Exotic hadrons as heavy hadronic molecules and their partners

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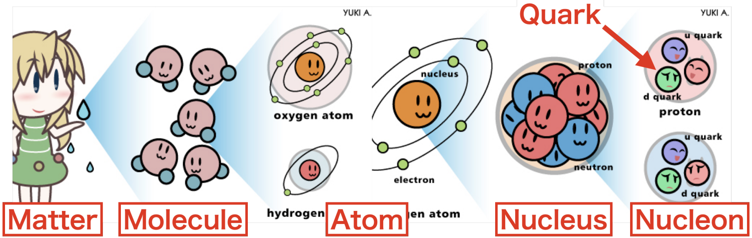
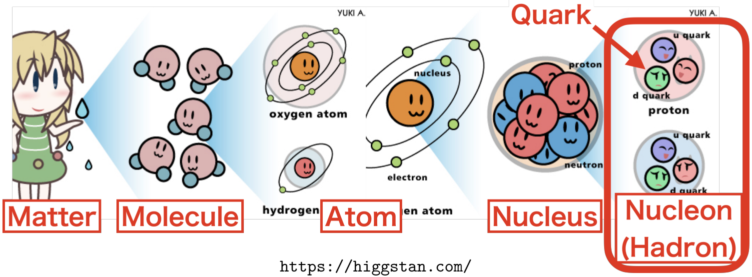
Hierarchical structure of matters



https://higgstan.com/

Hierarchical structure of matters



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- **Hadron**: Quark composite system (Nucleon is also a hadron)

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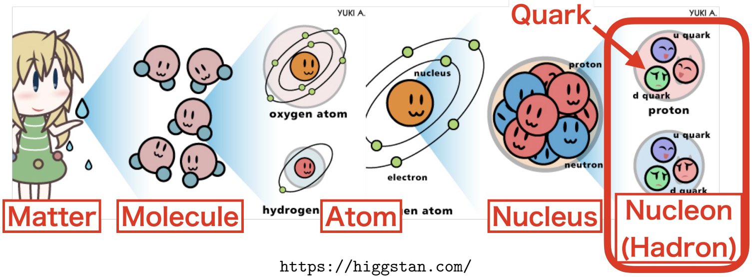

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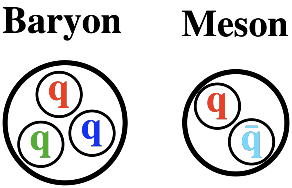
- **Hadron**: Quark composite system (Nucleon is also a hadron)
  - Ordinary hadrons:

    Baryons as qqq $(p, n, \Lambda, \Lambda_c, \Lambda_b, \ldots)$

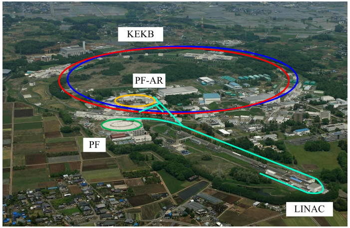
    Mesons as $q\bar{q}$ $(\pi, \rho, K, D, B, \ldots)$
  - Many hadrons have been explained by **qqq, $q\bar{q}$** !



Observations of exotic hadrons

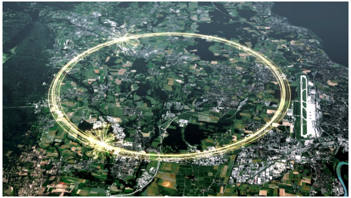
- Experimental studies of hadrons in accelerator facilities

KEK (e^+e^-) @Tsukuba



Japanese accelerator!

LHC (pp,PbPb,...), CERN @Geneve



Large Hadron Collider

Observations of **exotic hadrons**

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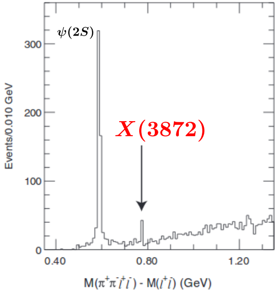
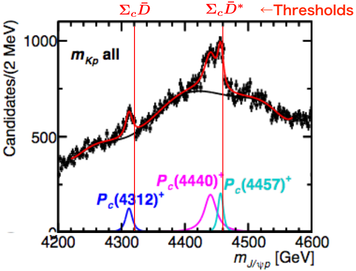
KEK (e^+e^-) @Tsukuba LHC (pp,PbPb,...), CERN @Geneve



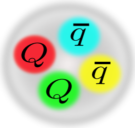


$X(3872)$, 2003 P_c pentaquarks, 2019

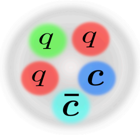
- Their masses, decays, quantum numbers, etc. cannot be explained by the ordinary hadron picture (qqq, $q\bar{q}$) $\Rightarrow$ **Exotic hadrons!?**
- Recently, New exotic hadrons have been reported Every Year in the charm quark sector ($m_c \sim 1.3$ GeV $\gg m_u \sim 0.002$ GeV)

Candidates of Exotic structures?

Compact multiquarks



Tetraquark

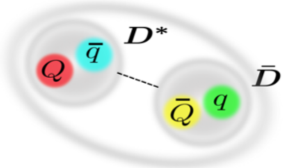


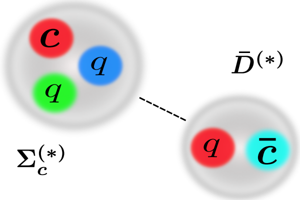
Pentaquark

- Exotics as multiquark states

Hadronic molecules

Near thresholds?





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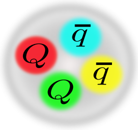

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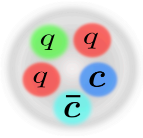


Pentaquark

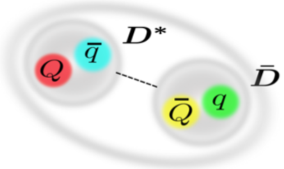
- Exotics as multiquark states

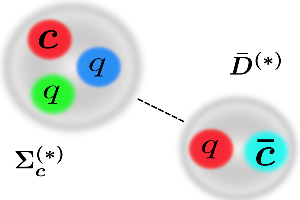
Q. Do they exist?

What is their internal structure?

Hadronic molecules

Near thresholds?

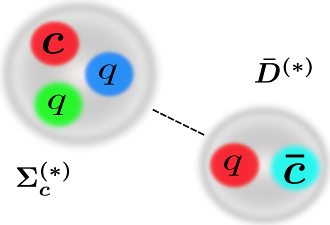




Hadronic molecules?

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

→ expected **near the thresholds**



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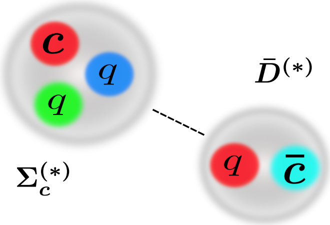
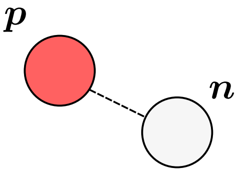


Analogous to Deuteron



$B = 2.2$ MeV

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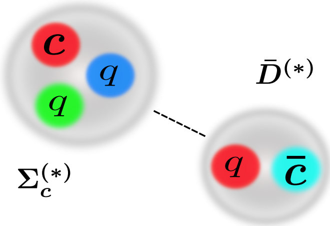
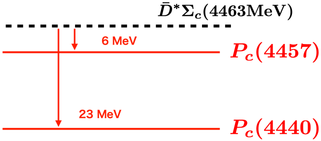


$P_c = \bar{D}^{(*)}\Sigma_c^{(*)}$ **molecules?**



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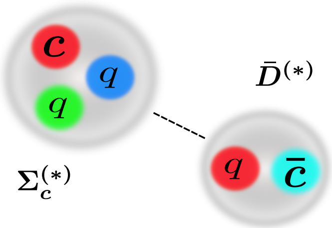

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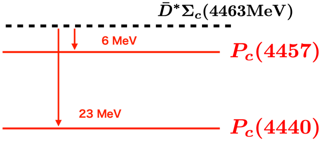
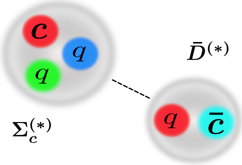


- Exotic hadrons near thresholds
  - $D\bar{D}^*$: $X(3872)$, $Z_c(3900)$,..., DD^*: T_{cc}
  - $B\bar{B}^*$: Z_b, $Z_b{}'$
  - $\bar{D}^{(*)}\Sigma_c^{(*)}$: P_c F. K. Guo, *et. al.*, Rev.Mod.Phys.**90**(2018)015004,Y. Y., *et. al.*, J.Phys.G**47**(2020)053001,...

Questions in the study of hadronic molecules

Q. Are exotic hadrons near thresholds explained as hadronic molecules?



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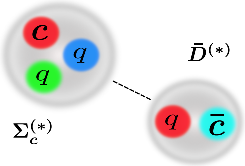

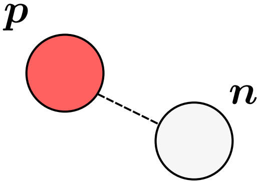

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How are such composite states constructed?

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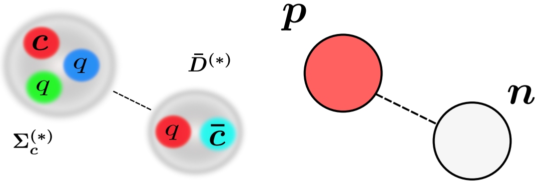

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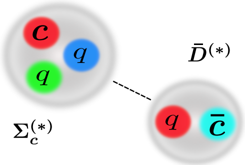

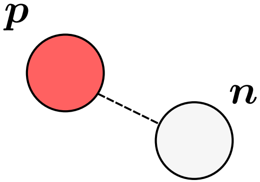

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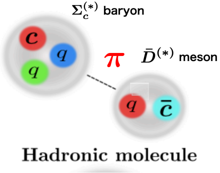

- Long-range int.: π exchange
- Short-range int.: ρ, ω, σ exchanges? Quark exchanges?

$\Rightarrow$ Do we *really* understand the nuclear force?

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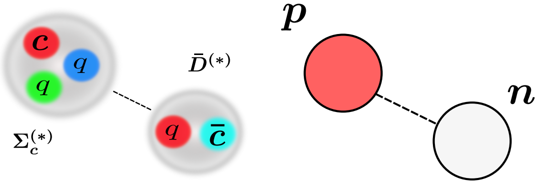

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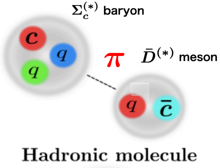

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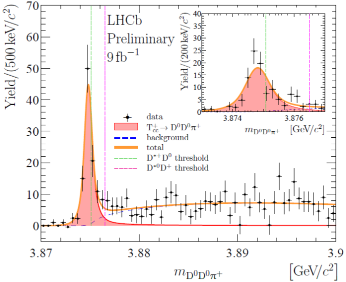
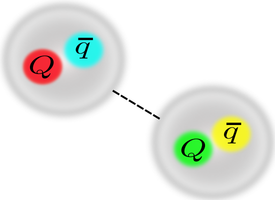
- Hadronic molecules provides an opportunity to reexamine nuclear physics

Doubly charmed tetraquark T_{cc}

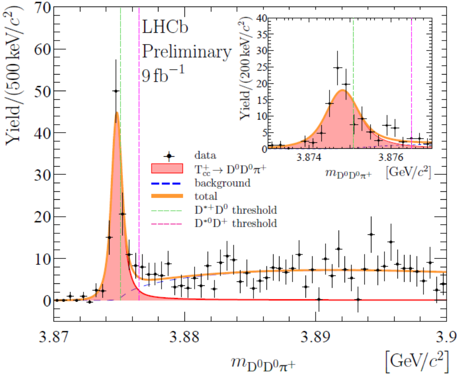




LHCb, Nature Phys. **18** (2022) 751-754, Nature Commun. **13** (2022) 3351

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

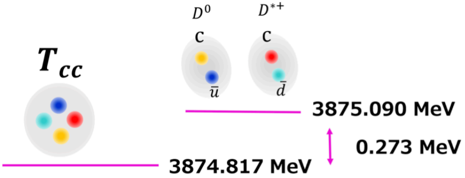


- The Breit–Wigner parameterization

$\Delta M_{BW} = -273 \pm 61 \pm 5^{+11}_{-14}$ 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, $\Gamma_{pole} = 48 \pm 2^{+0}_{-14}$

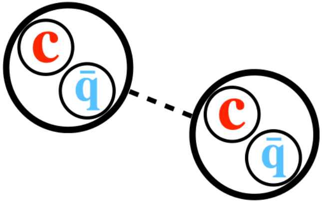


- Found **just below the DD^* threshold** $\to$ DD^* molecule?

Why T_{cc}?

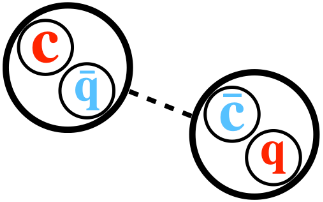
- First **doubly-charmed** tetraquark $\leftrightarrow$ There have been many reports of **Hidden-charmed** tetraquark XYZ

Doubly-charmed T_{cc}



At least, $cc\bar{q}\bar{q}$

Hidden-charmed XYZ



Coupled to $c\bar{c}$

(See Poster of K. Miyake)

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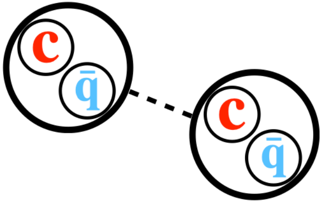
$\Rightarrow$ Minimal quark content is $cc\bar{u}\bar{d}$ (4 quarks) $\rightarrow$ **Genuine exotic state**

Doubly-charmed T_{cc}



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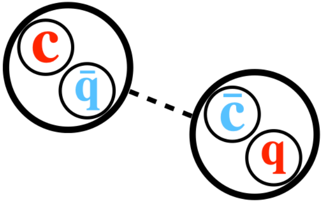

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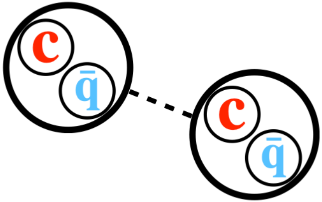
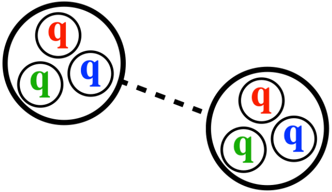
- Simple interactions rather than the nuclear force
  π can be exchanged between light quarks $q, \bar{q}$

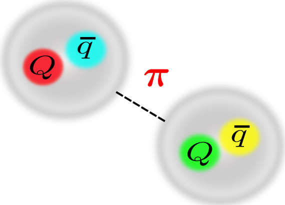
Doubly-charmed T_{cc} | **Two nucleons NN**



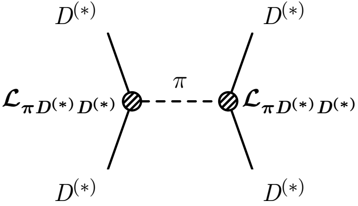


Only $\bar{q}q$ join the int. | Six q's join the int.

Meson exchange potentials (π, ρ, ω, σ)



$\Longrightarrow$



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

(Contact term is removed)

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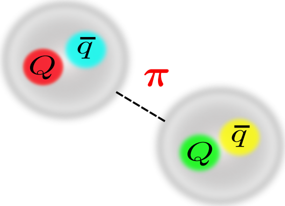

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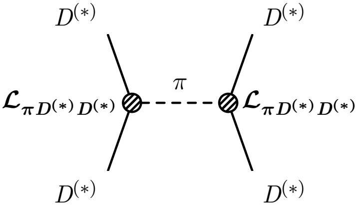

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- Form factor with Cutoff Λ

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

Table Coupling constants

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 $B_{T_{cc}}$

- Binding energy is obtained by solving the Schrödinger equations.

Numerical results: $D^{(*)}D^{(*)}$ bound state T. Asanuma, *et. al.*, PRD 110, 074030 (2024)

- Cutoff Λ is determined to reproduce the T_{cc} binding energy

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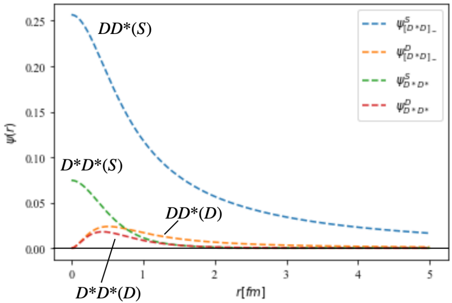
- $\pi\rho\omega\sigma$ exchanges $\to$ We find $\mathbf{\Lambda = 1182}$ **MeV (Bound)**

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 π exchange attraction is not enough to generate a bound state $\Rightarrow$ The short-range interaction is also important.
- ***DD*(S)* is dominant.** Loosely bound state.

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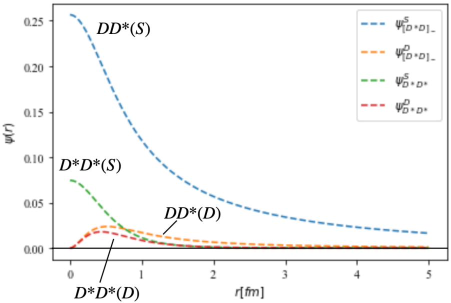

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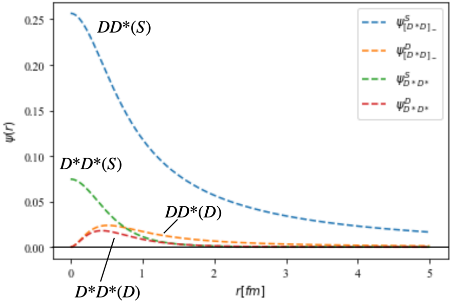
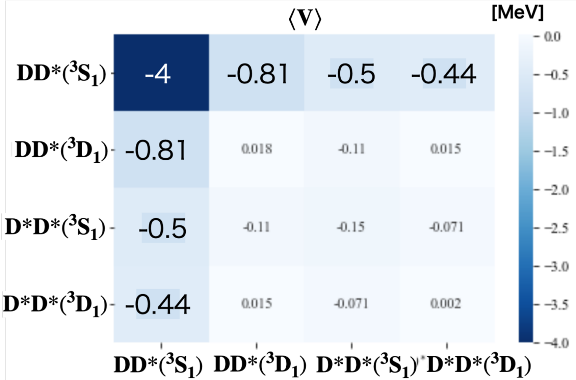
$\sqrt{\langle r^2 \rangle}$	**6.42** fm

Wave functions

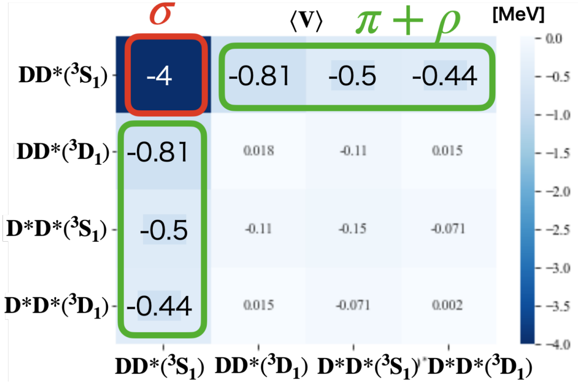


- The π exchange attraction is not enough to generate a bound state $\Rightarrow$ The short-range interaction is also important.
- ***DD*(S)* is dominant.** Loosely bound state.

Energy expectation values

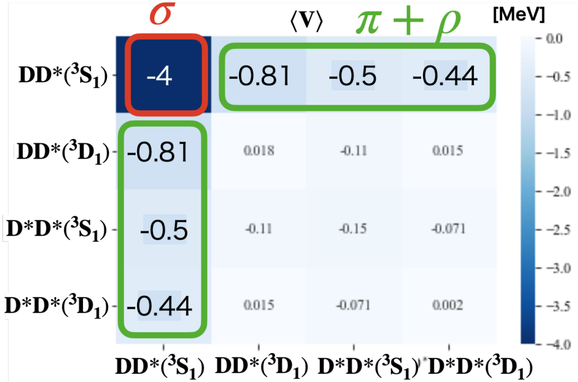


Energy expectation values



- **Strong attraction from the σ exchange** in the $DD^*(^3S_1)$ diagonal component
- Attraction of the off-diagonal components from $\pi + \rho$

Energy expectation values

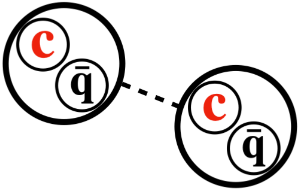


- **Strong attraction from the σ exchange** in the $DD^*({}^3S_1)$ diagonal component
- Attraction of the off-diagonal components from $\pi + \rho$
- **Attraction from the isospin independent int (σ ex.)** is also important in the nuclear force.

From T_{cc} to other exotic states

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

T_{cc} as DD^* molecule

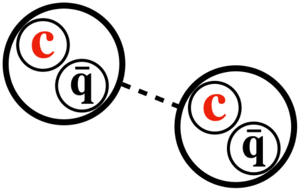


From T_{cc} to other exotic states

- 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

$\boldsymbol{T_{cc}}$ as $\boldsymbol{DD^*}$ molecule



From T_{cc} to other exotic states

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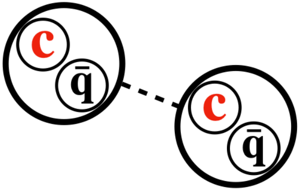
  - Heavy quark flavor symmetry $\boldsymbol{c} \to \boldsymbol{b}$: T_{bb} as BB^*

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

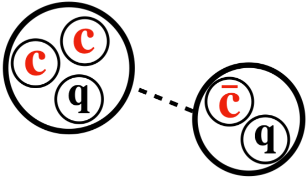
    $\Rightarrow$ multicharm states

$\Rightarrow$ Observations of such partners in future experiments would confirm T_{cc} as a hadronic moelcule

$\boldsymbol{T_{cc}}$ as $\boldsymbol{DD^*}$ molecule



$\boldsymbol{\bar{D}\Xi_{cc}}$ molecule



From $D^{(*)}D^{(*)}$ to $B^{(*)}B^{(*)}$ (T_{bb}) M. Sakai, Y.Y, PRD 109, 054016 (2024)

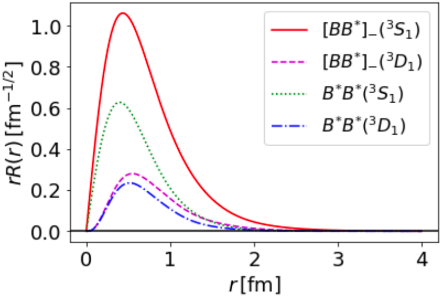
- The bottom counterpart of T_{cc} which has not been reported so far
- Employing the same parameters used in T_{cc}

From $D^{(*)}D^{(*)}$ to $B^{(*)}B^{(*)}$ (T_{bb}) M. Sakai, Y.Y, PRD 109, 054016 (2024)

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

B	**46.0 MeV (Bound)**
$P_{BB^*}(^3S_1)$	70.7%
$P_{BB^*}(^3D_1)$	4.71%
$P_{B^*B^*}(^3S_1)$	21.6%
$P_{B^*B^*}(^3D_1)$	3.00%
$\sqrt{\langle r^2 \rangle}$	0.62 fm

Wave functions



- Deeply bound state
- The large mass of $B^{(*)}$ suppresses the kinetic term.
  $BB^* - B^*B^*$ mixing is enhanced due to the small $\Delta m_B = m_{B^*} - m_B$

From $D^{(*)}D^{(*)}$ to $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ T. Asanuma, Y.Y, M. Harada, PRD 110, 074030 (2024)

- Employing the same parameters used in T_{cc}

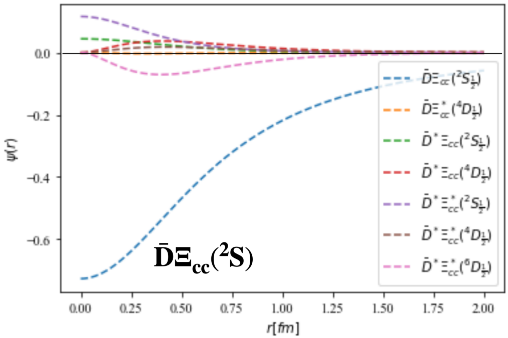
From $D^{(*)}D^{(*)}$ to $\bar{D}^{(*)}\Xi_{cc}^{(*)}$

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

- Employing the same parameters used in T_{cc}
- We obtain **the $\bar{D}\Xi_{cc}$ bound state for $I(J^P) = 0(1/2^-)$!**

Λ	1182 MeV **(Input)**
B	**7.46 MeV (Bound)**
$P_{\bar{D}\Xi_{cc}}(^2S_{1/2})$	98.3%
$P_{\bar{D}\Xi^*_{cc}}(^4D_{1/2})$	0.0012 %
$P_{\bar{D}^*\Xi_{cc}}(^2S_{1/2})$	0.076 %
$P_{\bar{D}^*\Xi_{cc}}(^4D_{1/2})$	0.30 %
$P_{\bar{D}^*\Xi^*_{cc}}(^2S_{1/2})$	0.28 %
$P_{\bar{D}^*\Xi^*_{cc}}(^4D_{1/2})$	0.074 %
$P_{\bar{D}^*\Xi^*_{cc}}(^6D_{1/2})$	0.97 %
$\sqrt{\langle r^2 \rangle}$	1.38 fm

Wave functions



- Attraction is generated in the similar way to T_{cc}: Strong σ ex., and the tensor force of π ex.
- $\bar{D}\Xi_{cc}$ would be found in the future experiment as a partner of T_{cc}

Summary

- Exotic hadrons as hadronic molecules have been discussed.

$\Rightarrow$ Understanding how such states are constructed and which interactions are important.

- 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
- Symmetries predict partner states of T_{cc}
  - We obtained T_{bb} as a bottom counterpart and $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ as a superflavor partner.
  - We hope these exotic states will be found in future experiments.

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

Thank you for your kind attention.