Heavy hadron spectroscopy: exotic hadrons as molecular states near thresholds

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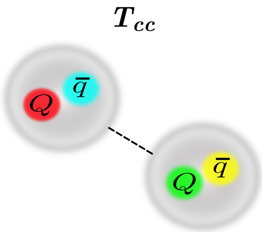
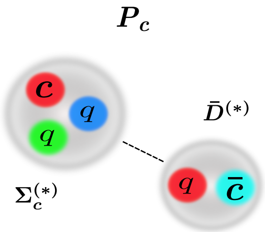
Department of Physics, Nagoya University, Japan

The 20th International Conference on Hadron Spectroscopy and Structure (HADRON 2023), Genova, Italy, 5-9 June 2023

Today's talk
Exotic hadrons near Thresholds

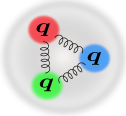




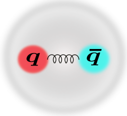
1. **Introduction**
   Exotic hadrons, Hadronic molecules
2. T_{cc} $(cc\bar{q}\bar{q})$ **tetraquark**
3. P_c **and** P_{cs} $(qqqc\bar{c})$ **pentaquarks**
4. **Summary**

Hadron structure: Constituent quark model

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



Baryon(proton,nucleon,...)



Meson (ρ,$K^{(*)}$,...)

Hadron structure: Constituent quark model

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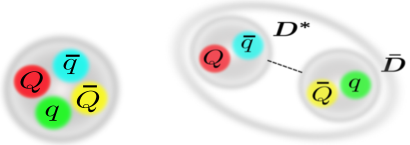
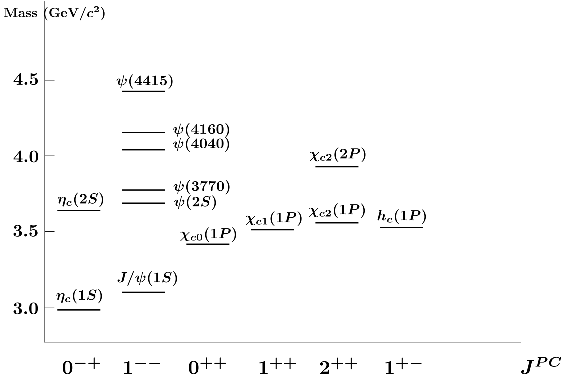
Baryon(proton,nucleon,...) Meson (ρ,$K^{(*)}$,...)

- 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

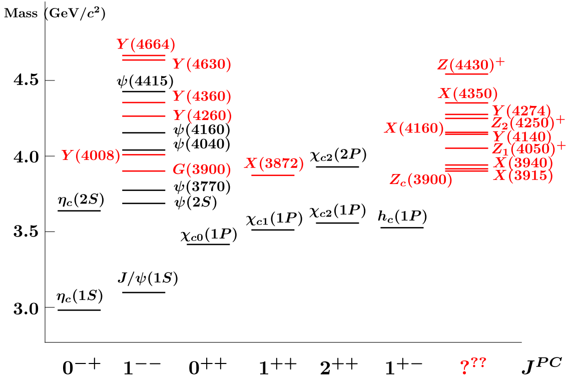
$\Downarrow$

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

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}^+, $P_{cs}(4338)$, $T_{cs}(2900)$
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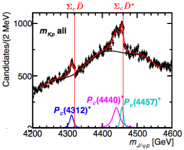
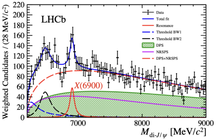
  Nature Commun. **13** (2022) 3351
- **2023:** $T^{\theta}_{\psi s1}(4000)^0$
  LHCb, arXiv:2301.04899[hep-ex]

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

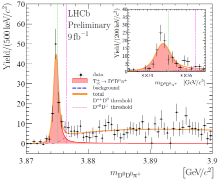
P_c



$X(6900)$



T_{cc}



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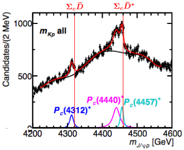

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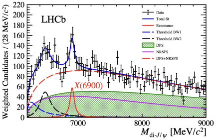

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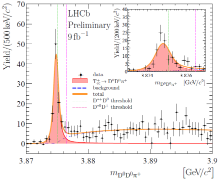
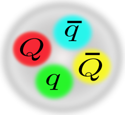
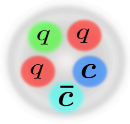


Candidates of Exotic structures?

Compact multiquarks



Tetraquark

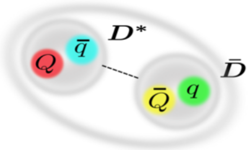


Pentaquark

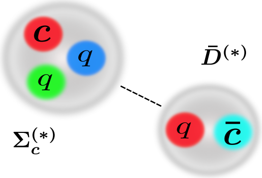
- Exotics as multiquark states

Hadronic molecules

Near thresholds?



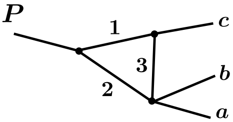
Meson-Meson



Meson-Baryon

Triangle Singularity

Near thresholds?



(w/o Resonance)

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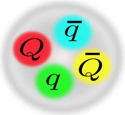

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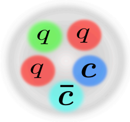
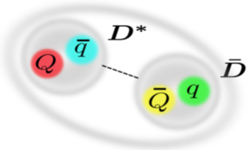


Pentaquark

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

Hadronic molecules

Near thresholds?



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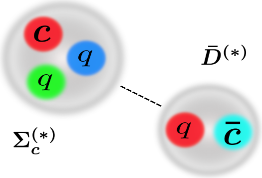

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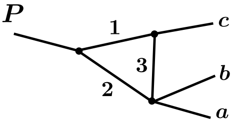

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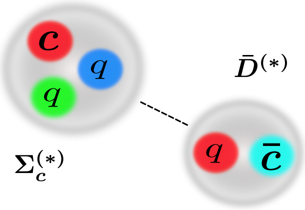
Hadronic molecules?

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

→ expected **near the thresholds**



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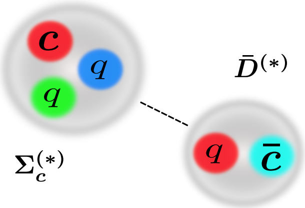
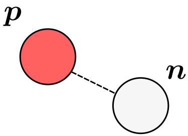


Analogous to Deuteron



$B = 2.2$ MeV

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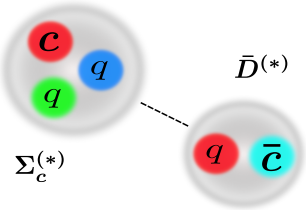
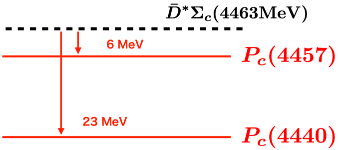


$P_c = \bar{D}^{(*)}\Sigma_c^{(*)}$ **molecules?**



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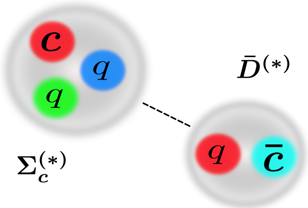

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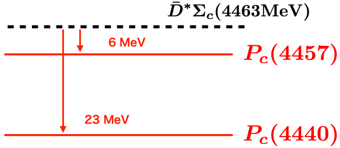

- Exotic hadrons near thresholds
  - $D\bar{D}^*$: $X(3872)$, $Z_c(3900)$,..., DD^*: T_{cc}
  - $B\bar{B}^*$: Z_b, Z_b'
  - $\bar{D}^{(*)}\Sigma_c^{(*)}$: P_c F. K. Guo, *et. al.*, Rev.Mod.Phys.**90**(2018)015004,Y. Y., *et. al.*, J.Phys.G**47**(2020)053001,...

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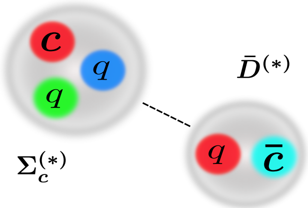
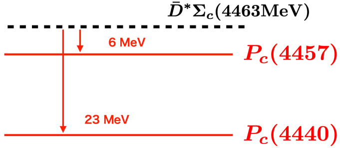
$$P_c = \bar{D}^{(*)}\Sigma_c^{(*)} \text{ molecules?}$$





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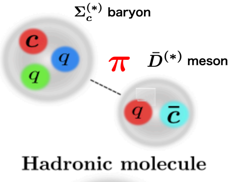
Long-range int. **One pion exchange potential**

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



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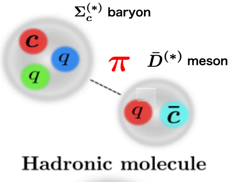
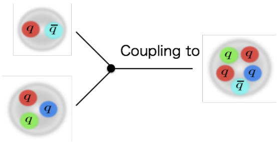
Short-range int. Many models

For T_{cc}, • ρ, ω, σ meson exchanges (analogy to Nuclear force)

For P_c, • Mixing of Hadronic molecule & Compact state

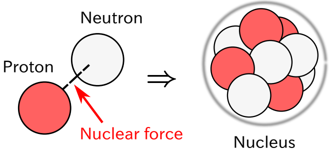


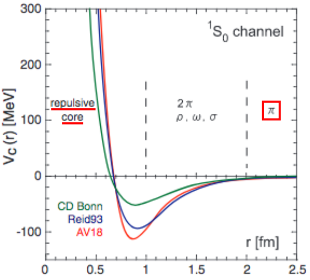


OPEP

One pion exchange potential in the nuclear force

- **Nucleon-nucleon interaction** is "known"
  = Many experimental data and Long history



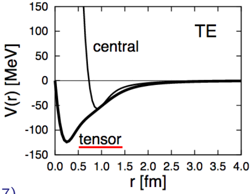


- Long-range interaction: **π exchange**
  ($m_\pi \sim$ 140 MeV, pseudoscalar(0^-)) ,
  $+\sigma$ ($\sim$ 500 MeV, midde-range, scalar(0^+)),
  $+\rho, \omega$ ($\sim$ 770 MeV, short-range, vector(1^-)) ,...

- **Tensor term** produces the strong attraction.

$$V_\pi(r) = \vec{\sigma}_1 \cdot \vec{\sigma}_2 Y(r) + \mathbf{S_{12}(r)T(r)}$$

Spin Operator — Tensor Operator → S-D mixing



⇒ inducing **coupled channel effects**

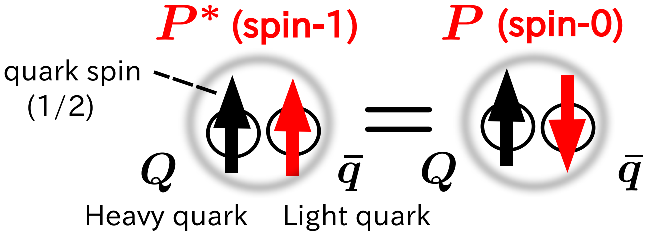
Heavy Quark Spin Symmetry and Mass degeneracy

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

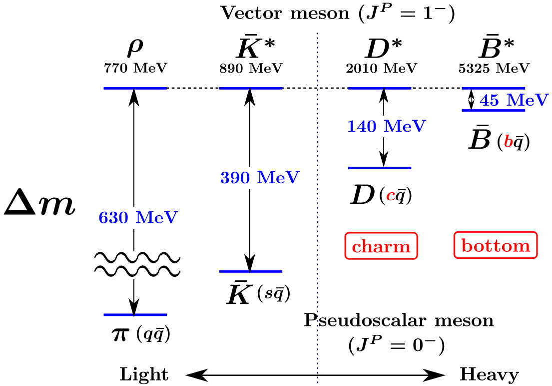
- e.g. $Q\bar{q}$ meson



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

Mass degeneracy of heavy hadrons

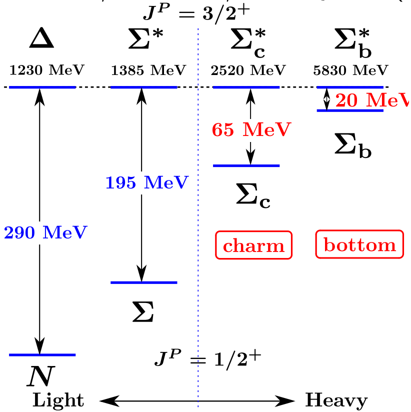
- Mass difference between vector and pseudoscalar mesons. ($Q\bar{q}$, $q = u, d$)



- Δm decreases when the quark mass increases.

Mass degeneracy of heavy hadrons

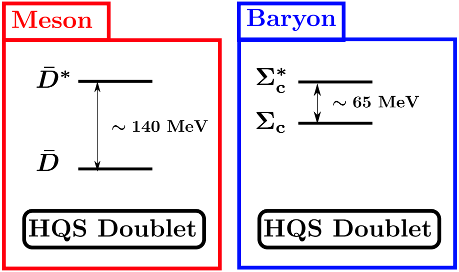
- Mass difference between $1/2^+$ and $3/2^+$ baryons. (Qqq)

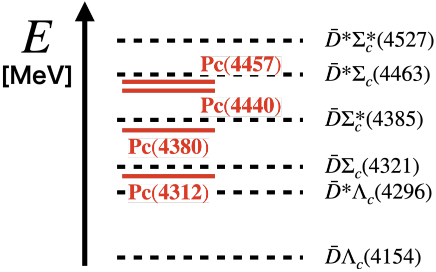


- Δm decreases when the quark mass increases.
  ⇒ **Degeneracy of Heavy hadrons!**

Heavy Quark Spin Symmetry

Small $\Delta m_{\bar{D}\bar{D}^*}$ and $\Delta m_{\Sigma_c \Sigma_c^*}$ mass splittings



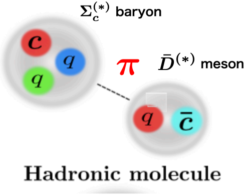


- There are **6 meson-baryon thresholds** near P_c
- Coupled by the π exchange interactions

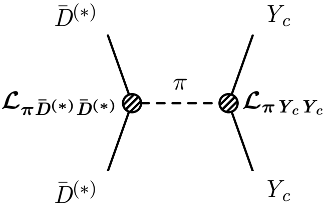
$\Leftrightarrow$ Coupled channel equations

One pion exchange potential in Exotics

- e.g. $\bar{D}^{(*)} Y_c$ interaction ($\bar{D}^{(*)} = \bar{D}, \bar{D}^*$ and $Y_c = \Lambda_c, \Sigma_c, \Sigma_c^*$)



$\Rightarrow$



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

(Contact term is removed)

$g_{\pi D} = 0.59, g_{\pi Y_c} = 1.00$ determined by the π emission decay

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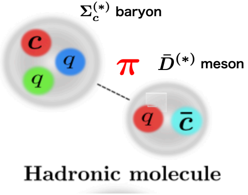

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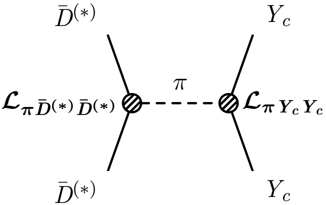

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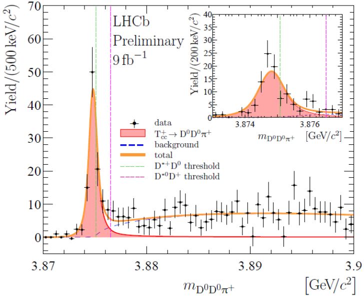
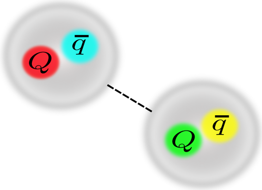
- Coupling constants: **Small $g_{\pi D}, g_{\pi Y_c} < g_{\pi N}$** (Nuclear force)
  $\rightarrow$ OPEP becomes less important...

$g_{\pi D(\bar{c}\mathbf{q})}$	$g_{\pi Y_c(c\mathbf{qq})}$	$g_{\pi N(\mathbf{qqq})}$
0.59	1.0	1.3

Doubly charmed tetraquark T_{cc}



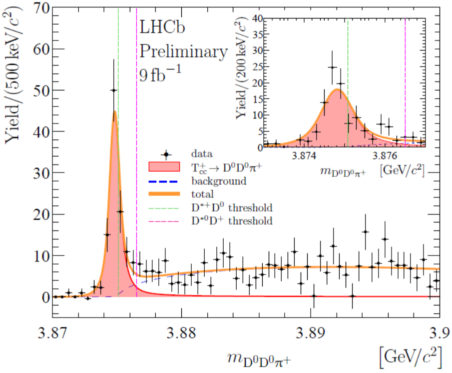


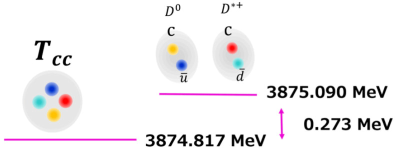
T. Asanuma, Master thesis; T. Asanuma, YY, M. Harada in preparation

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

- $T_{cc}^{+}(cc\bar{u}\bar{d})$ has been reported in LHCb! $\to$ Genuine Exotic hadron

  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: $I(J^P) = 0(1^+)$

What is the structure of T_{cc}?

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

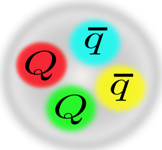
References related to T_{cc}

- 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,

  ...

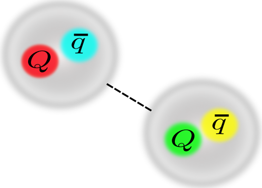


- Hadronic molecule (DD^*)

  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,

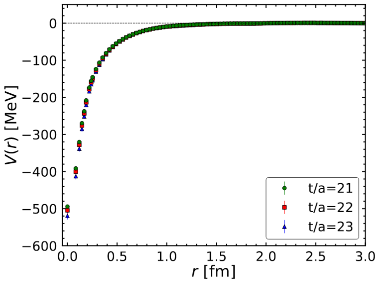
  S.Aoki, T.Aoki, PoS(LATTICE2022)049,

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

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

DD^* potential in Lattice QCD by HALQCD [2302.04505]

- Result at unphysical $m_\pi = 146$ MeV ($>$ Physical $m_\pi = 135$ MeV)



- $(2+1)$-flavor lattice simulation
- Only DD^* channel
  $\rightarrow DD^* - D^*D^*$ coupling is missing
- **Attractive** for all distance
  $\leftrightarrow$ No strong Pauli repulsion

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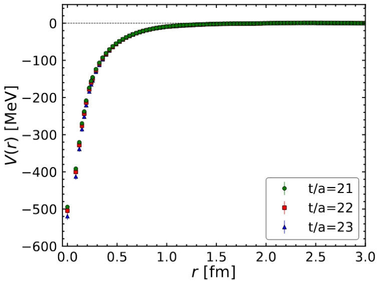

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$$V_{\text{fit}}(r; m_\pi) = \sum_{i=1,2} a_i e^{-(r/b_i)^2} + a_3(1 - e^{-(r/b_3)^2})^n \left(\frac{e^{-m_\pi r}}{r}\right)^n$$

- Best fit: $\boldsymbol{n = 2}$ $\to$ **Two π exchange** rather than One π ex ($n = 1$)

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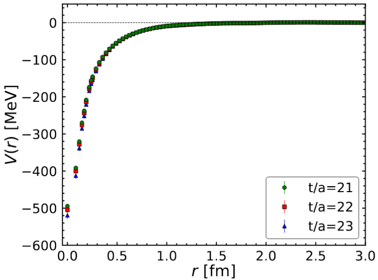

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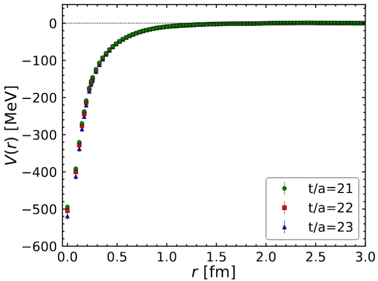

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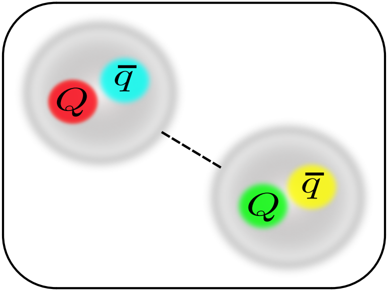
- Best fit: $\boldsymbol{n = 2}$ $\to$ **Two π exchange** rather than One π ex ($n = 1$)
- At $m_\pi = 146$ MeV, **Unbound**, while at $m_\pi \to 135$ MeV, $\boldsymbol{B = 10}$ **keV**

$D^{(*)}D^{(*)}$ molecule with the meson exchange potential

T. Asanuma, Master thesis; T. Asanuma, YY, M. Harada in preparation



- Heavy quark spin symmetry + Tensor force
  $\Rightarrow DD^*({}^3S_1, {}^3D_1), D^*D^*({}^3S_1, {}^3D_1)$ channel coupling
- Interactions: $\pi\rho\omega\sigma$ exchange potentials
  $\Rightarrow$ The cutoff parameter is determined to reproduce the LHCb data

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

T. Asanuma, Master thesis; T. Asanuma, YY, M. Harada in preparation

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

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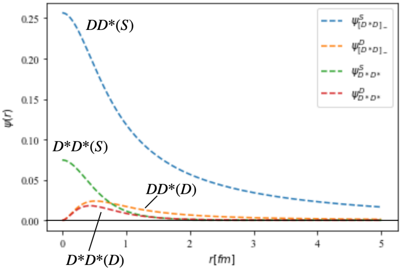
- Cutoff Λ is determined to reproduce the T_{cc} binding energy
- Only π exchange $\rightarrow$ **No bound state**
- $\pi\rho\omega\sigma$ exchanges $\rightarrow$ We find $\mathbf{\Lambda = 1182}$ **MeV (Bound)**

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.
- ***DD*(S)* is dominant.** Loosely bound state.

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T. Asanuma, Master thesis; T. Asanuma, YY, M. Harada in preparation

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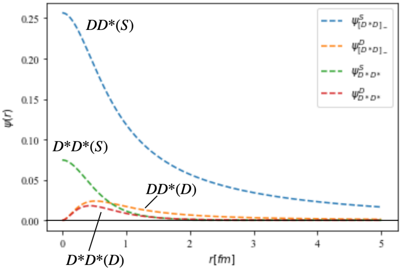

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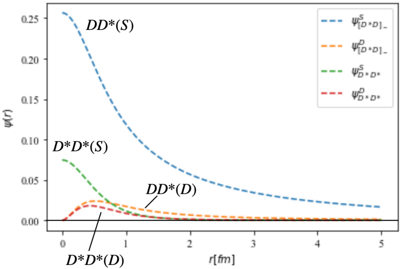

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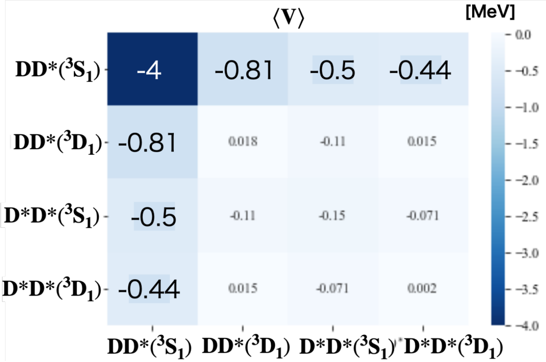
Energy expectation values

T. Asanuma, Master thesis; T. Asanuma, YY, M. Harada in preparation



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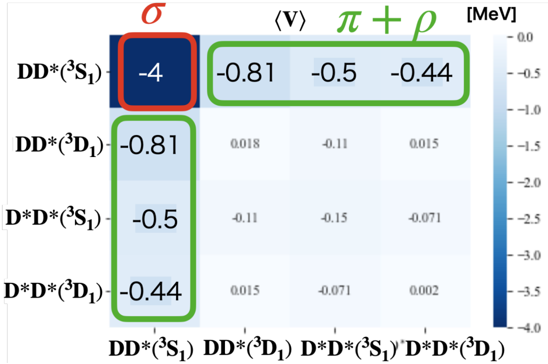
T. Asanuma, Master thesis; T. Asanuma, YY, M. Harada in preparation



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

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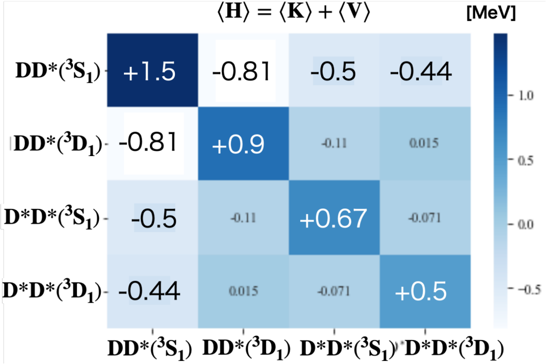

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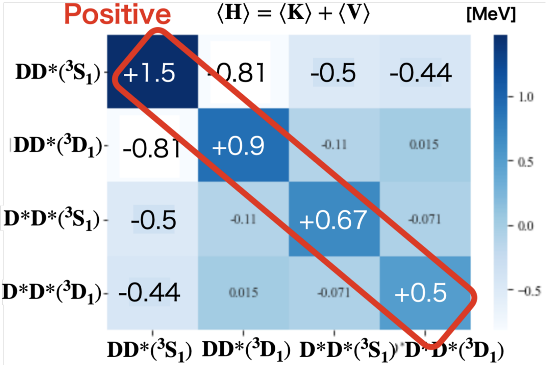
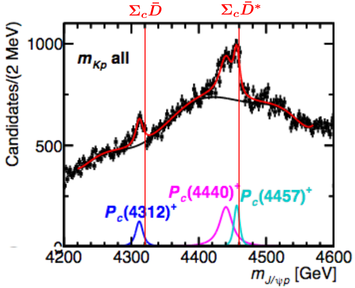
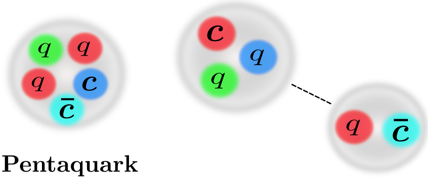


- **Strong attraction from the σ exchange** in the $DD^*(^3S_1)$ diagonal component
- Attraction of the off-diagonal components from $\pi + \rho$
- In $\langle H \rangle$, the positive diagonal components $\Rightarrow$ Importance of the off-diagonal components

P_c pentaquarks





Pentaquark (Compact)

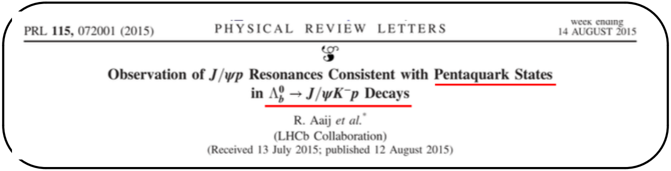
Hadronic molecule

Y.Y., H.Garcia-Tecocoatzi, A.Giachino, A.Hosaka, E.Santopinto, S.Takeuchi, M.Takizawa, PRD **101** (2020) 091502(R)

A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa, Y.Y, arXiv:2209.10413 [hep-ph]

Observation of two P_c pentaquarks in LHCb (2015)

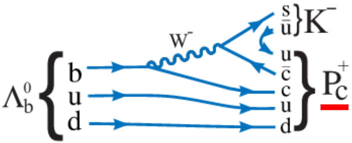
- Observation of the Hidden-charm Pentaquark ($c\bar{c}uud$) in $\Lambda_b^0 \to J/\psi K^- p$ Decay? R.Aaij, *et al.* (LHCb collaboration) PRL**115**(2015)072001


PRL **115,** 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

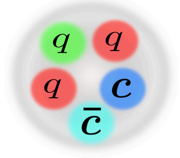
R. Aaij *et al.**
(LHCb Collaboration)
(Received 13 July 2015; published 12 August 2015)

P_c in $\Lambda_b^0 \to J/\psi p K^-$ decay



$\Rightarrow$

$c\bar{c}uud$ state ?

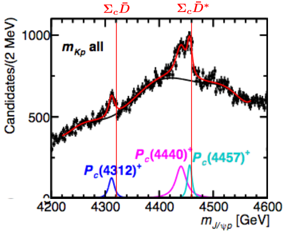


$P_c(4380)$: M =4380 MeV, Γ= 205 MeV

$P_c(4450)$: M =4449.8 MeV, Γ = 39 MeV

New LHCb analysis in 2019!

- R. Aaij, *et al.* Phys.Rev.Lett. 122 (2019) 222001



- $P_c(4450)$ in 2015 $\longrightarrow$ $P_c(4440)$ and $P_c(4457)$

  $P_c(4440)$: $(M, \Gamma) = (4440.3, 20.6)$ MeV
  $P_c(4457)$: $(M, \Gamma) = (4457.3, 6.4)$ MeV

- Observation of **New state!**

  $P_c(4312)$: $(M, \Gamma) = (4311.9, 9.8)$ MeV

- $P_c(4380)$ in 2015? "these fits can neither confirm nor contradict the existence of the $P_c(4380)^+$"

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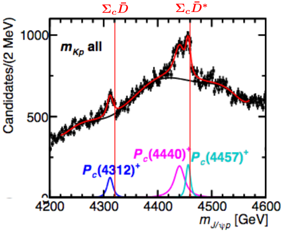

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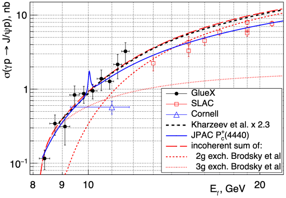
- Complementary experiments: $\gamma p \to J/\psi p$ in GlueX@J-Lab

  GlueX Collaboration, PRL**123**(2019)072001.

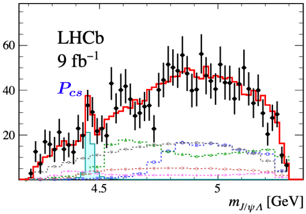
  $\to$ No triangle singularity

No evidence of $\gamma p \to P_c \to J/\psi p$ **?**



Strange partner $P_{cs}(qq\mathbf{s}c\bar{c})$ in 2020 and 2022!

- $\boldsymbol{P_{cs}(4459)}$ in 2020 Ref. R.Aaij, *et al.* (LHCb), Sci. Bull. **66** (2021) 1278-1287,



▷ One P_{cs} state ?

$M = 4458.8 \pm 2.9^{+4.7}_{-1.1}$ MeV, $\Gamma = 17.3 \pm 6.5^{+8.0}_{-5.7}$ MeV

(below **the $\Xi_c^0 \bar{D}^{*0}$ threshold**)

▷ Two-peak structure hypothesis

$M_1 = 4454.9 \pm 2.7$ MeV, $\Gamma_1 = 7.5 \pm 9.7$ MeV

$M_2 = 4467.8 \pm 3.7$ MeV, $\Gamma_2 = 5.2 \pm 5.3$ MeV

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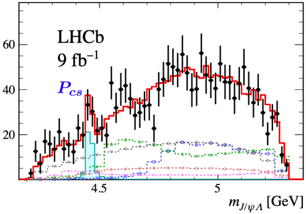

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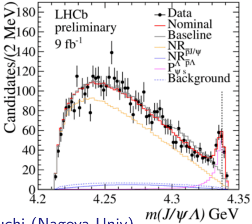
- $P_{cs}(4338)$ in 2022

https://lhcb-outreach.web.cern.ch/2022/07/05/observation-of-a-strange-pentaquark-a-doubly-charged-tetraquark-and-its-neutral-partner/



$M = 4338.2 \pm 0.7 \pm 0.4$ MeV

$\Gamma = 7.0 \pm 1.2 \pm 1.3$ MeV

(near the **$\Xi_c \bar{D}$ threshold**)

The preferred quantum numbers are $J^P = 1/2^-$.

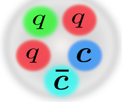
What is the structure of the pentaquarks?

Proposals of various structures!

H.X.Chen, *et al.*, Phys.Rept.**639**(2016)1, A.Esposito, *et al.*,Phys.Rept.**668**(2016)1, A.Ali,*et al.*,PPNP**97**(2017)123

- Compact pentaquark ($c\bar{c}qqq$)?

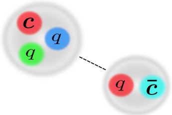
  S.G.Yuan, *et al.* (2012), L.Maiani, *et al,* (2015), S.Takeuchi, *et al,* (2017), J. Wu, *et al.* (2017), E. Hiyama, *et al.* (2018), ...



Pentaquark (Compact)

- Hadronic molecule ($\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$,...)?

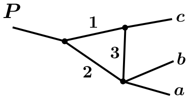
  J.-J.Wu *et al.,* (2010) (2011), C. Garcia-Recio, *et al.* (2013), R. Chen, *et al.* (2015), Y.Shimizu, *et al.* (2016-2019), C. W. Xiao, *et al.* (2019), M.-Z. Liu, *et al.* (2019), M. L. Du, *et al.* (2019), ...



Hadronic molecule

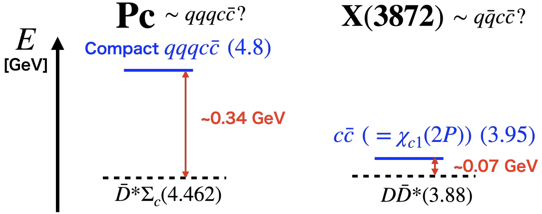
- Triangle singularity?
  (Non-resonant explanation)

  F.K.Guo, *et al.* (2015), X.H.Liu, *et al.* (2016), S.X.Nakamura PRD103, L111503 (2021), ...



Mixture of the hadronic molecule and compact state

- **Hadronic molecule + Compact state** (Massive)



S.Takeuchi, M.Takizawa, PLB**764**(2017)254

S.Takeuchi, et. al, PTEP**2013**,093D01, PTEP**2014**,123D01

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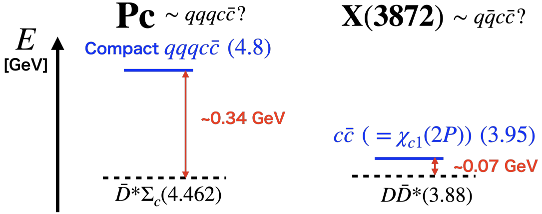

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⇒ **Level repulsion generating an attraction** in the hadronic molecules

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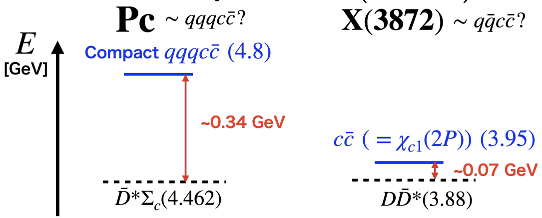

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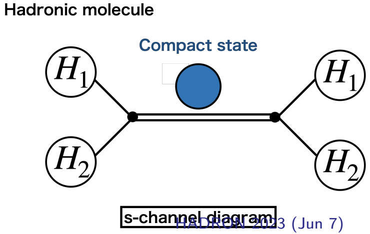
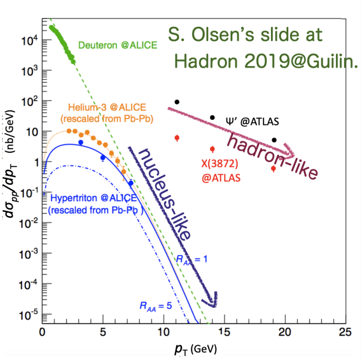
⇒ **Level repulsion generating an attraction** in the hadronic molecules

- **Hadronic molecule** coupling to **Compact state** ⇒ Effective hadron interaction



Evidence of the compact component in Exotics?

$\boldsymbol{X(3872)}$ near the $D\bar{D}^*$ threshold $\Rightarrow$ $D\bar{D}^*$ molecule?



- Production cross sections: Molecules (Nuclei) vs Compact state ($\psi(2S)$)
- **$(d\sigma/dp)_{X(3872)}$ is similar $(d\sigma/dp)_{\psi(2S)}$**
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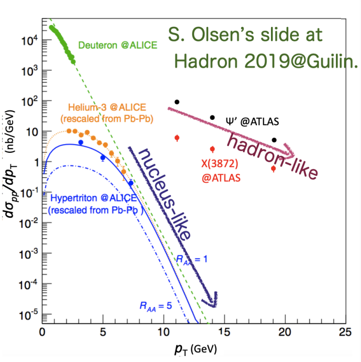

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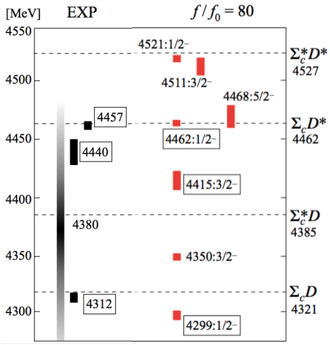
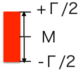
  Or **Mixture of $D\bar{D}^*$ molecular and compact states?**

For New P_c states by LHCb in 2019, $V_\pi + V_{5q}$

Y.Y., H.Garcia-Tecocoatzi, A.Giachino, A.Hosaka, E.Santopinto, S.Takeuchi, M.Takizawa, PRD **101** (2020) 091502(R)



($f_0 = 6$ MeV)



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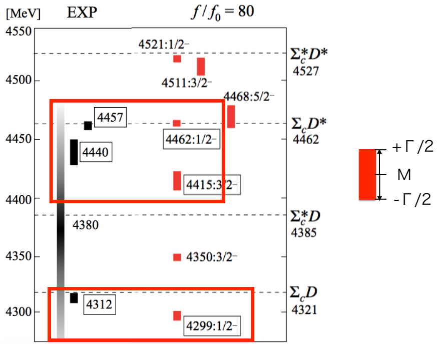

- **Agreement with $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$**

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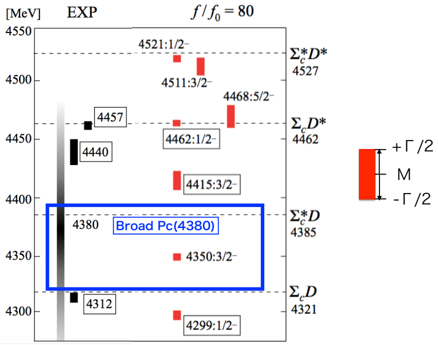

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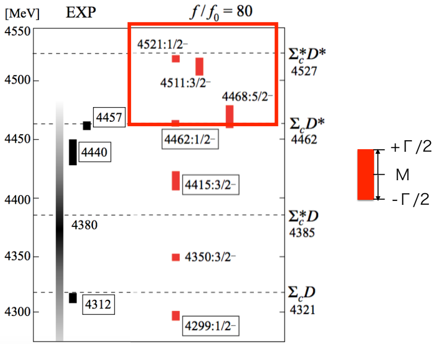

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- Predictions: $(1/2^-, 3/2^-, 5/2^-)$ states below $\bar{D}^* \Sigma_c^*$

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Y.Y., H.Garcia-Tecocoatzi, .**01** (2020) 091502(R)

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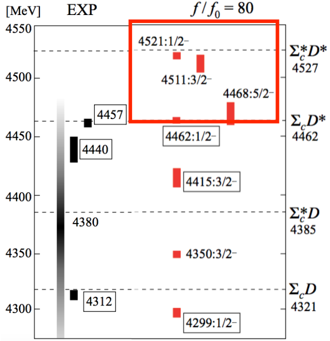
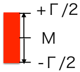
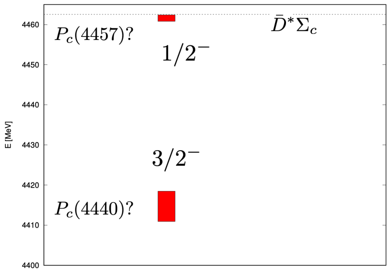




P_c	LHCb (M, Γ)	J^P	Ours $5q$+OPEP	C. W. Xiao, *et al.*, PRD**100**(2019)014021 Local hidden gauge	M. Z. Liu, *et al.*, PRL**122**(2019)242002 Cont (B)	M. L. Du, *et al.*, 2102.07159 Cont+OPEP (IIB)
$P_c(4312)$	(4312,9.8)	$1/2^-$	(4299,9.4)	(4306,15)	4306	(4313,6)
$P_c(4380)$	(4380,205)	$3/2^-$	(4350,5)	(4374,14)	4371	(4376,12)
$P_c(4440)$	(4440,21)	$3/2^-$	(4415,15)	(4452,3.0)	4440 (input)	(4441,8)
$P_c(4457)$	(4457,6.4)	$1/2^-$	(4462,3.2)	(4453,23)	4457 (input)	(4461,10)
P_c	—	$1/2^-$	(4521,2.8)	(4520,22)	4523	(4525,18)
P_c	—	$3/2^-$	(4511,14)	(4519,14)	4517	(4520,24)
P_c	—	$5/2^-$	(4468,18)	(4519,0)	4500	(4500,16)

Role of Interactions in P_c



- Our J^P assignment
  $P_c(4440)$: $3/2^-$
  $P_c(4457)$: $1/2^-$

$\boldsymbol{E(1/2^-) > E(3/2^-)}$

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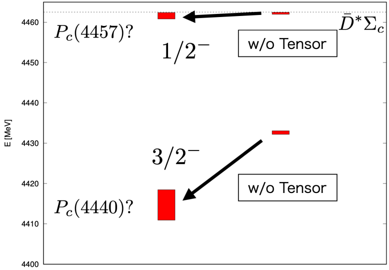

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- with Tensor (original) vs without Tensor for V^π

$\Rightarrow$ Mass and Width are **reduced!**

$1/2^-$: $(E, \Gamma) = (4462, 1.6)$ [MeV] $\Rightarrow (4462, \mathbf{0.48})$ [MeV]

$3/2^-$: $(E, \Gamma) = (4415, 7.5)$ [MeV] $\Rightarrow \mathbf{(4433, 0.88)}$ [MeV]

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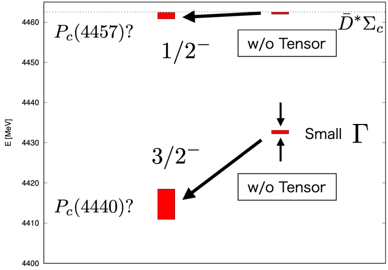

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▷ V^{5q}: Major role to determine **Energy Levels**

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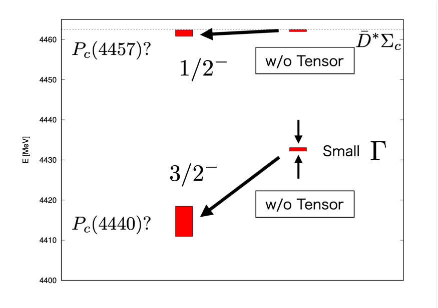

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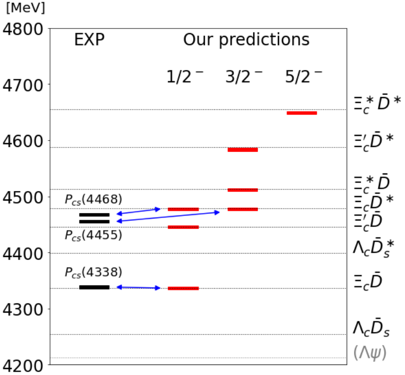
▷ V^{5q}: Major role to determine **Energy Levels**

▷ V^π: Major role to enhance **Decay Width** (Channel-coupling effect)

Numerical results for $J^P = 1/2^-, 3/2^-, 5/2^-$

Comparing EXP with the predicted masses



A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa, Y.Y, arXiv:2209.10413 [hep-ph]

- **Two $\Xi_c \bar{D}^*$ bound states**
  $\leftrightarrow P_{cs}(4468), P_{cs}(4455)$?

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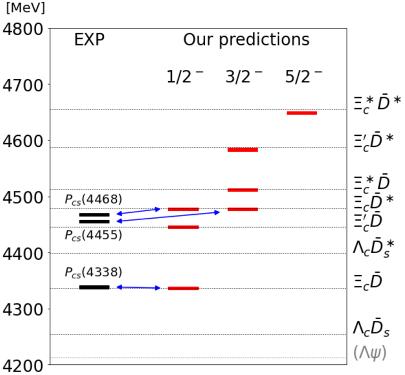

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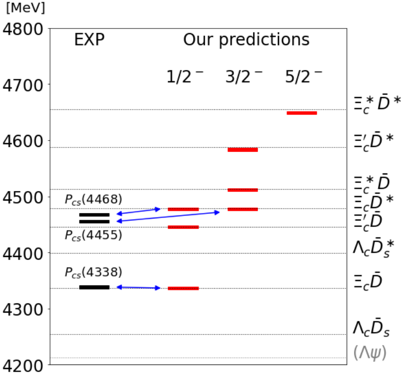

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Rich structure near the thresholds

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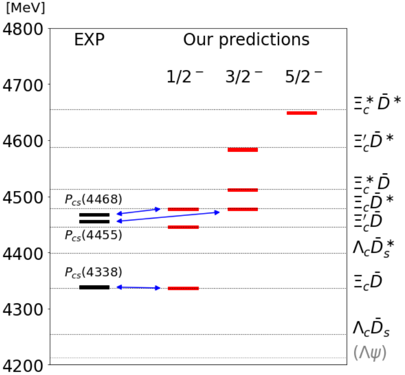
Comparing EXP with the predicted masses



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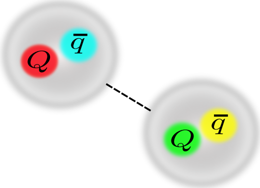
Rich structure near the thresholds

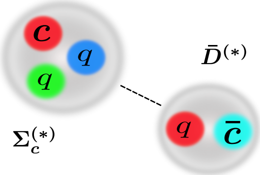
- The short-range interaction plays the important role to **generate the attraction** $\rightarrow$ Without the short-range int, no bound state is found.
- π exchange dominates to determine Γ (Channel-coupling effect)

Summary

T_{cc}



P_c

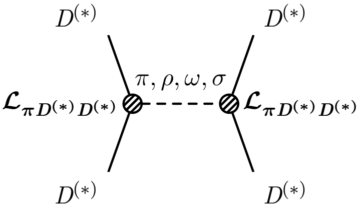


- Many exotic hadrons have been reported in the experiments $\Rightarrow$ Hadronic molecules are expected near thresholds
- OPEP is the important ingredient in the nuclear force, while less important in the heavy hadron interaction.
- **Short-range interaction** is a key ingredient to produce attractions in the heavy hadronic molecules.
  $\rightarrow$ Attractions generate **Rich structure** near thresholds.

Thank you for your kind attention.

Back up

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)

Channel couplings

- Numerical calculations for $J^P = 1/2^-, 3/2^-, 5/2^-$

Channels	$\bar{D}Y_c(^{2S+1}L)$ S:Spin, L: Orbital angular momentum, $\vec{J}=\vec{L}+\vec{S}$, P: Parity	
$1/2^-$	$\bar{D}\Lambda_c(^2S)$, $\bar{D}^*\Lambda_c(^2S,^4D)$, $\bar{D}\Sigma_c(^2S)$, $\bar{D}\Sigma_c^*(^4D)$, $\bar{D}^*\Sigma_c(^2S,^4D)$, $\bar{D}^*\Sigma_c^*(^2S,^4D,^6D)$	(10 ch)
$3/2^-$	$\bar{D}\Lambda_c(^2D)$, $\bar{D}^*\Lambda_c(^4S,^2D,^4D)$, $\bar{D}\Sigma_c(^2D)$, $\bar{D}\Sigma_c^*(^4S,^4D)$, $\bar{D}^*\Sigma_c(^4S,^2D,^4D)$, $\bar{D}^*\Sigma_c^*(^4S,^2D,^4D,^6D,^6G)$	(15 ch)
$5/2^-$	$\bar{D}\Lambda_c(^2D)$, $\bar{D}^*\Lambda_c(^2D,^4D,^4G)$, $\bar{D}\Sigma_c(^2D)$, $\bar{D}\Sigma_c^*(^4D,^4G)$, $\bar{D}^*\Sigma_c(^2D,^4D,^4G)$, $\bar{D}^*\Sigma_c^*(^6S,^2D,^4D,^6D,^4G,^6G)$	(16 ch)

- $S-D$ mixing etc induced by the Tensor force (S_{12})
- Solving the coupled-channel Schrödinger equations

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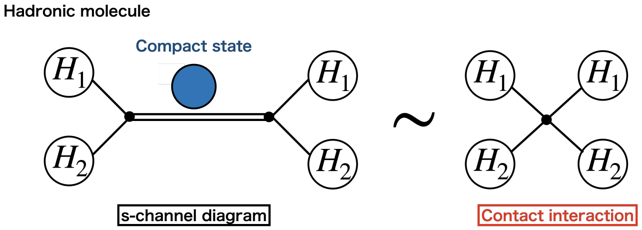

Free Parameters

Strength f and Gaussian para. α (→ may be fixed in the future)
(f is determined by the P_c data. $\alpha = 1$ fm^{-2} is fixed.)

Relative strength S_i $(i, j = \bar{D}^{(*)}\Lambda_c, \bar{D}^{(*)}\Sigma_c^{(*)})$

Spectroscopic factors ⇒ determined by **the spin structure** of $5q$

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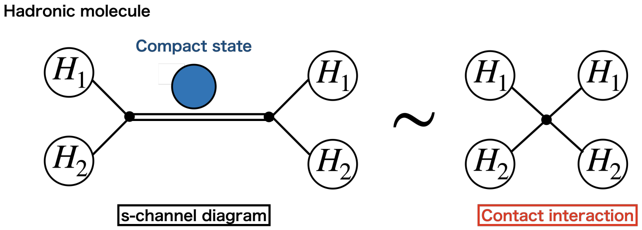

$\Rightarrow -fS_iS_je^{-\alpha r^2}$

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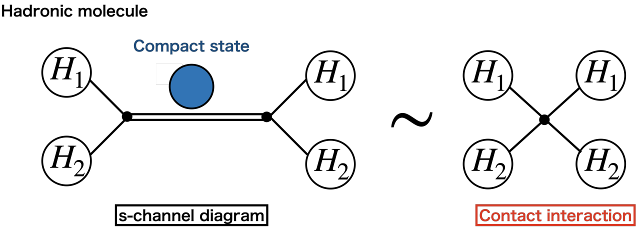

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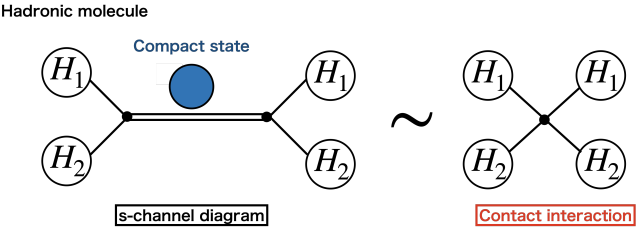

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