# Heavy hadronic molecules with pion exchange and quark core couplings


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in collaboration with

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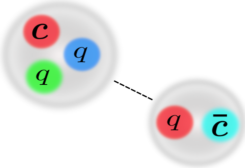
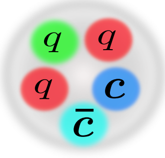
# Outline

1. **Introduction**
   - Exotic hadrons
   - Hidden-charm pentaquarks $P_c$
2. **Model Hamiltonian**
   - One pion exchange potential
   - Compact 5-quark potential
3. **Numerical results**: Solving Schrödinger equations
   - $P_c$
   - $P_{cs}$
4. **Summary**




**Hadronic molecule**

⇕ **Mixture?**




**Pentaquark (Compact)**

# Hadron structure: Constituent quark model

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


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

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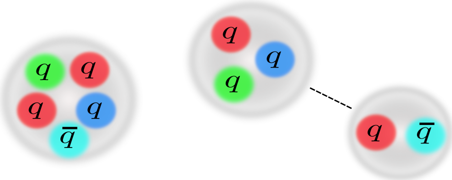
Baryon(proton,nucleon,...) Meson ($\rho$,$K^{(*)}$,...)

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

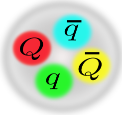



...

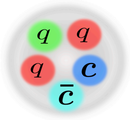
**Pentaquark (Compact)** **Hadronic molecule**

# Candidates of Exotic structures ?

Compact multiquarks

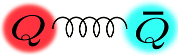



**Tetraquark**

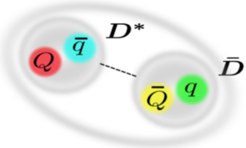



**Pentaquark**

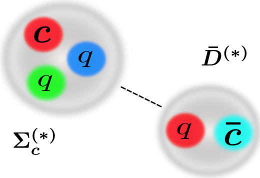
$Q\bar{Q}g$ Hybrid




Hadronic molecules

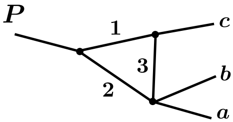



**Meson-Meson**




**Meson-Baryon**

Triangle Singularity

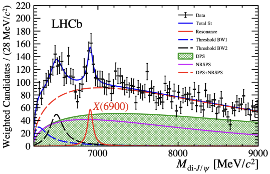



(w/o Resonance)

# Recent reports of Exotic hadrons!

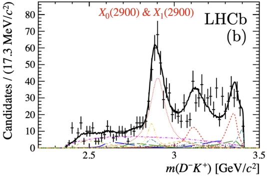
▷ $X(6900)$ $(cc\bar{c}\bar{c}?)$

LHCb, Science Bulletin 65 (2020) 1983



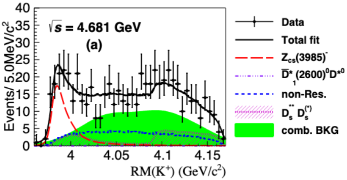

▷ $X_{0,1}(2900)$ $(\bar{c}\bar{s}ud?)$

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



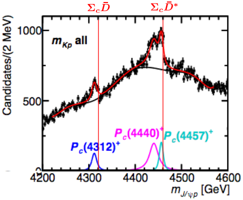

▷ $Z_{cs}$ $(c\bar{c}s\bar{u}?)$

BESIII, PRL126,102001 (2021)




▷ $P_c$ $(uudc\bar{c}?)$,

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



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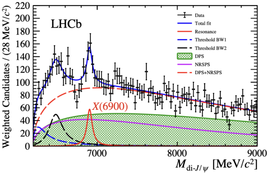


▷ $X_{0,1}(2900)$ **($\bar{c}\bar{s}ud$?)**

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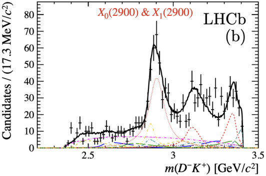
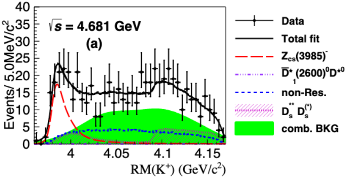


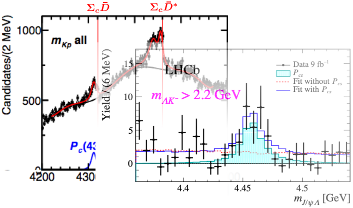

▷ $Z_{cs}$ **($c\bar{c}s\bar{u}$?)**

BESIII, PRL126,102001 (2021)



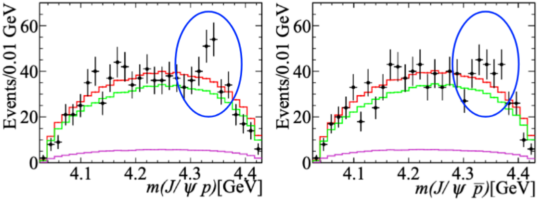

▷ $P_c$ **($uudc\bar{c}$?)**, $P_{cs}$ **($udsc\bar{c}$?)**

LHCb PRL**115**(2015)072001, **122**(2019)222001 , Sci.Bull.**66**(2021)1278-1287



# Very recent reports of Exotic hadrons!

- **New $P_c(4337)^+$ state** in $B_s^0 \to J/\psi p\bar{p}$ LHCb, 2108.04720 [hep-ex]



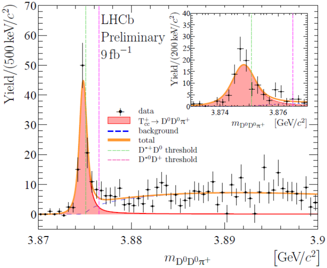

from Liupan An's talk (HADRON2021)

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

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

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

- **Doubly charmed tetraquark $T_{cc}^+(cc\bar{u}\bar{d})$** LHCb, 2109.01038, 2109.01056



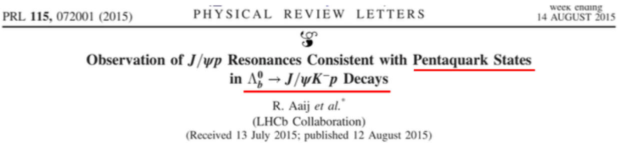

$\delta m_{BW} = -273 \pm 61$ keV below $D^{*+}D^0$

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

Isoscaler $J^P = 1^+$

# 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

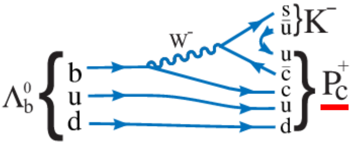

PRL **115**, 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

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

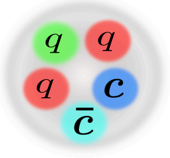
R. Aaij *et al.*[*]
(LHCb Collaboration)
(Received 13 July 2015; published 12 August 2015)

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

$c\bar{c}uud$ state ?




$\Rightarrow$

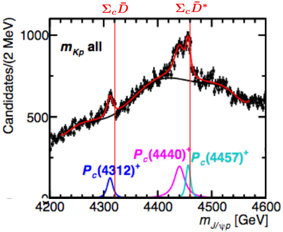



$P_c(4380)$: $M$ =4380 MeV, $\Gamma$= 205 MeV

$P_c(4450)$: $M$ =4449.8 MeV, $\Gamma$ = 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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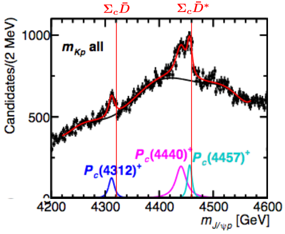


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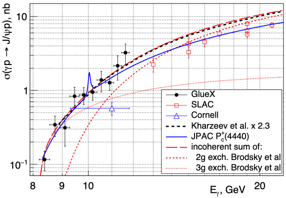
- Complementary experiments: $\gamma p \to J/\psi p$ in GlueX@J-Lab

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

  $\to$ No triangle singularity

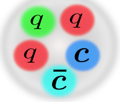
**No evidence** of $\gamma p \to P_c \to J/\psi p$



# 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



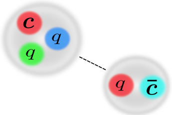
**Pentaquark (Compact)**

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

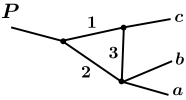
  J.-J.Wu *et al.,* (2010) (2011), C. Garcia-Recio, *et al.* (2013), R. Chen, *et al.* (2015), Y.Shimizu, *et al.* (2016-2019), C. W. Xiao, *et al.* (2019), M.-Z. Liu, *et al.* (2019), M. L. Du, *et al.* (2019), ...



**Hadronic molecule**

- Triangle singularity?
  **(Non-resonant explanation)**

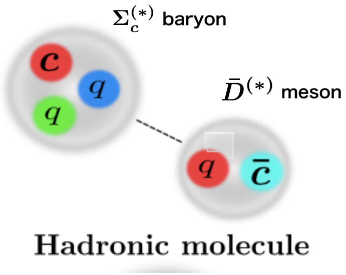
  F.K.Guo, *et al.* (2015), X.H.Liu, *et al.* (2016), S.X.Nakamura PRD103, L111503 (2021), ...



# Hadronic molecules?

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

→ expected **near the thresholds**



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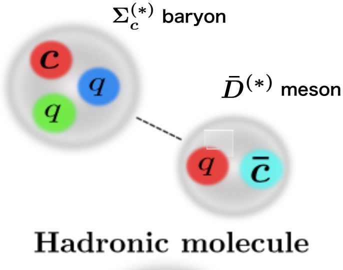
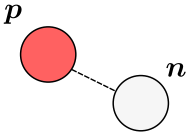



Analogous to Deuteron




$B = 2.2$ MeV

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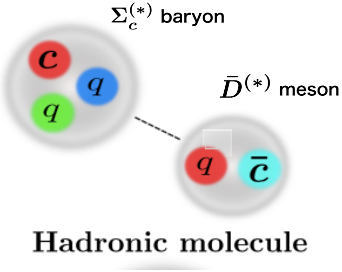
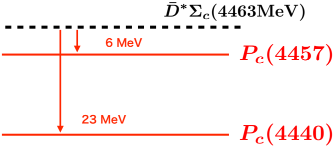



$P_c = \bar{D}^{(*)}\Sigma_c^{(*)}$ molecules?



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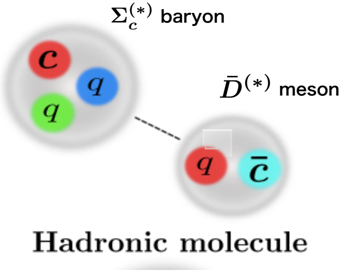


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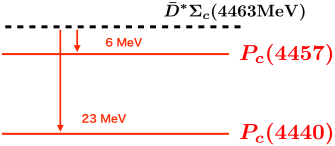


▷ Q. Interactions?: **Heavy hadron interactions** are not established yet...

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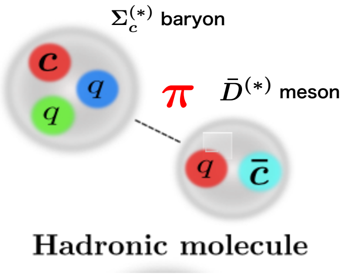


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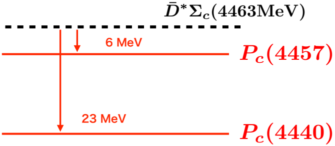


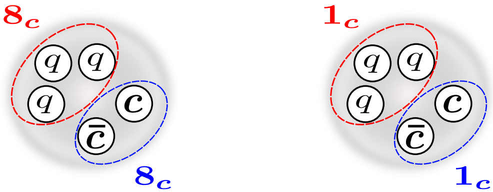

▷ Q. Interactions?: **Heavy hadron interactions** are not established yet...

⇒ Importance of **$\pi$ exchange** is expected due to the heavy quark symmetry! S. Yasui and K. Sudoh, Phys. Rev. D **80** (2009), 034008

⇒ Hadronic molecular structure is favored?

# Compact $5q$ 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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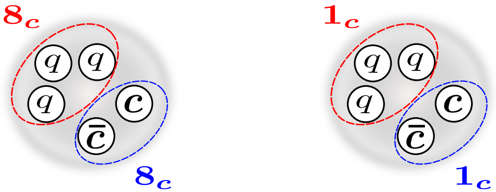


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- $[q^3\, 8_c\, 3/2]$: Color magnetic int. is attractive!

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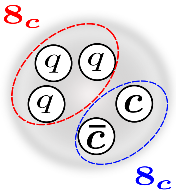


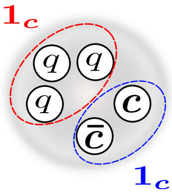


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- $[q^3\, 8_c\, 3/2]$: Color magnetic int. is attractive!

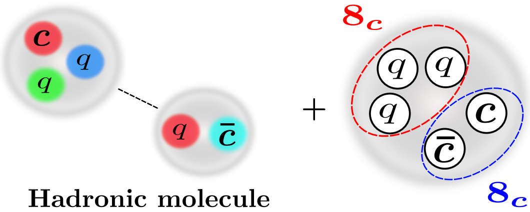
  $\Rightarrow$ Couplings to $(qqc)$ baryon-$(q\bar{c})$ meson, e.g. $\bar{D}\Sigma_c$, are allowed!

**Mixing of Compact state and Hadronic Molecule!**

# Model setup in this study

- **Hadronic molecule + Compact state ($5q$)**

$MB + 5q$



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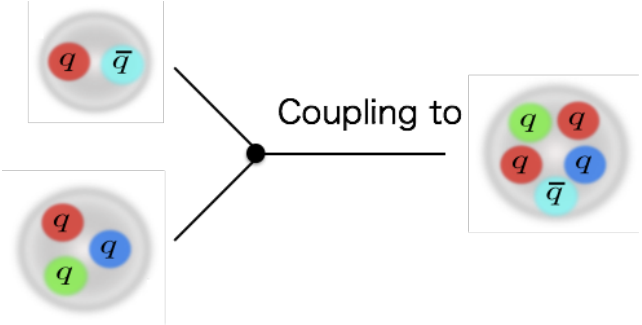
**$MB + 5q$**



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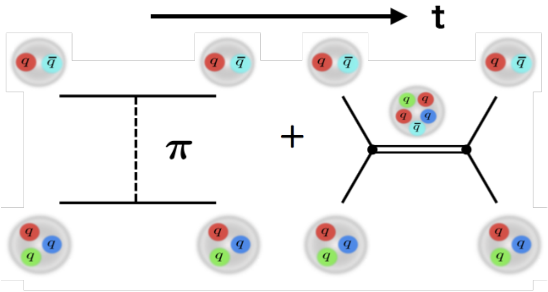
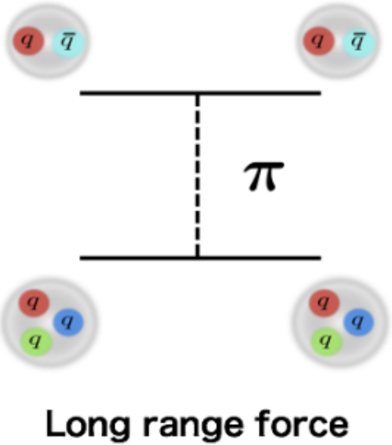
## Meson-Baryon interactions

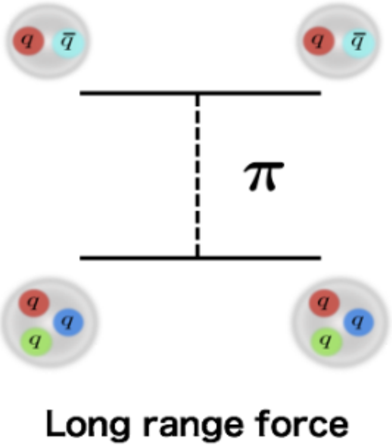



- **Long range** interaction: One pion exchange potential (OPEP)
- **Short range** interaction: $5q$ potential

# 1. Long range force: One pion exchange potential



# 1. Long range force: One pion exchange potential with Heavy quark spin symmetry



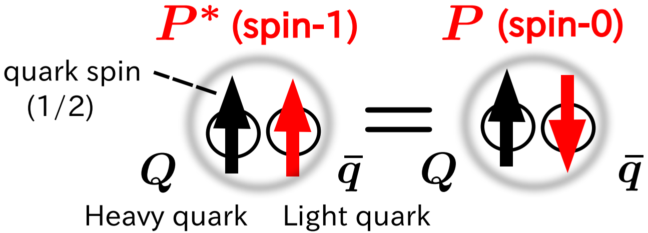
# Heavy Quark Spin Symmetry and Mass degeneracy

**Heavy Quark Spin Symmetry (HQS)** N.Isgur,M.B.Wise,PLB**232**(1989)113

- **Suppression of Spin-spin force** in $m_Q \to \infty$.

  $\Rightarrow$ **Mass degeneracy** of hadrons with the different $J$

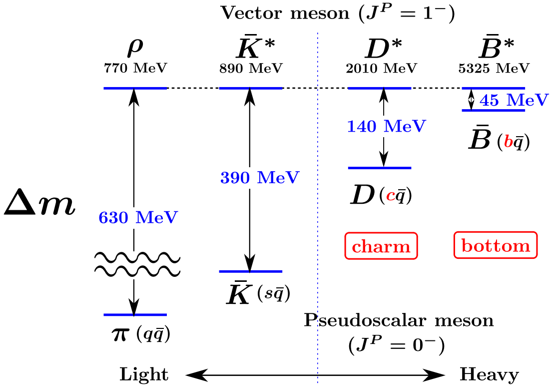
- e.g. $Q\bar{q}$ meson




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

# Mass degeneracy of heavy hadrons

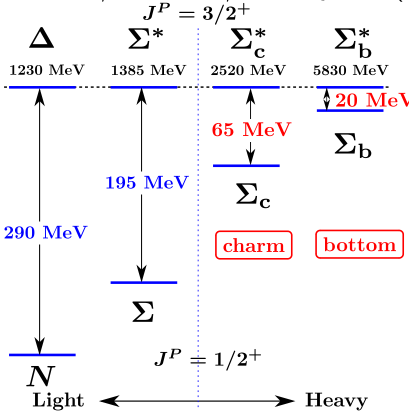
- Mass difference between vector and pseudoscalar mesons. ($Q\bar{q}$, $q = u, d$)




- $\Delta m$ decreases when the quark mass increases.

# Mass degeneracy of heavy hadrons

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



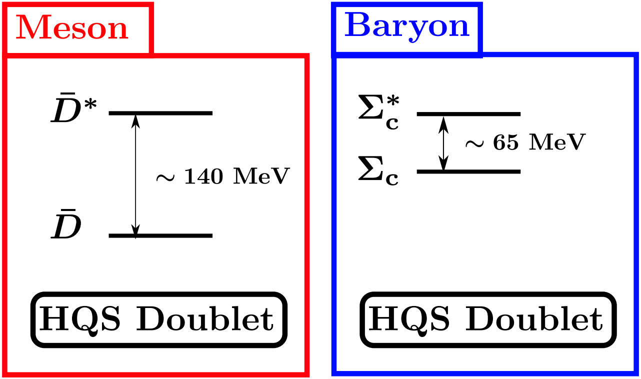

- $\Delta m$ decreases when the quark mass increases.
  $\Rightarrow$ **Degeneracy of Heavy hadrons!**

Heavy Quark Spin Symmetry

# Mass degeneracy → $\bar{D} - \bar{D}^*$, $\Sigma_c - \Sigma_c^*$ mixing!

- Mass Degeneracy of $(0^-, 1^-)$ Mesons, $(1/2^+, 3/2^+)$ Baryons

⇒ $(\bar{D}, \bar{D}^*)$ and $(\Sigma_c, \Sigma_c^*)$ mixing




- Coupled channels of $\bar{D}\Sigma_c$, $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$ and $\bar{D}^*\Sigma_c^*$!
  ⇒ These thresholds are close to each other

# Mass degeneracy $\rightarrow$ $\bar{D} - \bar{D}^*$, $\Sigma_c - \Sigma_c^*$ mixing!

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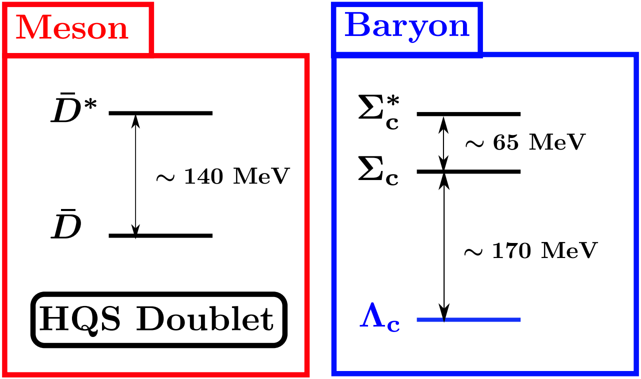


- Coupled channels of $\bar{D}\Sigma_c$, $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$ and $\bar{D}^*\Sigma_c^*$!
  $\Rightarrow$ These thresholds are close to each other
- In addition, $\Lambda_c$ $(cqq)$: $\bar{D}^{(*)}\Lambda_c$ channel!?

# Mass degeneracy → $\bar{D} - \bar{D}^*$, $\Sigma_c - \Sigma_c^*$ mixing!

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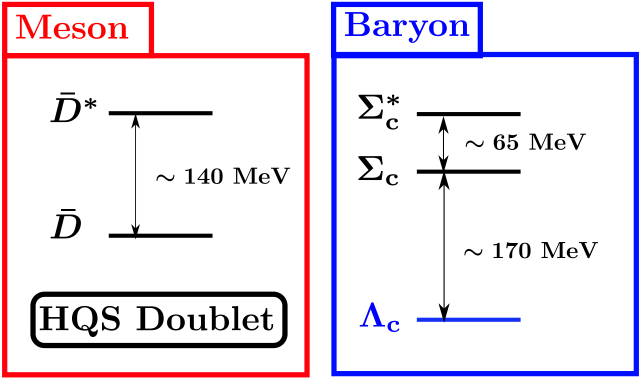
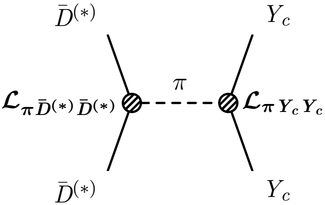



- 6 meson-baryon components

$$(1)\ \bar{D}\Lambda_c, (2)\ \bar{D}^*\Lambda_c, (3)\ \bar{D}\Sigma_c, (4)\ \bar{D}\Sigma_c^*,$$
$$(5)\ \bar{D}^*\Sigma_c, (6)\ \bar{D}^*\Sigma_c^*$$

# $\bar{D}^{(*)} Y_c$ Interaction: Long range force

- One pion exchange potential




$\bar{D}^{(*)}$: $\bar{D}$ or $\bar{D}^*$

$Y_c$: $\Lambda_c$, $\Sigma_c$ or $\Sigma_c^*$

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

**(Contact term is removed)**

$$g_\pi = 0.59, g_1 = 1.00$$

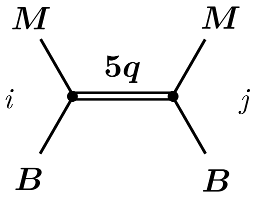
- Form factor with Cutoff $\Lambda$ (determined by the hadron size)

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

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

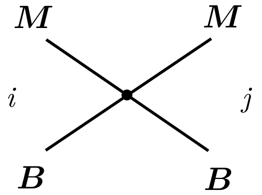
# Model: 5-quark potential

- 5-quark potential ⇒ s-channel diagram...But



# Model: 5-quark potential

- 5-quark potential $\Rightarrow$ **Local Gaussian potential** is employed.
  Massive $M_{5q}$ (few hundred MeV above $\bar{D}^*\Sigma_c^*$) $\rightarrow$ **Attractive**




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

Channel $i, j = \bar{D}^{(*)}\Lambda_c,\ \bar{D}^{(*)}\Sigma_c^{(*)}$ with $S-$wave

| $J$ | $[q^3 8 \frac{1}{2}]0$ | $[q^3 8 \frac{1}{2}]1$ | $[q^3 8 \frac{3}{2}]0$ | $[q^3 8 \frac{3}{2}]1$ |
|---|---|---|---|---|
| $\frac{1}{2}$ | 4816.2 | 4759.1 | - | 4772.2 |
| $\frac{3}{2}$ | - | 4822.3 | 4892.5 | 4835.4 |
| $\frac{5}{2}$ | - | - | - | 4940.7 |

Masses of compact $5q$ states
with the color octet (8) $q^3$

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

$> \bar{D}^*\Sigma_c^*(4527.1\,\text{MeV})$

$^*[q^3 8 S_{q^3}] S_{c\bar{c}}$

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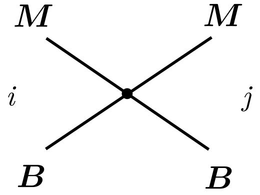


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## Free Parameters

Strength $f$ and Gaussian para. $\alpha$ ($\rightarrow$ may be fixed in the future)
($f$ vs $E$ will be shown latter. $\alpha = 1$ fm$^{-2}$ is fixed.)

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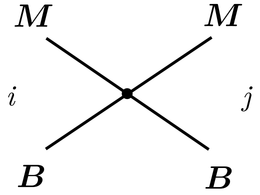


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Channel $i, j = \bar{D}^{(*)}\Lambda_{c}$, $\bar{D}^{(*)}\Sigma_{c}^{(*)}$ with $S-$wave

**Free Parameters**

Strength $\boldsymbol{f}$ and Gaussian para. $\boldsymbol{\alpha}$ (→ may be fixed in the future)
($f$ vs $E$ will be shown latter. $\alpha = 1$ fm$^{-2}$ is fixed.)

**Relative strength $S_i$**

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

# Spectroscopic factor $S_i$

- **Overlap** of the color-flavor-spin wavefunctions of 5-quark state and $\bar{D}Y_c$

$$S_i = \left\langle (\bar{D}Y_c)_i \,\middle|\, 5q \right\rangle$$

Table: Spectroscopic factors $S_i$ for each meson-baryon channel.

| $J$ | | $S_{c\bar{c}}$ | $S_{3q}$ | $\bar{D}\Lambda_c$ | $\bar{D}^*\Lambda_c$ | $\bar{D}\Sigma_c$ | $\bar{D}\Sigma_c^*$ | $\bar{D}^*\Sigma_c$ | $\bar{D}^*\Sigma_c^*$ |
|---|---|---|---|---|---|---|---|---|---|
| $1/2$ | (i) | 0 | $1/2$ | 0.4 | 0.6 | −0.4 | — | 0.2 | −0.6 |
| | (ii) | 1 | $1/2$ | 0.6 | −0.4 | 0.2 | — | −0.6 | −0.3 |
| | (iii) | 1 | $3/2$ | 0.0 | 0.0 | −0.8 | — | −0.5 | 0.3 |
| $3/2$ | (i) | 0 | $3/2$ | — | 0.0 | — | −0.5 | 0.6 | −0.7 |
| | (ii) | 1 | $1/2$ | — | 0.7 | — | 0.4 | −0.2 | −0.5 |
| | (iii) | 1 | $3/2$ | — | 0.0 | — | −0.7 | −0.8 | −0.2 |
| $5/2$ | (i) | 1 | $3/2$ | — | — | — | — | — | −1.0 |

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|---|---|---|---|---|---|---|---|---|---|
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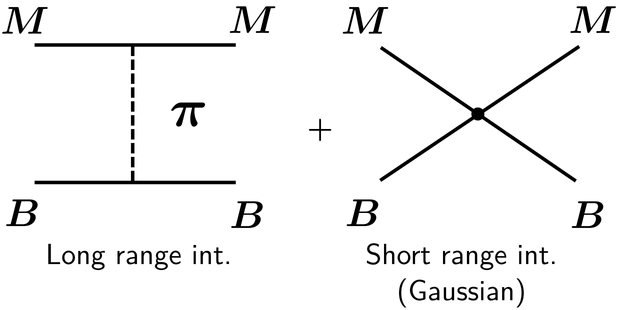
| 3/2 | (i) | 0 | 3/2 | — | 0.0 | — | **−0.5** | **0.6** | **−0.7** |
| | (ii) | 1 | 1/2 | — | **0.7** | — | 0.4 | −0.2 | −0.5 |
| | (iii) | 1 | 3/2 | — | 0.0 | — | **−0.7** | **−0.8** | −0.2 |
| 5/2 | (i) | 1 | 3/2 | — | — | — | — | — | **−1.0** |

- **Large $S_i$** will play an important role.

# Numerical Results for Hidden-charm sector



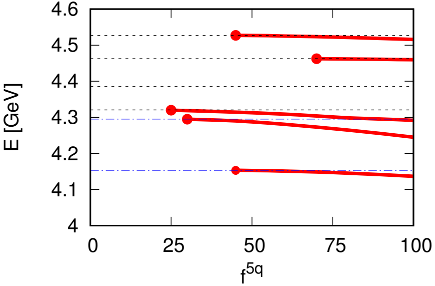

<u>Bound state and Resonance</u>

- 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)

# Results ($f^{5q}$ vs $E$) of charm $\bar{D}Y_c$ for $J^P = 1/2^-$

- Energy with $V_\pi + V^{5q}(f^{5q})$. (Y.Y. *et al*, PRD**96** (2017), 114031)

$J^P = 1/2^-$

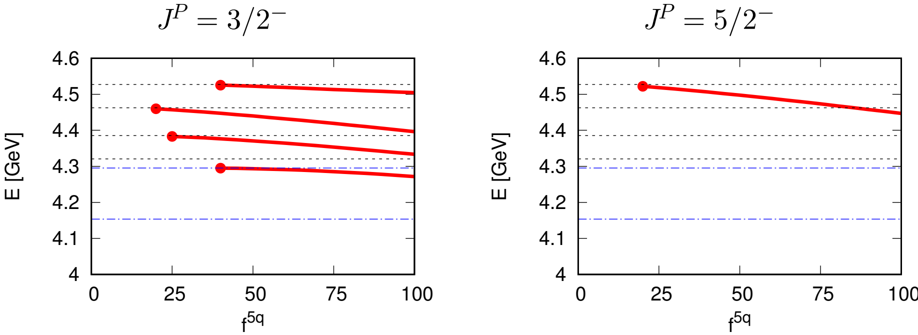



Dashed line: Thresholds, **Red line: Energy obtained**

- For small $f^{5q}$, **No bound state**
  $\Rightarrow$ The OPEP attraction is not enough to generate a state
- **$5q$ potential helps to generate the states near the thresholds**

# Results ($f^{5q}$ vs $E$) for $J^P = 3/2^-, 5/2^-$

- Energy with $V_\pi + V^{5q}(f^{5q})$. (Y.Y. *et al*, PRD**96** (2017), 114031)

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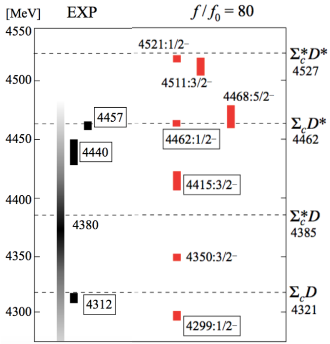
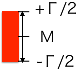
# For New $P_c$ states by LHCb in 2019

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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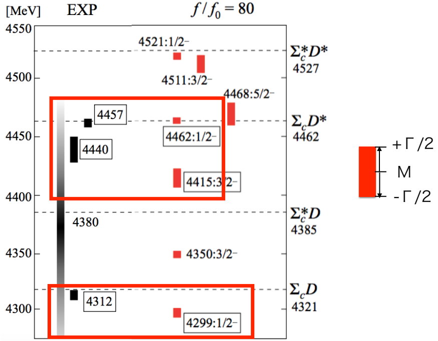


- **Agreement with $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$**

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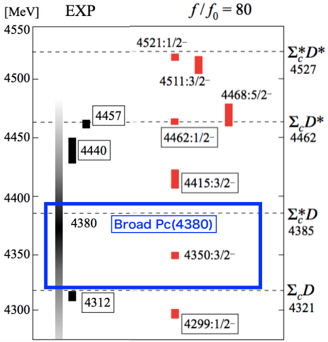


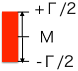


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- For Broad $P_c(4380)$, we obtain the similar mass. But width...?

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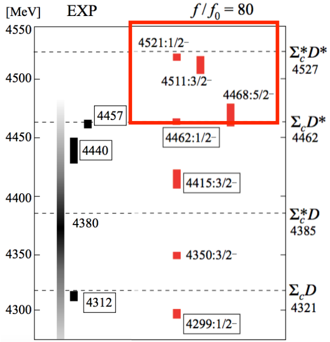


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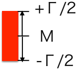
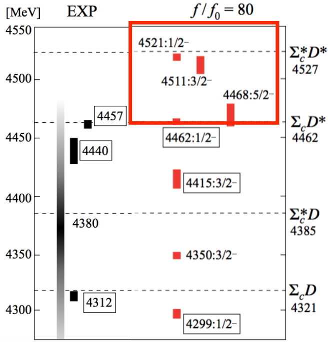


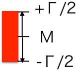

- **Agreement with $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$**
- For Broad $P_c(4380)$, we obtain the similar mass. But width...?
- Predictions: $(1/2^-, 3/2^-, 5/2^-)$ states below $\bar{D}^* \Sigma_c^*$

# For New $P_c$ states by LHCb in 2019

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

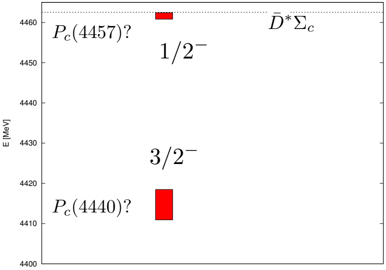
$(f_0 = 6 \text{ MeV})$




| $P_c$ | LHCb $(M,\Gamma)$ | $J^P$ | Ours<br>$5q$+OPEP | C. W. Xiao, *et al.*,<br>PRD**100**(2019)014021<br>Local hidden gauge | M. Z. Liu, *et al.*,<br>PRL**122**(2019)242002<br>Cont (B) | M. L. Du, *et al.*,<br>2102.07159<br>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
  $P_c(4440)$: $3/2^-$
  $P_c(4457)$: $1/2^-$

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

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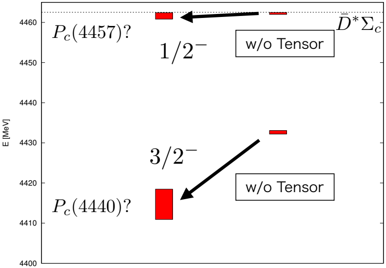


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$\boldsymbol{E(1/2^-) > E(3/2^-)}$

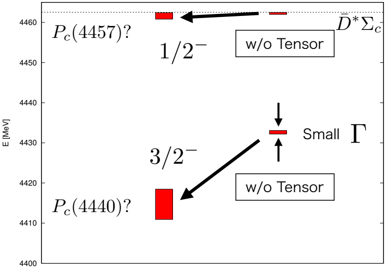
- with Tensor (original) vs without Tensor for $V^\pi$

⇒ Mass and Width are **reduced!**

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

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

# Role of Interactions in $P_c$

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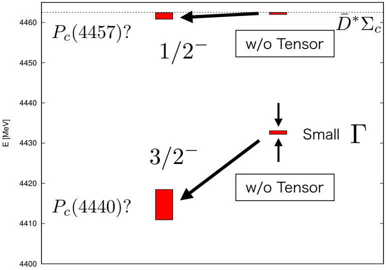
▷ $V^{5q}$: Major role to determine **Energy Levels**

# Role of Interactions in $P_c$

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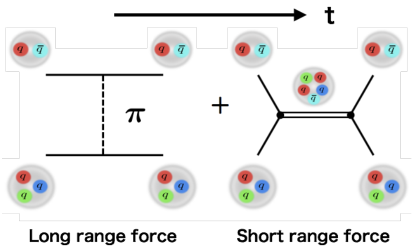
▷ $V^{5q}$: Major role to determine **Energy Levels**

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

# Summary

- Hidden-charm pentaquarks $P_c$ and $P_{cs}$ reported by LHCb
- Hadronic molecule + Compact multiquark Model was applied
  - Long range force: $\pi$ and $K$ exchanges
  - Short range force: Coupling to Compact $5q$ states ($5q$ potential)
- By solving the Schrödinger equations, $Y_c\bar{D}$ resonances are obtained close to thresholds
  - Short-range force determining $\boldsymbol{E_{re}}$
  - Long-range force doing $\mathbf{\Gamma}$




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

**Thank you for your kind attention.**