Exotic hadrons in the hybrid model of hadronic molecules and compact states

Yasuhiro Yamaguchi

Department of Physics, Nagoya University, Japan

in collaboration with

Hugo García-Tecocoatzi (INFN Genoa), Alessandro Giachino (INP, Cracow),

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

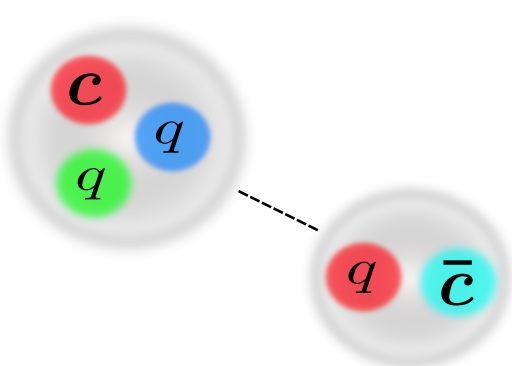
Sachiko Takeuchi (Japan Coll. Social Work), Makoto Takizawa (Showa Pharmaceutical Univ.),

Exotics and Exotic Phenomena in Heavy Ion Collisions (ExHIC), APCTP, South Korea

29 Sep - 1 Oct , 2022

Today's talk

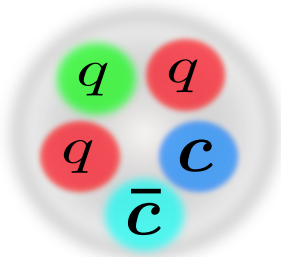
Exotic hadrons as hadronic molecule + compact state



Hadronic molecule

$\Longleftrightarrow$

Mixture?

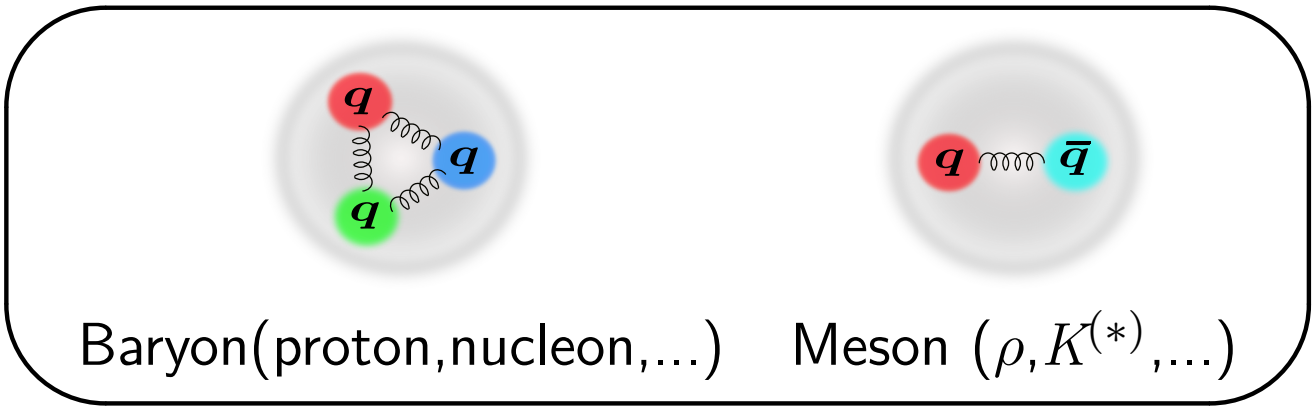


Pentaquark (Compact)

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 ($q\bar{q}$)



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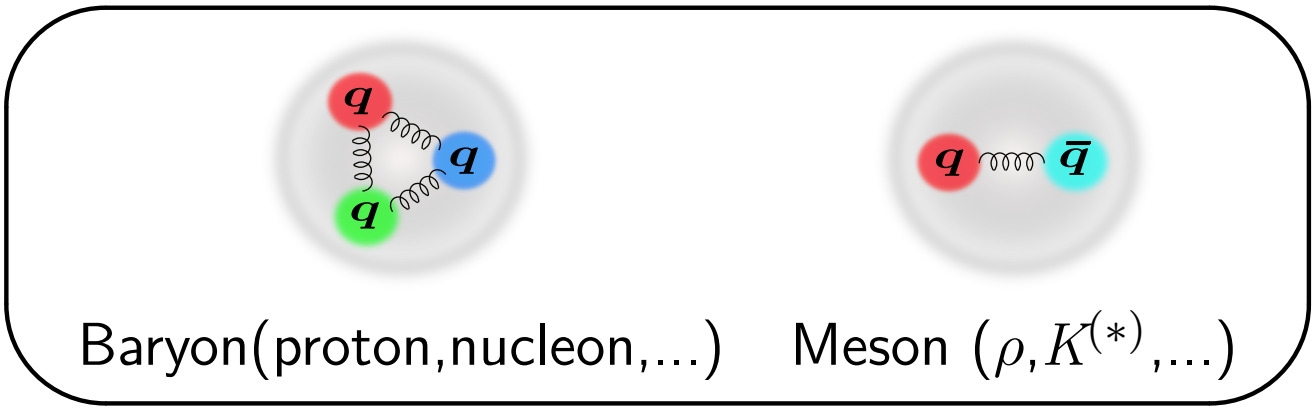
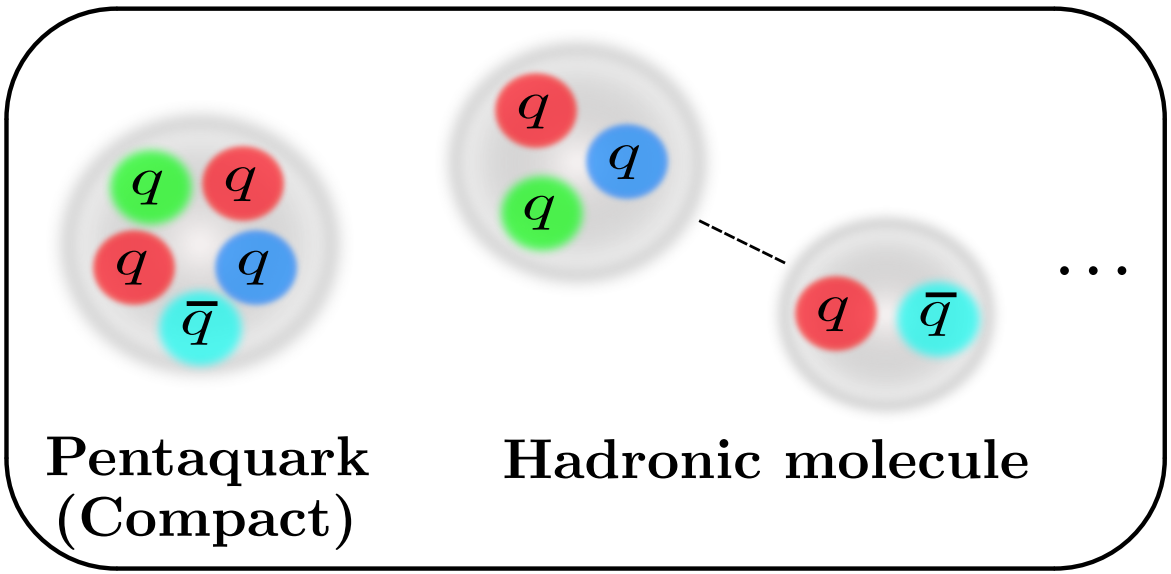
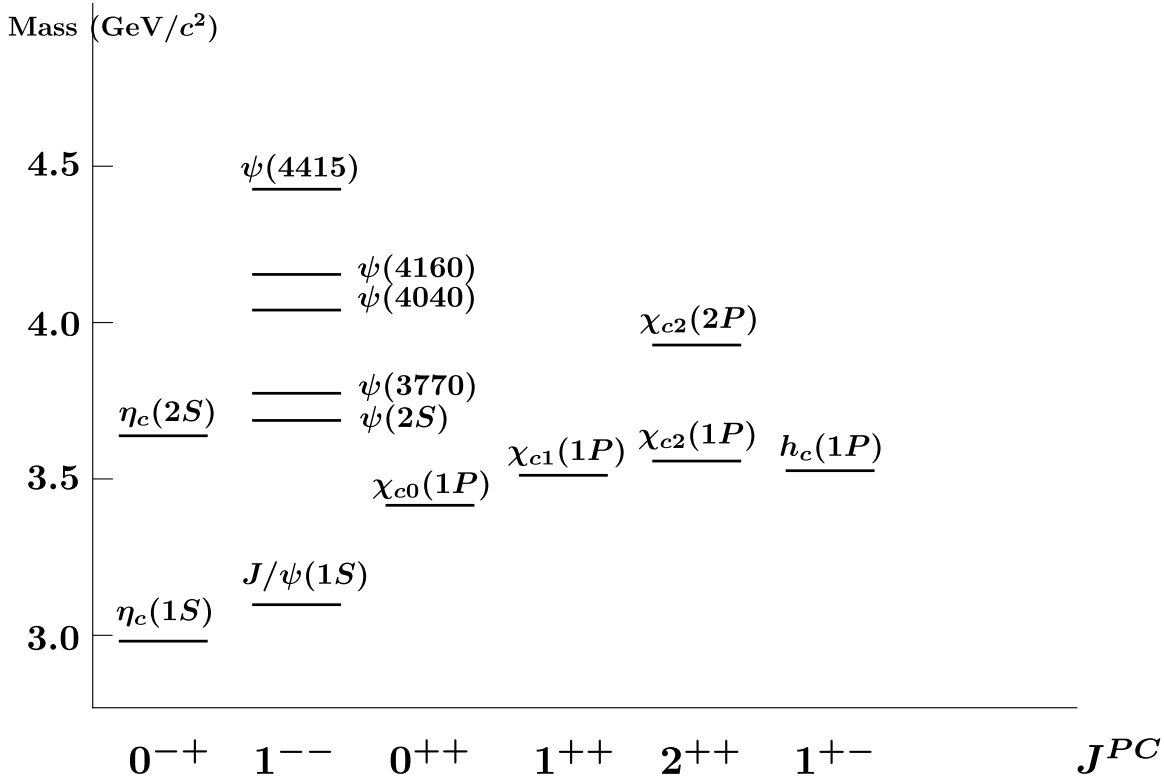


- Exotic Hadrons ($\neq qqq,\ q\bar{q}$): **Multiquark? Multihadron?**



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

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



one-g exchange

$+$

Confinement

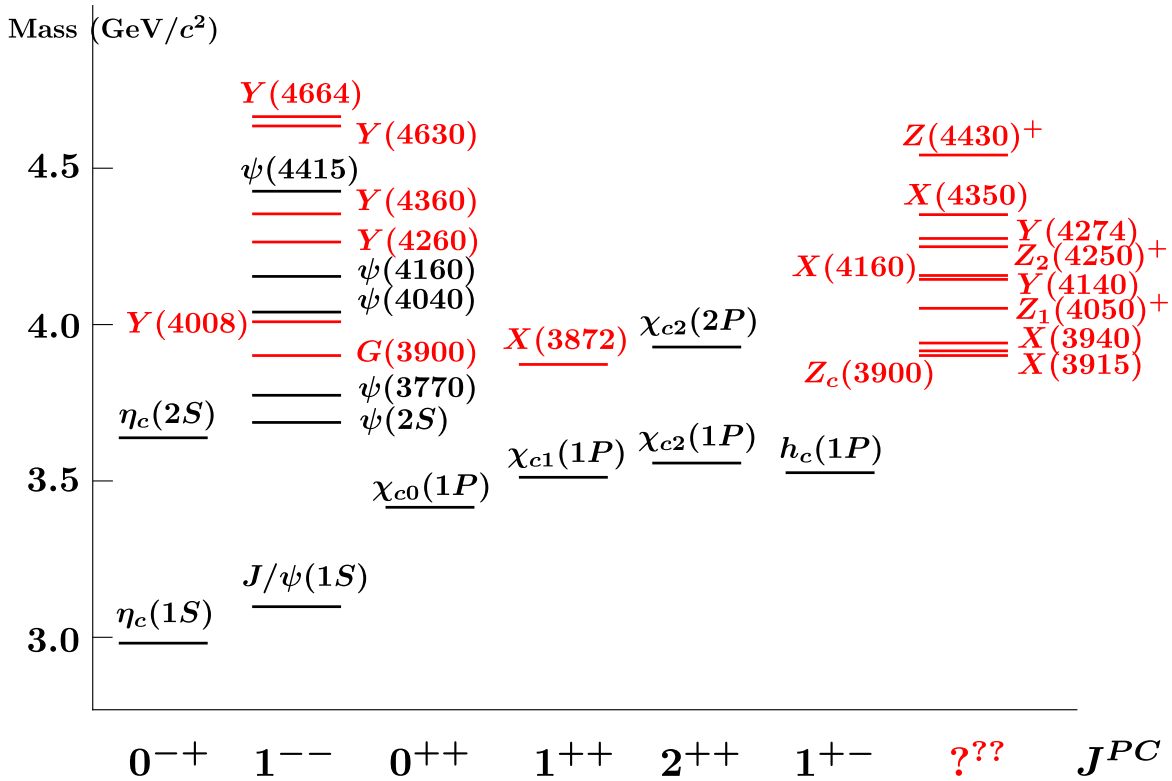
$\Downarrow$

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

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

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

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



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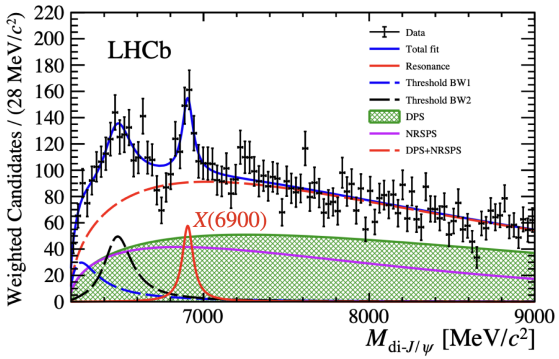
- Exotics $\neq c\bar{c}$ have been observed in the Experiments (BaBar, Belle, BESIII, LHCb,...) since the discovery of **$X(3872)$ in 2003!**

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

Recent reports of Exotic hadrons!

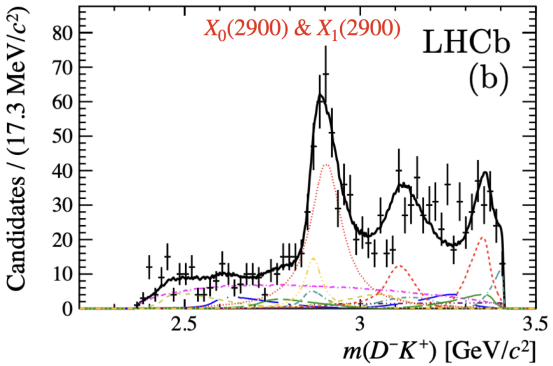
- $X(6900)$ $(cc\bar{c}\bar{c}?)$

LHCb, Science Bulletin 65 (2020) 1983



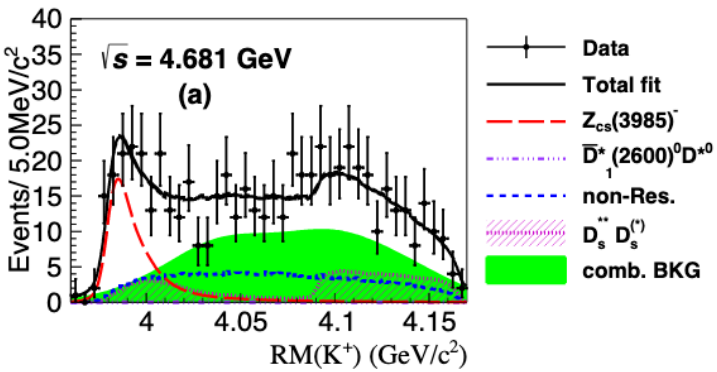
- $X_{0,1}(2900)$ $(\bar{c}\bar{s}ud?)$

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



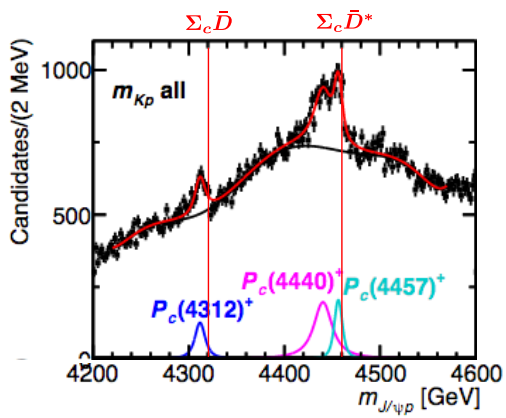
- Z_{cs} $(c\bar{c}s\bar{u}?)$

BESIII PRL126, 102001 (2021)



- P_c $(uudc\bar{c}?)$,

LHCb PRL**115**(2015)072001, PRL**122**(2019)222001



Recent reports of Exotic hadrons!

▷ $X(6900)$ $(cc\bar{c}\bar{c}?)$

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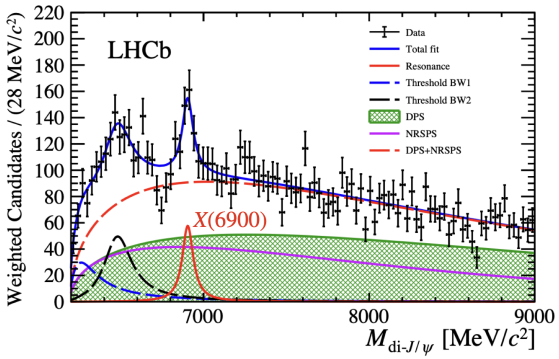
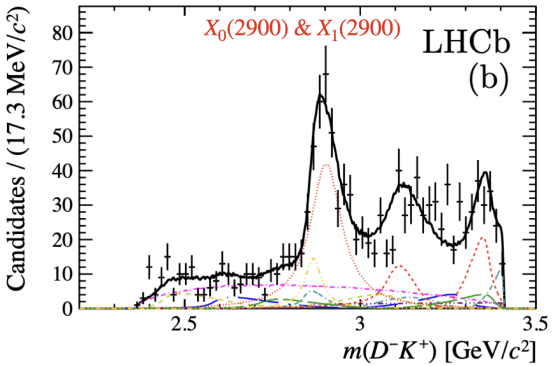


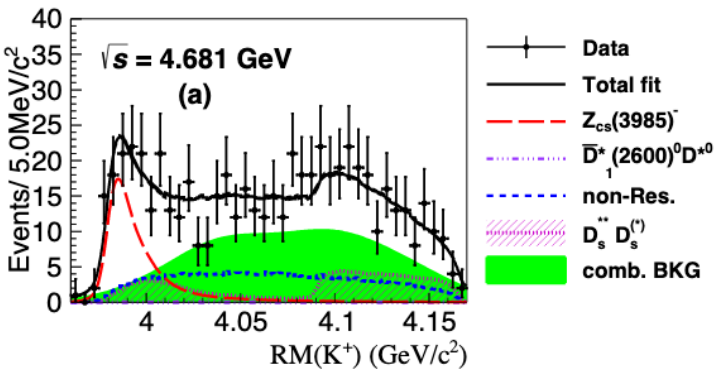
▷ $X_{0,1}(2900)$ $(\bar{c}\bar{s}ud?)$

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



▷ Z_{cs} $(c\bar{c}s\bar{u}?)$

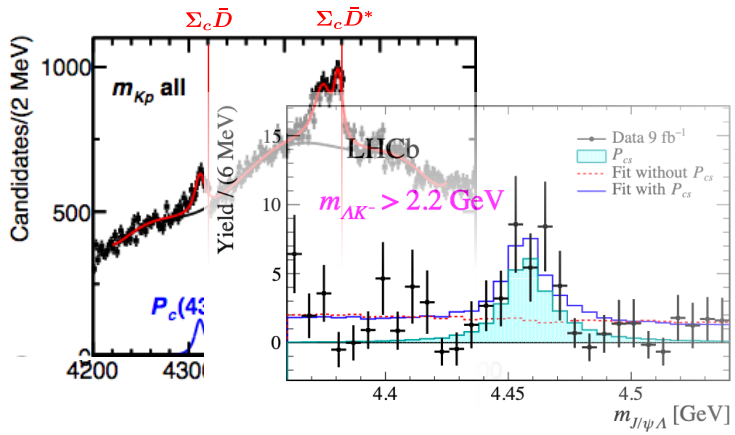
BESIII PRL126, 102001 (2021)



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

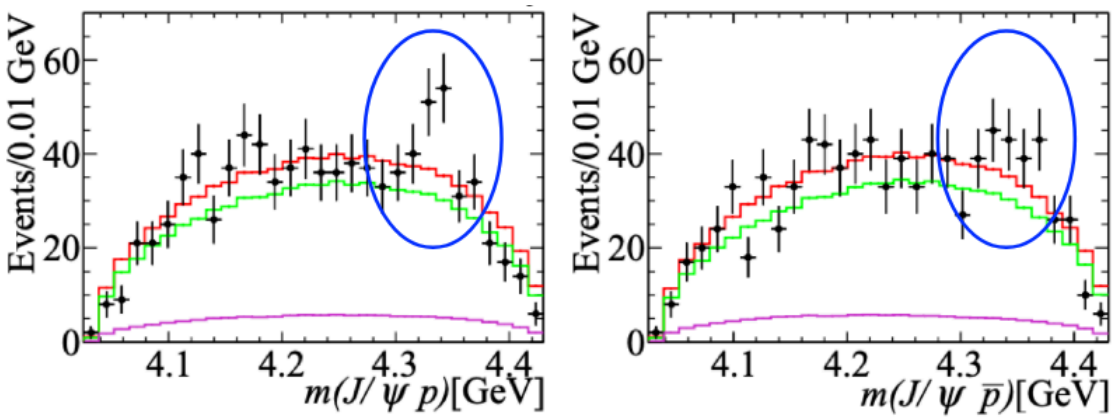
LHCb PRL**115**(2015)072001, PRL**122**(2019)222001

Sci.Bull.**66**(2021)1278



Very recent reports of Exotic hadrons!

- **New $P_c(4337)^+$ state** in $B_s^0 \to J/\psi p\bar{p}$ LHCb, PRL**128**(2022)062001



from Liupan An's talk (HADRON2021)

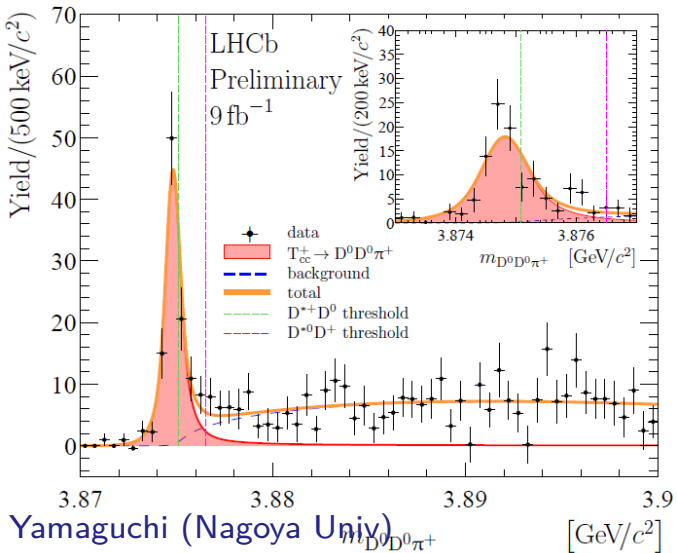
$M = 4337^{+7+2}_{-4-2}$ MeV

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



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

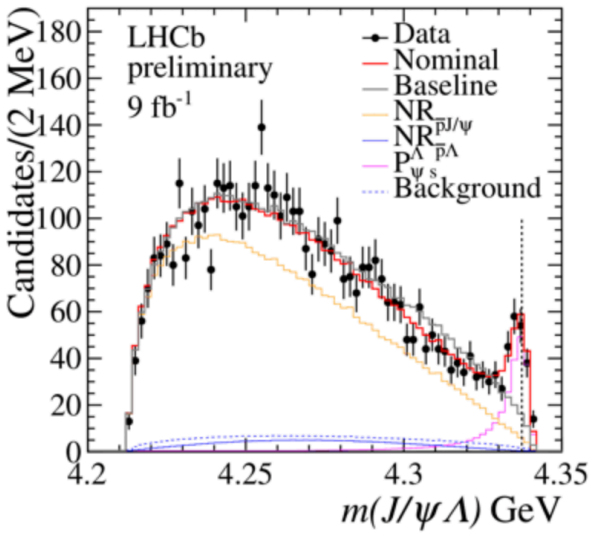
$\Gamma_{BW} = 410 \pm 165$ keV

Isoscaler $J^P = 1^+$

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

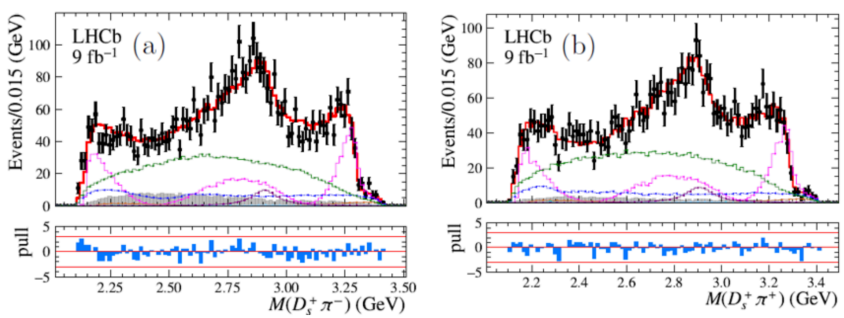


$M = 4338.2 \pm 0.7 \pm 0.4$ MeV

$\Gamma = 7.0 \pm 1.2 \pm 1.3$ 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 $B \to DD_s\pi$ **(LHCb)**



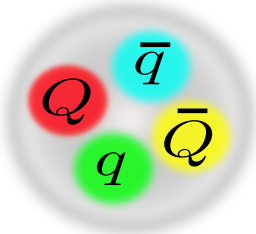
$M = 2.908 \pm 0.011 \pm 0.02$ GeV

$\Gamma = 0.136 \pm 0.023 \pm 0.011$ GeV

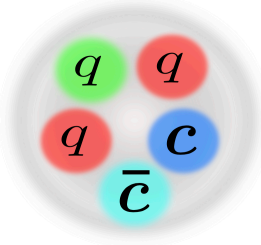
The quantum numbers are $J^P = 0^+$.

Candidates of Exotic structures?

Compact multiquarks

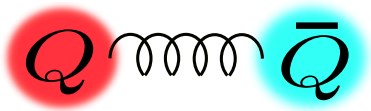


Tetraquark



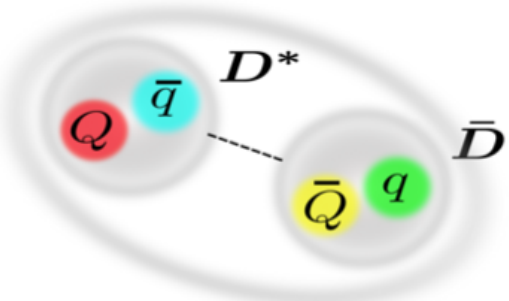
Pentaquark

$Q\bar{Q}g$ Hybrid

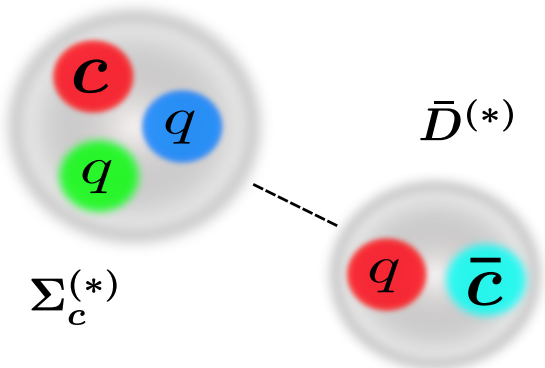


Hadronic molecules

Near thresholds?



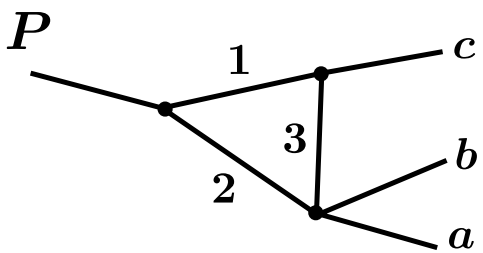
Meson-Meson



Meson-Baryon

Triangle Singularity

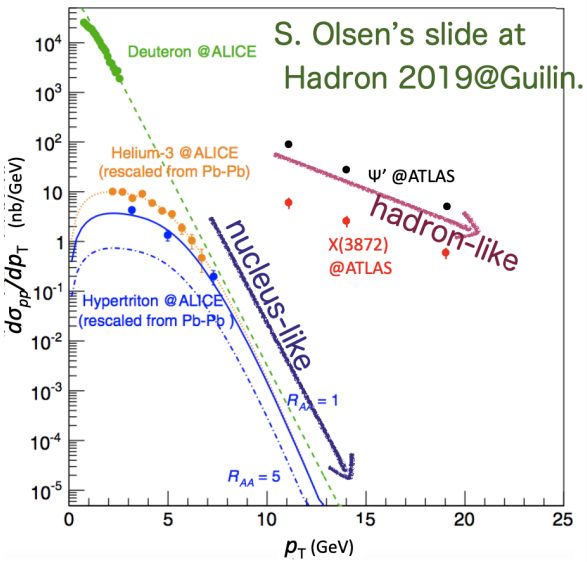
Near thresholds?



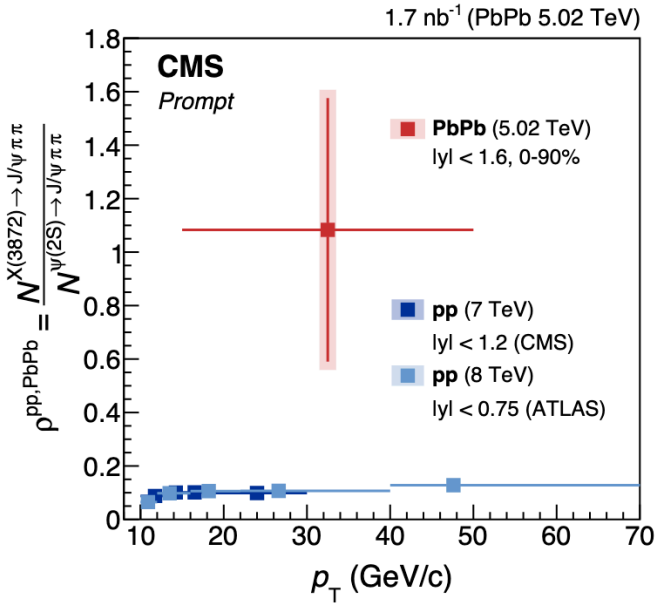
(w/o Resonance)

$X(3872)$ structure in high energy collisions

$X(3872)$: $D\bar{D}^*$ molecule? Compact tetraquark?



A. M. Sirunyan *et al.* [CMS], PRL**128** (2022) 032001



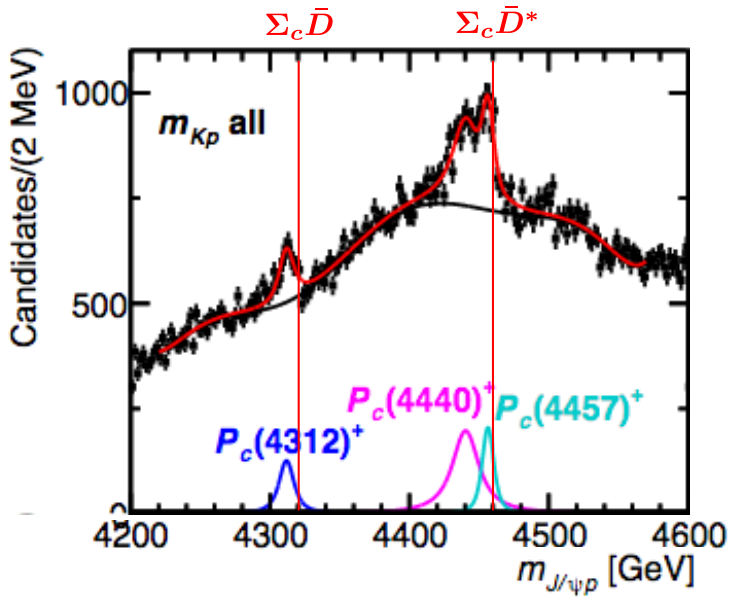
- In pp collision, $(d\sigma/dp)_{X(3872)}$ **is similar to that of $\psi(2S)$** rather than that of nuclei (a hadron composite) ?

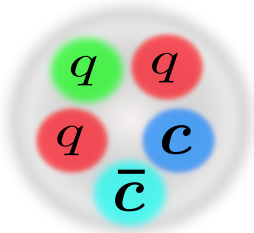
$\leftrightarrow$ Existence of the compact component? J.Phys.G 47 (2020) 5, 053001,

- CMS data being consistence with ExHIC analysis (molecule) ?
  ExHIC, PRL106(2011)212001, PRC84(2011)064910, PPNP95(2017)279-322

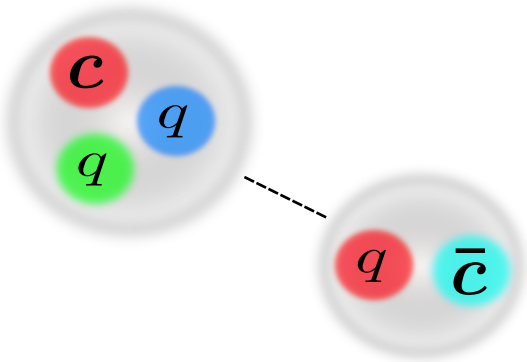
Studying the exotic structures in the high energy collision!

P_c pentaquarks





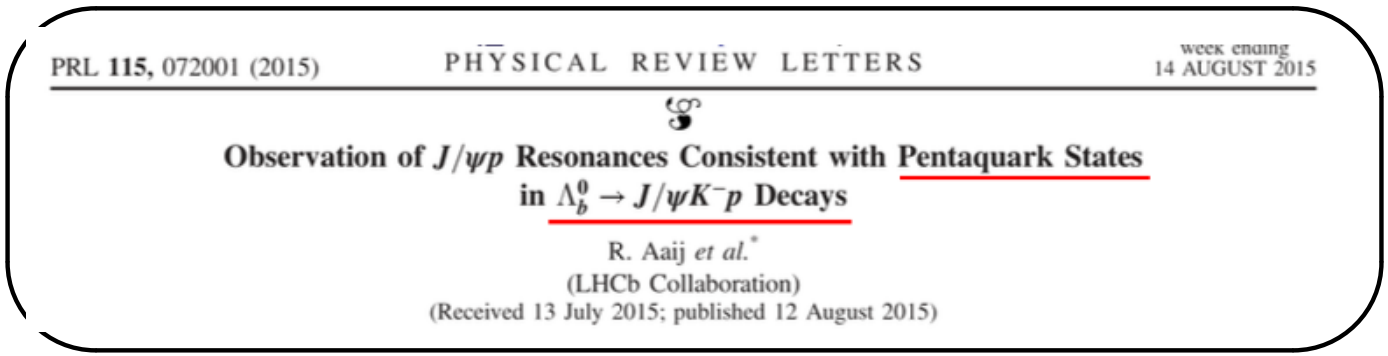
Pentaquark
(Compact)



Hadronic molecule

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

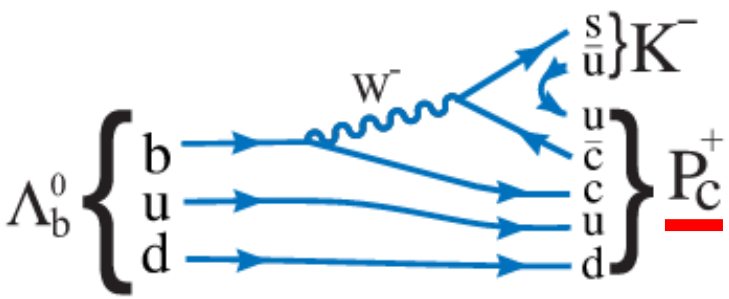

PRL 115, 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

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

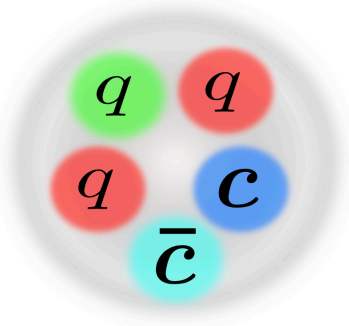
R. Aaij *et al.**
(LHCb Collaboration)
(Received 13 July 2015; published 12 August 2015)

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

$c\bar{c}uud$ state ?



$\Rightarrow$

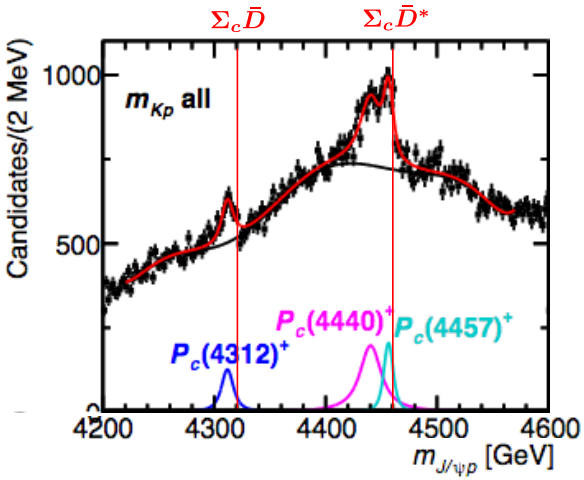


$P_c(4380)$: M =4380 MeV Γ= 205 MeV

$P_c(4450)$: 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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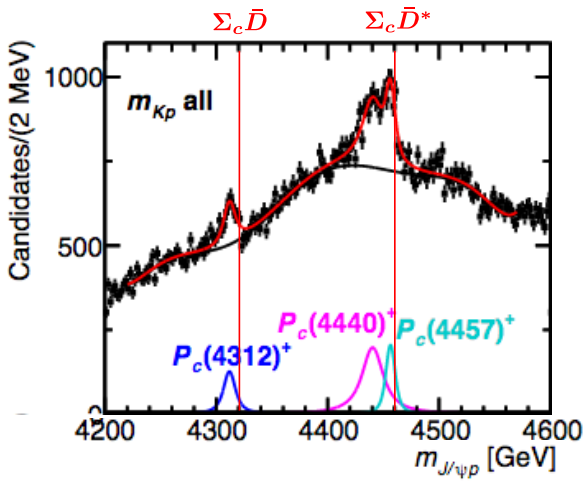
- R. Aaij, *et al.* Phys.Rev.Lett. 122 (2019) 222001



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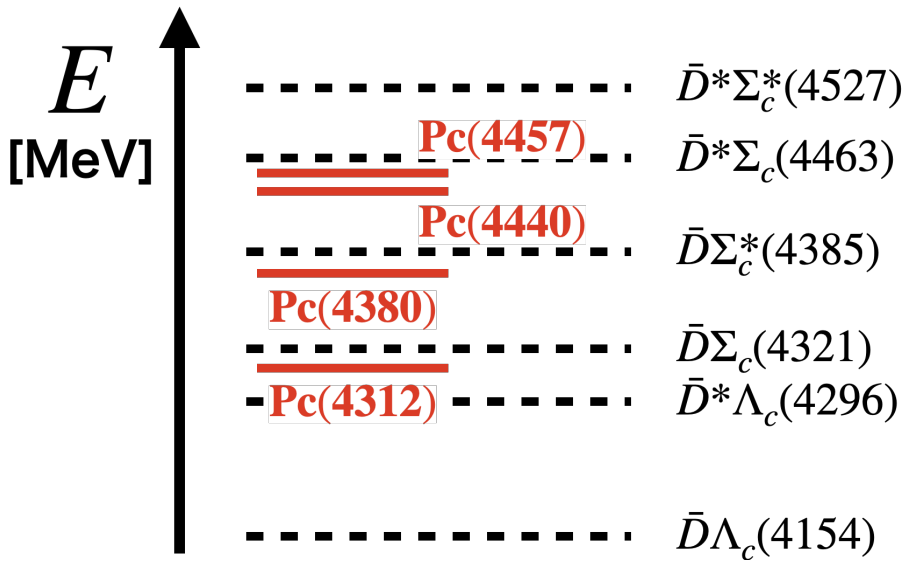


- There are **6 meson-baryon thresholds**

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), ...

- 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),

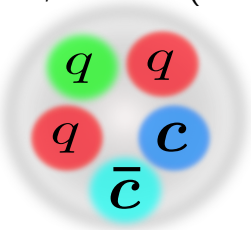
  C. W. Xiao, *et al.* (2019), M.-Z. Liu, *et al.* (2019), M. L. Du, *et al.* (2019),

  ...

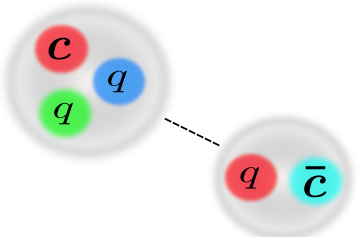
- Triangle singularity?
  (Non-resonant explanation)

  F.K.Guo, *et al.* (2015), X.H.Liu, *et al.* (2016),

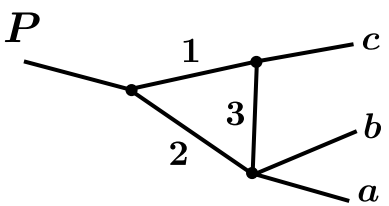
  S.X.Nakamura PRD103, L111503 (2021), ...



Pentaquark (Compact)



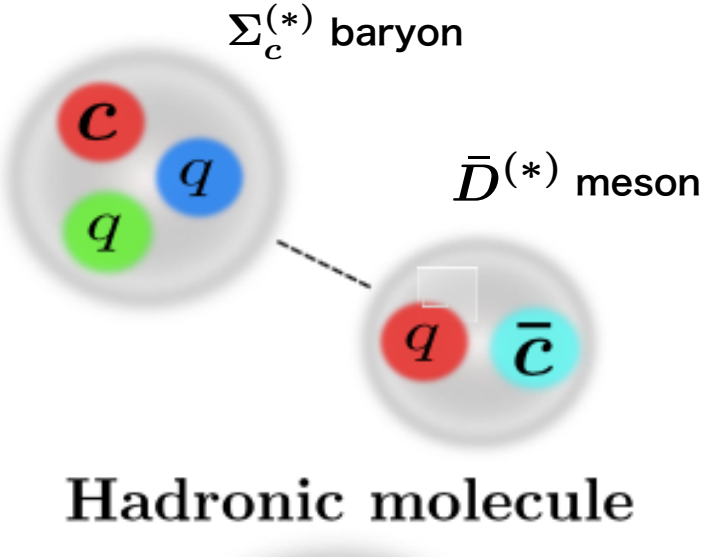
Hadronic molecule



Hadronic molecules?

- Exotics as Hadronic molecule $\Rightarrow$ Hadron (quasi) bound state

$\rightarrow$ expected **near the thresholds**



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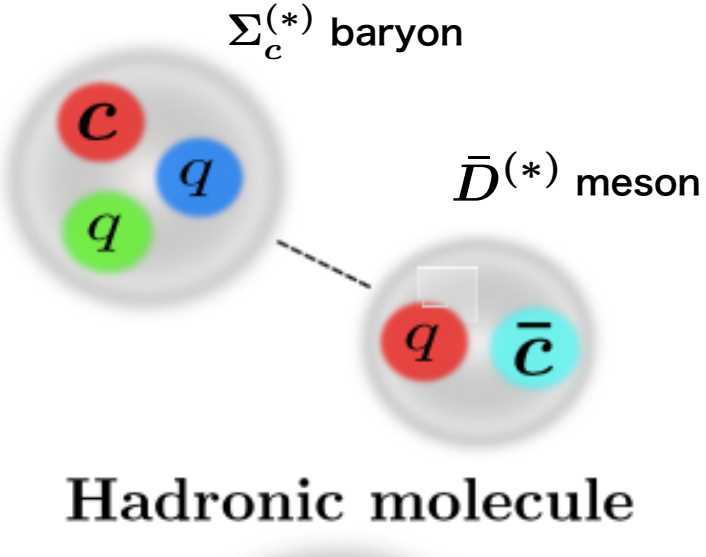
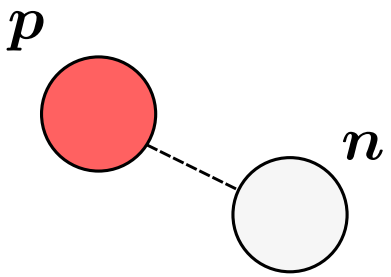


Analogous to Deuteron



$B = 2.2$ MeV

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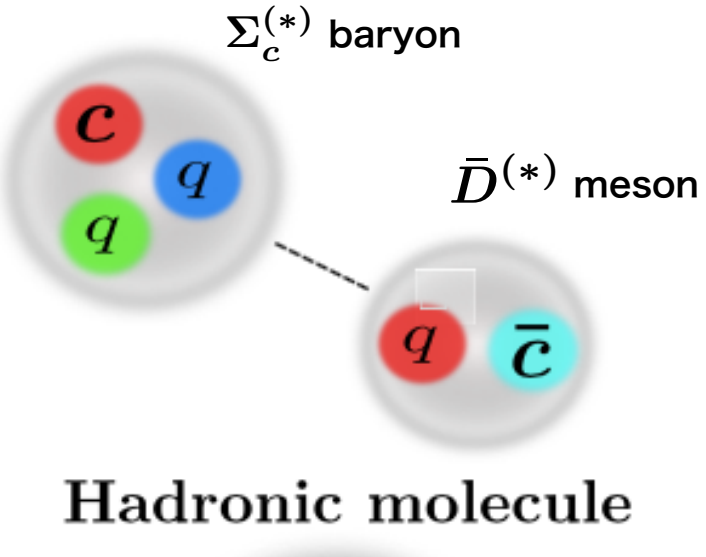
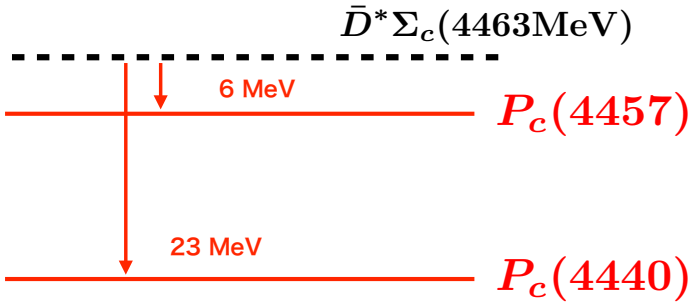


$P_c = \bar{D}^{(*)}\Sigma_c^{(*)}$ molecules?



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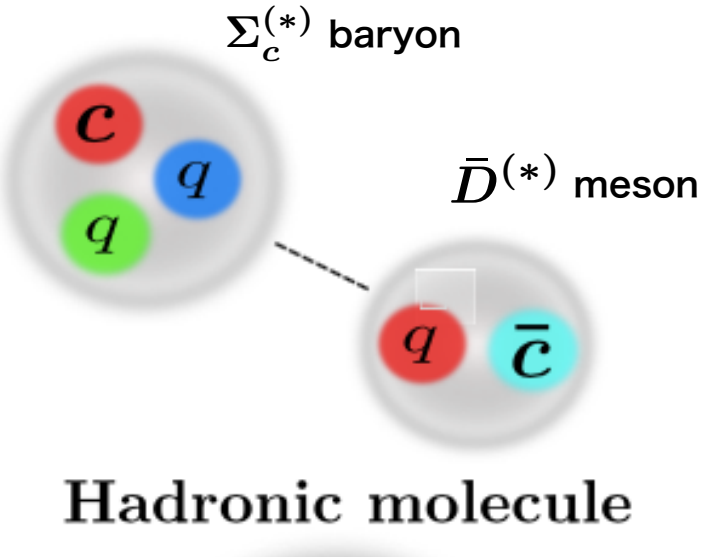

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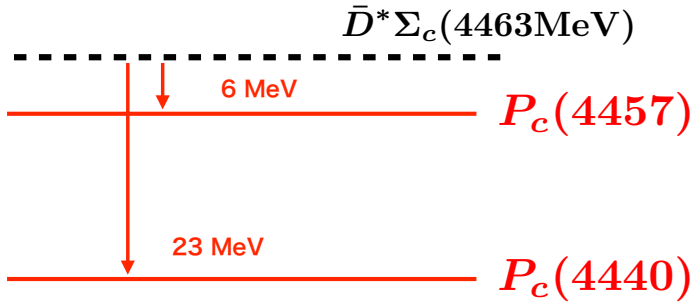

- Exotic hadrons near thresholds
  - $D\bar{D}^*$: $X(3872)$, $Z_c(3900)$,..., DD^*: T_{cc}
  - $B\bar{B}^*$: Z_b, $Z_b{}'$
  - $\bar{D}^{(*)}\Sigma_c^{(*)}$: P_c F. K. Guo, *et. al.*, Rev.Mod.Phys.**90**(2018)015004,Y. Y., *et. al.*, J.Phys.G**47**(2020)053001,...

Hadronic molecules?

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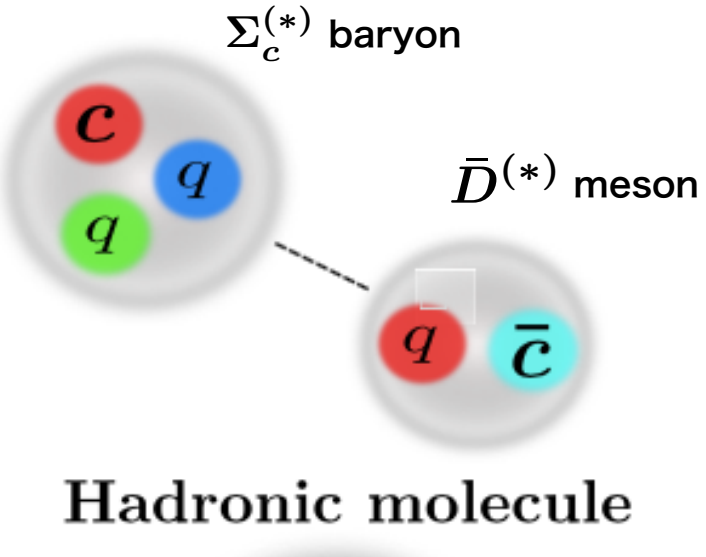

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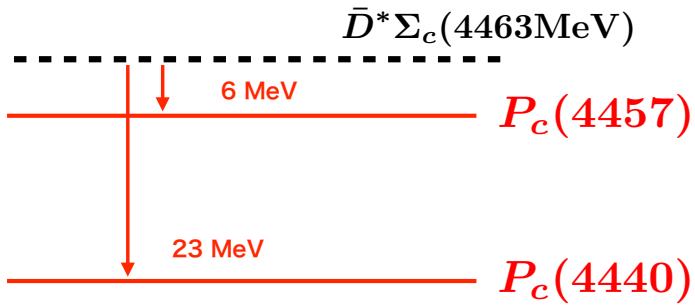

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Q. What is an interaction binding the constituent hadrons?

Hadron interactions

Problem Hadron interactions are **NOT established** yet...
due to the lack of the hadron-scattering data

($\leftrightarrow$ Lattice QCD, Femtoscopy, etc near future!)

How can we describe hadron interactions?

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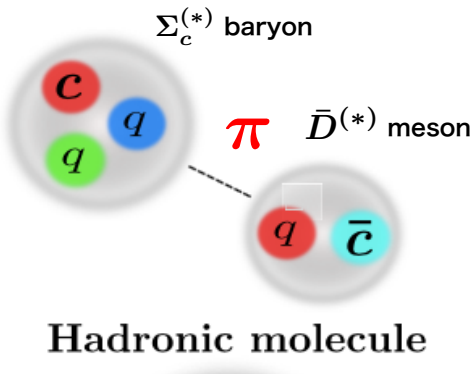
Hint 1 **One pion exchange potential (Long-range int.)**

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



OPEP

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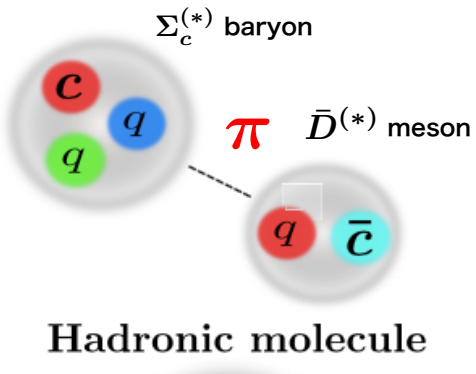
Hint 2 **Mixing of Hadronic molecule & Compact state**

$\Rightarrow$ Short-range int. between the constituent hadrons



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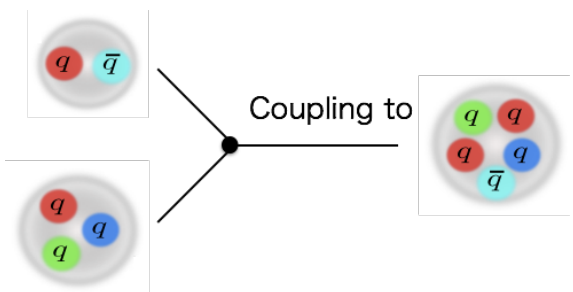
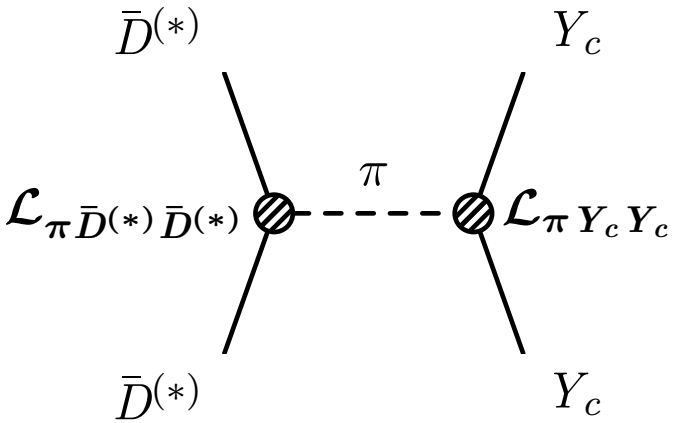


5-quark potential

One pion exchange potential (OPEP)

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



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

(Contact term is removed)

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

$\Rightarrow$ 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, $NN(^3S_1 - ^3D_1)$

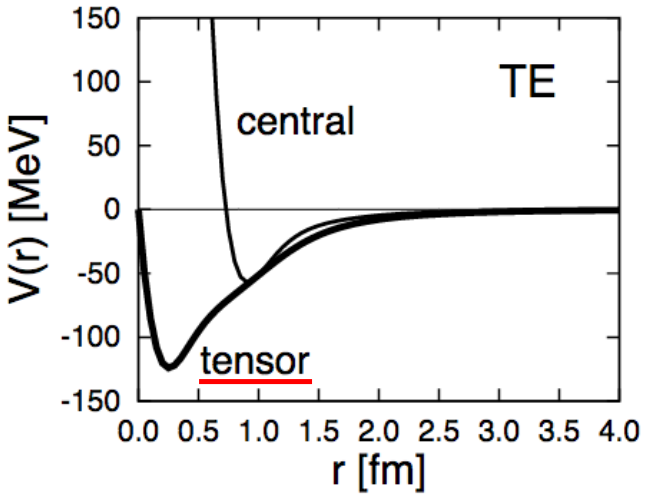


Table 2 Deuteron properties using the AV8' nucleon-nucleon potential.

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).

$\Rightarrow$ Tensor force produces a strong attraction

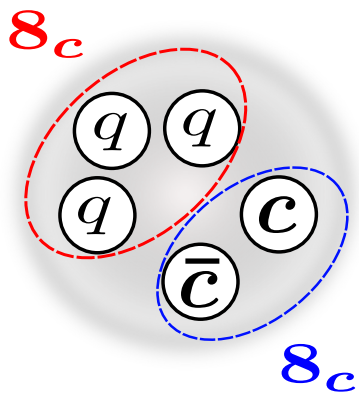
- **Tensor operator** $S_{12}(\hat{r}) = 3(\vec{S}_1 \cdot \hat{r})(\vec{S}_2 \cdot \hat{r}) - \vec{S}_1 \cdot \vec{S}_2$

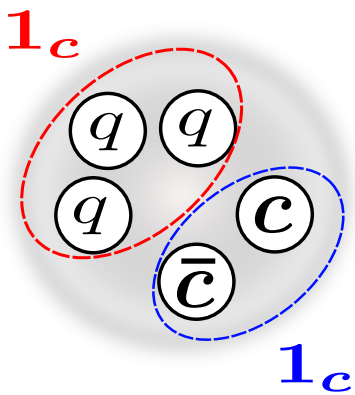
$\Rightarrow$ $\langle \psi_S | S_{12}\, T | \psi_D \rangle \neq 0$! (in general, $\langle \psi_L | S_{12}\, T | \psi_{L\pm 2} \rangle \neq 0$)

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





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

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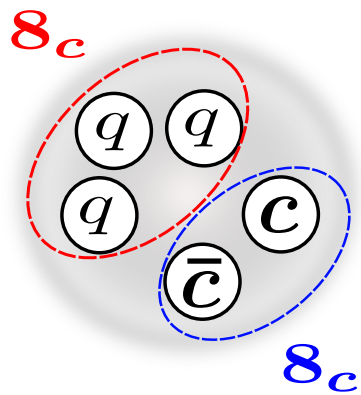

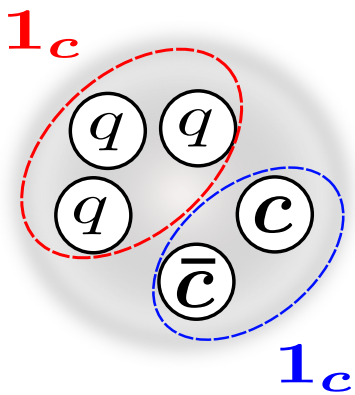

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- $[q^3\, 8_c\, 3/2]$: Color magnetic int. is attractive!

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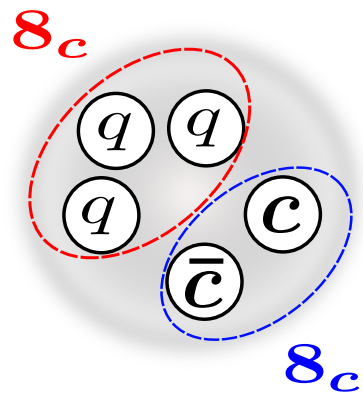

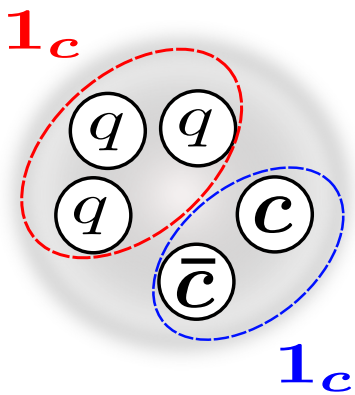

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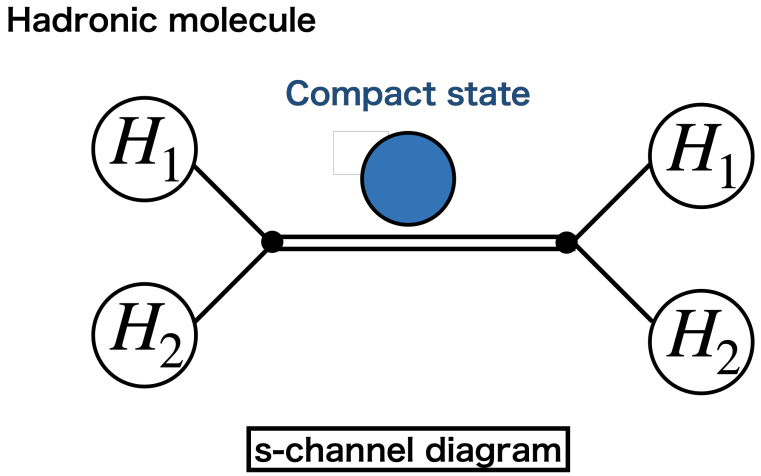
  $\Rightarrow$ Couplings to (qqc) baryon-$(q\bar{c})$ meson, e.g. $\bar{D}\Sigma_c$, are allowed!

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



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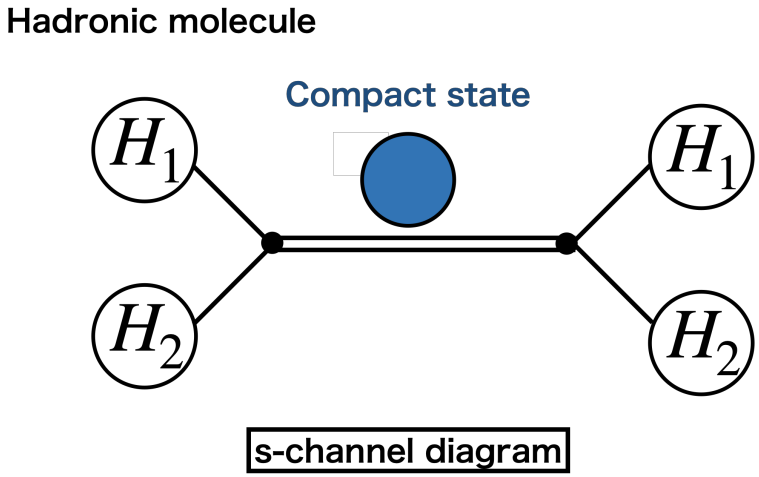
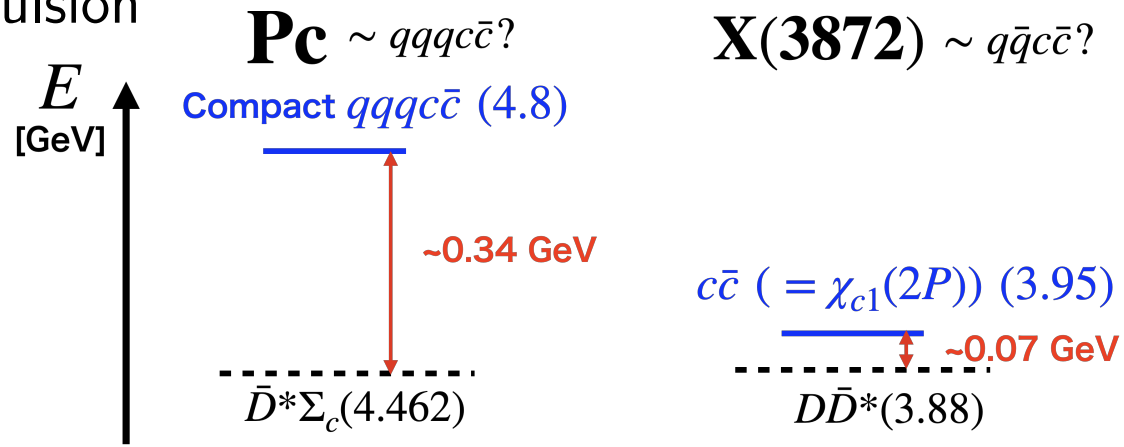


- Coupling to massive compact states producing **an attraction** = Level repulsion



S.Takeuchi, M.Takizawa, PLB**764**(2017)254 S.Takeuchi, et. al, PTEP**2013**,093D01, PTEP**2014**,123D01

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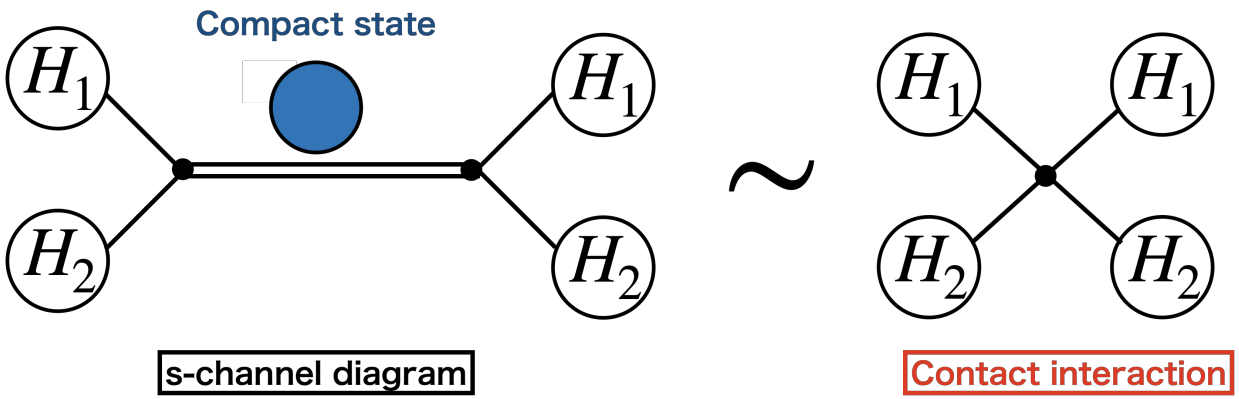
Hadronic molecule



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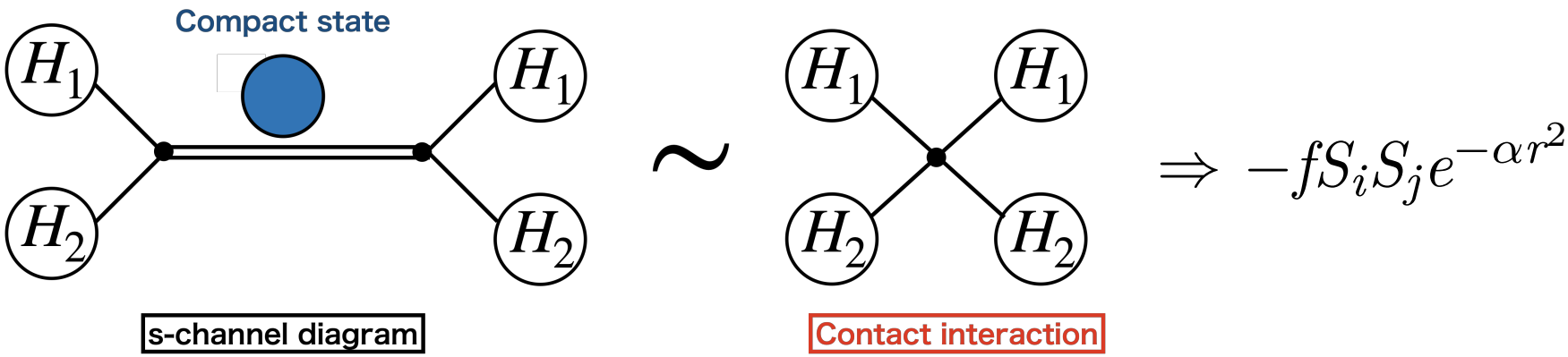

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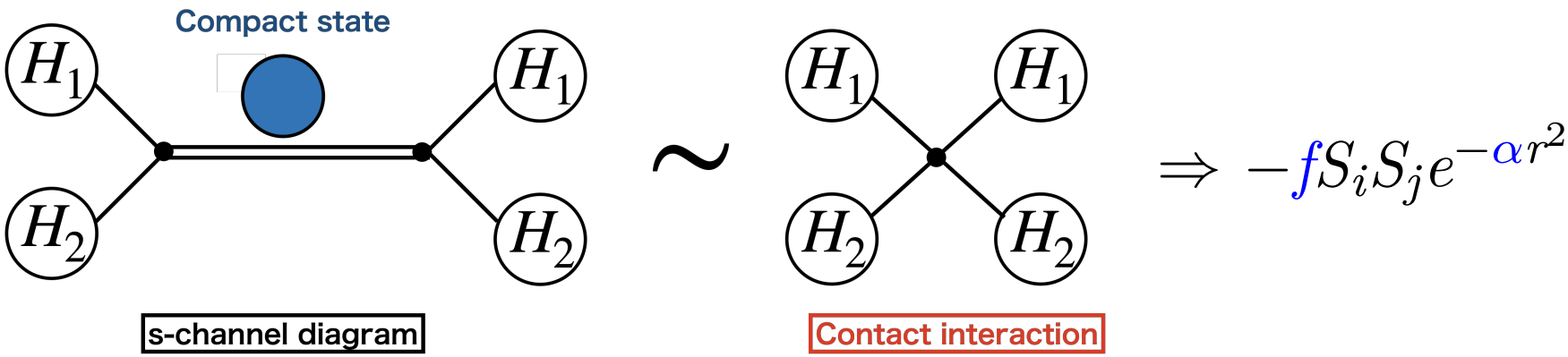

Free Parameters

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

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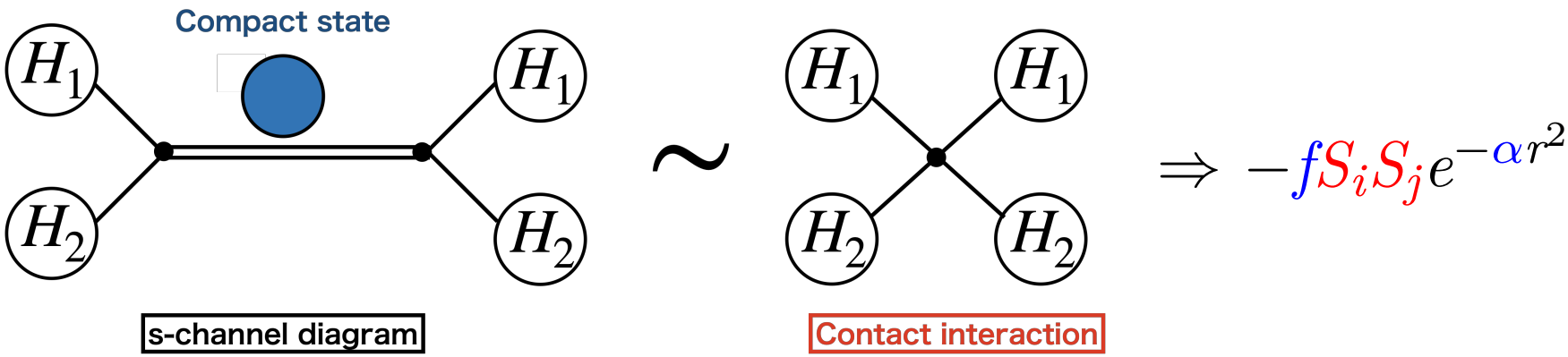

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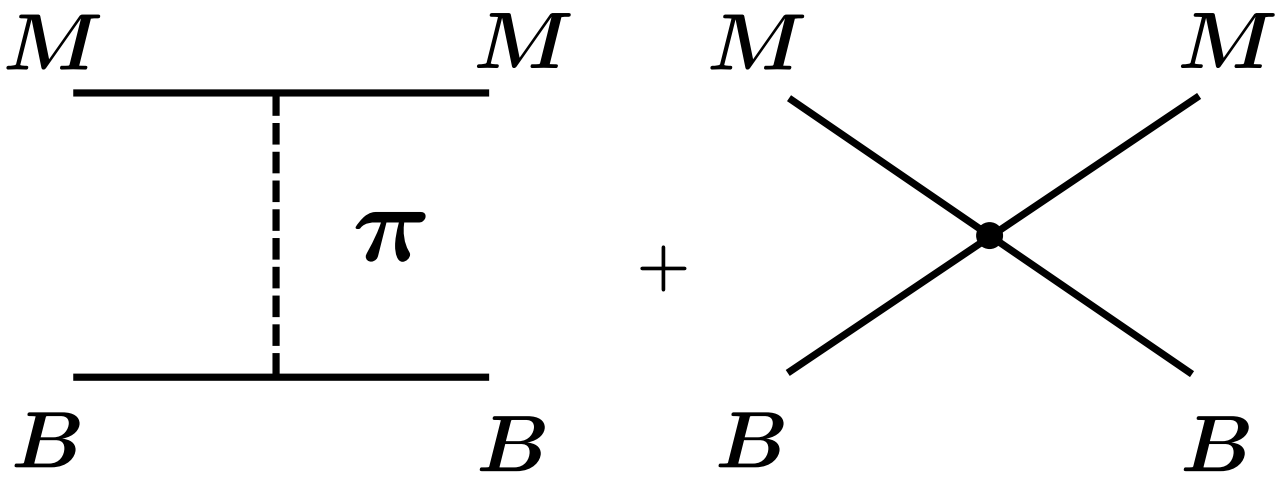
Relative strength S_i $\quad (i,j = \bar{D}^{(*)}\Lambda_c, \bar{D}^{(*)}\Sigma_c^{(*)})$

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

Numerical Results for Hidden-charm sector



Long range int.

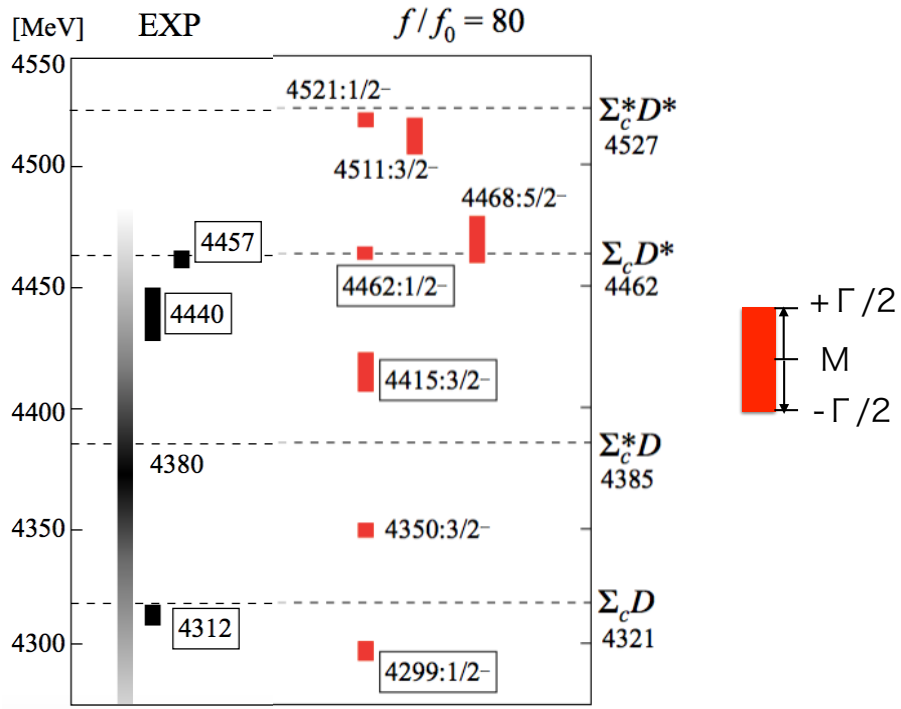
Short range int.
(Gaussian)

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)



($f_0 = 6$ MeV)

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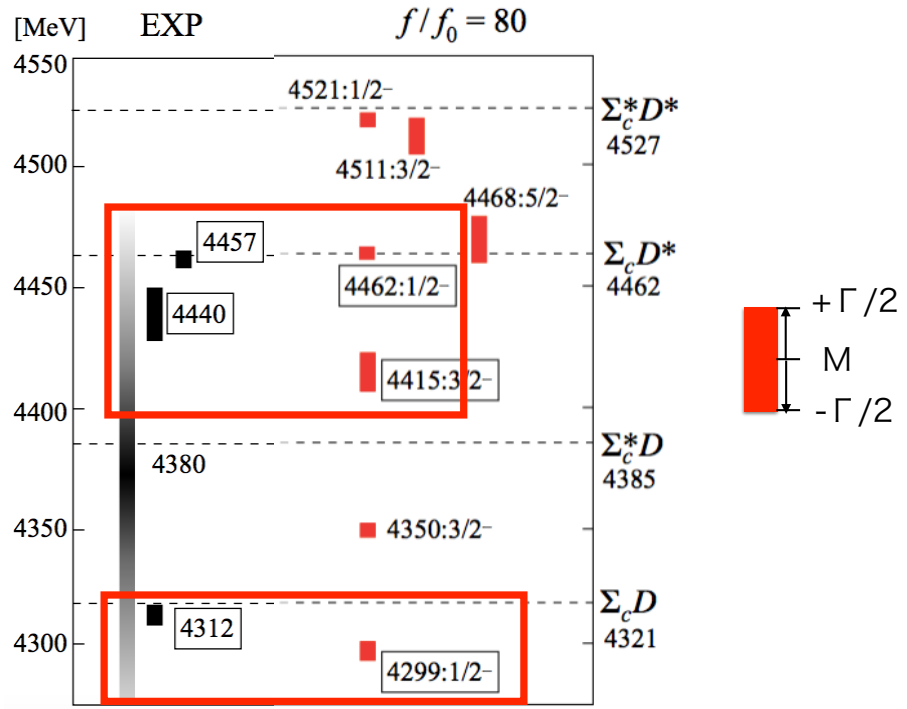

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- **Agreement with $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$**

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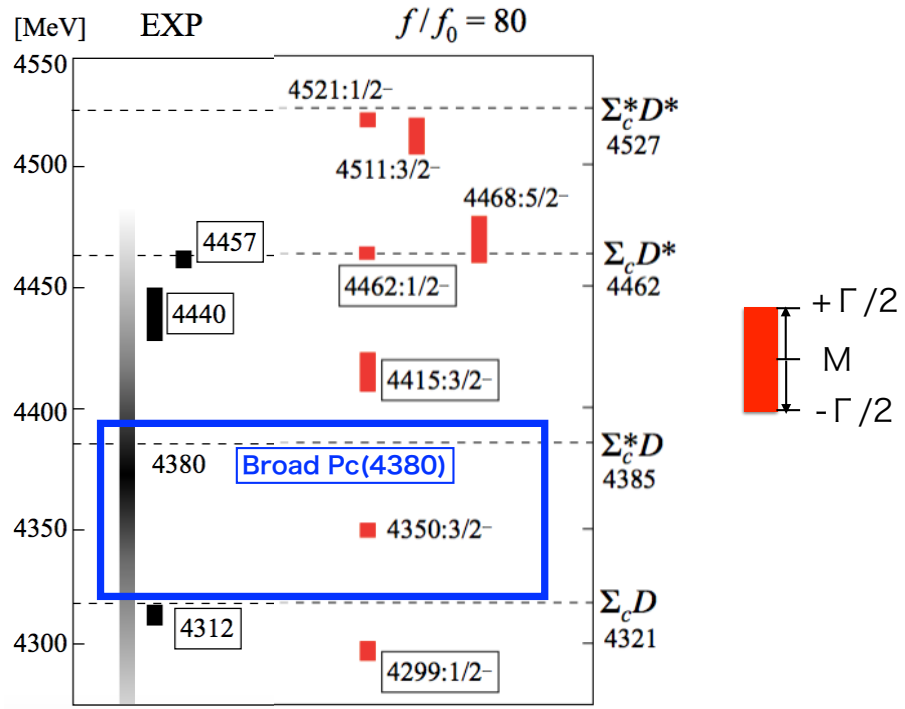

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- For Broad $P_c(4380)$, we obtain the similar mass. But width...?

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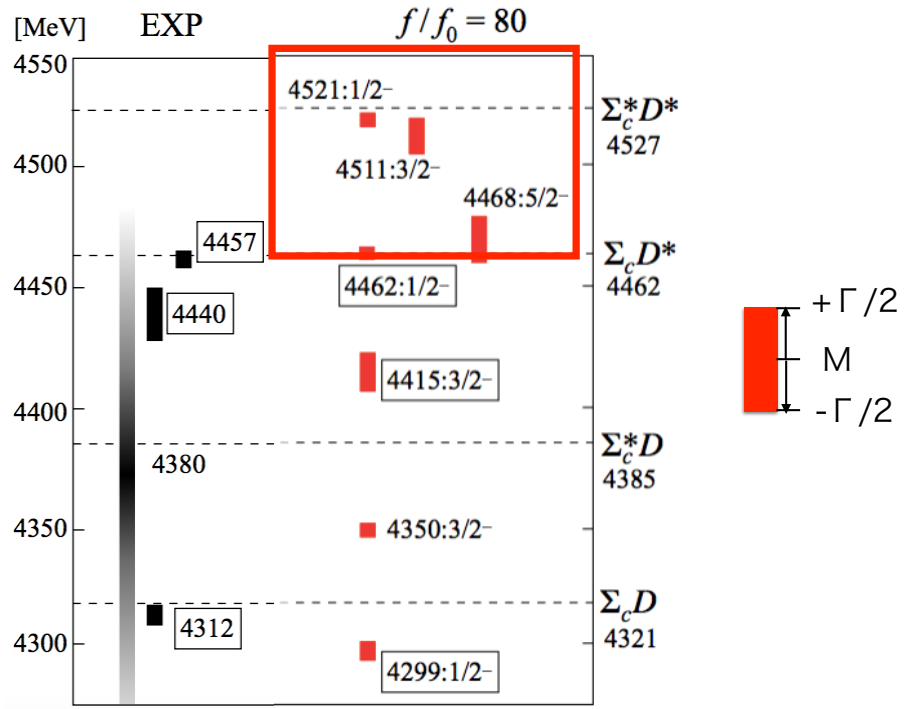

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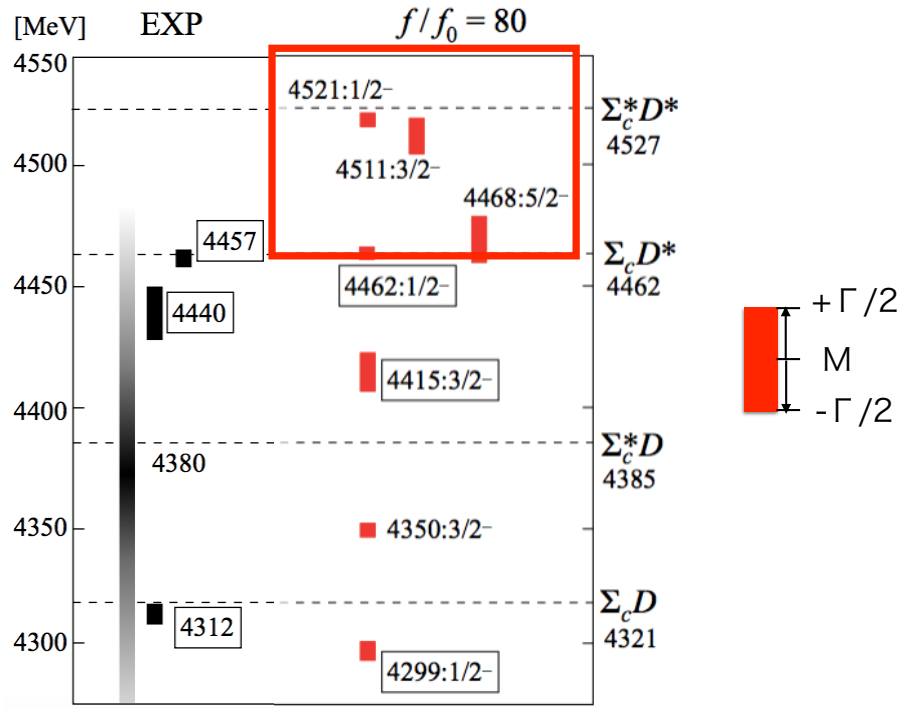
- **Agreement with $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$**
- For Broad $P_c(4380)$, we obtain the similar mass. But width...?
- Predictions: $(1/2^-, 3/2^-, 5/2^-)$ states below $\bar{D}^* \Sigma_c^*$

For New P_c states by LHCb in 2019

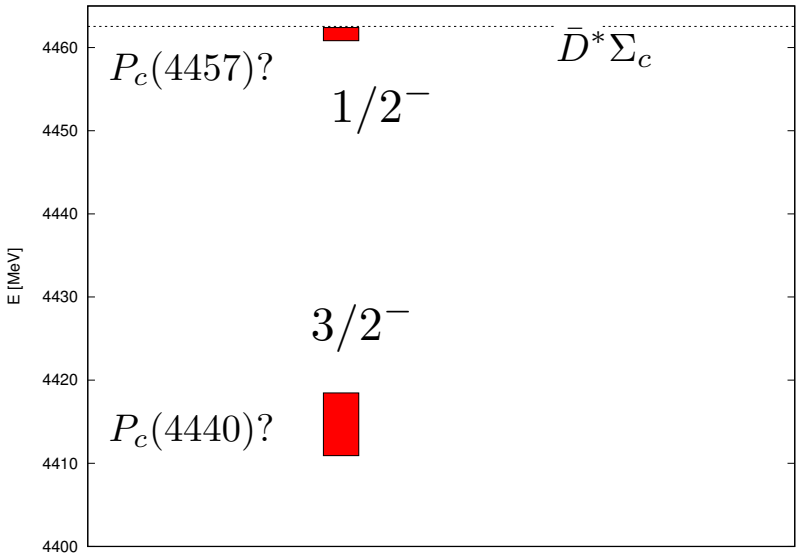
Y.Y., H.Garcia-Tecocoatzi, .**01** (2020) 091502(R)



($f_0 = 6$ MeV)

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



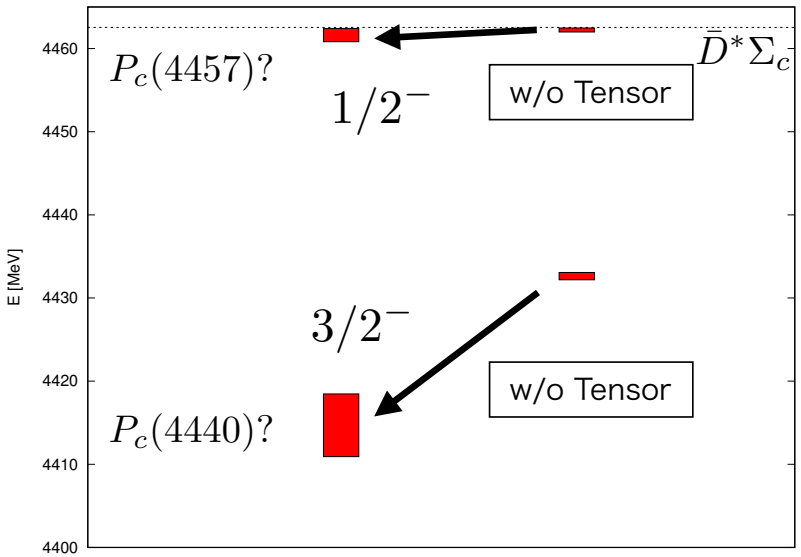
- Our J^P assignment

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

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

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

Role of Interactions in P_c



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

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

- 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]

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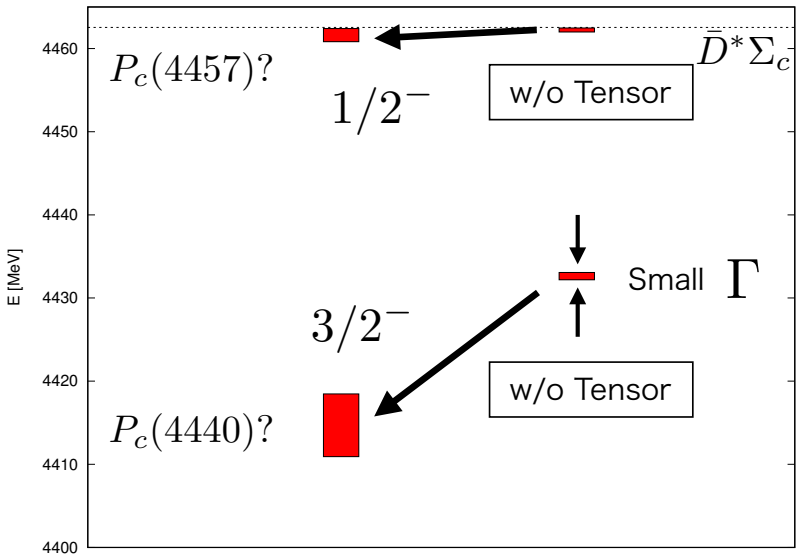
Role of Interactions in P_c



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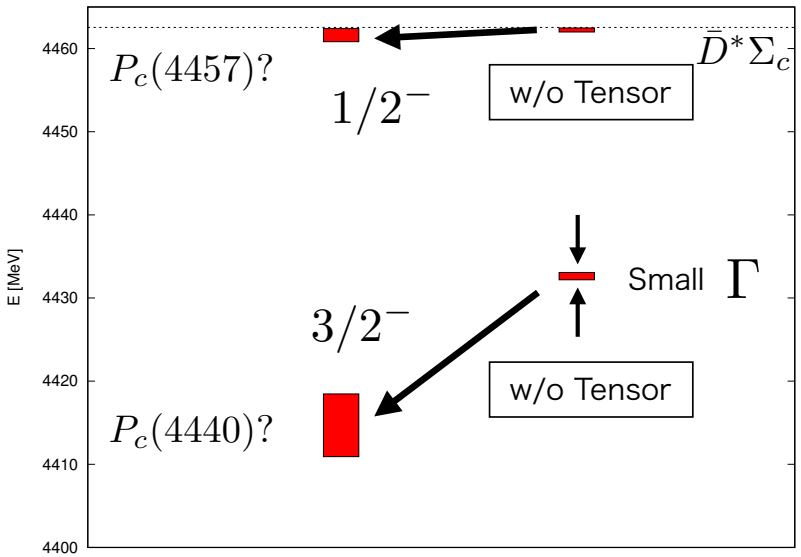
- V^{5q}: Major role to determine **Energy Levels**

Role of Interactions in P_c



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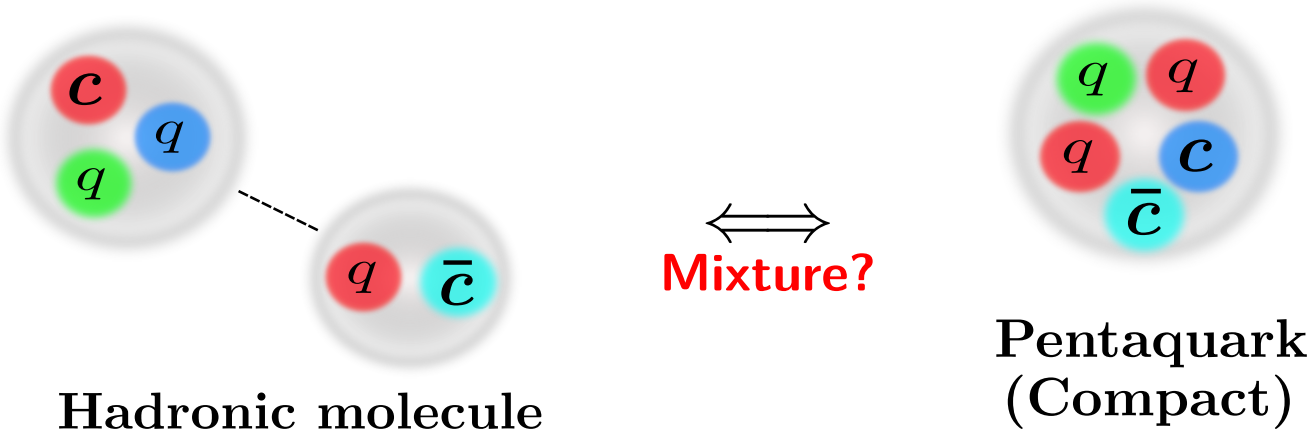
- V^{5q}: Major role to determine **Energy Levels**
- V^π: Major role to enhance **Decay Width** (Channel-coupling effect)

Today's talk

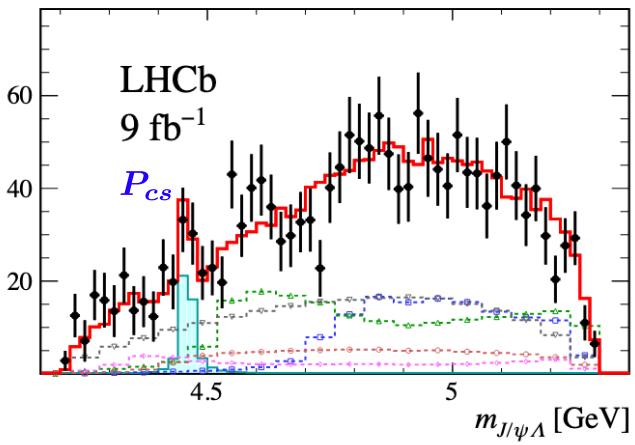
Exotic hadrons as hadronic molecule + compact state



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 $P_{cs}(qqsc\bar{c})$ 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 ?

  $M = 4458.8 \pm 2.9^{+4.7}_{-1.1}$ 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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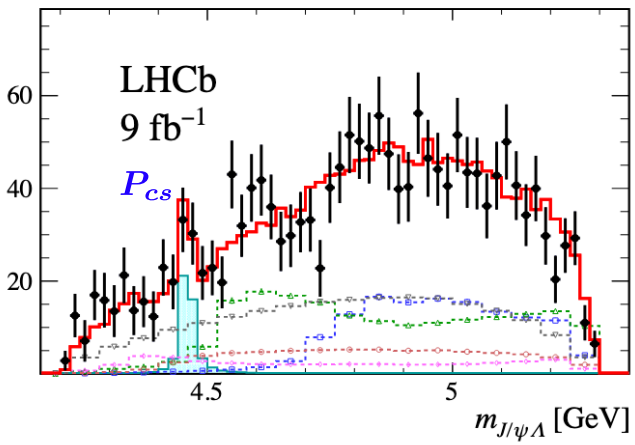

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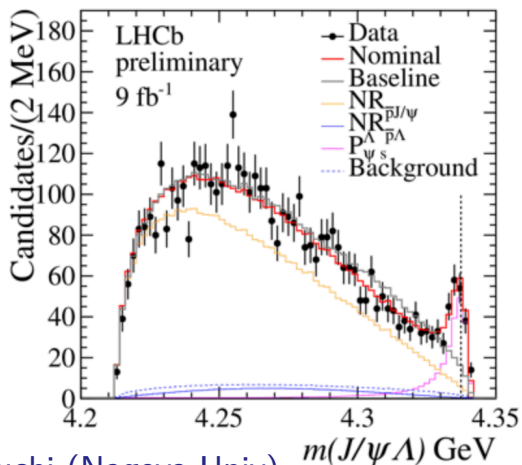
- $P_{cs}(4338)$ in 2022

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



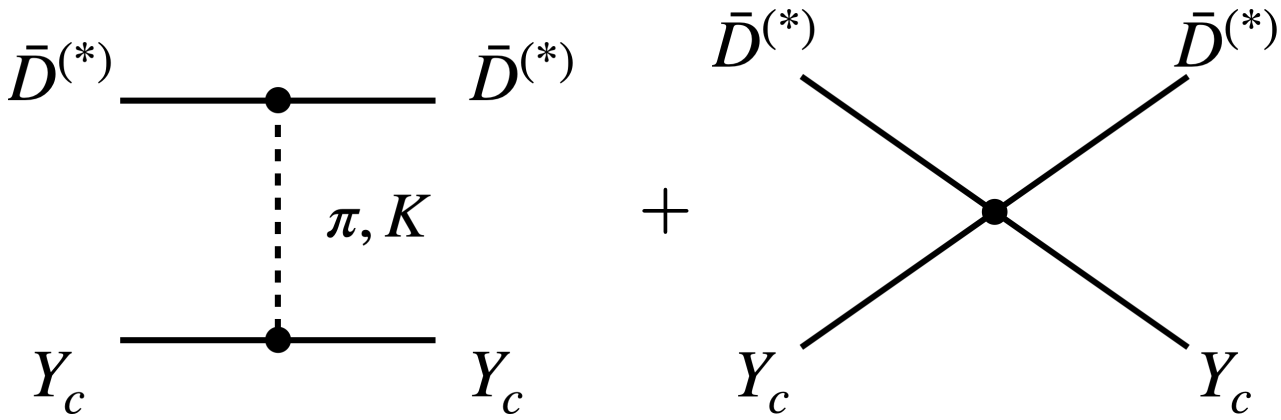
$M = 4338.2 \pm 0.7 \pm 0.4$ MeV

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

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

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

Numerical Results for Strange Hidden Charm



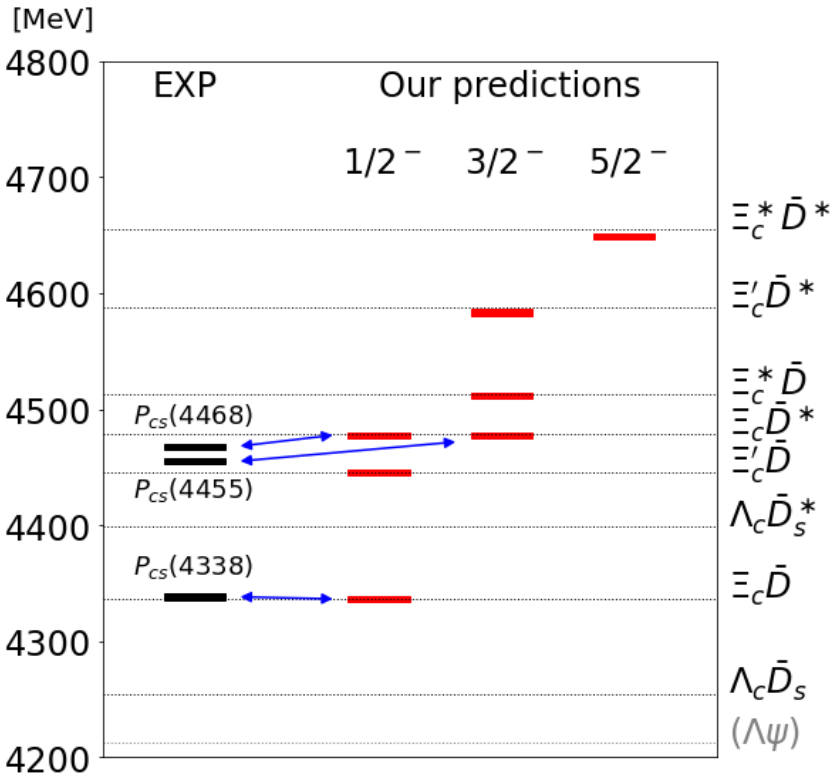
Long range int. Short range int. (Gaussian)

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**
  $\leftrightarrow P_{cs}(4468), P_{cs}(4455)$?

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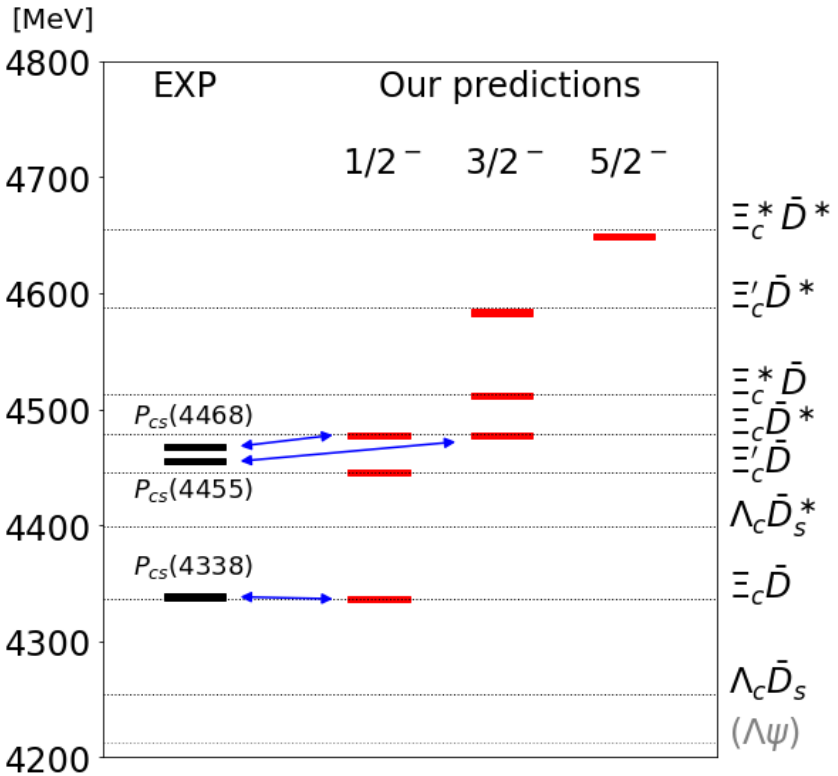

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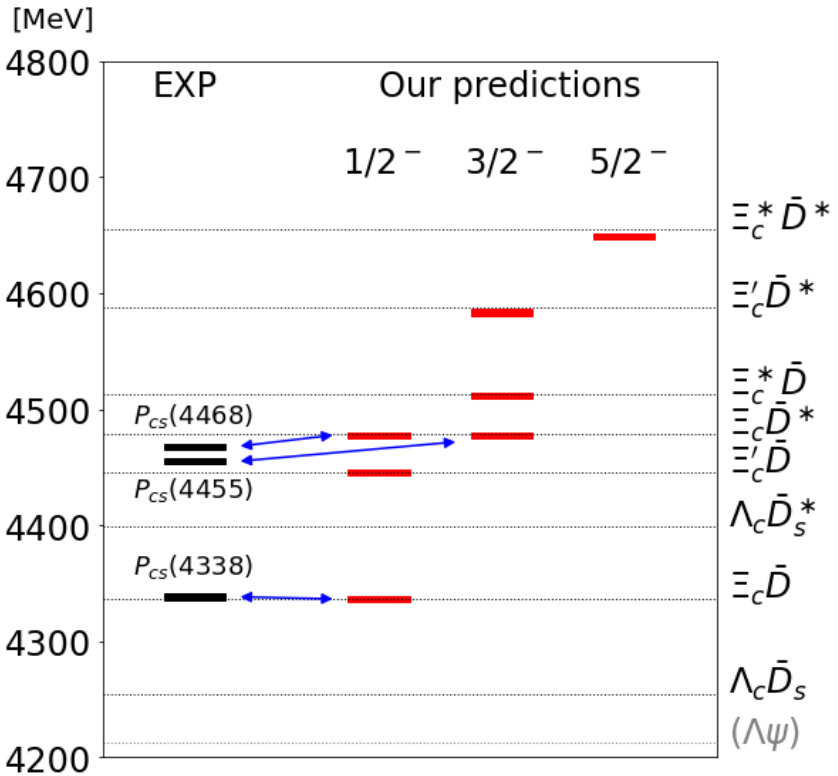

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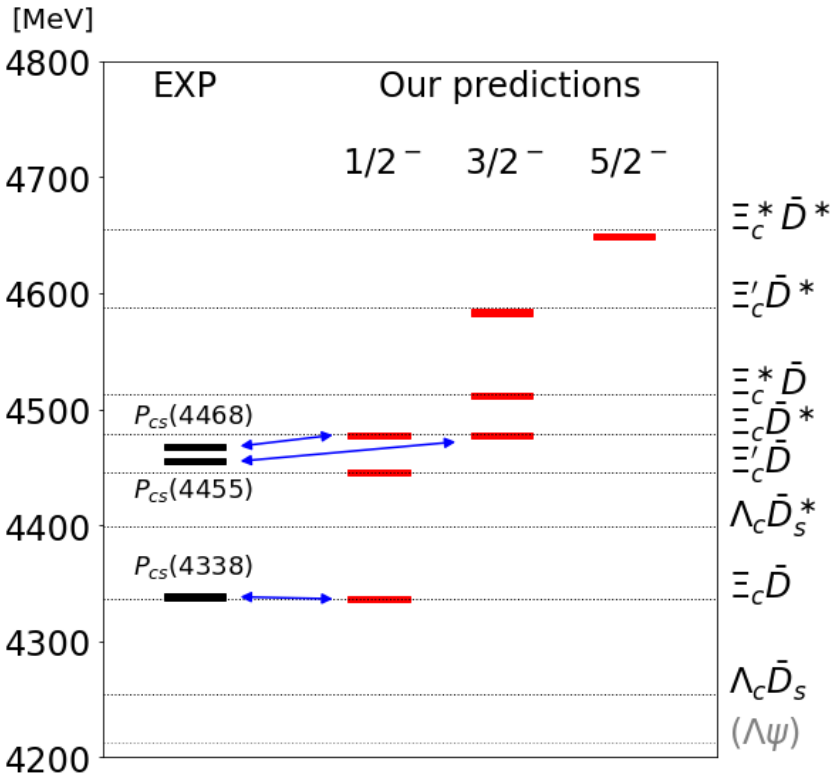
- **Four new predictions**

Rich structure near the thresholds

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

Comparing EXP with the predicted masses



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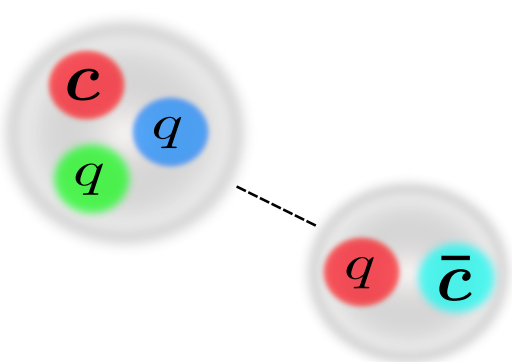
- **Four new predictions**

Rich structure near the thresholds

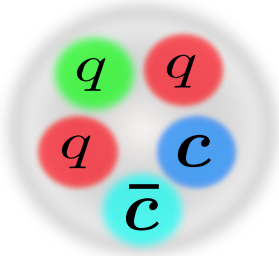
- The short-range interaction plays the important role to **generate the attraction** $\rightarrow$ Without the short-range int, no bound state is found.
- π exchange dominates to determine Γ (Channel-coupling effect)

Summary



Hadronic molecule

Mixture?



Pentaquark (Compact)

- 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]

Thank you for your kind attention.