P_{cs} pentaquarks as a mixture state of hadronic molecules and compact multiquarks

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in collaboration with

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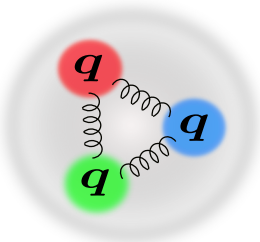
Atsushi Hosaka (RCNP, Osaka Univ.), Elena Santopinto (INFN Genoa),

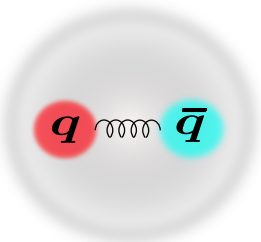
Sachiko Takeuchi (Japan Coll. Social Work), Makoto Takizawa (Showa Pharmaceutical Univ.),

International symposium on Clustering as a Window on the Hierarchical Structure of Quantum Systems (CLUSHIQ2022), Sendai, Japan
31 Oct - 3 Nov, 2022

Hadrons as a quark cluster

- Hadron = **Cluster system** of the elementary particle "Quark"
- Ordinary Hadrons: Baryon (qqq) and Meson ($q\bar{q}$)





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

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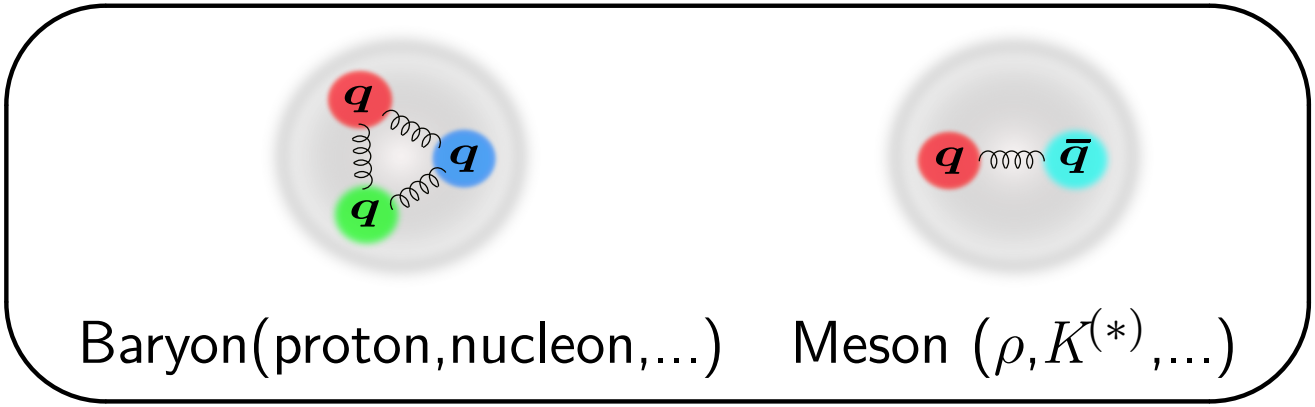
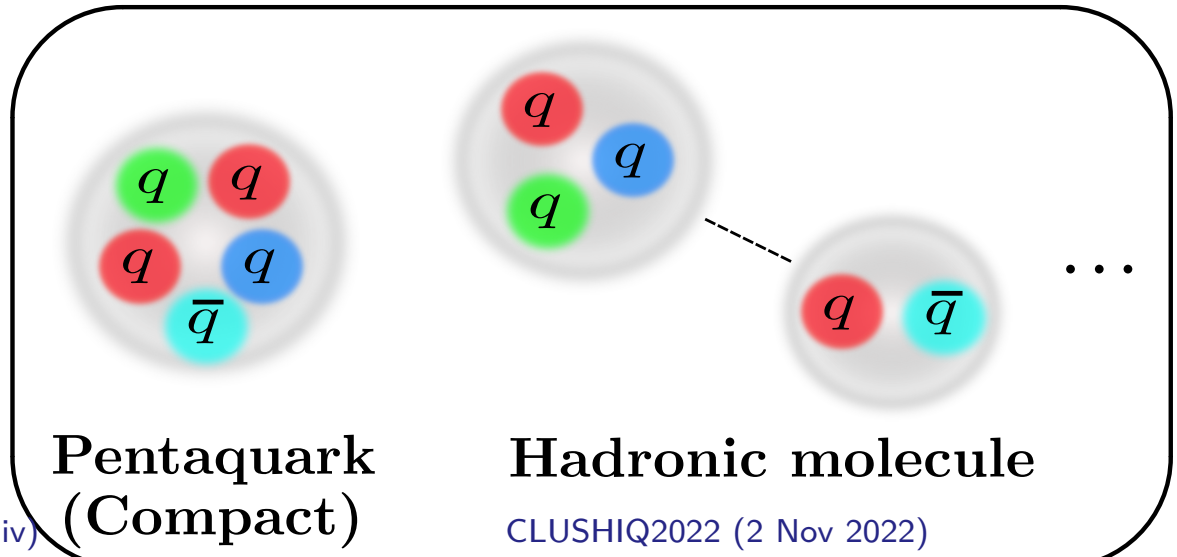
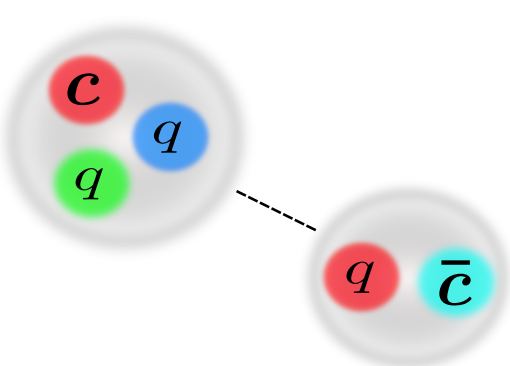


- **Exotic Hadrons ($\neq qqq$, $q\bar{q}$)**
  Compact multiquark cluster? Hadron cluster (= Hadronic molecule)?



Today's talk

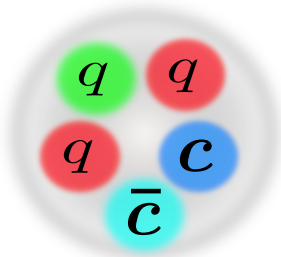
Exotic hadrons as hadronic molecule + compact state



Hadronic molecule

$\Longleftrightarrow$

Mixture?

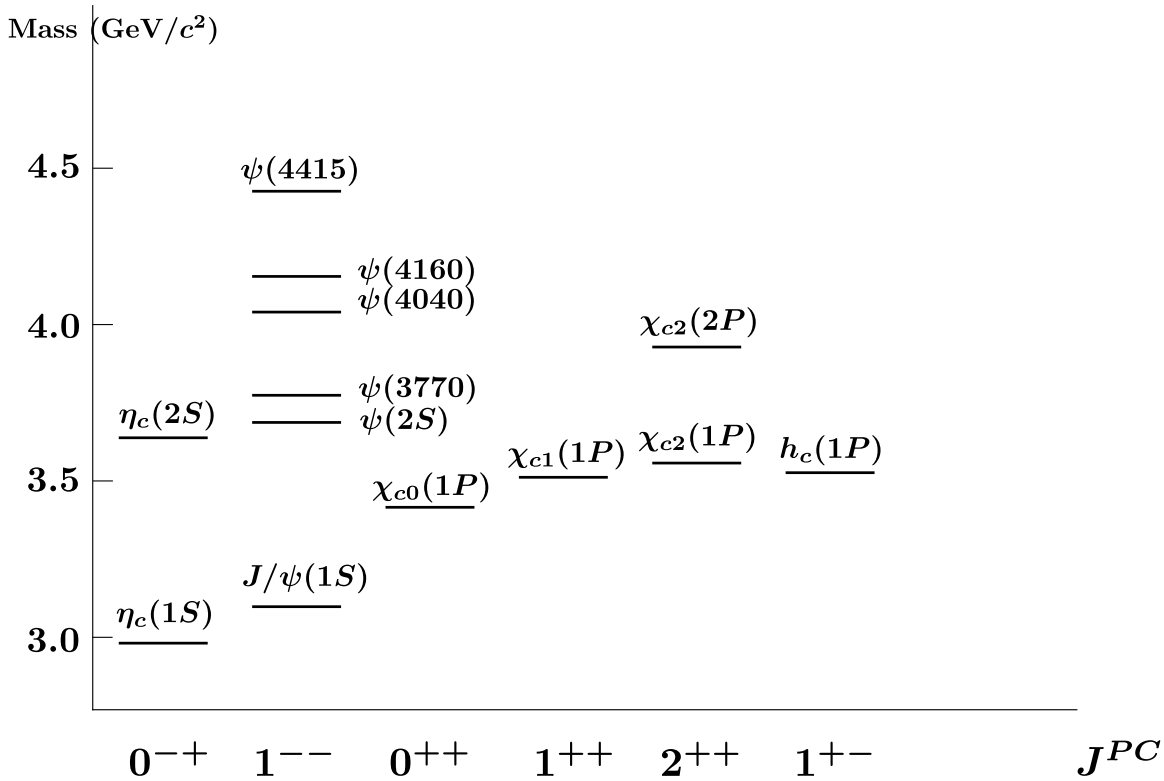


Pentaquark (Compact)

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**

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

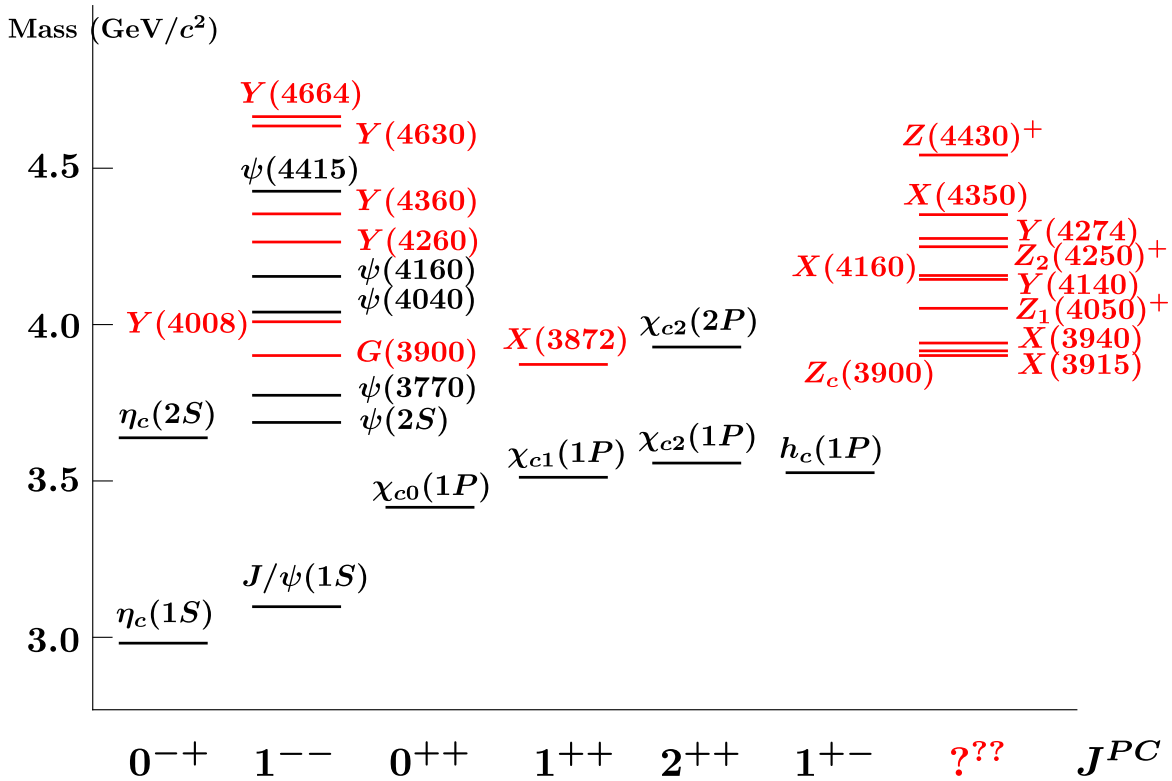
$\Downarrow$

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

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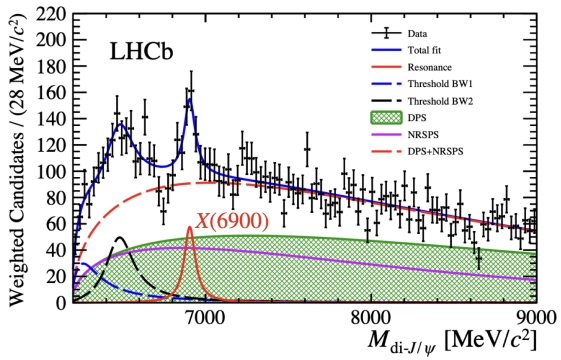
- Exotics $\neq c\bar{c}$ have been observed in the Experiments (BaBar, Belle, BESIII, LHCb,...) since the discovery of **$X(3872)$ in 2003!**

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

Recent reports of Exotic hadrons!

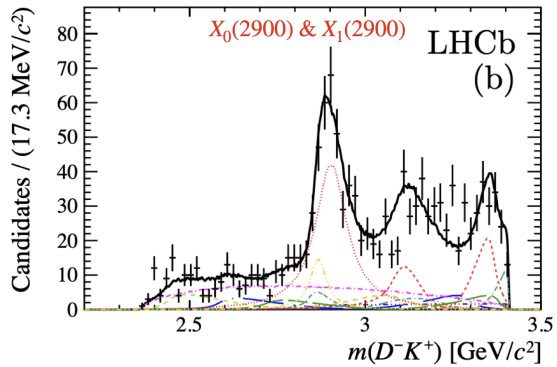
- $X(6900)$ $(cc\bar{c}\bar{c}?)$

LHCb, Science Bulletin 65 (2020) 1983



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

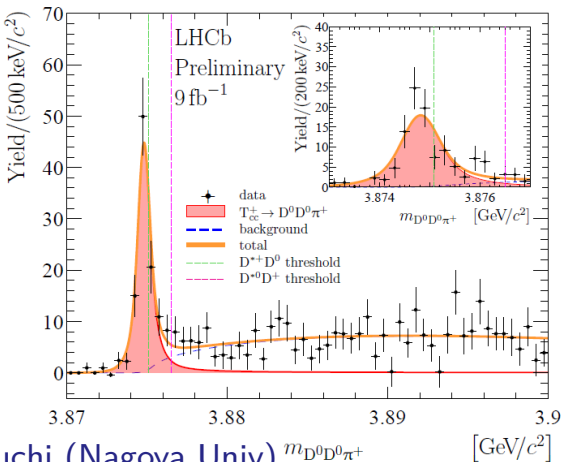
LHCb, PRL125, 242001 (2020), PRD102, 112003 (2020)



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

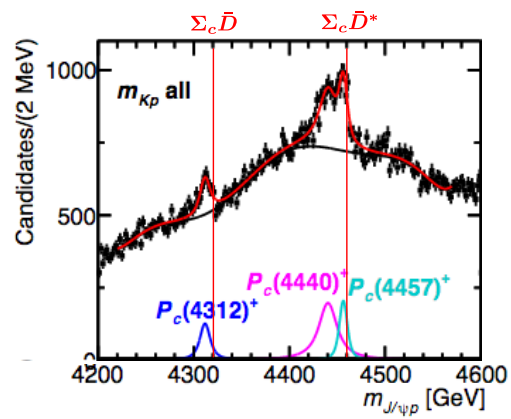
LHCb, Nature Phys. **18** (2022) 751-754,

Nature Commun. **13** (2022) 3351



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

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



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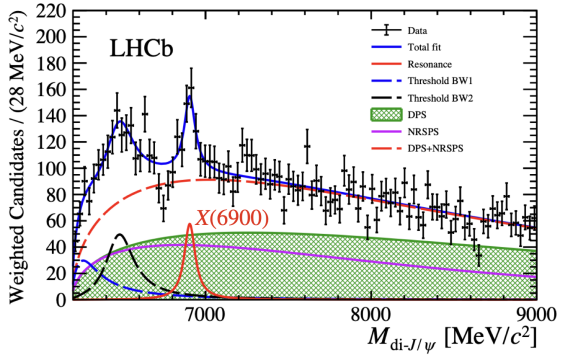

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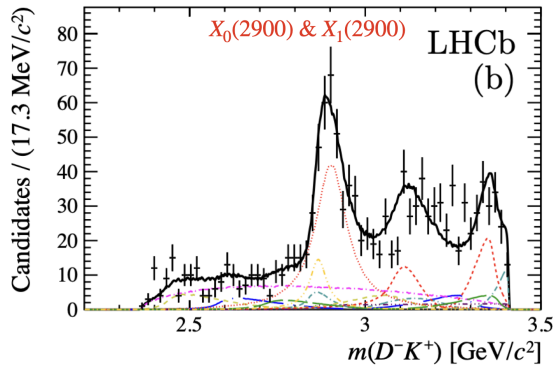

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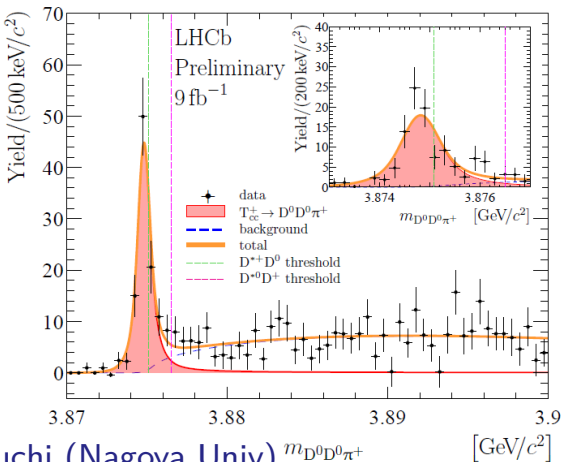
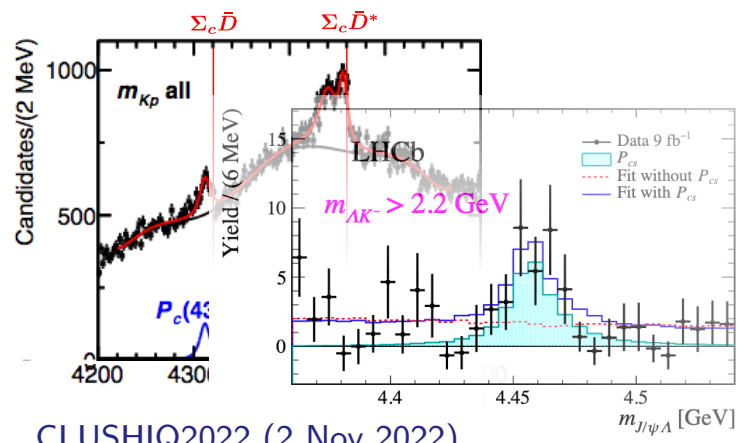


- P_c $(uudc\bar{c}?)$, P_{cs} $(udsc\bar{c}?)$

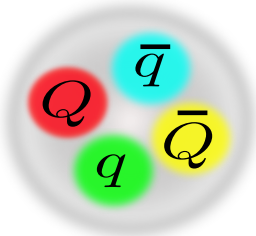
LHCb PRL**115**(2015)072001, PRL**122**(2019)222001

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

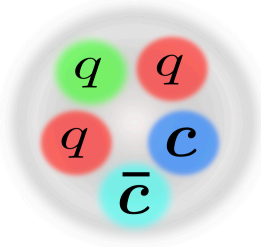


Candidates of Exotic structures?

Compact multiquarks

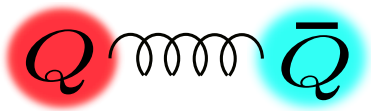


Tetraquark



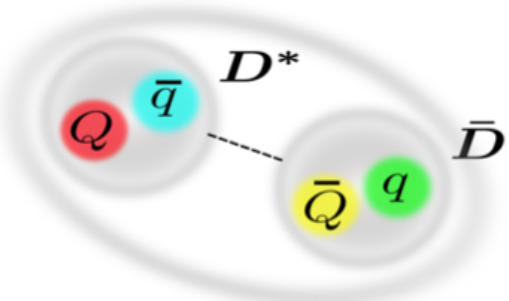
Pentaquark

$Q\bar{Q}g$ Hybrid

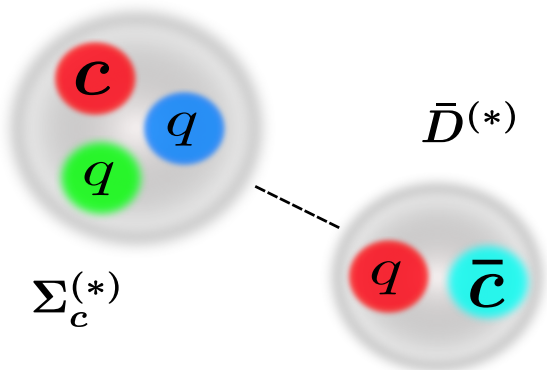


Hadronic molecules

Near thresholds?



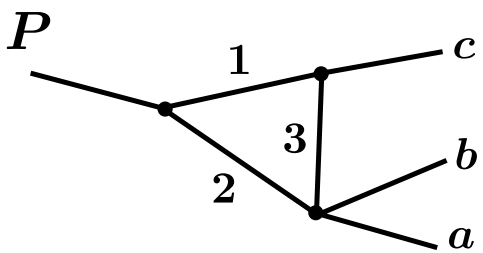
Meson-Meson



Meson-Baryon

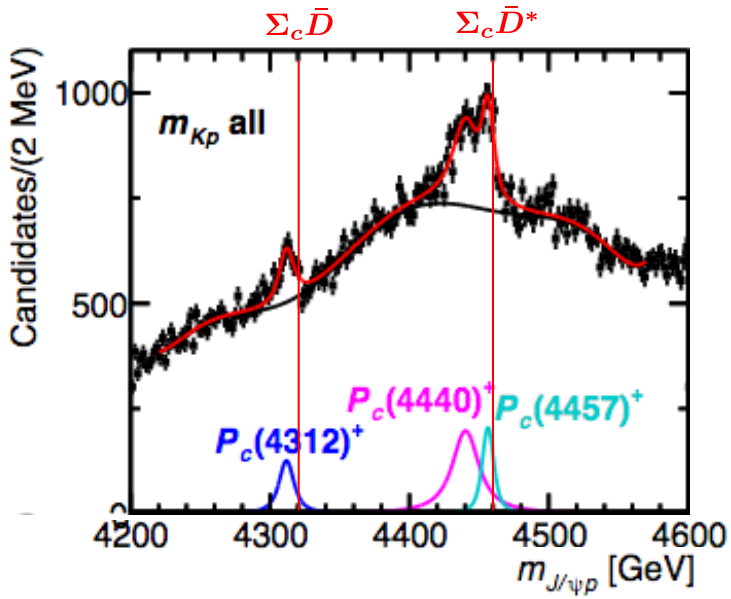
Triangle Singularity

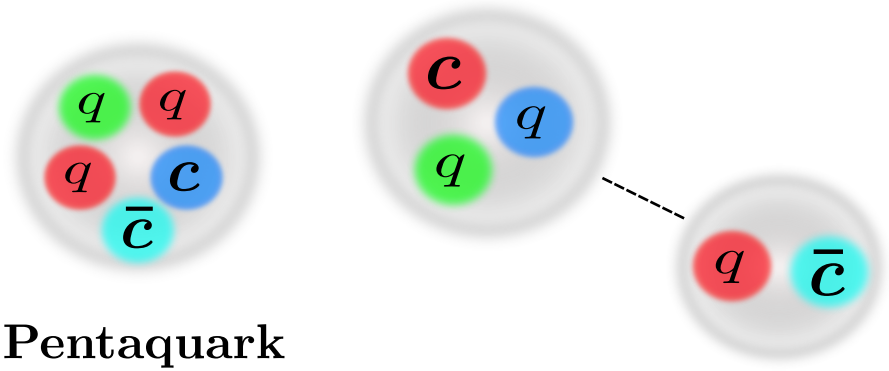
Near thresholds?



(w/o Resonance)

P_c pentaquarks



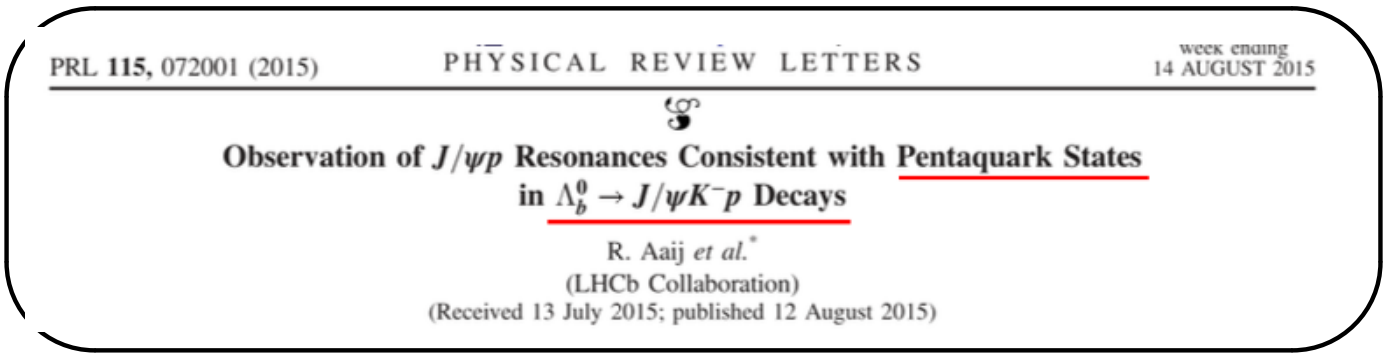


Pentaquark (Compact)

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

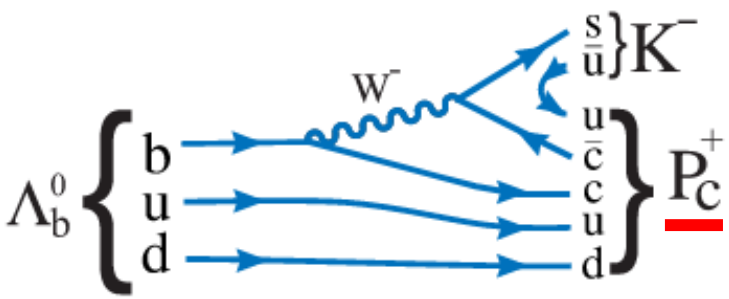

PRL 115, 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

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

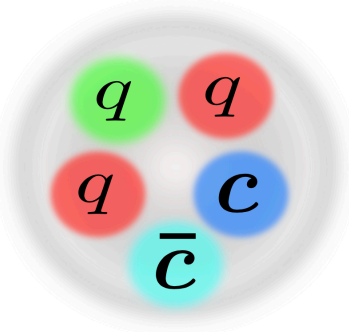
R. Aaij *et al.**
(LHCb Collaboration)
(Received 13 July 2015; published 12 August 2015)

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

$c\bar{c}uud$ state ?



$\Rightarrow$

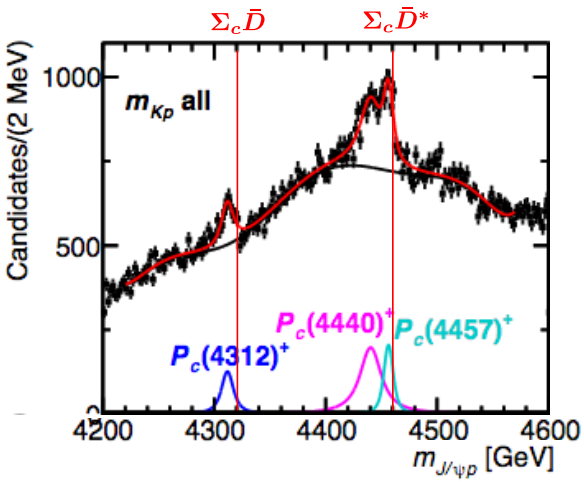


$P_c(4380)$: M =4380 MeV, Γ= 205 MeV

$P_c(4450)$: 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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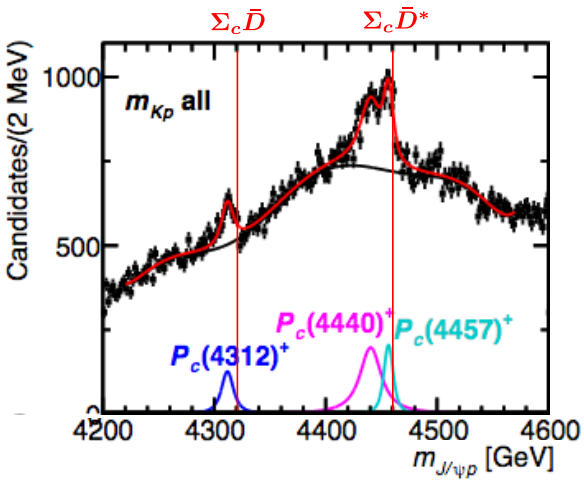

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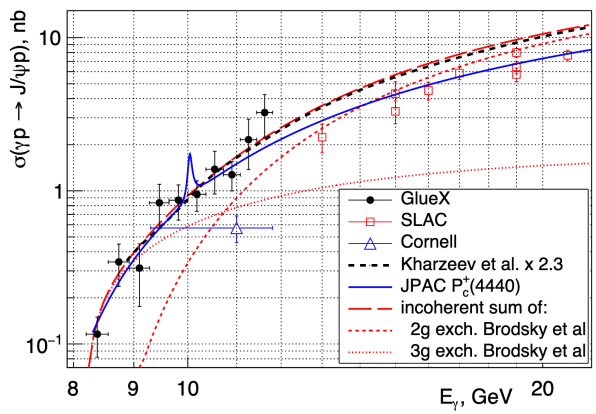
- Complementary experiments: $\gamma p \to J/\psi p$ in GlueX@J-Lab

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

  $\to$ No triangle singularity

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



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),

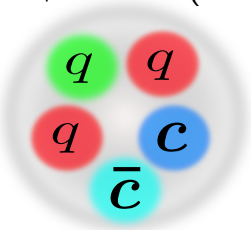
  C. W. Xiao, *et al.* (2019), M.-Z. Liu, *et al.* (2019), M. L. Du, *et al.* (2019),

  ...

- Triangle singularity?
  (Non-resonant explanation)

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

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



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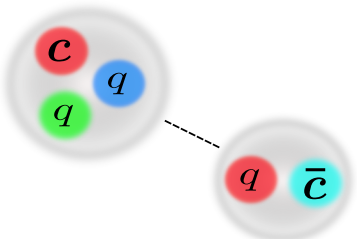
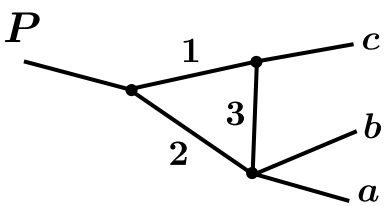


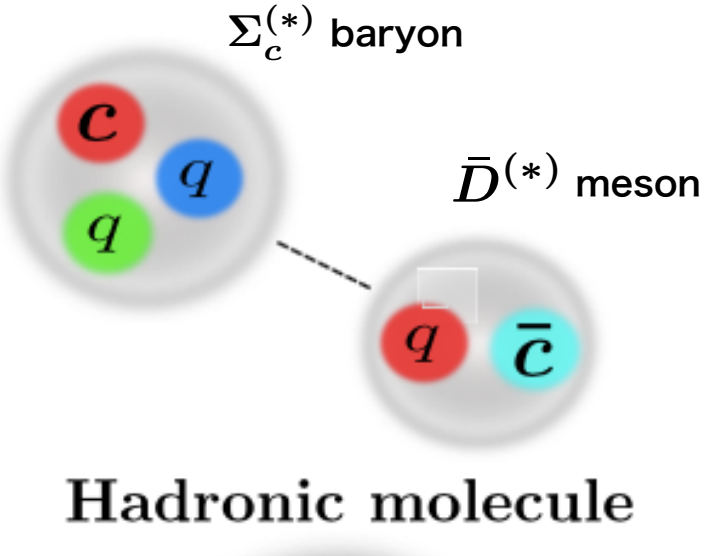
Hadronic molecule



Hadronic molecules?

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

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



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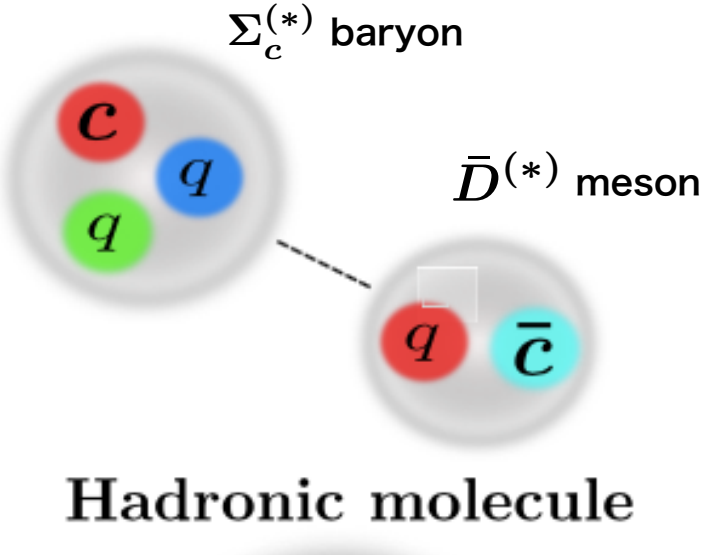
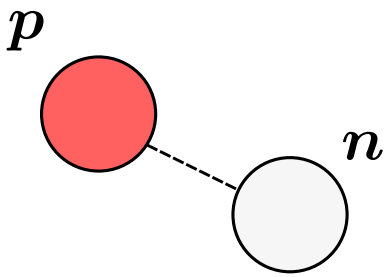


Analogous to Deuteron



$B = 2.2$ MeV

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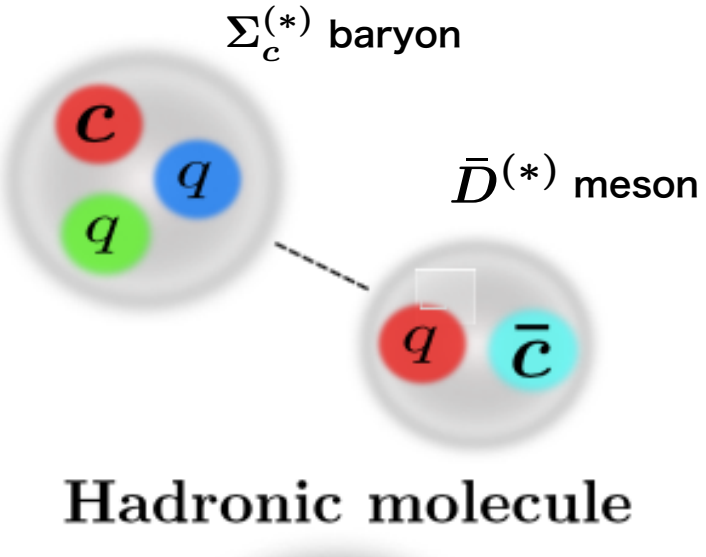
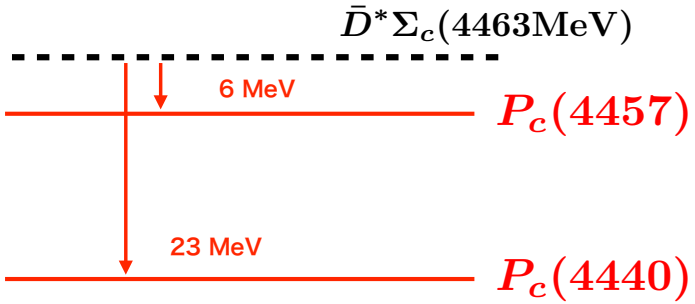


$P_c = \bar{D}^{(*)}\Sigma_c^{(*)}$ molecules?



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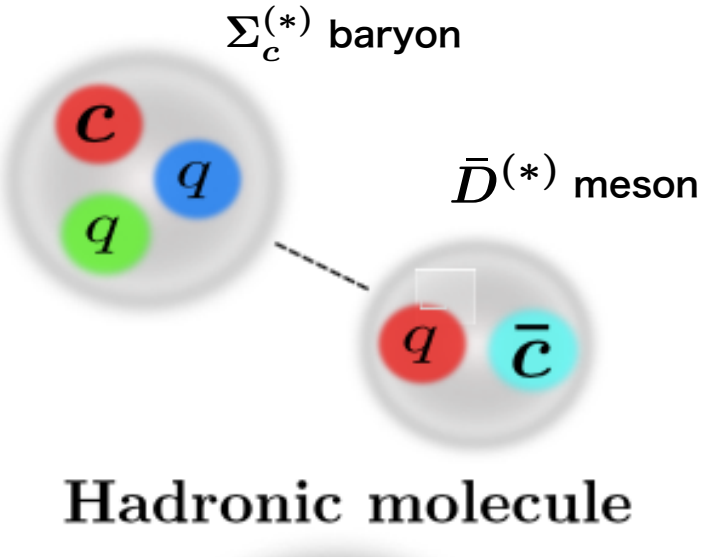

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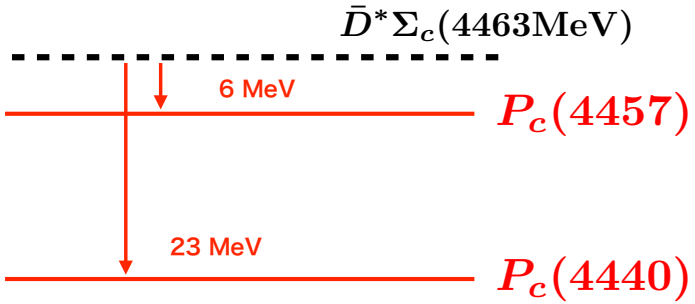
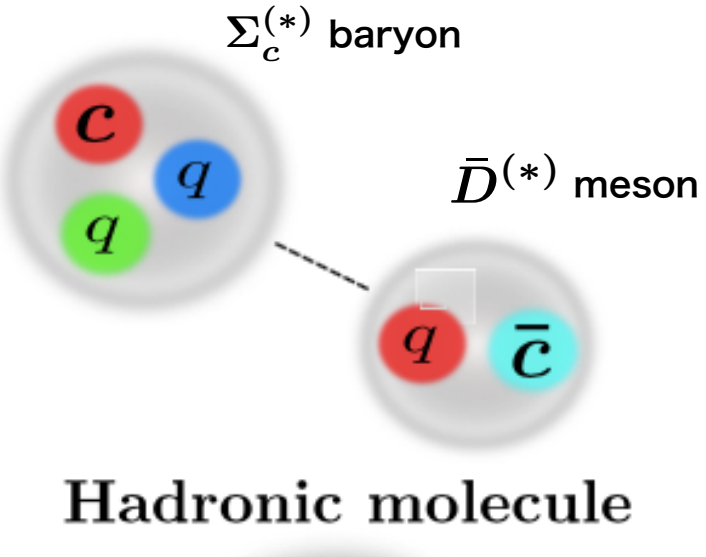


- Exotic hadrons near thresholds
  - $D\bar{D}^*$: $X(3872)$, $Z_c(3900)$,..., DD^*: T_{cc}
  - $B\bar{B}^*$: Z_b, $Z_b{}'$
  - $\bar{D}^{(*)}\Sigma_c^{(*)}$: P_c F. K. Guo, *et. al.*, Rev.Mod.Phys.**90**(2018)015004,Y. Y., *et. al.*, J.Phys.G**47**(2020)053001,...

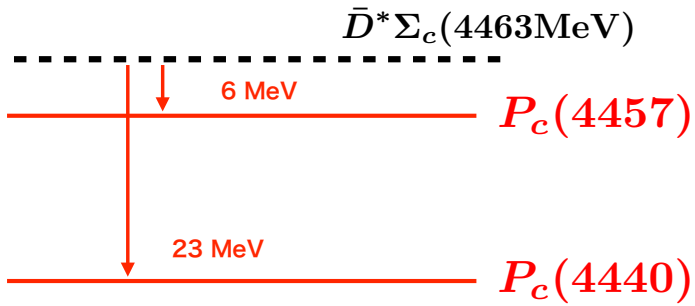
Hadronic molecules?

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

→ expected **near the thresholds**



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



- 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,...

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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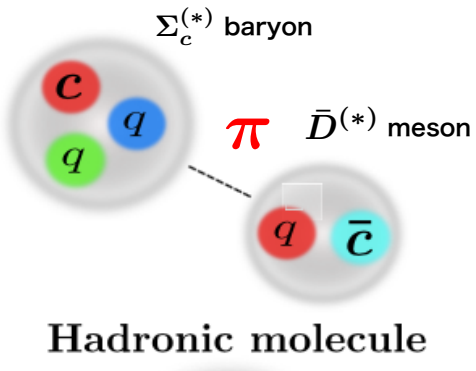
How can we describe hadron interactions?

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

Problem Hadron interactions are **NOT established** yet...
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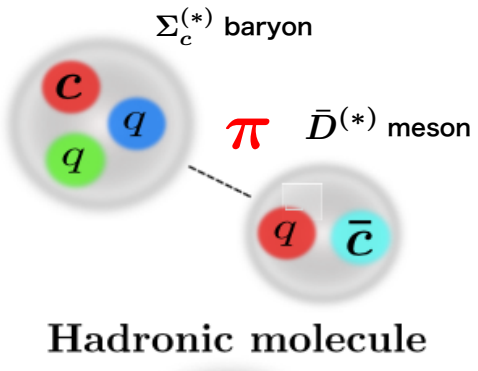
How can we describe hadron interactions?

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

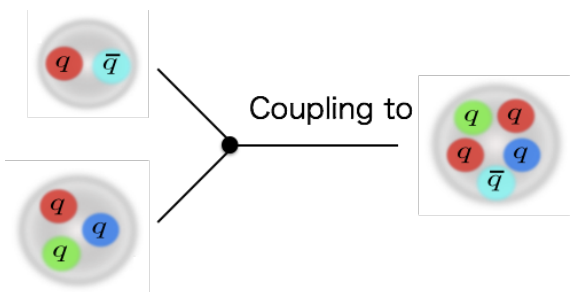
- Long-range int. known in the nuclear force !
- Chiral and Heavy quark spin symmetries

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

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



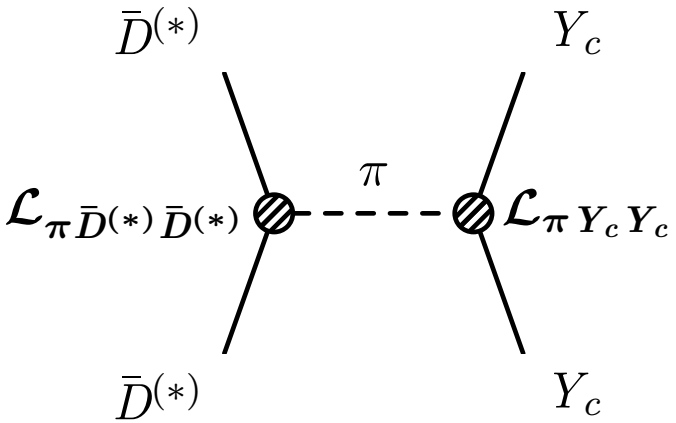
OPEP



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

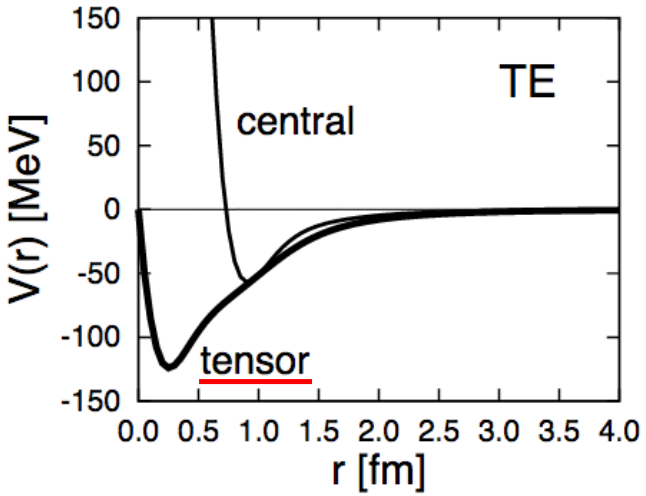


Table 2 Deuteron properties using the AV8' nucleon-nucleon potential.

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

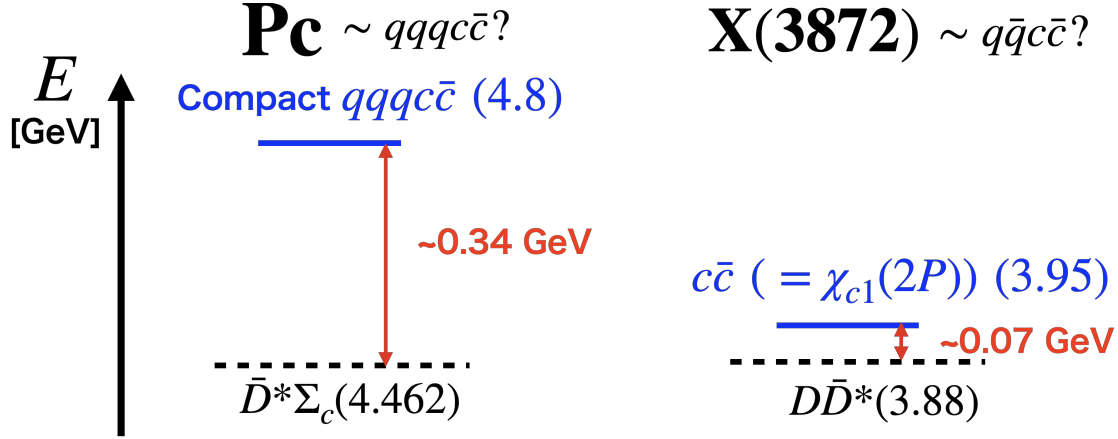
- **Tensor operator** $S_{12}(\hat{r}) = 3(\vec{S}_1 \cdot \hat{r})(\vec{S}_2 \cdot \hat{r}) - \vec{S}_1 \cdot \vec{S}_2$

$\Rightarrow$ $\langle \psi_S | S_{12}\, T | \psi_D \rangle \neq 0$! (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!

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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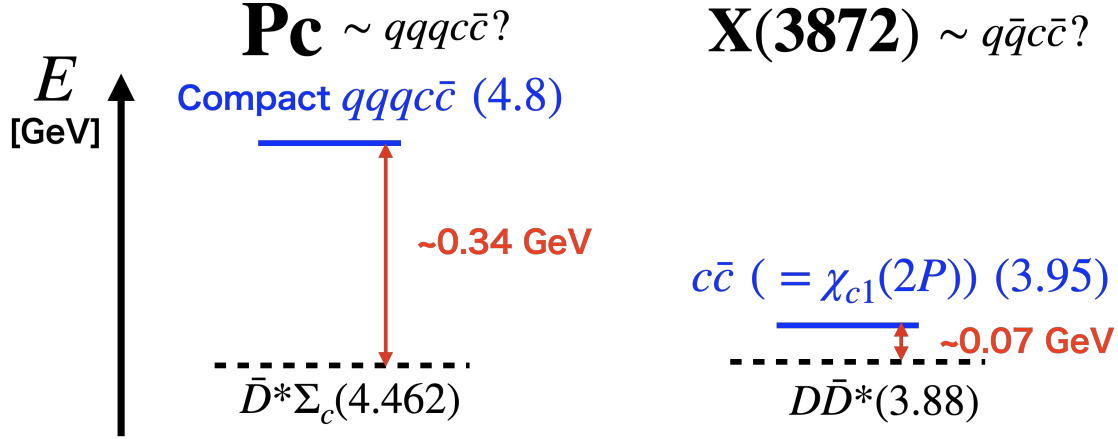

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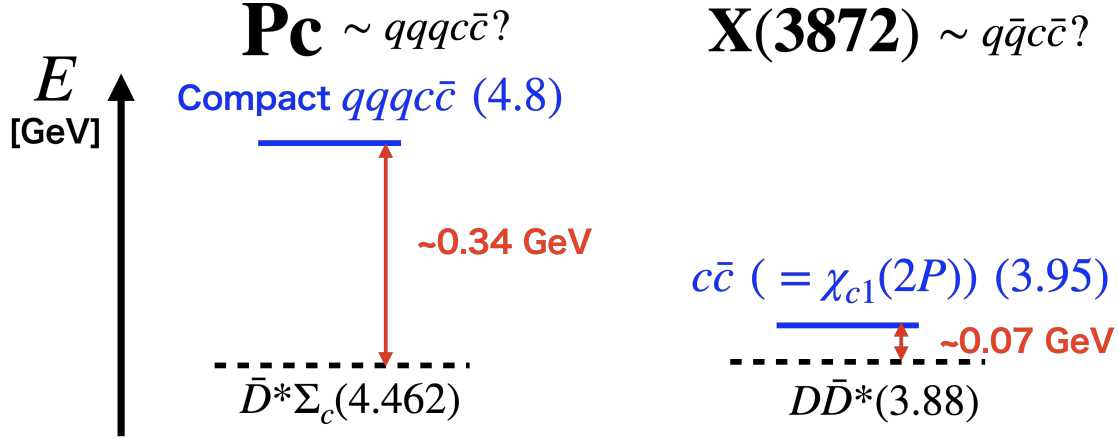
S.Takeuchi, et. al, PTEP**2013**,093D01, PTEP**2014**,123D01

$\Rightarrow$ **Level repulsion generating an attraction** in the hadronic molecules

Mixture of the hadronic molecule and compact state

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

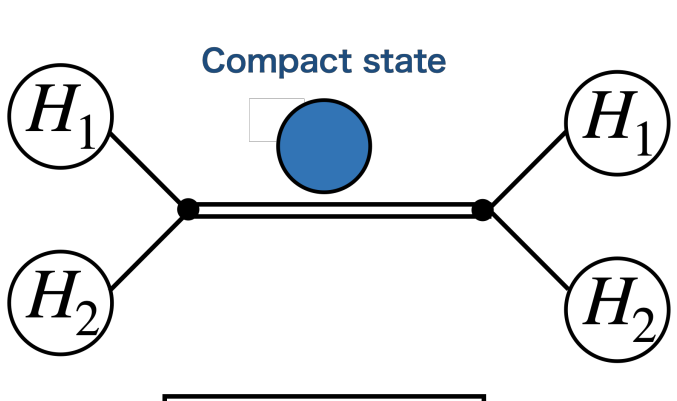


S.Takeuchi, M.Takizawa, PLB**764**(2017)254

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

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

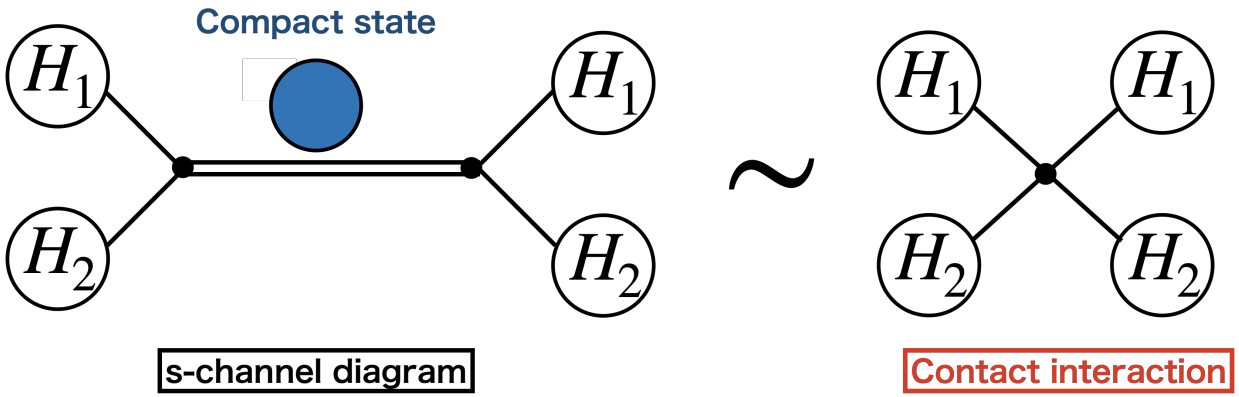
- **Hadronic molecule** coupling to **Compact state** ⇒ Effective hadron interaction



Mixture of the hadronic molecule and compact state

- **Hadronic molecule** + **Compact state** $\Rightarrow$ Effective hadron interaction

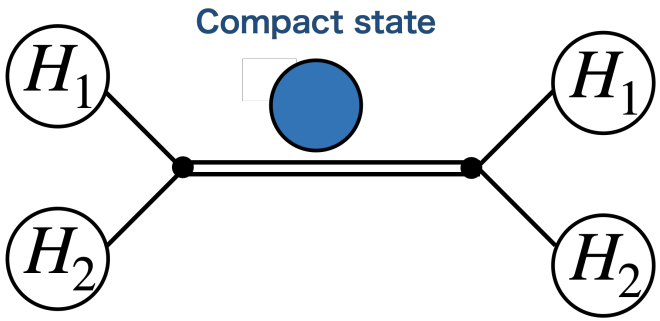
Hadronic molecule



Mixture of the hadronic molecule and compact state

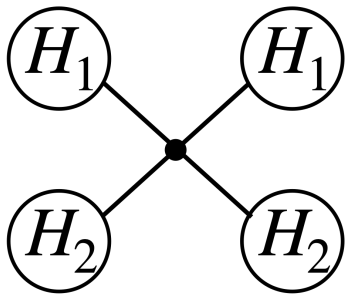
- **Hadronic molecule** + **Compact state** $\Rightarrow$ Effective hadron interaction

Hadronic molecule



s-channel diagram

$\sim$



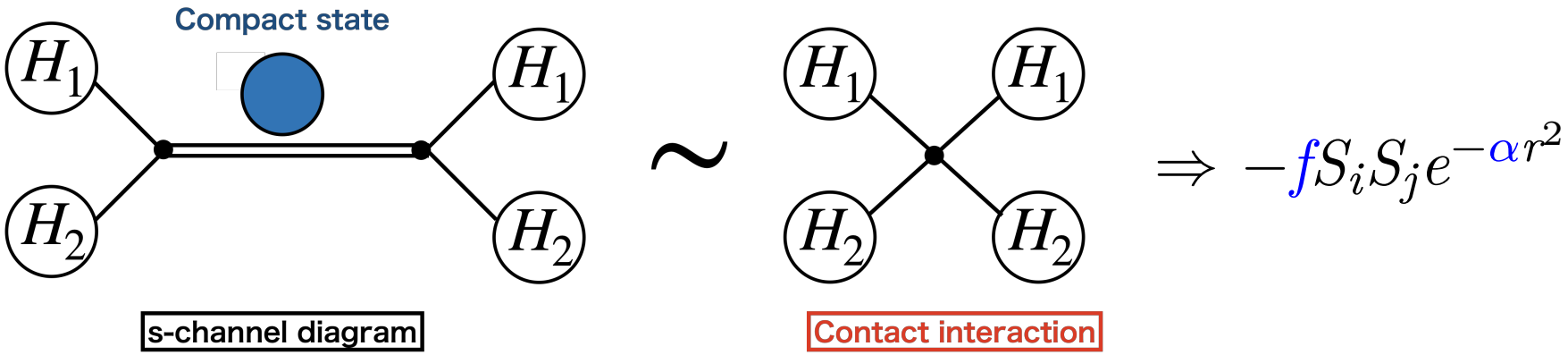
Contact interaction

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

Mixture of the hadronic molecule and compact state

- **Hadronic molecule** + **Compact state** $\Rightarrow$ Effective hadron interaction

Hadronic molecule



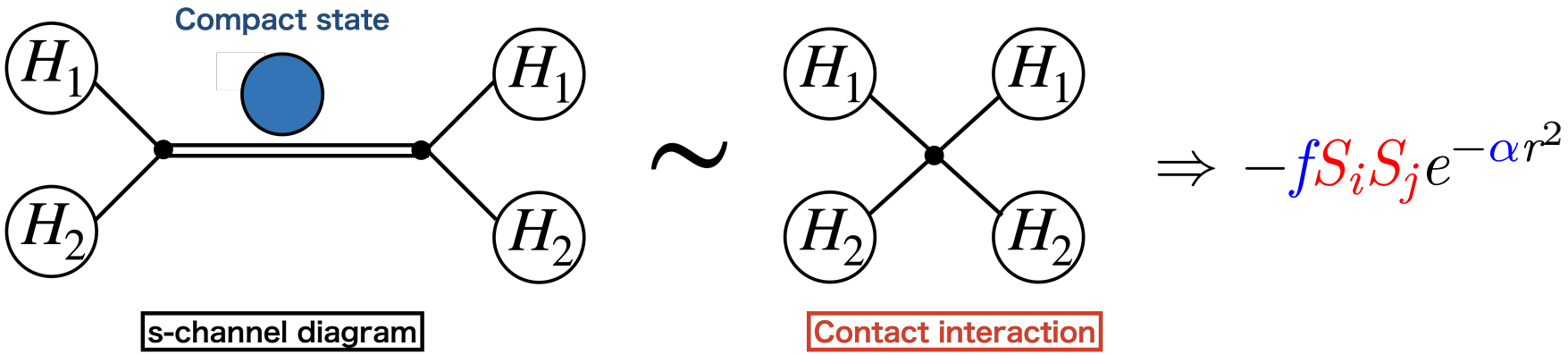
Free Parameters

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

Mixture of the hadronic molecule and compact state

- **Hadronic molecule** + **Compact state** $\Rightarrow$ Effective hadron interaction

Hadronic molecule



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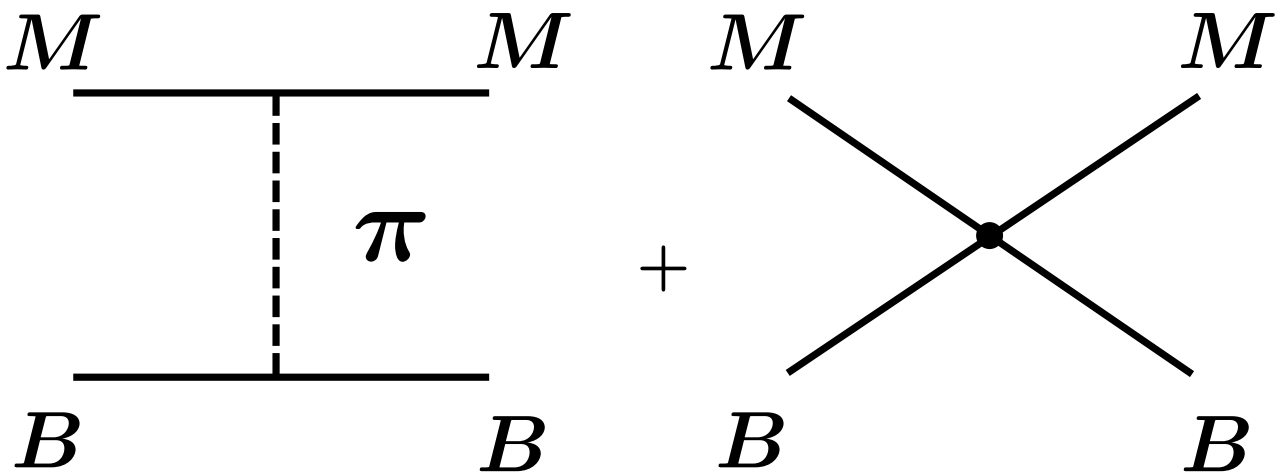
(f is determined by the P_c data. $\alpha = 1$ fm^{-2} is fixed.)

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

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

Numerical Results for Hidden-charm sector



Long range int.

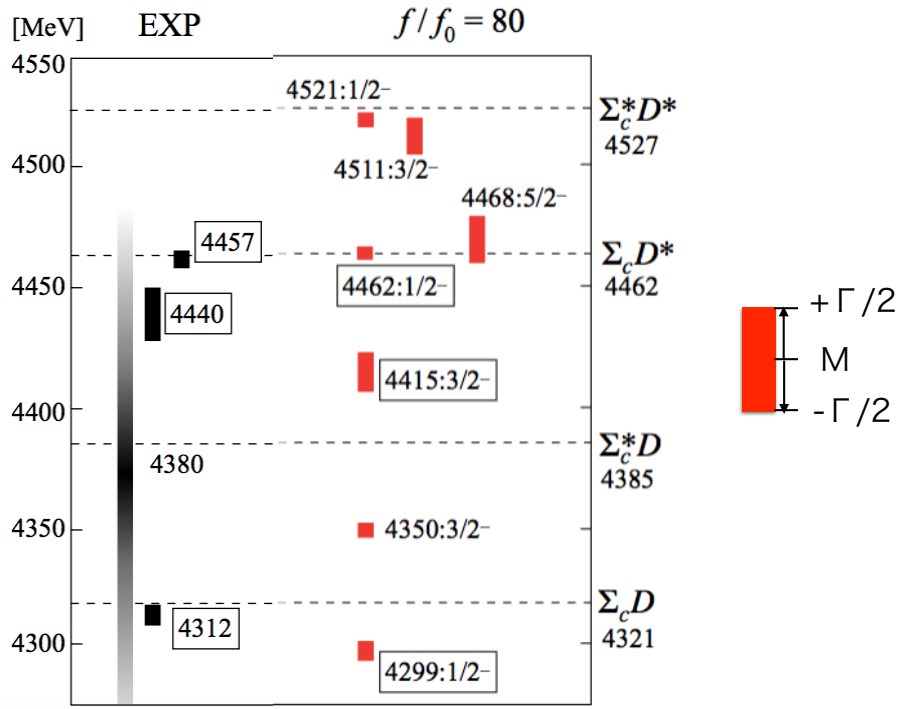
Short range int.
(Gaussian)

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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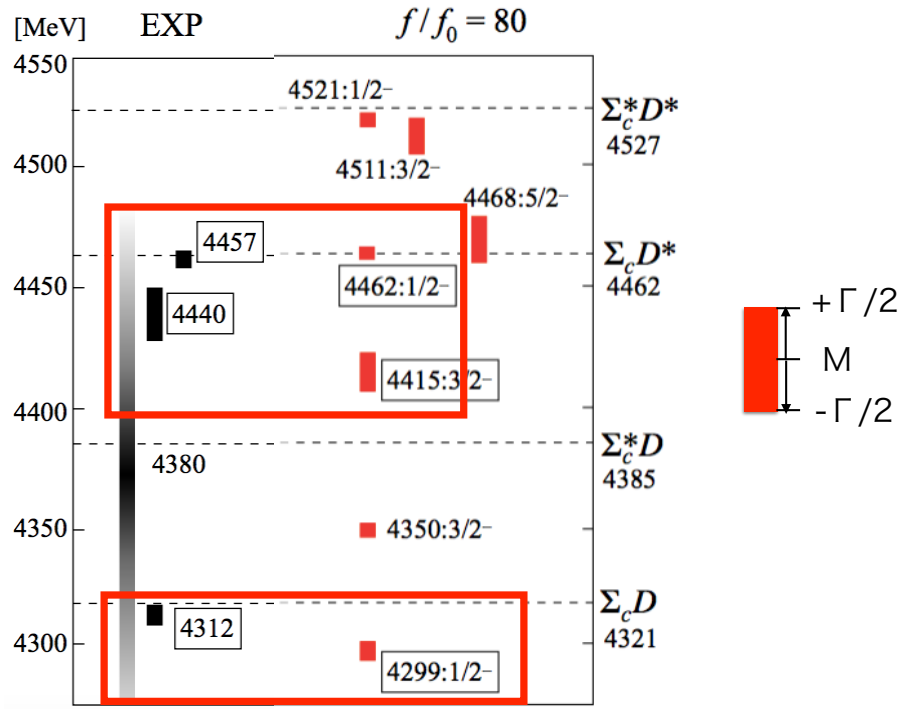

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- **Agreement with $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$**

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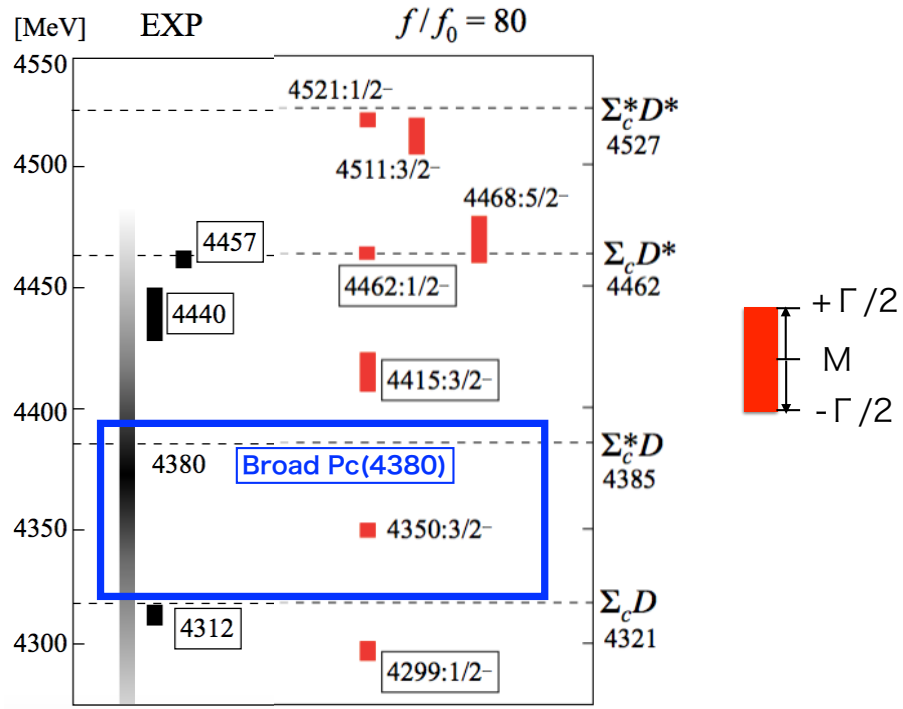

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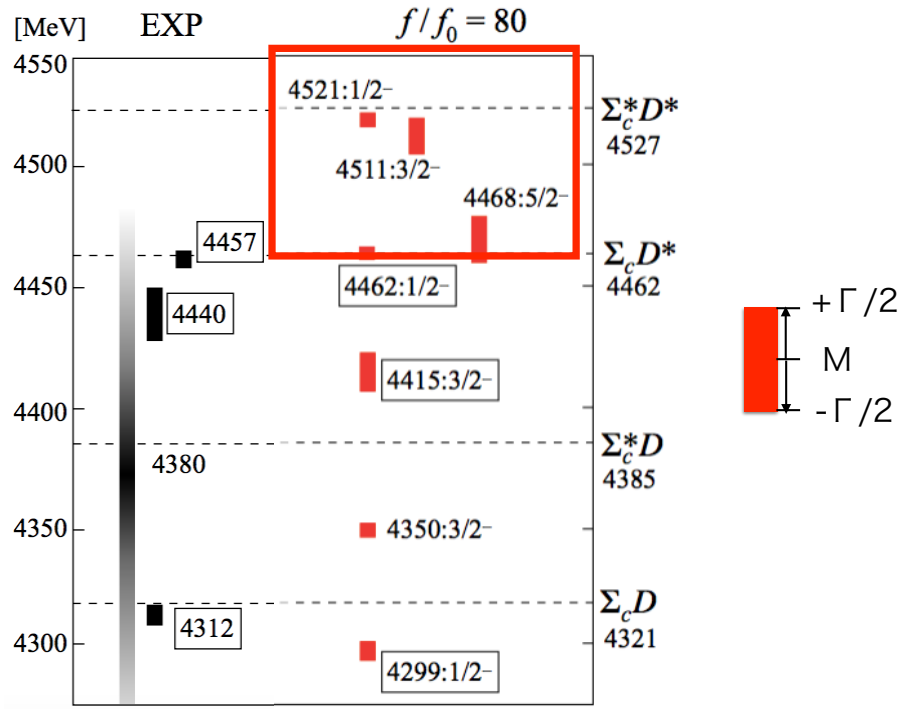

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- Predictions: $(1/2^-, 3/2^-, 5/2^-)$ states below $\bar{D}^* \Sigma_c^*$

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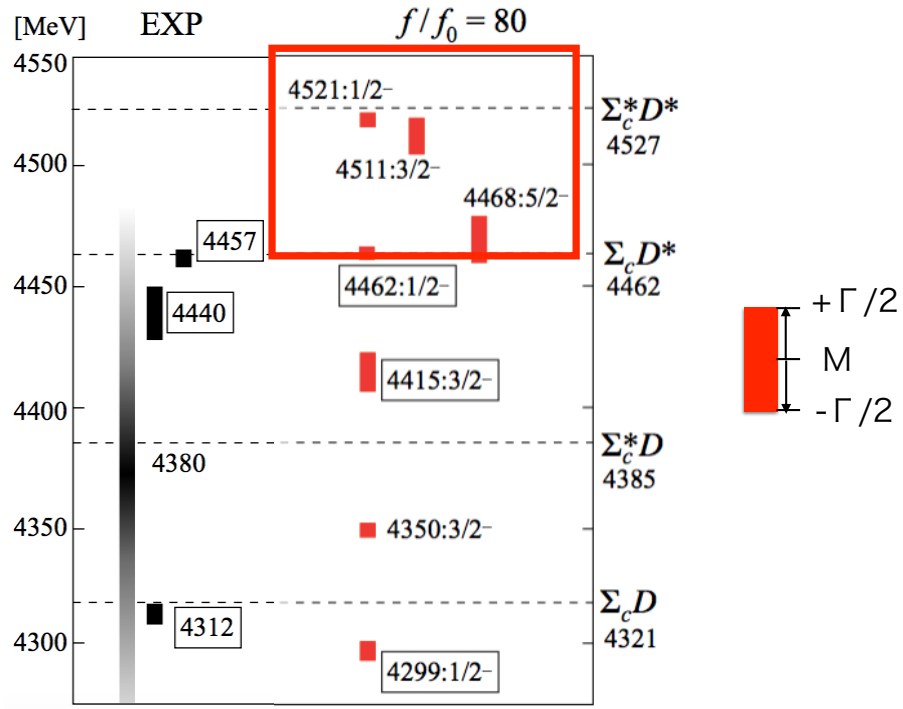
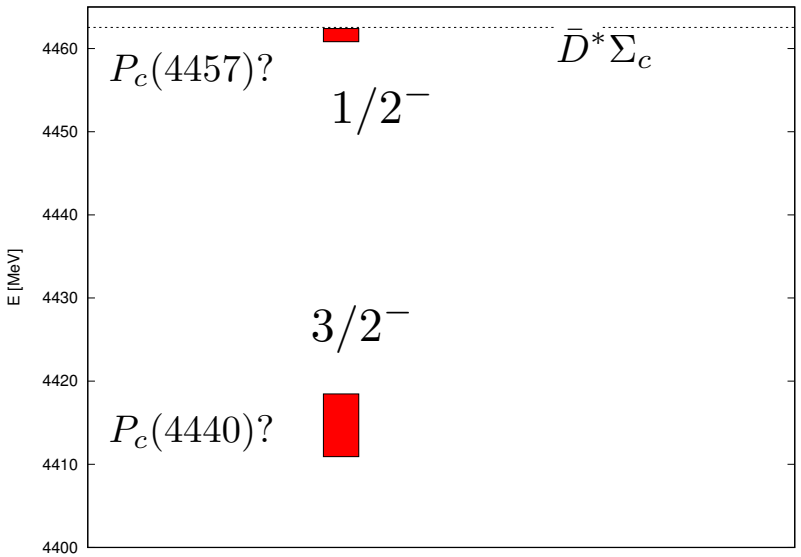
Y.Y., H.Garcia-Tecocoatzi, .**01** (2020) 091502(R)



($f_0 = 6$ 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



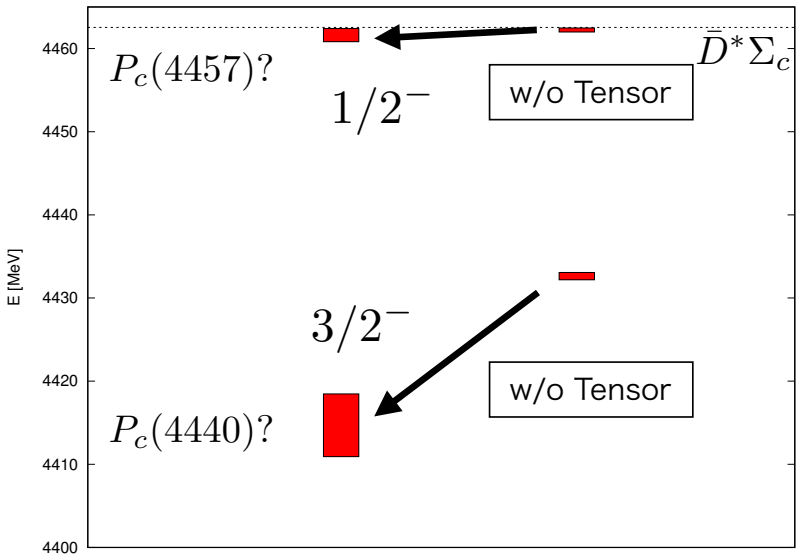
- Our J^P assignment

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

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

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

Role of Interactions in P_c



▷ Our J^P assignment

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

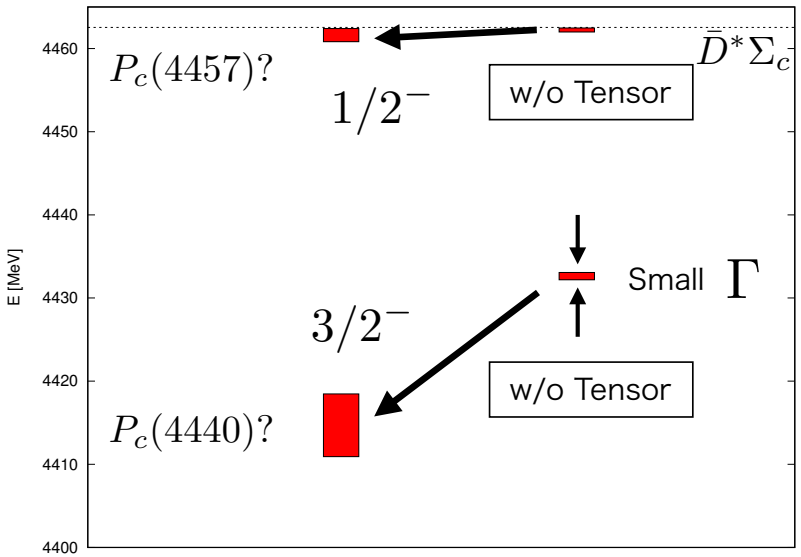
- with Tensor (original) vs without Tensor for V^π

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

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

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

Role of Interactions in P_c



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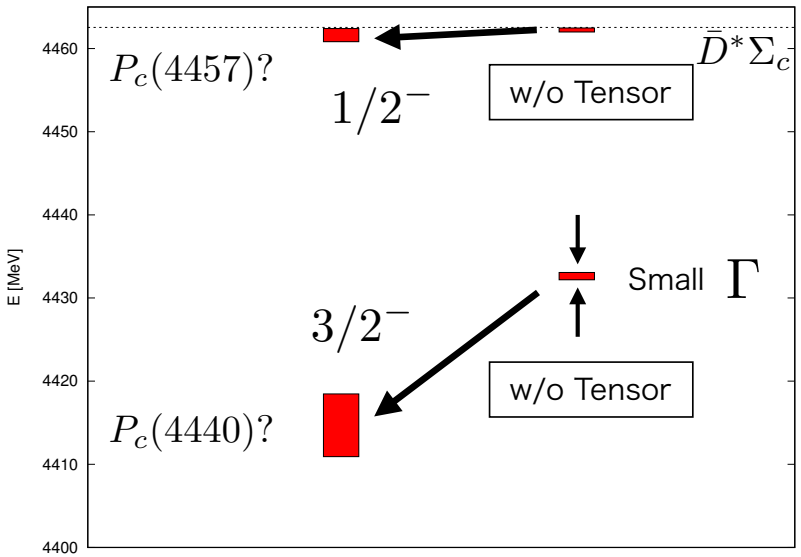
- V^{5q}: Major role to determine **Energy Levels**

Role of Interactions in P_c



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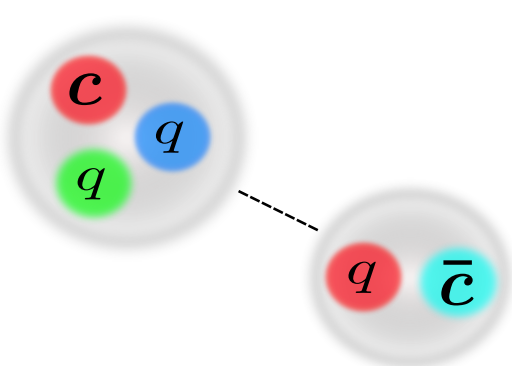
▷ V^{5q}: Major role to determine **Energy Levels**

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

Today's talk

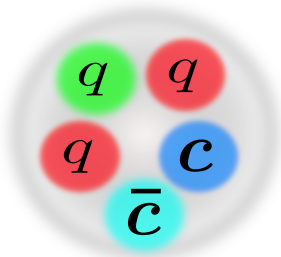
Exotic hadrons as hadronic molecule + compact state



Hadronic molecule

$\Longleftrightarrow$

Mixture?

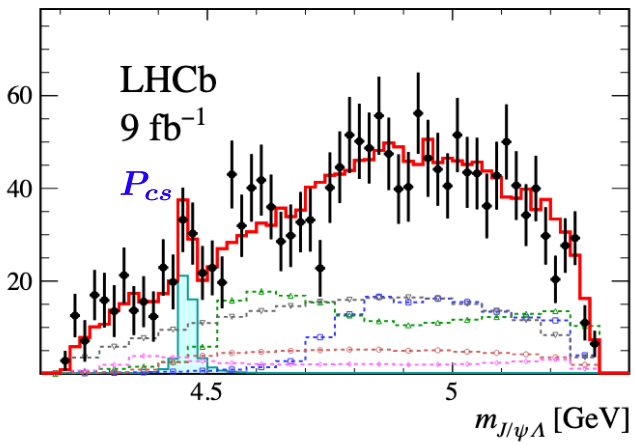


Pentaquark (Compact)

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**

Strange partner $P_{cs}(qqs c\bar{c})$ 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**)

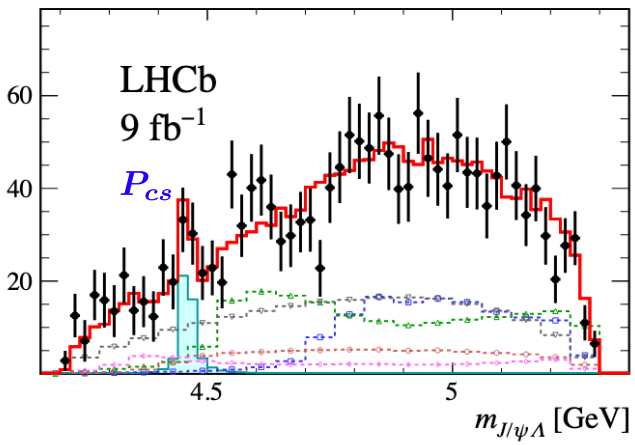
▷ Two-peak structure hypothesis

$M_1 = 4454.9 \pm 2.7$ 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

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

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



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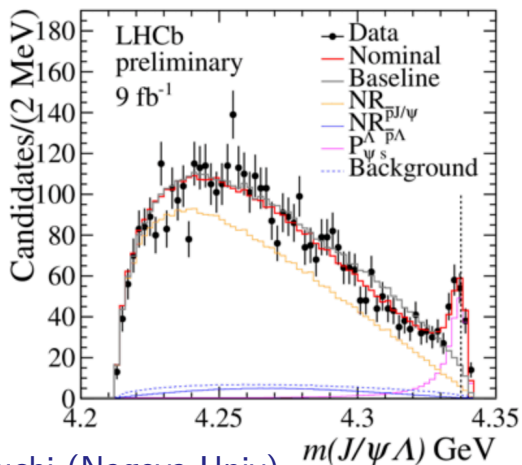
- $P_{cs}(4338)$ in 2022

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



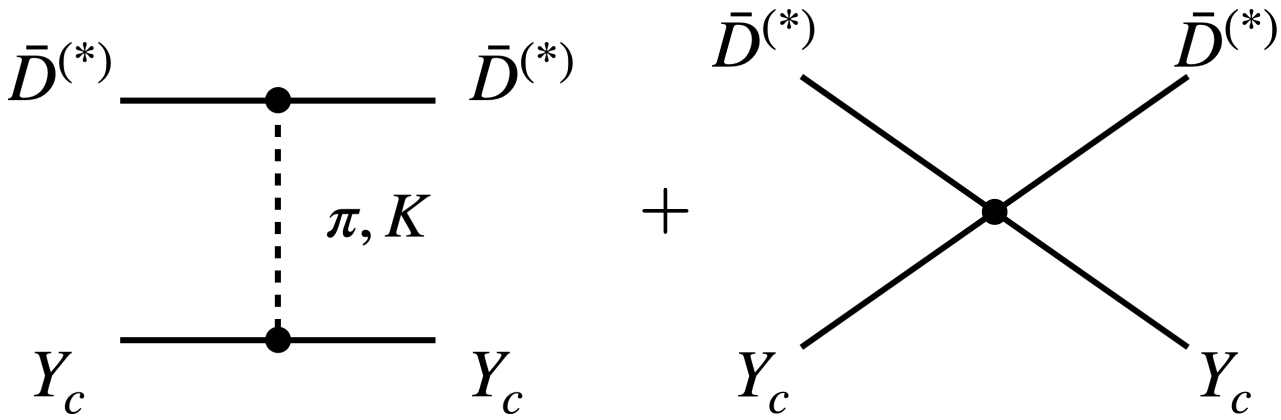
$M = 4338.2 \pm 0.7 \pm 0.4$ MeV

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

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

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

Numerical Results for Strange Hidden Charm



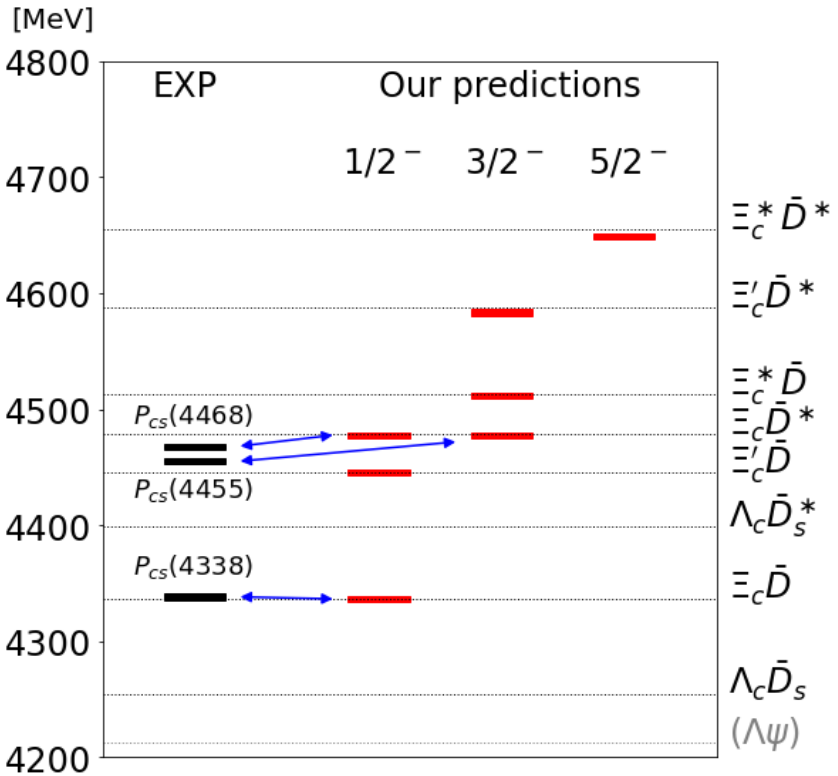
Long range int. Short range int. (Gaussian)

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

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

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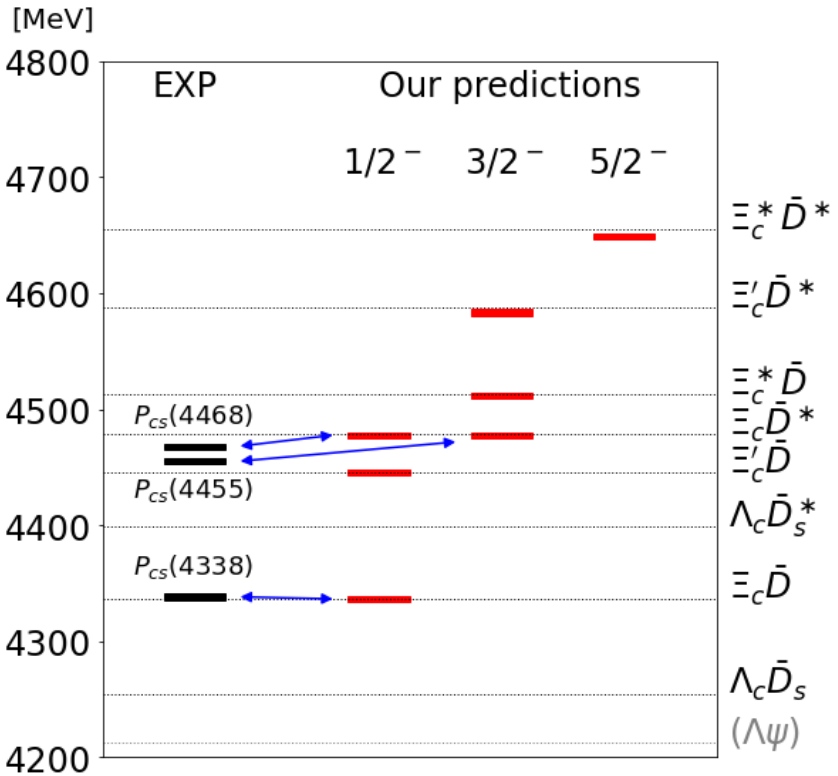

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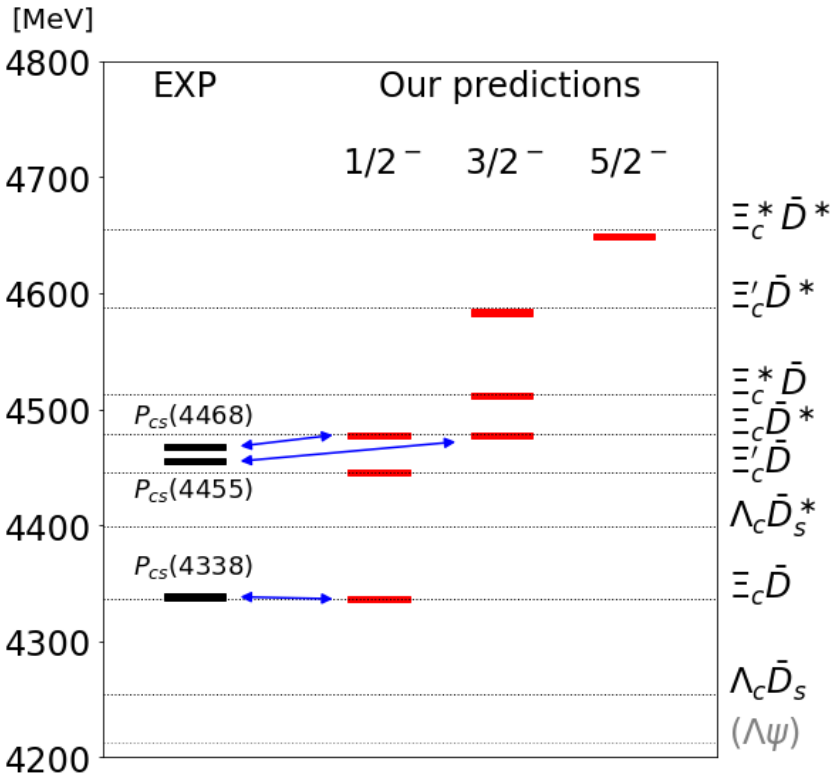

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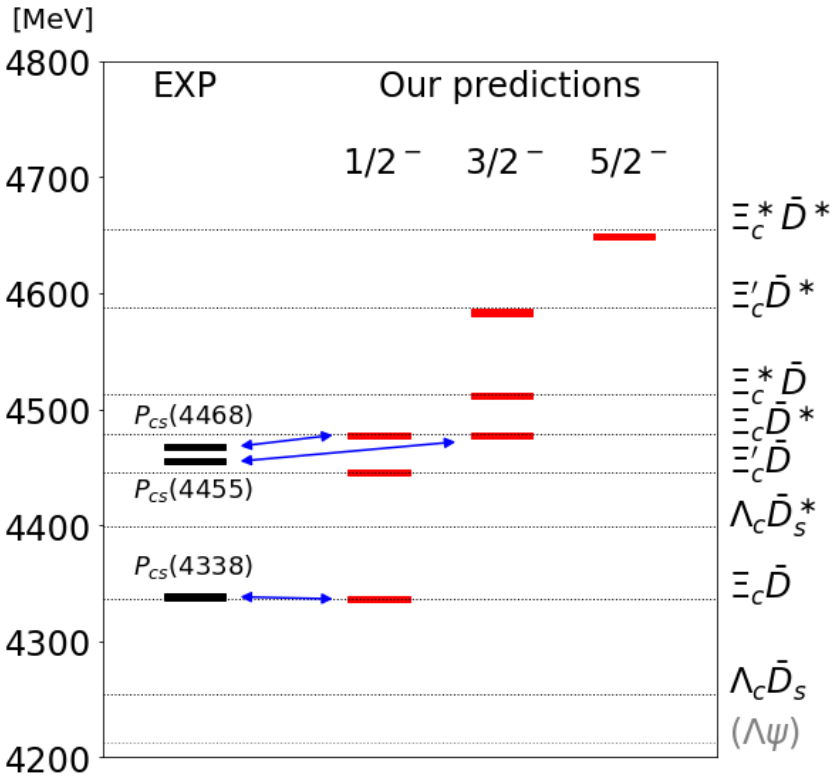
- **Four new predictions**

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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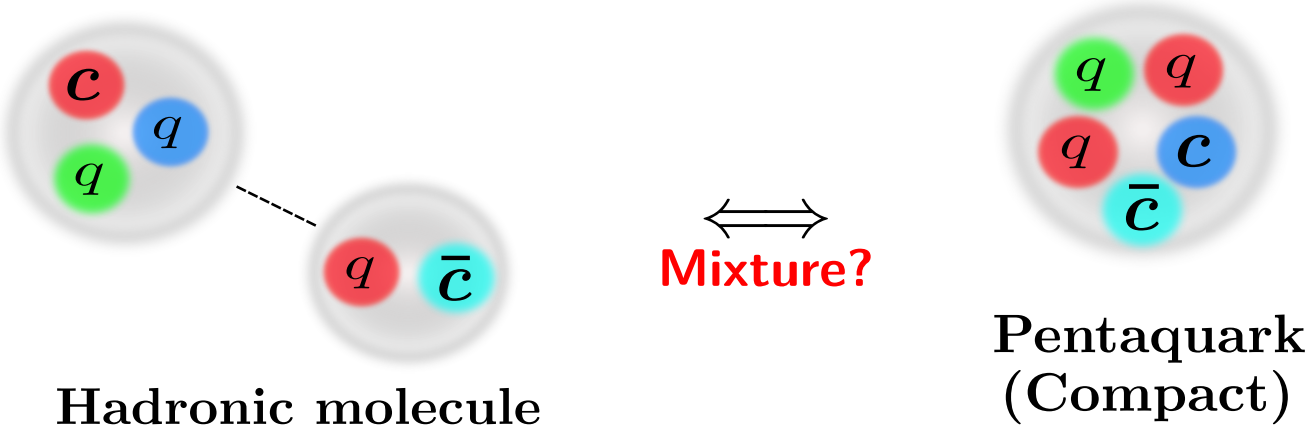
- **Four new predictions**

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



- 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.