

Hidden-charm pentaquarks as a hadronic molecule coupled to compact multiquarks

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in collaboration with

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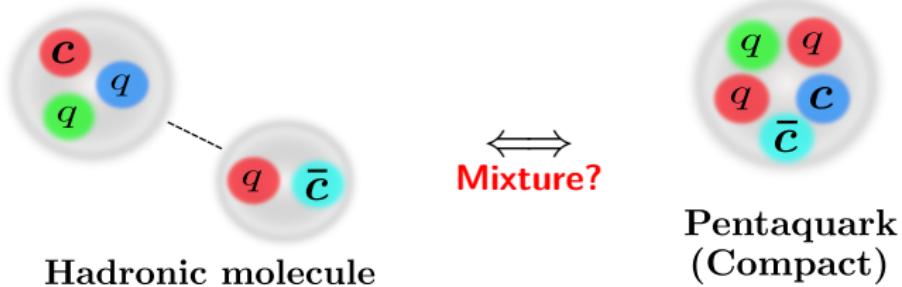
Atsushi Hosaka (RCNP, Osaka Univ.), Elena Santopinto (INFN Genoa),

Sachiko Takeuchi (Japan Coll. Social Work), Makoto Takizawa (Showa Pharmaceutical Univ.),

The 13th International Workshop on the Physics of Excited Nucleons, Santa
Margherita Ligure, Genova, Italy
17 Oct - 21 Oct , 2022

Today's talk

Exotic hadrons as hadronic molecule + compact state



1. Introduction

Exotic hadron, Our mixture model

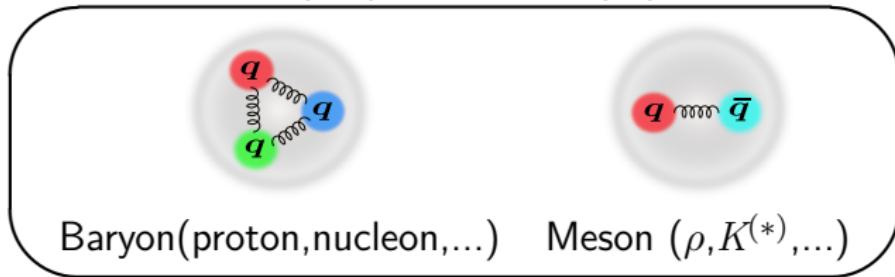
2. Numerical results: P_c ($qqqc\bar{c}$) pentaquark

3. Numerical results: P_{cs} ($qqsc\bar{c}$) pentaquark

4. Summary

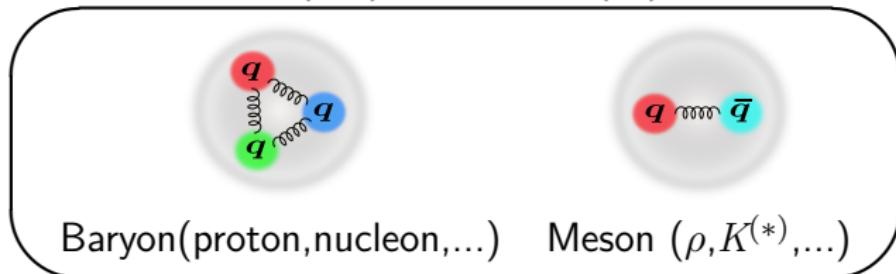
Hadron structure: Constituent quark model

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

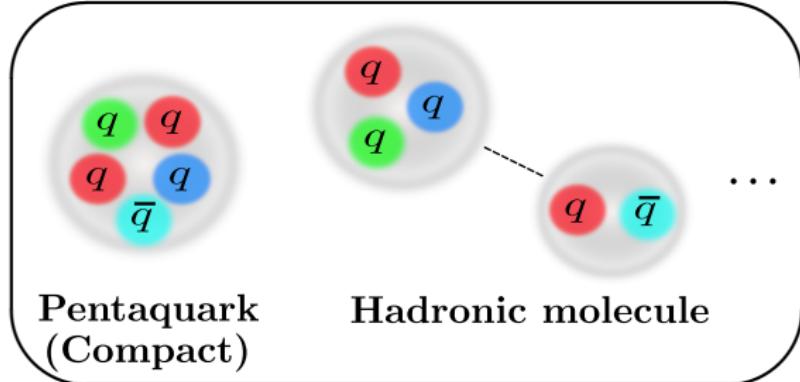


Hadron structure: Constituent quark model

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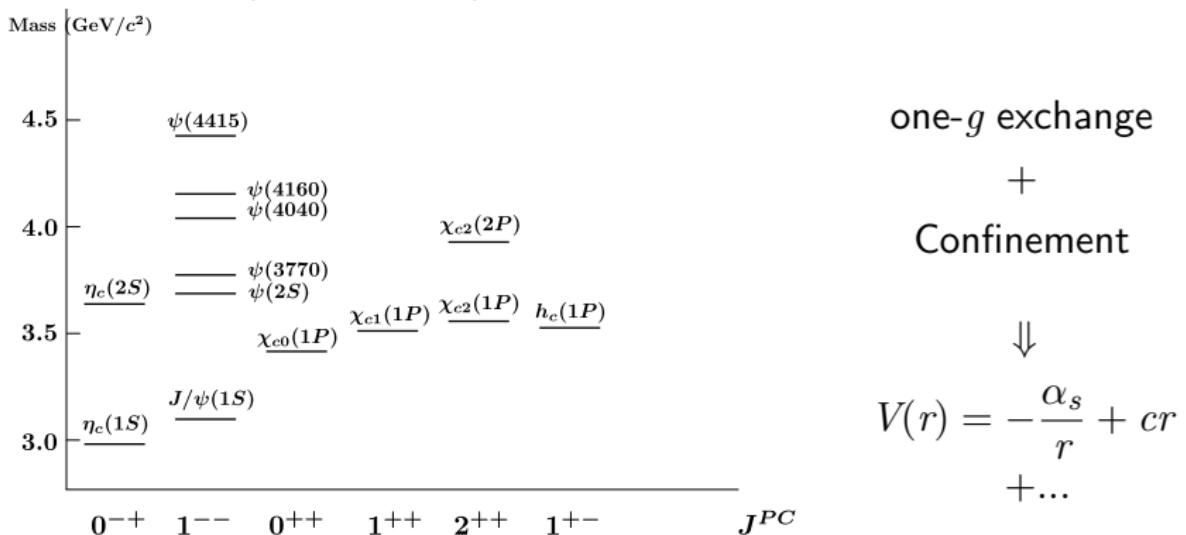


- ▶ Exotic Hadrons ($\neq qqq, q\bar{q}$): **Multiquark? Multihadron?**



Observations of **exotic hadrons** ($\neq q\bar{q}$, qqq) containing $c\bar{c}$

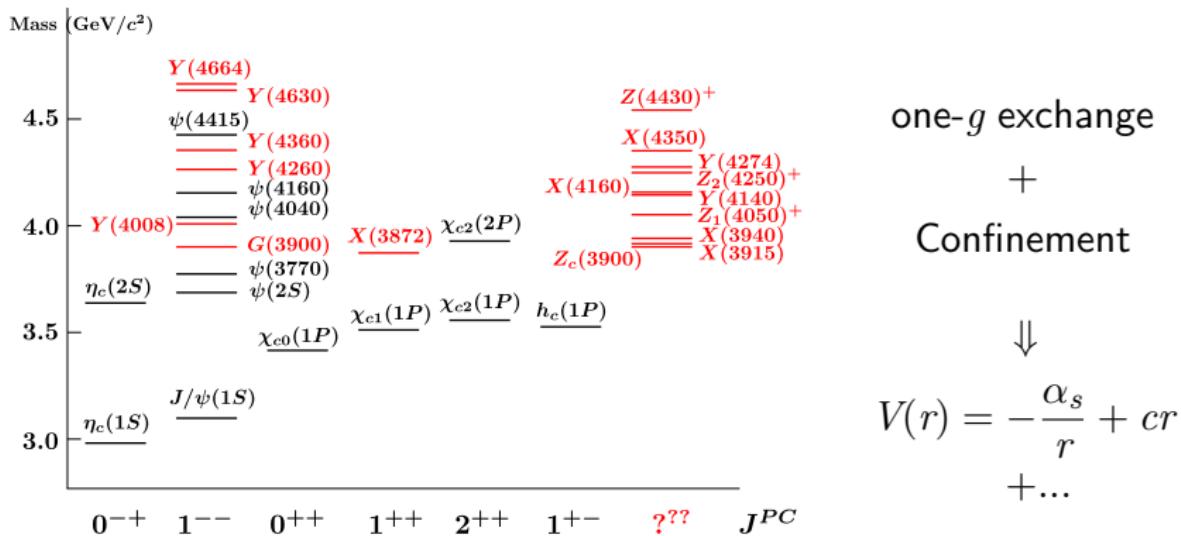
- e.g. $c\bar{c}$ mesons (Charmonium) sector



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

Observations of **exotic hadrons** ($\neq q\bar{q}, qqq$) containing $c\bar{c}$

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



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

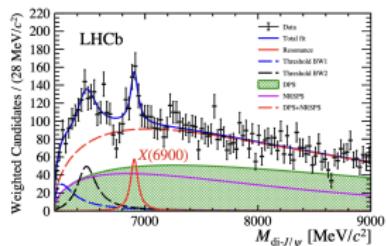
- Exotics $\neq c\bar{c}$ have been observed in the Experiments (BaBar, Belle, BESIII, LHCb,...) since the discovery of **$X(3872)$ in 2003!**

Q. What is their exotic structure? How do they form such structure?

Recent reports of Exotic hadrons!

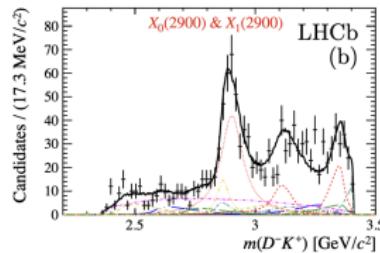
▷ $X(6900)$ ($cc\bar{c}\bar{c}?$)

LHCb, Science Bulletin 65 (2020) 1983



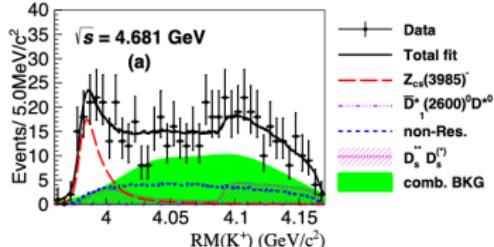
▷ $X_{0,1}(2900)$ ($\bar{c}sud?$)

LHCb, PRL125, 242001 (2020), PRD102, 112003 (2020)



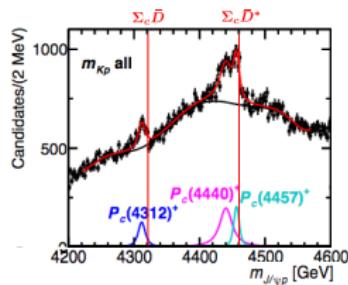
▷ Z_{cs} ($c\bar{c}s\bar{u}?$)

BESIII PRL126, 102001 (2021)



▷ P_c ($uudc\bar{c}?$)

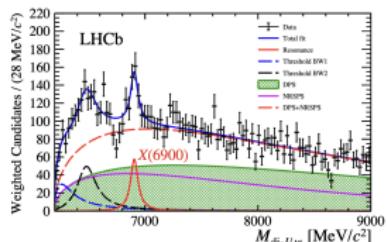
LHCb PRL115(2015)072001, PRL122(2019)222001



Recent reports of Exotic hadrons!

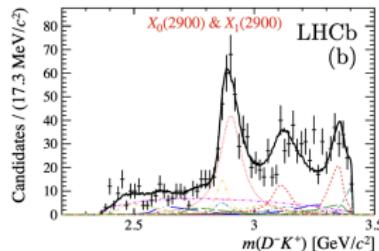
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LHCb, Science Bulletin 65 (2020) 1983



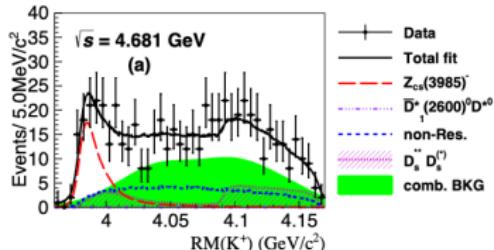
▷ $X_{0,1}(2900)$ ($\bar{c}sud?$)

LHCb, PRL125, 242001 (2020), PRD102, 112003 (2020)



▷ Z_{cs} ($c\bar{c}s\bar{u}$?)

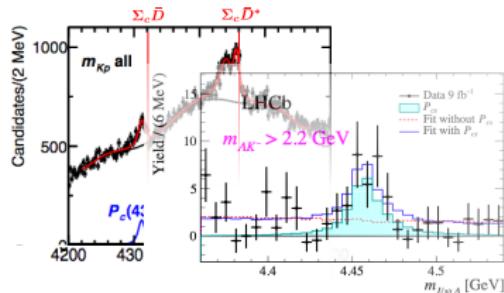
BESIII PRL126, 102001 (2021)



▷ P_c ($uudcc\bar{c}$?), P_{cs} ($udsc\bar{c}$?)

LHCb PRL115(2015)072001, PRL122(2019)222001

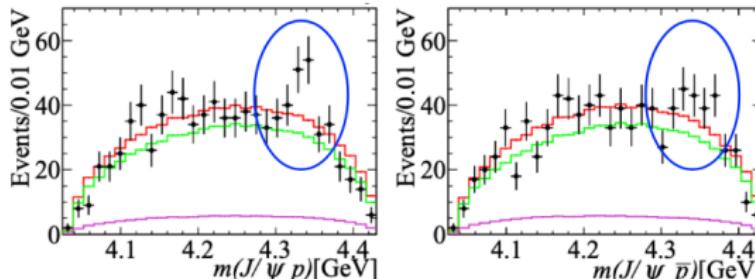
Sci.Bull.66(2021)1278



Very recent reports of Exotic hadrons!

- New $P_c(4337)^+$ state in $B_s^0 \rightarrow J/\psi p\bar{p}$

LHCb, PRL **128**(2022)062001



from Liupan An's talk (HADRON2021)

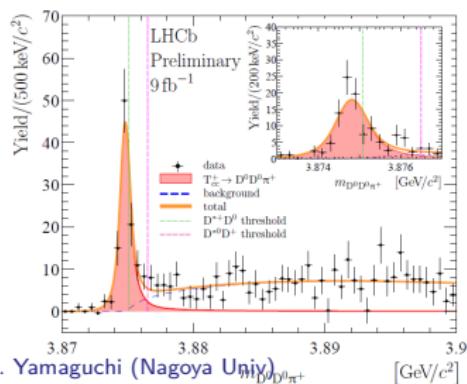
$$M = 4337^{+7+2}_{-4-2} \text{ MeV}$$

$$\Gamma = 29^{+26+14}_{-12-14} \text{ MeV}$$

The best J^P hypothesis $\Rightarrow 1/2^+$

- Doubly charmed tetraquark $T_{cc}^+(cc\bar{u}\bar{d})$

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



Y. Yamaguchi (Nagoya Univ.)

$$\delta m_{BW} = -273 \pm 61 \text{ keV below } D^*+D^0$$

$$\Gamma_{BW} = 410 \pm 165 \text{ keV}$$

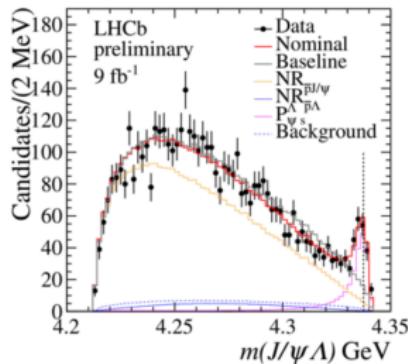
$$\text{Isoscaler } J^P = 1^+$$

NSTAR2022 (19 Oct 2022)

Very very recent reports of Exotic hadrons with **Strangeness!**

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

- New $P_{cs}(4338)^0$ ($P_{\psi s}^\Lambda$) state ($udsc\bar{c}$) in $B^- \rightarrow J/\psi \Lambda p$ (**LHCb**)

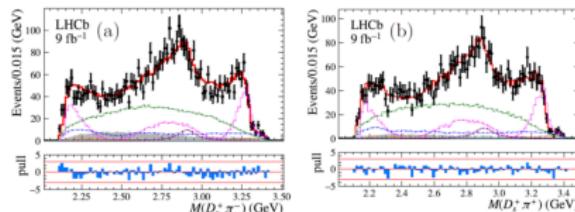


$$M = 4338.2 \pm 0.7 \pm 0.4 \text{ MeV}$$

$$\Gamma = 7.0 \pm 1.2 \pm 1.3 \text{ MeV}$$

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

- New tetraquarks $T_{cs}(2900)^{++}$ and $T_{cs}(2900)^0$ ($c\bar{s}q\bar{q}$) in $B \rightarrow D D_s \pi$ (**LHCb**)



$$M = 2.908 \pm 0.011 \pm 0.02 \text{ GeV}$$

$$\Gamma = 0.136 \pm 0.023 \pm 0.011 \text{ GeV}$$

The quantum numbers are $J^P = 0^+$.

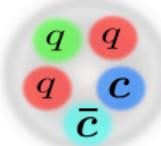
Candidates of Exotic structures?

Compact multiquarks



Tetraquark

$Q\bar{Q}g$ Hybrid

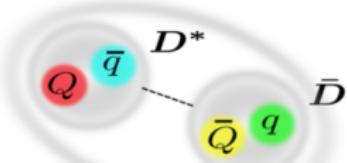


Pentaquark

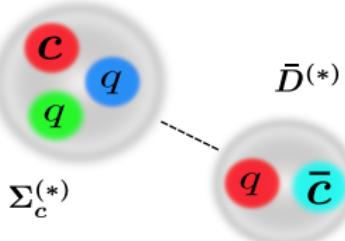


Hadronic molecules

Near thresholds?



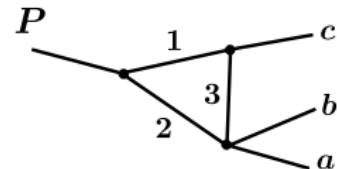
Meson-Meson



Meson-Baryon

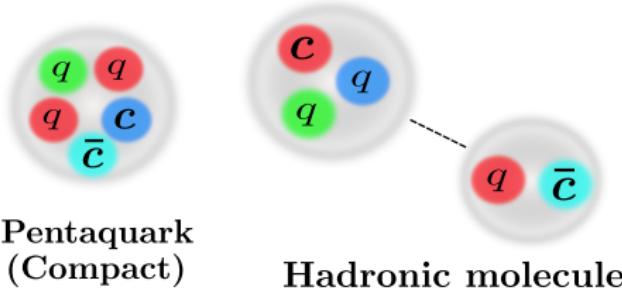
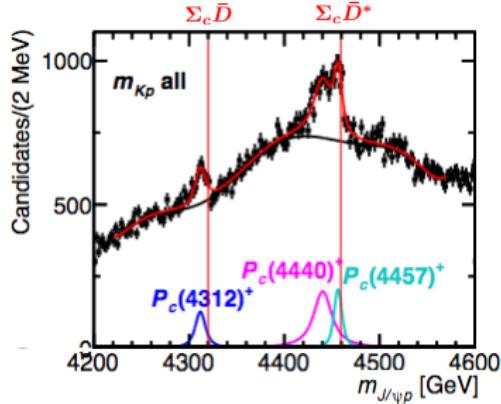
Triangle Singularity

Near thresholds?



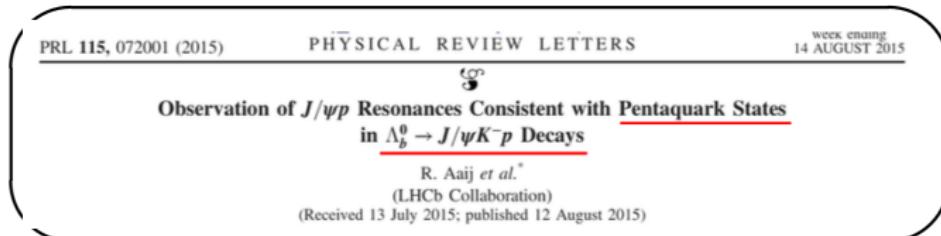
(w/o Resonance)

P_c pentaquarks



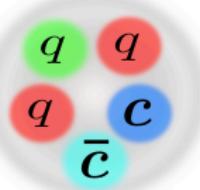
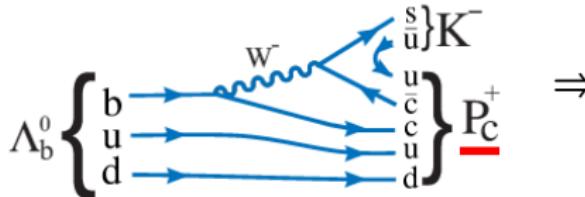
Observation of two P_c pentaquarks in LHCb (2015)

- Observation of the Hidden-charm Pentaquark ($c\bar{c}uud$)
in $\Lambda_b^0 \rightarrow J/\psi K^- p$ Decay? R.Aaij, et al. (LHCb collaboration) PRL115(2015)072001



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

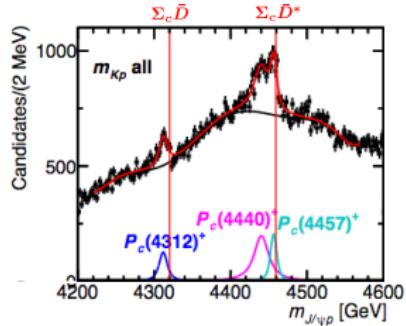
$c\bar{c}uud$ state ?



$$P_c(4380): \quad M = 4380 \text{ MeV} \quad P_c(4450): \quad M = 4449.8 \text{ MeV}$$
$$\Gamma = 205 \text{ MeV} \quad \Gamma = 39 \text{ MeV}$$

New LHCb analysis in 2019!

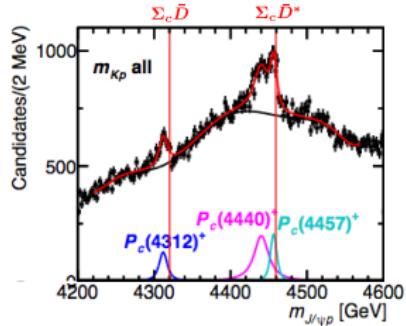
- R. Aaij, et al. Phys.Rev.Lett. 122 (2019) 222001



- $P_c(4450)$ 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 $P_c(4380)^+$ ”

New LHCb analysis in 2019!

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



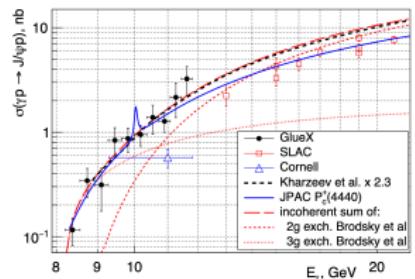
- $P_c(4450)$ in 2015 $\rightarrow P_c(4440)$ and $P_c(4457)$
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- $P_c(4312)$: $(M, \Gamma) = (4311.9, 9.8)$ MeV
- $P_c(4380)$ in 2015? “these fits can neither confirm nor contradict the existence of the $P_c(4380)^+$ ”

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

GlueX Collaboration, PRL 123(2019)072001.

→ No triangle singularity

No evidence of $\gamma p \rightarrow P_c \rightarrow J/\psi p$



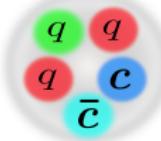
What is the structure of the pentaquarks?

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 ($c\bar{c}qqq$)?

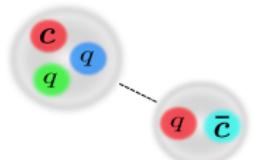
S.G.Yuan, et al. (2012), L.Maiani, et al. (2015), S.Takeuchi, et al, (2017),
J. Wu, et al. (2017), E. Hiyama, et al. (2018), ...



Pentaquark
(Compact)

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

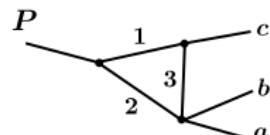
J.-J.Wu et al., (2010) (2011), C. Garcia-Recio, et al. (2013),
R. Chen, et al. (2015), Y.Shimizu, et al. (2016-2019),
C. W. Xiao, et al. (2019), M.-Z. Liu, et al. (2019), M. L. Du, et al. (2019),
...



Hadronic molecule

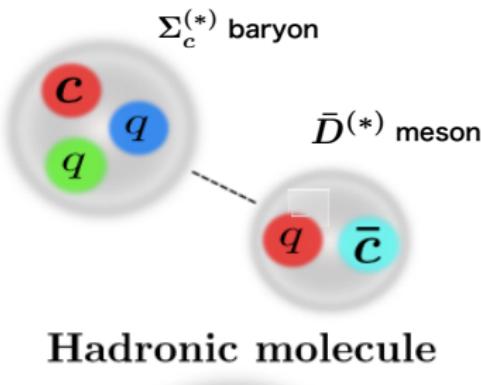
► Triangle singularity? (Non-resonant explanation)

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



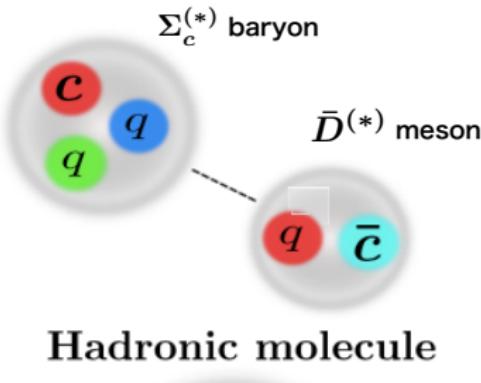
Hadronic molecules?

- ▶ Exotics as Hadronic molecule \Rightarrow Hadron (quasi) bound state
- expected **near the thresholds**

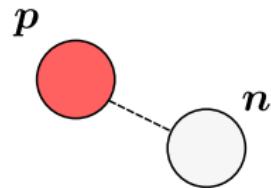


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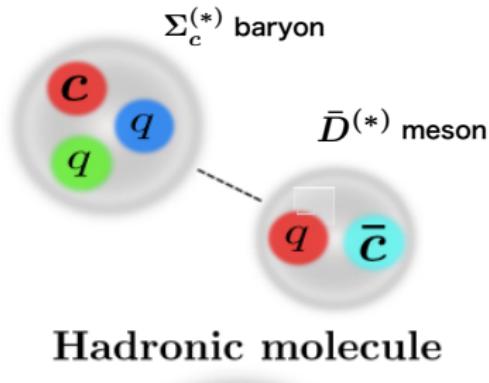
Analogous to Deuteron



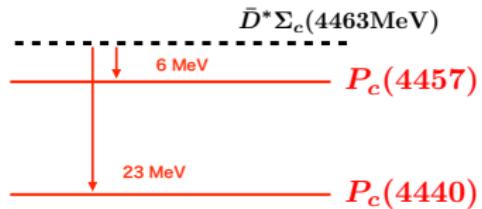
$B = 2.2 \text{ MeV}$

Hadronic molecules?

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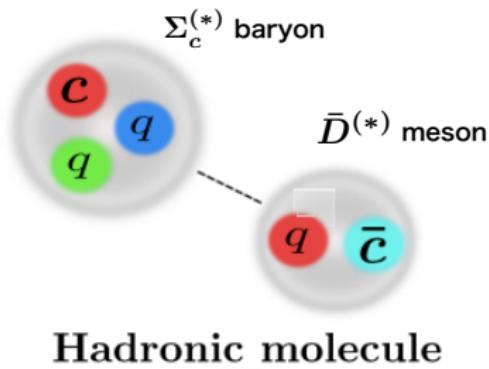


$P_c = \bar{D}^{(*)}\Sigma_c^{(*)}$ molecules?

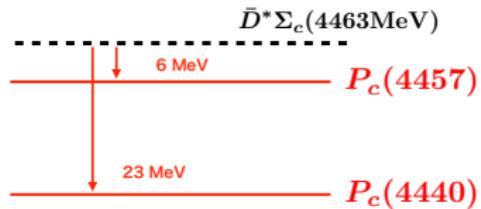


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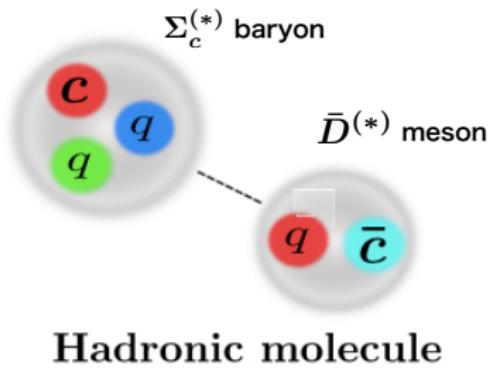


- ▶ Exotic hadrons near thresholds

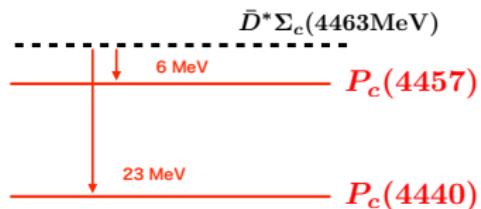
- ▶ $D\bar{D}^*$: $X(3872)$, $Z_c(3900)$, ..., DD^* : T_{cc}
- ▶ $B\bar{B}^*$: Z_b , Z_b'
- ▶ $\bar{D}^{(*)}\Sigma_c^{(*)}$: P_c F. K. Guo, et. al., Rev.Mod.Phys. **90**(2018)015004, Y. Y., et. al., J.Phys.G **47**(2020)053001, ...

Hadronic molecules?

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



- ▶ Exotic hadrons near thresholds

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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?

Hadron interactions

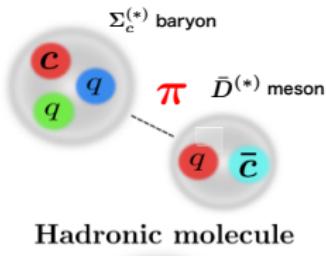
Problem

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How can we describe hadron interactions?

Hint 1 One pion exchange potential (Long-range int.)

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



OPEP

Hadron interactions

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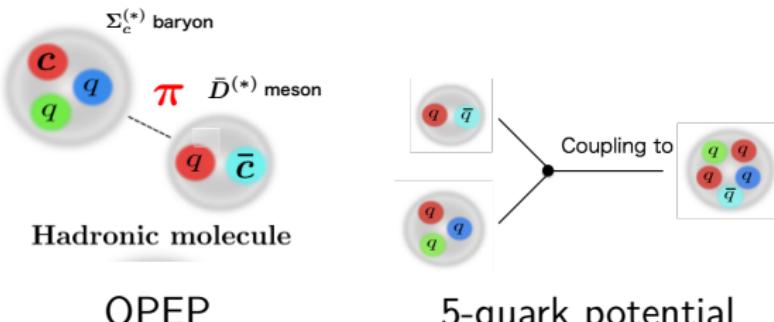
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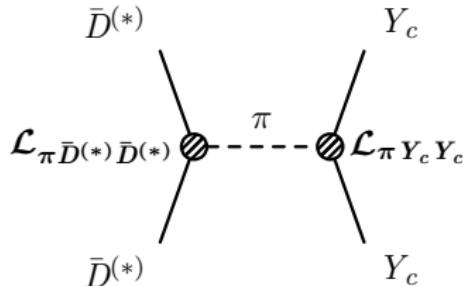
Hint 2 Mixing of Hadronic molecule & Compact state

\Rightarrow Short-range int. between the constituent hadrons



One pion exchange potential (OPEP)

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



$$V^\pi(r) = -\frac{g_\pi g_1}{3f_\pi^2} \left[\vec{S}_1 \cdot \vec{S}_2 C(r) + S_{S_1 S_2} T(r) \right]$$

(Contact term is removed)

$g_\pi = 0.59, g_1 = 1.00$ determined by the π emission

- ⇒ OPEP induces channel couplings among $\bar{D}\Lambda_c$, $\bar{D}^*\Lambda_c$, $\bar{D}\Sigma_c$, $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$, and $\bar{D}^*\Sigma_c^*$ (6 meson-baryon channels!)

- Form factor with Cutoff Λ (determined by the hadron size)

$$F(\vec{q}^2) = \frac{\Lambda^2 - m_\pi^2}{\Lambda^2 + \vec{q}^2}, \quad \Lambda_{\bar{D}} \sim 1130 \text{ MeV}, \Lambda_{Y_c} \sim 840 \text{ MeV}$$

Y.Y, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa, PRD **96**(2017)114031

Tensor force in NN ($^3S_1 - ^3D_1$)

- **Tensor force** in Deuteron, $NN(^3S_1 - ^3D_1)$

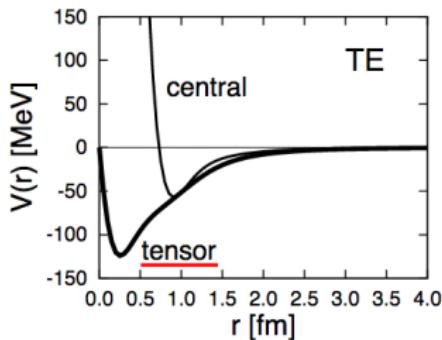


Table 2 Deuteron properties using the AV8' nucleon-nucleon potential.

Energy	-2.24 [MeV]
Kinetic	19.88
(SS)	11.31
(DD)	8.57
Central	-4.46
(SS)	-3.96
(DD)	-0.50
Tensor	-16.64
(SD)	-18.93
(DD)	2.29
LS	-1.02

K. Ikeda, T. Myo, K. Kato and H. Toki, Lect. Notes Phys. **818**, 165 (2010).

⇒ Tensor force produces a strong attraction

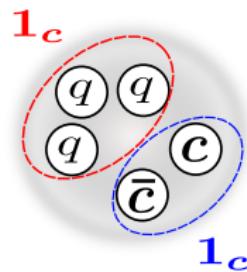
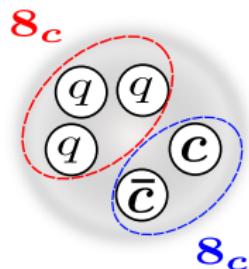
► **Tensor operator** $S_{12}(\hat{r}) = 3(\vec{S}_1 \cdot \hat{r})(\vec{S}_2 \cdot \hat{r}) - \vec{S}_1 \cdot \vec{S}_2$

⇒ $\langle \psi_S | S_{12} T | \psi_D \rangle \neq 0!$ (in general, $\langle \psi_L | S_{12} T | \psi_{L\pm 2} \rangle \neq 0$)

Coupling to D -wave ($L \neq 0$) components is important!

Mixing of the hadronic molecule and compact state?

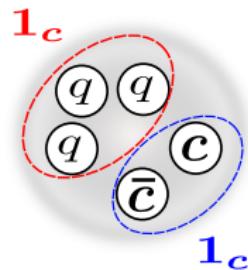
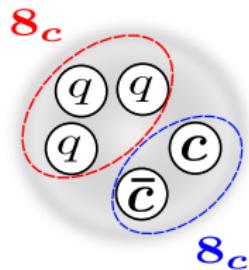
- ▶ S. Takeuchi and M. Takizawa, PLB**764** (2017) 254-259.
 P_c states by the quark cluster model
- ▶ 5-quark configurations



$$S_{q^3} = 1/2, 3/2, \quad S_{c\bar{c}} = 0, 1 \quad S_{q^3} = 1/2, \quad S_{c\bar{c}} = 0, 1$$

Mixing of the hadronic molecule and compact state?

- ▶ S. Takeuchi and M. Takizawa, PLB**764** (2017) 254-259.
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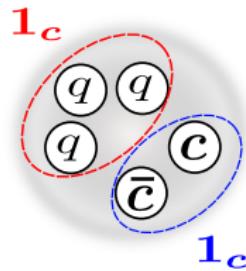
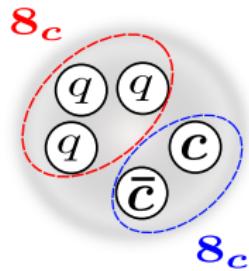


$$S_{q^3} = 1/2, \underline{\textcolor{red}{3/2}}, S_{c\bar{c}} = 0, 1 \quad S_{q^3} = 1/2, S_{c\bar{c}} = 0, 1$$

- ▶ $[q^3 8_c 3/2]$: Color magnetic int. is attractive!

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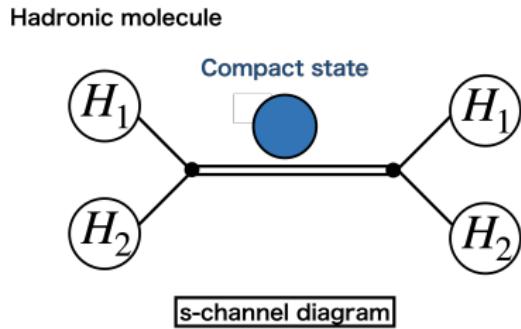
$$S_{q^3} = 1/2, \underline{3/2}, S_{c\bar{c}} = 0, 1 \quad S_{q^3} = 1/2, S_{c\bar{c}} = 0, 1$$

- ▶ $[q^3 8_c 3/2]$: Color magnetic int. is attractive!
⇒ Couplings to (qqc) baryon- $(q\bar{c})$ meson, e.g. $\bar{D}\Sigma_c$, are allowed!

Mixing of Compact state and Hadronic Molecule!

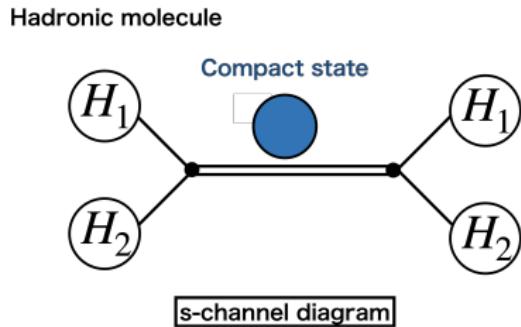
Mixture of the hadronic molecule and compact state

- ▶ Hadronic molecule + Compact state \Rightarrow Short-range interaction in the molecule

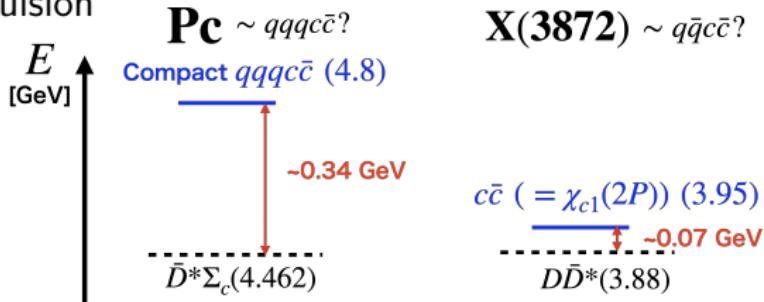


Mixture of the hadronic molecule and compact state

- ▶ Hadronic molecule + Compact state \Rightarrow Short-range interaction in the molecule



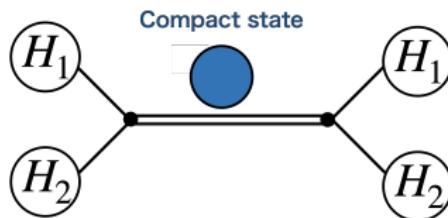
- ▶ Coupling to massive compact states producing **an attraction**
= Level repulsion



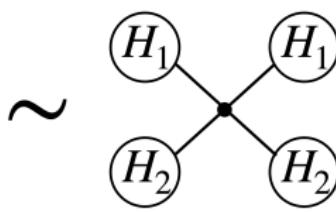
Mixture of the hadronic molecule and compact state

- ▶ Hadronic molecule + Compact state \Rightarrow Short-range interaction in the molecule

Hadronic molecule



s-channel diagram

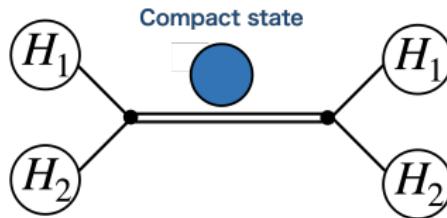


Contact interaction

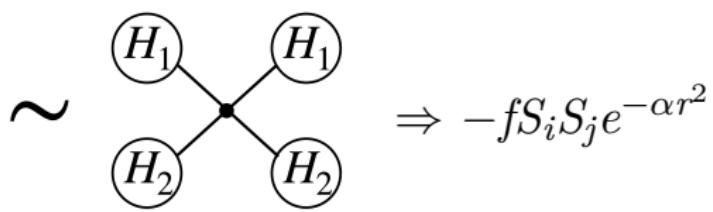
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Hadronic molecule



s-channel diagram



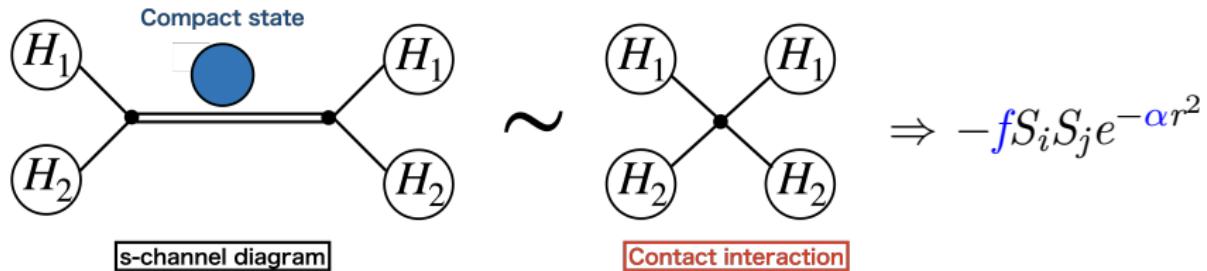
Contact interaction

$$\Rightarrow -f S_i S_j e^{-\alpha r^2}$$

Mixture of the hadronic molecule and compact state

- ▶ Hadronic molecule + Compact state \Rightarrow Short-range interaction in the molecule

Hadronic molecule



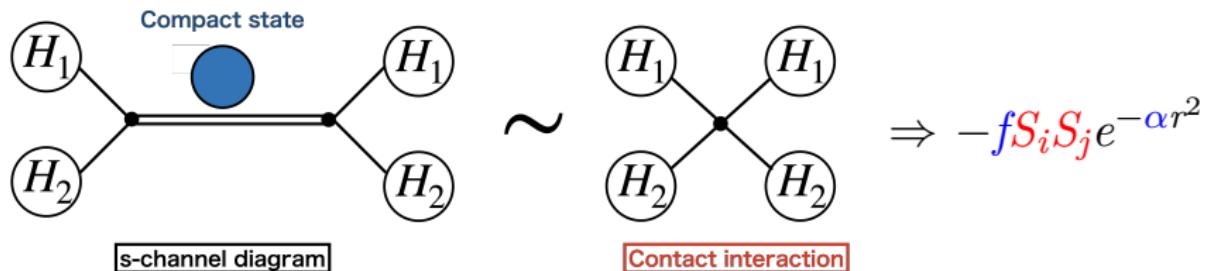
Free Parameters

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

Mixture of the hadronic molecule and compact state

- ▶ Hadronic molecule + Compact state \Rightarrow Short-range interaction in the molecule

Hadronic molecule



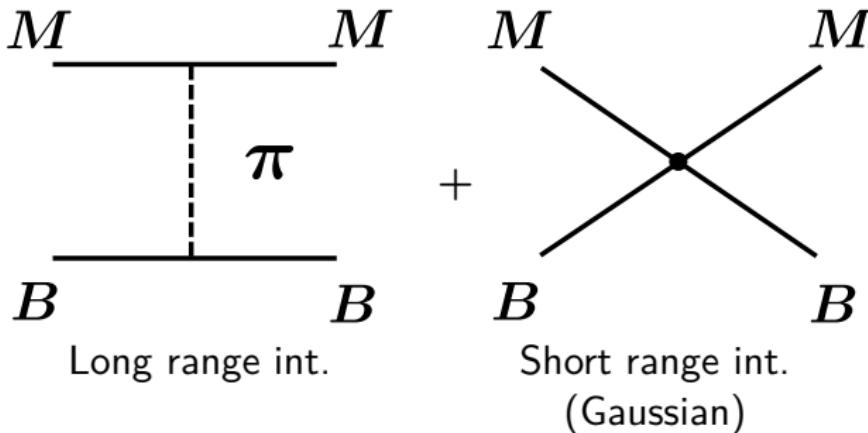
Free Parameters

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

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

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

Numerical Results for Hidden-charm sector

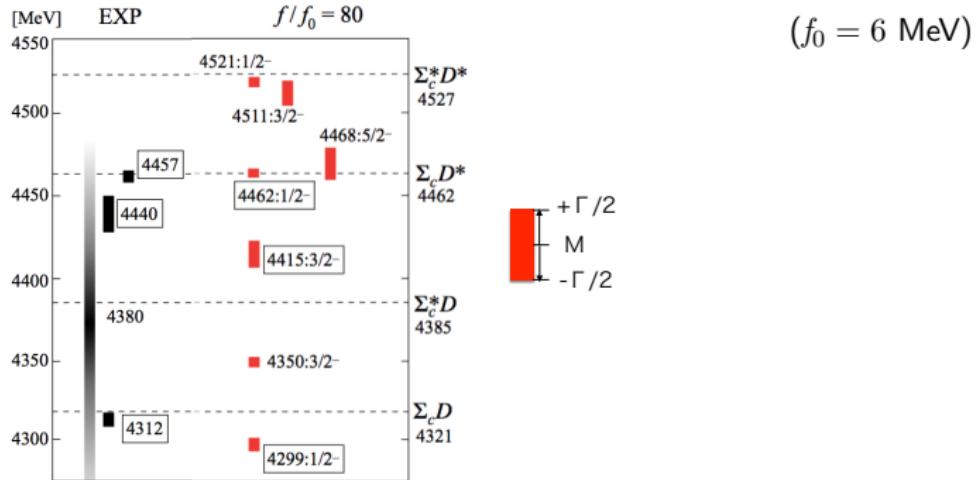


Bound state and Resonance

- ▶ Coupled-channel Schrödinger equation for $\bar{D}\Lambda_c$, $\bar{D}^*\Lambda_c$, $\bar{D}\Sigma_c$, $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$, $\bar{D}^*\Sigma_c^*$ (6 MB components).
- ▶ For $J^P = 1/2^-, 3/2^-, 5/2^-$ (Negative parity)

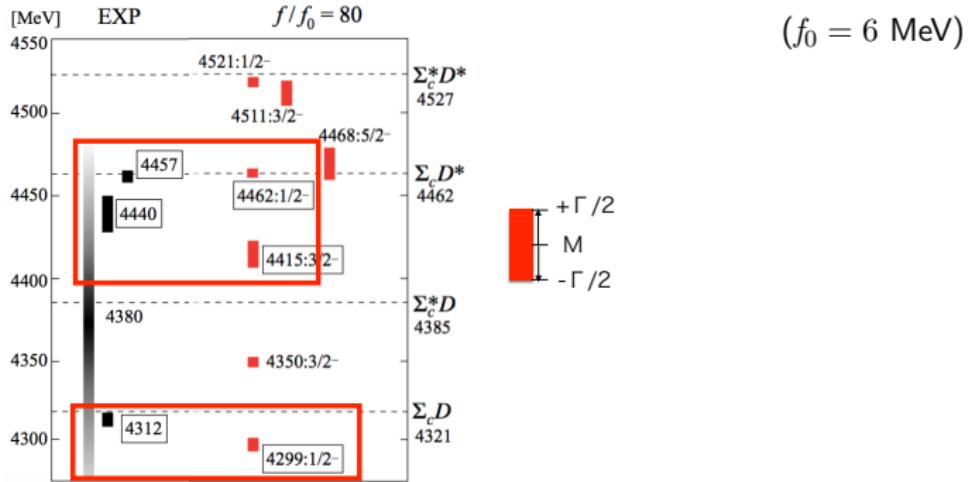
For New P_c states by LHCb in 2019

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



For New P_c states by LHCb in 2019

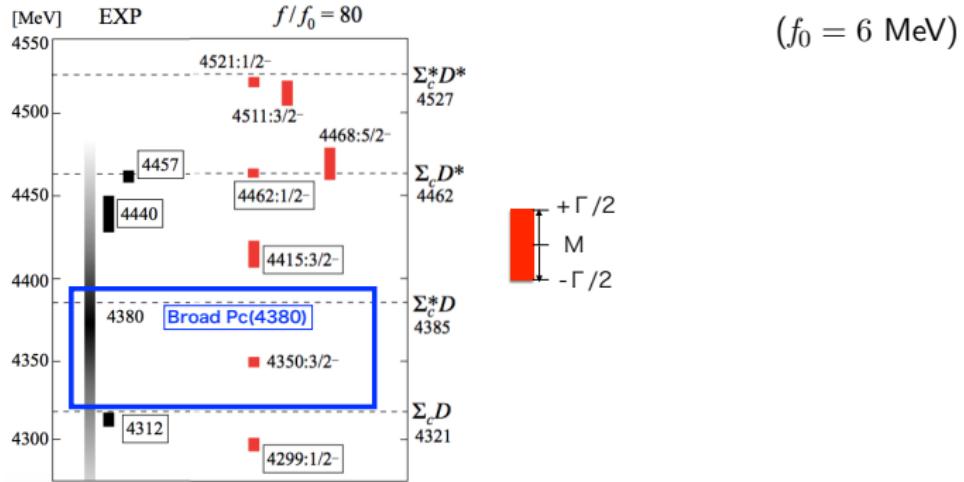
Y.Y., H.Garcia-Tecocoatzi, A.Giachino, A.Hosaka, E.Santopinto, S.Takeuchi, M.Takizawa, PRD **101** (2020) 091502(R)



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

For New P_c states by LHCb in 2019

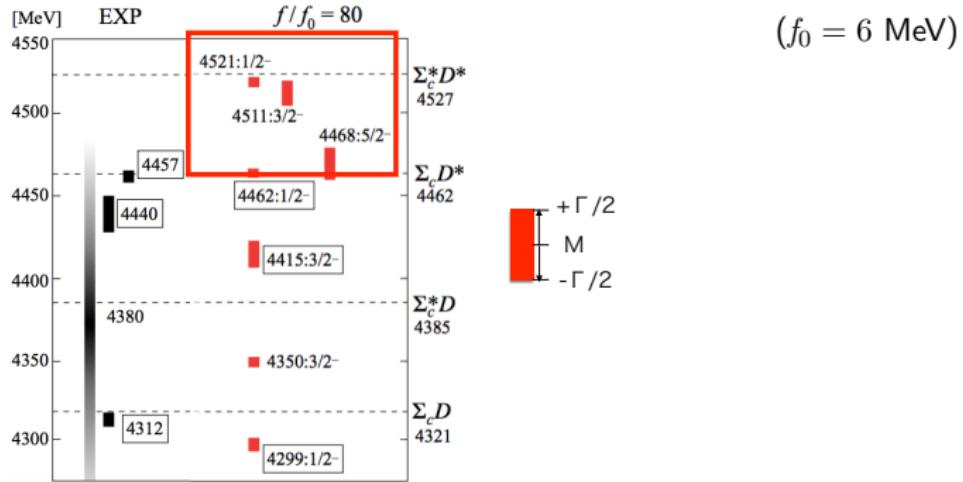
Y.Y., H.Garcia-Tecocoatzi, A.Giachino, A.Hosaka, E.Santopinto, S.Takeuchi, M.Takizawa, PRD **101** (2020) 091502(R)



- ▶ **Agreement with $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$**
- ▶ For Broad $P_c(4380)$, we obtain the similar mass. But width...?

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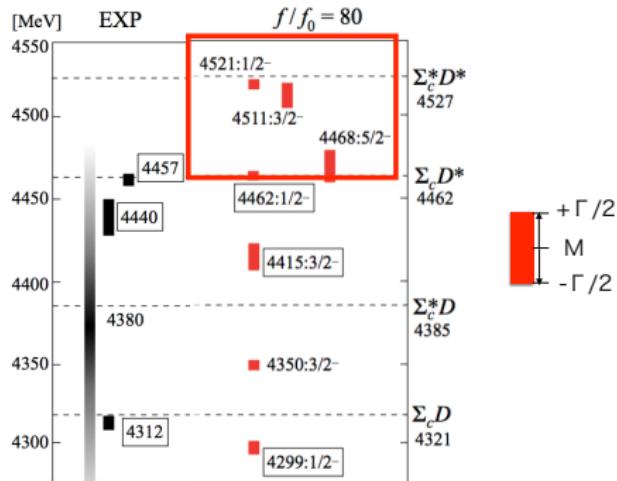
- ▶ **Agreement with $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$**
- ▶ For Broad $P_c(4380)$, we obtain the similar mass. But width...?
- ▶ Predictions: $(1/2^- , 3/2^- , 5/2^-)$ states below $\bar{D}^* \Sigma_c^*$

For New P_c states by LHCb in 2019

Y.Y., H.Garcia-Tecocoatzi,

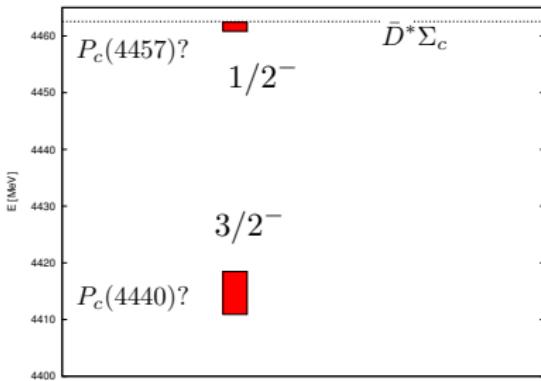
01 (2020) 091502(R)

$(f_0 = 6 \text{ MeV})$



P_c	LHCb (M, Γ)	J^P	Ours $5q+\text{OPEP}$	C. W. Xiao, et al., PRD100(2019)014021 Local hidden gauge	M. Z. Liu, et al., PRL122(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



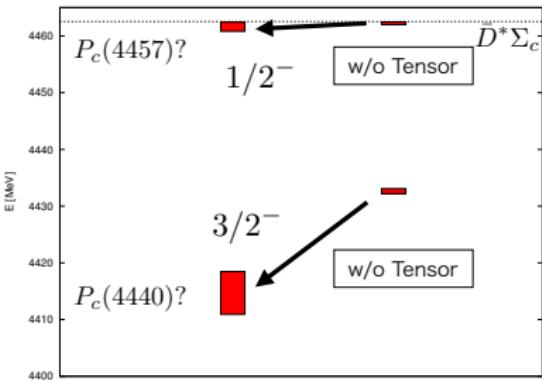
► Our J^P assignment

$P_c(4440)$: $3/2^-$

$P_c(4457)$: $1/2^-$

$$E(1/2^-) > E(3/2^-)$$

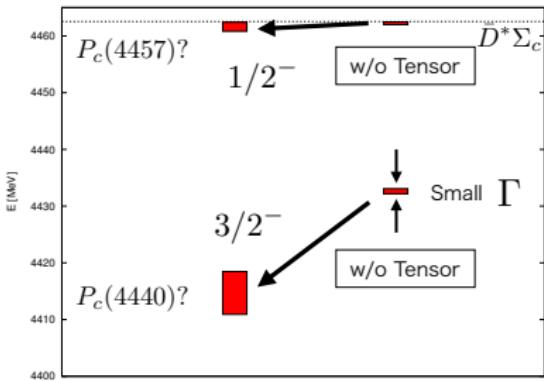
Role of Interactions in P_c



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

- ▶ with Tensor (original) vs without Tensor for V^π
- ⇒ Mass and Width are **reduced!**
 - $1/2^-$: $(E, \Gamma) = (4462, 1.6)$ [MeV] ⇒ $(4462, \textcolor{blue}{0.48})$ [MeV]
 - $3/2^-$: $(E, \Gamma) = (4415, 7.5)$ [MeV] ⇒ $(\textcolor{blue}{4433}, \textcolor{blue}{0.88})$ [MeV]

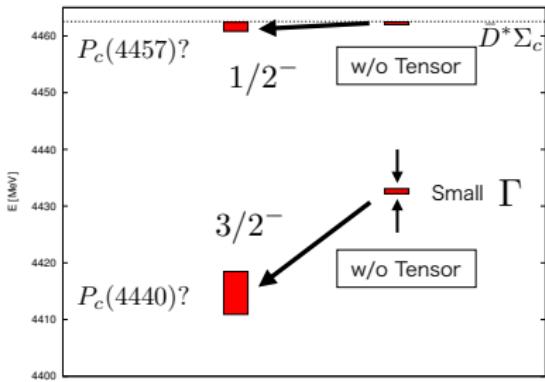
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- V^{5q} : Major role to determine **Energy Levels**

Role of Interactions in P_c

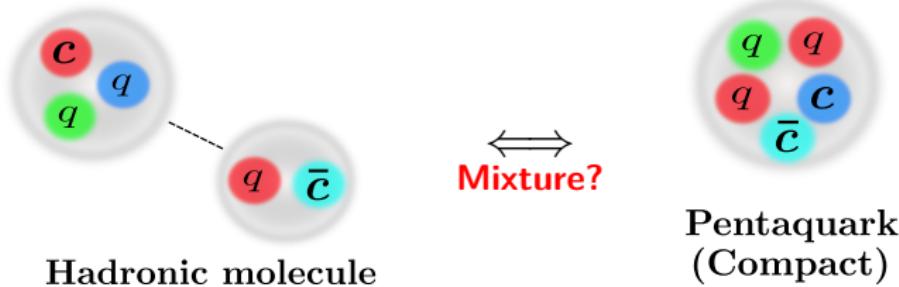


▷ Our J^P assignment
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- ▶ with Tensor (original) vs without Tensor for V^π
- ⇒ Mass and Width are **reduced!**
 - $1/2^-$: $(E, \Gamma) = (4462, 1.6)$ [MeV] $\Rightarrow (4462, \textcolor{blue}{0.48})$ [MeV]
 - $3/2^-$: $(E, \Gamma) = (4415, 7.5)$ [MeV] $\Rightarrow (\textcolor{blue}{4433}, \textcolor{blue}{0.88})$ [MeV]
- ▷ V^{5q} : Major role to determine **Energy Levels**
- ▷ V^π : Major role to enhance **Decay Width** (Channel-coupling effect)

Today's talk

Exotic hadrons as hadronic molecule + compact state



1. Introduction

Exotic hadron, Our mixture model

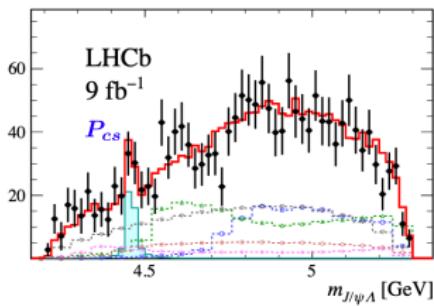
2. Numerical results: P_c ($qqqc\bar{c}$) pentaquark

3. Numerical results: P_{cs} ($qqsc\bar{c}$) pentaquark

4. Summary

Strange partner $P_{cs}(qq\textcolor{red}{sc}\bar{c})$ in 2020 and 2022!

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



► One P_{cs} state ?

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

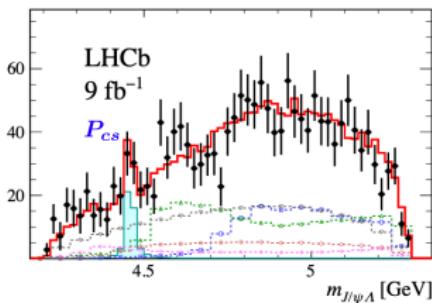
(below the $\Xi_c^0 \bar{D}^{*0}$ threshold)

► Two-peak structure hypothesis

$$M_1 = 4454.9 \pm 2.7 \text{ MeV}, \Gamma_1 = 7.5 \pm 9.7 \text{ MeV}$$
$$M_2 = 4467.8 \pm 3.7 \text{ MeV}, \Gamma_2 = 5.2 \pm 5.3 \text{ MeV}$$

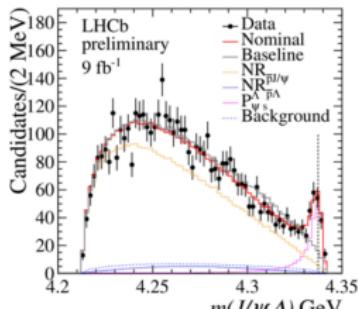
Strange partner $P_{cs}(qq\bar{s}c\bar{c})$ in 2020 and 2022!

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



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

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



Y. Yamaguchi (Nagoya Univ)

- One P_{cs} state ?

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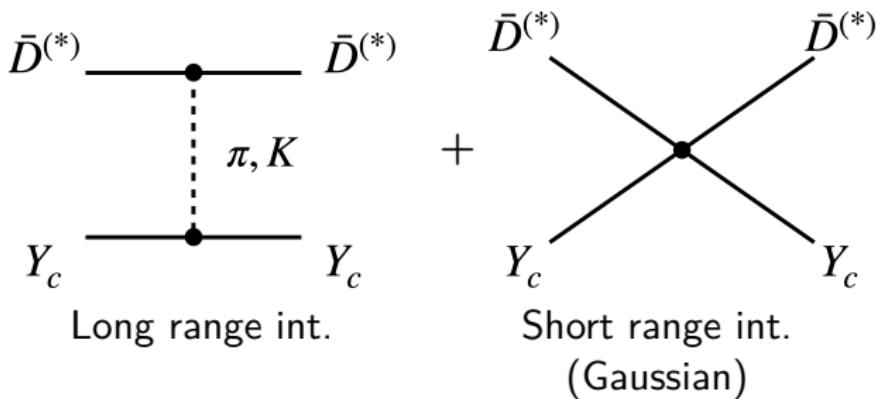
$$M = 4338.2 \pm 0.7 \pm 0.4 \text{ MeV}$$

$$\Gamma = 7.0 \pm 1.2 \pm 1.3 \text{ MeV}$$

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

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

Numerical Results for Strange Hidden Charm

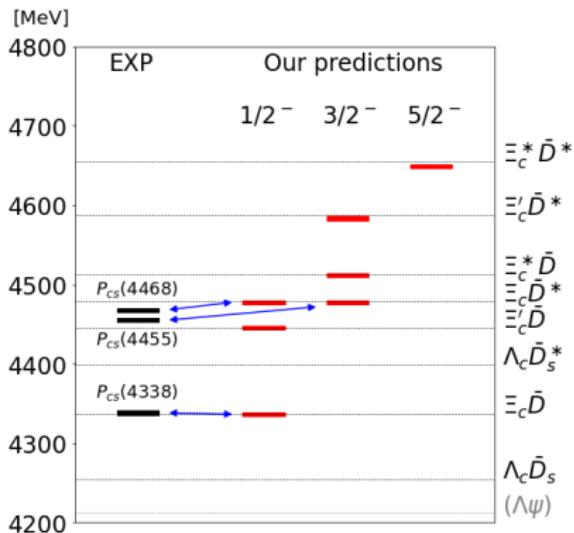


Bound state and Resonance

- ▶ Coupled-channel Schrödinger equation for $\bar{D}_s \Lambda_c$, $\bar{D}_s^* \Lambda_c$, $\bar{D} \Xi_c$, $\bar{D}^* \Xi_c$, $\bar{D} \Xi'_c$, $\bar{D} \Xi_c^*$, $\bar{D}^* \Xi'_c$, $\bar{D}^* \Xi_c^*$ (8 MB components).
- ▶ Method: Gaussian expansion method + Complex scaling method
- ▶ For $J^P = 1/2^-, 3/2^-, 5/2^-$ (Negative parity)

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

Comparing EXP with the predicted masses

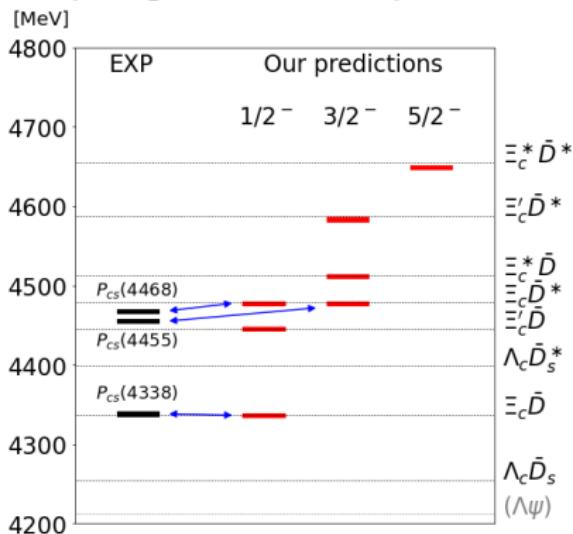


A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi,
M. Takizawa, Y.Y, arXiv:2209.10413 [hep-ph]

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

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

Comparing EXP with the predicted masses

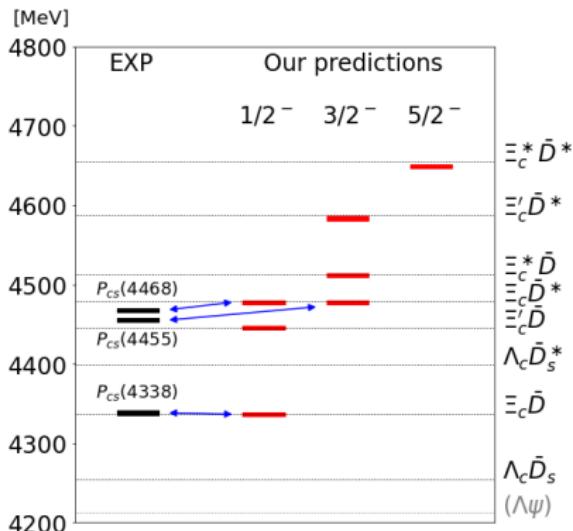


A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi,
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- ▶ Two $\Xi_c \bar{D}^*$ bound states
 $\leftrightarrow P_{cs}(4468), P_{cs}(4455)?$
- ▶ One $\Xi_c \bar{D}$ bound state
 $\leftrightarrow P_{cs}(4338)?$

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

Comparing EXP with the predicted masses



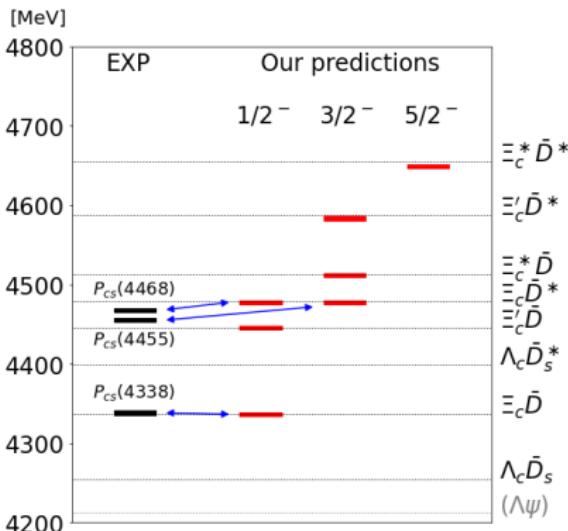
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- ▶ Two $\Xi_c \bar{D}^*$ bound states
 $\leftrightarrow P_{cs}(4468), P_{cs}(4455)?$
- ▶ One $\Xi_c \bar{D}$ bound state
 $\leftrightarrow P_{cs}(4338)?$
- ▶ Four new predictions

Rich structure near the thresholds

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

Comparing EXP with the predicted masses



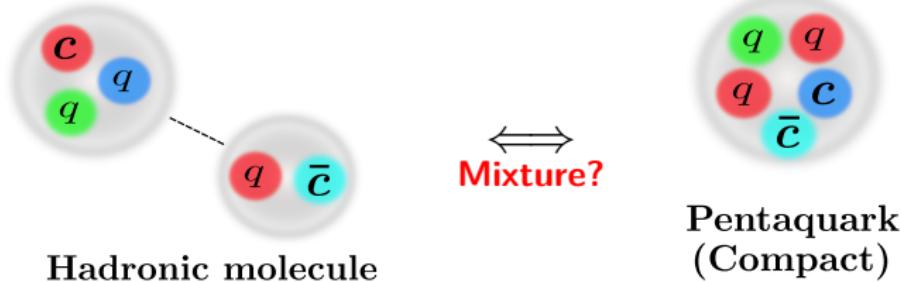
A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi,
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- ▶ Two $\Xi_c \bar{D}^*$ bound states
 $\leftrightarrow P_{cs}(4468), P_{cs}(4455)?$
- ▶ One $\Xi_c \bar{D}$ bound state
 $\leftrightarrow P_{cs}(4338)?$
- ▶ Four new predictions

Rich structure near the thresholds

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

Summary



- ▶ Many exotic hadrons have been reported in the experiments
 - ▶ Hadronic molecule + compact state model
 - ▶ Long-range int. : π exchange potential
 - ▶ Short-range int. : Coupling to the compact state
 - ▶ P_c and P_{cs} resonances are obtained near the thresholds.
 - ▶ Short-range int. determining E_{re}
 - ▶ Long-range int. enhancing Γ

Y.Y. A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa, Phys. Rev. D 101 (2020) 091502(R),

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