クォークコアとの結合を伴うハドロン分子状態

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in collaboration with

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

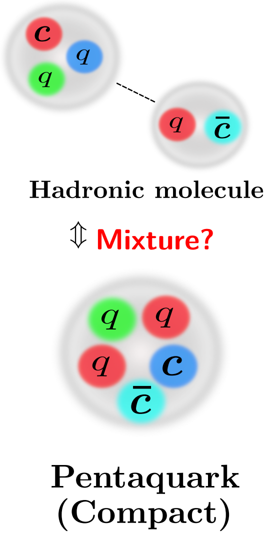
Sachiko Takeuchi (Japan Coll. Social Work), Makoto Takizawa (Showa Pharmaceutical Univ.).

基研研究会「核力に基づいた原子核の構造と反応」

京都大学基礎物理学研究所, 京都 12/7-10, 2021

Outline

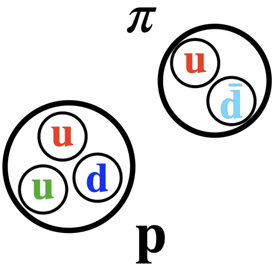
1. Introduction
   - Exotic hadrons
   - Hidden-charm pentaquarks P_c
2. Model setup
   - One pion exchange potential
   - Compact 5-quark potential
3. Numerical results for P_c
4. Summary



ハドロン: 構成クォーク模型

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

up, down (u, d)



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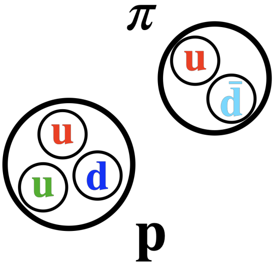

- よく知られているハドロン
  → 核子や π 中間子: 原子核、核力のもと **(u, d の世界)**

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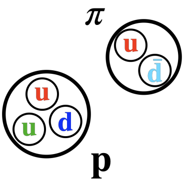

$u, d \sim 2 - 5$ MeV

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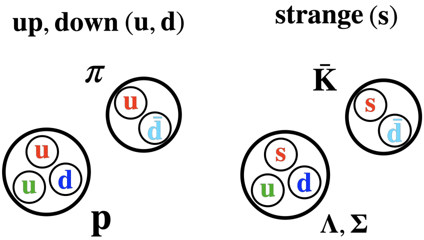

$u, d \sim 2-5$ MeV　　$s \sim 90$ MeV

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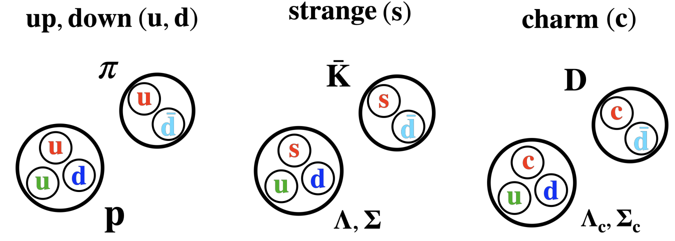

$u, d \sim 2-5$ MeV $s \sim 90$ MeV $c \sim 1.3$ GeV

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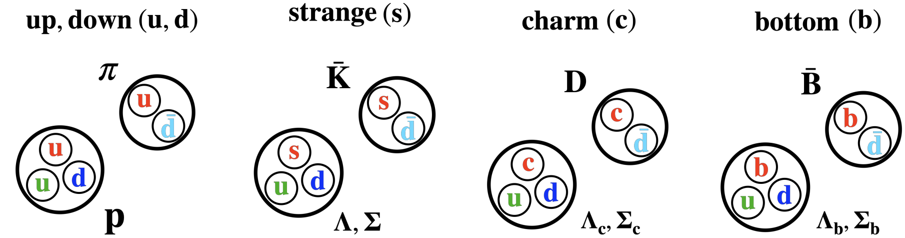

$u, d \sim 2-5$ MeV　　$s \sim 90$ MeV　　$c \sim 1.3$ GeV　　$b \sim 4$ GeV

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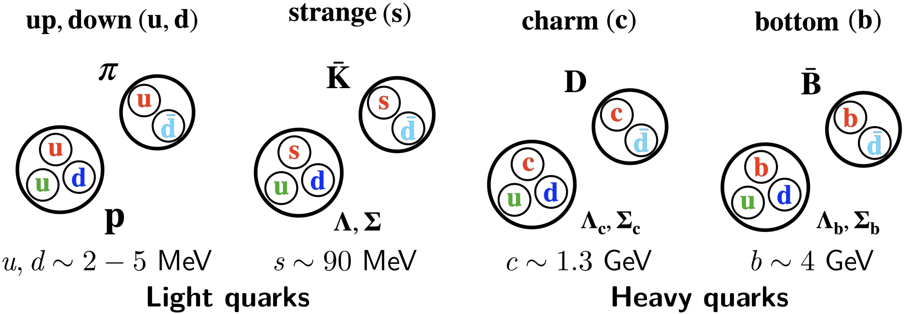

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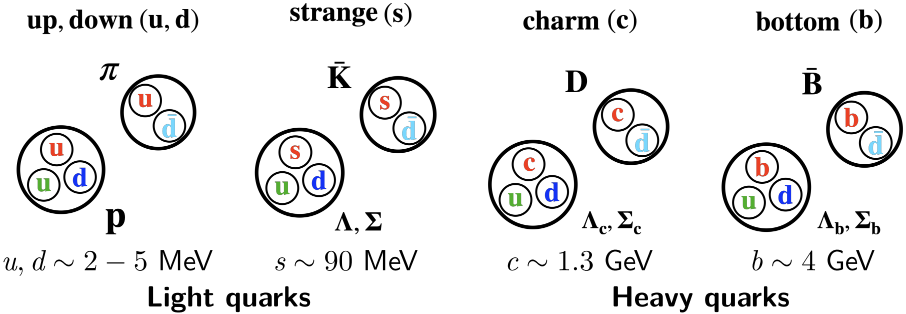

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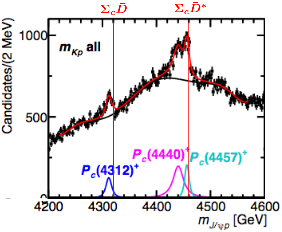
- 異なるフレーバー**(s, c, b)**を含むハドロン: 加速器実験で生成
- 多くのハドロンの性質は**qqq, $q\bar{q}$ で説明されてきた!**

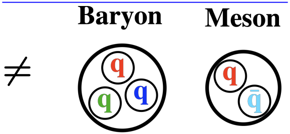
エキゾチックハドロンの発見報告

- 加速器実験で**ピーク構造**の報告 → **新しいハドロン (共鳴) か!?**

R. Aaij, *et al.* PRL122 (2019) 222001



- ***qqq* や *q$\bar{q}$* で説明できない状態**も発見される



⇒ **エキゾチックな構造**を持つ新ハドロンの可能性!

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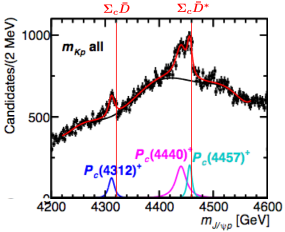

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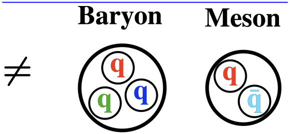

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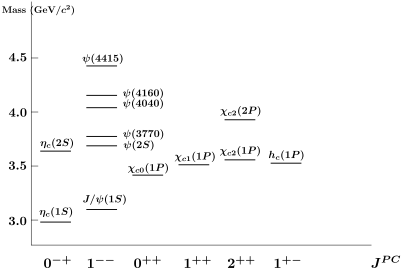

- **$c\bar{c}$ の領域で数多くの発見** (BaBar, Belle, BESIII, LHCb,...)

  Meson 系: X, Y, Z (代表例: $X(3872)$)
  Baryon 系: P_c, P_{cs}

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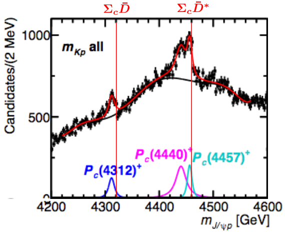

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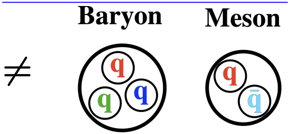

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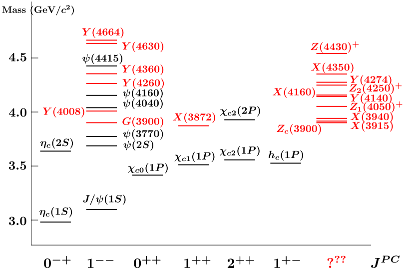

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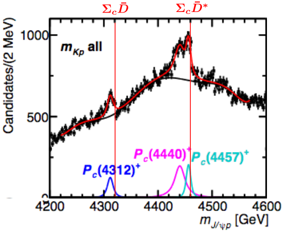

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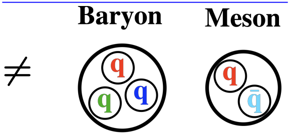

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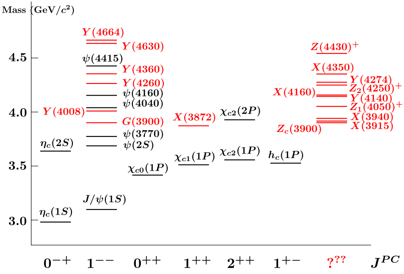

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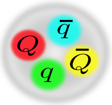
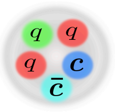
Q. 構造は何か? 形成機構は?

エキゾチック構造の候補: 多クォーク状態など

Compact multiquarks

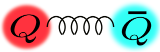


Tetraquark

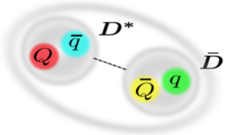


Pentaquark

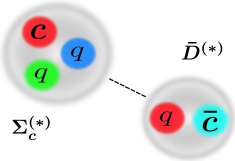
$Q\bar{Q}g$ Hybrid



Hadronic molecules

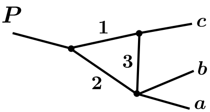


Meson-Meson



Meson-Baryon

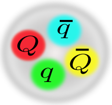
Triangle Singularity



(w/o Resonance)

エキゾチック構造の候補: 多クォーク状態など

Compact multiquarks



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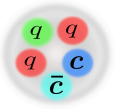

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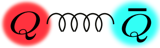

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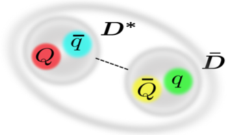

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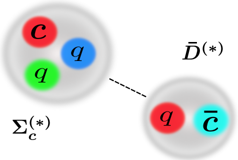

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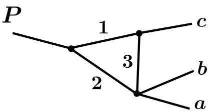

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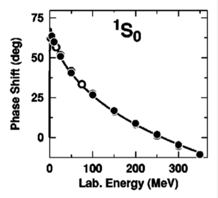
- 様々な議論が行われてきた $\leftrightarrow$ しかし、なかなか決着はつかず...

  なぜ? ハドロン相互作用がよくわかっていない

Hadron interaction

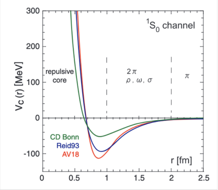
▶ よく知られているハドロン間力 · · · **核子-核子相互作用 (核力)**

NN scattering data



R. Machleidt, PRC**63**(2001)024001

NN realistic potential



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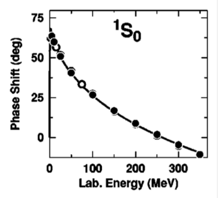

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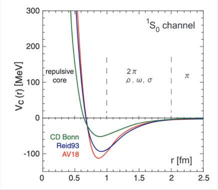

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- チャームハドロンの相互作用 ··· **よくわかっていない**
  - 散乱データ ··· チャームハドロンは**不安定**
    ↔ 今後の格子 QCD や重イオン衝突実験研究への期待

Ref. Y. Ikeda *et al.* [HAL QCD], PRL**117**(2016)242001, A. Ohnishi, Symposium (JPS 2021 Autumn meeting) ...

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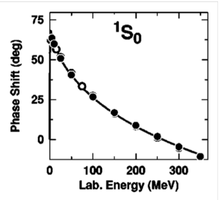

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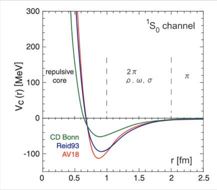

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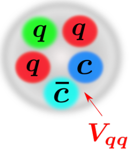
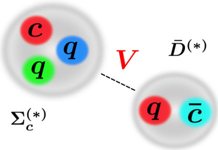
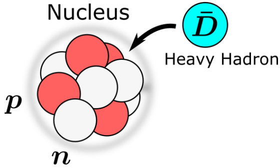
- **対称性や微視的模型 (クォーク模型)**に基づいた相互作用模型構築
  - メソン交換力 (**π 交換**: カイラル対称性の自発的破れ)
  - クォーク間力 (グルーオン交換), クォーク交換力...

ヘビーエキゾチックハドロンスペクトロスコピー

コンパクト状態　　**ハドロン分子**　　**ハドロン原子核**





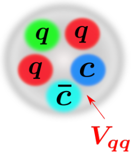


$\cdots$

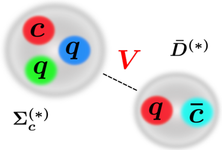
$\Rightarrow$ 非相対論的な (少数) 多体系の束縛・共鳴状態の問題 (質量・崩壊幅)

ヘビーエキゾチックハドロンスペクトロスコピー

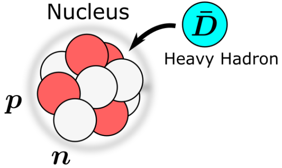
コンパクト状態



ハドロン分子



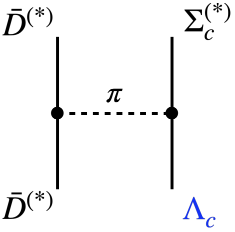
ハドロン原子核



· · ·

⇒ 非相対論的な (少数) 多体系の束縛・共鳴状態の問題 (質量・崩壊幅)

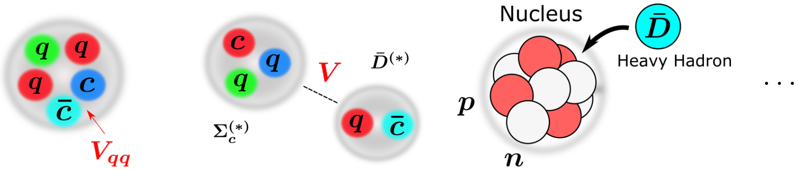
→ **チャンネル結合 (テンソル力、粒子が変わる)**有り、**3 体以上**の系は、ハドロンの人には難しい...



- π 交換が導くチャンネル結合の例

ヘビーエキゾチックハドロンスペクトロスコピー

コンパクト状態　**ハドロン分子**　**ハドロン原子核**



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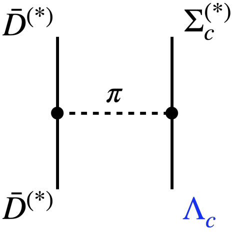
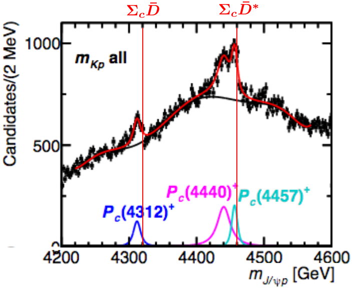
ハドロンの人には難しい... ← **原子核の人助けて!**

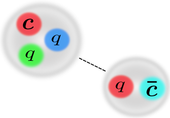


- π 交換が導くチャンネル結合の例

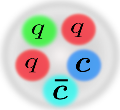
Hidden-charm pentaquarks P_c



R.Aaij, *et al.* (LHCb collaboration) PRL**115**(2015)072001, PRL**122**(2019)222001



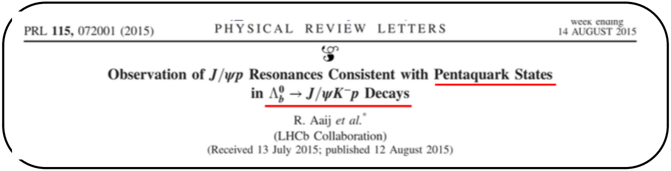
Hadronic molecule ?



Pentaquark (Compact) ?

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



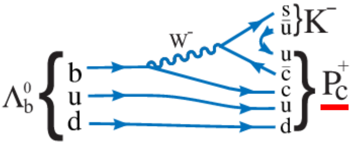
PRL **115,** 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

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

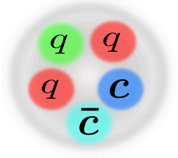
R. Aaij *et al.**
(LHCb Collaboration)
(Received 13 July 2015; published 12 August 2015)

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

$c\bar{c}uud$ state ?



$\Rightarrow$

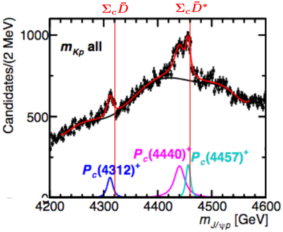


$P_c(4380)$: M =4380 MeV, Γ= 205 MeV

$P_c(4450)$: 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 $P_c(4380)^+$"

New LHCb analysis in 2019!

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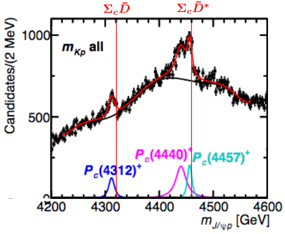

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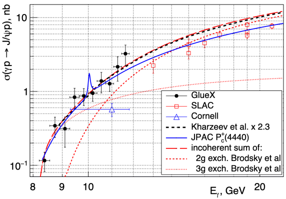
- Complementary experiments: $\gamma p \to J/\psi p$ in GlueX@J-Lab

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

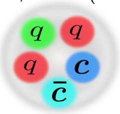
  S.G.Yuan, *et al.* (2012), L.Maiani, *et al,* (2015), S.Takeuchi, *et al,* (2017), J. Wu, *et al.* (2017), E. Hiyama, *et al.* (2018), ...

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

  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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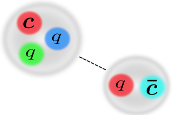
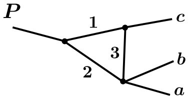


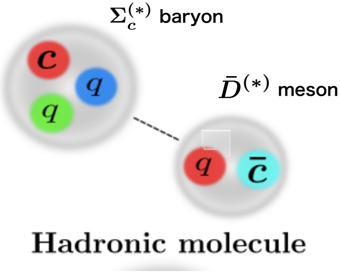
Hadronic molecule



Hadronic molecules?

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

→ expected **near the thresholds**



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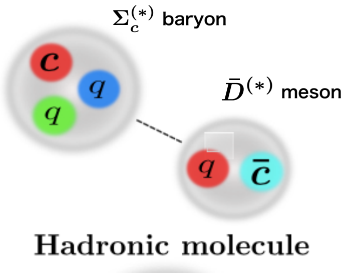
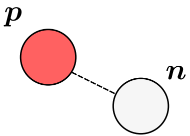


Analogous to Deuteron



$B = 2.2$ MeV

Hadronic molecules?

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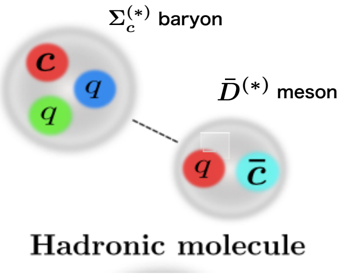
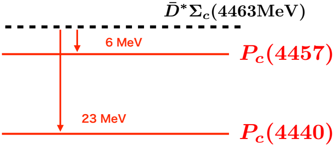
→ expected **near the thresholds**



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



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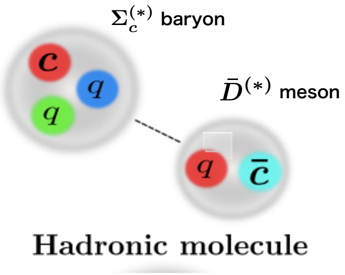

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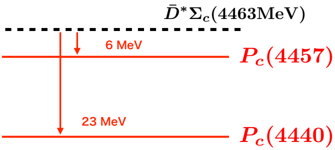

▷ Q. Interactions?: **Heavy hadron interactions** are not established yet...

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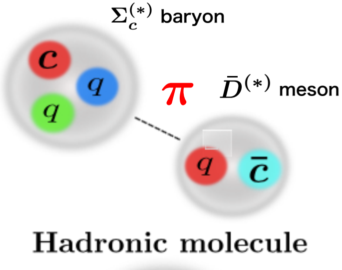

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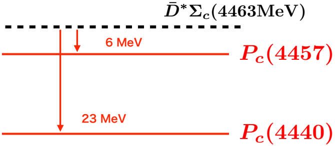


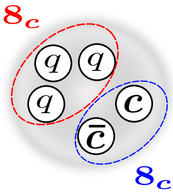
▷ Q. Interactions?: **Heavy hadron interactions** are not established yet...

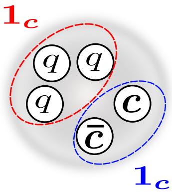
⇒ Importance of π **exchange** is expected due to the heavy quark symmetry! S. Yasui and K. Sudoh, Phys. Rev. D **80** (2009), 034008

⇒ 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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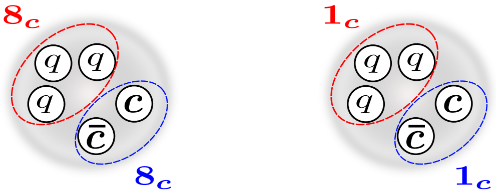

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- $[q^3\, 8_c\, 3/2]$: Color magnetic int. is attractive!

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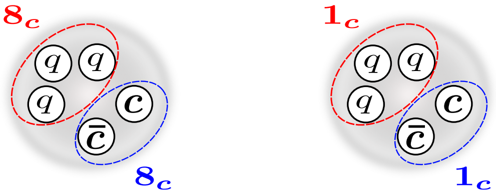

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- $[q^3\, 8_c\, 3/2]$: Color magnetic int. is attractive!

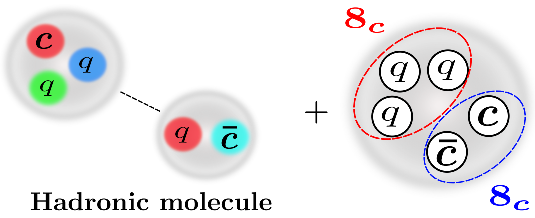
  ⇒ Couplings to (qqc) baryon-$(q\bar{c})$ meson, e.g. $\bar{D}\Sigma_c$, are allowed!

Mixing of Compact state and Hadronic Molecule!

Model setup in this study

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

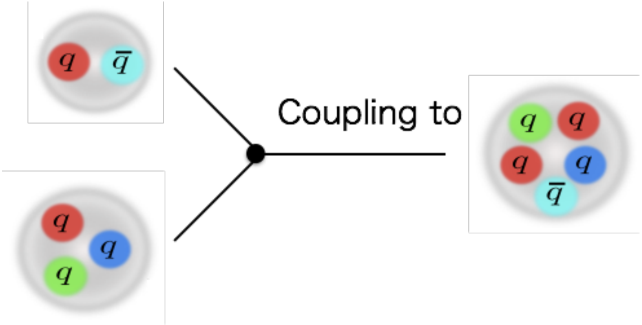
$MB + 5q$



Model setup in this study

- **Hadronic molecule + Compact state ($5q$)**
  $\Rightarrow$ Meson-Baryon couples to $5q$ (Feshbach projection)

$MB + 5q$



Model setup in this study

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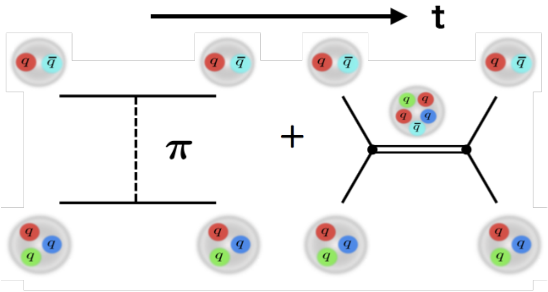
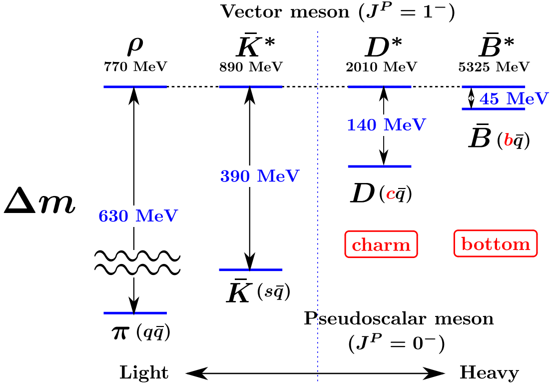
Meson-Baryon interactions



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

Mass degeneracy of heavy hadrons

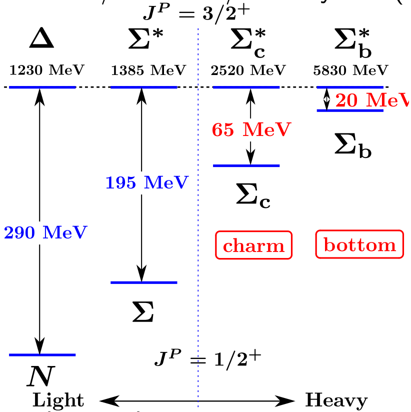
- **Suppression of the spin-spin int. in $m_Q \to \infty$**
  $\Rightarrow$ Heavy quark spin symmetry
- Mass difference between vector and pseudoscalar mesons. ($Q\bar{q}$, $q = u, d$)



- Δm decreases when the quark mass increases.

Mass degeneracy of heavy hadrons

- **Suppression of the spin-spin int. in $m_Q \to \infty$**
  $\Rightarrow$ Heavy quark spin symmetry
- Mass difference between $1/2^+$ and $3/2^+$ baryons. (Qqq)

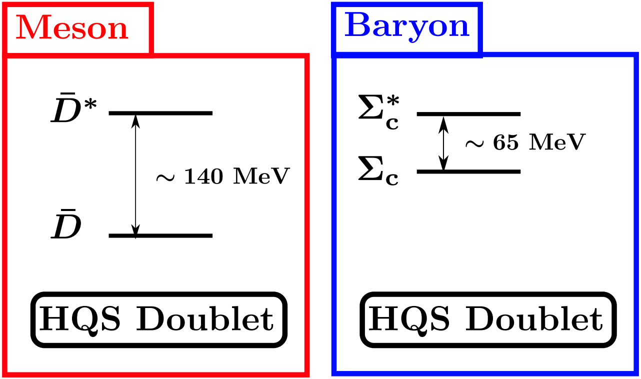


- Δm decreases when the quark mass increases.
  $\Rightarrow$ **Degeneracy of Heavy hadrons!**

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

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

$\Rightarrow$ $(\bar{D}, \bar{D}^*)$ and (Σ_c, Σ_c^*) mixing



- 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

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

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

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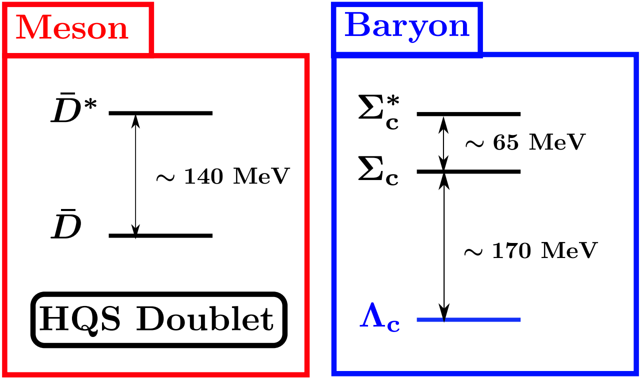
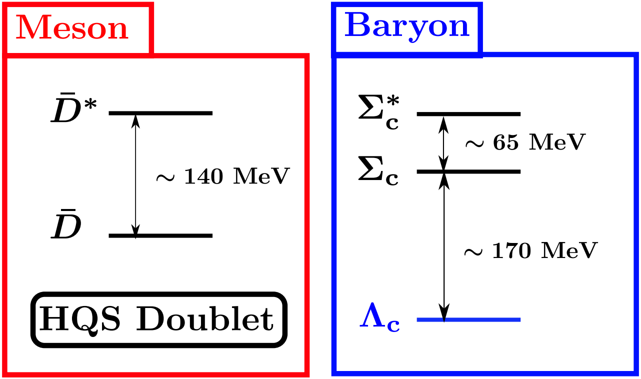


- Coupled channels of $\bar{D}\Sigma_c$, $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$ and $\bar{D}^*\Sigma_c^*$!
  ⇒ These thresholds are close to each other
- In addition, Λ_c (cqq): $\bar{D}^{(*)}\Lambda_c$ channel!?

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 (Σ_c,Σ_c^*) mixing

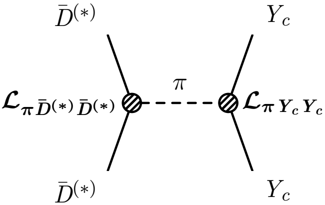


- 6 meson-baryon components

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

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

- One pion exchange potential



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

Y_c: Λ_c, Σ_c or Σ_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)

$g_\pi = 0.59, g_1 = 1.00$

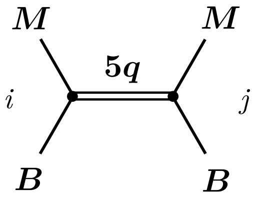
- Form factor with Cutoff Λ (determined by the hadron size)

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

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

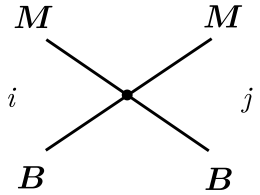
Model: 5-quark potential

- 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 $\bar{D}^{*}\Sigma_{\rm c}^{*}$) $\to$ **Attractive**



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

Channel $i, j = \bar{D}^{(*)}\Lambda_{\rm c},\ \bar{D}^{(*)}\Sigma_{\rm c}^{(*)}$ 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.

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

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

Model: 5-quark potential

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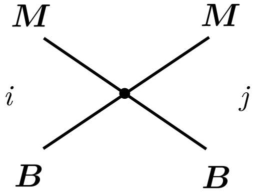
  Massive M_{5q} (few hundred MeV above $\bar{D}^{*}\Sigma_c^{*}$) → **Attractive**



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

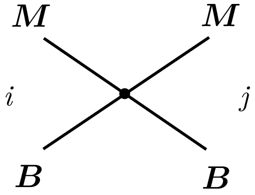
Channel $i, j = \bar{D}^{(*)}\Lambda_c,\ \bar{D}^{(*)}\Sigma_c^{(*)}$ with $S-$wave

Free Parameters

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

Model: 5-quark potential

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

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 $\bar{D}Y_\mathrm{c}$

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

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

J		$S_{c\bar{c}}$	S_{3q}	$\bar{D}\Lambda_\mathrm{c}$	$\bar{D}^*\Lambda_\mathrm{c}$	$\bar{D}\Sigma_\mathrm{c}$	$\bar{D}\Sigma_\mathrm{c}^*$	$\bar{D}^*\Sigma_\mathrm{c}$	$\bar{D}^*\Sigma_\mathrm{c}^*$
$1/2$	(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

Spectroscopic factor S_i

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

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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
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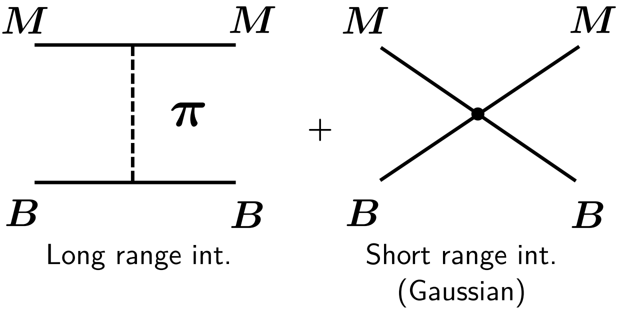
	(iii)	1	3/2	—	0.0	—	**−0.7**	**−0.8**	−0.2
5/2	(i)	1	3/2	—	—	—	—	—	**−1.0**

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

Numerical Results for Hidden-charm sector



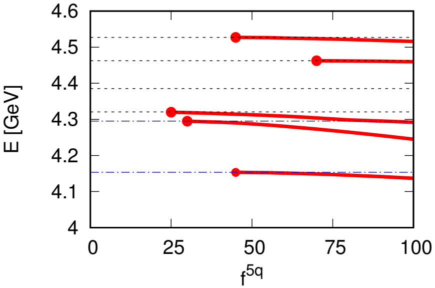
<u>Bound state and Resonance</u>

- 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)

$J^P = 1/2^-$



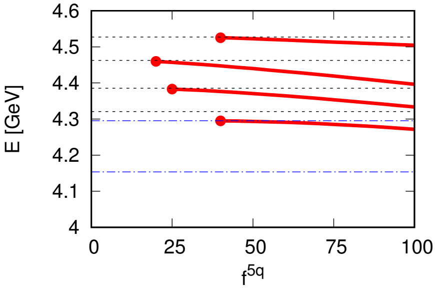
Dashed line: Thresholds, **Red line: Energy obtained**

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

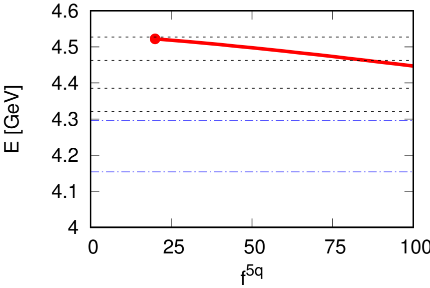
Results (f^{5q} vs E) for $J^P = 3/2^-, 5/2^-$

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

$J^P = 3/2^-$



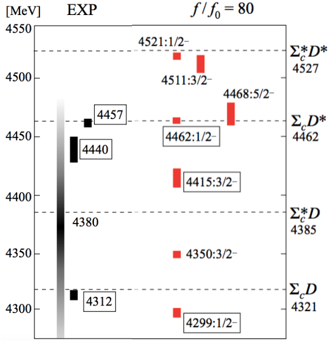
$J^P = 5/2^-$



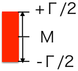
- For small f^{5q}, **No bound state**
  $\Rightarrow$ The OPEP attraction is not enough to generate a state
- **$5q$ potential helps to generate the states near the thresholds**

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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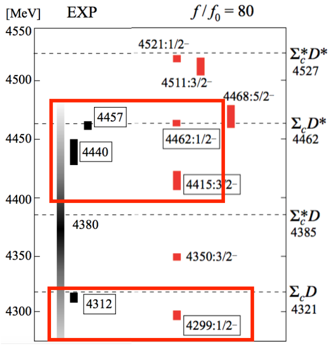

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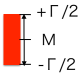

- **Agreement with $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$**

For New P_c states by LHCb in 2019

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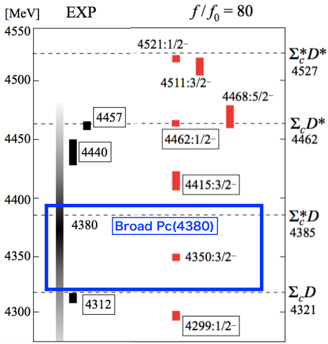
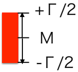


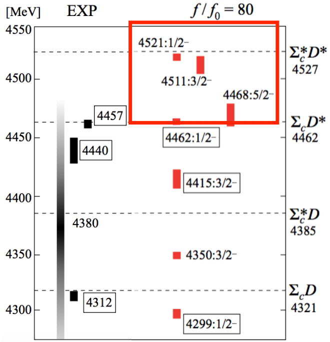
$(f_0 = 6$ MeV$)$



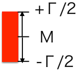
- **Agreement with $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$**
- For Broad $P_c(4380)$, we obtain the similar mass. But width...?

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)

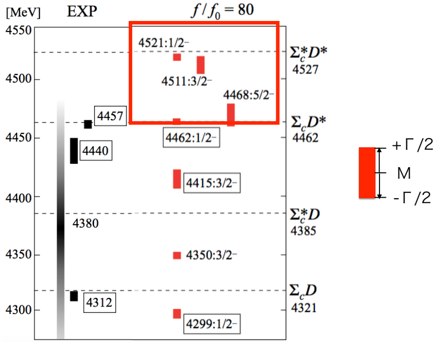


- **Agreement with $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$**
- For Broad $P_c(4380)$, we obtain the similar mass. But width...?
- Predictions: $(1/2^-, 3/2^-, 5/2^-)$ states below $\bar{D}^* \Sigma_c^*$

For New P_c states by LHCb in 2019

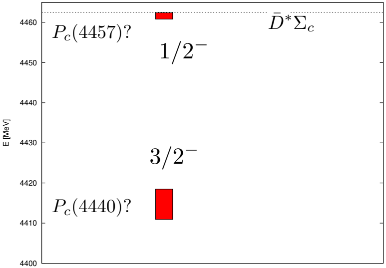
Y.Y., H.Garcia-Tecocoatzi, .**01** (2020) 091502(R)

($f_0 = 6$ 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)

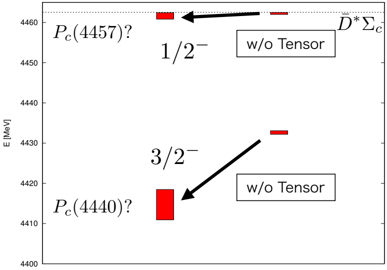
Role of Interactions in P_c



- 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
$P_c(4440)$: $3/2^-$
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$\boldsymbol{E(1/2^-) > E(3/2^-)}$

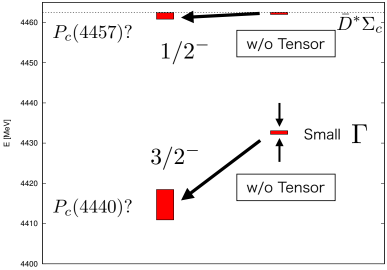
- with Tensor (original) vs without Tensor for V^π

⇒ Mass and Width are **reduced!**

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

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

Role of Interactions in P_c



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

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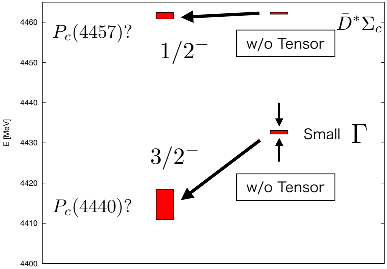
▷ V^{5q}: Major role to determine **Energy Levels**

Role of Interactions in P_c



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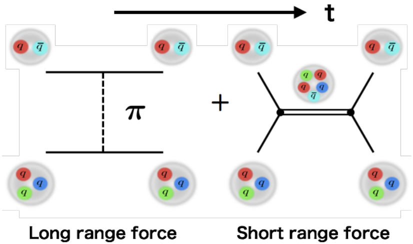
▷ V^{5q}: Major role to determine **Energy Levels**

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

Summary

- Hidden-charm pentaquarks P_c reported by LHCb
- Hadronic molecule + Compact multiquark Model was applied
  - Long range force: π 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 $\boldsymbol{\Gamma}$



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.