Novel pentaquark picture for Roper-like heavy baryons from chiral symmetry

Daiki Suenaga (RCNP, Osaka U., Japan)

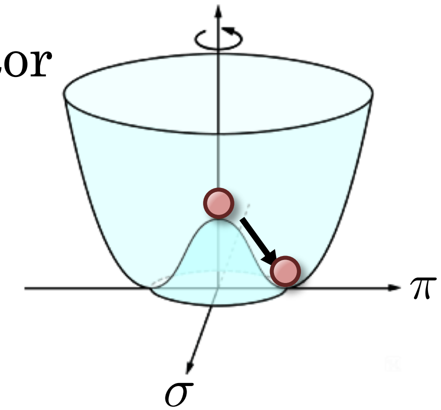
Based on
[1] D. S. , A. Hosaka; 2101.09764 (to appear in PRD)

1. Introduction

D. S. , A. Hosaka; 2101.09764
(to appear in PRD)

• Chiral symmetry in light sector

– Chiral symmetry breaking is important for light sector

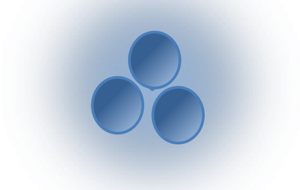


- – Mass generation $m_q \sim 5\,\mathrm{MeV} \;\to\; M_q \sim 300\,\mathrm{MeV}$
- – Low-energy theorems for nucleons and pions

:

– The qqq and $qqq\bar{q}q$ picture for nucleon sector from chiral symmetry

qqq picture

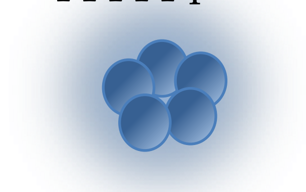


$B_R^i \sim [q^T C\gamma_5 q]q_R^i$

$B_L^i \sim [q^T C\gamma_5 q]q_L^i$

naïve nucleon for $N(939)$

$qqq\bar{q}q$ picture



$B_R'^i \sim [q^T C\gamma_5 q]q_L^j(\bar{q}_L^j q_R^i)$

$B_L'^i \sim [q^T C\gamma_5 q]q_R^j(\bar{q}_R^j q_L^i)$

mirror nucleon for $N(1535)$

$\to$ parity partner structure

i, j, k : flavor index

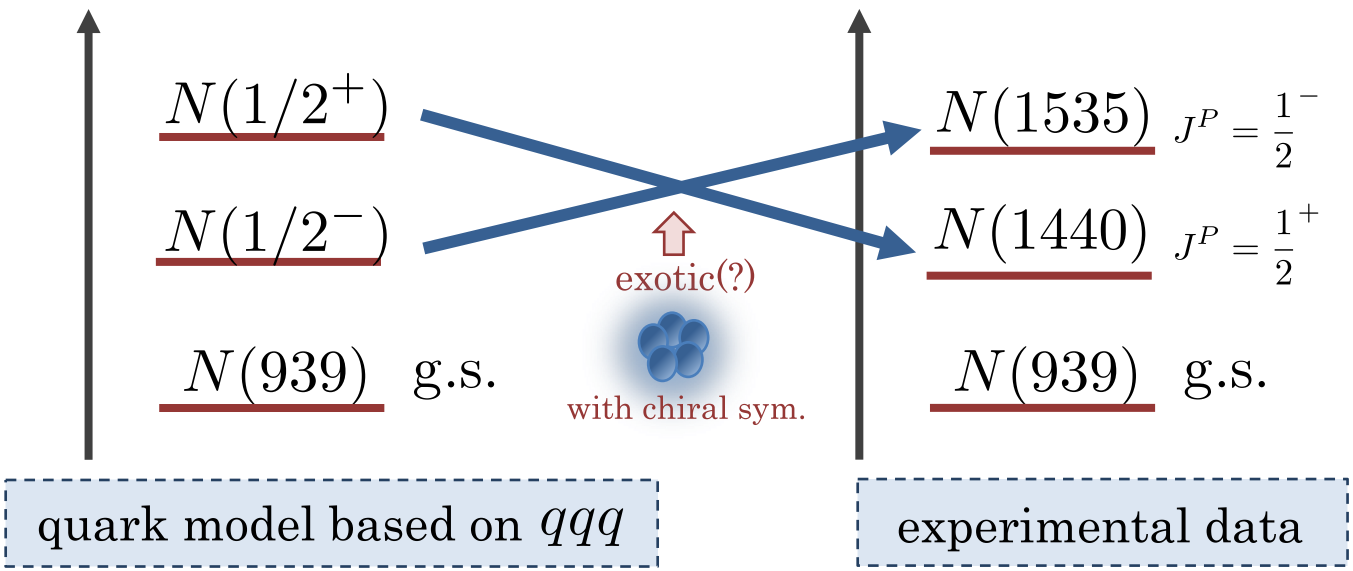
$$q_{R(L)} = \frac{1 \pm \gamma_5}{2} q$$

Detar-Kunihiro, PRD(1989)
Jido-Oka-Hosaka, PTP(2001)

e.g. Parity Doublet Model

1. Introduction

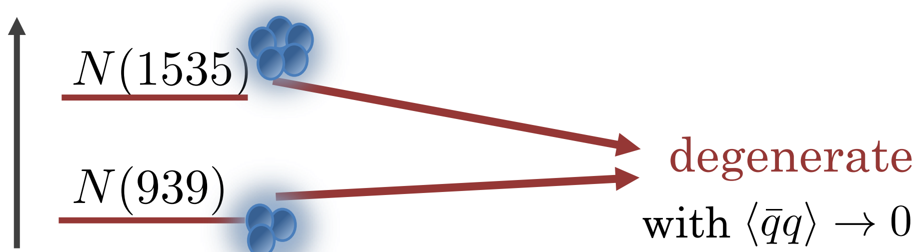
- **Exotic picture for nucleon sector**
  - The inverse mass hierarchy could be solved by the $qqq\bar{q}q$ picture



c.f. dynamical model
Suzuki et al, PRL(2010)

  - The parity partner structure of naïve (qqq) and mirror ($qqq\bar{q}q$) nucleons is suggested by lattice QCD

Detar-Kogut, PRL(1987)
Aarts et al, JHEP(2017)



D. S. , A. Hosaka; 2101.09764
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• Exotic picture for nucleon sector

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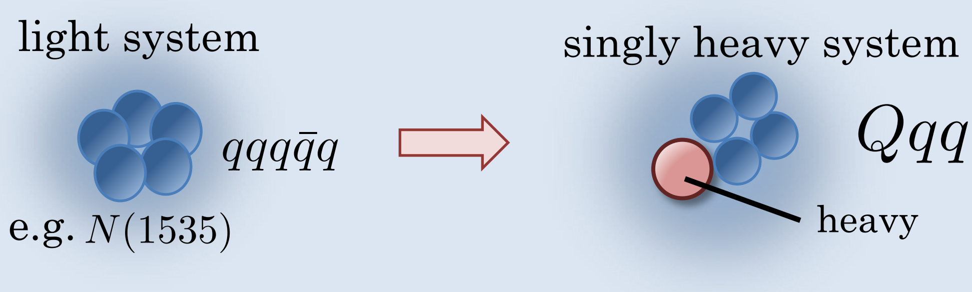
Q: Exotic picture for singly heavy baryons with chiral symmetry?



$Qqq\bar{q}q$? $\rightarrow$ Yes!

(This talk)

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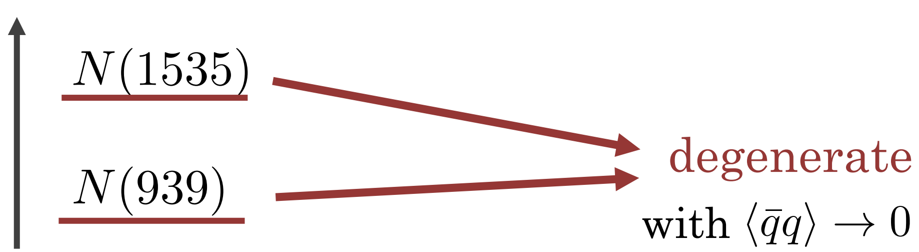
Detar-Kogut, PRL(1987)
Aarts et al, JHEP(2017)



1. Introduction

D. S. , A. Hosaka; 2101.09764
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- **Λ_c baryons from chiral symmetry**
  - The spectrum of $J^P = 1/2^+$ singly heavy baryons $(j_l = 0, s_Q = 1/2)$
    heavy quark spin-singlet

(Roper-like) excited state $(J^P = 1/2^+)$	$\Lambda_c(2765)$	$\Xi_c(2970)$
g.s.	$\Lambda_c(2286)$	$\Xi_c(2467)$

Moon et al. (Belle), PRD(2021)
Arifi et al, PRD(2020)

  - From chiral symmetry point of view, the interpolating field for these baryons with three-quark picture is

$$B_i \sim \frac{1}{\sqrt{2}}\left[Q^a(d_R)^a_i - Q^a(d_L)^a_i\right]$$

Qqq

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

$$(d_L)^a_i \sim \epsilon_{ijk}\epsilon^{abc}(q^T_L)^b_j C(qL)^c_k$$

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

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$\Lambda_c(2765)$ ✕ $\Xi_c(2970)$ ✕

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i, j, k : flavor index
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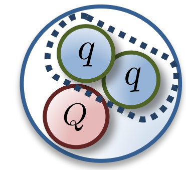
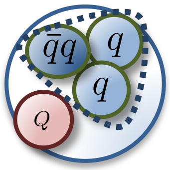
Only $\Lambda_c(2286)$ and $\Xi_c(2467)$ is treated

⇨ Need another field for $\Lambda_c(2765)$ and $\Xi_c(2970)$
$(\rightarrow$ exotic$)$

- **Diquark fields**





  - We introduce two types of diquark fields

    i) *conventional diquark*

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

i, j, k : flavor index
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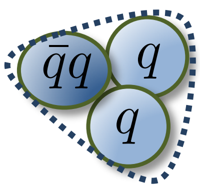
    ii) *mirror diquark*



$$(d'_R)^a_i \sim \epsilon_{jkl}\epsilon^{abc}(q^T_R)^b_k C(q_R)^c_l[(\bar{q}_L)^d_i(q_R)^d_j]$$
$$(d'_L)^a_i \sim \epsilon_{jkl}\epsilon^{abc}(q^T_L)^b_k C(q_L)^c_l[(\bar{q}_R)^d_i(q_L)^d_j]$$

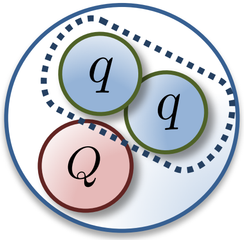
  - The chiral representation of d_R, d_L, d'_R, d'_L are

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

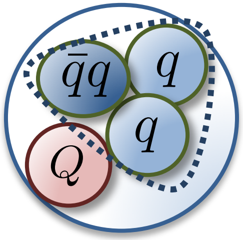
← chiral rep. is flipped like in a *mirror*
[c.f. mirror nucleon for $N(1535)$]

- **Heavy baryon fields**
  - The heavy baryons are simply given by adding a heavy quark Q to the diquarks

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



B_R, B_L



B'_R, B'_L

> Q is not excited but acts as a spectator for diquarks

  - The chiral transformation law of B_R, B_L and B'_R, B'_L is

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

with

$$g_R \in SU(3)_R$$
$$g_L \in SU(3)_L$$

2. Model

- **Heavy baryon Lagrangian**
  - The effective Lagrangian invariant under $SU(3)_L \times SU(3)_R$ is obtained as

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

with meson nonet $\Sigma = S + iP$

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

D. S. , A. Hosaka; 2101.09764
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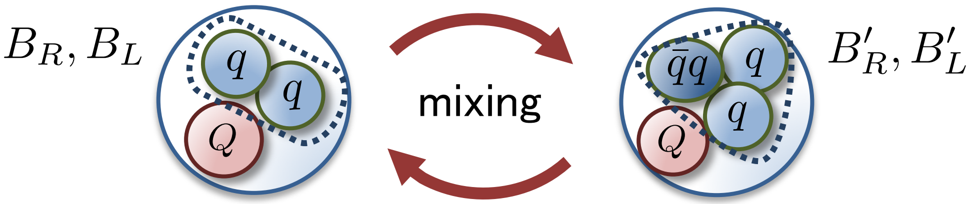
& - \mu_3 (\bar{B}_R B'_L + \bar{B}'_L B_R + \bar{B}_L B'_R + \bar{B}'_R B_L) \\
& - g_1 (\bar{B}_L \Sigma^* B_R + \bar{B}_R \Sigma^T B_L) - g_2 (\bar{B}'_R \Sigma^* B'_L + \bar{B}'_L \Sigma^T B_R) \\
& - g_3 (\bar{B}'_R \Sigma^* B_R + \bar{B}_L \Sigma^* B'_L + \bar{B}_R \Sigma^T B'_R + \bar{B}'_L \Sigma^T B_L) \,,
\end{aligned}
$$

with meson nonet $\Sigma = S + iP$

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

  - $B_{R(L)}$ and $B'_{R(L)}$ can mix with each other



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- **Heavy baryon masses**

H : higher / L : lower
$\pm$: parity

  - The mass eigenvalues are obtained as

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

with
$$m_{\pm,i} = \mu_1 \mp g_1\sigma_i$$
$$m'_{\pm,i} = \mu_2 \mp g_2\sigma_i$$
$$\tilde{m}_{\pm,i} = \mu_3 \mp g_3\sigma_i$$

$$\begin{cases} \sigma_1 = \sigma_2 \equiv \sigma_q \\ \sigma_3 \equiv \sigma_s \end{cases}$$

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

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

  - The corresponding eigenstates are

$$\begin{pmatrix} B^L_{\pm,i} \\ B^H_{\pm,i} \end{pmatrix} = \begin{pmatrix} \cos\theta_{B_{\pm,i}} & \sin\theta_{B_{\pm,i}} \\ -\sin\theta_{B_{\pm,i}} & \cos\theta_{B_{\pm,i}} \end{pmatrix} \begin{pmatrix} B_{\pm,i} \\ B'_{\pm,i} \end{pmatrix}$$ with $\tan\theta_{B_{\pm,i}} = \dfrac{2\tilde{m}_{\pm,i}}{m_{\pm,i} - m'_{\pm,i}}$ satisfied

3. Analysis and Result

D. S. , A. Hosaka; 2101.09764
(to appear in PRD)

- **Parameter determination**

  - Baryons masses as inputs to fix parameters

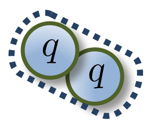
$$\Lambda_c(2286),\ \Lambda_c(2765),\ \Xi_c(2470),\ \Xi_c(2967)\ \text{and}\ \Lambda_c(2890)$$

$\frac{1}{2}^+$ (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 as inputs



Y. Bi, et al, Chin. Phys. C (2016)

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

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

M. Harada, et. al. , PRD (2020)

- **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

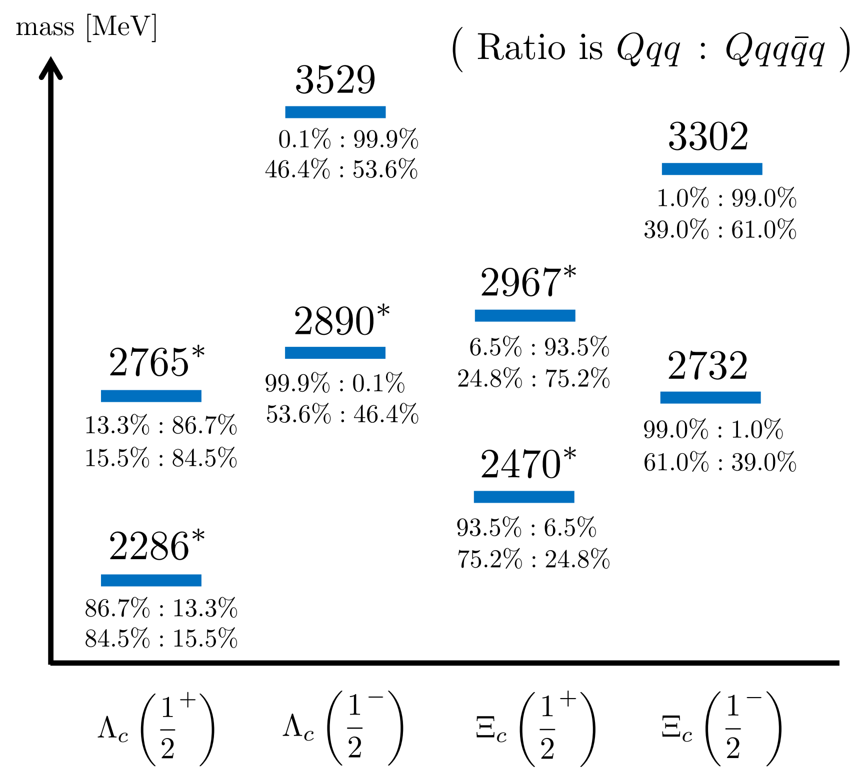
with $m_B = 2868\,\mathrm{MeV}$

  - The resultant mass spectrum

mass

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

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



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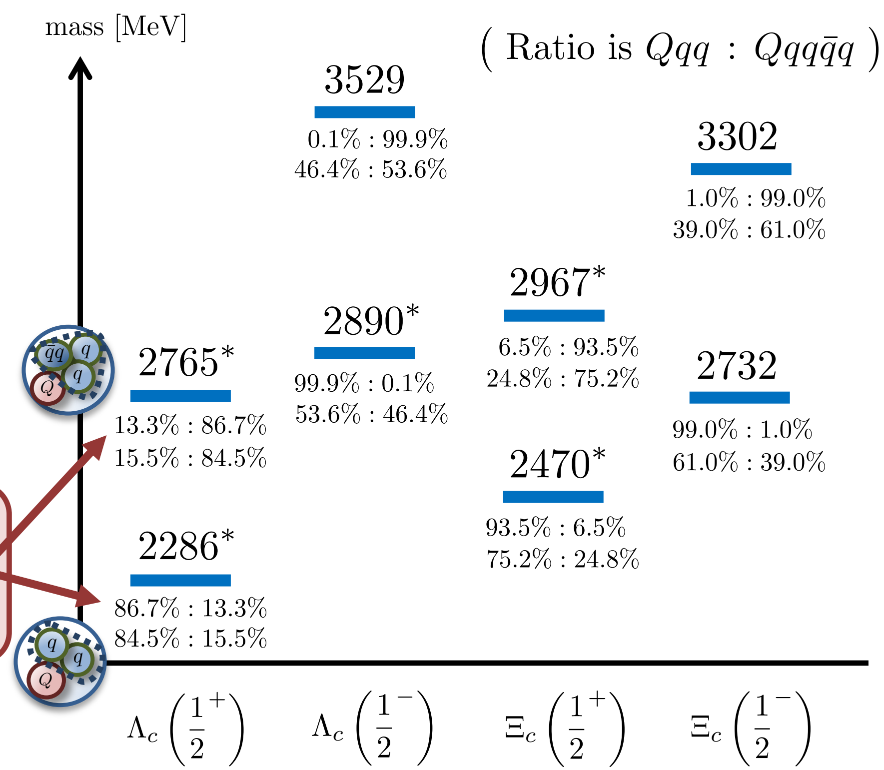

Excited $\Lambda_c(2765)$ is mostly $Qqq\bar{q}q$
while $\Lambda_c(2286)$ is mostly Qqq

3. Analysis and Result

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• General relations

Sum rule (mass formula)

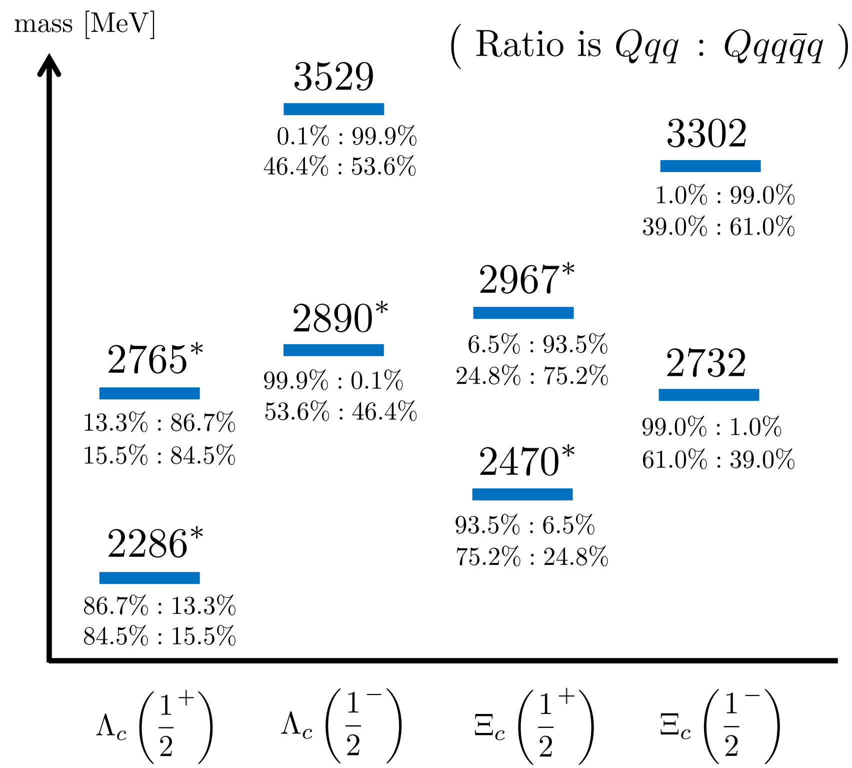
$$\sum_{p=\pm,n=H,L} M(B^n_{p,i=1,2}) = \sum_{p=\pm,n=H,L} M(B^n_{p,i=3})$$

four Ξ_c masses $=$ four Λ_c masses

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 one pion, eta, kaon emission decay



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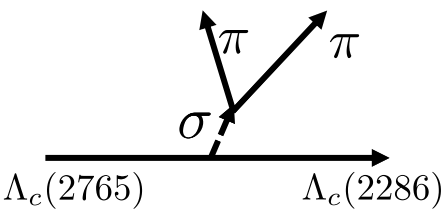
- **Suppression of direct decay**

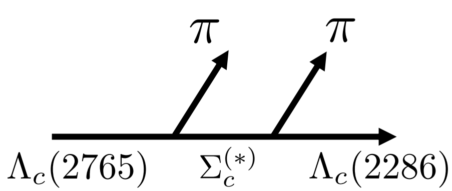
$\Lambda_c(2765)$-$\Lambda_c(2286)$-σ coupling disappears

Direct $\pi\pi$ decay of $\Lambda_c(2765)$ is suppressed

× suppressed

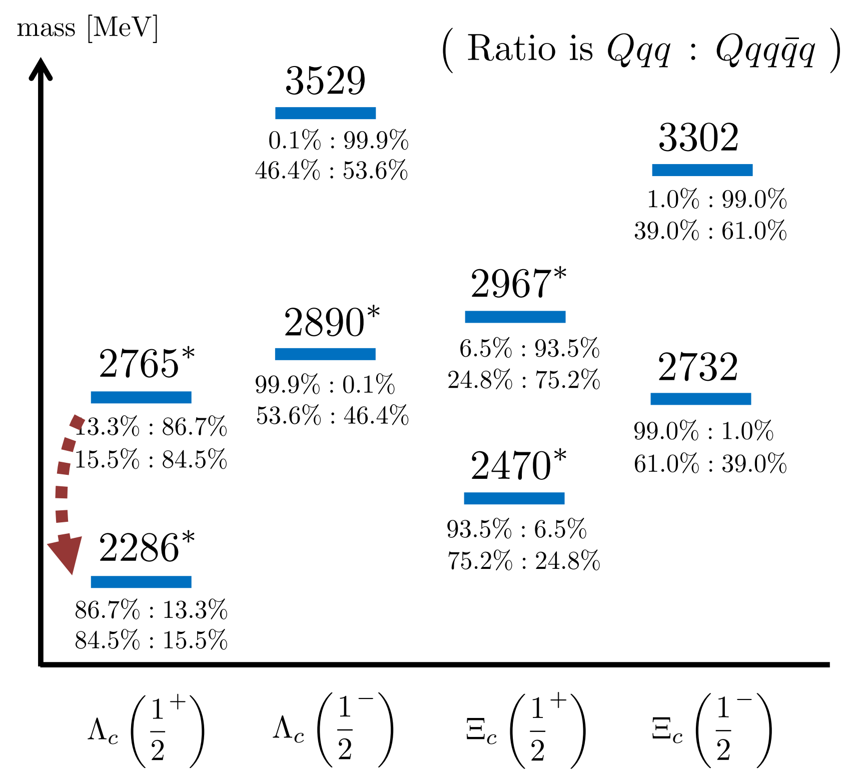


○ survive



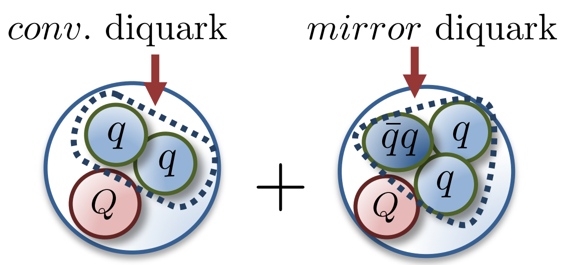
consistent with experimental data

A. J. Arifi, et. al. , PRD 101 (2020) 11, 111502



4. Conclusion

- **Summary**
  - We proposed a new $Qqq\bar{q}q$ in addition to Qqq state to explain $J^P = 1/2^+$ spectrum of $\Lambda_c(\Xi_c)$ from chiral symmetry



  - Not only positive-parity but also negative-parity states were predicted
  - $\Lambda_c(2765)$ $[\Xi_c(2970)]$ was mostly $Qqq\bar{q}q$ while $\Lambda_c(2286)$ $[\Xi_c(2467)]$ was Qqq
  - A sum rule (mass formula) and Goldberger-Treiman relation were derived
  - Does mirror diquark $qq\bar{q}q$ play a significant role for $N(1440)$?