Hadronic molecules near thresholds: T_{cc} and its partners

Yasuhiro Yamaguchi,

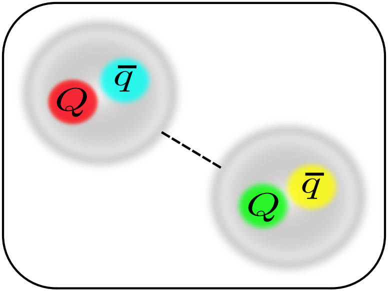
Department of Physics, Nagoya University, Japan

T. Asanuma, Y.Y, M. Harada, Phys. Rev. D 110, 074030 (2024)

M. Sakai, Y.Y, Phys. Rev. D 109, 054016 (2024)

East Asian Workshop on Exotic Hadrons 2024
8-11 December 2024, Nanjing, China

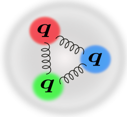
Outline



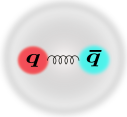
1. **Introduction**
   Exotic hadrons, T_{cc} tetraquark
2. **T_{cc} as a DD^* molecule, and T_{bb}**
3. **$\bar{D}^{(*)}\Xi_{cc}^{(*)}$ molecule as a superflavor partner of T_{cc}**
4. **Summary**

Hadron structure: Constituent quark model

- Hadron $=$ Quark composite system
- Ordinary Hadrons: Baryon (qqq) and Meson ($q\bar{q}$)



Baryon(proton,nucleon,...)



Meson (ρ,$K^{(*)}$,...)

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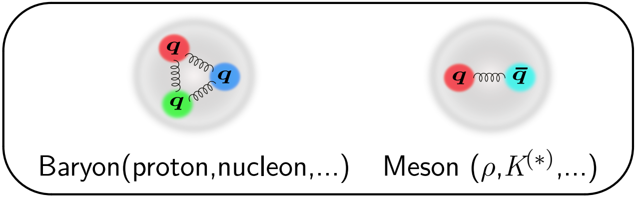
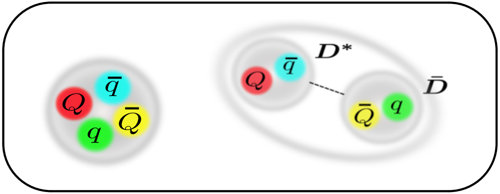
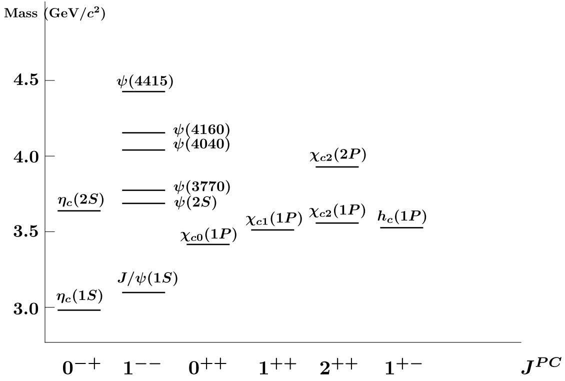


- Exotic Hadrons ($\neq qqq$, $q\bar{q}$): **Multiquark? Multihadron?**



Observations of exotic hadrons containing $c\bar{c}$

- e.g. $c\bar{c}$ mesons (Charmonium) sector



one-g exchange

$+$

Confinement

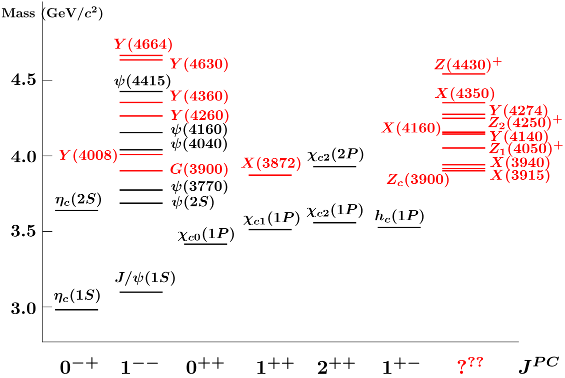
$\Downarrow$

$$V(r) = -\frac{\alpha_s}{r} + cr$$
$$+ \ldots$$

N. Brambilla, *et al.* Eur.Phys.J.C **71**(2011)1534, S. Godfrey and N. Isgur, PRD**32**(1985)189

Observations of exotic hadrons containing $c\bar{c}$

- e.g. $c\bar{c}$ mesons (Charmonium) sector and **Unexpected X, Y, Z**



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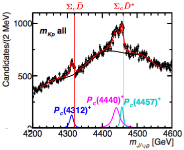
- Many Exotics $\neq c\bar{c}$ have been observed in the Experiments (BaBar, Belle, BESIII, LHCb,...) since the discovery of **$X(3872)$ in 2003!**

Recent reports of exotic hadrons

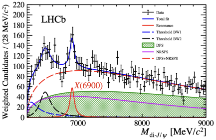
- **2019:** $P_c(4312)$, $P_c(4440)$, $P_c(4457)$
  LHCb, PRL**122**(2019)222001
- **2020:** $X(6900)$, $X_{0,1}(2900)$
  LHCb, Science Bulletin 65 (2020) 1983, PRL125, 242001 (2020), PRD102, 112003 (2020)
- **2021:** Z_{cs}, P_{cs}
  BESIII PRL126, 102001 (2021), LHCb Sci.Bull.**66**(2021)1278
- **2022:** $P_c(4337)$, T_{cc}^{+}, $P_{cs}(4338)$, $T_{cs}(2900)$
  LHCb, PRL**128**(2022)062001, Nature Phys. **18** (2022) 751-754, Nature Commun. **13** (2022) 3351
- **2023:** $T^{\theta}_{\psi s1}(4000)^0$, **2024:** $h_c(4300)$
  LHCb, arXiv:2301.04899[hep-ex], LHCb arXiv:2406.03156

- New exotic hadrons have been reported Every Year, especially at **Large Hadron Collider (LHC)**
- One of the important topics in the hadron spectroscopy!

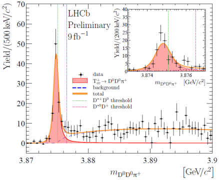
P_c



$X(6900)$



T_{cc}



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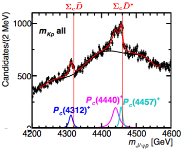

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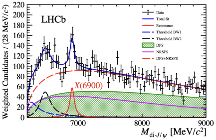
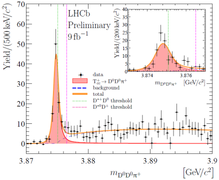
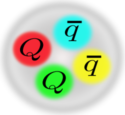


T_{cc}

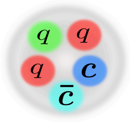


Candidates of Exotic structures?

Compact multiquarks



Tetraquark

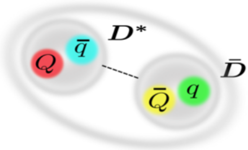


Pentaquark

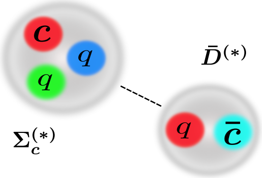
- Exotics as multiquark states

Hadronic molecules

Near thresholds?



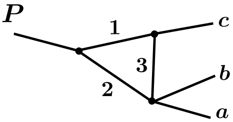
Meson-Meson



Meson-Baryon

Triangle Singularity

Near thresholds?



(w/o Resonance)

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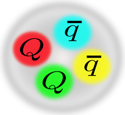
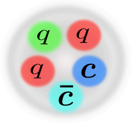


Tetraquark

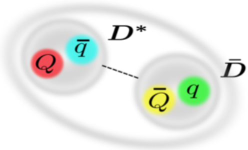


Pentaquark

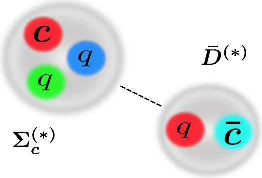
- Exotics as multiquark states
- Triangle singularity producing a peak structure $\neq$ a resonance

Hadronic molecules

Near thresholds?



Meson-Meson



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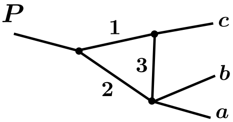

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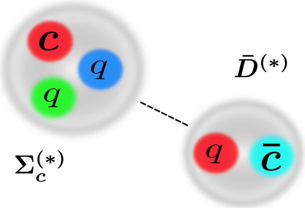
Hadronic molecules?

- Exotics as Hadronic molecule ⇒ Hadron (quasi) bound state

→ expected **near the thresholds**



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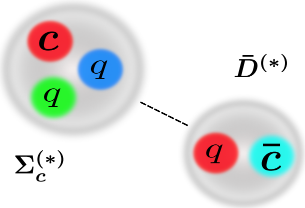
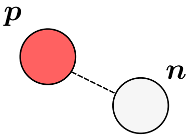


Analogous to Deuteron



$B = 2.2$ MeV

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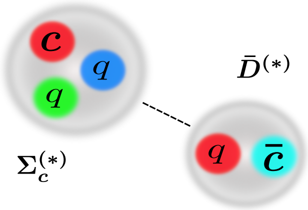
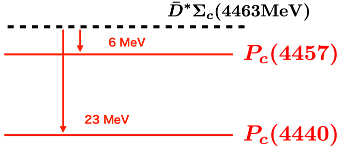


$$P_c = \bar{D}^{(*)}\Sigma_c^{(*)} \text{ molecules?}$$



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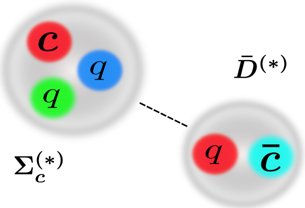

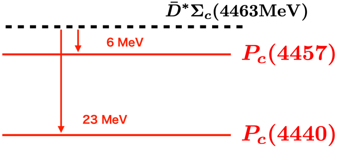

- Exotic hadrons near thresholds
  - $D\bar{D}^*$: $X(3872)$, $Z_c(3900)$,..., DD^*: T_{cc}
  - $B\bar{B}^*$: Z_b, Z_b'
  - $\bar{D}^{(*)}\Sigma_c^{(*)}$: P_c F. K. Guo, *et. al.*, Rev.Mod.Phys.**90**(2018)015004,Y. Y., *et. al.*, J.Phys.G**47**(2020)053001,...

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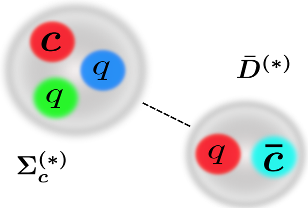

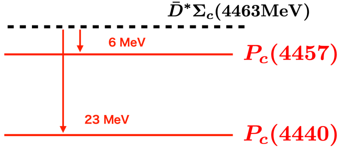

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Q. What is an interaction binding the constituent hadrons?

Hadron interactions

Problem Hadron interactions are **NOT established** yet...
due to the lack of the hadron-scattering data
($\leftrightarrow$ Lattice QCD, Femtoscopy, etc near future!)

How can we describe hadron interactions?

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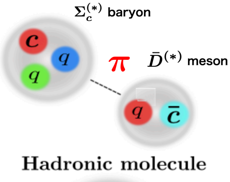
Long-range int. **One pion exchange potential**

- Long-range int. known in the nuclear force !
- Chiral and Heavy quark spin symmetries



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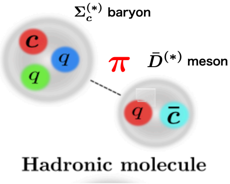
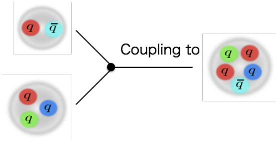
Short-range int. Many models

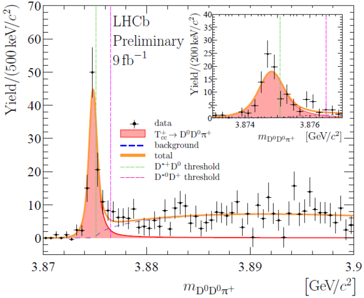
- ρ, ω, σ meson exchanges (analogy to Nuclear force)
- Quark exchanges, Mixing of Compact state, etc.

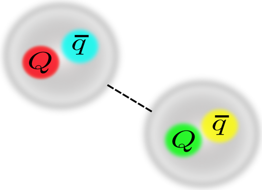




OPEP

Doubly charmed tetraquark T_{cc}



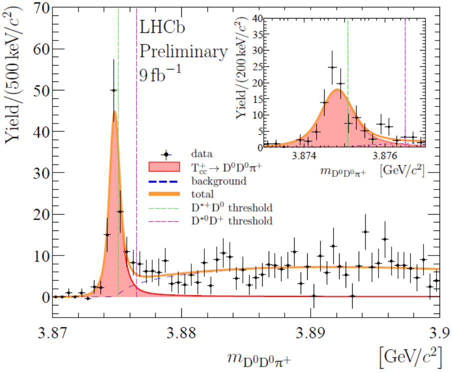


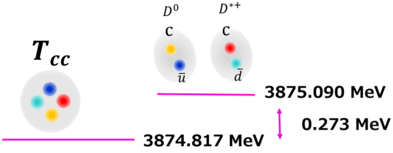
LHCb, Nature Phys. **18** (2022) 751-754, Nature Commun. **13** (2022) 3351

Doubly charmed tetraquark T_{cc} in LHCb (2022)

- $T^+_{cc}(cc\bar{u}\bar{d})$ has been reported in LHCb!

  LHCb, Nature Phys. **18** (2022) 751-754, Nature Commun. **13** (2022) 3351





- The Breit–Wigner parameterization

  $\Delta M_{BW} = -273 \pm 61 \pm 5^{+11}_{-14}$ keV

  $\Gamma_{BW} = 410 \pm 165 \pm 43^{+18}_{-38}$ keV

- Model analysis, $T_{cc} \sim DD^*$

  $\Delta M_{pole} = -360 \pm 40^{+4}_{-0}$ keV

  $\Gamma_{pole} = 48 \pm 2^{+0}_{-14}$

- Found **just below the DD^* threshold**
- The quantum number: $J^P = 1^+$, and $I = 0$ is favored.

What is the structure of T_{cc}?

See review Hua-Xing Chen, *et. al.*, Rep. Prog. Phys. **86** (2023) 026201

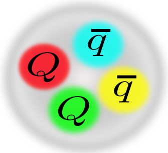
References related to T_{cc}

- Compact tetraquark $(cc\bar{q}\bar{q})$?

  J. L. Ballot *et. al.*, PLB**123**(1983)449, S. Zouzou, *et. al.*, ZPC**30**(1986)457,

  S.H.Lee, S.Yasui, EPJC**64**(2009)283, Q. Meng, *et. al.*, PLB**824**(2022)136800,

  ...

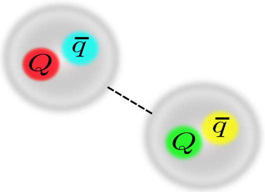


- Hadronic molecule (DD^*)

  A.V.Manohar, M.B.Wise, NPB**399**(1993)17,

  S.Ohkoda, *et. al.*, PRD**86**(2012)034019,

  J.-B Cheng, *et. al.*, PRD**106**(2022)016012 ...



- Lattice QCD

  Y.Ikeda, *et. al.*, [HALQCD], PLB**729**(2014)85,

  S.Aoki, T.Aoki, PoS(LATTICE2022)049,

  M. Padmanath and S. Prelovsek, PRL**129**(2022)032002,

  Y. Lyu, *et al.*, arXiv:2302.04505, ...

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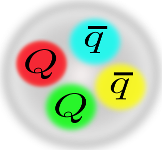
  ...

  See also Talks of **M. Tanaka (10 Dec), M. Harada (11 Dec)**



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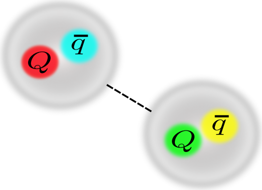

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T_{cc} elucidates charmed hadron interactions

- T_{cc} as $\bar{c}\bar{c}qq$ or DD^* which is a **"deuteron" in the charm sector!**
  (Deuson N. A. Tornqvist, Z. Phys. C61, 525 (1994))

  Providing fundamental interactions such as DD^*, qq

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  Providing fundamental interactions such as DD^*, qq

  - $\boldsymbol{SU(3)_f}$ **symmetry** $\boldsymbol{u, d \to s}$

    $\Rightarrow T_{ccs}(\bar{c}\bar{c}sq)$, $\bar{c}\bar{c}ss$ **Providing interactions with Strangeness**

T_{cc} elucidates charmed hadron interactions

- T_{cc} as $\bar{c}\bar{c}qq$ or DD^* which is a **"deuteron" in the charm sector!** (Deuson N. A. Tornqvist, Z. Phys. C61, 525 (1994))

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    M. Tanaka, Y.Y, M. Harada, PRD 110, 016024 (2024) (T_{ccs} spectrum)

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    T. Asanuma, Y.Y, M. Harada, PRD 110, 074030 (2024) M. Sakai, Y.Y, PRD 109, 054016 (2024)

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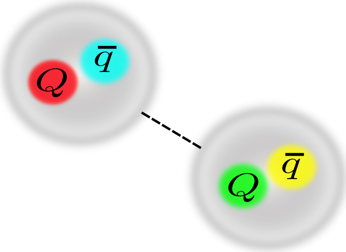
T_{cc} analysis in this study

T. Asanuma, Y.Y, M. Harada, Phys. Rev. D 110, 074030 (2024) M. Sakai, Y.Y, Phys. Rev. D 109, 054016 (2024)



- Studing T_{cc} as the DD^* molecule
- Heavy quark spin symmetry induces the $D - D^*$ mixing
  $\to DD^* - D^*D^*$ coupled channel analysis
- Interactions: The meson exchange potentials, $\pi, \rho, \omega, \sigma$

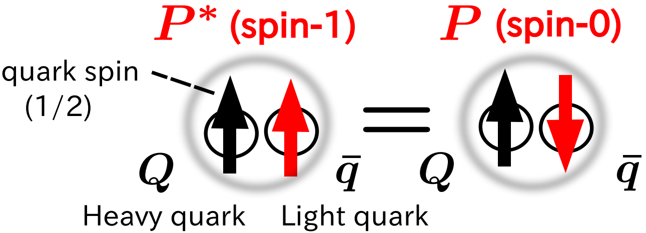
Heavy Quark Spin Symmetry and Mass degeneracy

Heavy Quark Spin Symmetry (HQS) N.Isgur,M.B.Wise,PLB**232**(1989)113

- **Suppression of Spin-spin force** in $m_Q \to \infty$.

  $\Rightarrow$ **Mass degeneracy** of hadrons with the different J

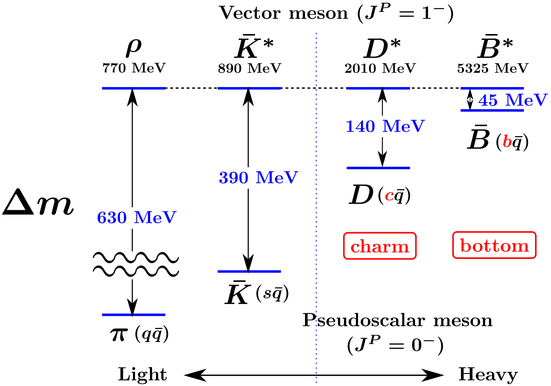
- e.g. $Q\bar{q}$ meson



$\Rightarrow$ Mass degeneracy of spin-0 and spin-1 states!

Mass degeneracy of heavy hadrons

- Mass difference between vector and pseudoscalar mesons. ($Q\bar{q}$, $q = u, d$)



- Δm decreases when the quark mass increases.

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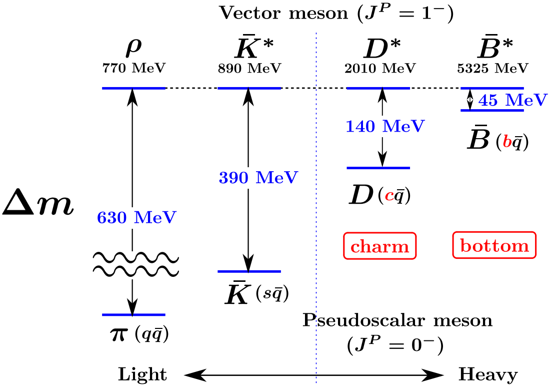
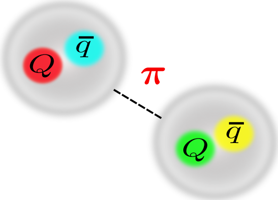


- Δm decreases when the quark mass increases.
  $\Rightarrow$ **Degeneracy of Heavy hadrons!**

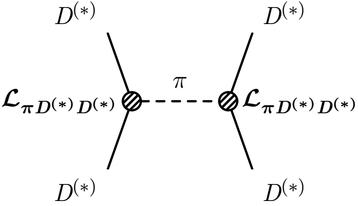
Heavy Quark Spin Symmetry $\Rightarrow$ **$D - D^*$ mixing is induced!**

One pion exchange potential

- $D - D^*$ mixing (channel couplings) enhances the one meson exchange interaction
  $\rightarrow$ In particular, $DD\pi$ is forbidden, while $DD^*\pi$ is allowed.



$\Rightarrow$



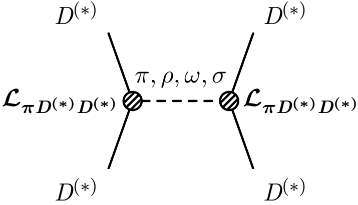
$$V^{\pi}(r) = \left(\frac{g_\pi}{2f_\pi}\right)^2 \frac{1}{3}\left[\vec{S}_1 \cdot \vec{S}_2 C(r) + S_{S_1 S_2} T(r)\right]$$

(Contact term is removed)

- Form factor with Cutoff Λ

$$F(\vec{q}^{\,2}) = \frac{\Lambda^2 - m_\pi^2}{\Lambda^2 + \vec{q}^{\,2}}$$

Coupling constants of the meson exchange potential

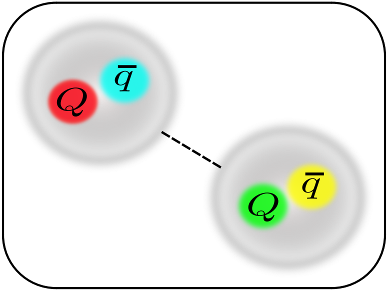


π	g_π	0.59	$D^* \to D\pi$ [1]
ρ, ω	β	0.9	Lattice [2]
	λ	0.56 GeV^{-1}	B decay [3]
σ	g_σ	3.4	$\boldsymbol{g_{\sigma NN}/3}$ [4]
Cutoff	Λ		Fix to reproduce $B_{T_{cc}}$

[1] R. Casalbuoni, *et. al.*, Phys. Rept. **281** (1997), 145-238, [2] Ming-Zhu Liu *et. al.*, Phys. Rev. D **99**, 094018(2019)

[3] C. Isola *et. al.*, Phys. Rev. D **68**, 114001 (2003), [4] R. Chen *et. al.*, Phys. Rev. D **96** 116012(2017)

Numerical results of the $D^{(*)}D^{(*)}$ bound state



- Channel couplings: $DD^*(^3S_1, ^3D_1), D^*D^*(^3S_1, ^3D_1)$
- Solving Schrödinger equations by using the Gaussian expansion method

  E. Hiyama, Y. Kino and M. Kamimura, Prog. Part. Nucl. Phys. **51** (2003), 223-307
- Interactions: $\pi\rho\omega\sigma$ exchange potentials

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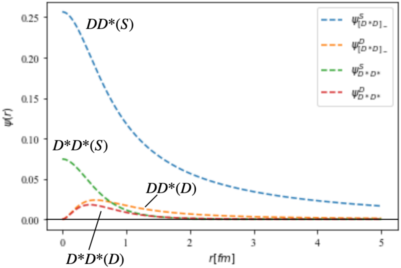
- $\pi\rho\omega\sigma$ exchanges $\to$ We find $\mathbf{\Lambda = 1182}$ **MeV (Bound)**

Λ	**1182 MeV**
B	0.27 MeV **(Input)**
$P_{DD^*}(^3S_1)$	98.7%
$P_{DD^*}(^3D_1)$	0.840%
$P_{D^*D^*}(^3S_1)$	0.348%
$P_{D^*D^*}(^3D_1)$	0.106%
$\sqrt{\langle r^2\rangle}$	6.42 fm

Wave functions



- The OPEP attraction is not enough to generate a bound state $\Rightarrow$ The short-range interaction is also important.
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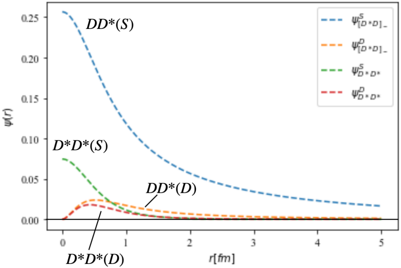

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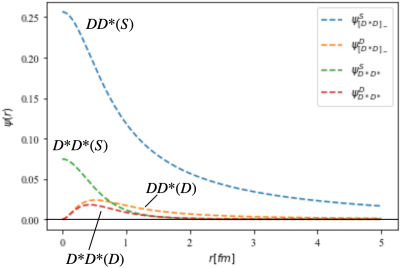

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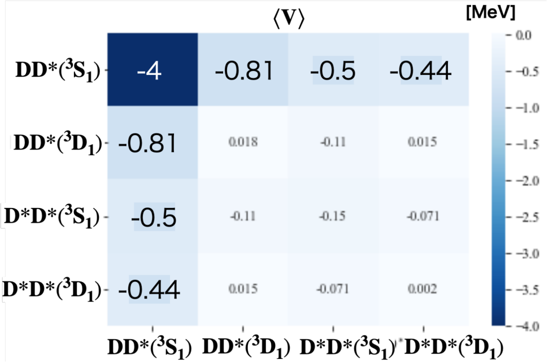

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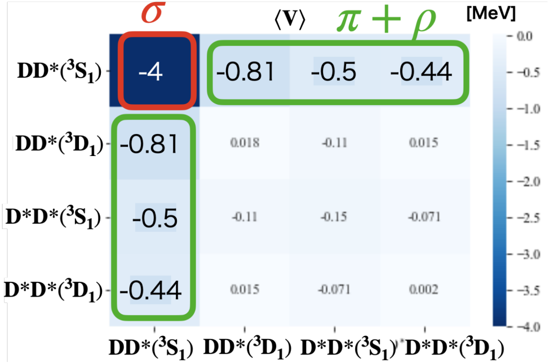

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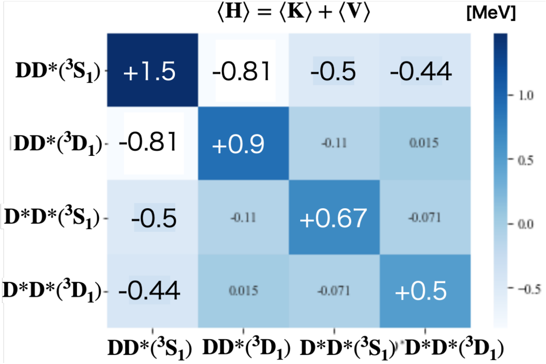

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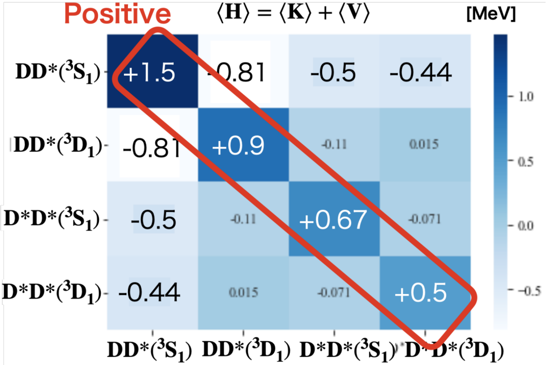
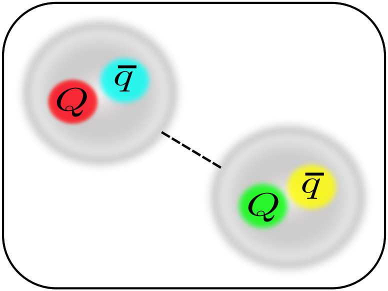


- **Strong attraction from the σ exchange** in the $DD^*({}^3S_1)$ diagonal component
- Attraction of the off-diagonal components from $\pi + \rho$
- In $\langle H \rangle$, the positive diagonal components $\Rightarrow$ Importance of the off-diagonal components

From T_{cc} to other exotic states

- T_{cc} can be understood by the hadronic molecular picture



- Then, symmetries predict its partner states
  - Heavy quark flavor symmetry $\boldsymbol{c} \to \boldsymbol{b}$: T_{bb} as BB^*

    $\Rightarrow$ Large mass of B ($\sim$ 5280 MeV $> D(1870)$) suppresses a kinetic energy
    $\to$ Likely bound
  - Superflavor symmetry $\boldsymbol{c} \to \bar{\boldsymbol{c}}\bar{\boldsymbol{c}}$: $\bar{D}\Xi_{cc}$ pentaquark $(cc\bar{c}qq)$

    $\Rightarrow$ multicharm states

From $D^{(*)}D^{(*)}$ to $B^{(*)}B^{(*)}$ (T_{bb})

- The bottom counterpart of T_{cc} which has not been reported so far
- Employing the same parameters used in T_{cc}

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B	46.0 MeV
$P_{BB^*}(^3S_1)$	70.7%
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$P_{B^*B^*}(^3S_1)$	21.6%
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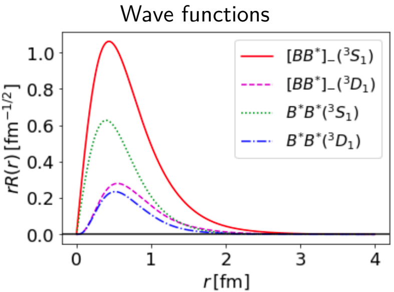
$\sqrt{\langle r^2 \rangle}$	0.62 fm



- **$BB^*(S)$ is dominant.** $B^*B^*(S)$ is also important, while the ratio is small in T_{cc} ($\leq 1\%$)

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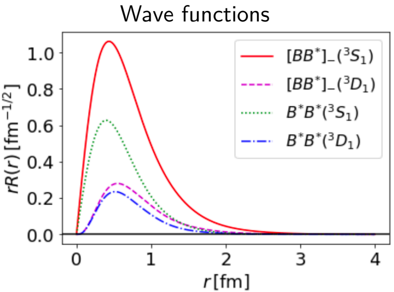

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- $\bar{D} \leftrightarrow \Xi_{cc}$ by **the superflavor symmetry**
  (known as the heavy quark-antidiquark symmetry (HADS))
  H. Georgi and M. B. Wise, PLB**243**(1990)279, M.J.Savage, M.B.Wise PLB**248**(1990)177
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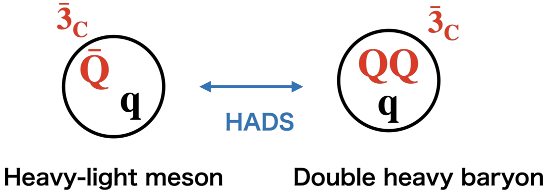

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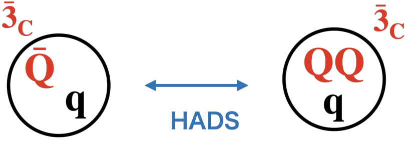
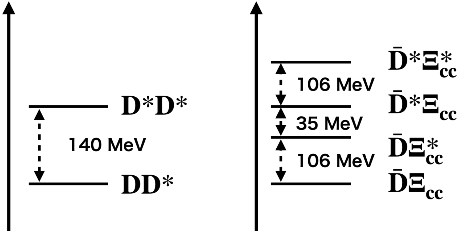


Heavy-light meson **Double heavy baryon**

- The interactions can be described by **the common coupling constant**

Coupled Channels of the $\bar{D}\Xi_{cc}$ molecule

- Heavy quark spin symmetry induces the channel couplings



$D(0^-)$: 1867 MeV, $D^*(1^-)$: 2009 MeV

$\Xi_{cc}(1/2^+)$: 3621 MeV, $\Xi^*_{cc}(3/2^+)$: 3727 MeV **(prediction)**

N.Brambilla, *et.al.*, PRD**72**(2005)034021, S.Fleming, T.Mehen, PRD**73**(2006)034502

- For $J^P = 1/2^-$

$\boldsymbol{\bar{D}\Xi_{cc}(^2S)}$, $\boldsymbol{\bar{D}\Xi^*_{cc}(^4D)}$,

$\boldsymbol{\bar{D}^*\Xi_{cc}(^2S,^4D)}$, $\boldsymbol{\bar{D}^*\Xi^*_{cc}(^2S,^4D,^6D)}$

Numerical results: $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ bound state

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Λ	1182 MeV **(Input)**
B	**7.46 MeV**
$P_{\bar{D}\Xi_{cc}}(^2S_{1/2})$	98.3%
$P_{\bar{D}\Xi_{cc}^*}(^4D_{1/2})$	0.0012 %
$P_{\bar{D}^*\Xi_{cc}}(^2S_{1/2})$	0.076 %
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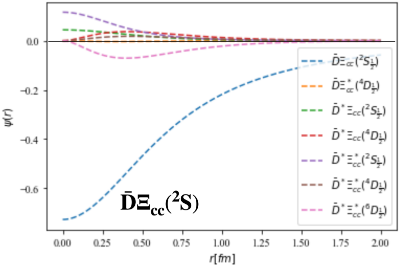
Wave functions



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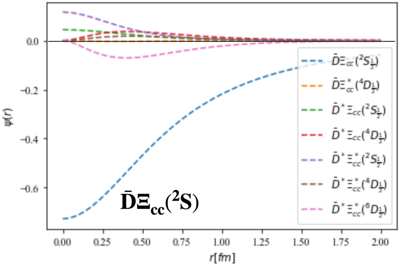

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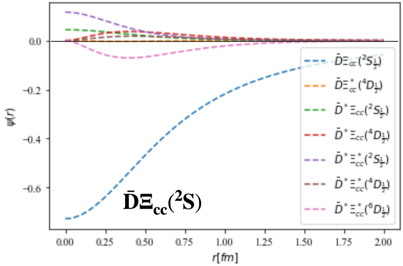
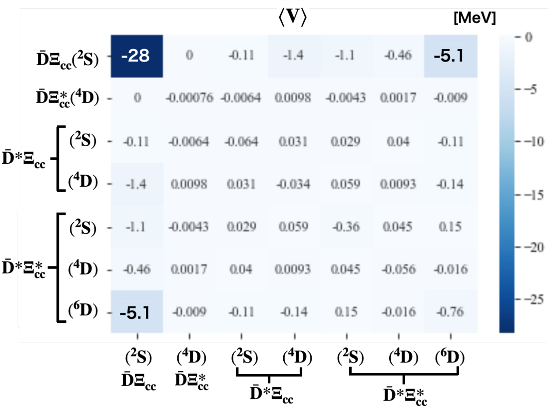
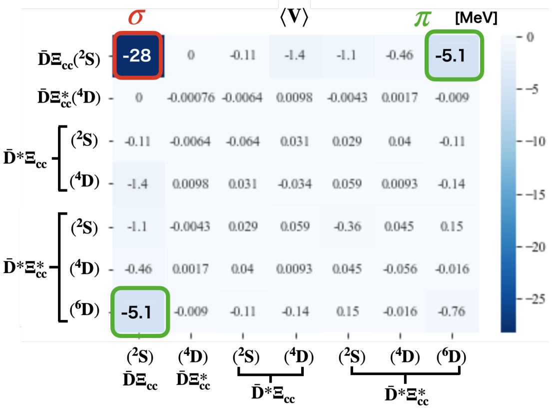


- Dominant component: $\bar{D}\Xi_{cc}(^2S)$ **$\sim$ 98.3 %**
- Second "dominant": $\bar{D}^*\Xi^*_{cc}(^6D)$ **$\sim$ 1 %** $\leftrightarrow$ $M_{\bar{D}^*\Xi^*_{cc}} - M_{\bar{D}\Xi_{cc}} = 247$ MeV

Energy expectation values of $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ for $I(J^P) = 0(1/2^-)$

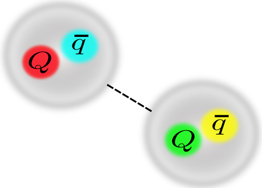


Energy expectation values of $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ for $I(J^P) = 0(1/2^-)$



- **Strong attraction from the σ exchange** in the $\bar{D}\Xi_{cc}(^2S)$ diagonal component
- Attraction in the $\bar{D}\Xi_{cc}(^2S) - \bar{D}^*\Xi^*_{cc}(^6D)$, produced by the OPEP tensor force

Summary



- Doubly charmed tertaquark T_{cc} has attracted a lot of interest.
  - T_{cc} as a $D^{(*)}D^{(*)}$ molecule with the one boson exchange potentials
  - Importance of the σ exchange and the tensor force of the π exchange
    $\rightarrow$ Important role of the $DD^* - D^*D^*$ mixing
  - T_{bb} bound state as a bottom counterpart is also obtained.
- $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ as a superflavor partner
  - Obtaining the bound state for $J^P = 1/2^-$
  - Importance of the $\bar{D}^*\Xi_{cc}^*$ channel

Ref. T. Asanuma, Y.Y, M. Harada, Phys. Rev. D 110, 074030 (2024),

M. Sakai, Y.Y, Phys. Rev. D 109, 054016 (2024)