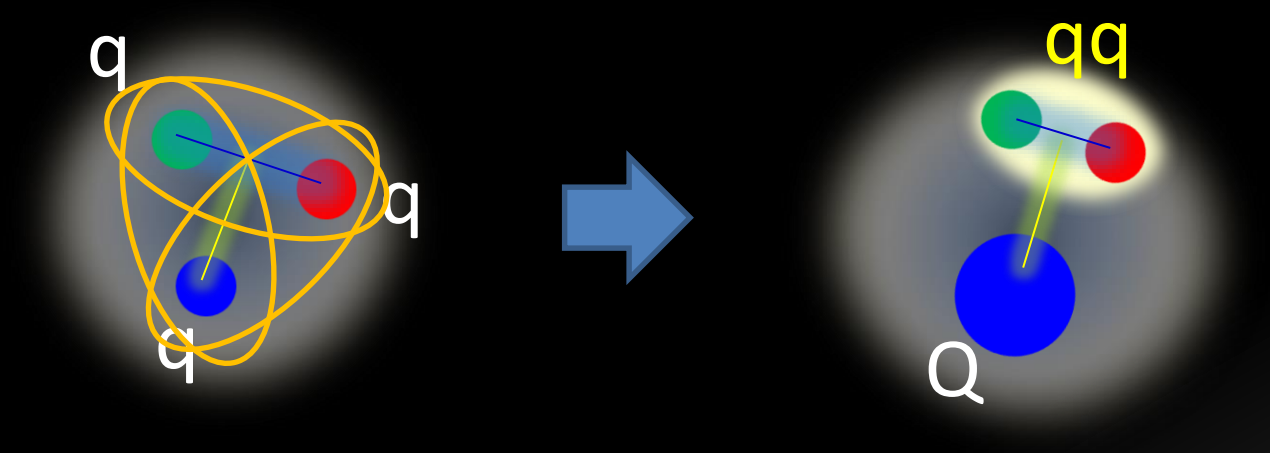
Dynamics of Effective DoF

- Non-trivial gluon field
- Confinement

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

- ✓ *Diquark correlation*
  - short-range spin-spin correlation
  - source of $\langle qq \rangle$ in highly dense matter
- ✓ *Systematics of SS/LS forces*
  - Origin? : OGE vs III, else
- ✓ *Quark motions in "quark core"*
  - Size of "cloud"/"core"

Roles of Heavy Flavors



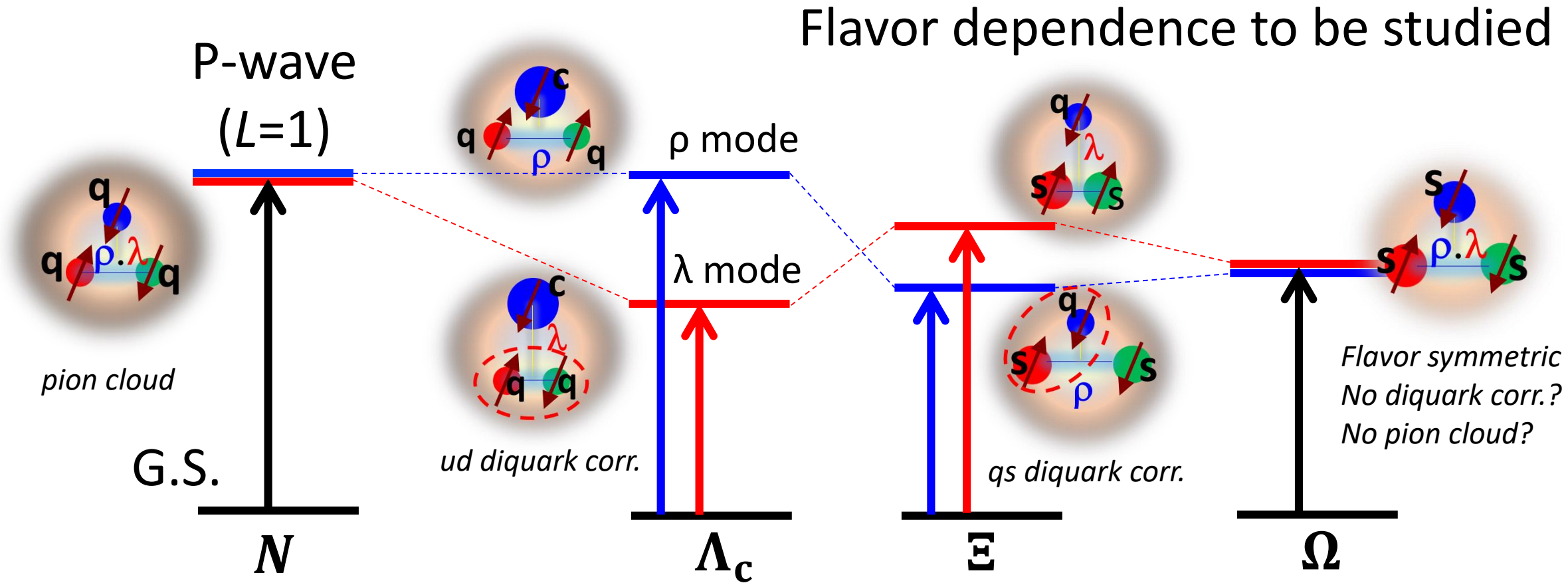
$$V_{CMI} \sim [\alpha_s/(m_i m_j)]*(\lambda_i,\lambda_j)(\sigma_i,\sigma_j)$$
$$\rightarrow 0 \text{ if } m_{i,j} \rightarrow \infty$$

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

- 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.

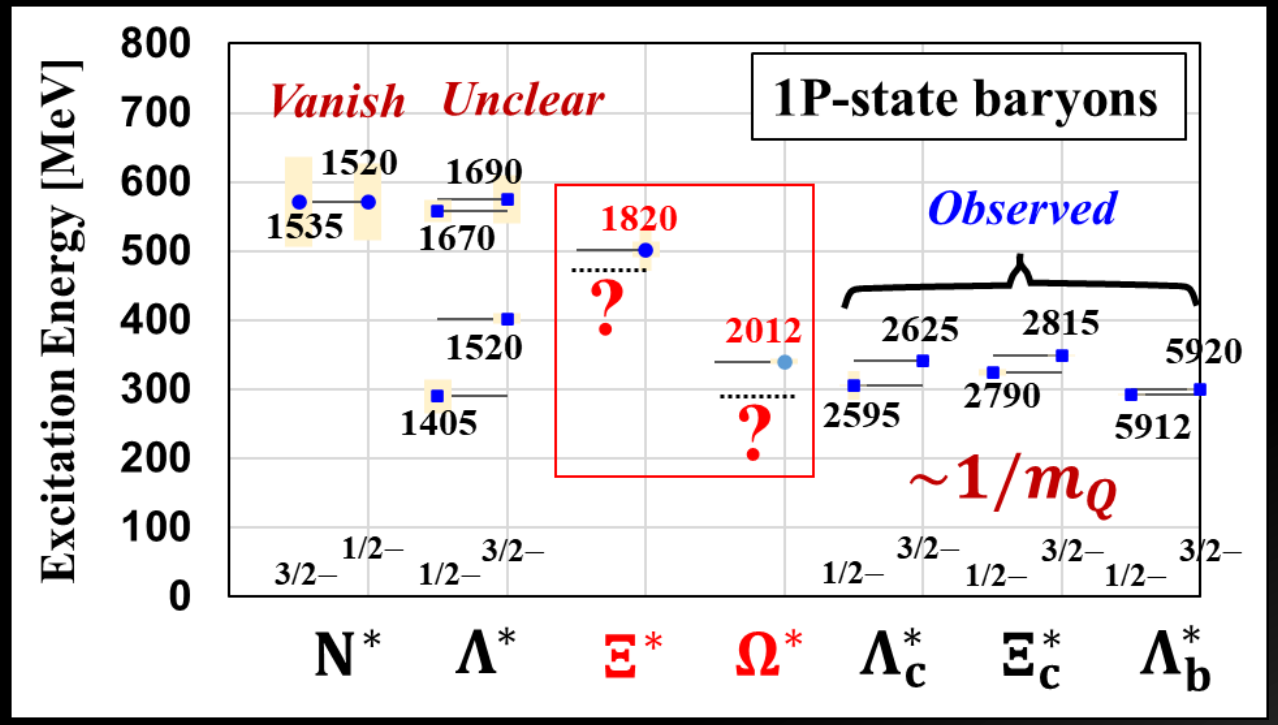
Spectroscopy of strange and charmed baryons

※Disentangle motions of a quark pair by introducing different flavors



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

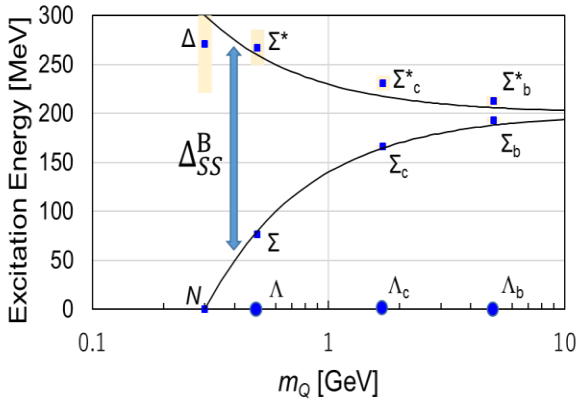
Systematic behaviors in Excited Baryons



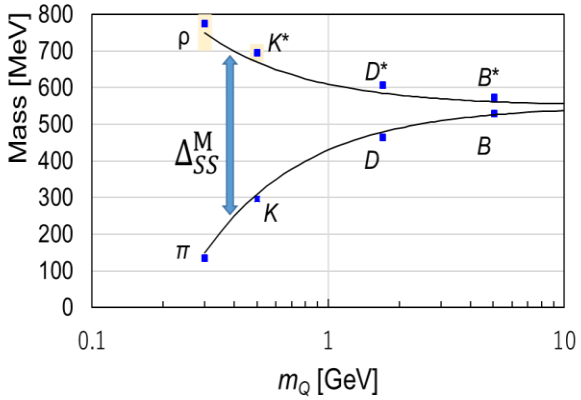
- *ΔM's btw 8tet and 10plet baryons are well explained by the SS int.*
  - *ΔM's btw PS and V mesons as well*
  - *CMI by OGE seems successful.*
  - OGE cannot explain the small LS splitting in N* and finite one in Heavy Baryons

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

Baryons (Decuplet-Octet)

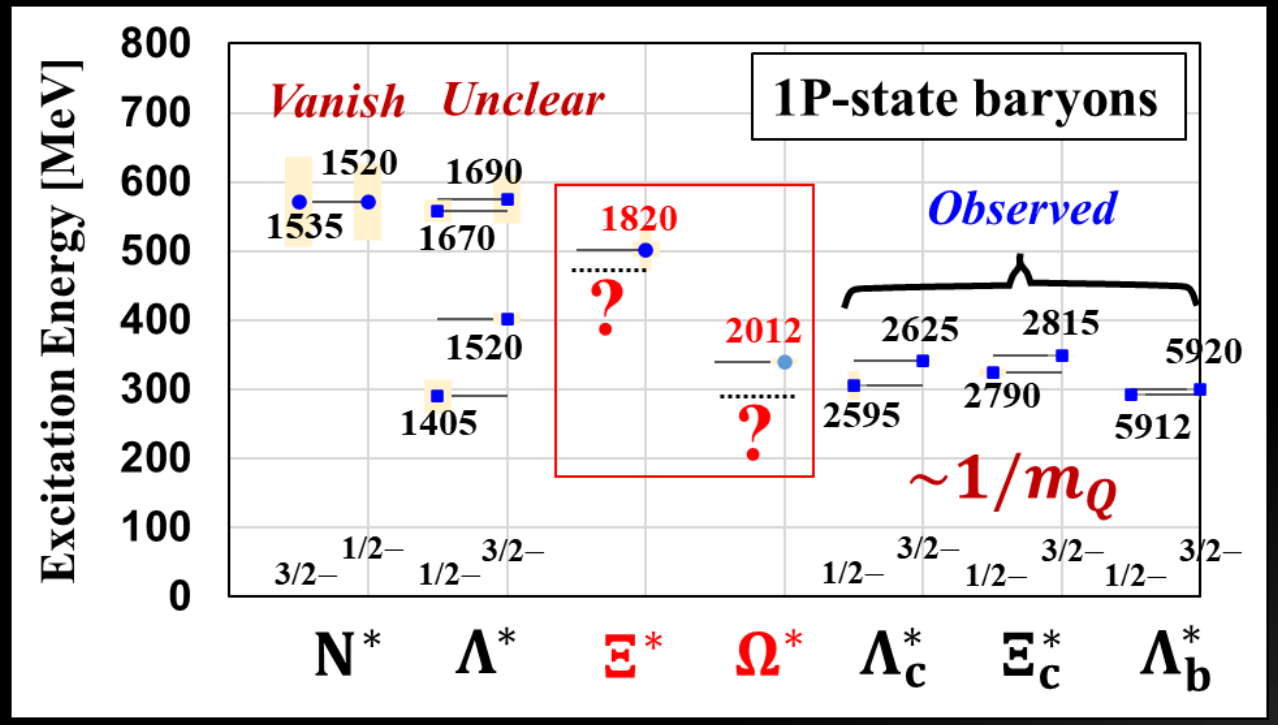


Mesons(V – PS)



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

Systematic behaviors in Excited Baryons



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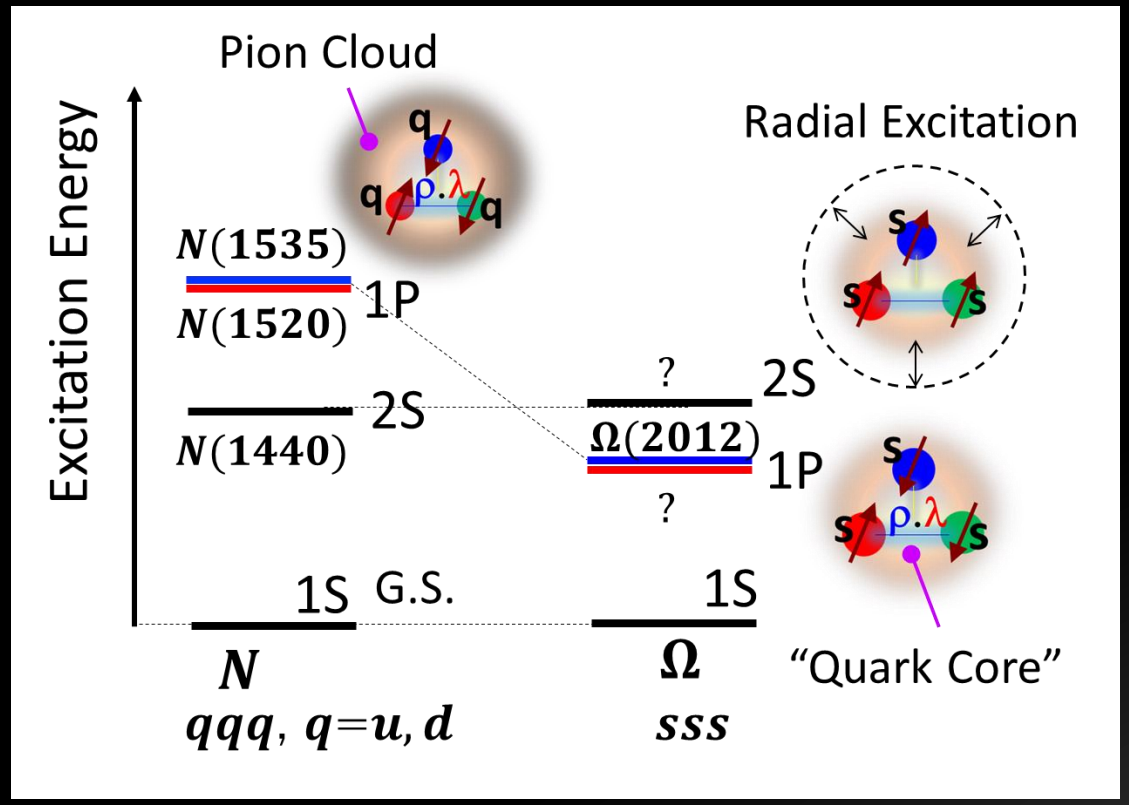
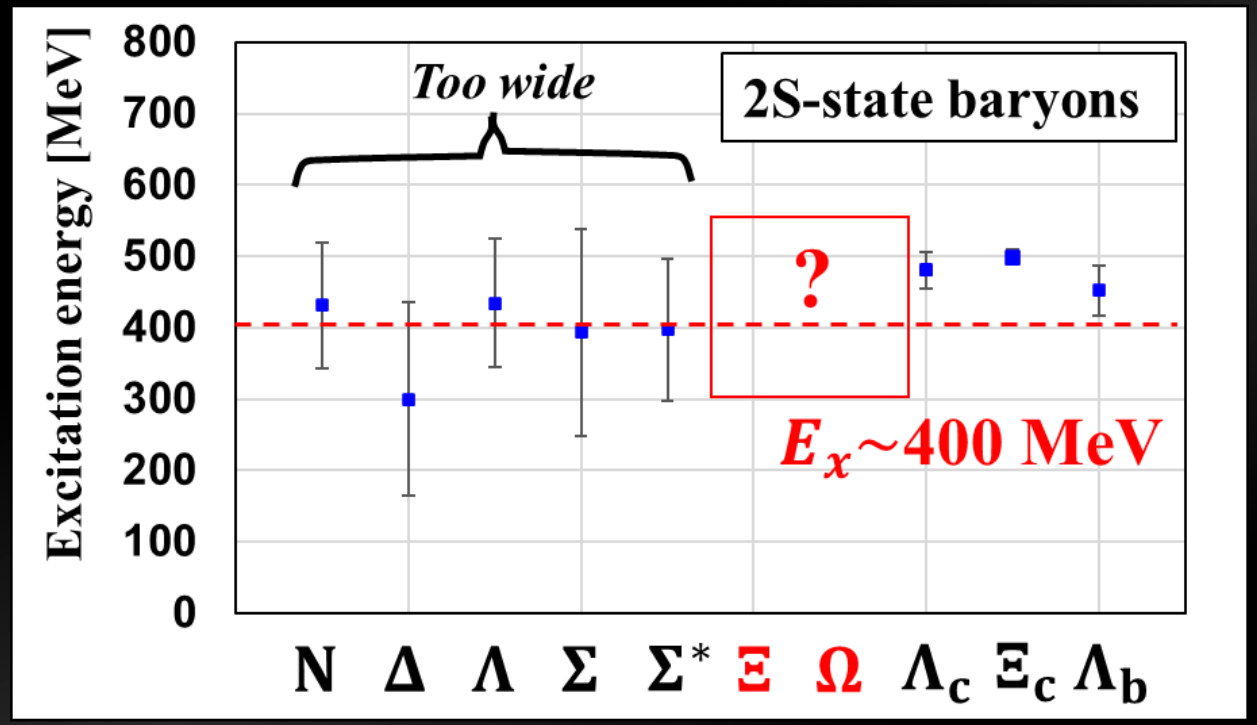
  - *CMI by OGE seems successful.*
  - OGE cannot explain the small LS splitting in N* and finite one in Heavy Baryons
- A cancellation scenario in LS
  - Instanton Induced Int. (III) [KMT int.]
    - Same structure as OGE
    - Effective for only light quarks
    - $U_A(1)$ anomaly in III introduces $\Delta M(\eta' - \eta)$
  - OGE + Instanton Induced Int. (III) in SS
    - No affect in SS splitting both in Baryons and Mesons
  - OGE – III in LS

S. Takeuchi, Nucl. Phys. A **642**, 543 (1998).

Systematic behaviors in Excited Baryons





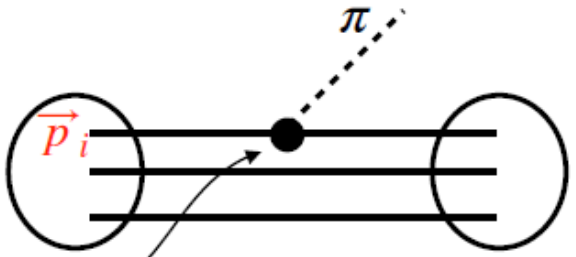
※Universality of "Roper Like" states:
By chance or Mechanism behind them?

Prof. Hosaka's slide

(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

$$\langle \text{Roper} | \mathcal{O} | \text{G.S.} \rangle \sim \langle \vec{\sigma} \cdot \vec{q} \rangle (\cancel{a_0} + a_2 \vec{p}_i^{\,2} + \cdots)$$

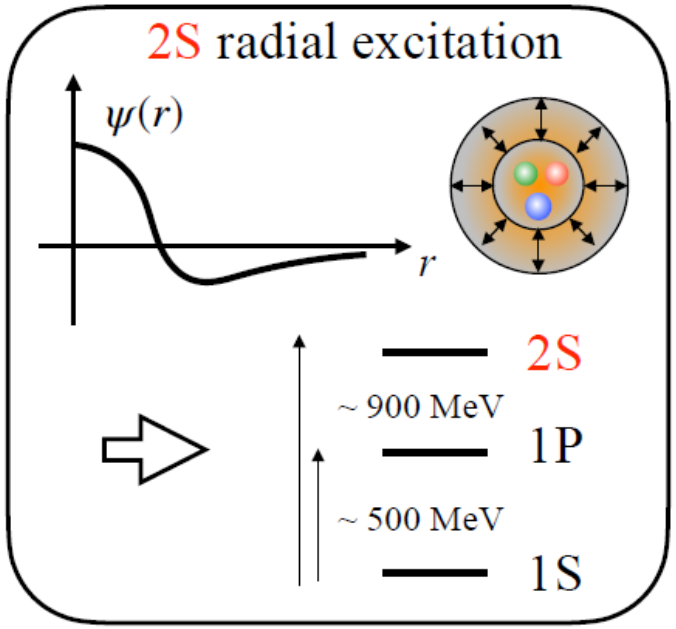
Leading order (LO) suppressed

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



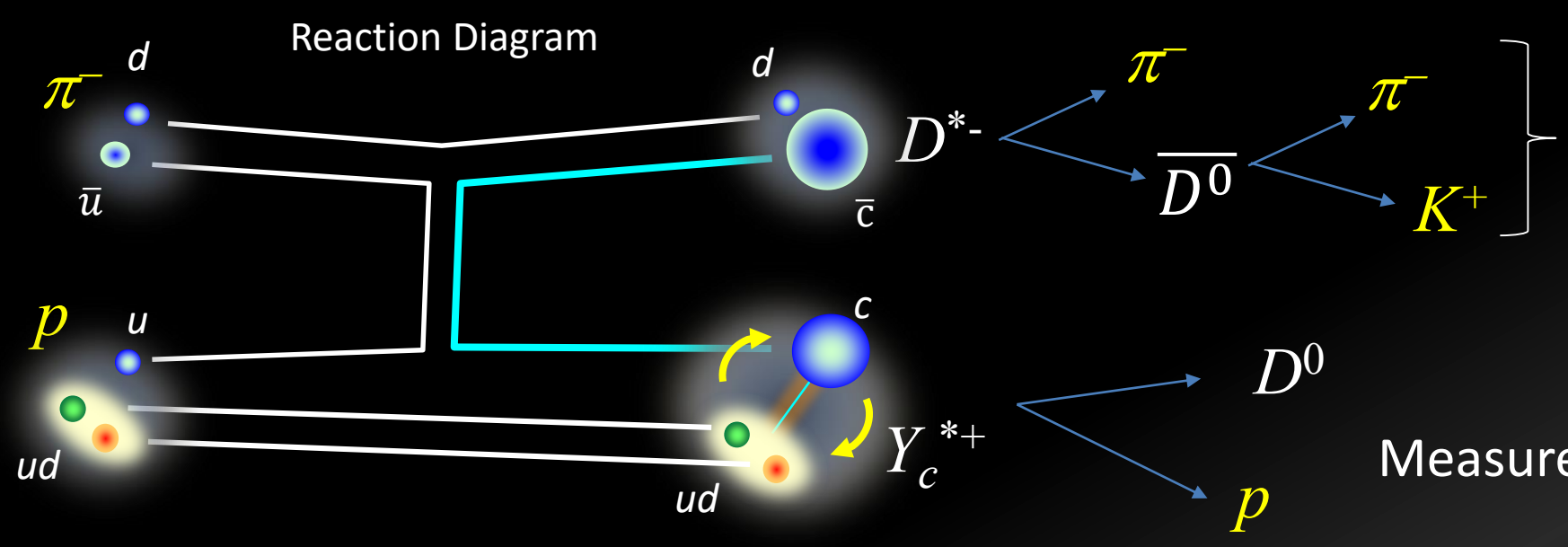
A. Jafar Arifi's Talk in Parallel Session 1-B

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

What we will explore at π20 and K10

- $\Lambda_c^*(cud)$ @ π20
  - $1P_\lambda,\ 2P_{\lambda\lambda}$: Establish "ud" diquark corr.
  - $1P_\rho(1/2^-)$: $U_A(1)$ anomalous mass term
- $\Xi^*(qss)$ Baryons @ π20/K10
  - $1P_\rho$: *LS* splitting → "us/ds" diquark corr.
- $\Omega^*(sss)$ Baryons @ K10
  - $1P$: *LS* origin of V_{conf} → no OGE/III contributed
  - $2S$: width → $\langle p^2\rangle \sim 1/\langle r^2\rangle$ (size of "Quark Core")

Production and Decay of Charmed Baryons



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

Measure Decay particles , too

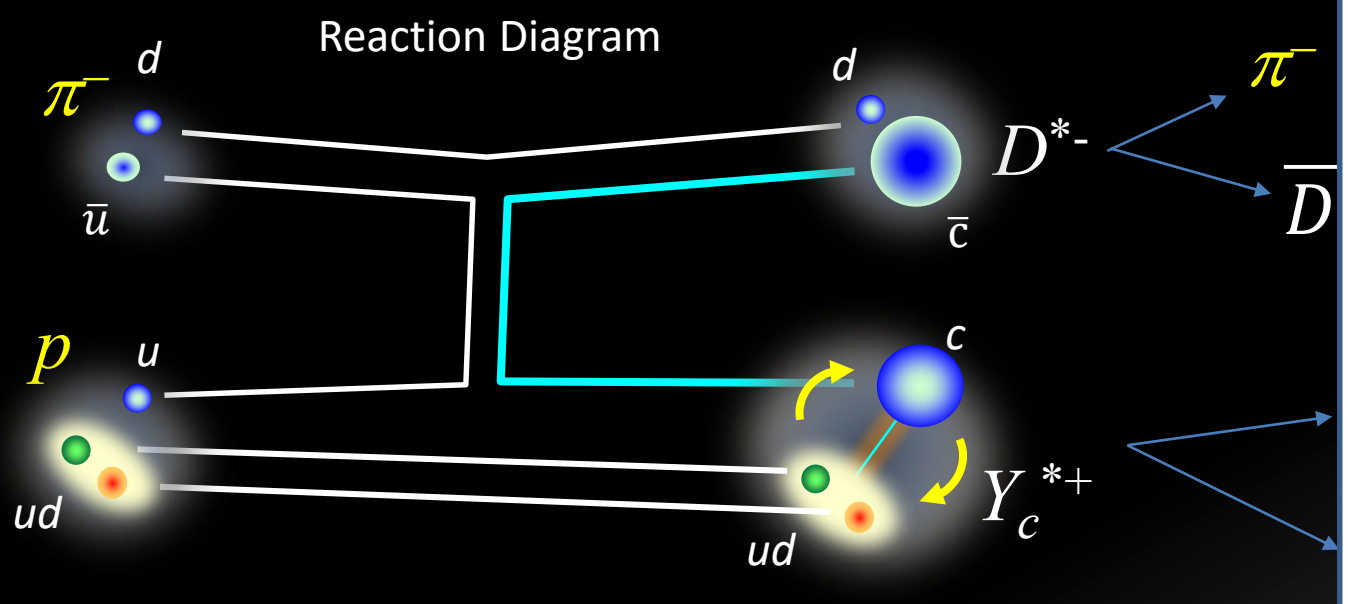
References for estimations on production cross sections:

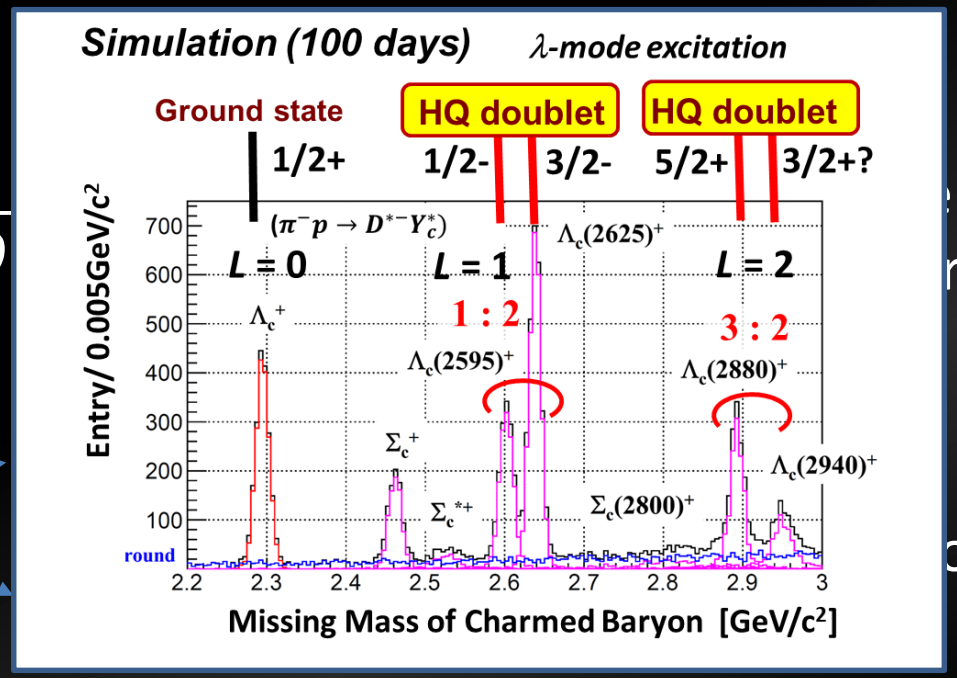
Reggeon Exchange: S.H. Kim, A. Hosaka, H.C. Kim, and HN, Phys.Rev. D92 (2015) 094021

Single-quark involved process: S.H. Kim, A. Hosaka, H.C. Kim, and HN, PTEP, (2014) 103D01

Two-quark involved process: S.I. Shim, A. Hosaka, H.C. Kim, PTEP 2020, (2020) 5, 053D01

Production and Decay of Charmed Baryons

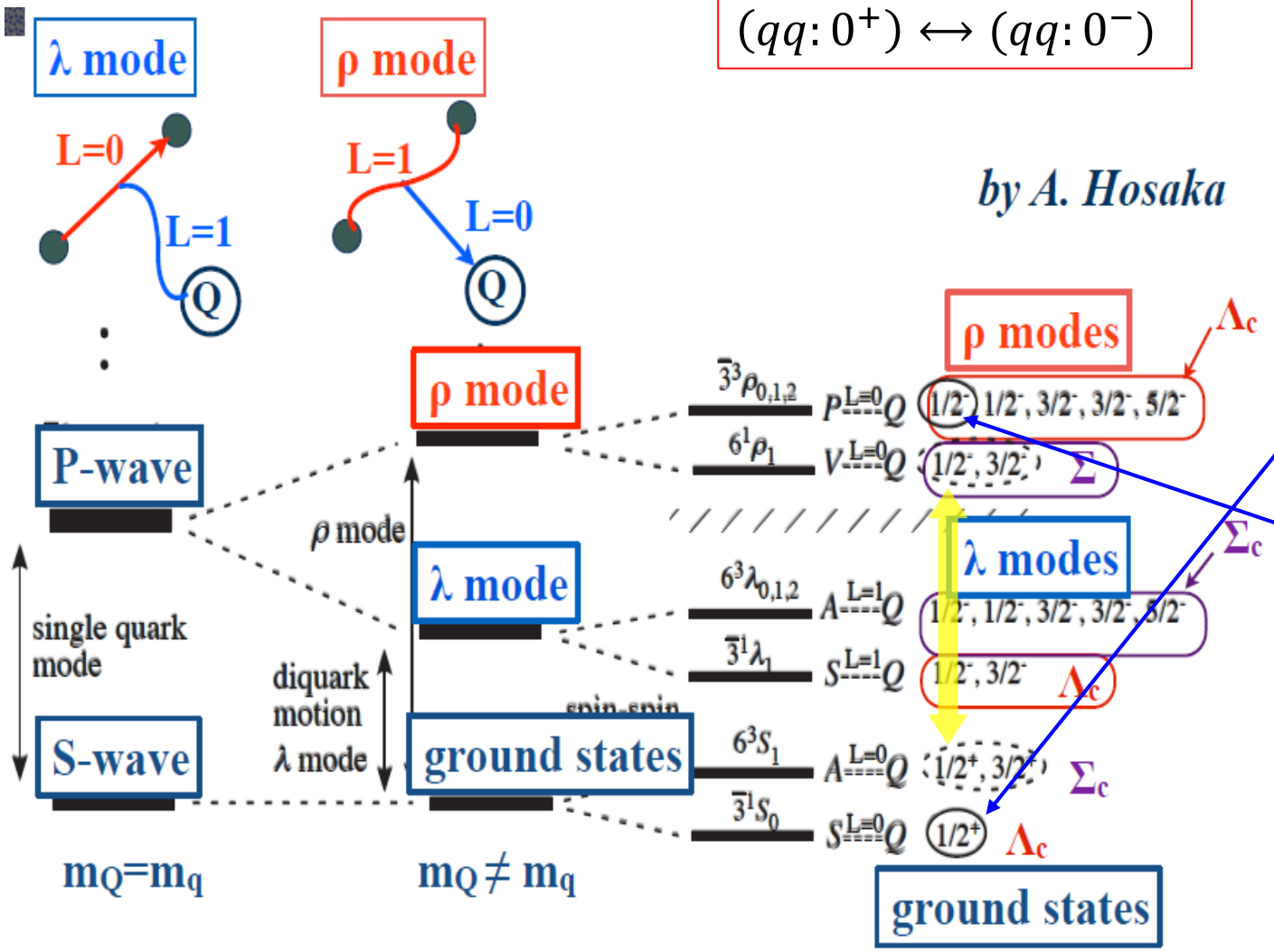




- Introducing a finite orbital angular momentum L ⇒ favor λ-mode excitations
  - Establish "*ud*" diquark motion in baryon
- Production ratio of the HQ doublet to be L:L+1 ⇒ Spin, Parity
  - The ratio would be a measure of how "*ud*" is correlated.
- Production and Decay measurement ⇒ Branching Ratio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

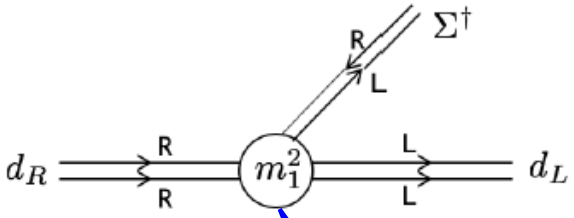
Diquark in Heavy Baryons

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



by A. Hosaka

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



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

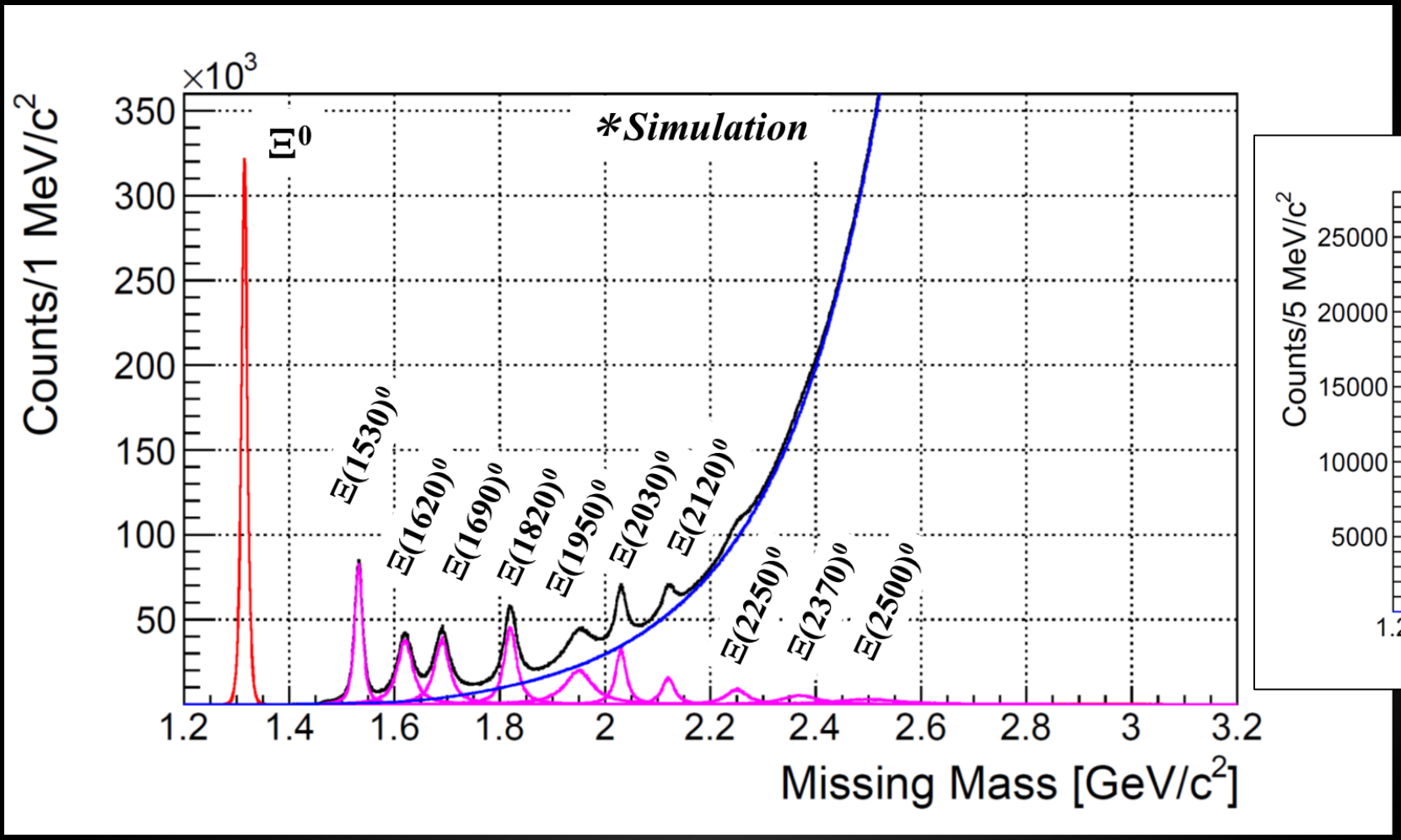
$$P_i^a = \frac{1}{\sqrt{2}}(d_{R,i}^a + d_{L,i}^a)$$

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

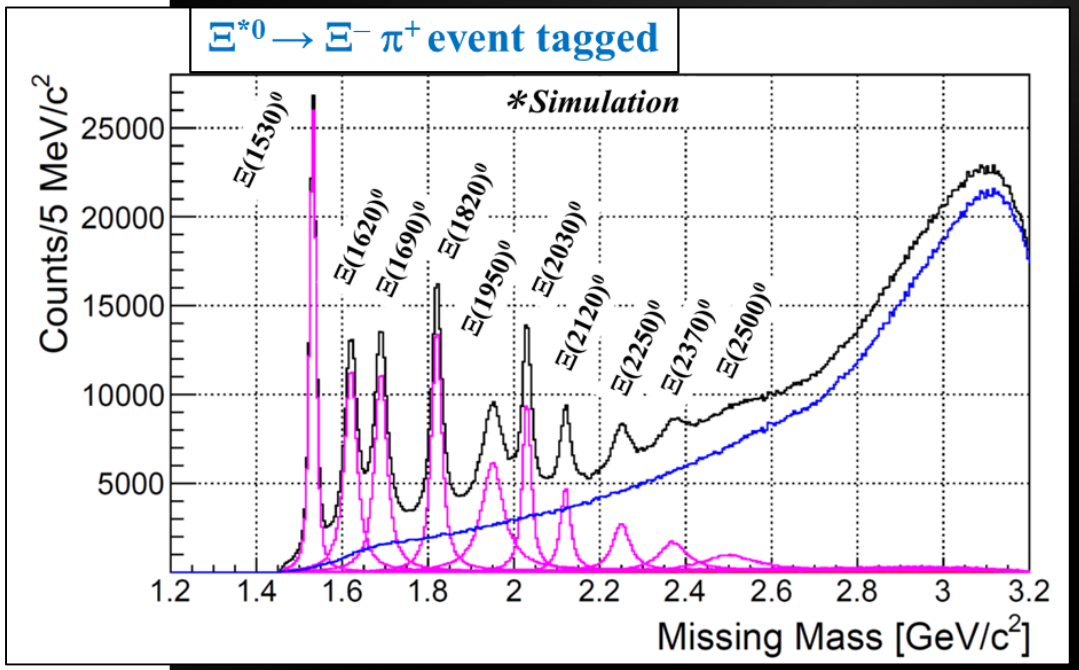
Kim et al, Phys.Rev.D 102 (2020) 014004

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

※simulation: known states are included w/ BG estimated by JAM.
Many of their J^P have yet to be determined.



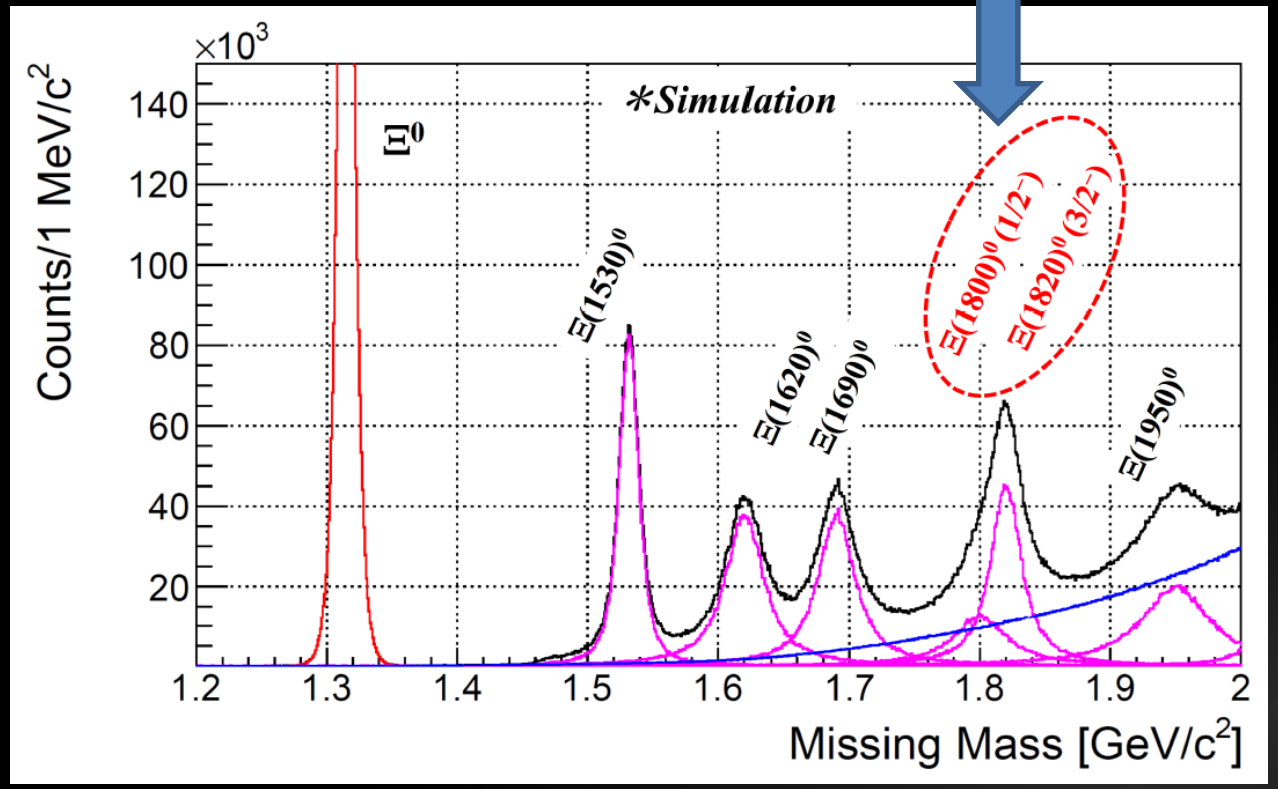
Tagged spectrum showing BG reduction.



Closed-up the low-lying Ξ states

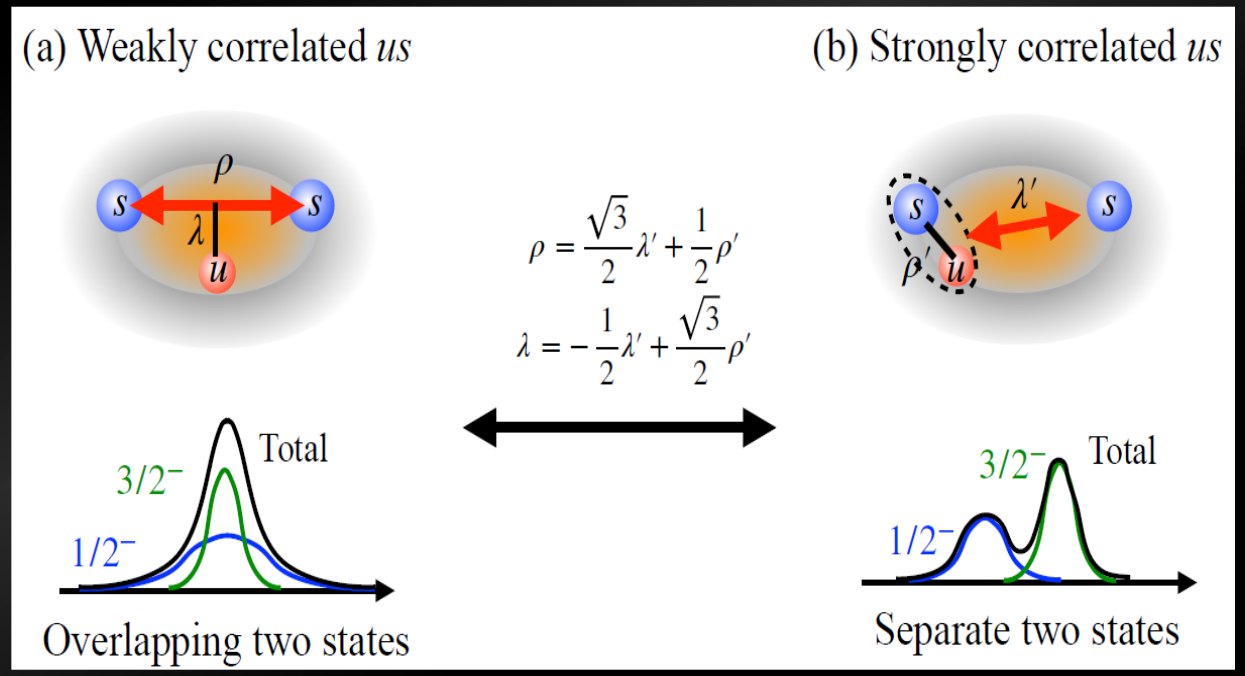
GS

1*P* states
(ρ-mode)



※Ξ(1800)1/2- assumed for demo.

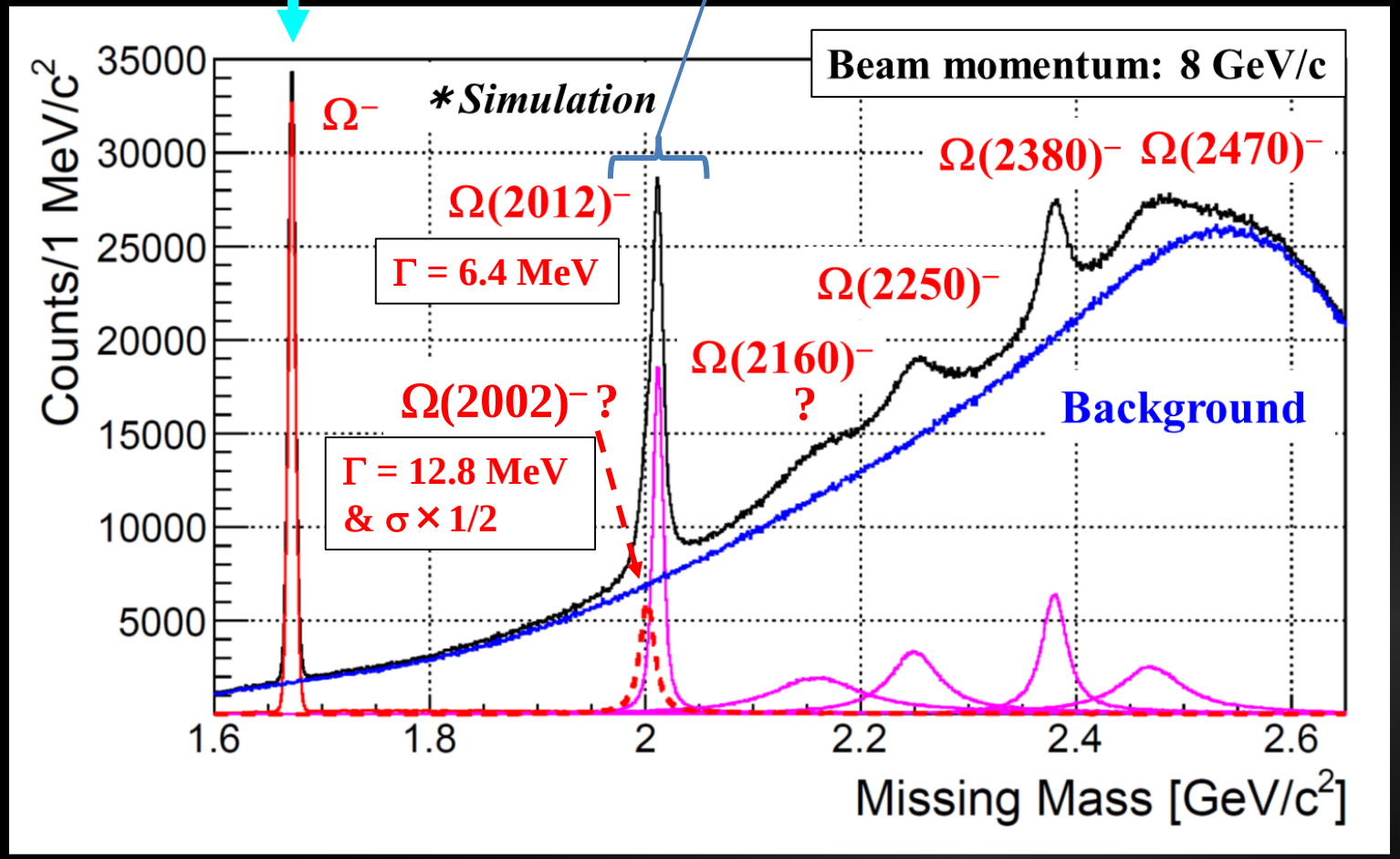
- Interest of ρ-mode excited states
  - Ξ(1820)3/2- to be confirmed
  - *LS* partner (1/2-) to be found
  - Reveal *us*-diquark correlation



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

63 nb assumed

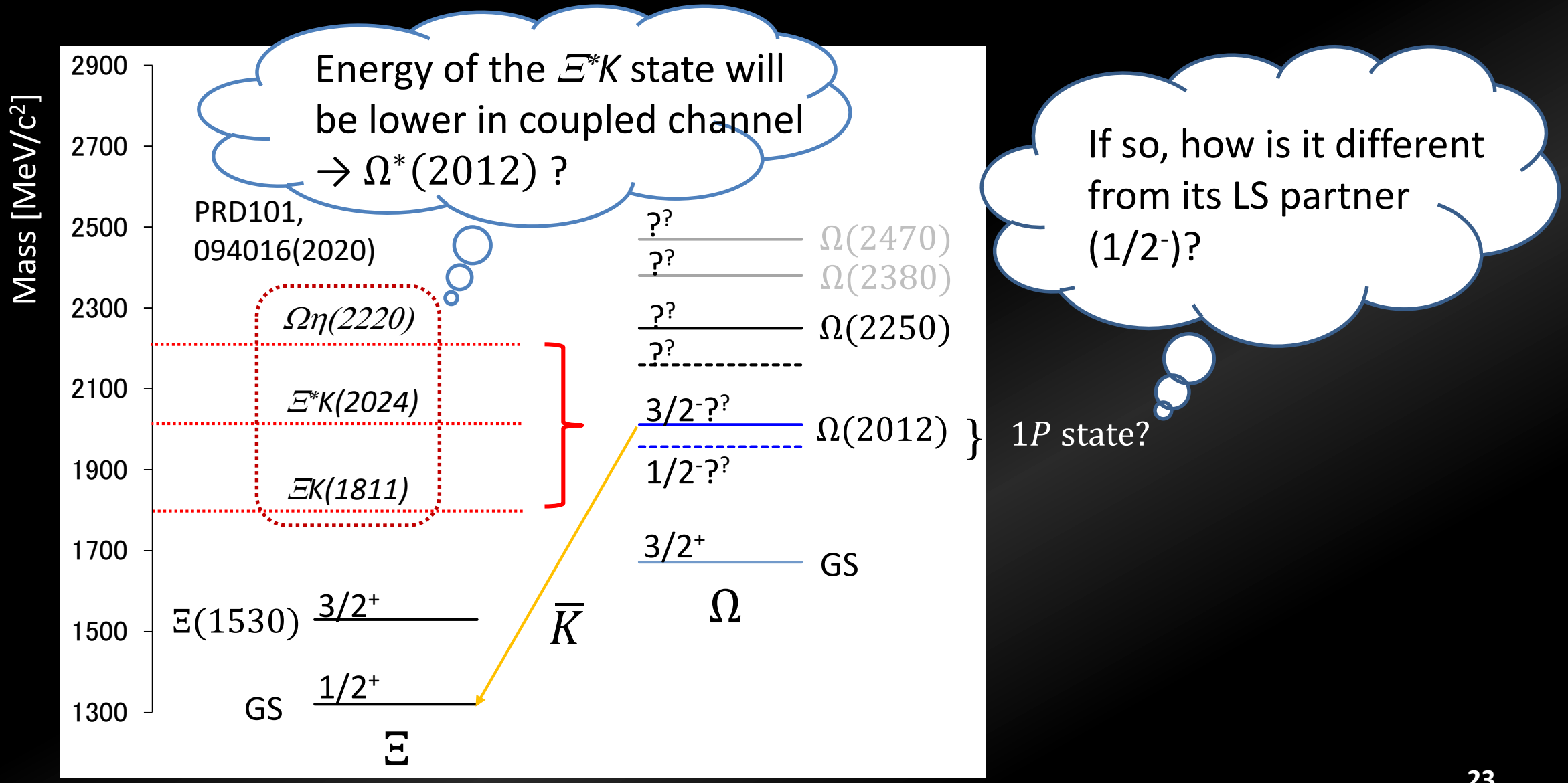
1P states?



Physics Highlight

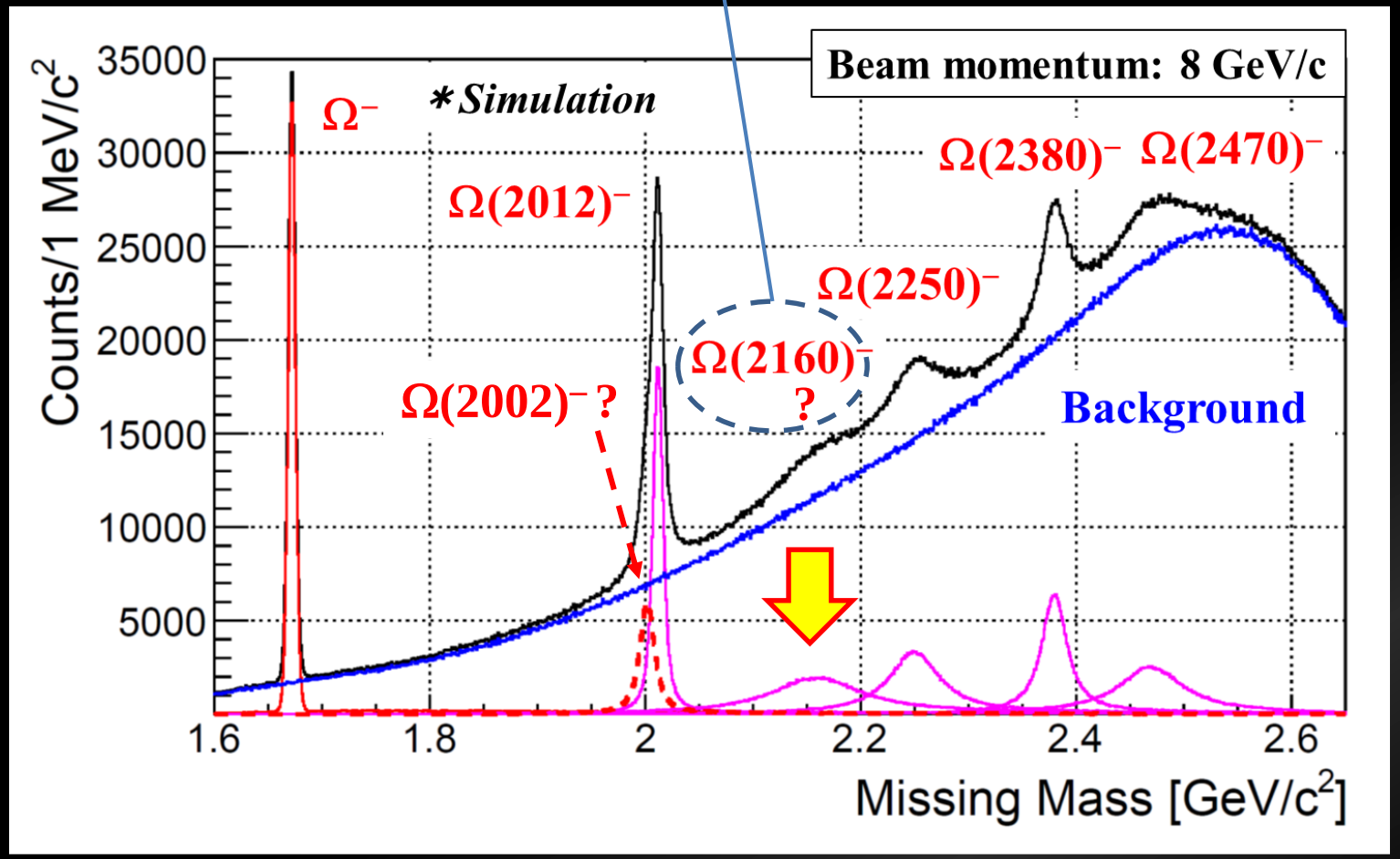
- 1P excited states
  - Ω(2012) J^P to be measured
    - 3/2-?
  - *LS* partner (1/2-) to be found
    - No LS splitting by CQM due to flavor symmetry
  - If a Finite *LS* splitting, Relativistic effect in confinement force?
- Is Ω(2012) : $\Xi^*\bar{K}$ Molecular?
  - PRD101, 094016(2020)

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



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

Roper (2S state)?



Physics Highlight

- 2S excited states
  - Radial excitation
  - So-called Roper-like state, yet to be found
    - $\Omega(2160), \Gamma \sim 100$ MeV assumed in the Sim.
  - The width
    - $\propto \langle p^2 \rangle$: "Quark core" size no pion cloud
  - The excitation energy
    - Universality?

Summary

- Spectroscopy of Baryon: good place to investigate dynamics of effective DoF, through which nature of low-E QCD, behavior of non-trivial QCD vacuum, is to be revealed.
- J-PARC provides unique opportunities.