Pentaquark picture for singly heavy baryons based on a chiral model

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in collaboration with Hiroto Takada,
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Makoto Oka

1. Introduction

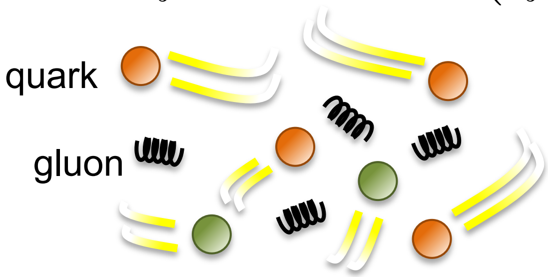
• Hadrons and QCD

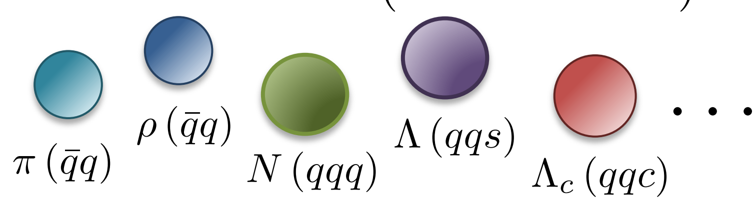
- Hadron properties are in-principle described by QCD dynamics

$$Z_{\mathrm{QCD}} = \int D\bar{\psi} D\psi DA \exp\left(i \int d^4x \mathcal{L}_{\mathrm{QCD}}\right)$$

$$Z_{\mathrm{hadron}} = \int DH \exp\left(i \int d^4x \mathcal{L}_{\mathrm{hadron}}\right)$$

$(H = \mathrm{hadrons})$

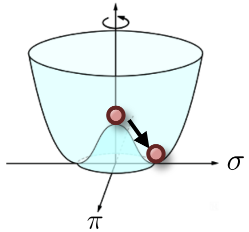




$$Z_{\mathrm{QCD}} \approx Z_{\mathrm{hadron}}$$

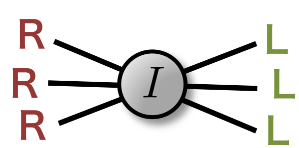
⇨ Hadrons must respect symmetry properties of QCD

eg <u>Chiral symmetry breaking</u>



- mass generation
- low-energy theorem

<u>$U(1)_A$ anomaly</u>



- $U(1)_A$ non-conservation
- topological nature of QCD

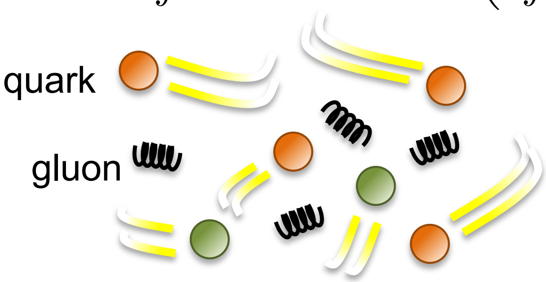
1. Introduction

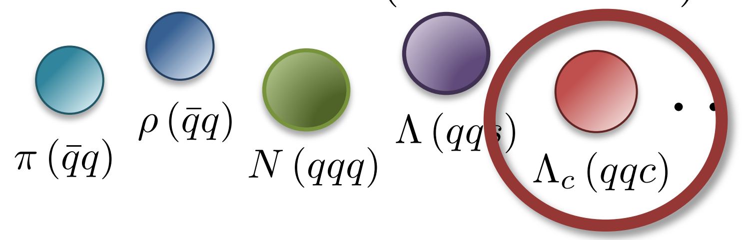
• Hadrons and QCD

- Hadron properties are in-principle described by QCD dynamics

$$Z_{\rm QCD} = \int D\bar{\psi} D\psi DA \exp\left(i \int d^4x \mathcal{L}_{\rm QCD}\right) \qquad Z_{\rm hadron} = \int DH \exp\left(i \int d^4x \mathcal{L}_{\rm hadron}\right)$$

$(H = \text{hadrons})$



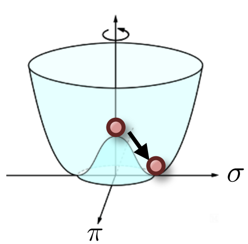


$$Z_{\rm QCD} \approx Z_{\rm hadron}$$

⇨ Hadrons must respect symmetry properties of QCD

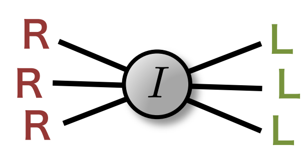
This talk

eg **Chiral symmetry breaking**



- mass generation
- low-energy theorem

$U(1)_A$ anomaly

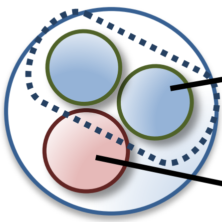


- $U(1)_A$ non-conservation
- topological nature of QCD

1. Introduction

• Diquark in SHBs

- We employ (heavy quark)-(diquark) picture for singly heavy baryons (SHBs)



diquark $qq, qq(\bar{q}q), \cdots$
- chiral symmetry breaking
- $U(1)_A$ anomaly

heavy quark Q
= spectator
- heavy quark spin symmetry (HQSS)

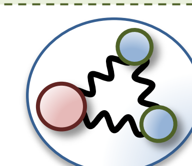
Our approach

- We try to describe SHBs with a field-theoretical method based on chiral symmetry, $U(1)_A$ anomaly, and HQSS

- Note: Diquarks are NOT observable (confinement) but are useful in studying the baryon spectrum

eg, Jaffe-Wilczek (2003). Hong-Sohn-Zahed (2004)

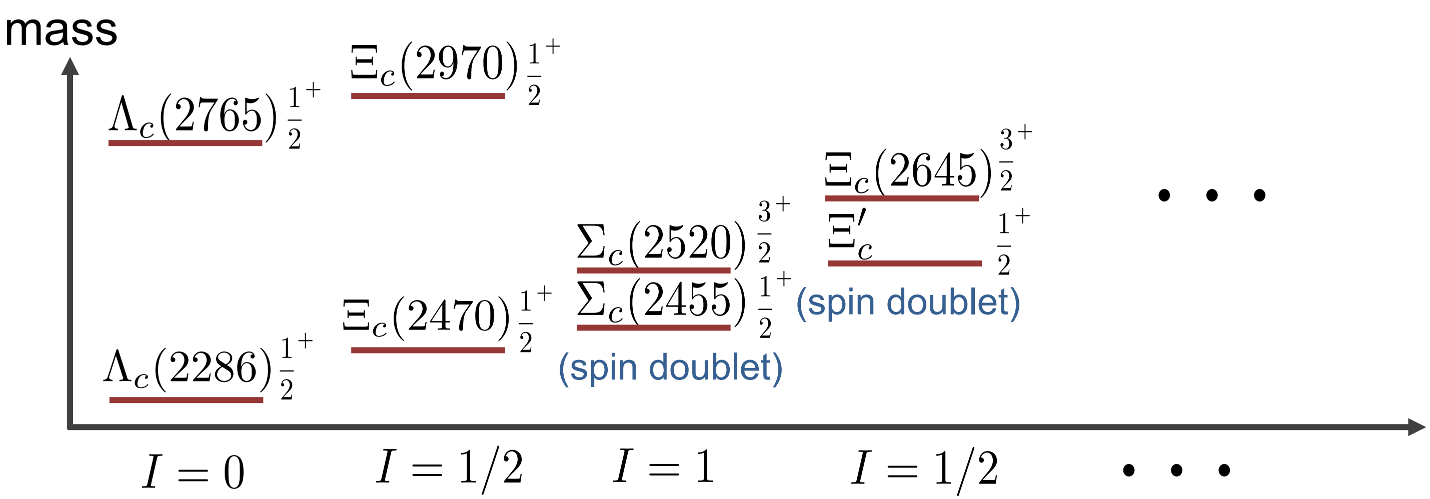
⇔ quark model (constituent quarks are confined but useful)



1. Introduction

- **SHB in chiral models**

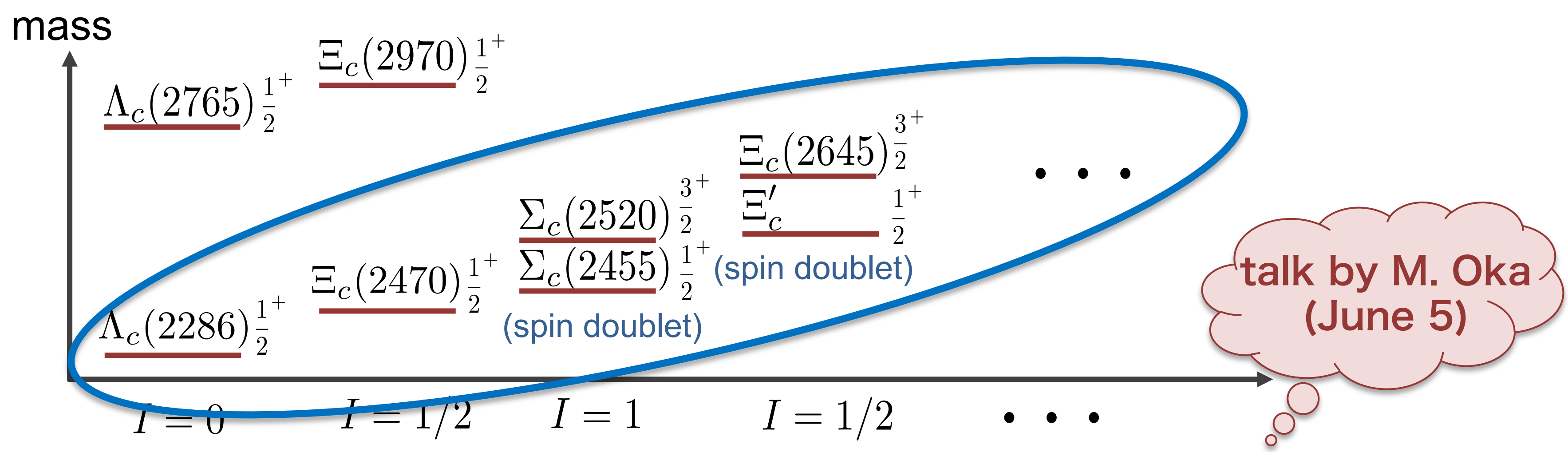
  - Mass spectrum of SHB in charmed sector



1. Introduction

- **SHB in chiral models**

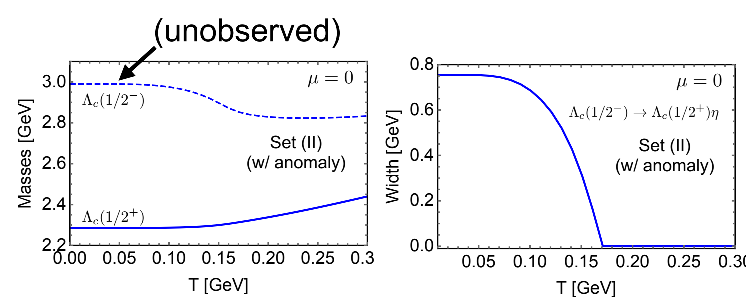
- Mass spectrum of SHB in charmed sector



- Some works were devoted to rather lower states (and their chiral partners)

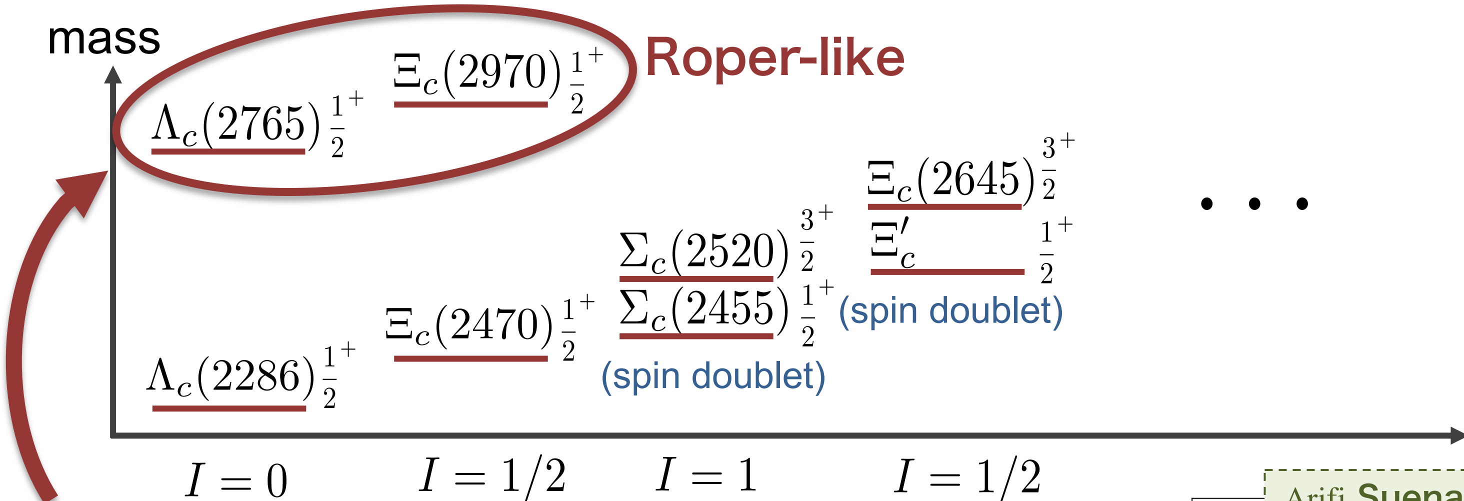
Kawakami-Harada (2018, 2019), Harada-Liu-Oka-Suzuki (2020) Dmitrasinovic-Chen (2020), Kawakami-Harada-Oka-Suzuki (2020), Kim-Hiyama-Oka-Suzuki (2020), Kim-Oka-Suzuki (2021) Kim-Oka-**Suenaga**-Suzuki (2022)

- Chiral-partner structure on $\Lambda_c(\mathrm{g.s.})$ at high T was also examined **Suenaga**-Oka, [hep-ph] 2305.09730



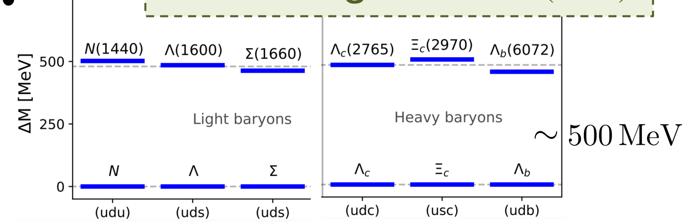
• SHB in chiral models

- Mass spectrum of SHB in charmed sector



- The Roper-like SHBs are rather mysterious

• Arifi-**Suenaga**-Hosaka-Oh(2022)



- Universality of mass differences
- Comparably large decay width of $\Lambda_c(2765)$, $\Xi_c(2970)$ ($\Gamma_{\rm ex} \sim 50\,\mathrm{MeV}$)

⟺ $\Gamma_{\rm th} \sim 5\,\mathrm{MeV}$ in NON-relativistic quark model, but improved by rel. corrections

Nagahiro et al (2017), Arifi-**Suenaga**-Hosaka (2021)

→ chiral model description

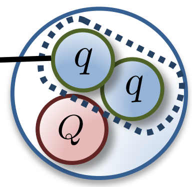
1. Introduction

- **Pentaquark picture for $\Lambda_c(2765)$ and $\Xi_c(2970)$**

- We invent pentaquark components made of tetra-diquark $qq(\bar{q}q)$ to describe the Roper-like SHBs within a chiral model

Suenaga-Hosaka (2021, 2022)

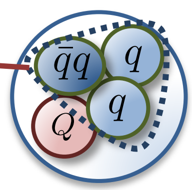
conventional diquark
qq



mostly $\sim$ $\Lambda_c(2286)$, $\Xi_c(2470)$ $\left(\frac{1}{2}^+\right)$

ground state

tetra-diquark
$qq(\bar{q}q)$



mostly $\sim$ $\Lambda_c(2765)$, $\Xi_c(2970)$ $\left(\frac{1}{2}^+\right)$

Roper-like state

The mass difference is $\sim 500\,\mathrm{MeV}$

⇕ reasonable

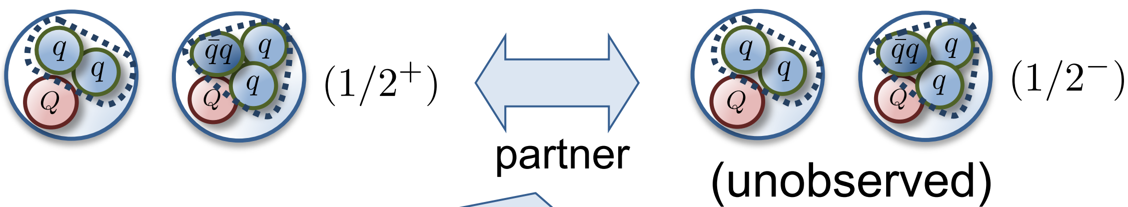
Sigma meson mass is $M(\bar{q}q) \sim 500\,\mathrm{MeV}$

1. Introduction

- **Pentaquark picture for $\Lambda_c(2765)$ and $\Xi_c(2970)$**

- Chiral partners are also predicted

Suenaga-Hosaka, PRD 104, 034009 (2021)

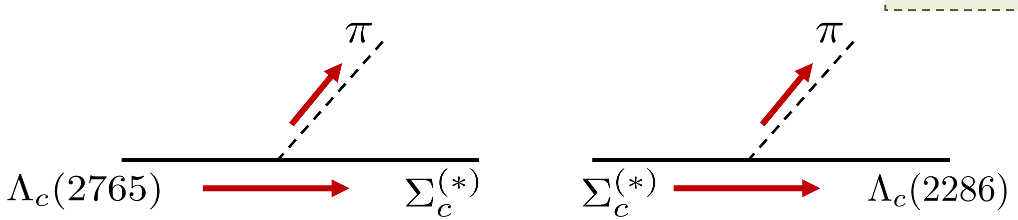


all of them are HQS-singlet

mass degeneracy when chiral symmetry is restored

- Large decay widths of $\Lambda_c(2765)$ and $\Xi_c(2970)$ are explained with reasonable value with $(\text{axial charge}) \sim 0.5$

Suenaga-Hosaka, PRD 105, 074036 (2022)



This talk

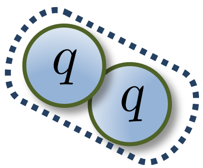
- I present predicted mass spectrum and decay width of the chiral partners

2. Model

- **Diquark fields**

  - We introduce two types of diquarks

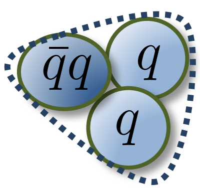
i) *conventional diquark*



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

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

ii) *tetra-diquark*

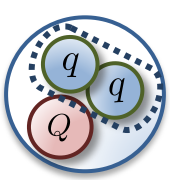


$$(d'_R)^a_i \sim \epsilon_{jkl}\epsilon^{abc}(q_R^T)^b_k C(q_R)^c_l[(\bar{q}_L)^d_i(q_R)^d_j]$$
$$(d'_L)^a_i \sim \epsilon_{jkl}\epsilon^{abc}(q_L^T)^b_k C(q_L)^c_l[(\bar{q}_R)^d_i(q_L)^d_j]$$

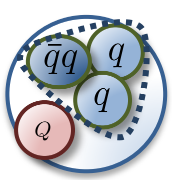
- The chiral representation and axial charges of d_R, d_L, d'_R, d'_L are

$$d_R \sim (\mathbf{1}, \bar{\mathbf{3}})_{+2}\ ,\quad d_L \sim (\bar{\mathbf{3}}, \mathbf{1})_{-2}$$
$$d'_R \sim (\bar{\mathbf{3}}, \mathbf{1})_{+4}\ ,\quad d'_L \sim (\mathbf{1}, \bar{\mathbf{3}})_{-4}$$

- The baryon fields are $\begin{cases} B_{R(L)} \sim Q d_{R(L)} \\ B'_{R(L)} \sim Q d'_{R(L)} \end{cases}$



3-quark



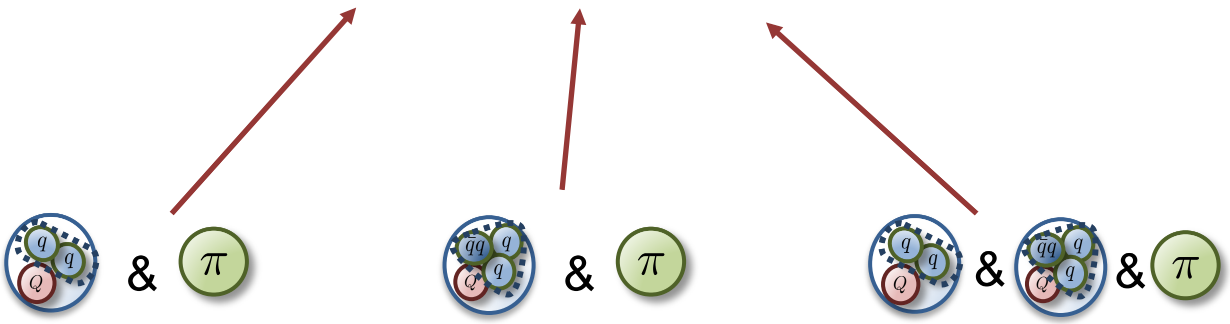
5-quark

2. Model

- **Lagrangian**

  - Our Lagrangian is invariant under $SU(3)_L \times SU(3)_R$ chiral symmetry but incorporate $U(1)_A$ anomaly, which can be separate into three parts:

$$\mathcal{L} = \mathcal{L}_3 + \mathcal{L}_5 + \mathcal{L}_{\rm mix}$$



  - Our counting scheme:

    1. include interactions invariant under $SU(3)_L \times SU(3)_R$ chiral and $U(1)_A$ axial symmetry

    2. add $U(1)_A$ breaking terms with minimum number of meson fields

2. Model

- **Lagrangian**

- More concretely

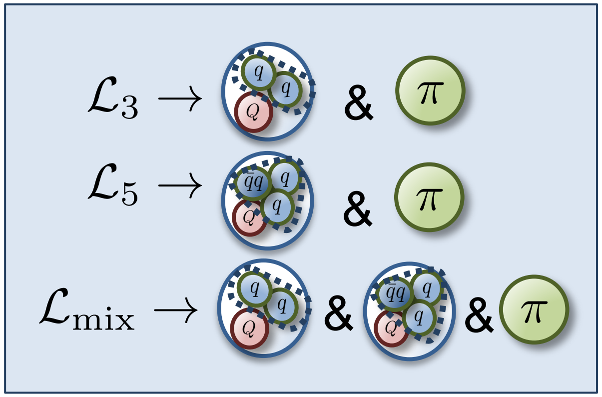
$$\mathcal{L} = \mathcal{L}_3 + \mathcal{L}_5 + \mathcal{L}_{\rm mix}$$

$$\begin{aligned}\mathcal{L}_3 = \sum_{\chi=L,R} \left(\bar{B}_\chi i v\cdot\partial B_\chi - \mu_1 \bar{B}_\chi B_\chi\right) - \frac{\mu_3}{f_\pi^2}\left[\bar{B}_L(\Sigma\Sigma^\dagger)^T B_L + \bar{B}_R(\Sigma^\dagger\Sigma)^T B_R\right] \\ -\frac{g_1}{2f_\pi}\left(\epsilon_{ijk}\epsilon_{abc}\bar{B}_{L,k}\Sigma_{ia}\Sigma_{jb}B_{R,c} + \text{h.c.}\right) - g_1'\left(\bar{B}_L\Sigma^* B_R + \text{h.c.}\right)\end{aligned}$$

$$\begin{aligned}\mathcal{L}_5 = \sum_{\chi=L,R} \left(\bar{B}'_\chi i v\cdot\partial B'_\chi - \mu_2 \bar{B}'_\chi B'_\chi\right) - \frac{\mu_4}{f_\pi^2}\left[\bar{B}'_R(\Sigma\Sigma^\dagger)^T B'_R + \bar{B}'_L(\Sigma^\dagger\Sigma)^T B'_L\right] \\ -\frac{g_2}{6f_\pi^3}\left[(\epsilon_{abc}\epsilon_{ijk}\Sigma^\dagger_{ci}\Sigma^\dagger_{bj}\Sigma^\dagger_{ak})(\bar{B}'_R\Sigma^* B'_L) + \text{h.c.}\right] - \frac{g_3}{2f_\pi^3}\left(\epsilon_{abc}\epsilon_{ijk}\bar{B}'_{R,l}\Sigma^\dagger_{cl}\Sigma^\dagger_{bi}\Sigma^\dagger_{aj}\Sigma^\dagger_{dk}B'_{L,d} + \text{h.c.}\right) \\ +g_2'\left(\bar{B}'_R\Sigma^* B'_L + \bar{B}'_L\Sigma^T B'_R\right)\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{\rm mix} = -g_4\left(\bar{B}'_R\Sigma^* B_R + \bar{B}_L\Sigma^* B'_L + \text{h.c.}\right) \\ -\mu_1'\left(\bar{B}_R B'_L + \bar{B}'_L B_R + \bar{B}_L B'_R + \bar{B}'_R B_L\right)\end{aligned}$$

$\Sigma = S + iP \sim (\mathbf{3}, \bar{\mathbf{3}})_{-2}$ is meson nonet



- **Lagrangian**

  - More concretely

$$\mathcal{L} = \mathcal{L}_3 + \mathcal{L}_5 + \mathcal{L}_{\text{mix}}$$

$$\mathcal{L}_3 = \sum_{\chi=L,R} (\bar{B}_\chi i v \cdot \partial B_\chi - \mu_1 \bar{B}_\chi B_\chi) - \frac{\mu_3}{f_\pi^2}\left[\bar{B}_L(\Sigma\Sigma^\dagger)^T B_L + \bar{B}_R(\Sigma^\dagger\Sigma)^T B_R\right]$$
$$-\frac{g_1}{2f_\pi}\left(\epsilon_{ijk}\epsilon_{abc}\bar{B}_{L,k}\Sigma_{ia}\Sigma_{jb}B_{R,c} + \text{h.c.}\right) - \underline{g_1'(\bar{B}_L\Sigma^* B_R + \text{h.c.})}$$ anomaly

$$\mathcal{L}_5 = \sum_{\chi=L,R} (\bar{B}'_\chi i v \cdot \partial B'_\chi - \mu_2 \bar{B}'_\chi B'_\chi) - \frac{\mu_4}{f_\pi^2}\left[\bar{B}'_R(\Sigma\Sigma^\dagger)^T B'_R + \bar{B}'_L(\Sigma^\dagger\Sigma)^T B'_L\right]$$
$$-\frac{g_2}{6f_\pi^3}\left[(\epsilon_{abc}\epsilon_{ijk}\Sigma^\dagger_{ci}\Sigma^\dagger_{bj}\Sigma^\dagger_{ak})(\bar{B}'_R\Sigma^* B'_L) + \text{h.c.}\right] - \frac{g_3}{2f_\pi^3}\left(\epsilon_{abc}\epsilon_{ijk}\bar{B}'_{R,l}\Sigma^\dagger_{cl}\Sigma^\dagger_{bi}\Sigma^\dagger_{aj}\Sigma^\dagger_{dk}B'_{L,d} + \text{h.c.}\right)$$
$$+\underline{g_2'\left(\bar{B}'_R\Sigma^* B'_L + \bar{B}'_L\Sigma^T B'_R\right)}$$ anomaly

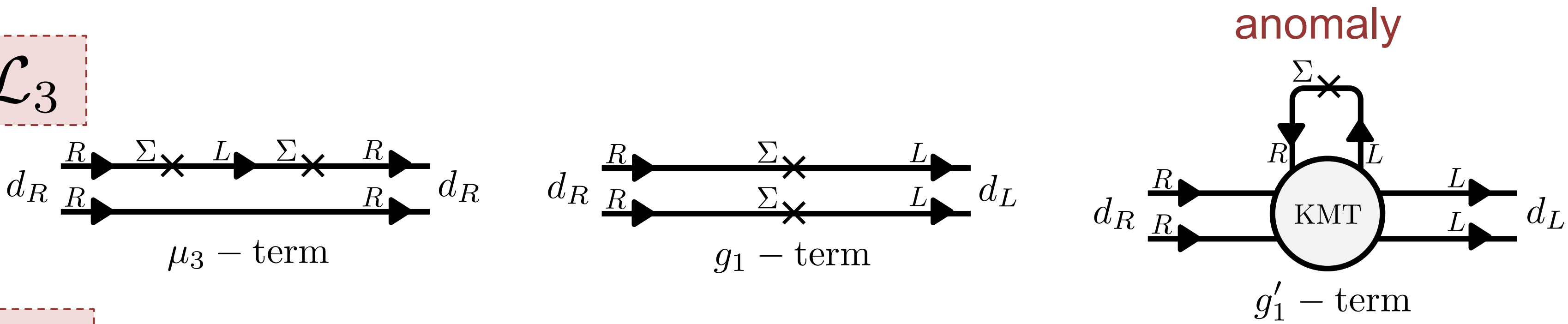
$$\mathcal{L}_{\text{mix}} = -g_4(\bar{B}'_R\Sigma^* B_R + \bar{B}_L\Sigma^* B'_L + \text{h.c.})$$
$$\underline{-\mu_1'(\bar{B}_R B'_L + \bar{B}'_L B_R + \bar{B}_L B'_R + \bar{B}'_R B_L)}$$ anomaly

only g_1', g_2', μ_1' terms are $U(1)_A$ NON-invariant

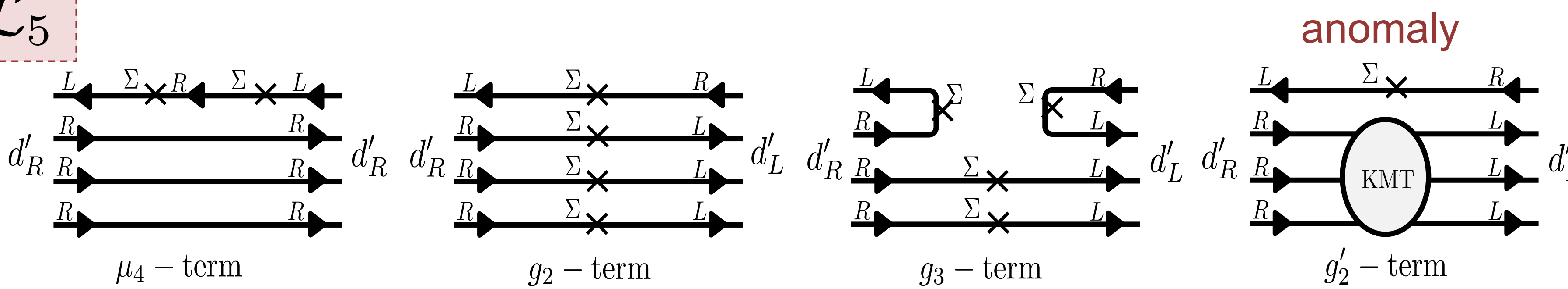
$\Sigma = S + iP \sim (\mathbf{3}, \bar{\mathbf{3}})_{-2}$ is meson nonet

- **Quark line diagram**

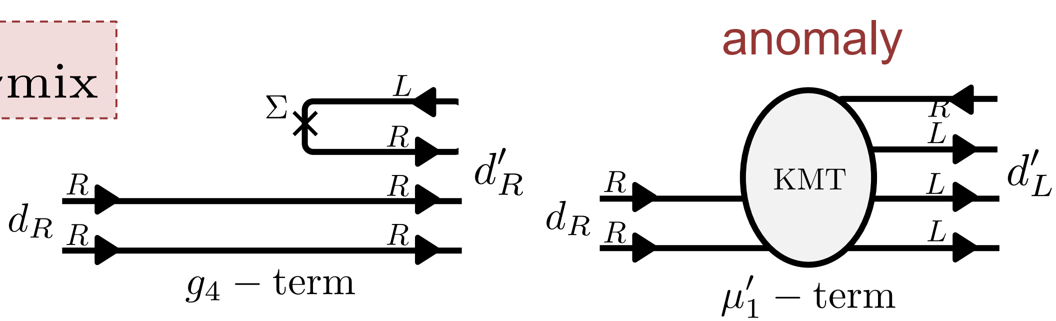
$\mathcal{L}_3$



$\mathcal{L}_5$



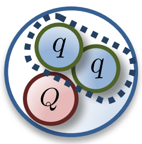
$\mathcal{L}_{\rm mix}$



g_1', g_2', μ_1' terms include KMT-type interactions

3. Analysis and results

- **3-quark SHBs with no mixing:** $\mathcal{L}_{\rm mix} = 0$
  - Under chiral symmetry breaking $\langle \Sigma \rangle = f_\pi {\rm diag}(1, 1, A)$ with $A = 1.38$
  - The mass of 3-quark SHBs with no mixing $\mathcal{L}_{\rm mix} = 0$ is obtained as



ground-state

$$\left\{ \begin{array}{rcl} M(\Lambda_c^{[\mathbf{3}]}(\pm)) & = & m_B + \mu_1 + \mu_3 \mp f_\pi (g_1 + A g_1') \ , \\ M(\Xi_c^{[\mathbf{3}]}(\pm)) & = & m_B + \mu_1 + A^2 \mu_3 \mp f_\pi (A g_1 + g_1') \end{array} \right.$$

$$B_\pm = \frac{1}{\sqrt{2}} (B_R \mp B_L)$$

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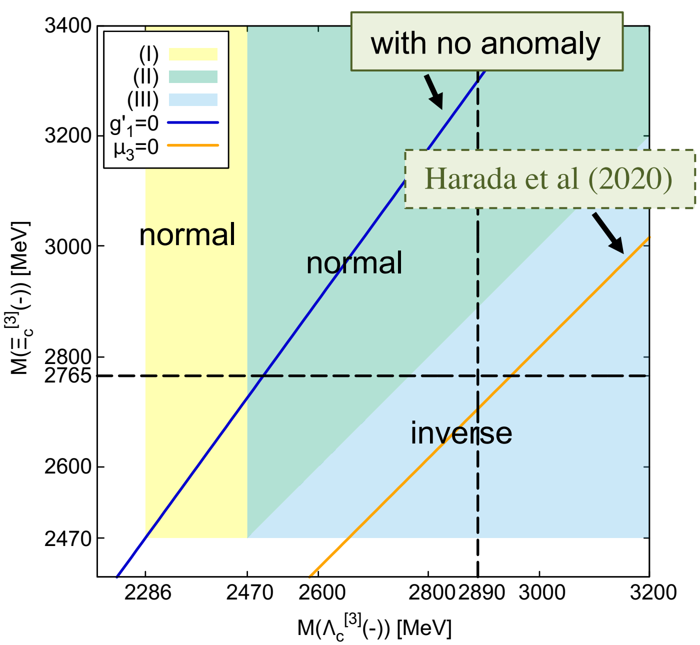


input $M(\Lambda_c^{[3]}(+)) = 2286\,\text{MeV} \quad M(\Xi_c^{[3]}(+)) = 2470\,\text{MeV}$

(I) $M(\Lambda_c^{[3]}(+)) < M(\Lambda_c^{[3]}(-)) < M(\Xi_c^{[3]}(+)) < M(\Xi_c^{[3]}(-))$ normal

(II) $M(\Lambda_c^{[3]}(+)) < M(\Xi_c^{[3]}(+)) < M(\Lambda_c^{[3]}(-)) < M(\Xi_c^{[3]}(-))$ normal

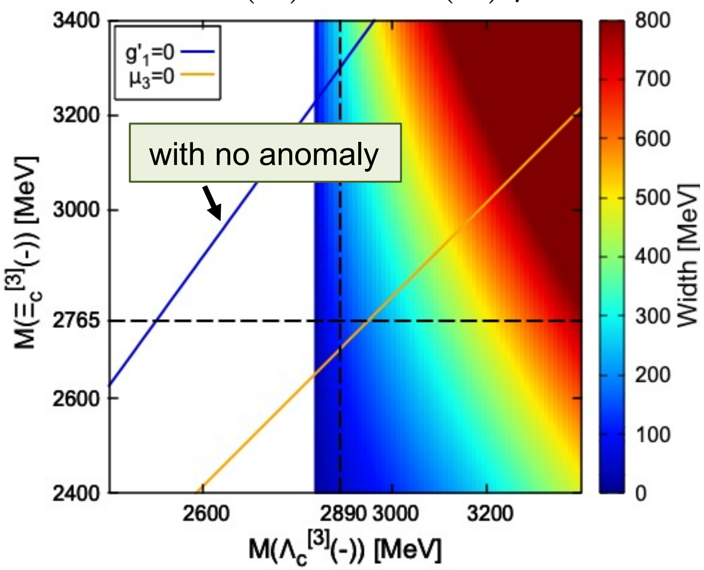
(III) $M(\Lambda_c^{[3]}(+)) < M(\Xi_c^{[3]}(+)) < M(\Xi_c^{[3]}(-)) < M(\Lambda_c^{[3]}(-))$ inverse

Anomalous g_1' term can lead to the **inverse** mass hierarchy

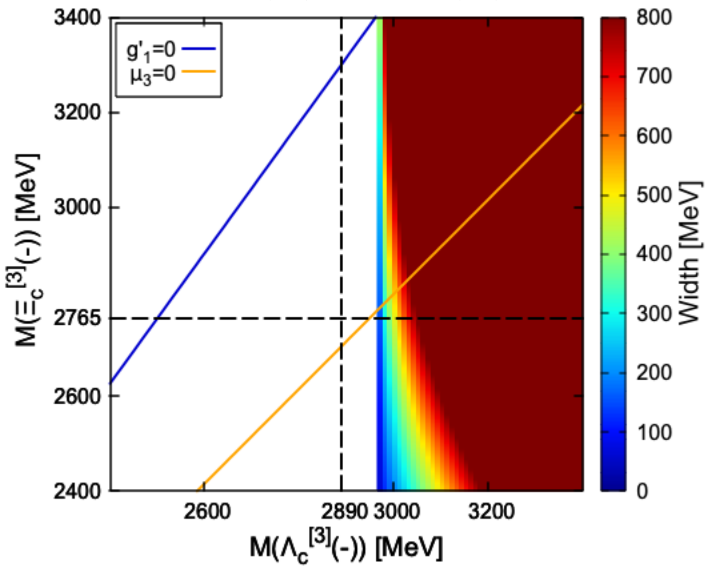
3. Analysis and results

- **3-quark SHBs with no mixing:** $\mathcal{L}_{\rm mix} = 0$
  - Decay widths of $\Lambda_c^{[3]}(-)$ are evaluated

$\Lambda_c^{[\mathbf{3}]}(-) \to \Lambda_c^{[\mathbf{3}]}(+)\eta$



$\Lambda_c^{[\mathbf{3}]}(-) \to \Xi_c^{[\mathbf{3}]}(+)K$



$M(\Lambda_c^{[3]}(-)) = 2890\,\mathrm{MeV}$
quark model
(Yoshida et al 2015)

$M(\Xi_c^{[3]}(-)) = 2765\,\mathrm{MeV}$
chiral $Q-qq$ model
(Kim et al 2020)

- Decay widths abruptly increase above thresholds (chiral partner property)

- Anomaly and $\eta - \eta'$ mixing can milder such sudden increase

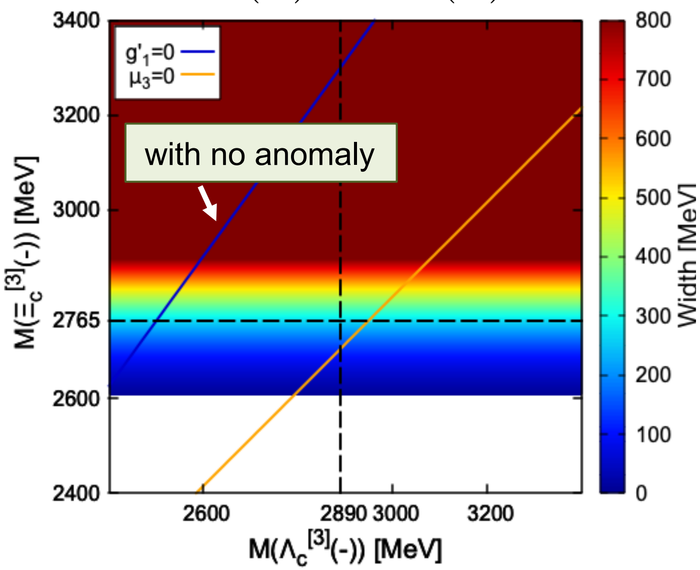
Kawakami-Harada-Oka-Suzuki (2020)

3. Analysis and results

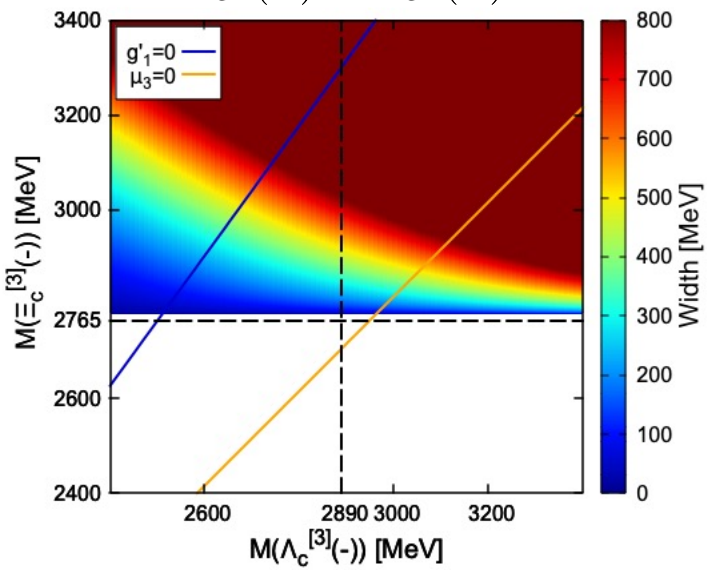
- **3-quark SHBs with no mixing: $\mathcal{L}_{\rm mix} = 0$**

  - Decay widths of $\Xi_c^{[3]}(-)$ are evaluated

$\Xi_c^{[\mathbf{3}]}(-) \to \Xi_c^{[\mathbf{3}]}(+)\pi$



$\Xi_c^{[\mathbf{3}]}(-) \to \Lambda_c^{[\mathbf{3}]}(+)K$



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(Kim et al 2020)

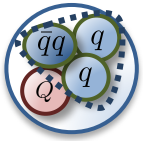
unknown J^P

- When assuming $\Xi_c^{[3]}(-)$ to be recently observed $\Xi_c(2923)$ or $\Xi_c(2930)$, the width becomes very large $\leftrightarrow$ experimentally $\Gamma_{\rm exp} \approx 10\,\mathrm{MeV}$

⇨ $\Xi_c(2923)$ or $\Xi_c(2930)$ CANNOT be 3-quark (dominant) SHB

3. Analysis and results

- **5-quark SHBs with no mixing:** $\mathcal{L}_{\rm mix} = 0$
  - The mass of 5-quark SHBs with no mixing $\mathcal{L}_{\rm mix} = 0$ is obtained as



Roper-like

$$\begin{cases} M(\Lambda_c^{[5]}(\pm)) = m_B + \mu_2 + A^2\mu_4 \pm A f_\pi \left[A(g_2+g_3)+g_2'\right] \\ M(\Xi_c^{[5]}(\pm)) = m_B + \mu_2 + \mu_4 \pm f_\pi \left[A(g_2+g_3)+g_2'\right] \end{cases}$$

  - g_2' (and $g_2,\ g_3$) can be absorbed into $h \equiv A(g_1+g_3)+g_2'$ ⇨ no anomaly effects

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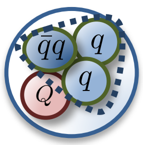

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  - For decays
$$\Gamma(\Xi_c(2967) \to \Xi_c^{[5]}(-)\pi) + \Gamma(\Xi_c(2967) \to \Lambda_c^{[5]}(-)K) \lesssim 20.9\ \text{MeV} \quad \text{(exp.)}$$
$$\Gamma(\Lambda_c(2765) \to \Xi_c^{[5]}(-)K) + \Gamma(\Lambda_c(2765) \to \Lambda_c^{[5]}(-)\eta) \lesssim 50\ \text{MeV} \quad \text{(exp.)}$$

⇩

$$2551\,\text{MeV} \lesssim M(\Lambda_c^{[5]}(-)) < M(\Lambda_c^{[5]}(+))$$
↓ assumption (P-wave): $M(\Lambda_c^{[5]}(+))$ (= 2765 MeV)

$$2811\,\text{MeV} \lesssim M(\Xi_c^{[5]}(-)) < M(\Xi_c^{[5]}(+))$$
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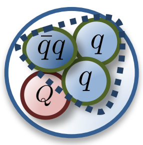

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- $\Xi_c(2923)$ or $\Xi_c(2930)$ can be assigned to $\Xi_c^{[5]}(-)$

3. Analysis and results

- **With mixing**

  - When mixing between 3-quark and 5-quark is present, mass reads

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

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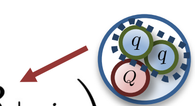
$\pm$: parity
H/L $\Leftrightarrow$ Higher/Lower

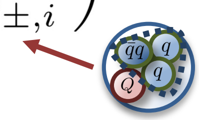
$$\begin{cases} m^{[\mathbf{2}]}_{\pm,i=1,2} = \mu_1 + A^2\mu_3 \mp f_\pi(Ag_1 + g_1') \\ m^{[\mathbf{2}]}_{\pm,i=3} = \mu_1 + \mu_3 \mp f_\pi(g_1 + Ag_1') \ , \\ m^{[\mathbf{4}]}_{\pm,i=1,2} = \mu_2 + \mu_4 \pm f_\pi h \ , \\ m^{[\mathbf{4}]}_{\pm,i=3} = \mu_2 + A^2\mu_4 \pm Af_\pi h \ , \\ \tilde{m}_{\pm,i=1,2} = \mu_1' \mp f_\pi g_4 \ , \\ \tilde{m}_{\pm,i=3} = \mu_1' \mp Af_\pi g_4 \ . \end{cases}$$

# of effective parameters: 9
(except for f_π, A)

  - The mass eigenstates are

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





3. Analysis and results

- **With mixing but no anomaly**

- When anomaly is absent, $g'_1 = \mu'_1 = 0$ $\rightarrow$ # of effective parameters: 7

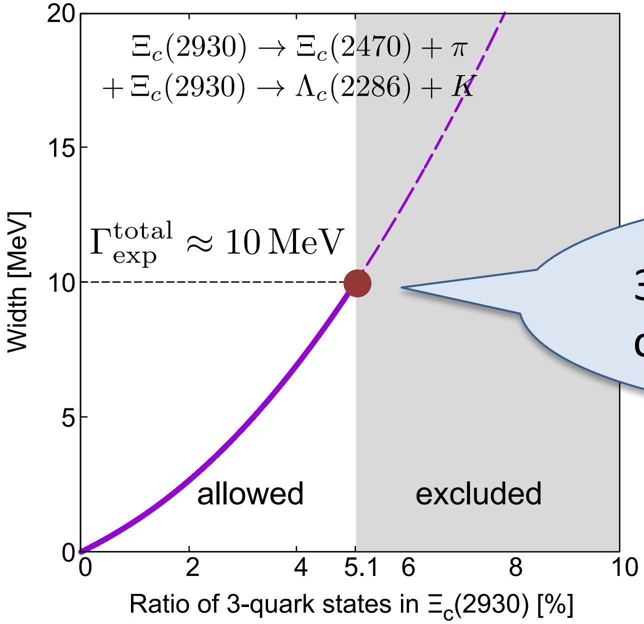
- We take these 6 inputs

$$M(\Lambda_c^L(+)) = 2286\,\mathrm{MeV} \quad M(\Lambda_c^H(+)) = 2765\,\mathrm{MeV}$$
$$M(\Xi_c^L(+)) = 2470\,\mathrm{MeV} \quad M(\Xi_c^H(+)) = 2967\,\mathrm{MeV}$$

$+$

$M(\Lambda_c^H(-)) = 2890\,\mathrm{MeV}$ (quark model)
$M(\Xi_c^L(-)) = 2939\,\mathrm{MeV}$ ($\Xi_c(2930)$)

Width of $\Xi_c(2930)$



3-quark component in $\Xi_c(2930)$ can be at most $\approx 5.1\%$

3. Analysis and results

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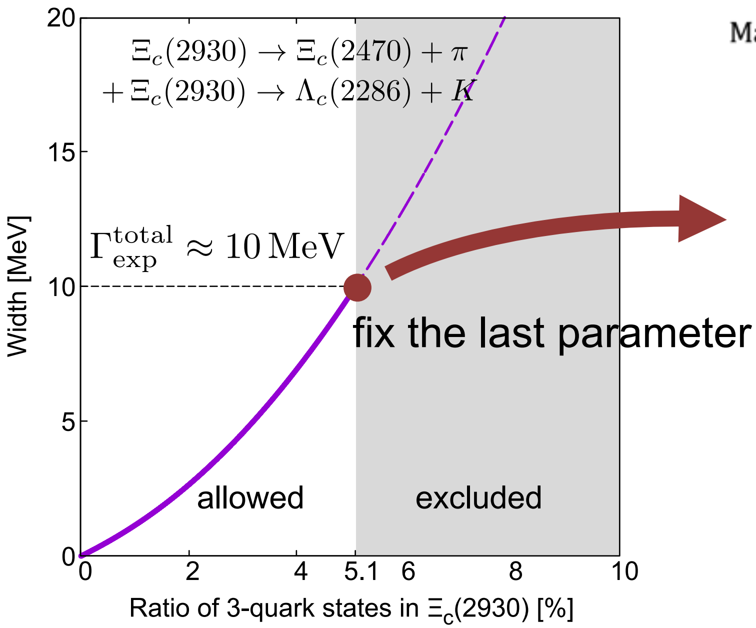
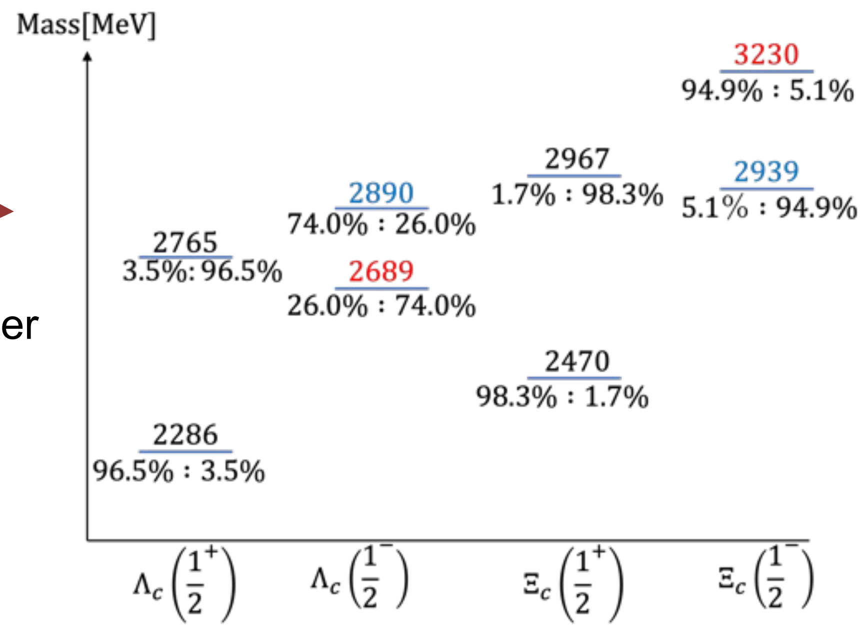


Mass spectrum $(Qqq : Qqq\bar{q}q)$



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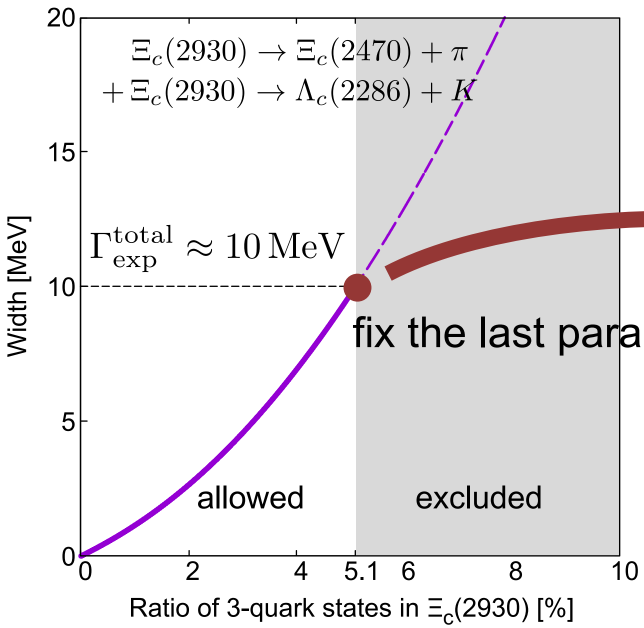
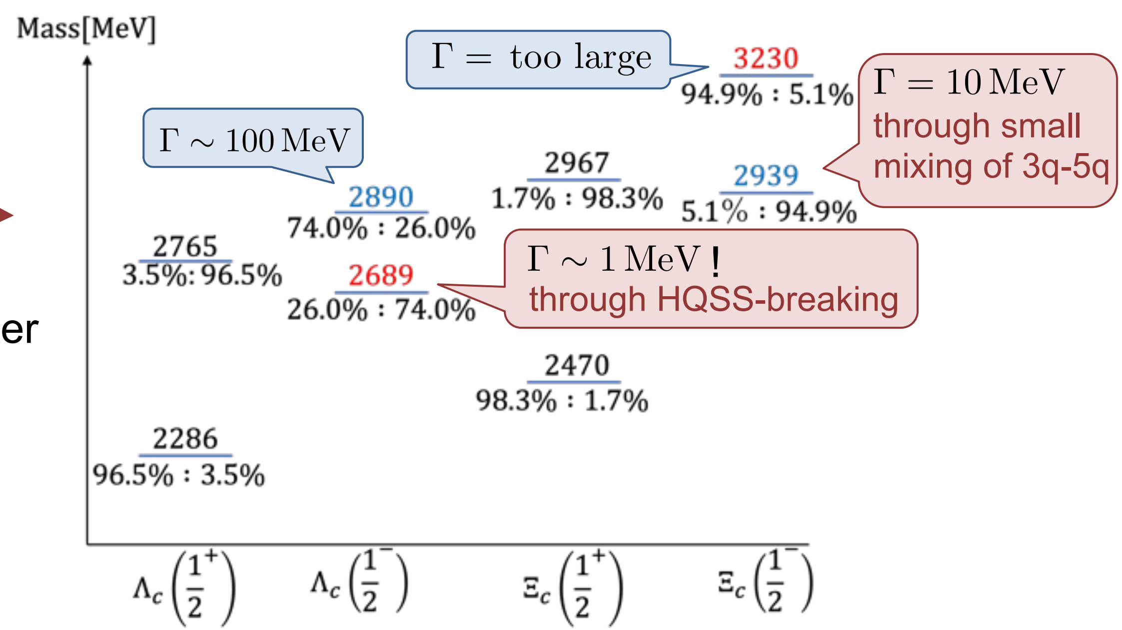


fix the last parameter

Mass spectrum $(Qqq : Qqq\bar{q}q)$



- **With mixing and anomaly**
  - As for the case with anomaly effects, one can consider inverse mass hierarchy for 3-quark dominant SHBs

input

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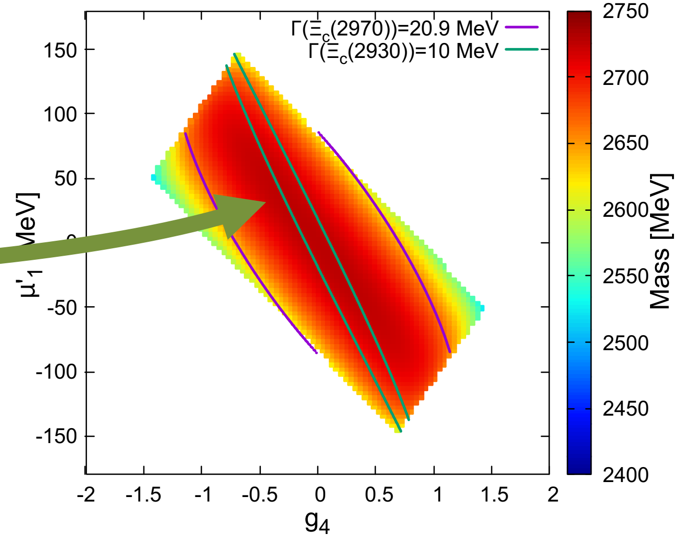
$M(\Xi_c^L(+)) = 2470\,\text{MeV}$ $M(\Xi_c^H(+)) = 2967\,\text{MeV}$
$+$
inverse
$M(\Xi_c^L(-)) = 2765\,\text{MeV}$ (ch. $Q-qq$ model)
$M(\Lambda_c^H(-)) = 2890\,\text{MeV}$ (quark model)
$M(\Xi_c^H(-)) = 2939\,\text{MeV}$ ($\Xi_c(2930)$)

- One can get constraint in, eg, $g_4 - \mu_1'$ plane from decay widths of

$\Gamma[\Xi_c(2930)] \approx 10\,\text{MeV}$ and $\Gamma[\Xi_c(2967)] \approx 20.9\,\text{MeV}$

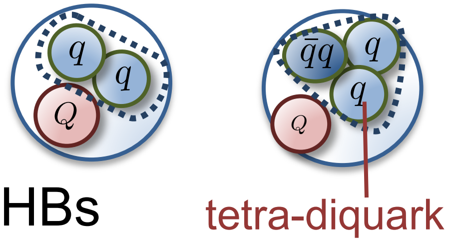
Only this region is allowed



- Constraint for $M(\Lambda_c^L(-))$ is also obtained, which is typically $M(\Lambda_c^L(-)) \sim 2700\,\text{MeV}$

4. Conclusions

- We argued 3-quark and 5-quark picture for HQS-singlet SHBs from chiral symmetry and anomaly



- Anomaly can lead to inverse mass hierarchy of 3-quark SHBs
- Anomaly does not affect mass of 5-quark SHBs
- When anomaly is absent, for instance we get the following mass spectrum with small mixings of 3-q and 5-q