D. S. , A. Hosaka, PRD 104 (2021) 3, 034009
D. S. , A. Hosaka, PRD 105 (2022) 7, 074036

Singly heavy baryons from chiral symmetry

Daiki Suenaga
(Special Postdoctoral Researcher at RIKEN)

末永大輝 (理研 基礎科学特別研究員)

My history

D. S. , A. Hosaka, PRD 104 (2021) 3, 034009
D. S. , A. Hosaka, PRD 105 (2022) 7, 074036

2018/3 - Ph.D. at Nagoya U. (Japan) under Prof. Masayasu Harada

→ D mesons in medium, parity doublet model in medium, Molecule picture for Pc, Skyrmion crystal, …

2018/5 - Visitor at Frankfurt U. (Germany)

→ + Linear sigma model with (axial) vectors in medium, …

2018/9 - Postdoc at Central China Normal U. (China)

→ + Massive gluon model in dense QCD, Casimir effects for D mesons, QCD Kondo effects in NJL-type model, …

My history

D. S. , A. Hosaka, PRD 104 (2021) 3, 034009
D. S. , A. Hosaka, PRD 105 (2022) 7, 074036

<u>2020/5</u> **- Postdoc at RCNP, Osaka U. (Japan)**

⇨ + Chiral model for heavy baryons, quark model with relativistic corrections, …

<u>2022/4</u> **- Postdoc at RIKEN (Japan)**

⇨ + Chiral model in two-color dense QCD for lattice QCD, Polyakov loop effective model in finite-volume system, …

<u>My research interest and strategy</u>

- To understand quark-gluon dynamics and hadron properties from **(field-theoretical) effective models focused on symmetry**

e.g., chiral symmetry, heavy quark symmetry, Z_{N_c} symmetry, …

1. Introduction
2. Mass spectrum
3. Decays of SHBs
4. Conclusions

1. Introduction

2. Mass spectrum

3. Decays of SHBs

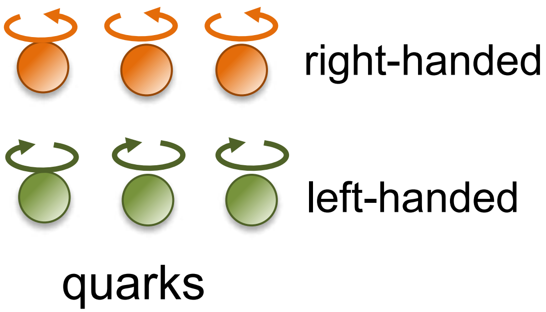
4. Conclusions

Introduction

D. S. , A. Hosaka, PRD 104 (2021) 3, 034009
D. S. , A. Hosaka, PRD 105 (2022) 7, 074036

- **"Symmetry" of light quarks**

  - QCD Lagrangian for light quarks has **chiral symmetry** (when $m_q \approx 0$)



separately conserved

(at classical level)

Noether theorem

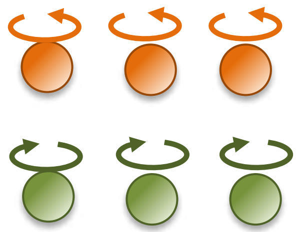
$$\partial_\mu j^\mu_R = 0$$

$$\partial_\mu j^\mu_L = 0$$

D. S. , A. Hosaka, PRD 104 (2021) 3, 034009
D. S. , A. Hosaka, PRD 105 (2022) 7, 074036

• "Symmetry" of light quarks

- QCD Lagrangian for light quarks has **chiral symmetry** (when $m_q \approx 0$)



separately conserved

(at classical level)

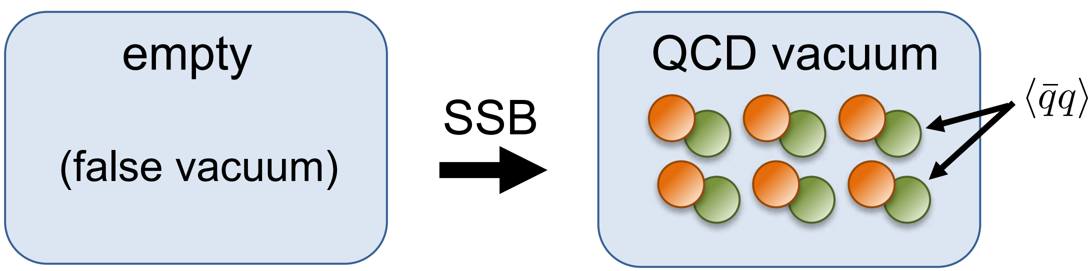
Noether theorem

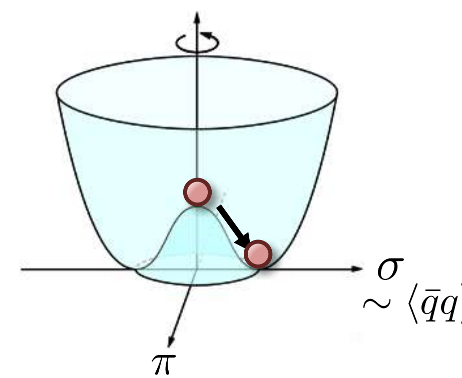
$$\partial_\mu j_R^\mu = 0$$

$$\partial_\mu j_L^\mu = 0$$

⇕ in reality

- Vacuum breaks chiral symmetry (spontaneous symmetry breaking: SSB)





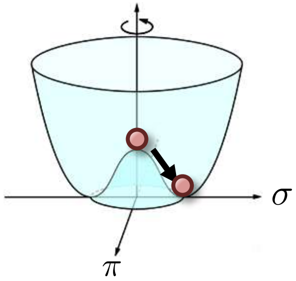
Nambu-Jona-Lasinio (1961)

- The vacuum is occupied by chiral condensates $\langle \bar{q}q \rangle$

⇒ Mass generation $m_q \sim 5\,\mathrm{MeV} \rightarrow M_q \sim 300\,\mathrm{MeV}$

Introduction

- **Chiral models**



- Chiral symmetry breaking is useful to understand light hadrons

- **Low-energy theorems** for N and π textbook by Cheng-Li

(Goldberger-Treiman relation, sum rules, Gell-Mann-Oakes-Renner relation, etc.)

- **Chiral perturbation theory (ChPT)** → systematics for NG bosons

Callan-Coleman-Wess-Zumino (1969), Weinberg (1979), Gasser-Leutwyler (1984, 1985), Ecker (1995)

$$\mathcal{L} = \frac{f_\pi^2}{4}\mathrm{Tr}[\partial_\mu U^\dagger \partial^\mu U] + \cdots$$ (nonlinear rep.)

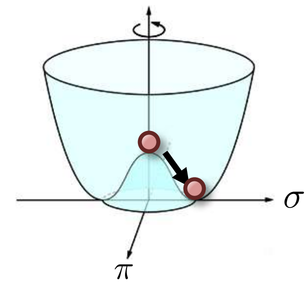
→ Hidden local symmetry (ChPT with vector mesons), baryon ChPT, etc.

Harada-Yamawaki (2003)

eg, Weinberg (1990, 1991)

D. S. , A. Hosaka, PRD 104 (2021) 3, 034009
D. S. , A. Hosaka, PRD 105 (2022) 7, 074036

• Chiral models



- Chiral symmetry breaking is useful to understand light hadrons

- **Low-energy theorems** for N and π (textbook by Cheng-Li)
  (Goldberger-Treiman relation, sum rules, Gell-Mann-Oakes-Renner relation, etc.)

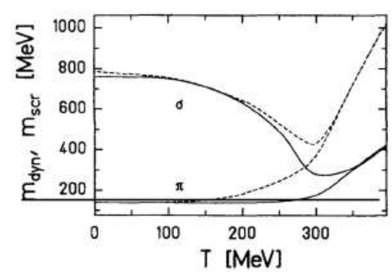
- **Chiral perturbation theory (ChPT)** → systematics for NG bosons
  Callan-Coleman-Wess-Zumino (1969), Weinberg (1979), Gasser-Leutwyler (1984, 1985), Ecker (1995)

$$\mathcal{L} = \frac{f_\pi^2}{4}\mathrm{Tr}[\partial_\mu U^\dagger \partial^\mu U] + \cdots$$ (nonlinear rep.)

→ Hidden local symmetry (ChPT with vector mesons), baryon ChPT, etc.
Harada-Yamawaki (2003) eg, Weinberg (1990, 1991)

- **Predictions** of hadrons at finite temperature/density with chiral symmetry restoration (eg, Hatsuda-Kunihiro (1994))
  (linear rep.)

:



⇒ Many model-independent relations, systematics, and predictions!

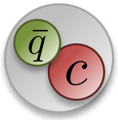
Introduction

D. S. , A. Hosaka, PRD 104 (2021) 3, 034009
D. S. , A. Hosaka, PRD 105 (2022) 7, 074036

• Symmetry of heavy hadrons

- Heavy-quark spin symmetry (HQSS) emerges

  ⇨ spin of a heavy quark is conserved (cf, NR quantum mechanics)

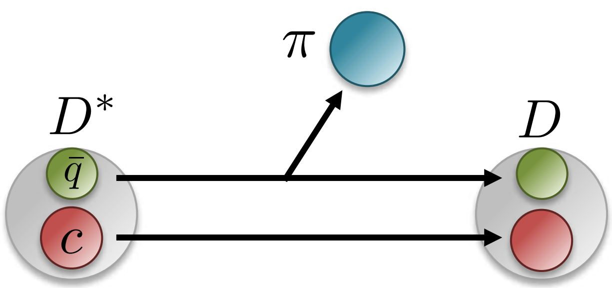
- For example, spin decomposition for D mesons  reads

$$2_q \otimes 2_c = \underbrace{1_D \oplus 3_{D^*}}$$

degenerate ← HQSS (suppression of magnetic int.)

cf, in NR quark model $H_{\mathrm{spin}} \propto \dfrac{\vec{s}_q \cdot \vec{s}_c}{m_q m_c} \to 0 \quad (\text{for } m_c \to \infty)$ ⇨ no splitting in (D, D^*)

- When focusing on, eg $D^* \to D\,\pi$

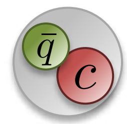


Introduction

- **Symmetry of heavy hadrons**

- Heavy-quark spin symmetry (HQSS) emerges

⇨ spin of a heavy quark is conserved (cf, NR quantum mechanics)

- For example, spin decomposition for D mesons  reads

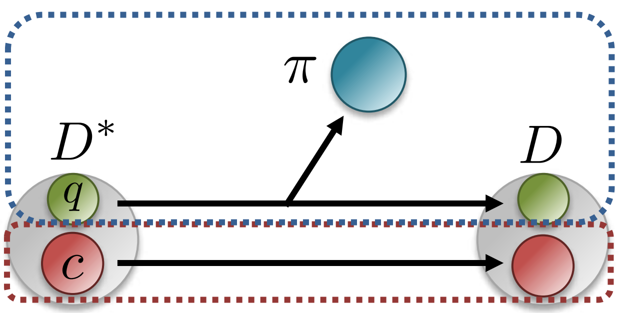
$$2_q \otimes 2_c = \underbrace{1_D \oplus 3_{D^*}}$$

degenerate ← HQSS (suppression of magnetic int.)

cf, in NR quark model $H_{\text{spin}} \propto \frac{\vec{s}_q \cdot \vec{s}_c}{m_q m_c} \to 0 \quad (\text{for } m_c \to \infty)$ ⇨ no splitting in (D, D^*)

- When focusing on, eg $D^* \to D\,\pi$

textbook by Manohar-Wise



Dynamics is governed the light sector with chiral symmetry

c quark serves as a spectator with HQSS

Introduction

• Heavy hadrons in chiral models so far

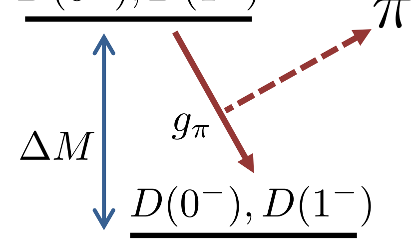
- Chiral model for heavy-light mesons with chiral partner structure

Nowak-Rho-Zahed (1993), Bardeen-Hill (1994)

$$\Delta M = M(0^+) - M(0^-) = M(1^+) - M(1^-) = g_\pi f_\pi$$

(extended GT relation)

Relation between masses and decay widths

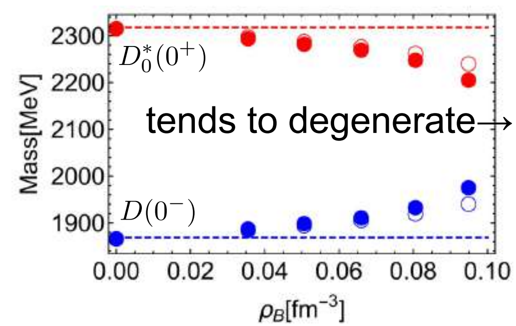


→ Predictions at finite temperature/density/volume with chiral symmetry restoration

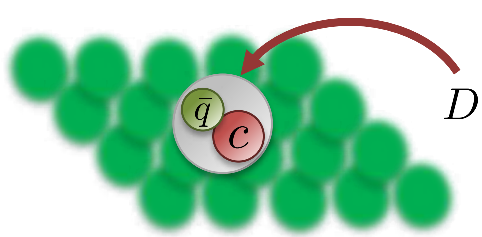
Sasaki (2014), Suenaga-Yasui-Harada (2017), Ishikawa-Nakayama-Suenaga-Suzuki (2019)

$$\Delta M^* = g_\pi f_\pi^* \to 0 \quad (f_\pi^* \to 0)$$

chiral restoration



for other approaches:
Skyrmion crystal: Suenaga-He-Ma-Harada (2015)
Sum rule: Buchheim-Hilger-Kämpfer-Leupold (2018)
BS approach: Montaña-Ramos-Tolós-Torres-Rincon (2020)



$D(\bar{D})$ meson in medium

⇨ information on chiral restoration there

Introduction

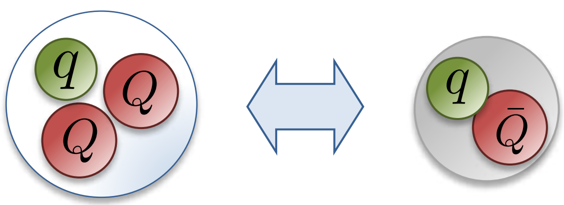
• Heavy hadrons in chiral models so far

- Chiral model for singly heavy baryons (→later in detail)

Kawakami-Harada (2018, 2019), Harada-Liu-Oka-Suzuki (2020), Dmitrasinovic-Chen (2020), Kawakami-Harada-Oka-Suzuki (2020), Suenaga-Hosaka (2021,2022)

- Chiral model for doubly heavy baryons

Bardeen-Eichten-Hill (2003), Ma-Harada (2015, 2016, 2017)

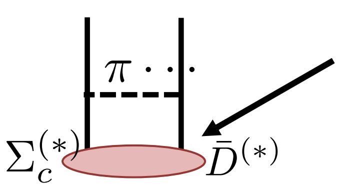


Analog of heavy-light mesons when focusing on chiral symmetry (Both have one q)

→ prediction of mass spectrum, decay widths, etc.

- Useful information for molecule picture of exotic hadrons

eg, Yamaguchi-Hosaka-Takeuchi-Takizawa (2020)



contributions to pentaquark (hadronic molecule)

Introduction

- **Singly heavy baryons (SHBs)**

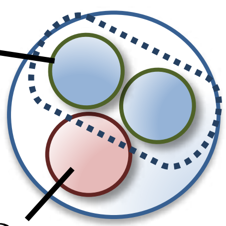
  - Diquarks (qq) from chiral symmetry viewpoint are less understood compared to mesons $(\bar{q}q)$

    eg, Hong-Sohn-Zahed (2004)

  - SHBs are useful to understand chiral symmetry for diquarks

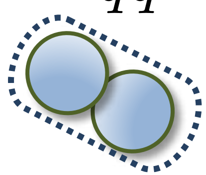
<u>SHBs</u>

diquark qq



heavy quark Q
= spectator

qq

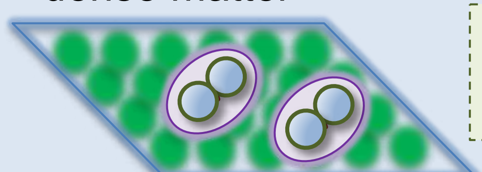


from chiral symmetry

- coupling with pions
- their change in medium with chiral restoration
- indication of diquark condensate (?)

- Diquark condensate is the Cooper pair of two quarks
  $\rightarrow$ color superconductivity

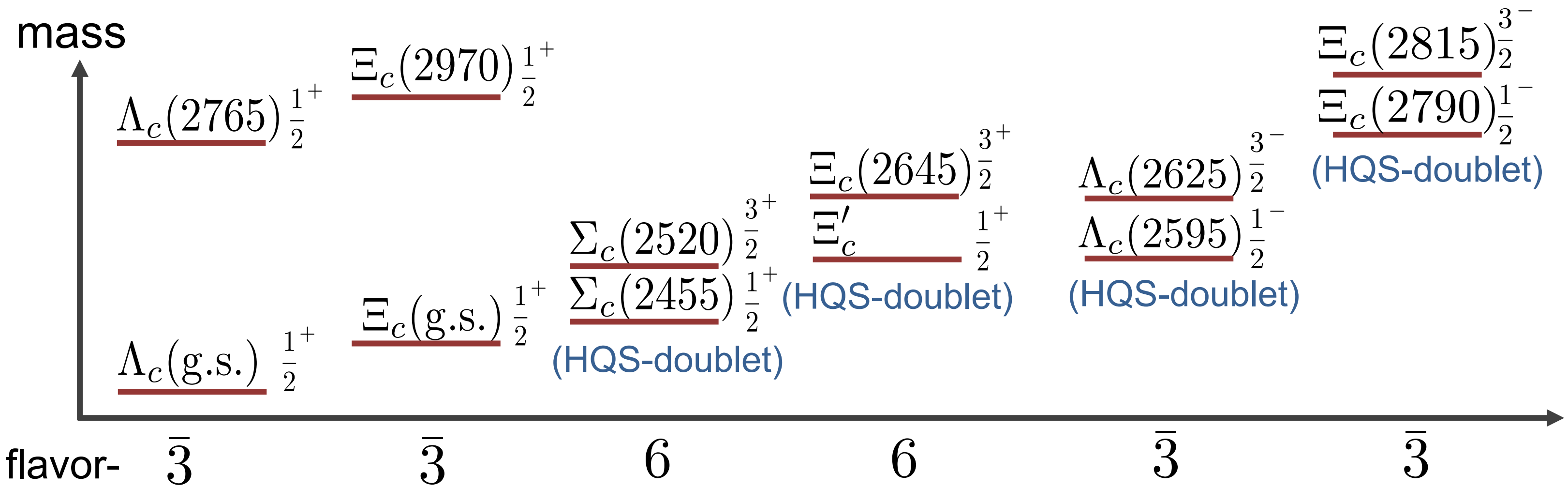
dense matter



Alford-Schmitt -Rajagopal-Schäfer (2008)

Introduction

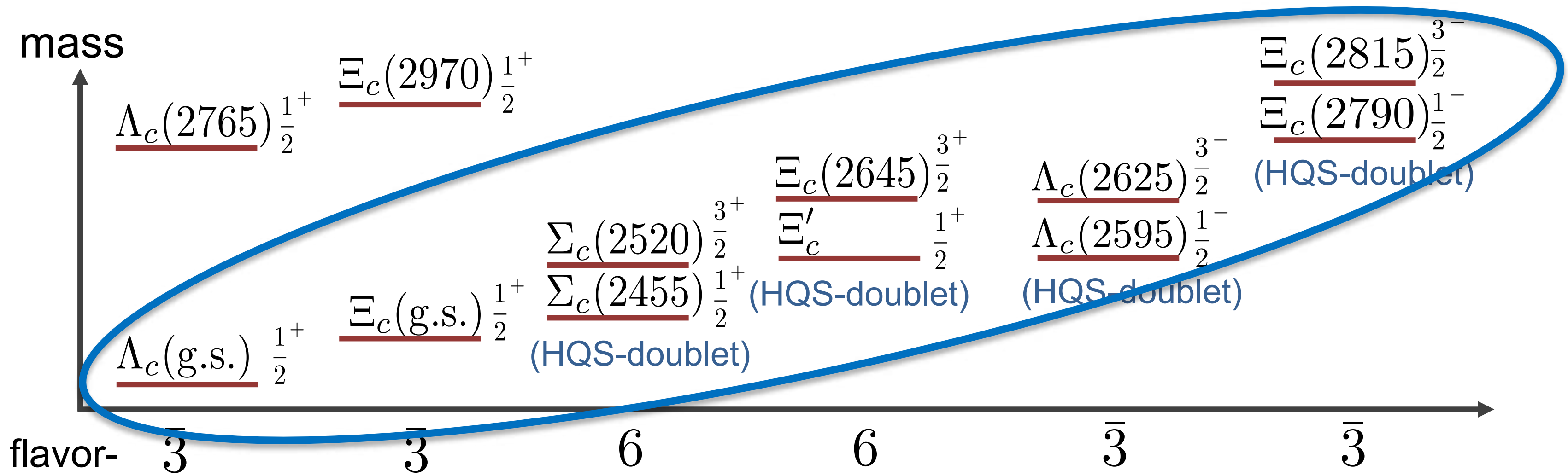
- **SHB in chiral models**
  - Mass spectrum of SHB in charmed sector



Introduction

- **SHB in chiral models**

  - Mass spectrum of SHB in charmed sector



  - Previous works on SHB in chiral models have been mostly devoted to rather lower states (and their chiral partners)

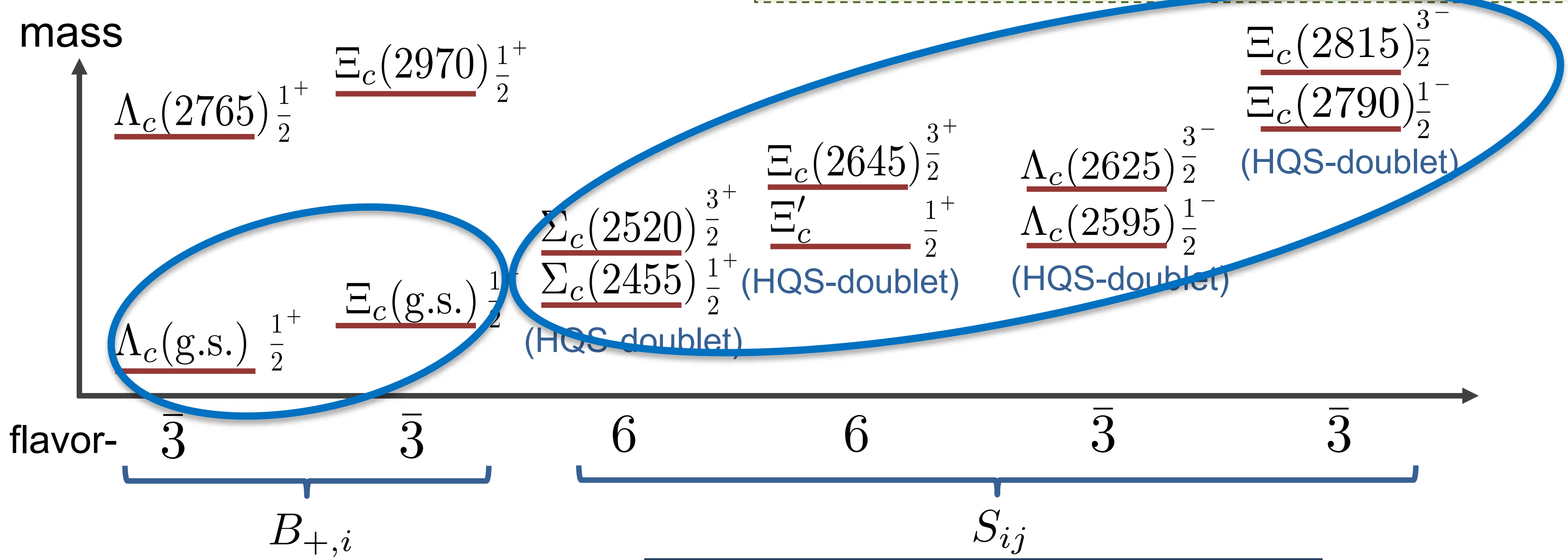
Kawakami-Harada (2018, 2019), Harada-Liu-Oka-Suzuki (2020)
Dmitrasinovic-Chen (2020), Kawakami-Harada-Oka-Suzuki (2020)

Introduction

D. S. , A. Hosaka, PRD 104 (2021) 3, 034009
D. S. , A. Hosaka, PRD 105 (2022) 7, 074036

- **Previous works**

Kawakami-Harada (2018, 2019), Harada-Liu-Oka-Suzuki (2020)
Dmitrasinovic-Chen (2020), Kawakami-Harada-Oka-Suzuki (2020)



$$B_{+,i} \sim Q^a(d_R)^a_i - Q^a(d_L)^a_i$$

with $(d_R)^a_i \sim \epsilon_{ijk}\epsilon^{abc}(q_R^T)^b_j C(q_R)^c_k$

$(d_L)^a_i \sim \epsilon_{ijk}\epsilon^{abc}(q_L^T)^b_j C(q_L)^c_k$

$(1, \bar{3})$ and $(\bar{3}, 1)$

$$S_{ij} \sim Q^a(\tilde{d})^{a,\mu}_{ij} = Q^q(\tilde{d})^{a,\mu}_{\{i,j\}} + Q^q(\tilde{d})^{a,\mu}_{[i,j]}$$

with $(\tilde{d})^{a,\mu}_{ij} \sim \epsilon^{abc}(q_L^T)^b_j C\gamma^\mu(q_R)^c_i$

$$(3, 3)$$

i, j, k : flavor index
a, b, c : color index

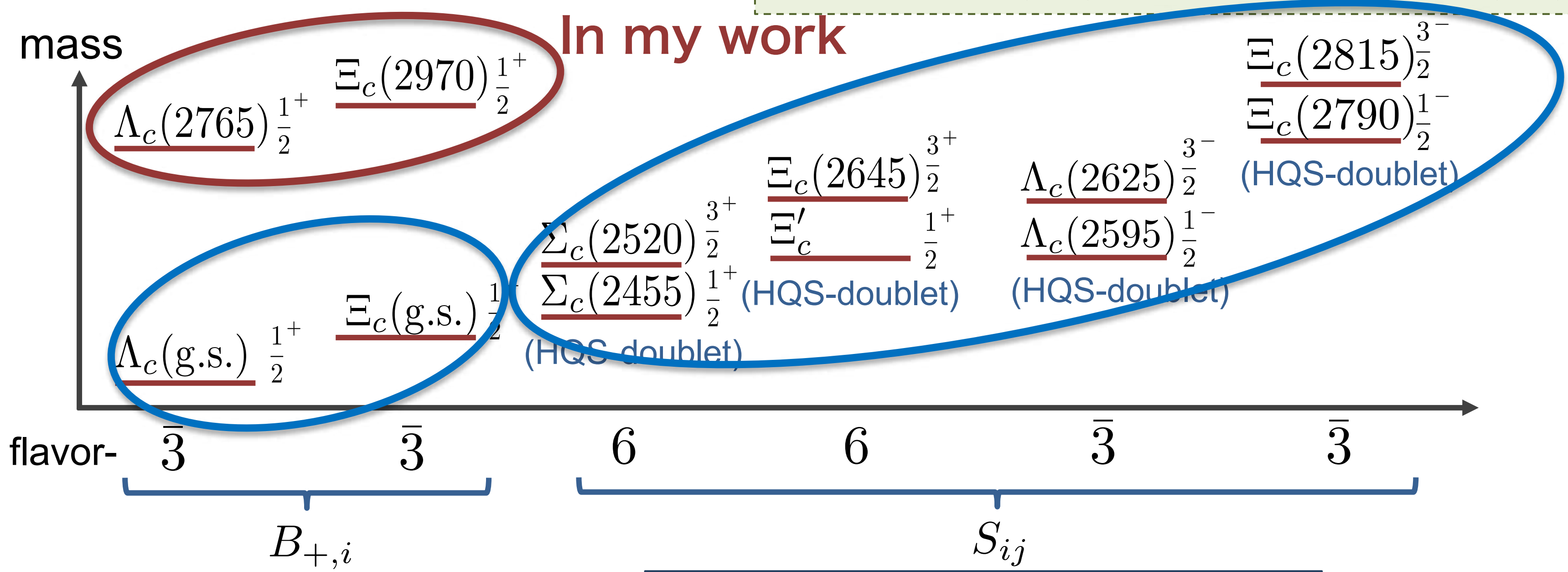
- Inverse mass hierarchy of diquarks, mass spectrum, predictions of EM decays, predictions on chiral partners, etc.

Introduction

D. S. , A. Hosaka, PRD 104 (2021) 3, 034009
D. S. , A. Hosaka, PRD 105 (2022) 7, 074036

- **Previous works**

Kawakami-Harada (2018, 2019), Harada-Liu-Oka-Suzuki (2020)
Dmitrasinovic-Chen (2020), Kawakami-Harada-Oka-Suzuki (2020)



$$B_{+,i} \sim Q^a(d_R)^a_i - Q^a(d_L)^a_i$$

with $(d_R)^a_i \sim \epsilon_{ijk}\epsilon^{abc}(q_R^T)^b_j C(q_R)^c_k$

$(d_L)^a_i \sim \epsilon_{ijk}\epsilon^{abc}(q_L^T)^b_j C(q_L)^c_k$

$(1, \bar{3})$ and $(\bar{3}, 1)$

$$S_{ij} \sim Q^a(\tilde{d})^{a,\mu}_{ij} = Q^q(\tilde{d})^{a,\mu}_{\{i,j\}} + Q^q(\tilde{d})^{a,\mu}_{[i,j]}$$

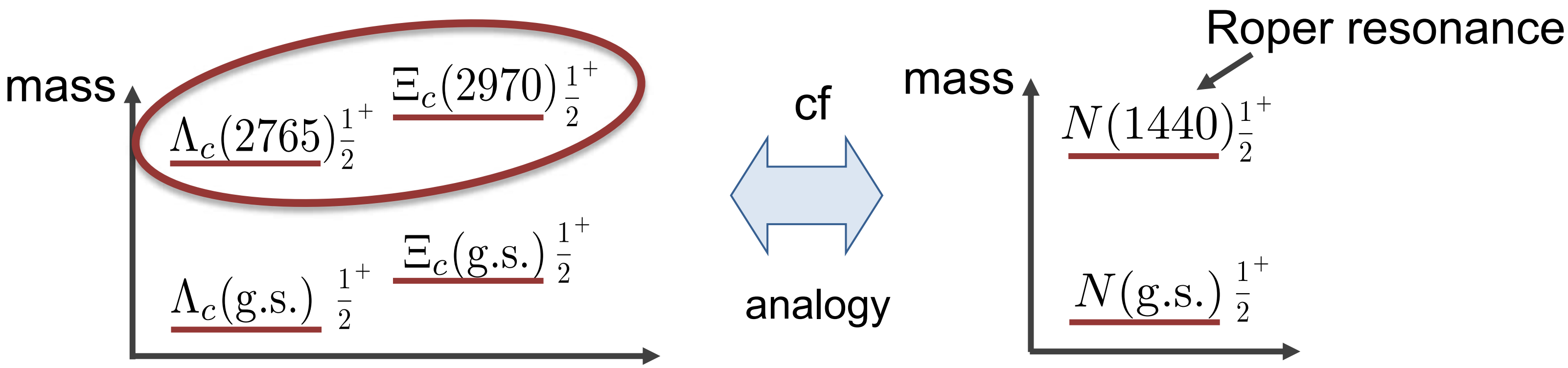
with $(\tilde{d})^{a,\mu}_{ij} \sim \epsilon^{abc}(q_L^T)^b_j C\gamma^\mu(q_R)^c_i$

$(3, 3)$

i, j, k : flavor index
a, b, c : color index

- Inverse mass hierarchy of diquarks, mass spectrum, predictions of EM decays, predictions on chiral partners, etc.

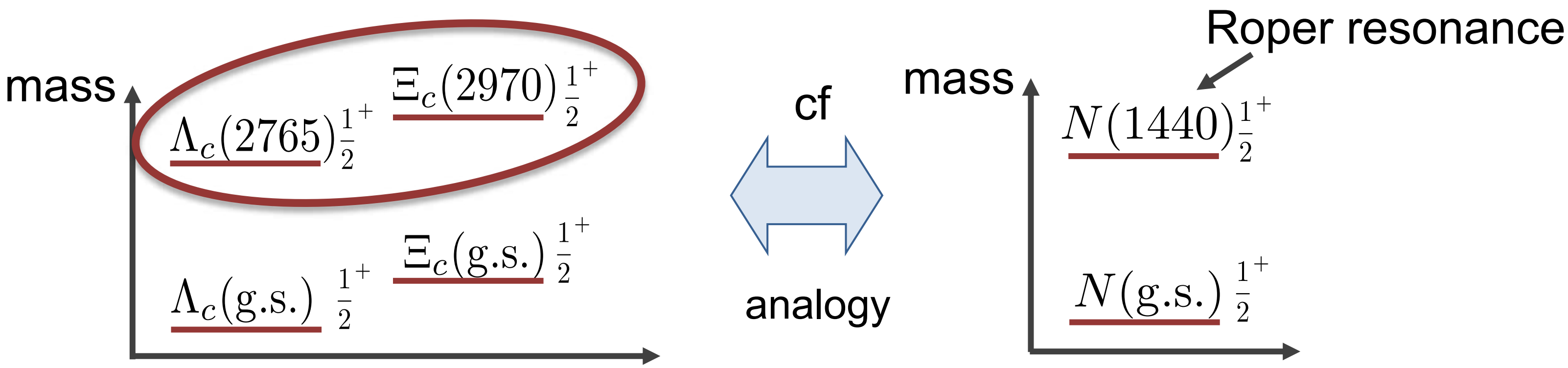
- **Roper-like SHBs in quark models**
  - $\Lambda_c(2765)$ and $\Xi_c(2970)$ are called **the Roper-like SHBs**



Introduction

- **Roper-like SHBs in quark models**

- $\Lambda_c(2765)$ and $\Xi_c(2970)$ are called the Roper-like SHBs



- Their masses seem to be reproduced rather well by a NR quark model

$m(\Lambda_c^*) = 2857\,\mathrm{MeV}\,,\ m(\Xi_c^*) = 3029\,\mathrm{MeV}$ (theory)

↑ no consideration of decay widths

Yoshida-Hiyama-Hosaka-Oka-Sadato (2017)

- The decay widths are found to be too small in a NR quark model (with harmonic oscillator potential)

$\Lambda_c(2765) \to \Sigma_c^{(*)}\pi$

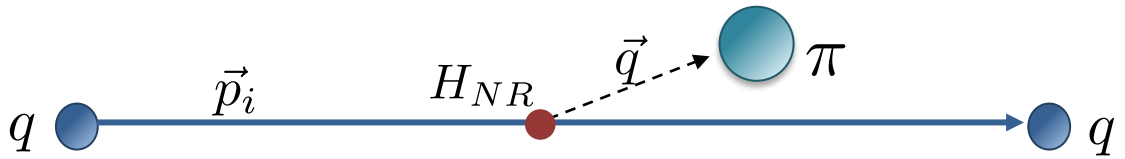
$\Gamma_{\mathrm{th.}} = (1.6 - 4.5)\,\mathrm{MeV}$ while $\Gamma_{\mathrm{ex.}} \approx 50\,\mathrm{MeV}$

Nagahiro-Yasui-Hosaka-Oka-Noumi (2017)

D. S. , A. Hosaka, PRD 104 (2021) 3, 034009
D. S. , A. Hosaka, PRD 105 (2022) 7, 074036

- **Decay of Roper-like SHBs**
  - The NR interaction up to $\mathcal{O}(1/m)$ reads $H_{NR} = g\left[\boldsymbol{\sigma}\cdot\boldsymbol{q} + \frac{\omega_\pi}{2m}\left(\boldsymbol{\sigma}\cdot\boldsymbol{q} - 2\boldsymbol{\sigma}\cdot\boldsymbol{p}_i\right)\right]$

(from chiral Lag.)



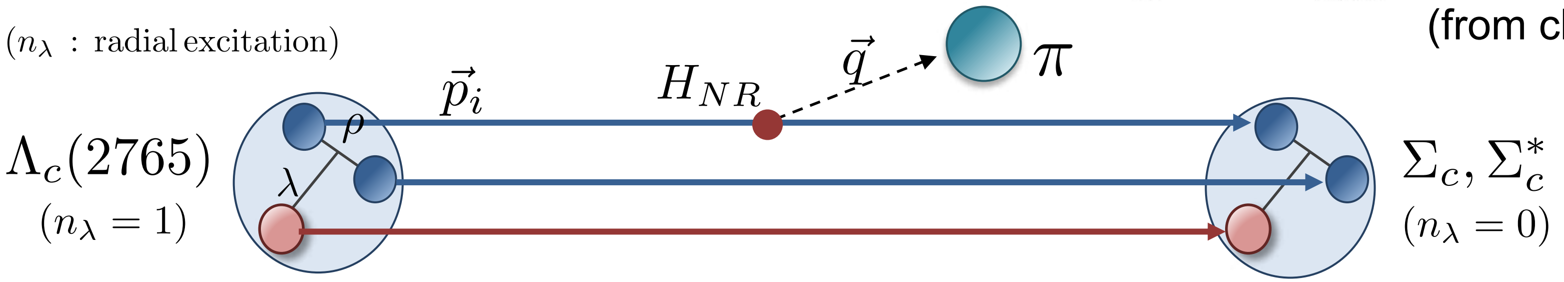
Introduction

- **Decay of Roper-like SHBs**

  - The NR interaction up to $\mathcal{O}(1/m)$ reads $H_{NR} = g\left[\boldsymbol{\sigma}\cdot\boldsymbol{q} + \frac{\omega_\pi}{2m}\left(\boldsymbol{\sigma}\cdot\boldsymbol{q} - 2\boldsymbol{\sigma}\cdot\boldsymbol{p}_i\right)\right]$

(from chiral Lag.)

$(n_\lambda$: radial excitation$)$



  - H_{NR} is of $\mathcal{O}(q^2)$ which is very small in the low-energy limit

$\mathcal{M} \sim \langle \Psi_{n_\lambda=0} | \Psi_{n_\lambda=1} \rangle \to 0$ **: forbidden process**

cf, photoexcitation of $N(1440)$

Kubota-Ohta (1976)

Introduction

D. S. , A. Hosaka, PRD 104 (2021) 3, 034009
D. S. , A. Hosaka, PRD 105 (2022) 7, 074036

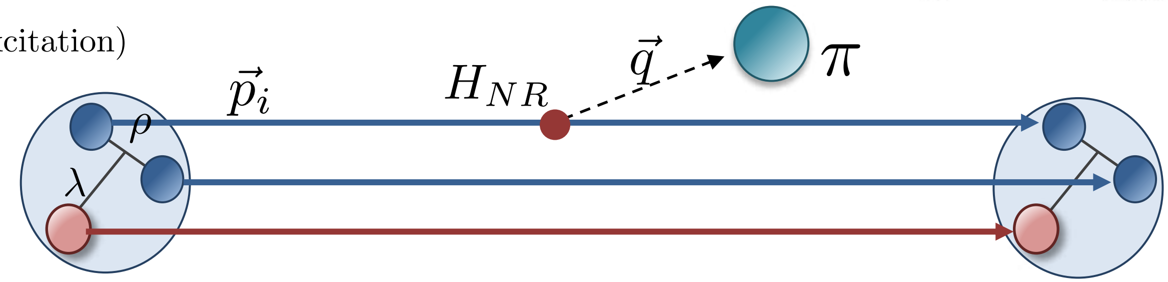
• Decay of Roper-like SHBs

- The NR interaction up to $\mathcal{O}(1/m)$ reads $H_{NR} = g\left[\boldsymbol{\sigma}\cdot\boldsymbol{q} + \frac{\omega_\pi}{2m}(\boldsymbol{\sigma}\cdot\boldsymbol{q} - 2\boldsymbol{\sigma}\cdot\boldsymbol{p}_i)\right]$

(from chiral Lag.)

$(n_\lambda$: radial excitation$)$

$\Lambda_c(2765)$
$(n_\lambda = 1)$



Σ_c, Σ_c^*
$(n_\lambda = 0)$

- H_{NR} is of $\mathcal{O}(q^2)$ which is very small in the low-energy limit

$\mathcal{M} \sim \langle \Psi_{n_\lambda=0} | \Psi_{n_\lambda=1} \rangle \to 0$ **: forbidden process**

cf, photoexcitation of $N(1440)$
Kubota-Ohta (1976)

- The relativistic corrections of $\mathcal{O}(1/m^2)$ can improve the shortcomings

Arifi-Suenaga-Hosaka (2021), Arifi-Suenaga-Hosaka-Oh (2022)

(becomes $\mathcal{O}(q^1)$)

- Understanding from chiral symmetry (= symmetry of relativistic theory) with field-theoretical method may be suitable for the Roper-like SHBs

1. Introduction

2. Mass spectrum

3. Decays of SHBs

4. Conclusions

Mass spectrum

D. S. , A. Hosaka, PRD 104 (2021) 3, 034009
D. S. , A. Hosaka, PRD 105 (2022) 7, 074036

- **Diquark fields**

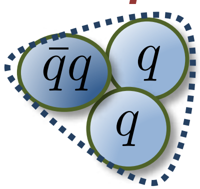
  - We introduce two types of diquarks toward understanding both the Roper-like and ground-state SHBs simultaneously

i) *conventional diquark*

$$(d_R)^a_i \sim \epsilon_{ijk}\epsilon^{abc}(q_R^T)^b_j C(q_R)^c_k$$
$$(d_L)^a_i \sim \epsilon_{ijk}\epsilon^{abc}(q_L^T)^b_j C(q_L)^c_k$$

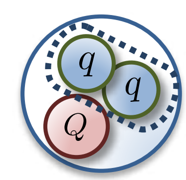
i, j, k : flavor index
a, b, c : color index

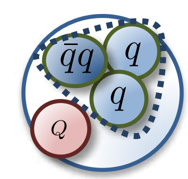
ii) *mirror diquark*



$$(d'_R)^a_i \sim \epsilon_{jkl}\epsilon^{abc}(q_R^T)^b_k C(q_R)^c_l[(\bar{q}_L)^d_i(q_R)^d_j]$$
$$(d'_L)^a_i \sim \epsilon_{jkl}\epsilon^{abc}(q_L^T)^b_k C(q_L)^c_l[(\bar{q}_R)^d_i(q_L)^d_j]$$

- The chiral representation of d_R, d_L, d'_R, d'_L are





$$d_R \sim (\mathbf{1}, \bar{\mathbf{3}}) \ , \quad d_L \sim (\bar{\mathbf{3}}, \mathbf{1})$$
$$d'_R \sim (\bar{\mathbf{3}}, \mathbf{1}) \ , \quad d'_L \sim (\mathbf{1}, \bar{\mathbf{3}})$$

← chiral rep. is flipped like in a *mirror*
[c.f. mirror nucleon for $N(1535)$]

Jodo-Oka-Hosaka, PTP(2001)

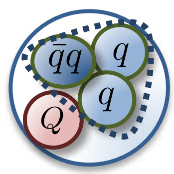
Mass spectrum

D. S. , A. Hosaka, PRD 104 (2021) 3, 034009
D. S. , A. Hosaka, PRD 105 (2022) 7, 074036

- **Heavy baryon fields**

  - The heavy baryons are simply given by adding a heavy Q to the diquarks

$$B_{R,i} \sim Q^a (d_R)^a_i \qquad B'_{R,i} \sim Q^a (d'_R)^a_i$$
$$B_{L,i} \sim Q^a (d_L)^a_i \qquad B'_{L,i} \sim Q^a (d'_L)^a_i$$



$$B_R \to B_R g_R^\dagger \qquad B'_R \to B'_R g_L^\dagger$$
$$B_L \to B_L g_L^\dagger \qquad B'_L \to B'_L g_R^\dagger$$

  - The $SU(3)_L \times SU(3)_R$ chiral symmetric Lagrangian is

$$\begin{aligned}
\mathcal{L}_{\rm eff} \;=\; & \sum_{s=L,R} \left\{ \bar{B}_s iv\cdot\partial B_s - \mu_1 \bar{B}_s B_s + \bar{B}'_s iv\cdot\partial B'_s - \mu_2 \bar{B}'_s B'_s \right\} \\
& - \mu_3 (\bar{B}_R B'_L + \bar{B}'_L B_R + \bar{B}_L B'_R + \bar{B}'_R B_L) \\
& - g_1 (\bar{B}_L \Sigma^* B_R + \bar{B}_R \Sigma^T B_L) - g_2 (\bar{B}'_R \Sigma^* B'_L + \bar{B}'_L \Sigma^T B_R) \\
& - g_3 (\bar{B}'_R \Sigma^* B_R + \bar{B}_L \Sigma^* B'_L + \bar{B}_R \Sigma^T B'_R + \bar{B}'_L \Sigma^T B_L) \,,
\end{aligned}$$

with meson nonet $\Sigma = S + iP$

S: $(\sigma, a_0, \cdots)$, P: $(\eta, \pi, \cdots)$

$$\Sigma \to g_L \Sigma g_R^\dagger$$

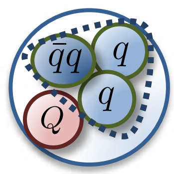
Mass spectrum

D. S. , A. Hosaka, PRD 104 (2021) 3, 034009
D. S. , A. Hosaka, PRD 105 (2022) 7, 074036

- **Heavy baryon fields**

- The heavy baryons are simply given by adding a heavy Q to the diquarks

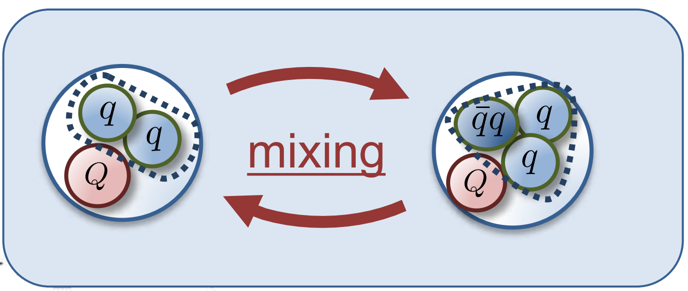
$$B_{R,i} \sim Q^a (d_R)^a_i \qquad B'_{R,i} \sim Q^a (d'_R)^a_i$$
$$B_{L,i} \sim Q^a (d_L)^a_i \qquad B'_{L,i} \sim Q^a (d'_L)^a_i$$



$$B_R \to B_R g_R^\dagger \qquad B'_R \to B'_R g_L^\dagger$$
$$B_L \to B_L g_L^\dagger \qquad B'_L \to B'_L g_R^\dagger$$

- The $SU(3)_L \times SU(3)_R$ chiral symmetric Lagrangian is

$$\mathcal{L}_{\rm eff} = \sum_{s=L,R} \Big\{ \bar{B}_s iv\cdot\partial B_s - \mu_1 \bar{B}_s B_s + \bar{B}'_s iv\cdot\partial B'_s$$
$$- \mu_3 (\bar{B}_R B'_L + \bar{B}'_L B_R + \bar{B}_L B'_R + \bar{B}'_R B_L)$$
$$- g_1 (\bar{B}_L \Sigma^* B_R + \bar{B}_R \Sigma^T B_L) - g_2 (\bar{B}'_R \Sigma^* B'_L +$$
$$- g_3 (\bar{B}'_R \Sigma^* B_R + \bar{B}_L \Sigma^* B'_L + \bar{B}_R \Sigma^T B'_R + \bar{B}'_L \Sigma^T B_L) \, ,$$



with meson nonet $\Sigma = S + iP$

S: $(\sigma, a_0, \cdots)$ $\quad$ P: $(\eta, \pi, \cdots)$

$$\Sigma \to g_L \Sigma g_R^\dagger$$

Mass spectrum

- **Heavy baryon masses**

  - Under chiral symmetry breaking $\langle\Sigma\rangle = \mathrm{diag}(\sigma_q, \sigma_q, \sigma_s)$ with $\sigma_q = 93\,\mathrm{MeV}$

  - The mass eigenvalues are obtained as

$$M(B^{H/L}_{+,i}) = m_B + \frac{1}{2}\left\{m_{+,i} + m'_{+,i} \pm \sqrt{(m_{+,i} - m'_{+,i})^2 + 4\tilde{m}^2_{+,i}}\right\} \Leftarrow J^P = 1/2^+$$

$$M(B^{H/L}_{-,i}) = m_B + \frac{1}{2}\left\{m_{-,i} + m'_{-,i} \pm \sqrt{(m_{-,i} - m'_{-,i})^2 + 4\tilde{m}^2_{-,i}}\right\} \Leftarrow J^P = 1/2^-$$

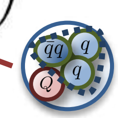
with
$$m_{\pm,i} = \mu_1 \mp g_1\sigma_i$$
$$m'_{\pm,i} = \mu_2 \mp g_2\sigma_i$$
$$\tilde{m}_{\pm,i} = \mu_3 \mp g_3\sigma_i$$
$$\begin{cases} \sigma_1 = \sigma_2 \equiv \sigma_q \\ \sigma_3 \equiv \sigma_s \end{cases}$$

$\mathrm{H/L} \Leftrightarrow \mathrm{Higher/Lower}$

[m_B is a mass parameter used to define heavy baryon effective theory]

  - The corresponding eigenstates are

$$\begin{pmatrix} B^L_{\pm,i} \\ B^H_{\pm,i} \end{pmatrix} = \begin{pmatrix} \cos\theta_{B_{\pm,i}} & \sin\theta_{B_{\pm,i}} \\ -\sin\theta_{B_{\pm,i}} & \cos\theta_{B_{\pm,i}} \end{pmatrix} \begin{pmatrix} B_{\pm,i} \\ B'_{\pm,i} \end{pmatrix}$$



$$B^{(\prime)}_{\pm} = \frac{1}{\sqrt{2}}(B^{(\prime)}_R \mp B^{(\prime)}_L)$$

Mass spectrum

D. S. , A. Hosaka, PRD 104 (2021) 3, 034009
D. S. , A. Hosaka, PRD 105 (2022) 7, 074036

• Parameter determination

- The following Baryons masses are inputs to fix parameters

$$\Lambda_c(2286),\ \Lambda_c(2765),\ \Xi_c(2470),\ \Xi_c(2967)\ \text{and}\ \Lambda_c(2890)$$

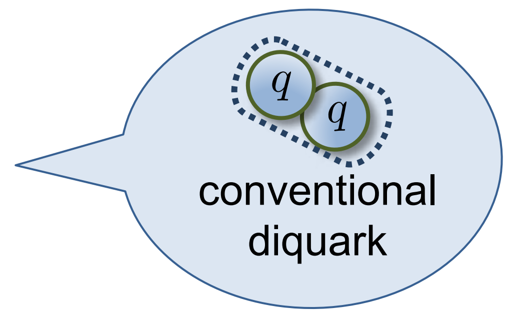
$\frac{1}{2}^+$ (g.s.) $\quad \frac{1}{2}^+$ (excited) $\quad \frac{1}{2}^+$ (g.s.) $\quad \frac{1}{2}^+$ (excited) $\quad \frac{1}{2}^-$

T. Yoshida, et al, PRD (2015)

(quark model prediction)

- Diquark masses without mixing from mirror ones measured by lattice simulation are also inputs

$$M(d_{+,i=3}) = 725\ \text{MeV} \qquad M(d_{+,i=1,2}) = 906\ \text{MeV}$$
$$M(d_{-,i=3}) = 1265\ \text{MeV} \qquad M(d_{-,i=1,2}) = 1142\,\text{MeV}$$



Y. Bi, et al, Chin. Phys. C (2016)
with M. Harada, et. al. , PRD (2020)

Mass spectrum

D. S. , A. Hosaka, PRD 104 (2021) 3, 034009
D. S. , A. Hosaka, PRD 105 (2022) 7, 074036

- **Results**

  - We get physically distinct two parameter sets as

	μ_1 [MeV]	μ_2 [MeV]	μ_3 [MeV]	g_1	g_2	g_3	σ_q [MeV]	σ_s MeV
(I)	-247	247	∓ 91.0	1.27	1.94	± 0.34	(93)	212
(II)	94.1	-94.1	± 246	1.27	1.94	± 0.34	(93)	212

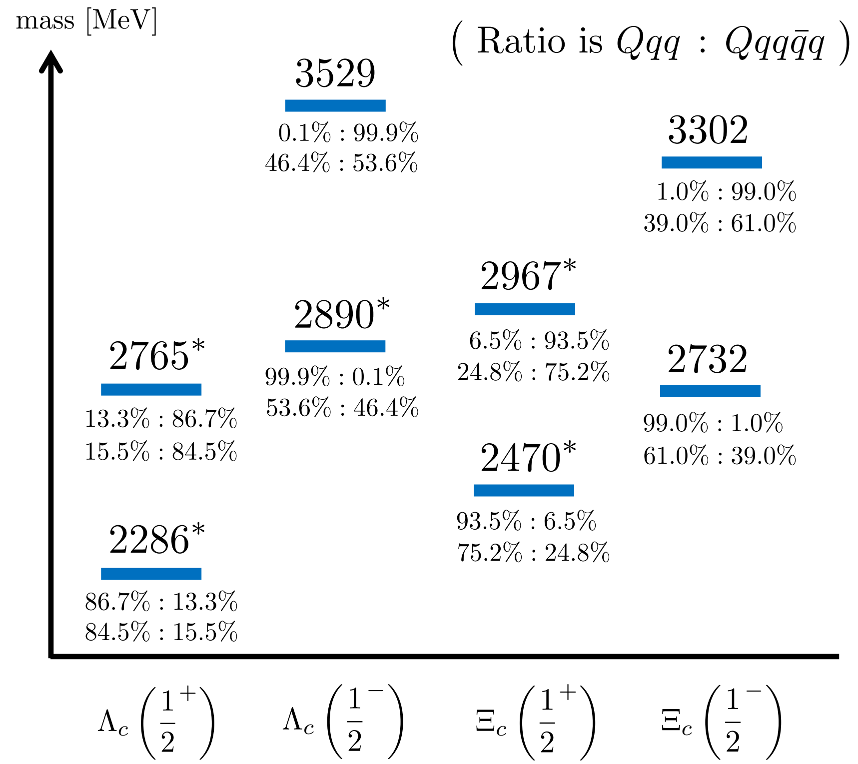
with $m_B = 2868\,\mathrm{MeV}$

  - The resultant mass spectrum

mass

$Qqq : Qqq\bar{q}q$ for (I)

$Qqq : Qqq\bar{q}q$ for (II)



Mass spectrum

D. S. , A. Hosaka, PRD 104 (2021) 3, 034009
D. S. , A. Hosaka, PRD 105 (2022) 7, 074036

- **Results**

  - We get physically distinct two parameter sets as

	μ_1 [MeV]	μ_2 [MeV]	μ_3 [MeV]	g_1	g_2	g_3	σ_q [MeV]	σ_s MeV
(I)	-247	247	∓ 91.0	1.27	1.94	± 0.34	(93)	212
(II)	94.1	-94.1	± 246	1.27	1.94	± 0.34	(93)	212

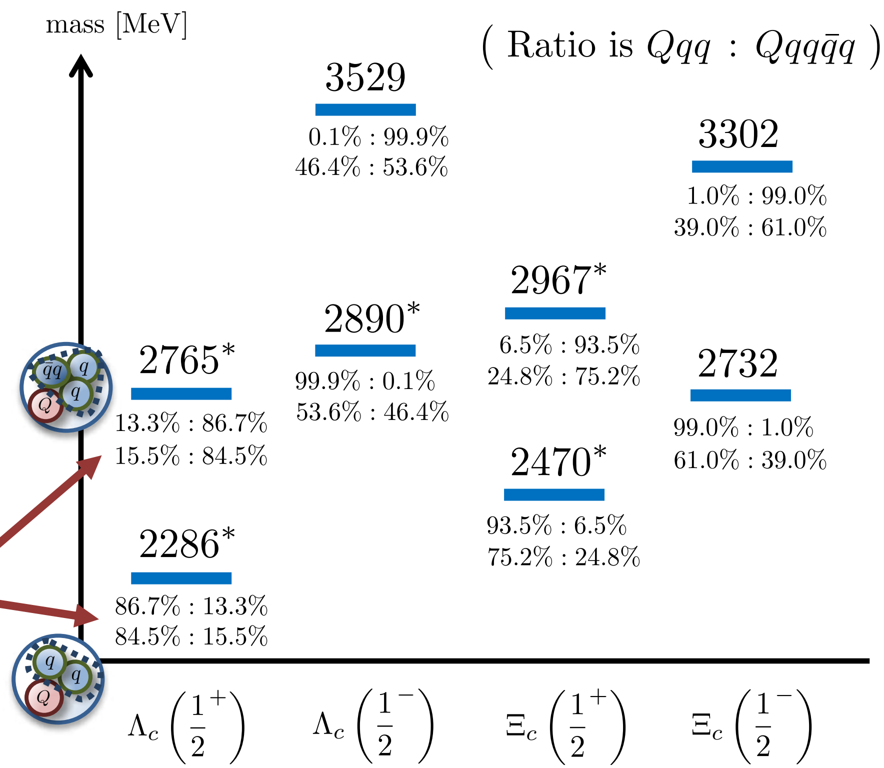
with $m_B = 2868\,\mathrm{MeV}$

  - The resultant mass spectrum

mass

$Qqq : Qqq\bar{q}q$ for (I)

$Qqq : Qqq\bar{q}q$ for (II)



Excited $\Lambda_c(2765)$ is mostly $Qqq\bar{q}q$ while $\Lambda_c(2286)$ is mostly Qqq

Mass spectrum

- **General relations**

Mass formula

$$\sum_{p=\pm,n=H,L} M(B^n_{p,i=1,2}) = \sum_{p=\pm,n=H,L} M(B^n_{p,i=3})$$

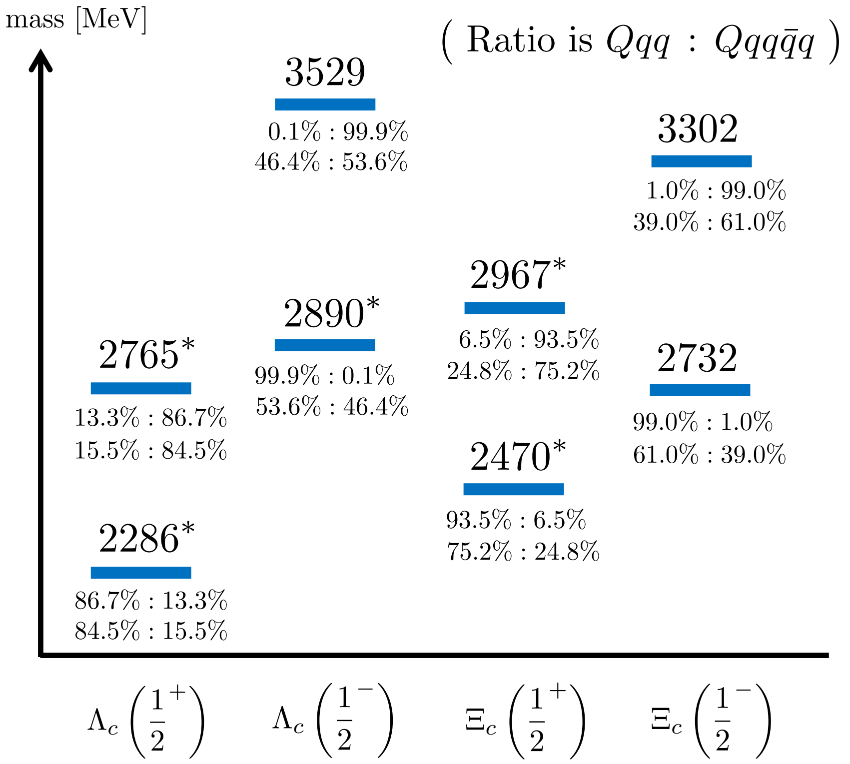
four Ξ_c masses $=$ four Λ_c masses

extended Goldberger-Treiman relation

$$\sum_{n=H,L} M(B^n_{-,i}) - \sum_{n=H,L} M(B^n_{+,i}) = 2(g_1+g_2)\sigma_i$$

Mass differences are related to NG boson emission decay

⇔ Distinct from quark models



1. Introduction

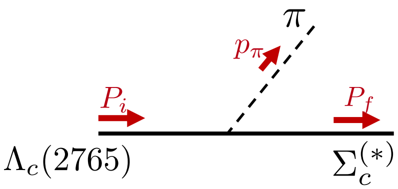
2. Mass spectrum

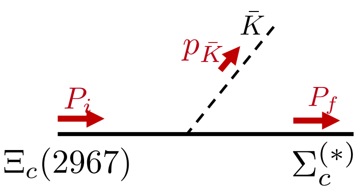
3. Decays of SHBs

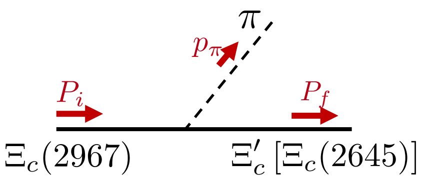
4. Conclusions

- **Decays of the Roper-like SHBs**

- We evaluate decays of the Roper-like SHBs by the following diagrams



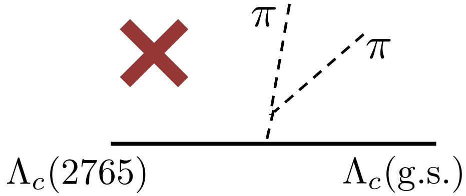




- Our model reads suppression of direct decays of e.g. $\Lambda_c(2765) \to \Lambda_c(\text{g.s.})\pi\pi$

⇒ Consistent with experimental data

Abe et al (Belle Collaboration) PRL(2007)



- Heavy quark spin-doublet SHBs are denoted by

$S^\mu_{ij} \sim Q^a(\tilde{d})^{a,\mu}_{ij}$ with a vector diquark $(\tilde{d})^{a,\mu}_{ij} \sim \epsilon^{abc}(q_L^T)^b_j C\gamma^\mu (q_R)^c_i$

$\tilde{d} \sim (\mathbf{3}, \mathbf{3})$

$$S^\mu = \underline{S^\mu_6} + S^\mu_{\bar{3}}$$

flavor symmetric

Harada-Liu-Oka-Suzuki PRD(2020)

$$S^\mu_6 = \begin{pmatrix} \Sigma_c^{I_z=1} & \frac{1}{\sqrt{2}}\Sigma_c^{I=0} & \frac{1}{\sqrt{2}}\Xi_c'^{I=1/2} \\ \frac{1}{\sqrt{2}}\Sigma_c^{I=0} & \Sigma_c^{I=-1} & \frac{1}{\sqrt{2}}\Xi_c'^{I=-1/2} \\ \frac{1}{\sqrt{2}}\Xi_c'^{I=1/2} & \frac{1}{\sqrt{2}}\Xi_c'^{I=-1/2} & \Omega_c \end{pmatrix}^\mu \ni \left\{ \begin{matrix} \Sigma_c(2520) & \Sigma_c(2455) \\ \Xi_c(2645) & \Xi_c' \end{matrix} \right.$$

Decays of SHBs

- **Lagrangian for the decays**

  - The chiral invariant Lagrangian reads

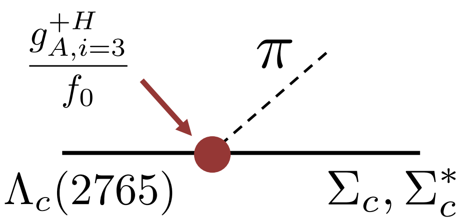
$$\mathcal{L}_{\rm int} = \frac{\sqrt{2}g_A}{f_0}\mathrm{Tr}\left[\bar{\mathcal{B}}_R\partial_\mu\Sigma^\dagger S^{T\mu} + \bar{\mathcal{B}}_L\partial_\mu\Sigma S^\mu + \mathrm{h.c.}\right] + \frac{\sqrt{2}g_A'}{f_0}\mathrm{Tr}\left[\bar{\mathcal{B}}_L'\partial_\mu\Sigma^\dagger S^{T\mu} + \bar{\mathcal{B}}_R'\partial_\mu\Sigma S^\mu + \mathrm{h.c,}\right]$$

with

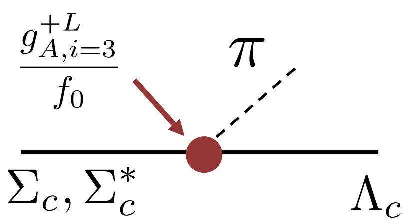
$$\begin{cases}(\mathcal{B}_R^{(\prime)})_{ij} = \epsilon_{ijk}(B_R^{(\prime)})_k \\ (\mathcal{B}_L^{(\prime)})_{ij} = \epsilon_{ijk}(B_L^{(\prime)})_k\end{cases}$$

$$f_0 = 101\ \mathrm{MeV}$$

  - Surprisingly this concise Lagrangian describes all of the following decays



and



and $(\Xi_c\ \mathrm{siblings})$

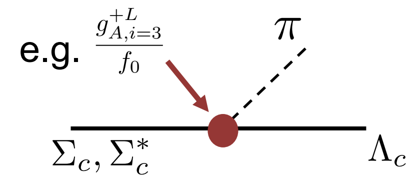
$g^{+H}_{A,i} \equiv g_A \sin\theta_{B_+^i} - g_A' \cos\theta_{B_+^i}$, $g^{+L}_{A,i} \equiv g_A \cos\theta_{B_+^i} + g_A' \sin\theta_{B_+^i}$ are axial charges

The mixing angles appear reflecting the Roper-like and ground-state baryons described by mixings of $B_{+,i}$ and $B'_{+,i}$

Decays of SHBs

D. S. , A. Hosaka, PRD 104 (2021) 3, 034009
D. S. , A. Hosaka, PRD 105 (2022) 7, 074036

- **Decay widths of Roper-like SHBs**

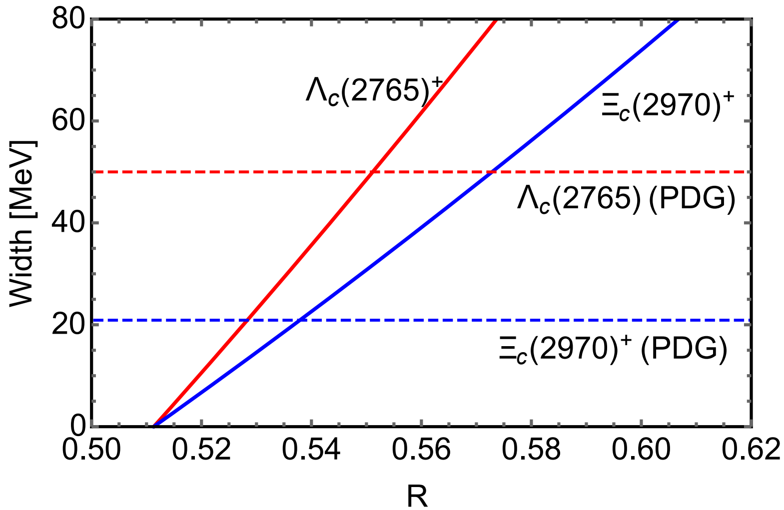


  - By using decay widths of HQS-doublet as inputs, we find

$$g^{+L}_{A,i=3} \approx g^{+L}_{A,i=1,2} \approx 0.512$$ (mostly flavor independent)

  - Decays of Roper-like $\Lambda_c(2765)$ and $\Xi_c(2970)$ are examined simultaneously with the following one parameter: $R^2 \equiv g_A^2 + g_A'^2 = (g^{+L}_{A,i})^2 + (g^{+H}_{A,i})^2$

R dependence of the widths



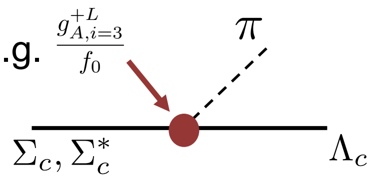
Decays of SHBs

$\mathrm{D.\,S.\,,A.\,Hosaka,PRD\,104\,(2021)\,3,034009}$

$\mathrm{D.\,S.\,,A.\,Hosaka,PRD\,105\,(2022)\,7,074036}$

- **Decay widths of Roper-like SHBs**

e.g.

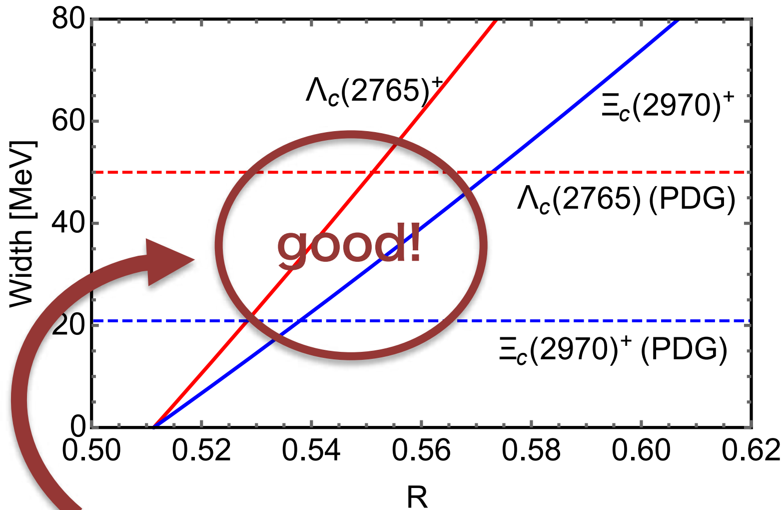


- By using decay widths of HQS-doublet as inputs, we find

$$g^{+L}_{A,i=3} \approx g^{+L}_{A,i=1,2} \approx 0.512$$ (mostly flavor independent)

- Decays of Roper-like $\Lambda_c(2765)$ and $\Xi_c(2970)$ are examined simultaneously with the following one parameter: $R^2 \equiv g_A^2 + g_A'^2 = (g^{+L}_{A,i})^2 + (g^{+H}_{A,i})^2$

R dependence of the widths



We found $R = 0.53 - 0.57$

The widths for $R = 0.53 - 0.57$

Decaying baryon	Channel	Width	PDG value
$\Lambda_c(2765)^+$	$\Sigma_c(2455)\pi$	12.7 - 41.6	
	$\Sigma_c(2520)\pi$	10.2 - 33.4	
	Sum	23.0 - 75.0	(50)
$\Xi_c(2970)^+$	$\Sigma_c(2455)\bar{K}$	0.704 - 2.30	
	$\Xi_c'\pi$	6.83 - 22.3	
	$\Xi_c(2645)$	7.03 - 22.9	
	Sum	14.6 - 47.6	$(20.9^{+2.4}_{-3.5})$
$\Xi_c(2970)^0$	$\Sigma_c(2455)\bar{K}$	0.577 - 1.88	
	$\Xi_c'\pi$	6.78 - 22.1	
	$\Xi_c(2645)$	6.97 - 22.7	
	Sum	14.3 - 46.7	

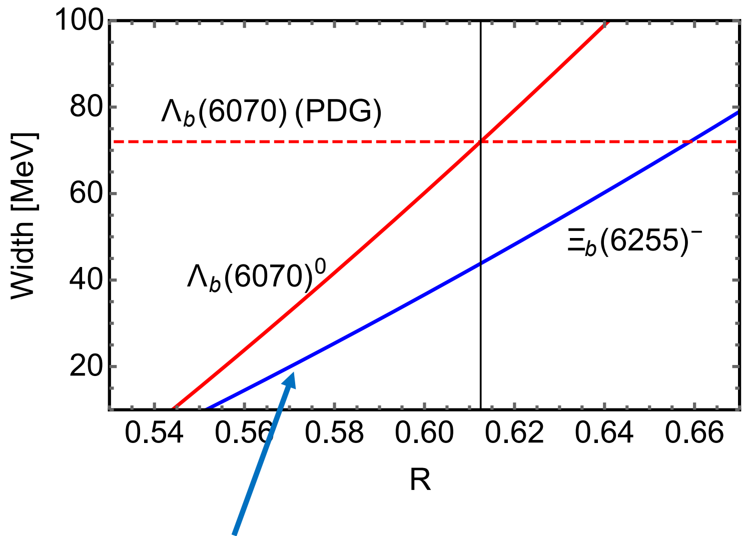
Decays of SHBs

- **Results for bottom sector**
  - By using decay widths of HQS-doublet as inputs, for bottom sector we find

$$g^{+L}_{A,i=3} \approx g^{+L}_{A,i=1,2} \approx 0.532$$ (again mostly flavor independent)

  - Decays of Roper-like $\Lambda_b(6070)$ and $\Xi_b(?)$ are examined simultaneously

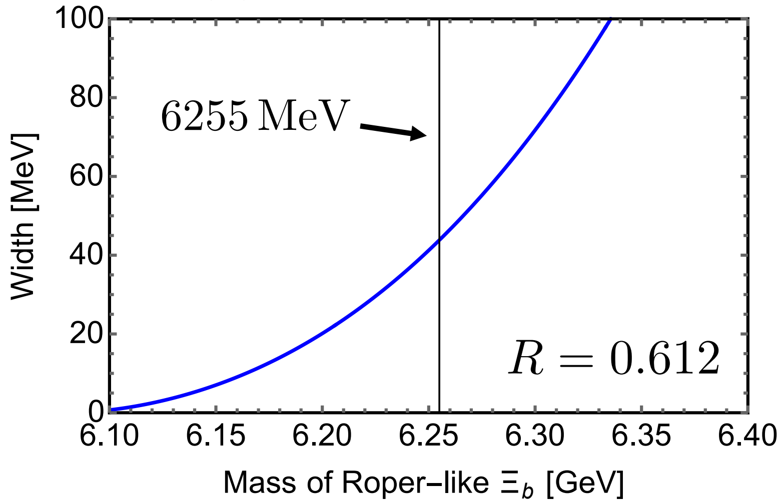
R dependence of the widths



We employ 6255 MeV for $\Xi_b(?)$ mass

quark model: Chen-Wei-Liu-Zhang PRD(2018)

$\Xi_b(?)$ mass dependence



Our prediction for the width of $\Xi_b(?)$

Conclusions

D. S. , A. Hosaka, PRD 104 (2021) 3, 034009
D. S. , A. Hosaka, PRD 105 (2022) 7, 074036

- We presented the chiral model describing mass spectrum and decays of the Roper-like SHBs
- We proposed that the Roper-like SHBs are mostly pentaquark states
- Properties of the negative-parity HQS-singlet SHBs ("chiral partners") were also presented
- The large decay width of the Roper-like SHBs $(\sim 50\,\mathrm{MeV})$ was naturally explained in our chiral model
  - × NR quark model
  - ◎ our chiral model

Future prospect

- In order to further confirm the pentaquark nature of the Roper-like SHBs, we are exploring their decays with $U(1)_A$ viewpoint (with Prof. M. Harada, M. Oka)
- Quark model computation for pentaquark picture for the Roper-like SHBs
- Modifications in medium (→ Any hints of diquark condensate?)