Threshold peaks in heavy hadrons P_c

Atsushi Hosaka, RCNP&ASRC,JAEA

- New data from LHC
- Possible interpretation
  - hadronic molecule with tensor force
- Former results from our work
  Yamaguchi et al (Japan-Italy), PRD96, 114031 (2017)
  Beihang-Osaka (PRL accepted)

Hadron Physics

Consistent understanding of hadrons
mass, life time, size, interactions, …

Studying heavy exotic hadrons is somewhat similar to investigating the social life of heavy quarks. The relevant questions one would be asking in this context are

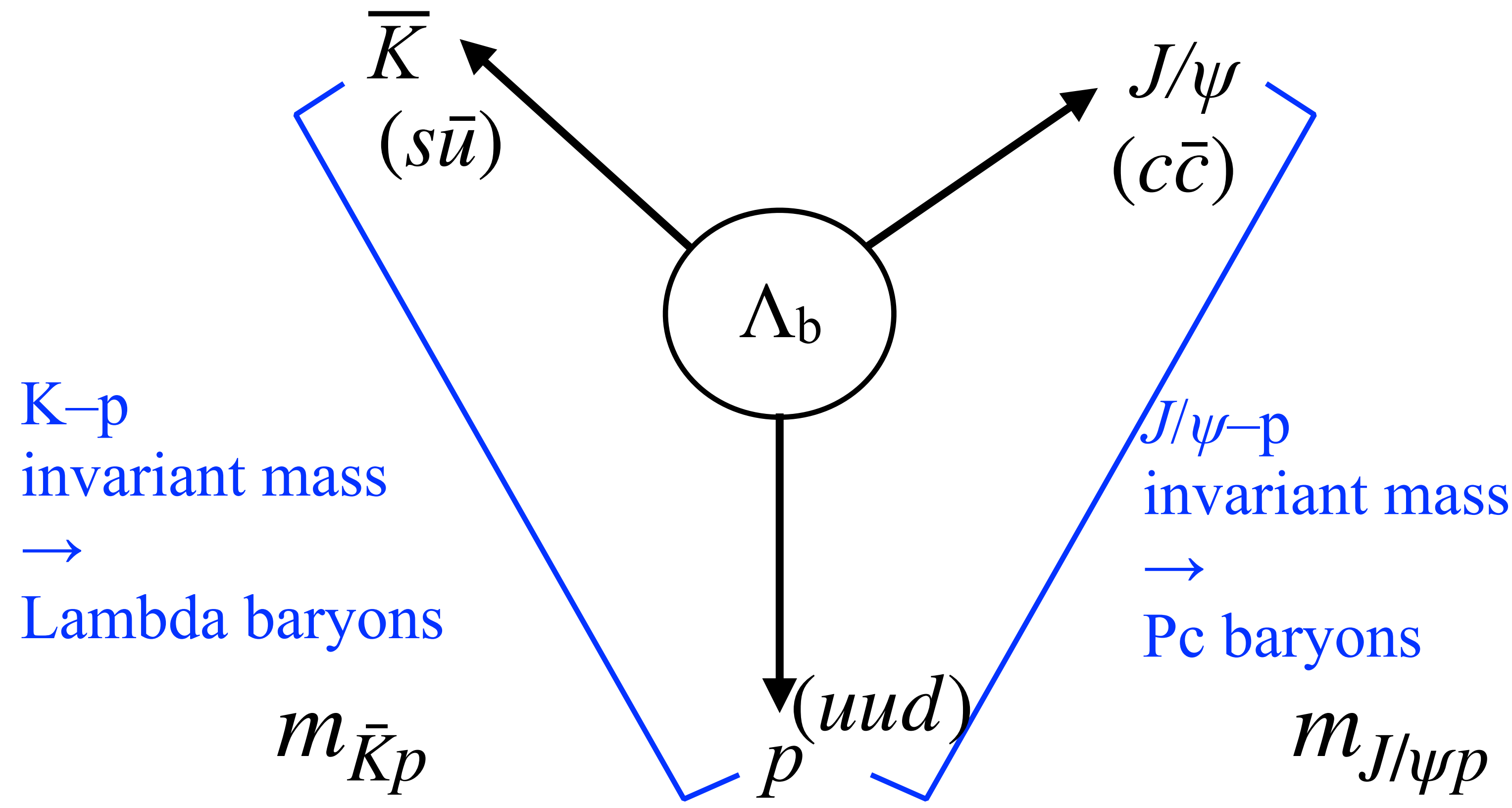
(a) Who with whom?
(b) For how long?
(c) A short episode? or
(d) "Till Death Us Do Part"?
(e) In the following I will try to answer some of the obvious concrete questions about exotic hadrons: Do they exist? If they do, which ones? What is their internal structure? How best to look for them?

Marek Karliner, QNP proceedings, 2018@Tsukuba

New Pc's from LHC

7-8 TeV pp collision $\Lambda_b \to p, J/\psi, K^-$

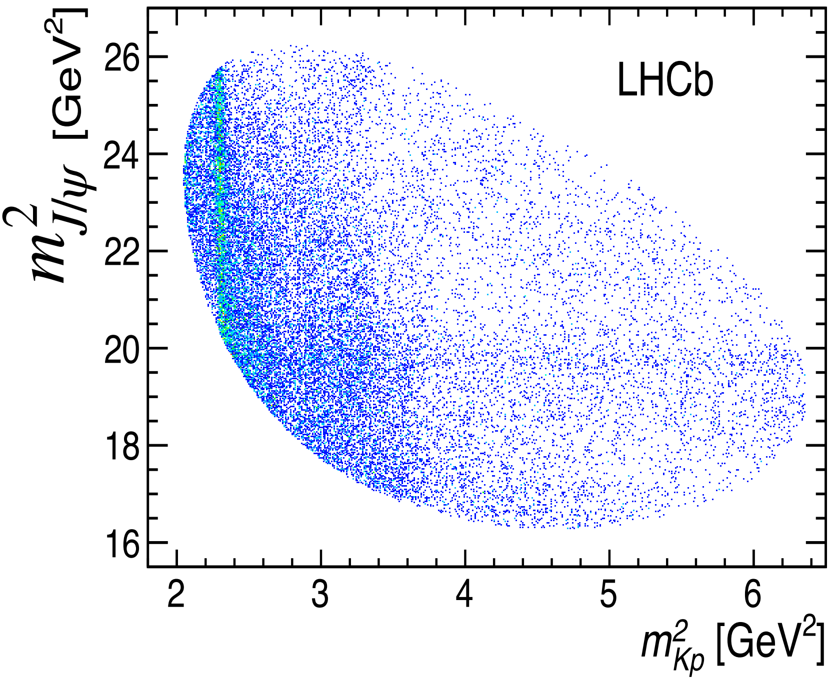
$bud \to uds c\bar{c} \to (uud)(c\bar{c})(s\bar{u})$

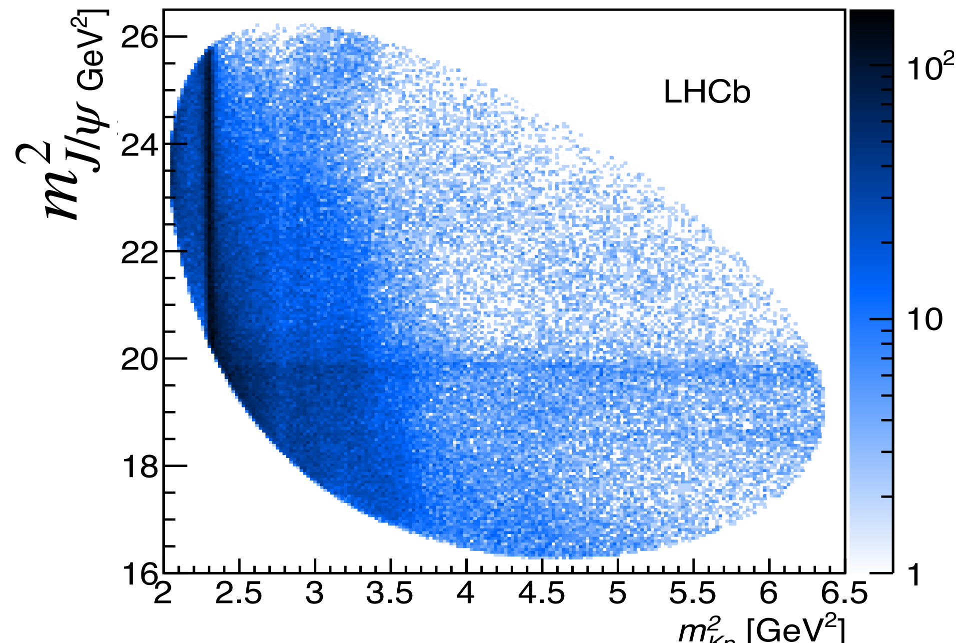


New Data from LHC

Dalitz plots for $m(\bar{K}p)$, $m(J/\psi\ p)$

2015 nine times more statistics → **2019**

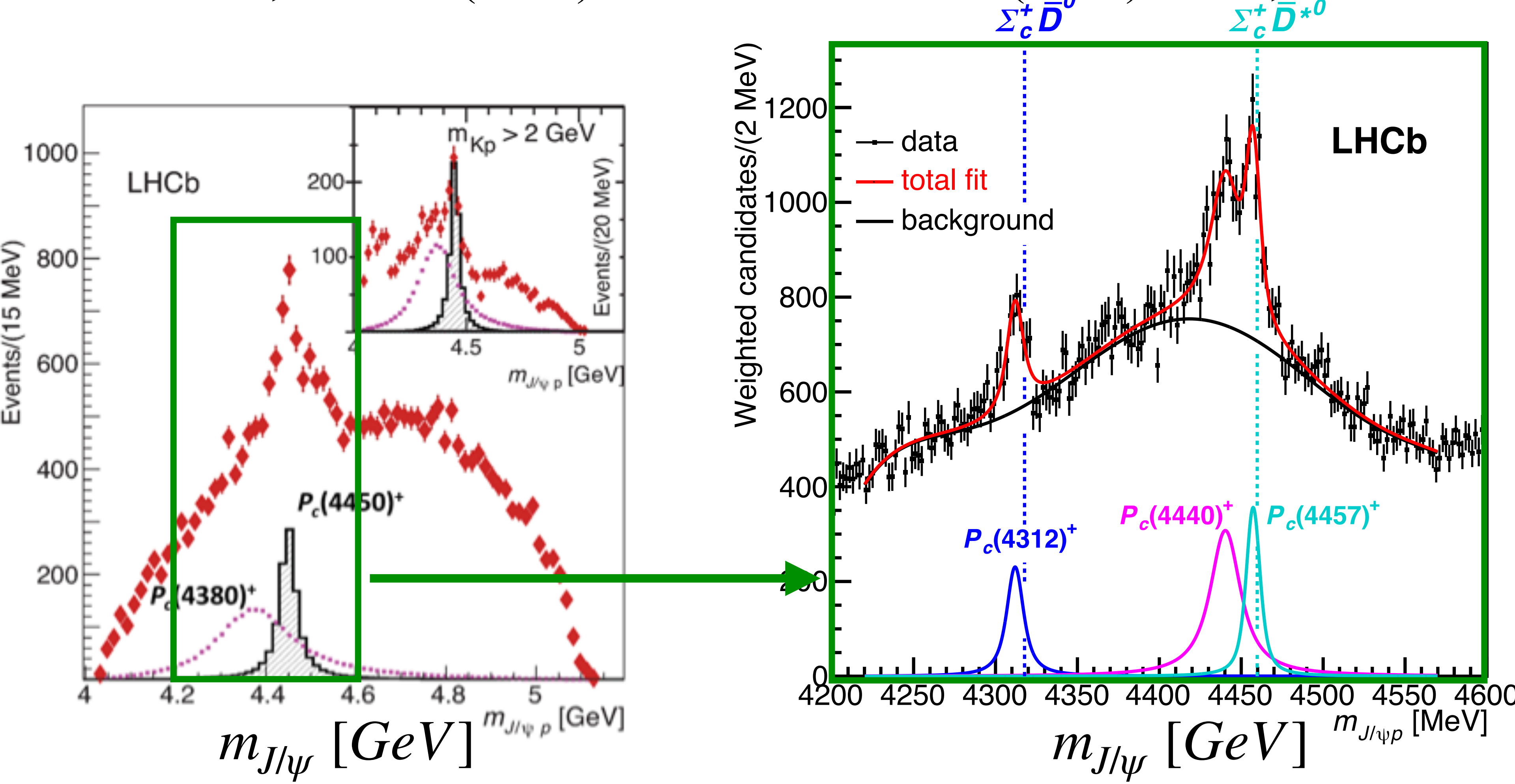




Invariant mass plots

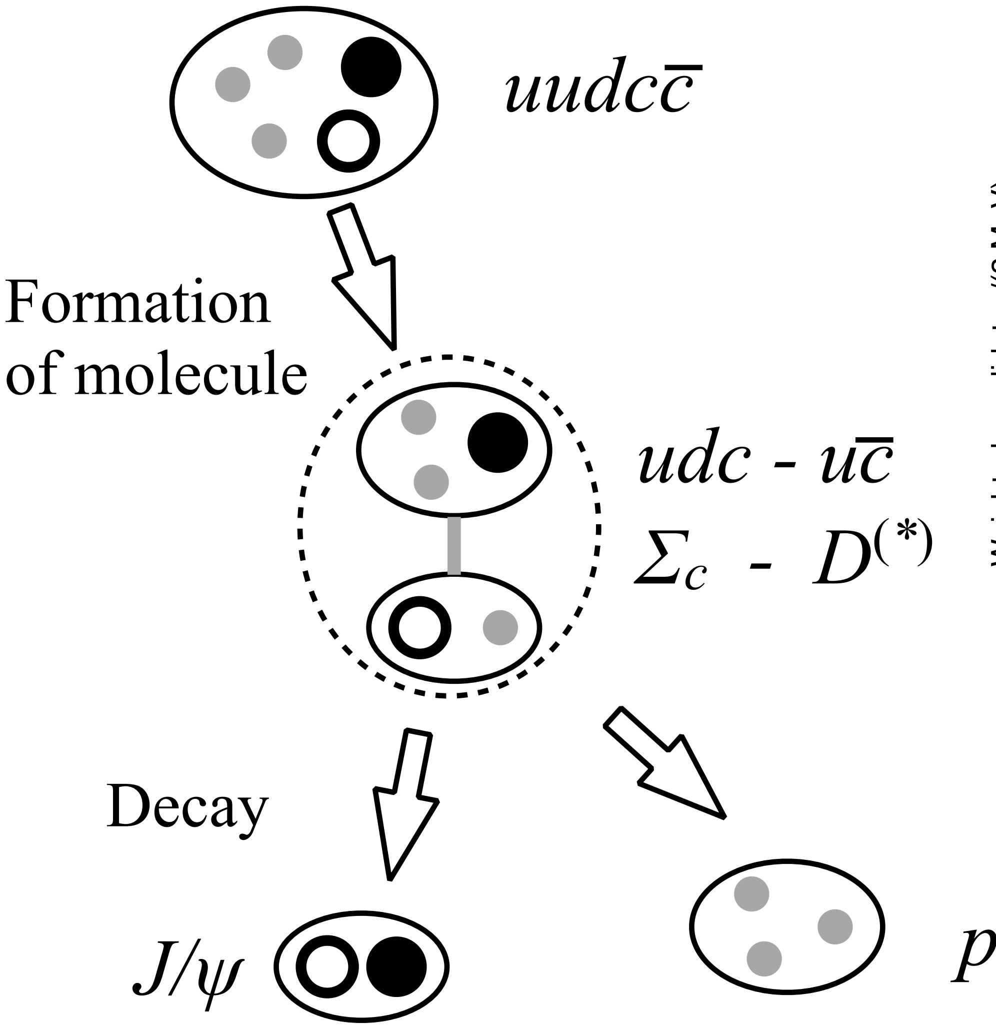
2015 → 9 times more data → 2019

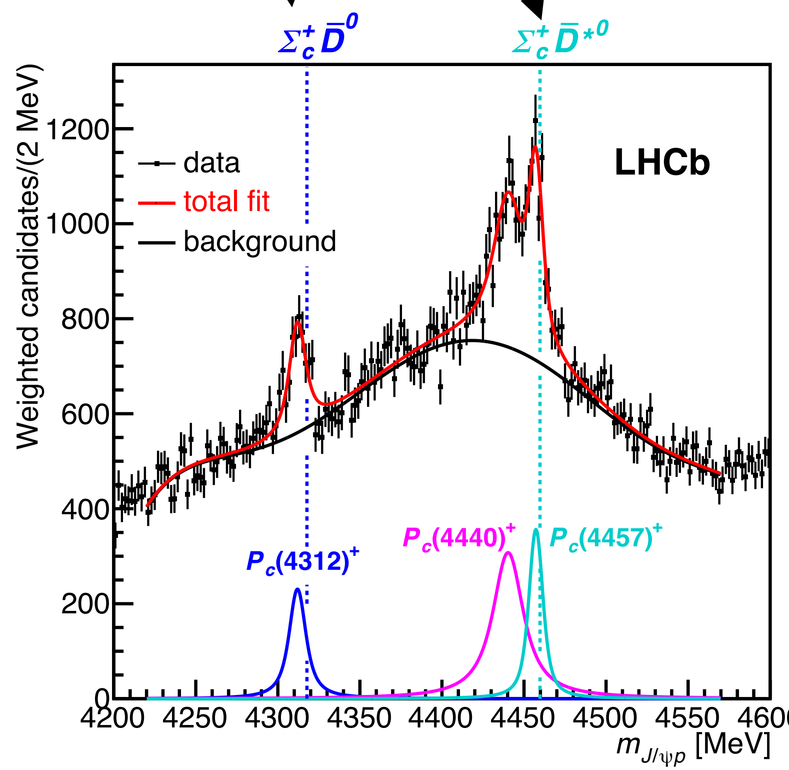
PRL115, 072001 (2015) PRL122 (2019) no.22, 222001



Hadronic Molecules

Three states are just below the thresholds





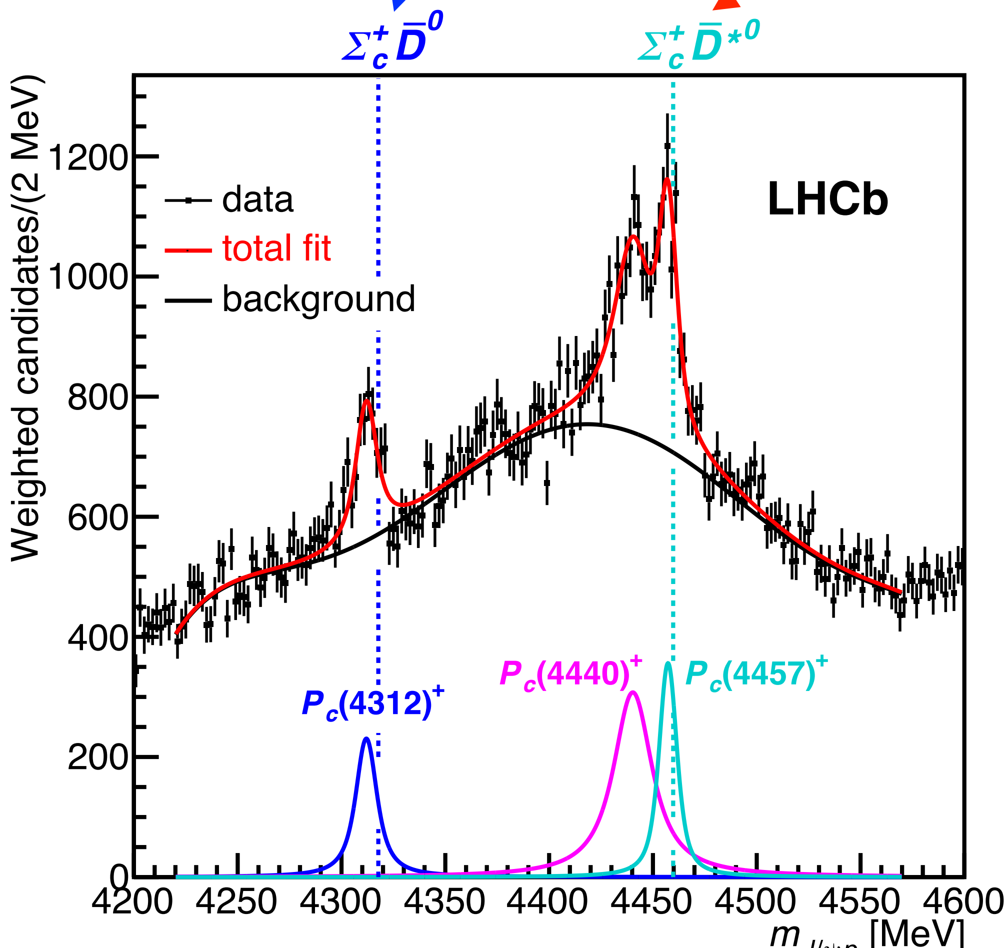
Near threshold particles $\Sigma_c D$ and $\Sigma_c D^*$ And interactions

J =0, 1/2

$J_{\text{tot}} = 1/2$

J =1, 1/2

$J_{\text{tot}} = 1/2, 3/2$



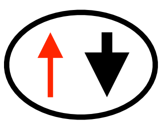
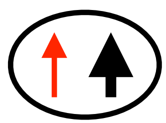
Heavy quark spin symmetry

Heavy spin inert, light spin active

Magnetic interaction of heavy particles is suppressed $\sim \dfrac{\sigma_1 \cdot \sigma_2}{m_1 m_2}$

Single hadron

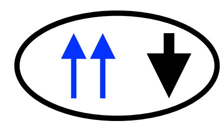
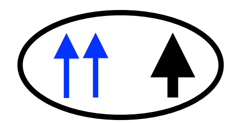
HQ spin doublet

 $\sim$ 

D $\quad$ D^*

$J = 0$ $\quad$ $J = 1$

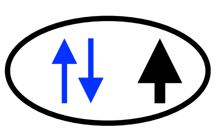
bad diquark, s = 1

 $\sim$ 

Σ_c $\quad$ $\Sigma_c{}^*$

$J = 1/2$ $\quad$ $J = 3/2$

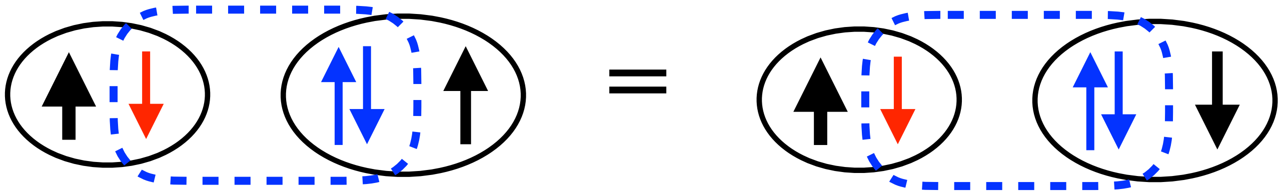
HQ spin singlet

 Λ_c $J = 1/2$

good diquark, s = 0

Heavy quark spin symmetry

Meson-Baryon $D^{(*)}$-$\Lambda^{(*)}$



$$J_{tot} = [s_q, s_d] = \mathbf{1/2}$$

s = **1/2**, **0**

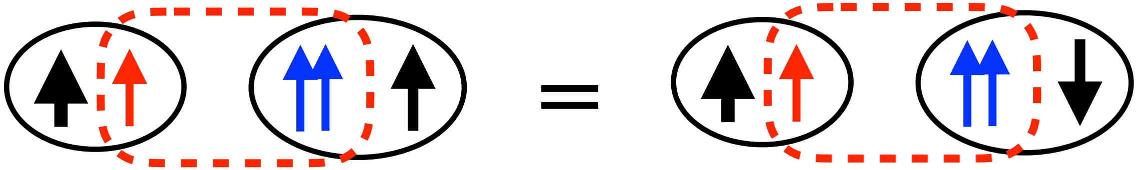
(assuming $L = 0$)

→ One independent interaction for $D^{(*)}$-Λ_c

One parameter determines the relative masses of $[D\Lambda]^{1/2}$, $[D^*\Lambda]^{1/2}$, $[D^*\Lambda]^{3/2}$

Heavy quark spin symmetry

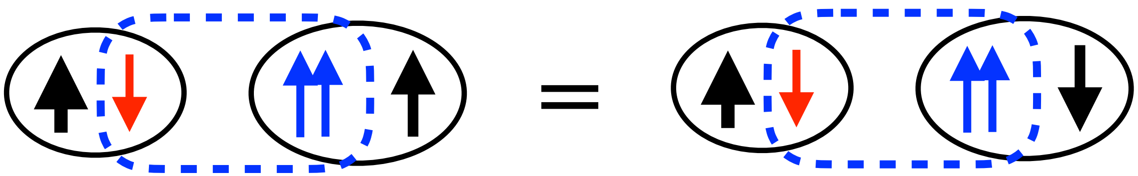
Meson-Baryon $D^{(*)}$-$\Sigma_c^{(*)}$



$J_{tot} = [s_q, s_d] = \mathbf{3/2}$

s_q: **1/2** s_d: **0**

$\neq$



$J_{tot} = [s_q, s_d] = \mathbf{1/2}$

D Σ_c

D^* $\Sigma_c{}^*$

→ **Two independent interactions for $D^{(*)}$-$\Sigma_c^{(*)}$**

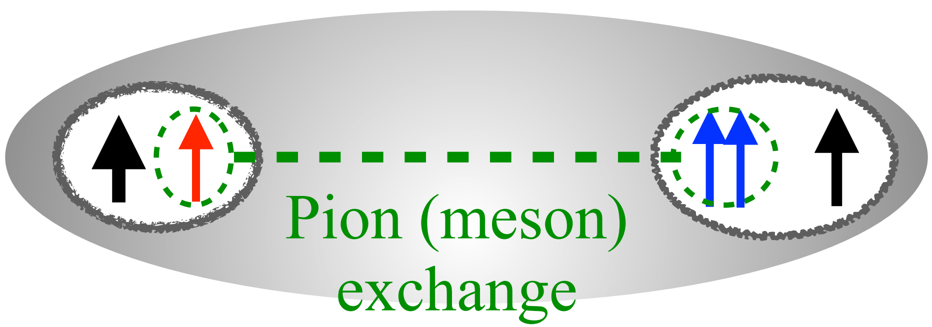
Two parameters determines the relative masses of

$[D\Sigma_c]^{1/2}$, $[D^*\Sigma_c]^{1/2}$, $[D^*\Sigma_c]^{3/2}$, $[D^*\Sigma_c{}^*]^{1/2}$, $[D^*\Sigma_c{}^*]^{3/2}$, $[D^*\Sigma_c{}^*]^{5/2}$

Models of $\Sigma_c D$, $\Sigma_c D^*$, $\Sigma_c^* D$, $\Sigma_c^* D^*$, ΛD ΛD^*

10 states of J = 1/2, 1/2, 3/2, 3/2, 1/2, 3/2, 5/2, 1/2, 1/2, 3/2

Loosely bound hadronic molecule



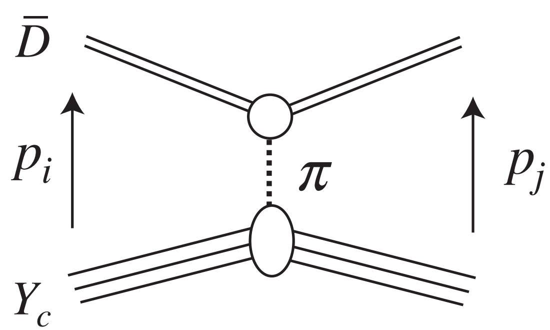
Tensor force of OPEP

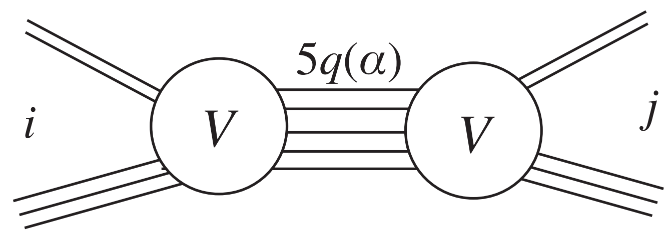
PHYSICAL REVIEW D **96,** 114031 (2017)

Hidden-charm and bottom meson-baryon molecules coupled with five-quark states

Yasuhiro Yamaguchi,[1,2] Alessandro Giachino,[2,3] Atsushi Hosaka,[4,5] Elena Santopinto,[2]
Sachiko Takeuchi,[6,1,4] and Makoto Takizawa[7,1,8]

Hadronic molecule with OPEP + 5q core





And in preparation for the new Pc’s data

Hamiltonian

$$H = \begin{pmatrix} H^{MB} & V \\ V^{\dagger} & H^{5q} \end{pmatrix}$$

- $MB = \Sigma_c D, \Sigma_c D^*, \Sigma_c{}^* D, \Sigma_c{}^* D^*, \Lambda D \;\; \Lambda D^*$ + **OPEP**
- $5q$ = *Color octet* $(qqq)(cc^{bar})$

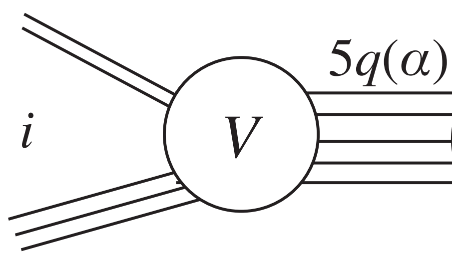
$$5q = [[qqq]_{\mathbf{8}} \cdot [\bar{c}c]_{\mathbf{8}}]_{\mathbf{1}}$$

Channel	$[q^3 8, \frac{1}{2}]0$	$[q^3 8, \frac{1}{2}]1$	$[q^3 8, \frac{3}{2}]0$	$[q^3 8, \frac{3}{2}]1$
J	1/2	1/2, 3/2	3/2	1/2, 3/2, 5/2

- $\langle i|V|\alpha\rangle = f\langle i|\alpha\rangle$

coupling strength = parameter

Spectroscopic factor



Equations

$$H^{MB}\psi^{MB} + V\psi^{5q} = E\psi^{MB},$$
$$V^{\dagger}\psi^{MB} + H^{5q}\psi^{5q} = E\psi^{5q}.$$

5q states are eliminated

$$\left(K^{MB} + V^{\pi} + V\frac{1}{E - H^{5q}}V^{\dagger}\right)\psi^{MB} = E\psi^{MB}$$

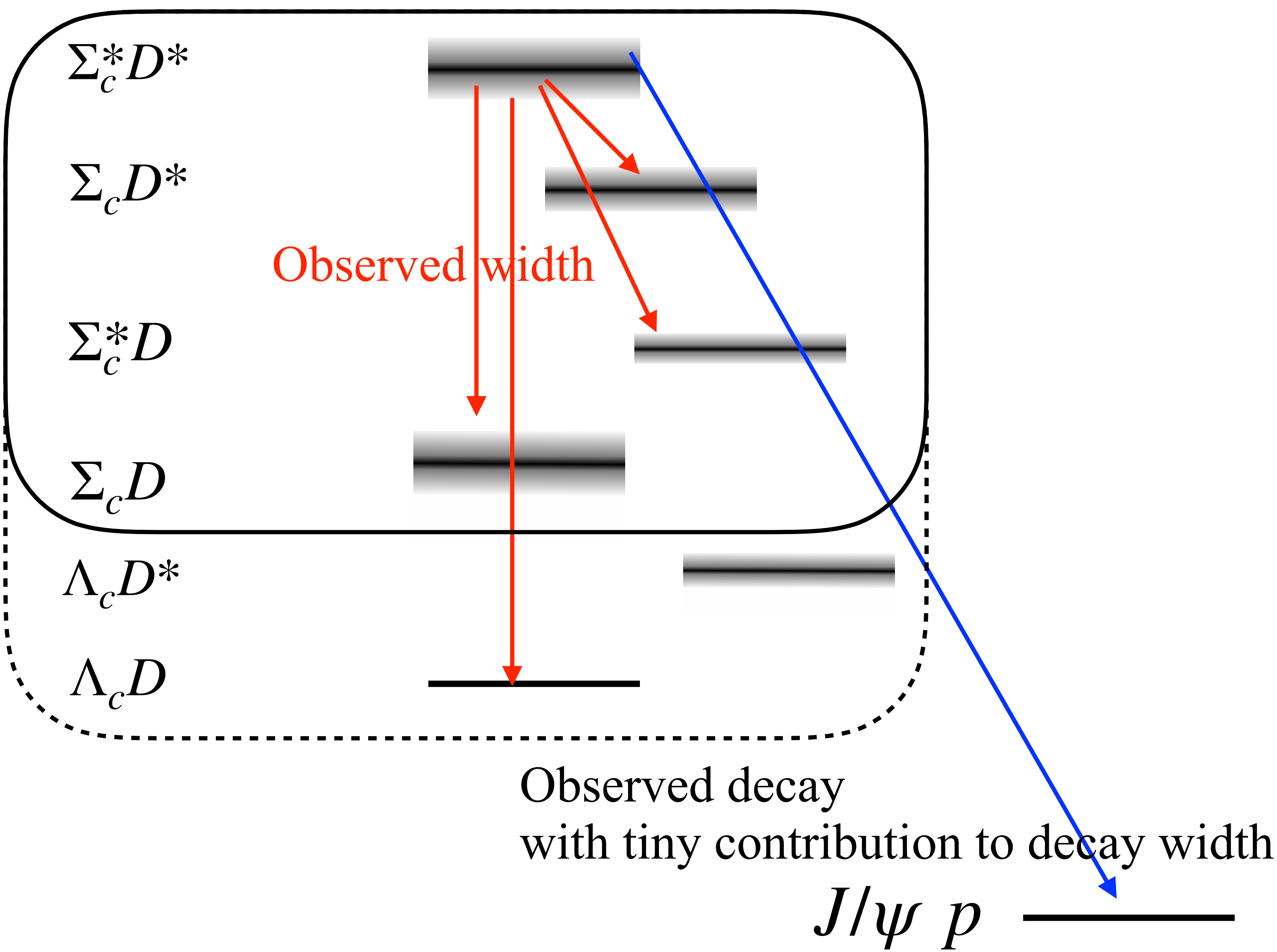
Kinetic term

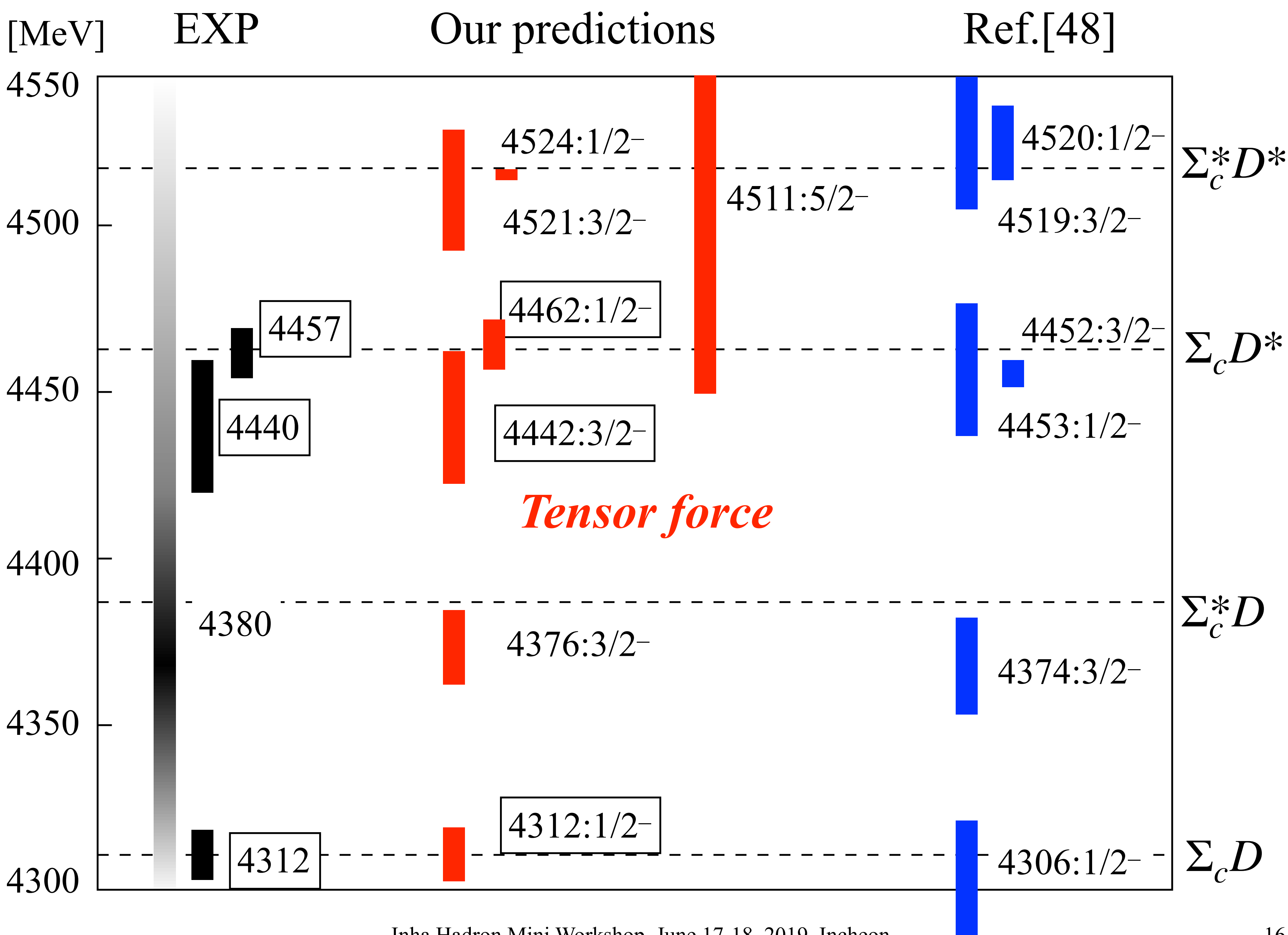
OPEP

Effective potential from 5q

Solving this equation, eigenstates (resonances), phase shits, …

Model spaces and thresholds





[MeV]
EXP
Our predictions
Ref.[48]
4550
4500
4450
4400
4350
4300
4457
4440
4380
4312
4524:1/2−
4521:3/2−
4462:1/2−
4442:3/2−
4511:5/2−
4376:3/2−
4312:1/2−
Tensor force
4520:1/2−
4519:3/2−
4452:3/2−
4453:1/2−
4374:3/2−
4306:1/2−
$\Sigma_c^* D^*$
$\Sigma_c D^*$
$\Sigma_c^* D$
$\Sigma_c D$

Emergence of a complete heavy-quark spin symmetry multiplet: seven molecular pentaquarks in light of the latest LHCb analysis

Ming-Zhu Liu,[1] Ya-Wen Pan,[1] Fang-Zheng Peng,[1] Mario Sánchez Sánchez,[2]
Li-Sheng Geng,[1,3,*] Atsushi Hosaka,[4,5,†] and Manuel Pavon Valderrama[1,6,‡]

e-Print: arXiv:1903.11560, PRL accepted (May 24)

A recent analysis by the LHCb collaboration suggests the existence of three narrow pentaquark-like states — the $P_c(4312)$, $P_c(4440)$ and $P_c(4457)$ — instead of just one in the previous analysis (the $P_c(4450)$). The closeness of the $P_c(4312)$ to the $\bar{D}\Sigma_c$ threshold and the $P_c(4440)/P_c(4457)$ to the $\bar{D}^*\Sigma_c$ one suggests a molecular interpretation of these resonances. We show that these three pentaquark-like resonances can be naturally accommodated in a contact-range effective field theory description that incorporates heavy-quark spin symmetry. This description leads to the prediction of all the seven possible S-wave heavy antimeson-baryon molecules (that is, there should be four additional molecular pentaquarks in addition to the $P_c(4312)$, $P_c(4440)$ and $P_c(4457)$), providing the first example of a heavy-quark spin symmetry molecular multiplet that is complete. If this is confirmed, it will not only give us an impressive example of the application of heavy-quark symmetries and effective field theories in hadron physics: it will also uncover a clear and powerful ordering principle for the molecular spectrum, reminiscent of the SU(3)-flavor multiplets to which the light hadron spectrum conforms.

$D(0^-)$-$\Sigma_c(1/2^+)$ → $J^P = 1/2^-$
$D(0^-)$-$\Sigma_c(3/2^+)$ → $J^P = 3/2^-$
$D^*(1^-)$-$\Sigma_c(1/2^+)$ → $J^P = 1/2^-, 3/2^-$
$D^*(1^-)$-$\Sigma_c(3/2^+)$ → $J^P = 1/2^-, 3/2^-, 5/2^-$

HQ対称性を満たす
相互作用2個のパラメータを
決めれば5つを予言できる

Masses of seven states are determined by two parameters

$$L = C_a Tr[H_c^\dagger H_c] S_c \cdot S_c^\dagger + C_b \sum_{i=1}^{3} Tr[H_c^\dagger \sigma_i H_c] S_c \cdot (J_i S_c^\dagger)$$

$$H_c = \frac{1}{\sqrt{2}}(D + \vec{D}^* \vec{\sigma}) \qquad S_c = \frac{1}{\sqrt{3}}(\Sigma_c \vec{\sigma} + \vec{\Sigma}^*{}_c)$$

$$V(\tfrac{1}{2}^-, \bar{D}\Sigma_c) = C_a\,,$$
$$V(\tfrac{3}{2}^-, \bar{D}\Sigma_c^*) = C_a\,,$$
$$V(\tfrac{1}{2}^-, \bar{D}^*\Sigma_c) = C_a - \tfrac{4}{3}C_b\,,$$
$$V(\tfrac{3}{2}^-, \bar{D}^*\Sigma_c) = C_a + \tfrac{2}{3}C_b\,,$$
$$V(\tfrac{1}{2}^-, \bar{D}^*\Sigma_c^*) = C_a - \tfrac{5}{3}C_b\,,$$
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$$V(\tfrac{5}{2}^-, \bar{D}^*\Sigma_c^*) = C_a + C_b\,,$$

M_J=3/2 < M_J=1/2

M_J=3/2 > M_J=1/2

Scenario	Molecule	J^P	B (MeV)	M (MeV)
A	$\bar{D}\Sigma_c$	$\frac{1}{2}^-$	13.1 – 14.5	4306.3 – 4307.7
A	$\bar{D}\Sigma_c^*$	$\frac{3}{2}^-$	13.6 – 14.8	4370.5 – 4371.7
A	$\bar{D}^*\Sigma_c$	$\frac{1}{2}^-$	Input	4457.3
A	$\bar{D}^*\Sigma_c$	$\frac{3}{2}^-$	Input	4440.3
A	$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}^-$	3.1 – 3.5	4523.2 – 4523.6
A	$\bar{D}^*\Sigma_c^*$	$\frac{3}{2}^-$	10.1 – 10.2	4516.5 – 4516.6
A	$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^-$	25.7 – 26.5	4500.2 – 4501.0
B	$\bar{D}\Sigma_c$	$\frac{1}{2}^-$	7.8 – 9.0	4311.8 – 4313.0
B	$\bar{D}\Sigma_c^*$	$\frac{3}{2}^-$	8.3 – 9.2	4376.1 – 4377.0
B	$\bar{D}^*\Sigma_c$	$\frac{1}{2}^-$	Input	4440.3
B	$\bar{D}^*\Sigma_c$	$\frac{3}{2}^-$	Input	4457.3
B	$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}^-$	25.7 – 26.5	4500.2 – 4501.0
B	$\bar{D}^*\Sigma_c^*$	$\frac{3}{2}^-$	15.9 – 16.1	4510.6 – 4510.8
B	$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^-$	3.2 – 3.5	4523.3 – 4523.6

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$$\boldsymbol{H_c = \frac{1}{\sqrt{2}}(D + \vec{D}^* \vec{\sigma})} \qquad \boldsymbol{S_c = \frac{1}{\sqrt{3}}(\Sigma_c \vec{\sigma} + \vec{\Sigma}^*{}_c)}$$

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B	$\bar{D}\Sigma_c^*$	$\frac{3}{2}^-$	8.3 – 9.2	4376.1 – 4377.0
B	$\bar{D}^*\Sigma_c$	$\frac{1}{2}^-$	Input	4440.3
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B	$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^-$	3.2 – 3.5	4523.3 – 4523.6

Summary

- Recent finding of ***Pc*** is very exciting
- They suggest something interesting near **the thresholds**
- **Hadronic molecule** is the most likely interpretation
- **Tensor force** acts on the spin doublet **JP = 1/2 and 3/2**
- A unique way to see the role of the tensor force, which is **the first example** in the strong interaction dynamics
- **Heavy and light (with SSB) flavors'** combination brings wealth structure of hadrons with **fine tunings**