対称性に基づく有効理論を用いたヘビーハドロン研究

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@ ELPH 研究会 C035

「実験、反応・構造計算、格子QCD で解き明かすハドロン分光」

(November 8, 2023)

Based on

- H. Takada, D. Suenaga, M. Harada, A. Hosaka and M. Oka, Phys.Rev.D 108 (2023) 5, 054033.
- Y.L. Ma and M. Harada, J.Phys.G 45 (2018) 7, 075006.
- T. Asanuma, Y. Yamaguchi and M. Harada, in preparation.

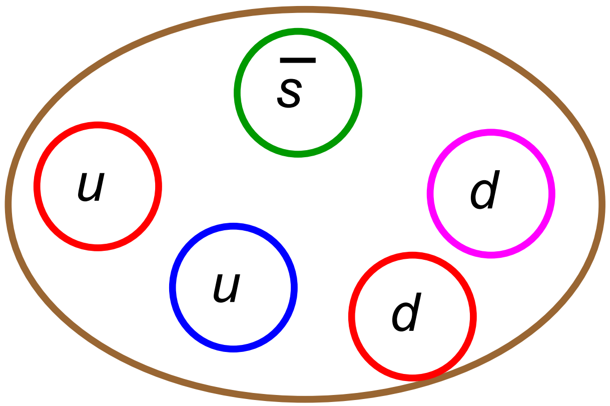
see also

- M. Tanaka, Y. Yamaguchi and M. Harada, in preparation.

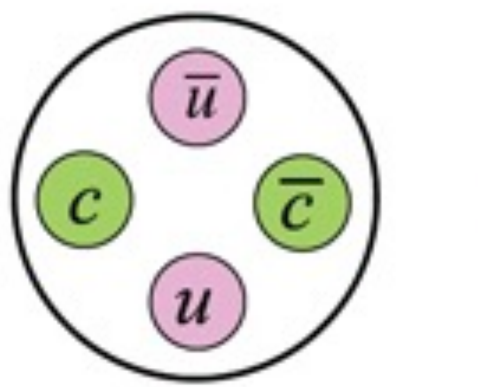
Introduction

Exotic Hadrons

- Pentaquark Θ^+
  - 2003: SPring-8
  - M = 1540 MeV

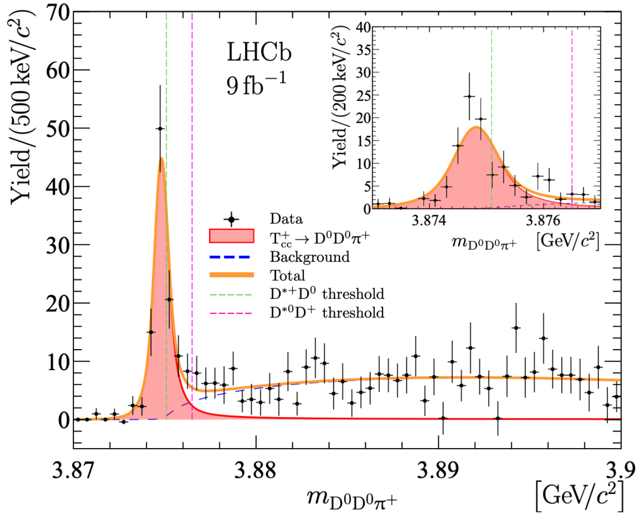


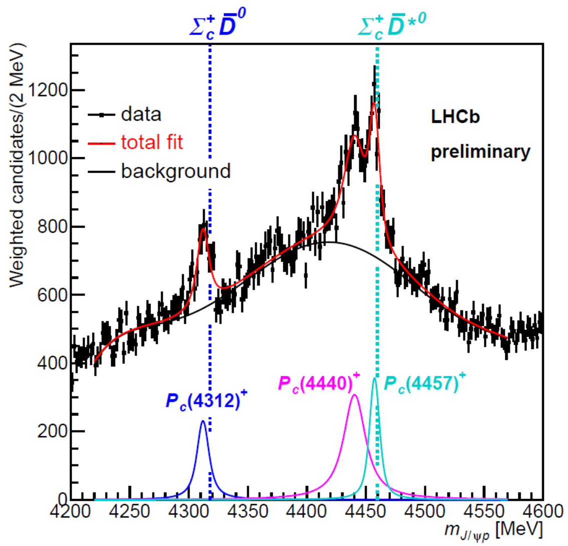
- Tetraquark X(3872)
  - 2003: Belle
  - M = 3872 MeV



more Exotic Hadrons

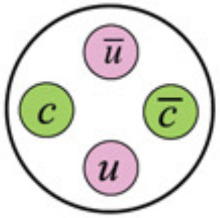
- Tetraquarks
  - X(3872) @ Bell (2003) …
  - X(6900) @ LHCb (2020)
  - Zcs(4681) @ BES III (2021)
  - Tcc(3875) @ LHCb (2022)
  - Tcs(2900) @ LHCb (2022)
  - …
- Pentaquarks
  - $\Theta^+(1540)$ @ SPring-8 (2003)
  - Pc(4380), Pc(4450) @ LHCb (2015)
  - Pc(4312), Pc(4440), Pc(4457) @ LHCb (2017)
  - Pc(4337) @ LHCb (2022)
  - Pcs(4338) @ LHCb (2022)
  - …
- more



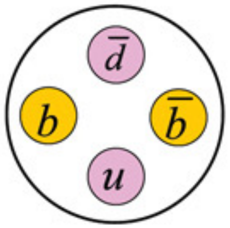


Quest for Exotic Hadrons

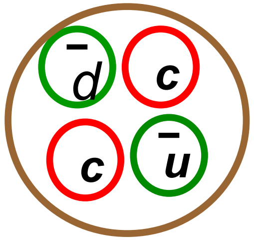
– Tetraquark



X(3872)、Y(4260)など



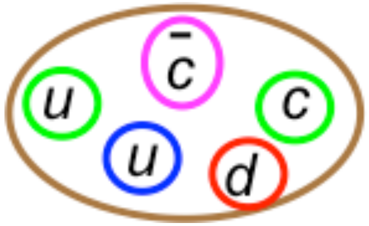
$Z_b(10610)$, $Z_b(10650)$



Tcc

…

– Pentaquark



Pc(4312)/Pc(4440)/Pc(4457)

…

- Why Now ?
- What is the structure?
- …

It is important to elucidate their structures.

対称性 (symmetries)
⇨ 構造解明 (elucidation of structure)

- フレーバー対称性 Flavor symmetry
  - フレーバー多重項(フレーバーパートナー)構造
  - Flavor multiplet (Flavor partner) structure
- カイラル対称性 Chiral symmetry
  - カイラルパートナーの質量階層性
  - Hierarchy of masses of chiral partners
- ヘビークォーク対称性 Heavy quark symmetry
  - ヘビークォークスピン多重項構造
  - Heavy-quark spin multiplet structure
- スーパーフレーバー対称性 Superflavor symmetry
  - スーパーフレーバーパートナーの質量階層性
  - Hierarchy of masses of superflavor partners

Outline

1. Introduction
2. SHBs based on the Heavy-quark symmetry and the chiral symmetry
3. DHBs based on the superflavor symmetry and the chiral symmetry
4. Tetraquark and Pentaquark based on the superflavor symmetry
5. Summary

2. SHBs based on the Heavy-quark symmetry and the chiral symmetry

H. Takada, D. Suenaga, M. Harada, A. Hosaka and M. Oka,
Phys.Rev.D 108 (2023) 5, 054033.

Chiral Partner structure for SHBs based on the chiral diquark picture

- SHB based on scalar and pseudoscalar chiral diquarks

M. Harada, Y. -R. Liu, M. Oka, K. Suzuki, PRD 101 (2020) 5, 054038
Y.Kawakami and M. Harada, M. Oka, K. Suzuki, PRD 102 (2020) 11, 114004

$$\Lambda_Q(1/2^+), \Xi_Q(1/2^+) \xleftrightarrow[\text{chiral partner}]{} \Lambda_Q(1/2^-), \Xi_Q(1/2^-)$$

- Comprehensive study of the decay widths in the framework of effective Lagrangian based on the chiral symmetry

H. Takada, D. Suenaga, M. Harada, A. Hosaka and M. Oka, K. Suzuki, PRD 108, 054033 (2023)

Lagrangian for SHBs

M. Harada, Y.-R. Liu, M. Oka, K. Suzuki, PRD 101 (2020) 5, 054038
Y.Kawakami and M. Harada, M. Oka, K. Suzuki, PRD 102 (2020) 11, 114004
H. Takada, D. Suenaga, M. Harada, A. Hosaka and M. Oka, PRD108 (2023), 054033

$$
\begin{aligned}
\mathcal{L}_3 = \sum_{\chi=L,R} & \left(\bar{B}_\chi\, iv\cdot\partial B_\chi - \mu_1 \bar{B}_\chi B_\chi\right) \\
& - \frac{\mu_3}{2f_\pi^2}\delta^c{}_\gamma \epsilon_{abc}\epsilon^{\alpha\beta\gamma}\left(\bar{B}_L^a (\Sigma\Sigma^\dagger)^b{}_\beta B_{L,\alpha} + \bar{B}_R^a(\Sigma^\dagger\Sigma)^b{}_\beta B_{R,\alpha}\right) \\
& - \frac{g_1}{2f_\pi}\epsilon_{ijk}\epsilon_{lmn}\left(\bar{B}_{L,k}\Sigma_{li}^T\Sigma_{mj}^T B_{R,n} + \bar{B}_{R,k}\Sigma_{li}^*\Sigma_{mj}^* B_{L,n}\right) \\
& - g_1'\left(\bar{B}_L \Sigma^* B_R + \bar{B}_R \Sigma^T B_L\right)
\end{aligned}
$$

Light meson field

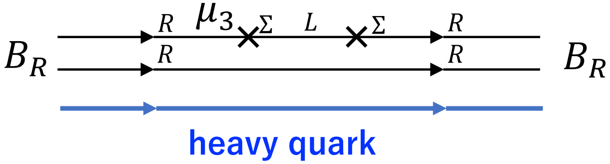
	scalar nonet		pseudo-scalar nonet
$\Sigma = \mathrm{diag}(f_\pi, f_\pi, Af_\pi) +$	σ_{ij}	$+$	$i\pi_{ij}$

VEV

$f_\pi = 93$ MeV : π meson decay constant
$A = \frac{2f_K - f_\pi}{f_\pi} \sim 1.38$

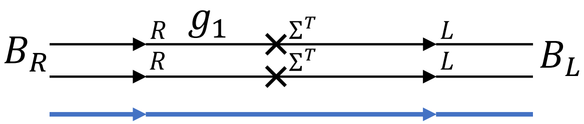
The chiral symmetry is spontaneously broken, which generates the mass difference between chiral partners.

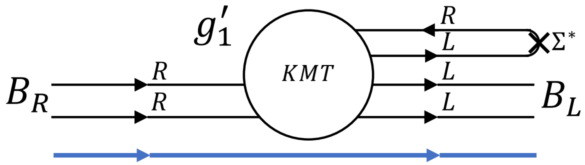
New term in H.Takada et al.



One quark interacts with 2 Σ with flipping its chirality twice.

M.Harada et al., PRD 101, 054038(2020)





Anomaly term including Kobayashi-Maskawa-'t Hooft (KMT)-type interaction

Masses and Decays of SHBs

$$
\begin{cases}
M(\Xi_c^{[3]}(\pm)) = \mu_1 + \dfrac{1+A^2}{2}\mu_3 \mp f_\pi (A g_1 + g_1') \\
M(\Lambda_c^{[3]}(\pm)) = \mu_1 + \mu_3 \mp f_\pi (g_1 + A g_1')
\end{cases}
$$

H. Takada, D. Suenaga, M. Harada, A. Hosaka and M. Oka PRD108 (2023), 054033

4 independent parameters

Inputs : $M(\Xi_c^{[3]}(+)) = 2470\ \mathrm{MeV},\ M(\Lambda_c^{[3]}(+)) = 2286\ \mathrm{MeV}$

Dependence of decay widths on the masses of $\Lambda_c(-)$ and $\Xi_c(-)$.

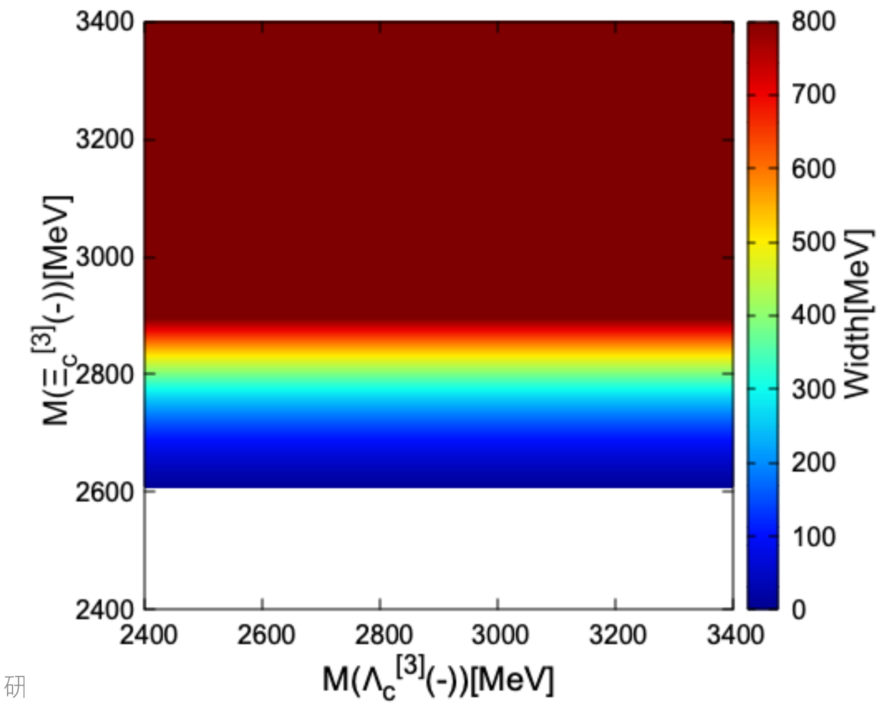
Ex: Decay width of $\Xi_c^{[3]}(-) \to \Xi_c^{[3]}(+)\pi$

Extended Goldberger-Treiman relation

$$
g = \frac{M(\Xi_c^{[3]}(-)) - M(\Xi_c^{[3]}(+))}{2 f_\pi}
$$

$$
\Gamma \propto \left(M(\Xi_c^{[3]}(-)) - M(\Xi_c^{[3]}(+)) \right)^3
$$

Large decay width for 3-quark state $\Xi_c\left(\frac{1}{2}^-\right)$



3. DHBs based on the superflavor symmetry and the chiral symmetry

- Y.L. Ma and M. Harada, J.Phys.G 45 (2018) 7, 075006.

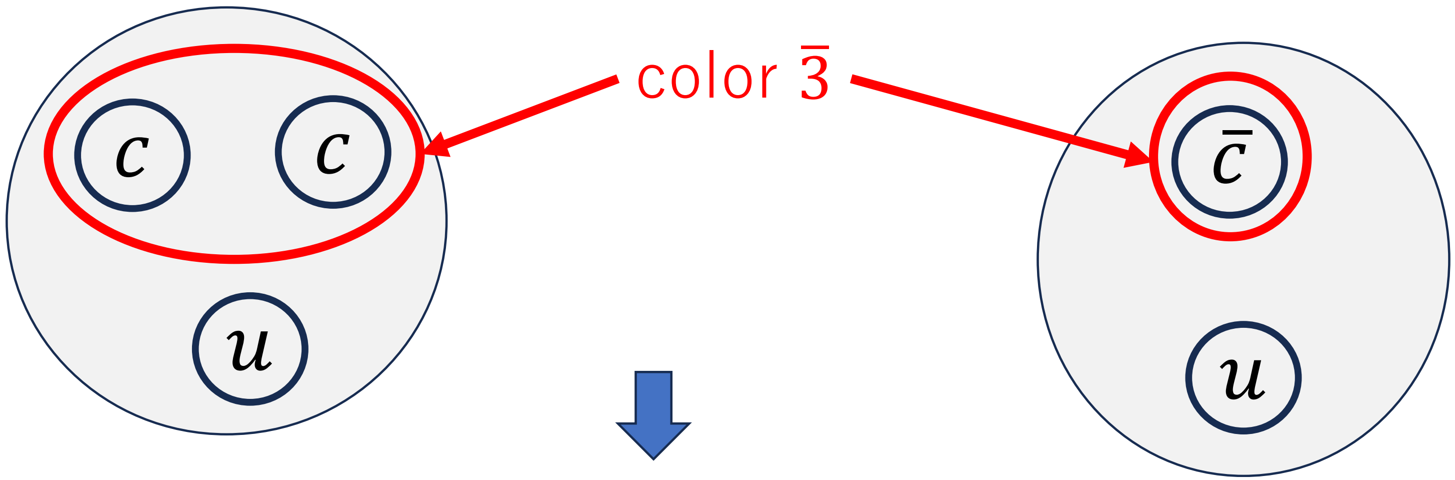
see also

- M. Tanaka, Y. Yamaguchi and M. Harada, in preparation

Superflavor symmetry

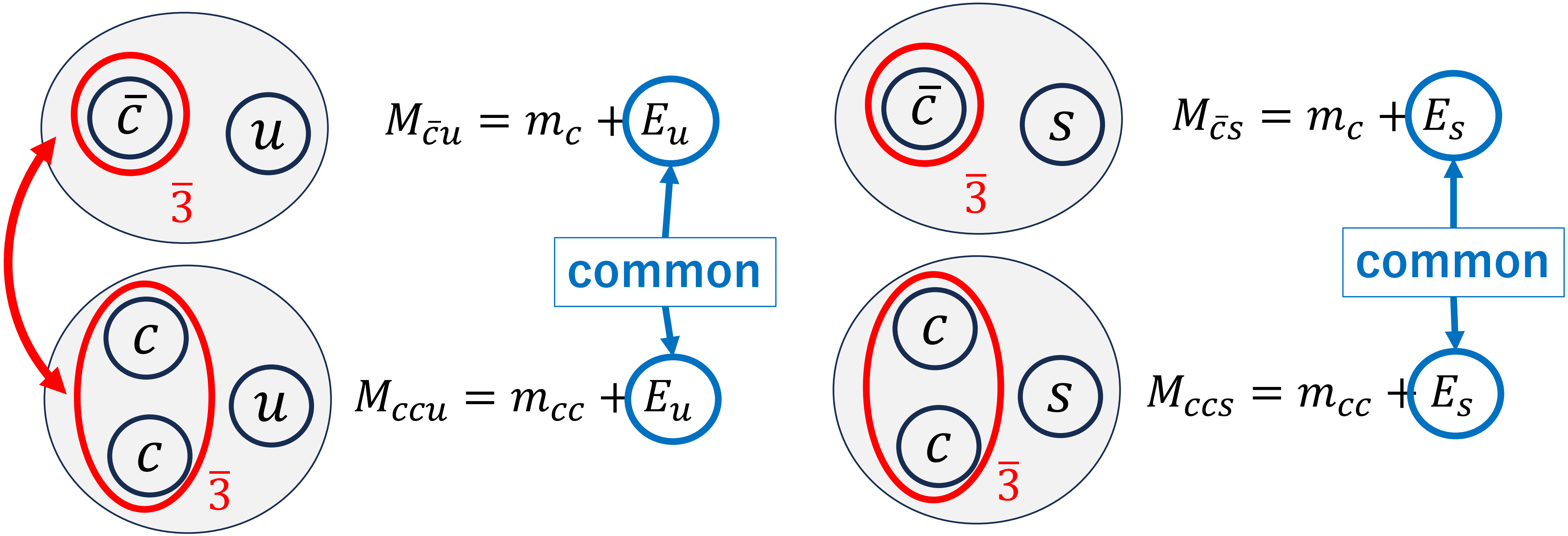
DHB (ex. Ξ_{cc})

HM (ex.$\bar{D}^0$)



- In the heavy quark limit $(m_c \to \infty)$,
  the same color electric force applies to cc and $\bar{c}$.
- The color-magnetic force is suppressed by $^1/_{m_c}$.
- The properties of DHBs and HMs are governed by the same dynamics of the same light-quark cloud.

Superflavor symmetry for masses of HMs & DHBs



$$M_{ccs} - M_{ccu} = M_{\bar{c}s} - M_{\bar{c}u}$$

Validity of Superflavor symmetry

$M_{ccs} - M_{ccu} = M_{\bar{c}s} - M_{\bar{c}u}$

	Mass(MeV)
Ξ_{cc}	3615
Ξ_{cc}^*	3703
Ω_{cc}	3733
Ω_{cc}^*	3793
$D^{\pm}$	1870
$D^{*\pm}$	2010
$D_s^{\pm}$	1968
$D_s^{*\pm}$	2112

lattice

cf: $M(\Xi_{cc}^{++}) = 3621\ MeV$ (LHCb)

H. Bahtiyar et al. (TRJQCD Collaboration), PRD102, 054513 (2020)

$$\bar{M}(\Omega_{cc}) - \bar{M}(\Xi_{cc}) = 100\ MeV$$

Superflavor symmetry is good !

PDG

$$\bar{M}(D_s) - \bar{M}(D^{\pm}) = 101\ MeV$$

$\bar{M}$: spin average

Chiral partner structure of DHBs

- Chiral partner structure for charmed mesons

M.A.Nowak, M.Rho and I.Zahed, PRD48, 4370 (1993)
W.A.Bardeen and C.T.Hill, PRD49, 409 (1994)

$[\bar{D}(0^-)\,,\ \bar{D}(1^-)]$ ⟷ Chiral partners ⟷ $[\bar{D}(0^+)\,,\ \bar{D}(1^+)]$

↓ Superflavor symmetry

- Chiral partner structure for doubly heavy baryons

$$\left[\Xi_{QQ'}(1/2^+)\,,\ \Xi_{QQ'}(3/2^+)\right] \quad \Xi_{bc}(1/2^+)$$

$$\left[\Xi_{QQ'}(1/2^-)\,,\ \Xi_{QQ'}(3/2^-)\right] \quad \Xi_{bc}(1/2^-)$$

Chiral partners

Pionic decays of DHBs based on the chiral partner structure combined with the superflavor symmetry

- Pionic decays are governed by the light degrees of freedom.
- Pionic decays of DHBs are equivalent to those of charmed mesons due to the superflavor symmetry.

Examples

- $\Gamma\left(\Xi_{QQ'}(1/2^-) \to \Xi_{QQ'}(1/2^+) + \pi^0\right)$
  $\simeq \Gamma\left(\bar{D}(0^+) \to \bar{D}(0^-) + \pi^0\right) \sim 100\,\text{MeV}$
- $\Gamma\left(\Xi_{QQ'}(1/2^-) \to \Xi_{QQ'}(1/2^+) + \pi^\pm\right)$
  $\simeq \Gamma\left(\bar{D}(0^+) \to \bar{D}(0^-) + \pi^\pm\right) \sim 200\,\text{MeV}$
- $\Gamma\left(\Omega_{QQ'}(1/2^-) \to \Omega_{QQ'}(1/2^+) + \pi^0\right)$
  $\simeq \Gamma\left(\bar{D}_s(0^+) \to \bar{D}_s(0^-) + \pi^0\right)$

Radiative decay widths

- Magnetic moments of DHBs are dominated by light-quark cloud.
- Magnetic moments of chiral partners are equivalent.

$$\frac{\Gamma\left(\Xi_{QQ'}(3/2^+) \to \Xi_{QQ'}(1/2^+) + \gamma\right)}{\Gamma\left(\Xi_{QQ'}(3/2^-) \to \Xi_{QQ'}(1/2^-) + \gamma\right)} = 1$$

- Magnetic moments of DHBs are equivalent to those of charmed mesons (superflavor symmetry).

$$\frac{\Gamma\left(\Xi_{QQ'}(3/2^\pm) \to \Xi_{QQ'}(1/2^\pm) + \gamma\right)}{\Gamma\left(\bar{D}(1^\pm) \to \bar{D}(0^\pm) + \gamma\right)} = \frac{4}{3}$$

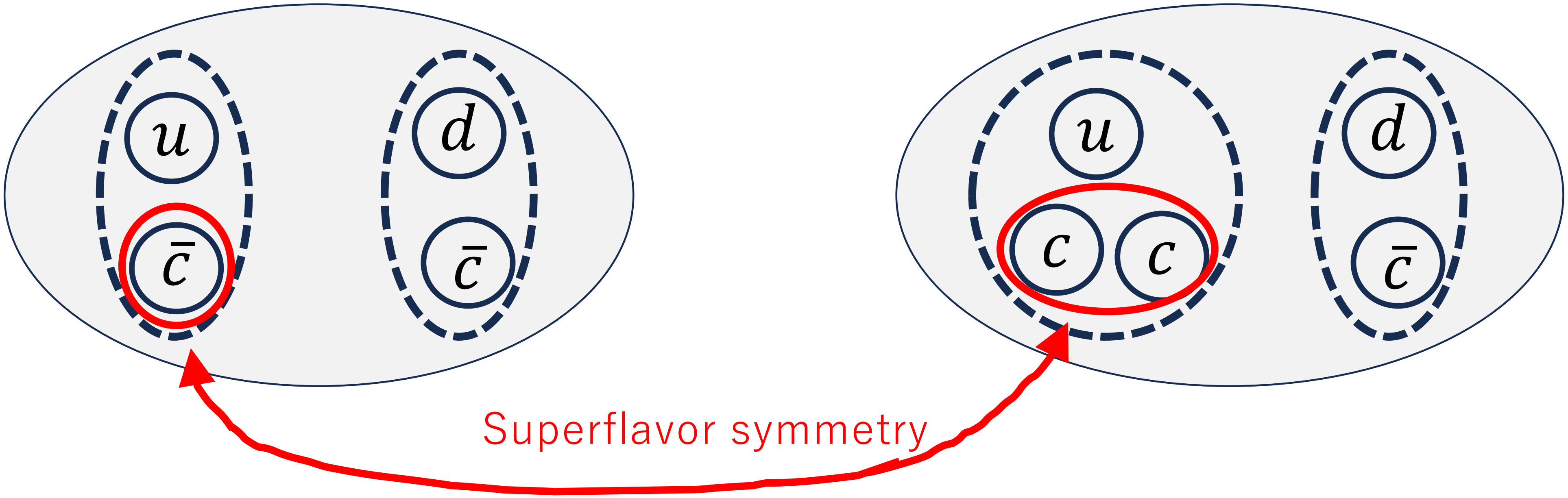
4. Tetraquark and Pentaquark based on the superflavor symmetry

T. Asanuma, Y. Yamaguchi and M. Harada, in preparation.

Outlook

$\bar{T}_{cc} \sim \bar{D}^{(*)}\bar{D}^{(*)}$ molecule

$\Xi_{cc}^{(*)}\bar{D}^{(*)}$ molecule



4.1. $D^{(*)}D^{(*)}$molecule

- Coupled channel effect
  - ➢ Heavy quark symmetry → (D, D^*) HQS doublet $[m_{D^*} - m_D \cong 140\text{MeV}]$

    ⇓

    Coupled channel effect is important.
  - ➢ Chiral symmetry → π has a derivative coupling to (D, D^*)

    ⇓
  - ➢ S-D mixing effect is important.
  - ➢ $I(J^P) = 0(1^+)$: 4 channels
    - ✓ $\frac{1}{\sqrt{2}}(DD^* - D^*D)$ $[\ {}^3S_1\ \&\ {}^3D_1]$
    - ✓ $D^*D^*[\ {}^3S_1\ \&\ {}^3D_1]$

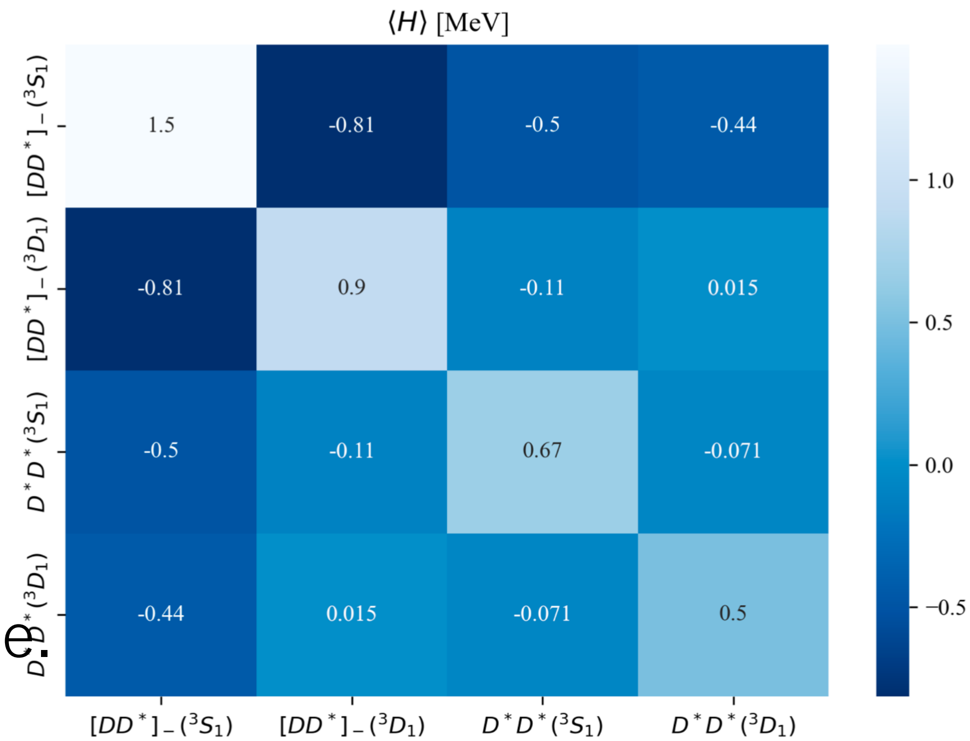
One Boson Exchange Potential (OBEP)

- $\pi, \sigma, \rho, \omega$ mesons
- coupling constants
  - π: $g_\pi = 0.59$ (from $D^* \to D\pi$ decay)
  - ρ, ω: $\beta g_V(\text{electric type}) = 5.31$; $\lambda g_V(\text{magnetic type}) = 0.504\text{GeV}^{-1}$
  - σ: 2 choices ; $g_\sigma^{(1)} = 3.4$ $\left[g_\sigma^{(2)} = 0.76\right]$
- Form factor
  - $F(q) = \frac{\Lambda^2 - \mu_{eff}^2}{\Lambda^2 + \boldsymbol{q}^2}$, $\mu_{eff}^2 = m_{ex}^2 - (q^0)^2$, $q^0 \cong \frac{m_2^2 - m_1^2 + m_3^2 - m_4^2}{2(m_3 + m_4)}$

Results (Λ is tuned to reproduced $m(T_{cc})|_{\mathrm{exp}}$)

Λ [MeV]	1160	1182	1200
$\mathrm{B_{in}}$ [MeV]	0.074	0.273	0.549
$P_{[DD^*]_-}(^3S_1)$	0.992	0.987	0.983
$P_{[DD^*]_-}(^3D_1)$	0.00545	0.00840	0.0103
$P_{D^*D^*}(^3S_1)$	0.00159	0.00348	0.00541
$P_{D^*D^*}(^3D_1)$	0.000542	0.00106	0.00151
$\sqrt{\langle r^2 \rangle}$ [fm]	11.33	6.42	4.70

- very large size $R \approx 6.4$ fm



- Diagonal part ($DD^*[\ ^3S_1]$) is repulsive.
  - $\langle DD^*[^3S_1]|H|DD^*[^3S_1]\rangle = 1.5$ MeV
- Off-diagonal ($DD^*[\ ^3S_1]$ & $DD^*[\ ^3D_1]$) is important.
  - $\langle DD^*[^3S_1]|H|DD^*[^3D_1]\rangle = -0.81$ MeV

4.2 $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ molecule $I(J^P) = 0(1/2^-)$

- Coupled channel analysis (7 chennels)
  - ➢ $\bar{D}\Xi_{cc}(^2S_{\frac{1}{2}}), \bar{D}\Xi_{cc}^*(^4D_{\frac{1}{2}}), \bar{D}^*\Xi_{cc}(^2S_{\frac{1}{2}}, ^4D_{\frac{1}{2}}), \bar{D}^*\Xi_{cc}^*(^2S_{\frac{1}{2}}, ^4D_{\frac{1}{2}}, ^6D_{\frac{1}{2}})$
    - ✓ note: (Ξ_{cc}, Ξ_{cc}^*) form HQS doublet
- OBEP: same as DD^*
  - ➢ $\bar{D}$ and Ξ_{cc} have the same light cloud (superflavor symmetry)
  - ➢ use of the same $\Lambda = 1182$ MeV.

- Result

Λ [MeV]	1160	1182	1200
B_{in} [MeV]	5.65	7.46	9.10
$P_{\bar{D}\Xi_{cc}}(^2S_{\frac{1}{2}})$	0.99	0.98	0.98
$P_{\bar{D}\Xi_{cc}^*}(^4D_{\frac{1}{2}})$	0.000008	0.000012	0.000017
$P_{\bar{D}^*\Xi_{cc}}(^2S_{\frac{1}{2}})$	0.00056	0.00076	0.00095
$P_{\bar{D}^*\Xi_{cc}}(^4D_{\frac{1}{2}})$	0.0026	0.0030	0.0033
$P_{\bar{D}^*\Xi_{cc}^*}(^2S_{\frac{1}{2}})$	0.0021	0.0028	0.0035
$P_{\bar{D}^*\Xi_{cc}^*}(^4D_{\frac{1}{2}})$	0.00068	0.00074	0.00079
$P_{\bar{D}^*\Xi_{cc}^*}(^6D_{\frac{1}{2}})$	0.0085	0.0097	0.011
$\sqrt{\langle r^2 \rangle}$ [fm]	1.54	1.38	1.28

- Boundstate exists!
  - ➢ Binding energy ≈ 7.5 MeV
  - ➢ Rather compact size : $R \approx 1.4$ fm

5. Summary

- Study of Exotic hadrons including heavy quark(s) based on
  - chiral symmetry
  - heavy quark symmetry
  - superflavor symmetry
- SHBs: chiral partners of $\Lambda_c(2286)$ & $\Xi_c(2470)$
  - Inverse mass hierarchy can occur due to $U(1)_A$ anomaly.
  - They generally have large widths.
- DHBs:
  - The mass relation to HMs based on the superflavor symmetry is well satisfied.
  - Masses of chiral partners are predicted.
  - The pionic and radiative decay widths are also predicted.
- Triple-heavy Pentaquark
  - Boundstate of $\bar{D}^{(*)}\Xi_{cc}^{(*)}$molecule related to $D^{(*)}D^{(*)}(T_{cc})$ by the superflavor symmetry.

Thank you for your attention.