Mass and Decay Width of T_{ccs} from symmetries

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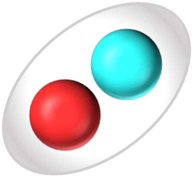
Introduction

Ordinary Hadrons···about ４００

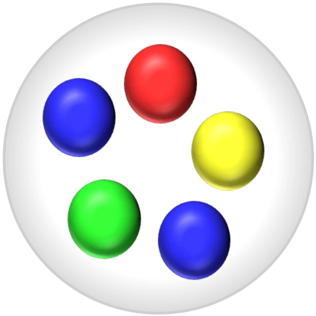
Baryon



Meson

Exotic Hadrons···about 40

Tetraquark



Pentaquark

Example：$X(3872){\sim}c\bar{c}u\bar{u}$ Belle,2003[1]
$P_c(4440)^+, P_c(4457)^+$ LHCb,2019[2]

Color configuration

Baryon：$3{\times}3{\times}3 = 1 + 8 + 8 + 10$

Meson：$3{\times}\bar{3} = 1 + 8$

diquark-like

Tetraquark：$3{\times}3{\times}\bar{3}{\times}\bar{3} = (\bar{3} + 6){\times}(3 + \bar{6}) = 1 + 1 + 8 + 8 + 27 + \cdots$

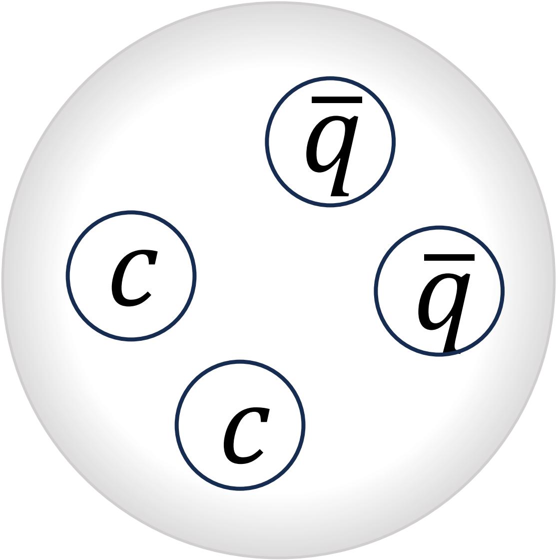
Which color singlets are important?
The one is from $3{\times}\bar{3}$
The other is from $6{\times}\bar{6}$

[1]Belle Collaboration, S.-K. Choi et al., Phys. Rev. Lett. 91, 262001 (2003).
[2]R. Aaji er al. (LHCb Collaboration) Phys.Rev. Lett 122, 222001 (2019)

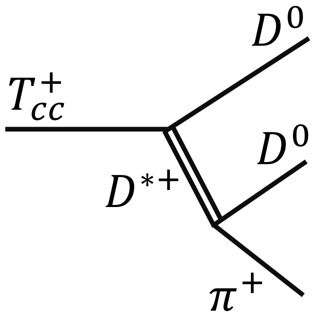
Introduction to T_{cc}^{+}

T_{cc}^{+} : LHCb,2021[3,4]

Mass(MeV)	3875
Width(keV)	48
Flavor	$cc\bar{u}\bar{d}$
J^P	1^+



- Very narrow peak
- $cc\bar{u}\bar{d}$: genuine exotic state
  (It cannot be realized in ordinary hadrons)
- LHCb favors isoscalar
- Decay : $T_{cc}^{+} \to D^0 D^0 \pi^+$ via D^*[4]



Possible decay modes

[3] R. Aaij et al. (LHCb), Nature Phys. 18, 751 (2022), arXiv:2109.01038 [hep–ex]
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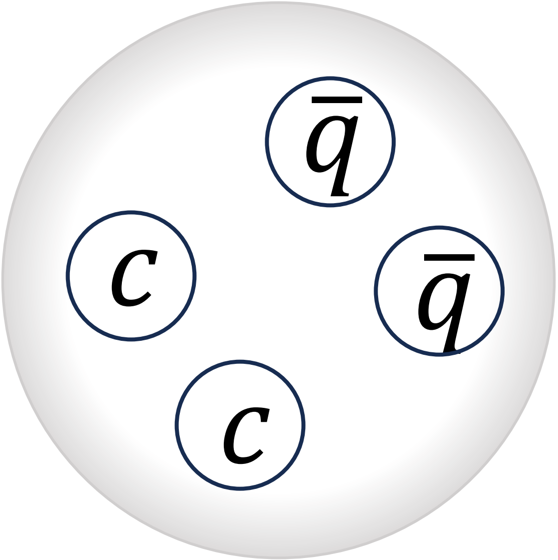

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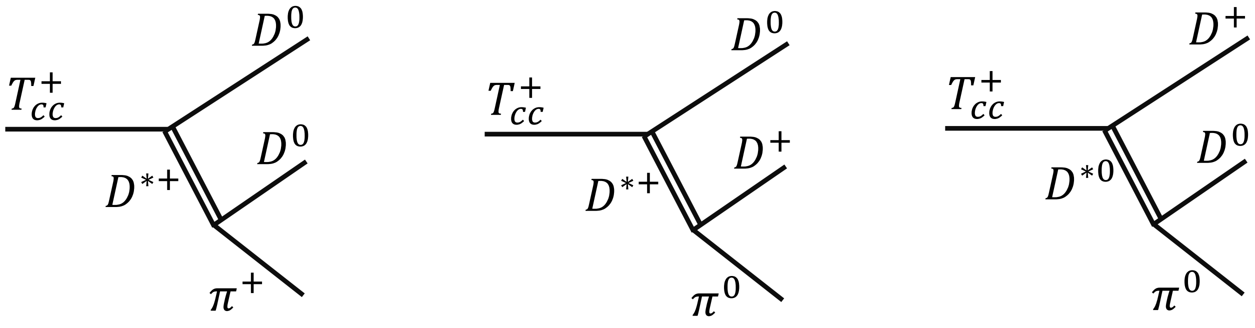

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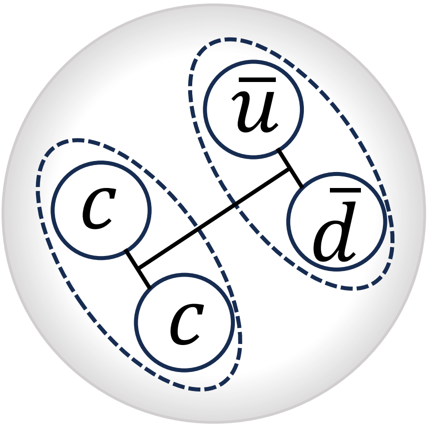
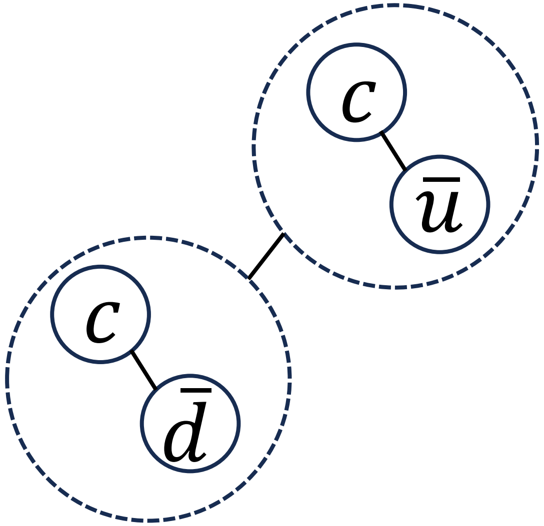


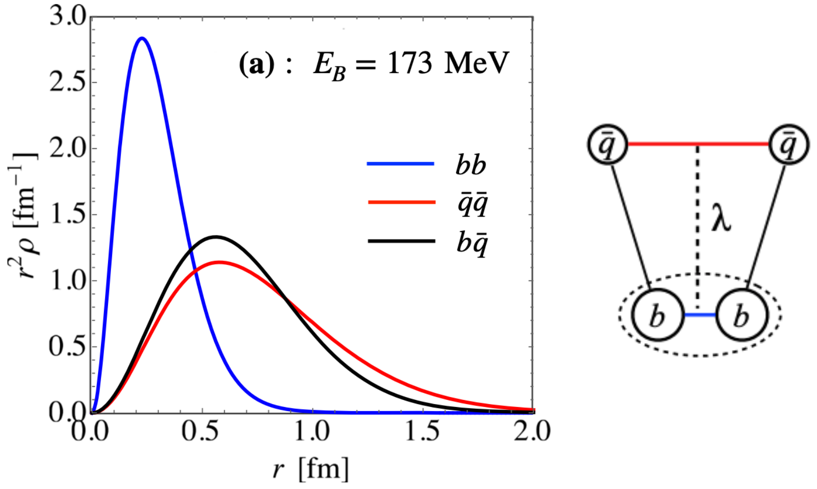
Diquark



Molecule

・What is the structure?
Diquarks, Molecule, or something else?

・Quark model[5] implies bb form compact object in the doubly bottom tetraquarks



[5] Q. Meng et al, Phys. Lett. B 824, 136800 (2022), arXiv:2106.11868

We employ diquark picture!

[3] R. Aaij et al. (LHCb), Nature Phys. 18, 751 (2022), arXiv:2109.01038 [hep–ex]
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Assumption of this study

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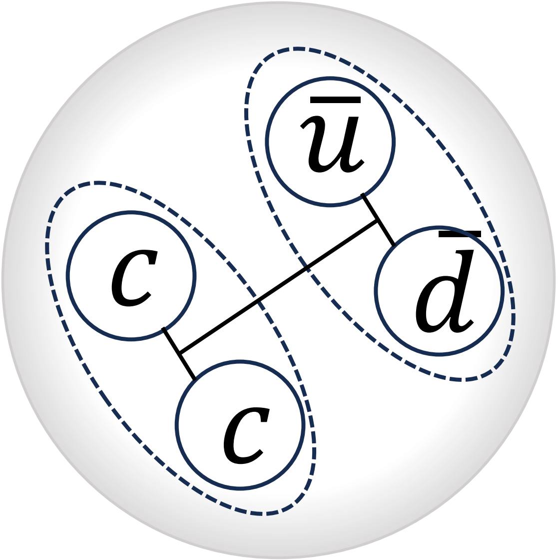

In this study,

- Assumption
  T_{cc} : cc diquark + $\bar{q}\bar{q}$ light quark cloud
  $q = u, d, s$
- No radial excitation between c and c
- Color rep. of diquark : $\bar{3}$ and 6

$$3 \times \bar{3} = 1 + 8$$
$$\bar{6} \times 6 = 1 + 8 + 27$$

Both color rep. can construct a color singlet.

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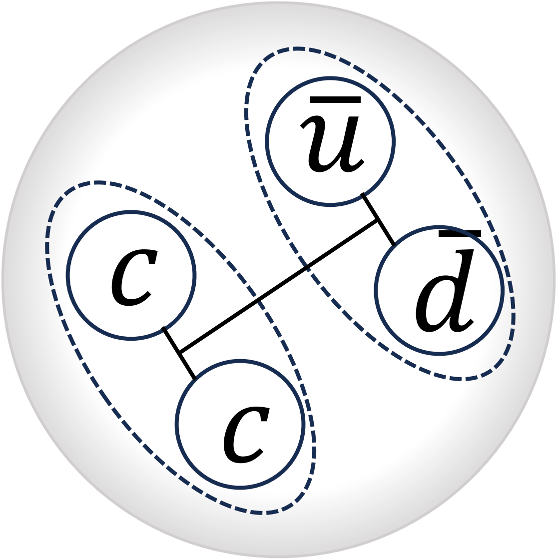

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  $3\times\bar{3} = 1 + 8$
  $6\times\bar{6} = 1 + 8 + 27$

  We assume it's $\bar{3}$ only
  More stable[6]?

Color factor
$C_F^{\bar{3}} = -\frac{2}{3}, C_F^{6} = \frac{1}{3}$

↓ Comparison with future experiment

We can study whether the color anti-triplet state of diquark is dominant in the DHTs or not.

[6]H.–X. Chen et al. Rept. Prog. Phys. 86, 026201 (2023), arXiv:2204.02649

Superflavor symmetry

Color rep. of QQ is $\bar{3}$

Color rep. of $\bar{Q}$ is $\bar{3}$

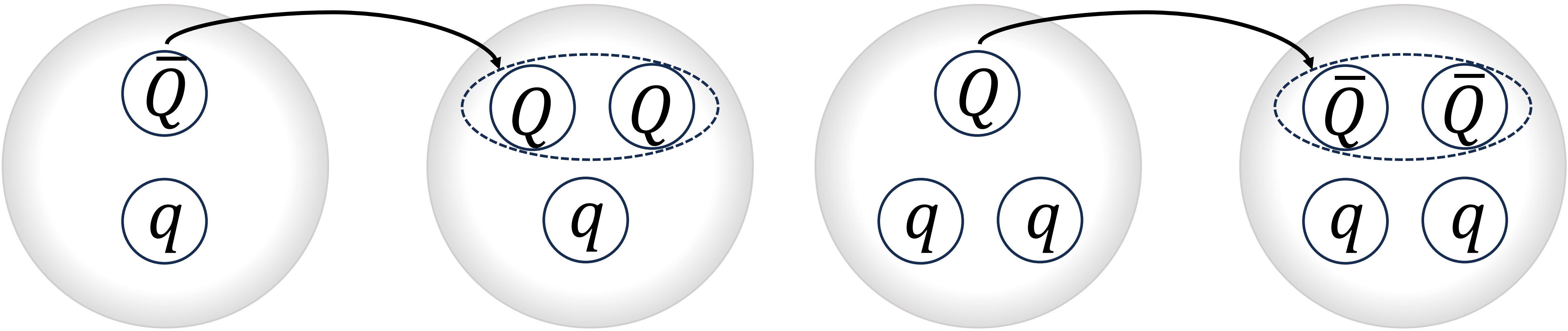
$Q = c, b$
$q = u, d, s$

→ <u>Superflavor symmetry(SFS)</u>

QQ and $\bar{Q}$ have the same interaction in the $m_Q \to \infty$ limit

[7]M. J. Savage and M. B. Wise, Phys. Lett. B 248, 177 (1990)
[8]H. Georgi and M. B. Wise, Phys. Lett. B 243, 279 (1990).
[9]S. Fleming and T. Mehen, Phys. Rev. D 73, 034502 (2006), arXiv:hep–ph/0509313

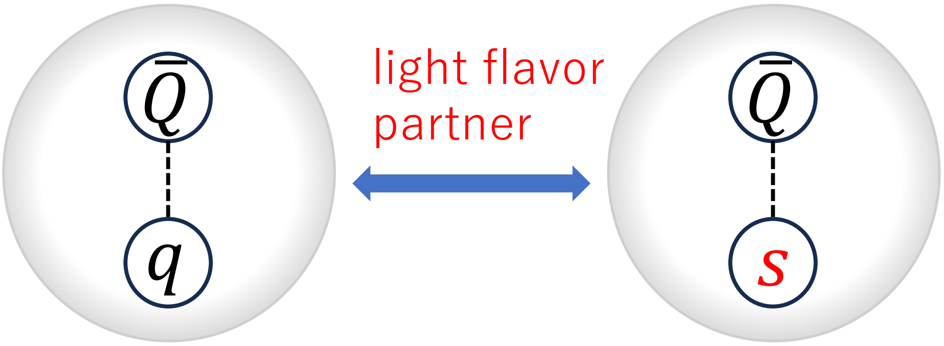
Heavy meson ↔ DHB　　　　SHB ↔ DHT



D, D_s, etc.　　Ξ_{cc}, Ω_{cc}, etc.　　Λ_c, Ξ_c, etc.　　T_{cc}, T_{ccs}, etc.

The relation between hadrons

- <u>SU(3) light flavor partner</u>
  Those that belong to the same flavor rep.



$Q = c, b$
$q = u, d$

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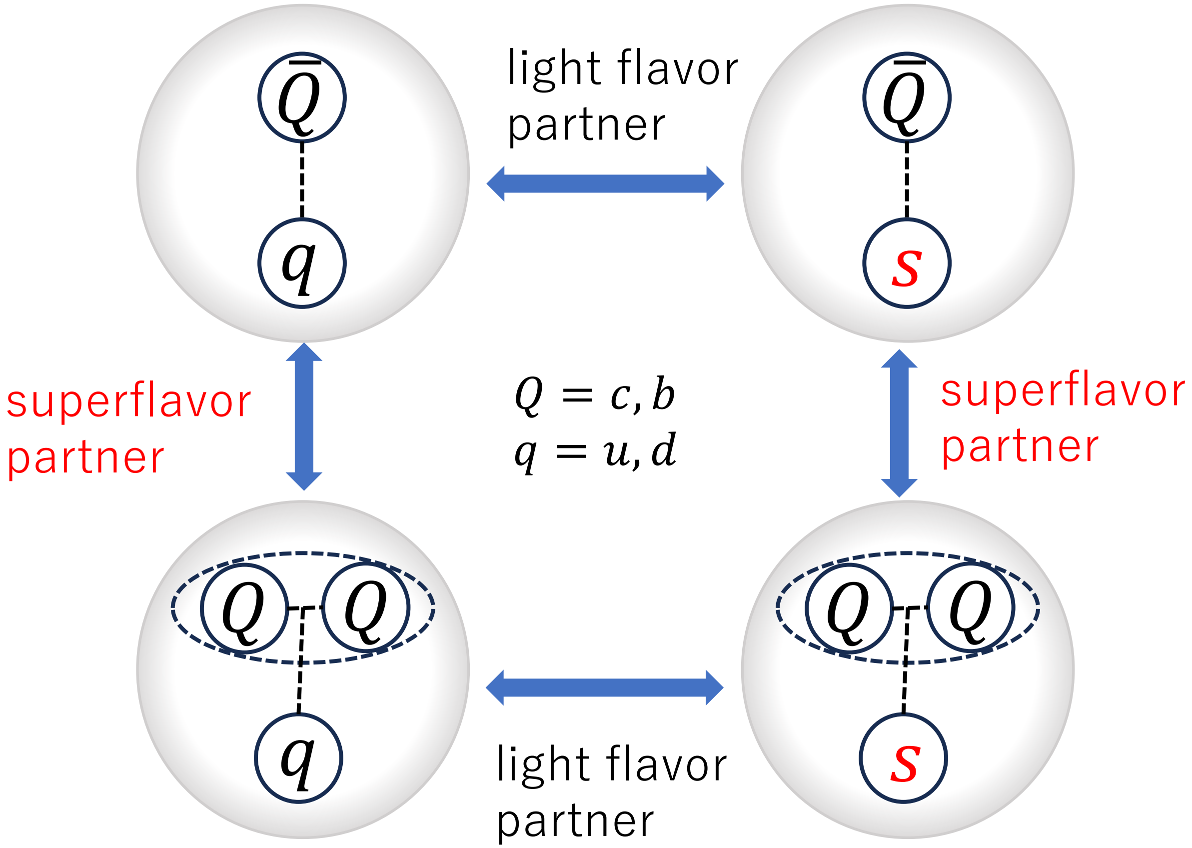


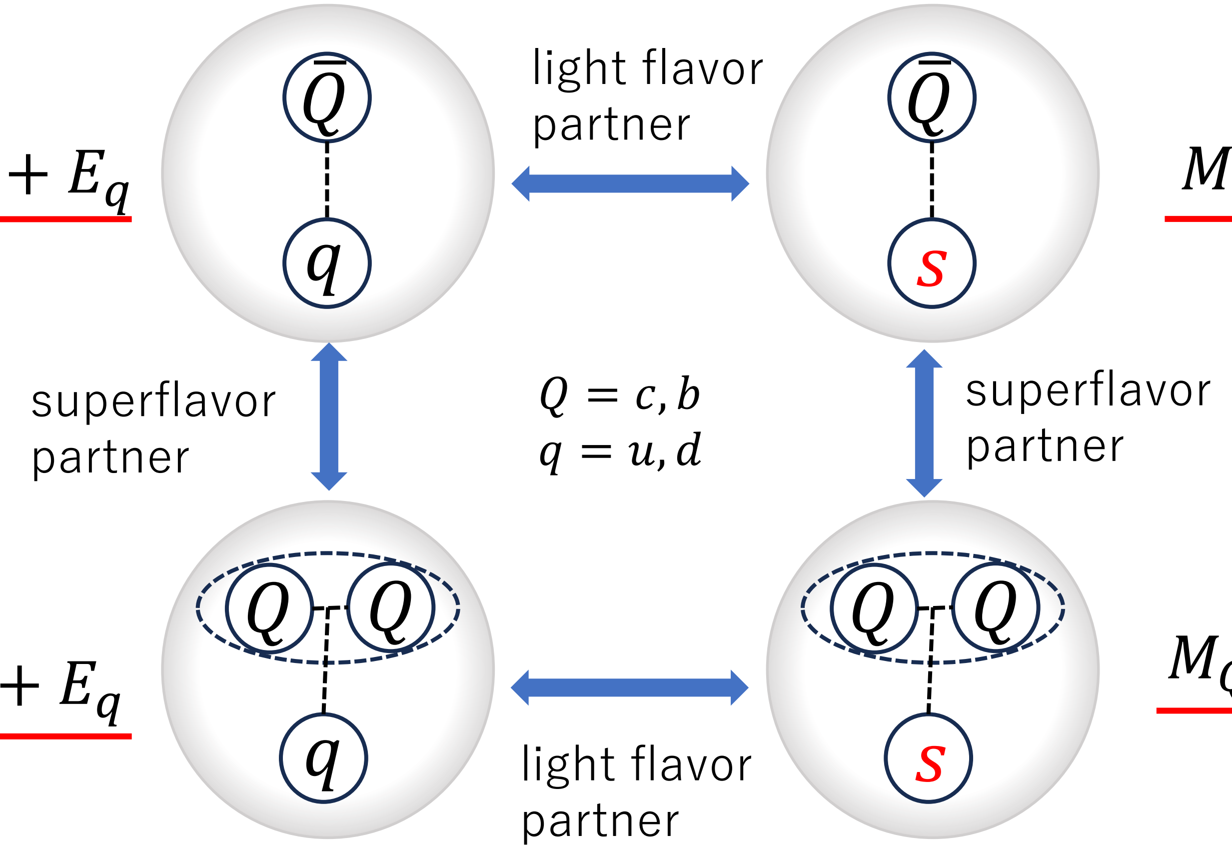
The relation between hadrons

Heavy-light interaction is included into light quark cloud.

We divide heavy hadron into a heavy object and light quark cloud based on heavy quark symmetry.

$M_{Qq} = M_Q + E_q$

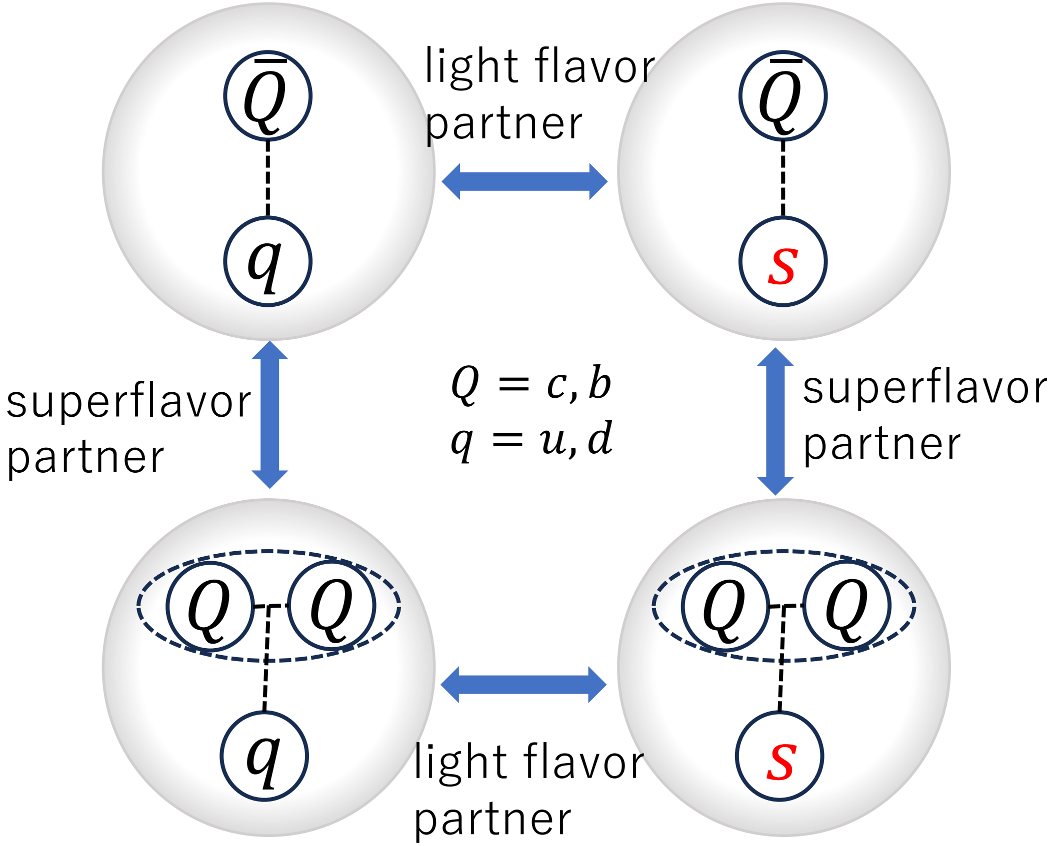
$M_{Qs} = M_Q + E_s$



$M_{QQq} = M_{QQ} + E_q$

$M_{QQs} = M_{QQ} + E_s$

The mass relation from superflavor symmetry



$$
\begin{cases}
M_{\bar{Q}q} = M_Q + E_q \\
M_{\bar{Q}s} = M_Q + E_s \\
M_{QQq} = M_{QQ} + E_q \\
M_{QQs} = M_Q + E_s
\end{cases}
$$

$$M_{QQs} - M_{QQq} = M_{\bar{Q}s} - M_{\bar{Q}q}$$

Superflavor symmetry implies that mass differences between flavor partners are the same in the superflavor partners.

The mass relation from superflavor symmetry

Superflavor symmetry implies that mass differences between flavor partners are the same in the superflavor partners

	Mass(MeV)	
Ξ_{cc}	3615	lattice[10]
Ξ_{cc}^{*}	3703	
Ω_{cc}	3733	
Ω_{cc}^{*}	3793	
$D^{\pm}$	1870	experiment
$D^{*\pm}$	2010	
$D_s^{\pm}$	1968	
$D_s^{*\pm}$	2112	

$$M(QQs) - M(QQq) = M(\bar{Q}s) - M(\bar{Q}q)$$

$$M_{ave}(\Xi_{cc}) - M_{ave}(\Omega_{cc}) = 100\ (\mathrm{MeV})$$

$$\|$$

$$M_{ave}(D^{\pm}) - M_{ave}(D_s^{\pm}) = 101\ (\mathrm{MeV})$$

※ M_{ave} means spin average

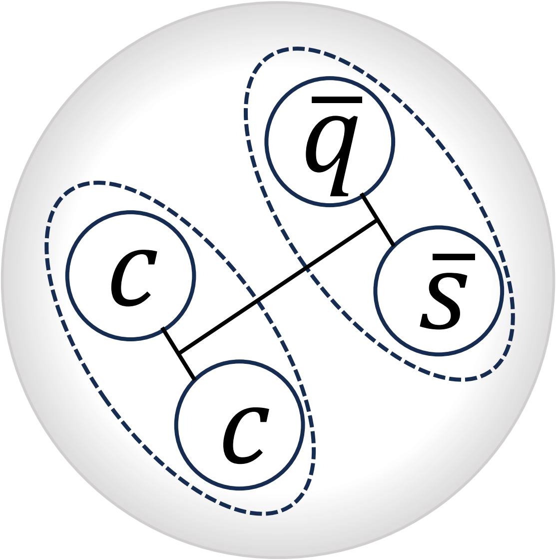
Superflavor symmetry holds with high accuracy!

[10]H. Bahtiyar et al. (TRJQCD Collaboration), Phys. Rev. D 102, 054513 (2020)

The existence of T_{ccs}^{+} from SFS

We naturally expect the existence of T_{ccs} $(\sim cc\bar{s}\bar{q})$ applying the mass relation of SFS to T_{cc}^{+}

$$\underbrace{M_{QQ\bar{s}\bar{q}}}_{T_{ccs}} - M_{QQ\bar{q}\bar{q}} = M_{\bar{Q}\bar{s}\bar{q}} - M_{\bar{Q}\bar{q}\bar{q}}$$



$T_{ccs}(\sim cc\bar{s}\bar{q})$

If T_{ccs}, as expected from SFS, really does exist,
it means that SFS holds true, and the color anti-triplet is dominant.

Prediction of T_{ccs}^{+} mass

	Mass(MeV)
T_{cc}^{+}	3875
Ξ_c^{+} Ξ_c^{0}	2468 2471
Λ_c^{+}	2286

These are experimental data from [3,4] and PDG

- Mass of T_{ccs}

$$M(T_{ccs}) - M(T_{cc}^{+}) = M(\Xi_c) - M(\Lambda_c^{+})$$

$$\rightarrow M(T_{ccs}) = 4059(\mathrm{MeV})$$

※This value is isospin averaged.

M.T. et al, in preparation

This result is derived from SFS and experimental data only with a simple calculation.

Decay of T_{ccs}^{+}

Initial	Final	Threshold (MeV)
T_{ccs}^{+}	$D^{*0}D_s^{+}$ $D^{0}D_s^{*+}$	3975 3977
T_{ccs}^{++}	$D^{*+}D_s^{+}$ $D^{+}D_s^{*+}$	3979 3982

These are experimental data from PDG

- Mass of T_{ccs}

$$M(T_{ccs}) - M(T_{cc}^{+}) = M(\Xi_c) - M(\Lambda_c^{+})$$

$$\rightarrow M(T_{ccs}) = 4059(\mathrm{MeV})$$

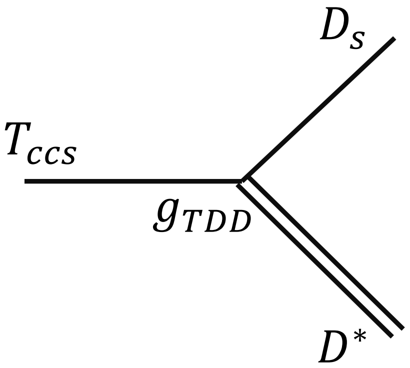
※This value is isospin averaged.

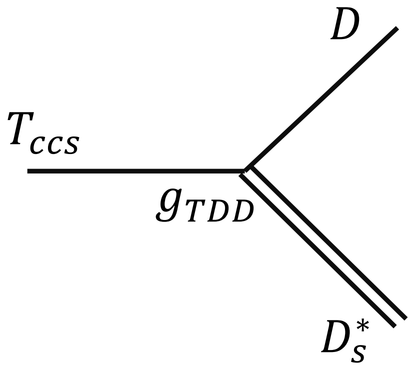
And we analyze decay width

$M(T_{ccs})$ is above the thresholds of D^*D_s and DD_s^*

⬇

We assume decay of T_{ccs}

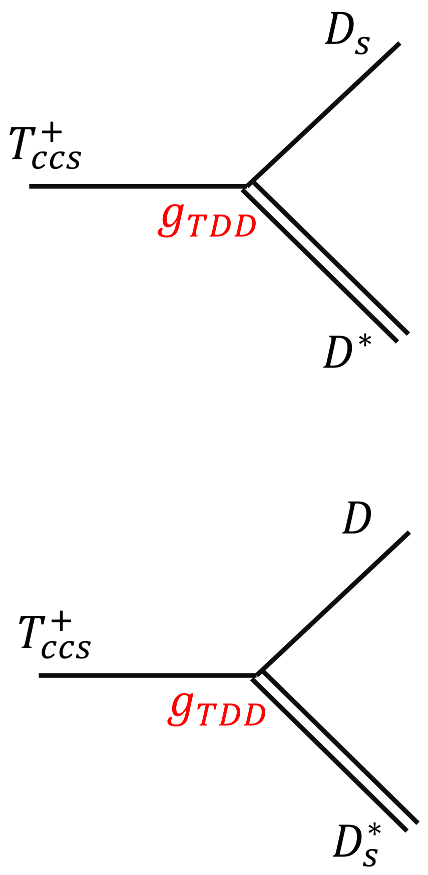




How to calculate decay width of T_{ccs}^{+}?

Effective lagrangian approach with $\mathrm{SU(3)_f}$ symmetry independent from SFS

- We assume decay of T_{ccs}^{+}



- T_{cc}^{+} is isoscalar, so flavor anti-symmetry
  →flavor rep. of T_{cc} and T_{ccs} is $\bar{3}$

- $\mathrm{SU(3)_f}$ transformation

$$\bar{T}_i^{\mu} \to \bar{T}_j^{\mu}\left(U^{\dagger}\right)^j{}_i \,,\; D_i \to D_j\left(U^{\dagger}\right)^j{}_i \,,\; D_i^{*\mu} \to D_j^{*\mu}\left(U^{\dagger}\right)^j{}_i$$

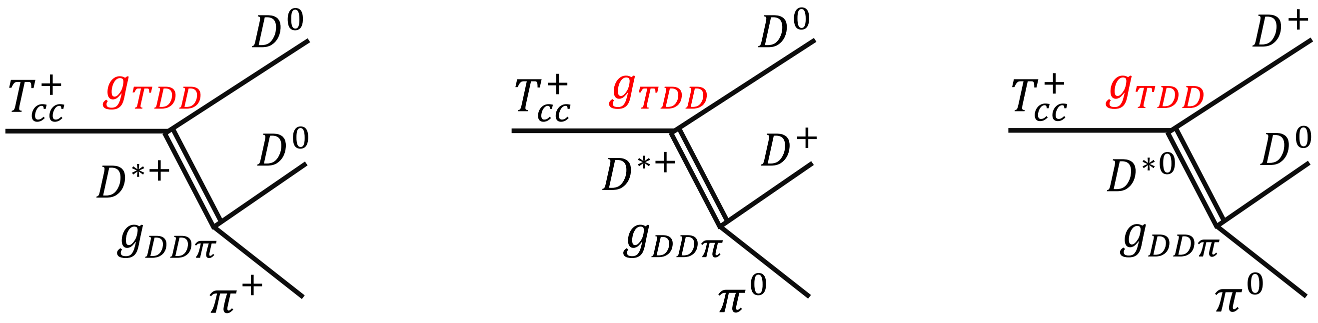
- Lagrangian exhibiting $\mathrm{SU(3)_f}$ symmetry

$$\mathcal{L} = g_{TDD}\varepsilon^{ijk}\bar{T}_i^{\mu}D_{\mu,j}^{*}D_k$$ ←One parameter, g_{TDD}

※$T_{cc} \to D^*D$ and $T_{ccs} \to D^*D_s$ share the coupling constant g_{TDD}

Determination of g_{TDD}

Decay of T_{cc}^{+}



$g_{DD\pi}$ is determined from $D^* \to D\pi$

Then, we obtain g_{TDD} from decay width of T_{cc}^{+} as

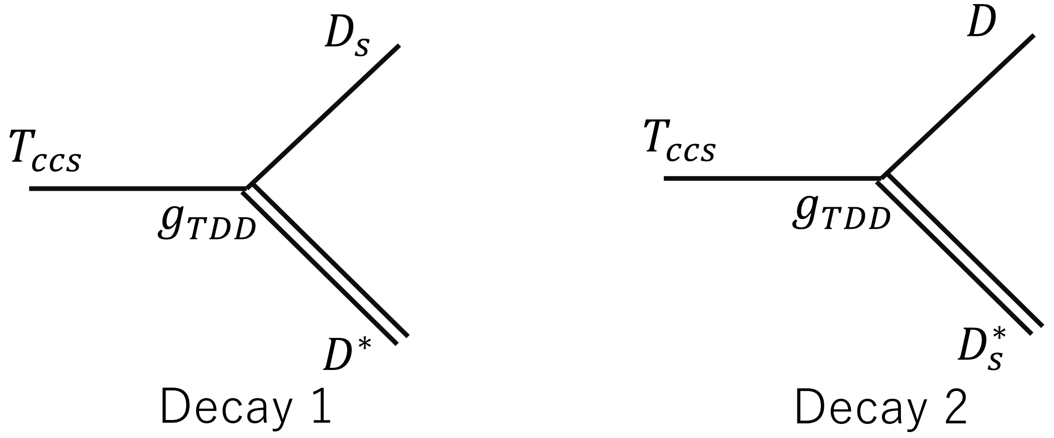
$$g_{TDD} = 0.68 \times 10^3 \text{ (MeV)}$$

Dimensionless coupling constant normalized by heavy hadron mass $M_{Heavy} \sim 10^3$(MeV)

$$\tilde{g}_{TDD} = \frac{g_{TDD}}{M_{Heavy}} \sim 1$$ this value is natural.

Analysis of T_{ccs}^{+}

Decay of T_{ccs}^{+}



We obtain decay width of T_{ccs}^{+}

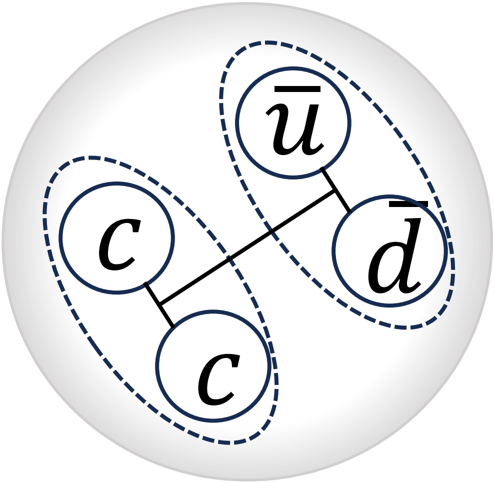
$$\Gamma(T_{ccs}) = g_{TDD}^2 \frac{|P_1| + |P_2|}{6\pi M_{T_{ccs}}^2}$$

$$= 1.2 \text{ (MeV)}$$ ←input $M_{T_{ccs}} = 4059$ (MeV)

M.T. et al, in preparation

※This result is predicted by only $\mathrm{SU(3)_f}$ symmetry.

Summary



We study T_{ccs} as composition of color anti-triplet cc-diquark

Mass of T_{ccs} from super flavor symmetry

$$M(T_{ccs}) = 4059 \text{ (MeV)}$$

Decay width of T_{ccs} from $\mathrm{SU}(3)_\mathrm{f}$ symmetry

$$\Gamma(T_{ccs}) = g_{TDD} \frac{|P_1|+|P_2|}{6\pi M_{T_{ccs}}^2} = 1.2 \text{ (MeV)}$$

If these results agree with future experimental data, it means that the color $\bar{3}$ heavy diquark(QQ) in DHT is dominant.

If not, we need to consider color 6 heavy diquark(QQ), even for ground state.

Thank you for your kind attention!