The 9th International Conference on Quarks and Nuclear Physics

Pentaquark states in the molecular picture

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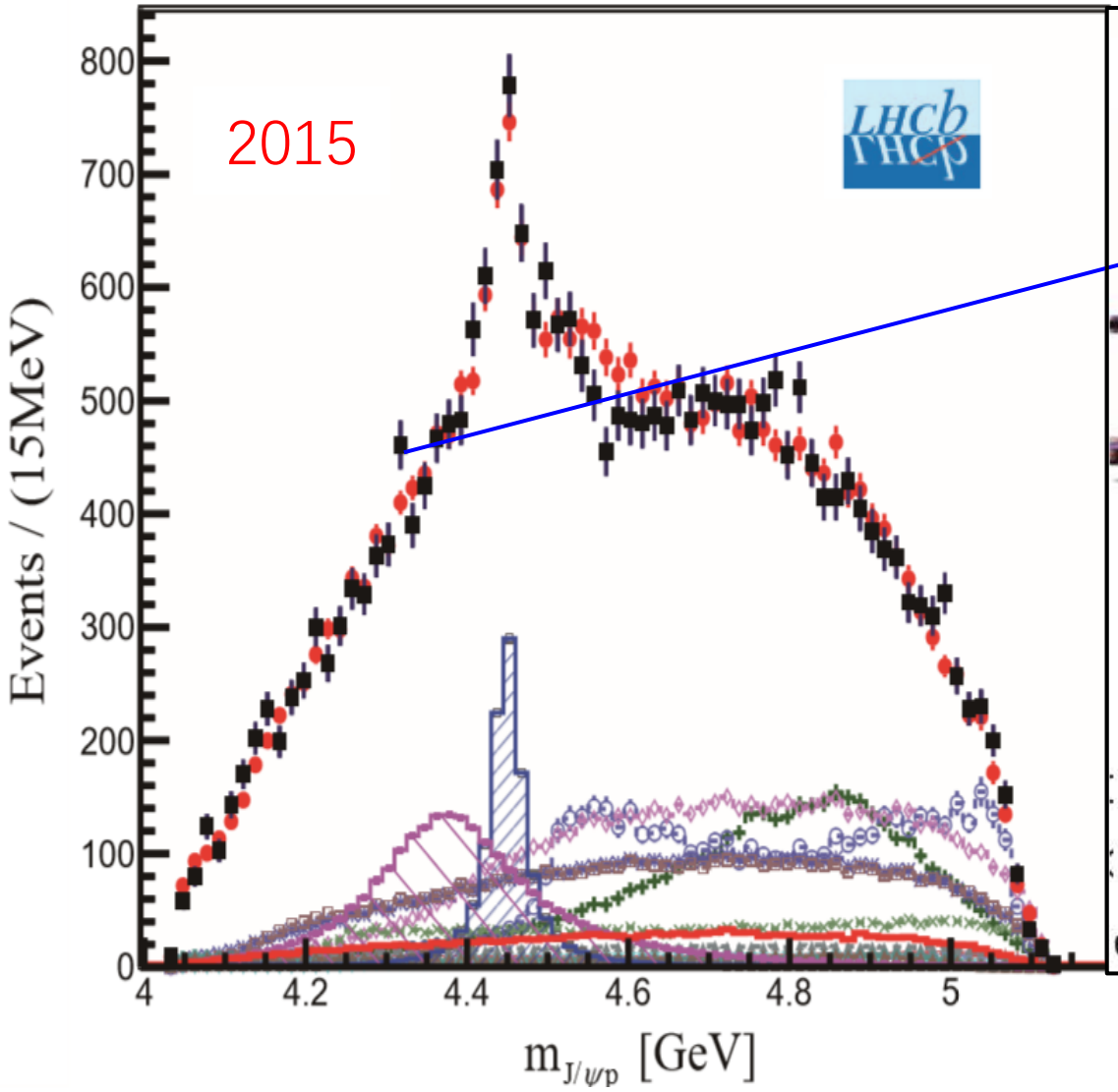
Outline

- Experimental progress on pentaquark states
- Molecular Interpretations
- How to verify the molecular nature
- Summary and outlook

Experimental progress on pentaquark states

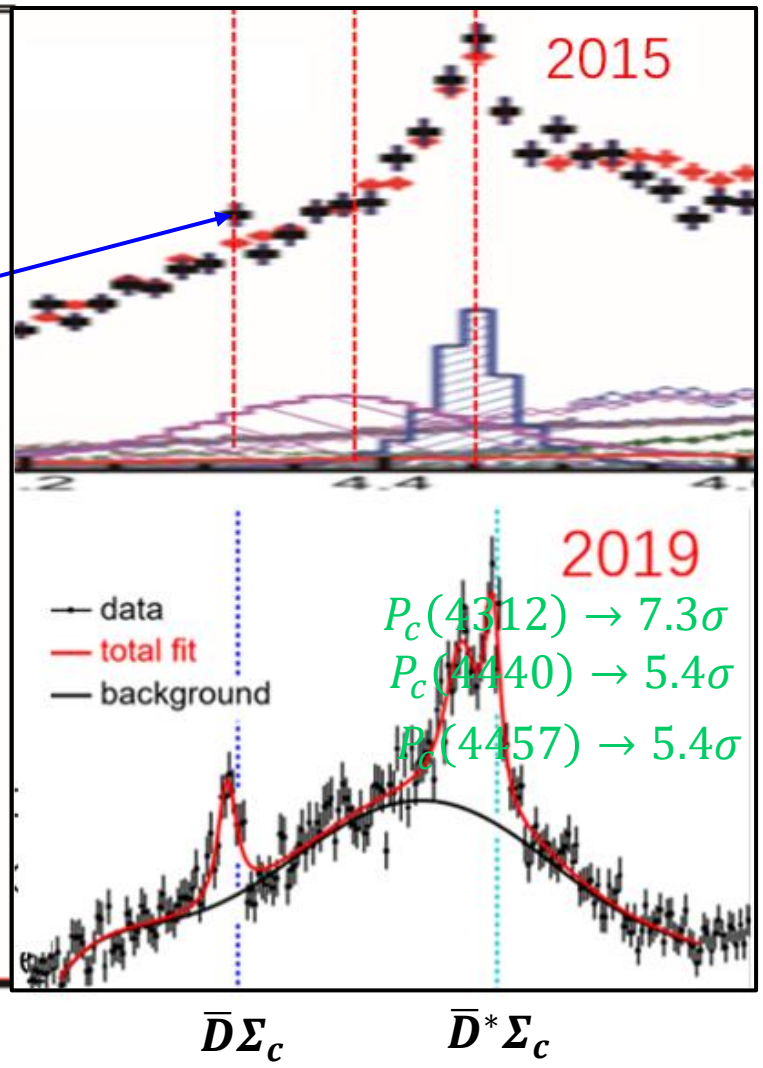
Experimental progress on pentaquark states

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



Phys.Rev.Lett. 115 (2015) 072001

4320 4380 4450



Phys.Rev.Lett. 122 (2019), 222001

2015

$$P_{c1} = 4380 \pm 8 \pm 29 + \frac{i}{2} 205 \pm 18 \pm 86$$

$$P_{c2} = 4449.8 \pm 1.7 \pm 2.5 + \frac{i}{2} 39 \pm 5 \pm 19$$

2019

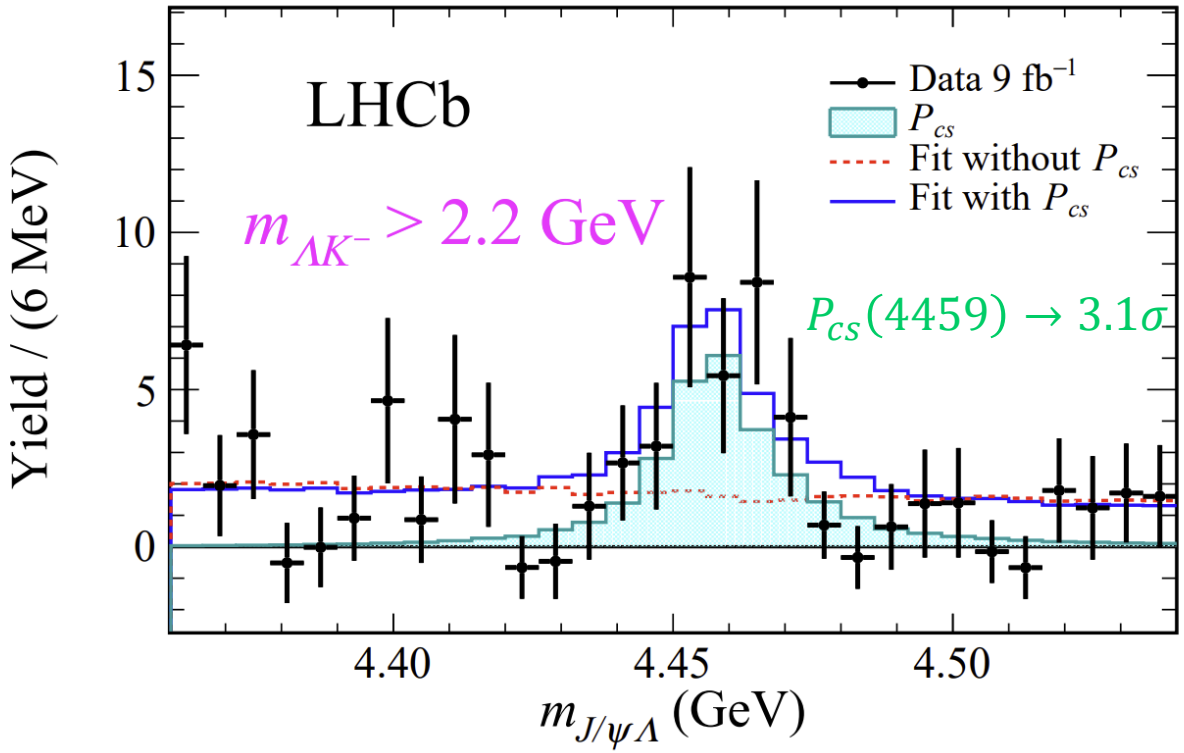
$$P_{c1} = 4311.9 \pm 0.7^{+6.8}_{-0.6} + \frac{i}{2} 9.8 \pm 2.7^{+3.7}_{-4.5}$$

$$P_{c2} = 4440.3 \pm 1.3^{+4.1}_{-4.7} + \frac{i}{2} 20.6 \pm 4.9^{+8.7}_{-10.1}$$

$$P_{c3} = 4457.3 \pm 0.6^{+4.1}_{-1.7} + \frac{i}{2} 6.4 \pm 2.0^{+5.7}_{-1.9}$$

Experimental progress on pentaquark states

$\Xi_b^- \to J/\psi \Lambda K^-$



Sci.Bull. 66 (2021) 1278-1287

$$P_{cs} = 4458.8 \pm 2.9^{+4.7}_{-1.1} + \frac{i}{2} 17.3 \pm 6.5^{+8.0}_{-5.7}$$

Production rates

$$Br(\Lambda_b^0 \to J/\psi p K^-) = 3.2^{+0.6}_{-0.5} \times 10^{-4}$$

$$Br(\Xi_b^- \to J/\psi \Lambda K^-) \approx 2.4 \times 10^{-6}$$

$$R = \frac{\mathcal{B}(\Lambda_b(\Xi_b) \to P_c(P_{cs})\bar{K})\mathcal{B}(P_c(P_{cs}) \to J/\psi p(\Lambda))}{\mathcal{B}(\Lambda_b(\Xi_b) \to \bar{K} J/\psi p(\Lambda))}$$

$P_c(4312) \to 0.30 \pm 0.07^{+0.34}_{-0.09}$

$P_c(4440) \to 1.11 \pm 0.33^{+0.22}_{-0.10}$

$P_c(4457) \to 0.53 \pm 0.16^{+0.15}_{-0.13}$

$P_c(4380) \to 8.4 \pm 0.7 \pm 4.2$

$P_c(4450) \to 4.1 \pm 0.5 \pm 1.1$

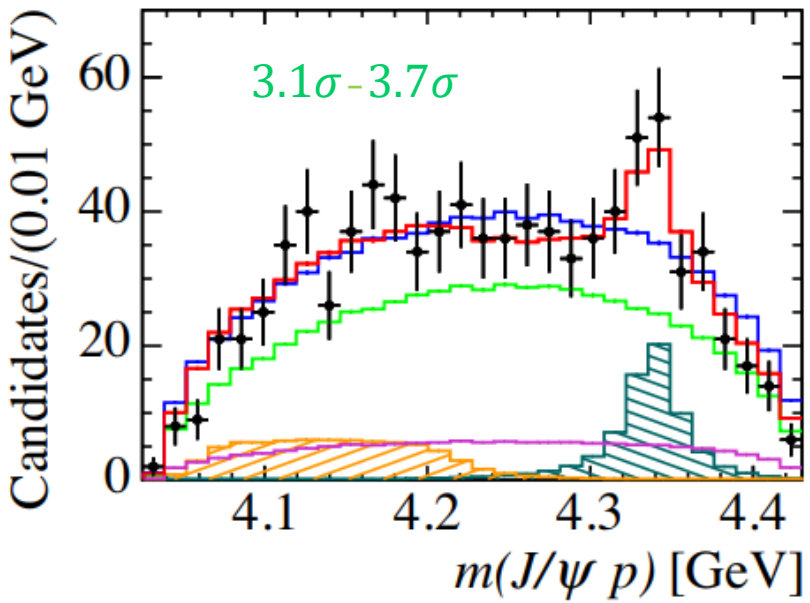
$P_{cs}(4459) \to 2.7^{+1.9+0.7}_{-0.6-1.3}$

$$P_{cs1} = 4454.9 \pm 2.7 + \frac{i}{2} 7.5 \pm 9.7$$

$$P_{cs2} = 4467.8 \pm 3.7 + \frac{i}{2} 5.2 \pm 5.3$$

Experimental progress on pentaquark states

$B_s^0 \to J/\psi p\bar{p}$ $\quad P_c = 4337^{+7+2}_{-4-2} + \frac{i}{2}29^{+26+14}_{-12-14}$



$P_c(4337) \to 0.22 \pm 0.086^{+0.085}_{-0.004}$

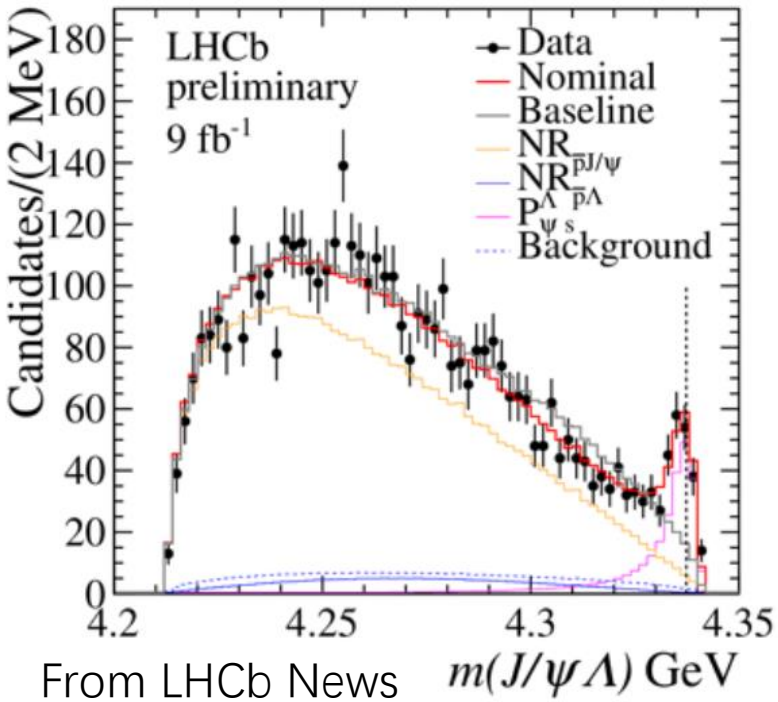
Phys.Rev.Lett. 128 (2022) 6, 062001

$Br(B_s^0 \to J/\psi p\bar{p}) = (3.58 \pm 0.19 \pm 0.39) \times 10^{-6}$

Phys.Rev.Lett. 122 (2019) 19, 191804

$B^- \to J/\psi \Lambda\bar{p}$

$P_{cs} = 4338.2 \pm 0.7 \pm 0.4 + \frac{i}{2}7.0 \pm 1.2 \pm 1.3$



From LHCb News

$P_{cs}(4338) \to 0.125 \pm 0.007$

$Br(B^- \to J/\psi \Lambda\bar{p}) = (11.8 \pm 3.1) \times 10^{-6}$

Phys.Rev. D98 (2018)3, 030001

Interpretations for the pentaquark states

- Molecules

Rui Chen, et al. Phys.Rev.D 100 (2019) 1, 011502
Ming-Zhu Liu, et al. Phys.Rev.Lett. 122 (2019) 24, 242001
Jun He. Eur.Phys.J.C 79 (2019) 5, 393
Chun-Wen Xiao, et al. Phys.Rev.D 100 (2019) 1, 014021
Hua-Xing Chen, et al. Phys.Rev.D 100 (2019) 5, 051501
Zhi-Hui Guo, et al. Phys.Lett.B 793 (2019) 144-149
Meng-Lin Du, et al. Phys.Rev.Lett. 124 (2020) 7, 072001
Meng Lu, et al. Phys.Rev.D 100 (2019) 1, 014031
T.J. Burns, et al. Phys.Rev.D 100 (2019) 11, 114033
Yasuhiro Yamaguchi, et al. Phys.Rev.D 101 (2020) 9, 091502
Yong-Hui Lin, et al. Phys.Rev.D 100 (2019) 5, 056005
Qi Wu, et al. Phys.Rev.D 100 (2019) 11, 114002
Shuntaro Sakai, et al. Phys.Rev.D 100 (2019) 7, 074007
Yubing Dong, et al. Eur.Phys.J.C 80 (2020) 4, 341
Fang-Zheng Peng, et al. Eur.Phys.J.C 81 (2021) 7, 666
Jun-Xu Lu, et al. Phys.Rev.D 104 (2021) 3, 034022
T.J. Burns, et al.. arXiv: 2207.00511
Marek Karliner, et al.. Phys.Rev.D 106 (2022) 3, 036024
…

- Compact multiquark states

Zhi-Gang Wang, Int.J.Mod.Phys.A 35 (2020) 01, 2050003
Ahmed Ali, et al. Phys.Lett.B 793 (2019) 365-371
Xin-Zhen Weng, et al. Phys.Rev.D 100 (2019) 1, 016014
Ahmed Ali, et al. JHEP 10 (2019) 256
Shi-Qing Kuang, et al. Eur.Phys.J.C 80 (2020) 5, 433
Jesse F. Giron, et al. Phys.Rev.D 104 (2021) 5, 054001
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- Hadrocharmonium states

Michael I. Eides, et al. Eur.Phys.J.C 78 (2018) 1, 36
Michael I. Eides, et al. Mod.Phys.Lett.A 35 (2020) 18, 2050151
Mao-Jun Yan, et al. Eur.Phys.J.C 82 (2022) 6, 574
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- Kinetical effect

Feng-Kun Guo, et al. Phys.Rev.D 92 (2015) 7, 071502
Xiao-Hai Liu, et al. Phys.Lett.B 757 (2016) 231-236
Melahat Bayar, et al. Phys.Rev.D 94 (2016) 7, 074039
Shi-Qing Kuang, et al. Eur.Phys.J.C 80 (2020) 5, 433
Chao-Wei Shen, et al. Symmetry 12 (2020) 10, 1611
Satoshi X. Nakamura, et al. Phys.Rev.D 104 (2021) 9, L091503
…

Molecular Interpretations

Lippmann-Schwinger Equation

Lippmann-Schwinger Equation $\left\langle \vec{k}' \middle| T \middle| \vec{k} \right\rangle = \left\langle \vec{k}' \middle| T \middle| \vec{k} \right\rangle + \int \frac{d^3\vec{q}}{(2\pi)^3} \left\langle \vec{k}' \middle| V \middle| \vec{q} \right\rangle G(s) \left\langle \vec{q} \middle| T \middle| \vec{k} \right\rangle$

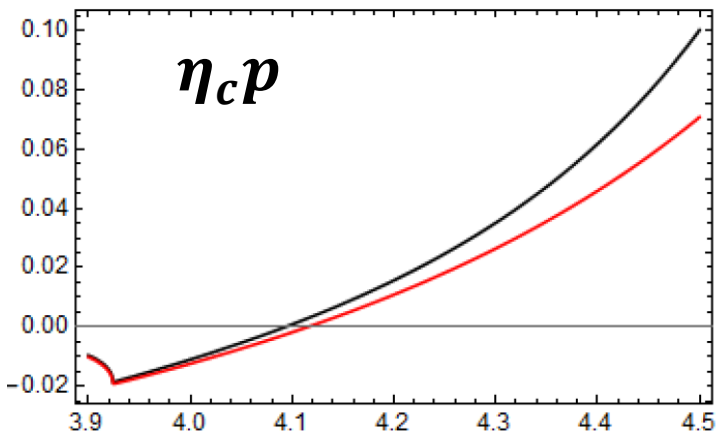
$$T = \frac{V}{1 - VG}$$

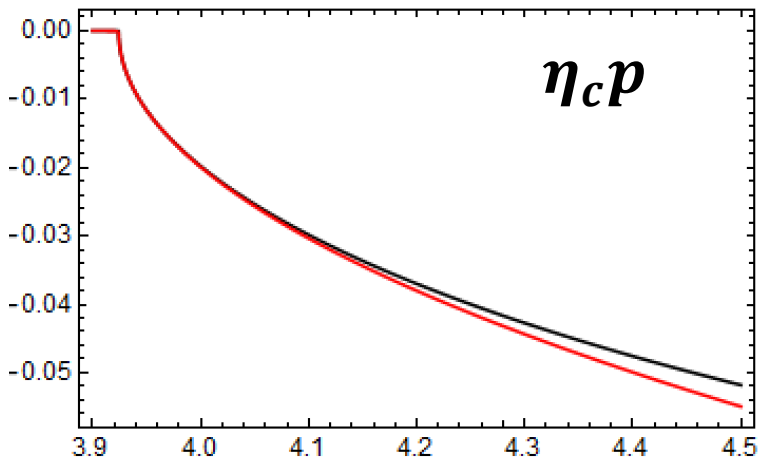
Separate potential $\left\langle \vec{k} \middle| V \middle| \vec{q} \right\rangle = C(\Lambda)\theta(\Lambda - |\vec{k}|)\theta(\Lambda - |\vec{q}|)$

Loop function

$$G1(s) = \int \frac{d^3\vec{q}}{(2\pi)^3} \frac{\omega_1 + \omega_2}{\omega_1\omega_2} \frac{1}{s - (\omega_1 + \omega_2)^2 + i\epsilon} \qquad G1_I(s) = G1_{II}(s) - i\frac{k1}{4\pi\sqrt{s}}$$

$$G2(s) = \int \frac{d^3\vec{q}}{(2\pi)^3} \frac{1}{\sqrt{s} - m_1 - m_1 - \frac{\vec{q}^2}{2\mu_{12}} + i\epsilon} \qquad G2_I(s) = G2_{II}(s) - i\frac{\mu_{12}}{\pi}k2$$





The relativistic effect is important for loop function of $\eta_c p$ as its mass threshold 600 MeV apart

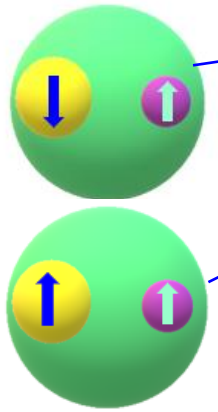
Contact-range potential

Heavy quark spin symmetry(HQSS)

QCD interaction cannot flip the spin of heavy quark $m_Q \to \infty$

$$J = J_l - \frac{1}{2}$$

$$J = J_l + \frac{1}{2}$$



Heavy quark

Brown muck made of light quark and glouns

$[D(0^-) \quad D^*(1^-)] \to 142$ MeV $\quad [\Sigma_c(1/2^+) \;\; \Sigma_c{}^*(3/2^+)] \to 64$ MeV

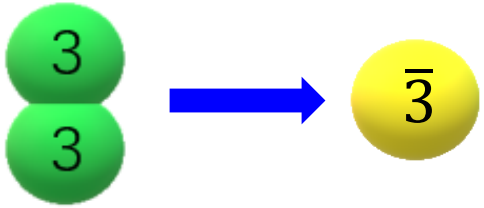
$[B(0^-) \quad B^*(1^-)] \to 46$ MeV $\quad [\Sigma_b(1/2^+) \;\; \Sigma_b{}^*(3/2^+)] \to 21$ MeV

The mass of hadron within spin multiplet would be degenerate

Heavy Anti-quark Di-quark symmetry(HADS)

Heavy diquark behaves as a heavy anti-quark from color freedom

$$3 \otimes 3 = 6 \oplus \bar{3}$$



$$m_{\Xi_{cc\,3/2}} - m_{\Xi_{cc\,1/2}} = \frac{3}{4}(m_{D*} - m_D) \approx 106.5 \text{ MeV}$$

$$m_{\Omega_{cc\,3/2}} - m_{\Omega_{cc\,1/2}} = \frac{3}{4}(m_{Ds*} - m_{Ds}) \approx 107.9 \text{ MeV}$$

Phys.Lett. B248 (1990) 177-180

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

Potentials

- $V(1/2^-, \Sigma_c \bar{D}) = C_a$

  $V(3/2^-, \Sigma_c^* \bar{D}) = C_a$

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

  $V(3/2^-, \Sigma_c \bar{D}^*) = C_a + \frac{2}{3} C_b$

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

  $V(3/2^-, \Sigma_c^* \bar{D}^*) = C_a - \frac{2}{3} C_b$

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

Experimental data

$$P_{c1} = 4311.9 \pm 0.7^{+6.8}_{-0.6} + \frac{i}{2} 9.8 \pm 2.7^{+3.7}_{-4.5}$$

$$P_{c2} = 4440.3 \pm 1.3^{+4.1}_{-4.7} + \frac{i}{2} 20.6 \pm 4.9^{+8.7}_{-10.1}$$

$$P_{c3} = 4457.3 \pm 0.6^{+4.1}_{-1.7} + \frac{i}{2} 6.4 \pm 2.0^{+5.7}_{-1.9}$$

Three experimental data and two unknown coupling constants

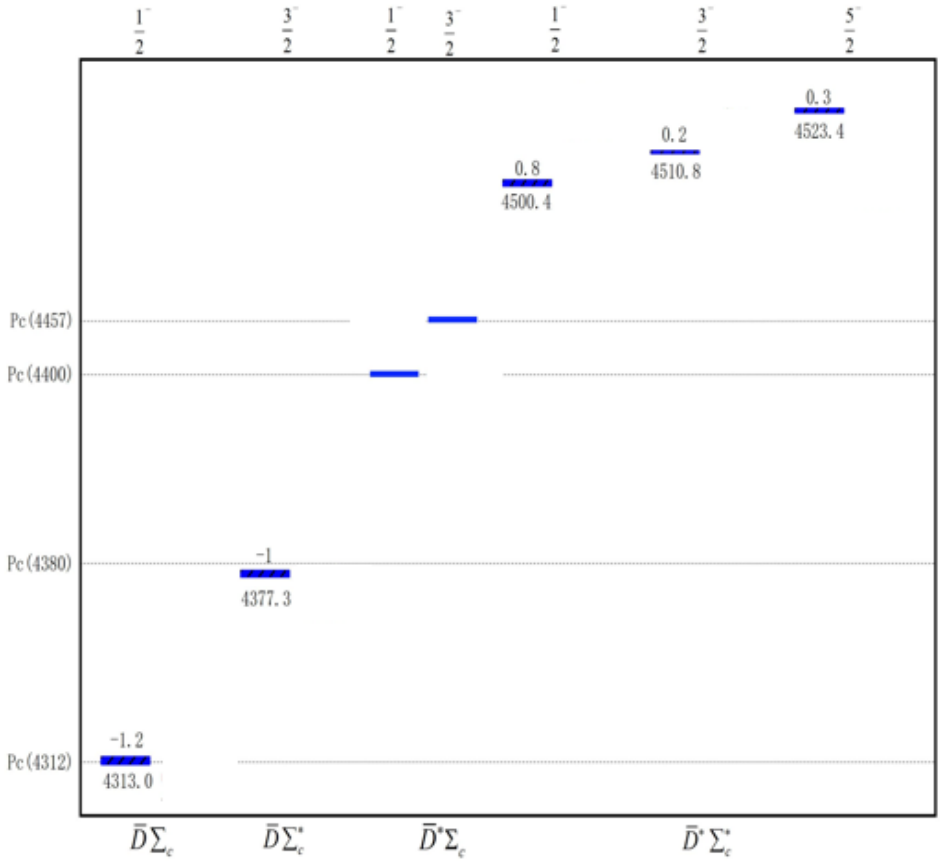
⇩

Ca and Cb can be determined !

Input

A	$\bar{D}^*\Sigma_c\ (3/2^-)\ Pc(4457)$	$\bar{D}^*\Sigma_c\ (1/2^-)\ Pc(4440)$
B	$\bar{D}^*\Sigma_c\ (1/2^-)\ Pc(4457)$	$\bar{D}^*\Sigma_c\ (3/2^-)\ Pc(4440)$

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



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

- Explain three states as $\bar{D}^{(*)}\Sigma_c$ bound states
- A complete multiplet hadronic molecules $\bar{D}^{(*)}\Sigma_c^{(*)}$

Fine structure of hadronic molecules

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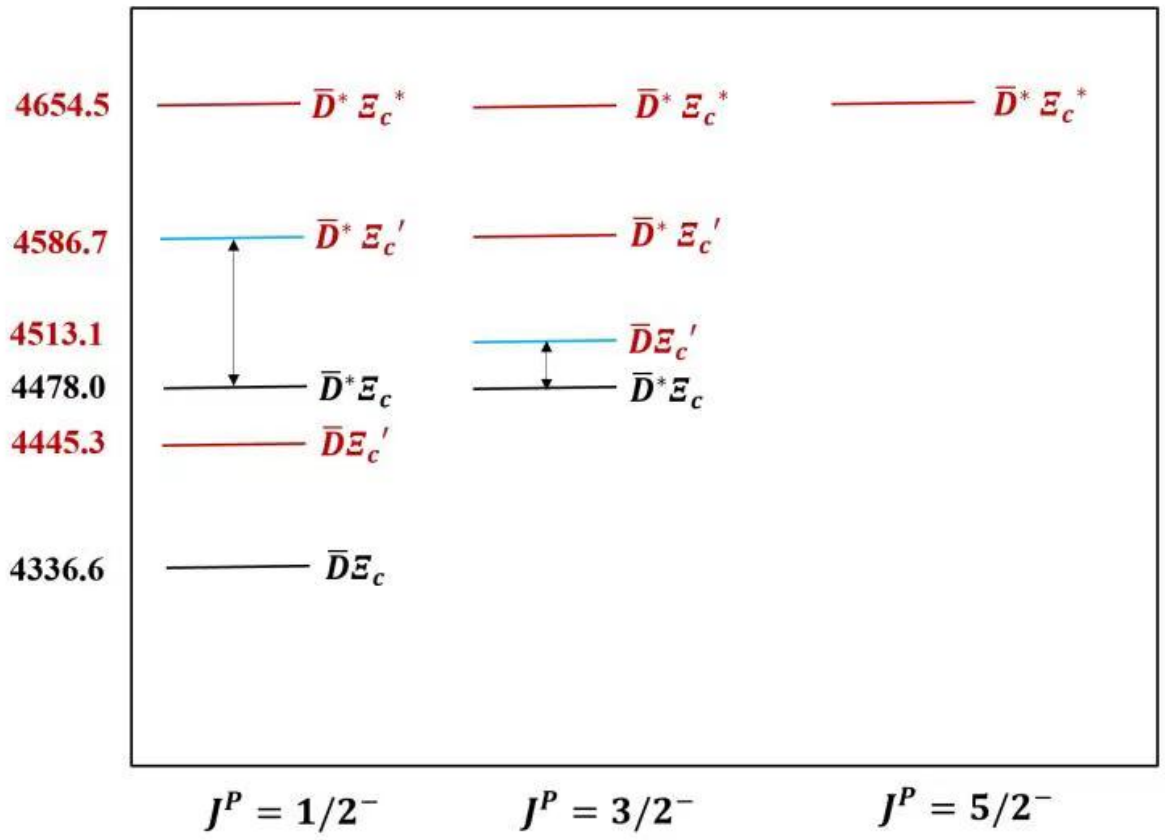
$\bar{D}^{(*)}\Xi_c'^{(*)}$ Molecules

Total 10 states



No experimental sign

$$\bar{D}^{(*)}\Sigma_c^{(*)} \xrightarrow[\text{7 states}]{\text{SU(3)-Flavor}} \bar{D}^{(*)}\Xi_c'^{(*)}$$

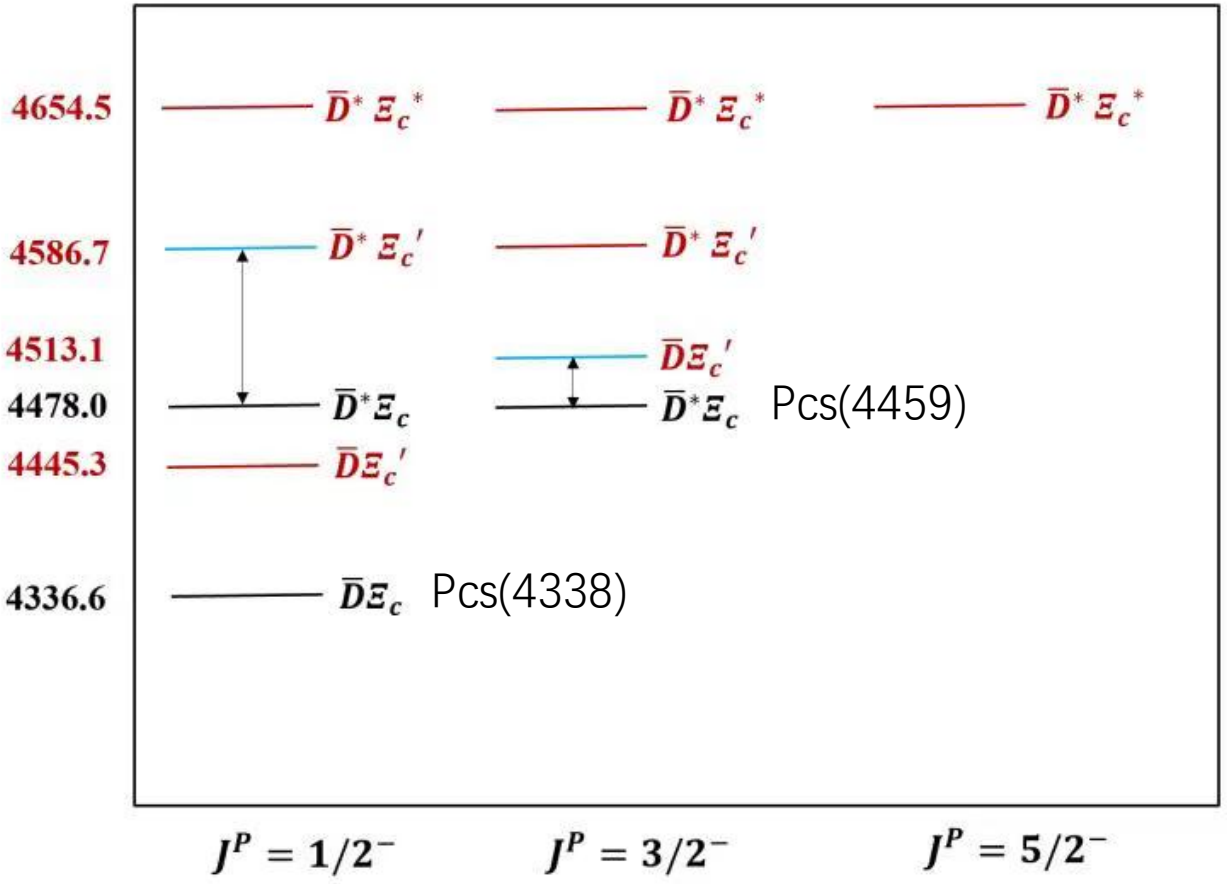
State	J^P	Λ(GeV)	B. E(A)	Mass(A)
$\bar{D}\Xi_c'$	$1/2^-$	1(0.5)	$8.5^{+17.4}_{-8.4}(9.3^{+8.7}_{-6.7})$	4437(4436)
$\bar{D}\Xi_c^*$	$3/2^-$	1(0.5)	$9.0^{+17.7}_{-8.8}(9.5^{+7.8}_{-6.7})$	4504(4504)
$\bar{D}^*\Xi_c'$	$1/2^-$	1(0.5)	$23.4^{+27.0}_{-18.9}(22.5^{+14.2}_{-12.3})$	4563(4564)
$\bar{D}^*\Xi_c'$	$3/2^-$	1(0.5)	$5.6^{+14.3}_{\dagger}(5.2^{+6.4}_{-4.3})$	4581(4581)
$\bar{D}^*\Xi_c^*$	$1/2^-$	1(0.5)	$28.0^{+29.4}_{-21.4}(26.3^{+15.5}_{-13.7})$	4627(4628)
$\bar{D}^*\Xi_c^*$	$3/2^-$	1(0.5)	$17.2^{+23.2}_{-14.9}(16.4^{+11.6}_{-9.8})$	4637(4638)
$\bar{D}^*\Xi_c^*$	$5/2^-$	1(0.5)	$4.0^{+12.5}_{\dagger}(3.3^{+5.1}_{-3.0})$	4651(4651)

Liu, et al. Phys.Rev.D 103 (2021) 3, 034003

- A complete multiplet hadronic molecules $\bar{D}^{(*)}\Xi_c'^{(*)}$
- SU(3)-flavor partners of $\bar{D}^{(*)}\Sigma_c^{(*)}$

$\bar{D}^{(*)}\Xi_c$ Molecules

$\bar{D}^{(*)}\Xi_c$



3 states!

$$\bar{D}^{(*)}\Sigma_c^{(*)} \xrightarrow{\text{SU(3)-Flavor}} \bar{D}^{(*)}\Xi_c$$

$\bar{D}^{(*)}\Xi_c$ Potential

$$V^{J^P=1/2^-}_{\bar{D}\Xi_c} = V^{J^P=1/2^-}_{\bar{D}^*\Xi_c} = V^{J^P=3/2^-}_{\bar{D}^*\Xi_c} = F_{1/2L}$$

Meson exchange theory

Couple Channel Potentials

$$V^{J=1/2}_{\bar{D}^*\Xi_c-\bar{D}^*\Xi_c'} = \begin{pmatrix} F_{1/2L} & D_a F'_{1/2} \\ D_a F'_{1/2} & \frac{7}{9}F_{1/2} + \frac{2}{9}F_{3/2} \end{pmatrix}$$

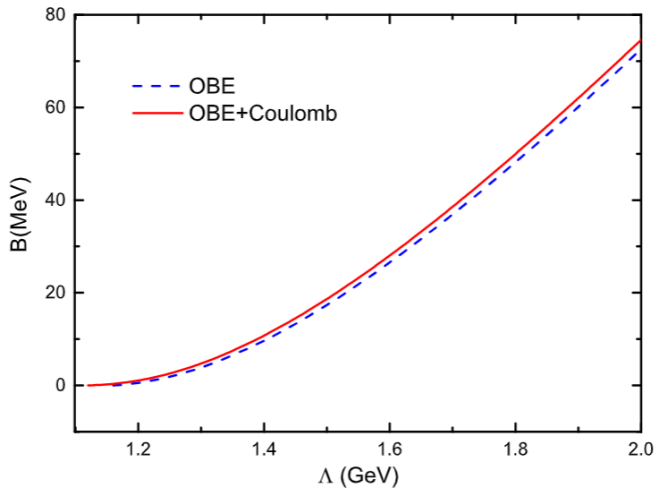
$$V^{J=3/2}_{\bar{D}^*\Xi_c-\bar{D}\Xi_c^*} = \begin{pmatrix} F_{1/2L} & D_b F'_{1/2} \\ D_b F'_{1/2} & \frac{1}{3}F_{1/2} + \frac{2}{3}F_{3/2} \end{pmatrix}$$

$\bar{D}^{(*)}\Xi_c$ Molecules

Fitting parameters of $\bar{D}^{(*)}\Xi_c$

$$V^{J^P=1/2^-}_{\bar{D}\Xi_c} = V^{J^P=1/2^-}_{\bar{D}^*\Xi_c} = V^{J^P=3/2^-}_{\bar{D}^*\Xi_c} = F_{1/2L}$$

$P_{cs}(4338)$



As cutoff=1.12 GeV, we obtain a very shallow bound state

$$V^{J=1/2}_{\bar{D}^*\Xi_c-\bar{D}^*\Xi'_c} = \begin{pmatrix} F_{1/2L} & D_a F'_{1/2} \\ D_a F'_{1/2} & \frac{7}{9}F_{1/2} + \frac{2}{9}F_{3/2} \end{pmatrix}$$

$P_c(4440)$

$P_c(4457)$

We only constrain the range of parameters

SU(3)-Flavor Partners of Pc(4440) and Pc(4457)

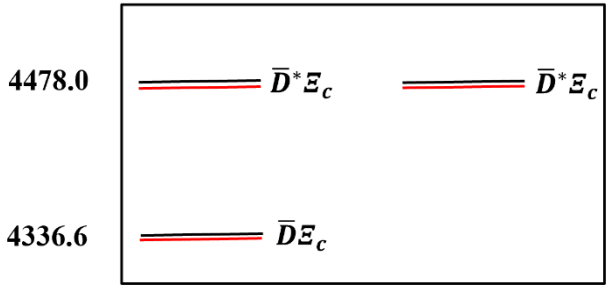
$$V^{J=3/2}_{\bar{D}^*\Xi_c-\bar{D}\Xi^*_c} = \begin{pmatrix} F_{1/2L} & D_b F'_{1/2} \\ D_b F'_{1/2} & \frac{1}{3}F_{1/2} + \frac{2}{3}F_{3/2} \end{pmatrix}$$

Keep the SU(3)-flavor partners exist

Widths are no more than those of Pc(4440) and Pc(4457)

$\bar{D}^{(*)}\Xi_c$ Molecules

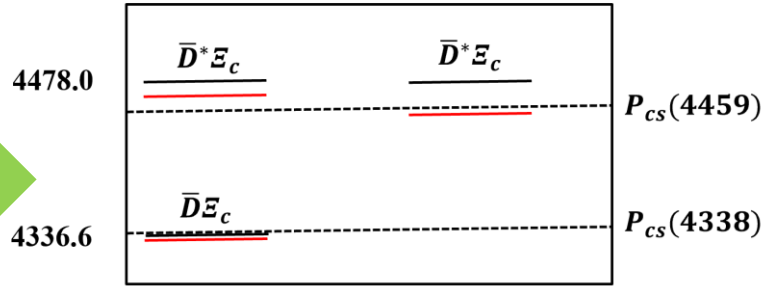
Degenerate states



$J^P = 1/2^-$ $J^P = 3/2^-$

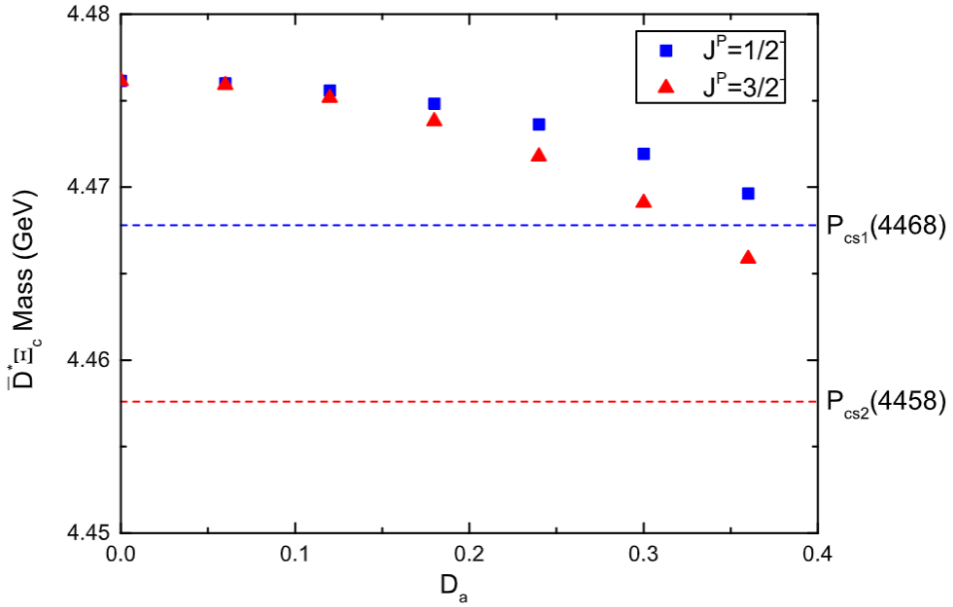
Couple channel

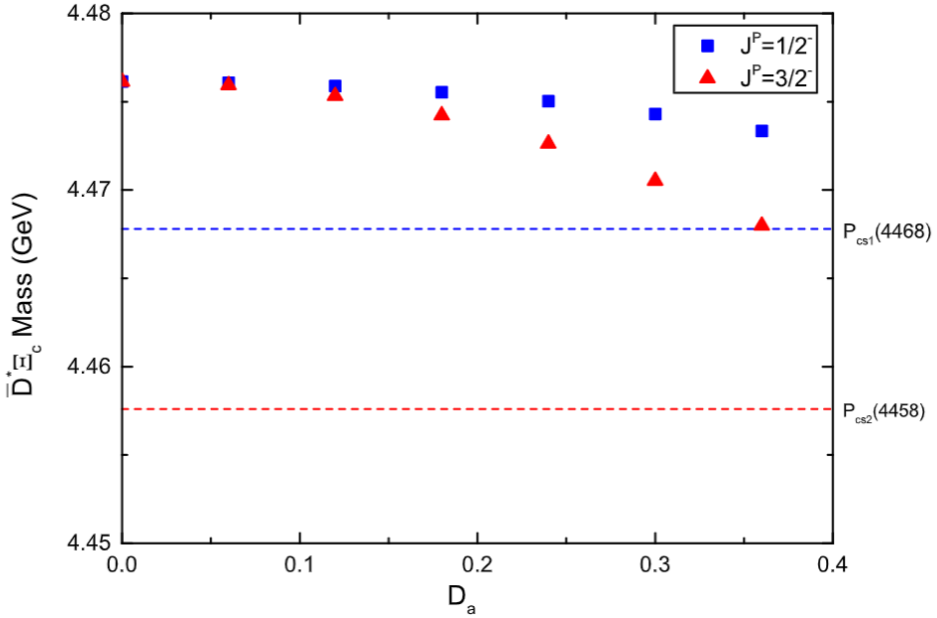
Degenerate states breaking



$J^P = 1/2^-$ $J^P = 3/2^-$

$\bar{D}^*\Xi_c$ Molecules

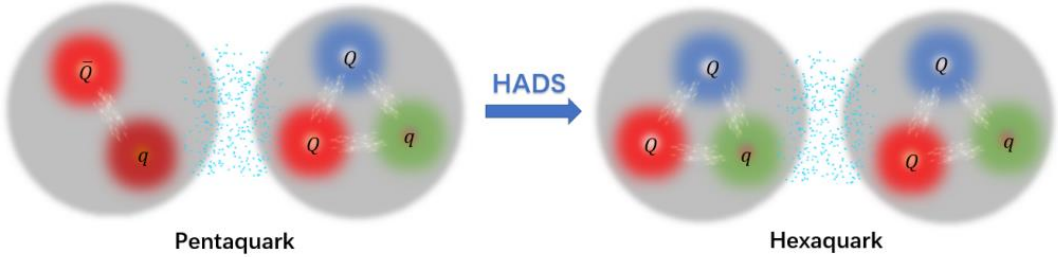




- $P_{cs}(4338)$ is a $\bar{D}\,\Xi_c$ hadronic molecule
- Two possible structures around $P_{cs}(4459)$ are $\bar{D}^*\Xi_c$ molecules

How to verify the molecular nature of pentaquark states

Triply charmed di-baryons molecules $\Xi_{cc}^{(*)}\Sigma_c^{(*)}$



$\Xi_{cc}^{(*)}\Sigma_c^{(*)}$ contact-range potentials

state	J^P	V	state	J^P	V
$\bar{D}\Sigma_c$	$1/2^-$	C_a	$\Xi_{cc}\Sigma_c$	0^+	$C_a+\frac{2}{3}C_b$
				1^+	$C_a-\frac{2}{9}C_b$
$\bar{D}\Sigma_c^*$	$3/2^-$	C_a	$\Xi_{cc}\Sigma_c^*$	1^+	$C_a+\frac{5}{9}C_b$
				2^+	$C_a-\frac{1}{3}C_b$
$\bar{D}^*\Sigma_c$	$1/2^-$	$C_a-\frac{4}{3}C_b$	$\Xi_{cc}^*\Sigma_c$	1^+	$C_a-\frac{10}{9}C_b$
	$3/2^-$	$C_a+\frac{2}{3}C_b$		2^+	$C_a+\frac{2}{3}C_b$
$\bar{D}^*\Sigma_c^*$	$1/2^-$	$C_a-\frac{5}{3}C_b$	$\Xi_{cc}^*\Sigma_c^*$	0^+	$C_a-\frac{5}{3}C_b$
	$3/2^-$	$C_a-\frac{2}{3}C_b$		1^+	$C_a-\frac{11}{9}C_b$
				2^+	$C_a-\frac{1}{3}C_b$
	$5/2^-$	C_a+C_b		3^+	C_a+C_b

Mass spectrum of $\Xi_{cc}^{(*)}\Sigma_c^{(*)}$

State	J^P	Threshold	Λ(GeV)	Scenario(A)	Scenario(B)
$\Xi_{cc}\Sigma_c$	0^+	6074.9	0.5(1)	$10.0^{+7.9}_{-6.4}$ $(17.9^{+20.8}_{-14.4})$	$30.4^{+15.5}_{-14.2}$ $(43.2^{+33.1}_{-27.2})$
$\Xi_{cc}\Sigma_c$	1^+	6074.9	0.5(1)	$18.4^{+11.3}_{-9.9}$ $(28.3^{+26.3}_{-20.1})$	$20.7^{+12.1}_{-10.8}$ $(31.2^{+27.7}_{-21.6})$
$\Xi_{cc}\Sigma_c^*$	1^+	6139.5	0.5(1)	$11.3^{+8.4}_{-7.0}$ $(20.0^{+25.4}_{-17.2})$	$29.6^{+15.1}_{-13.8}$ $(42.8^{+32.7}_{-26.9})$
$\Xi_{cc}\Sigma_c^*$	2^+	6139.5	0.5(1)	$20.0^{+11.8}_{-10.4}$ $(30.7^{+27.2}_{-21.2})$	$20.0^{+11.8}_{-10.4}$ $(30.8^{+27.3}_{-21.3})$
$\Xi_{cc}^*\Sigma_c$	1^+	6180.9	0.5(1)	$28.2^{+14.7}_{-13.4}$ $(41.0^{+32.0}_{-26.0})$	$12.2^{+8.8}_{-7.4}$ $(21.0^{+22.4}_{-16.2})$
$\Xi_{cc}^*\Sigma_c$	2^+	6180.9	0.5(1)	$10.2^{+8.0}_{-6.5}$ $(18.5^{+21.0}_{-14.8})$	$30.7^{+15.5}_{-14.2}$ $(44.1^{+33.3}_{-27.5})$
$\Xi_{cc}^*\Sigma_c^*$	0^+	6245.5	0.5(1)	$35.0^{+16.8}_{-15.6}$ $(50.2^{+35.6}_{-29.9})$	$7.6^{+6.7}_{-5.3}$ $(15.8^{+19.2}_{-13.0})$
$\Xi_{cc}^*\Sigma_c^*$	1^+	6245.5	0.5(1)	$29.9^{+15.2}_{-13.9}$ $(43.7^{+32.9}_{-27.2})$	$11.5^{+8.5}_{-7.0}$ $(20.7^{+22.0}_{-15.9})$
$\Xi_{cc}^*\Sigma_c^*$	2^+	6245.5	0.5(1)	$20.3^{+11.8}_{-10.5}$ $(31.6^{+27.5}_{-21.6})$	$20.3^{+11.8}_{-10.5}$ $(31.6^{+27.5}_{-21.6})$
$\Xi_{cc}^*\Sigma_c^*$	3^+	6245.5	0.5(1)	$7.6^{+6.7}_{-5.3}$ $(15.8^{+19.2}_{-13.0})$	$35.0^{+16.8}_{-15.6}$ $(50.2^{+35.6}_{-30.0})$

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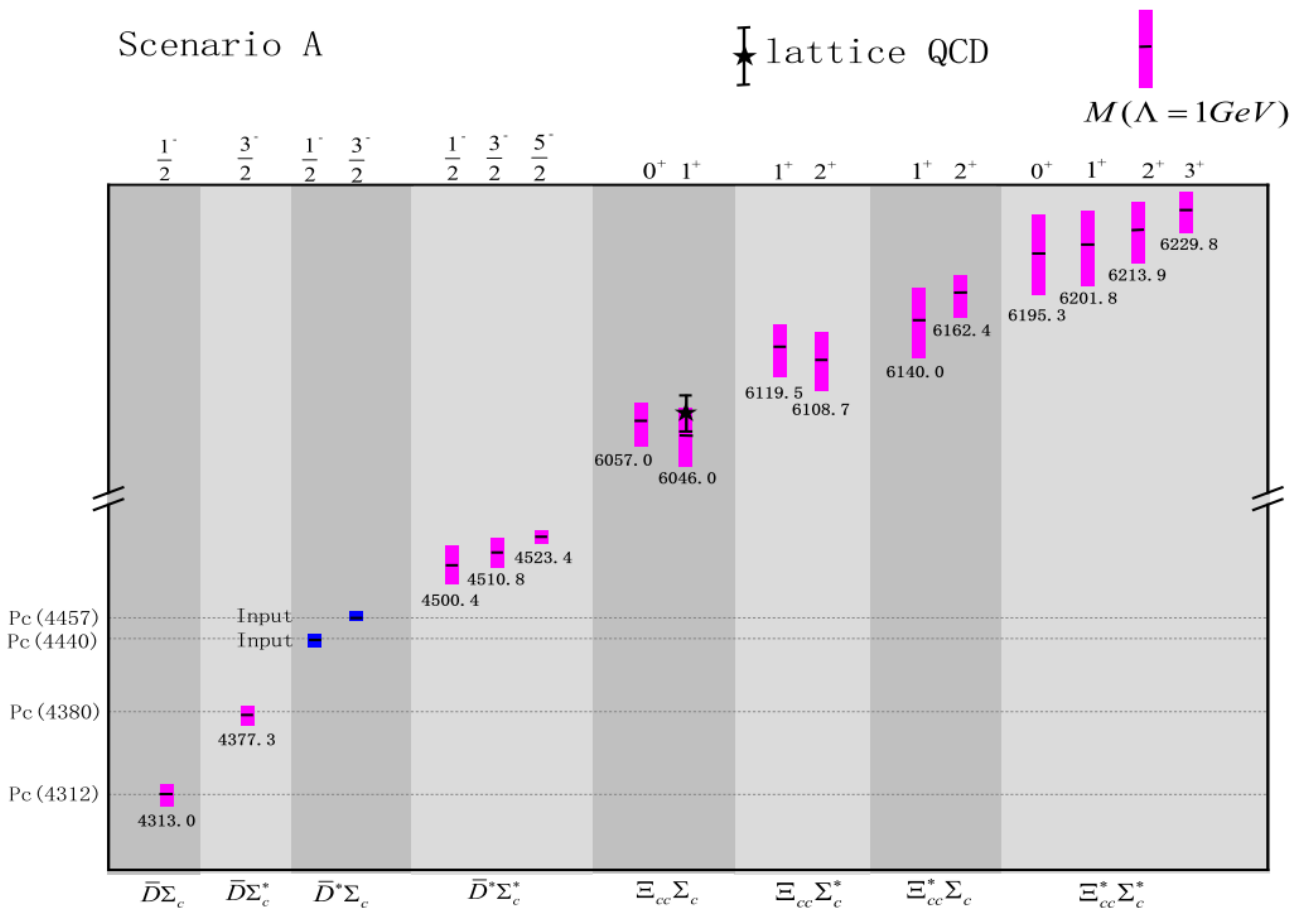
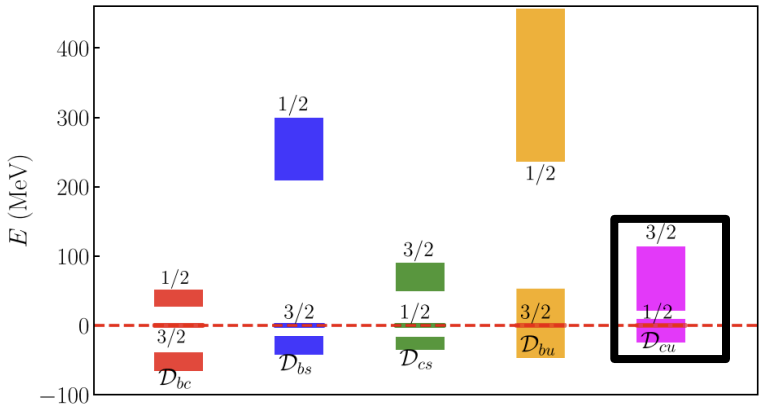
- $\bar{D}^{(*)}\Sigma_c^{(*)}$ molecules are expected to exist the triply charmed di-baryon molecules $\Xi_{cc}^{(*)}\Sigma_c^{(*)}$
- A complete HQSS multiplet hadronic molecules $\Xi_{cc}^{(*)}\Sigma_c^{(*)}$

Triply charmed di-baryons molecules $\Xi_{cc}^{(*)}\Sigma_c^{(*)}$

The Lattice QCD has simulated the $\Xi_{cc}^{(*)}\Sigma_c^{(*)}$ interactions



Ya-Wen Pan, et al. Phys.Rev.D 102 (2020) 1, 011504

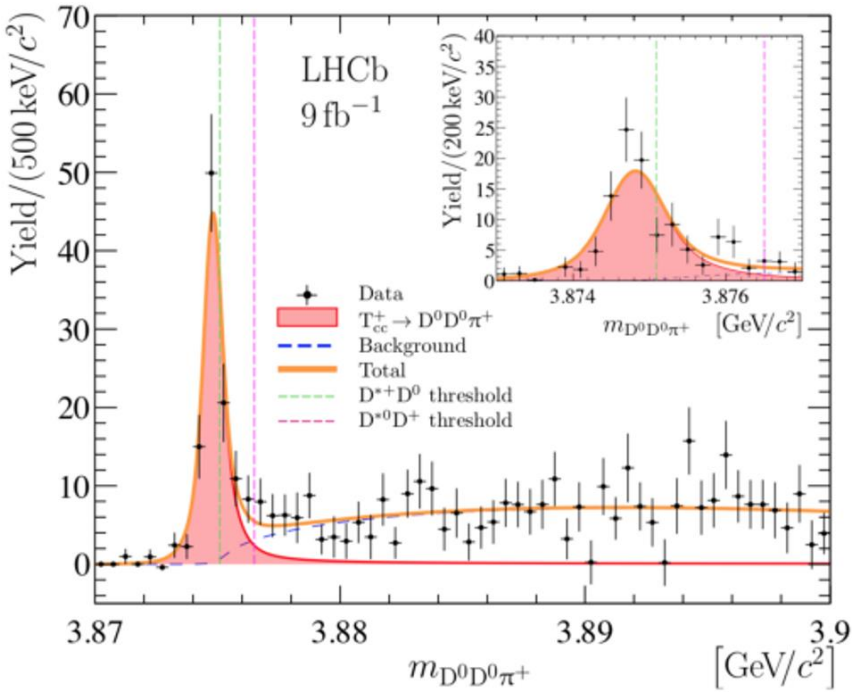


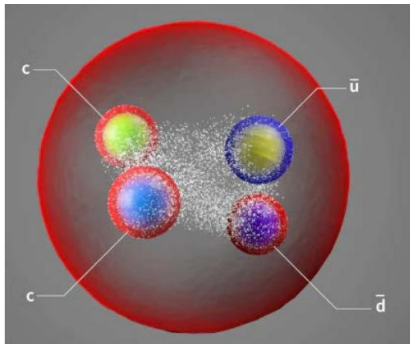
Parikshit Junnarkar and Nilmani Mathur. Phys.Rev.Lett. 123 (2019) 16, 162003

- The existence of $\Xi_{cc}^{(*)}\Sigma_c^{(*)}$ molecules could verify the molecular nature of Pc.
- The mass splitting of $\Xi_{cc}^{(*)}\Sigma_c^{(*)}$ molecules could help us determine the spin of Pc(4440) and Pc(4457) in the molecular picture

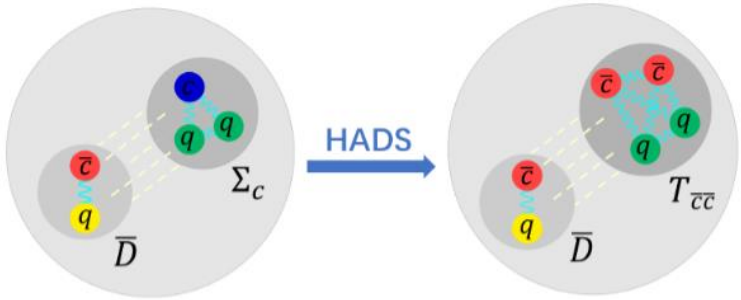
Triply charmed molecules composed of $\bar{D}^{(*)}T_{\bar{c}\bar{c}}^{(*)}$

Doubly charmed tetraquark states





Nature Phys. 18 (2022) 7, 751-754



Masses of $T_{\bar{c}\bar{c}}^{(*)}$

Tetraquark	[55]	[61]	[62]	[63]	A.V
$T_{\bar{c}\bar{c}}^0$	3999.8	4132	4032	3969.2	4033.3
$T_{\bar{c}\bar{c}}^1$	4124.0	4151	4117	4053.2	4111.3
$T_{\bar{c}\bar{c}}^2$	4194.9	4185	4179	4123.8	4170.7

55. J.-B. Cheng, et al. Chin. Phys. C 45, 043102 (2021)
61. Y. Kim , et al. Phys. Rev. D 105, 074021 (2022)
62. W.-X. Zhang, et al. Phys. Rev. D 104, 114011 (2021)
63. X.-Z. Weng, et al. Chin. Phys. C 46, 013102 (2022)

Triply charmed molecules composed of $\bar{D}^{(*)}T_{\bar{c}\bar{c}}^{(*)}$

Mass spectrum of $\bar{D}^{(*)}T_{\bar{c}\bar{c}}^{(*)}$

Molecule	J^P	Threshold	B.E.(Scenario A)	B.E.(Scenario B)
$\bar{D}T^0_{\bar{c}\bar{c}}$	0^-	5900.3	$24.1^{+39.4}_{-22.5}(16.5^{+16.1}_{-12.1})$	$32.1^{+44.9}_{-28.3}(23.3^{+19.3}_{-15.4})$
$\bar{D}T^1_{\bar{c}\bar{c}}$	1^-	5978.3	$24.7^{+39.7}_{-23.0}(16.8^{+16.2}_{-12.2})$	$32.8^{+45.3}_{-28.8}(23.6^{+19.4}_{-15.5})$
$\bar{D}T^2_{\bar{c}\bar{c}}$	2^-	6037.7	$25.2^{+40.0}_{-23.3}(17.0^{+16.2}_{-12.3})$	$33.4^{+45.5}_{-29.1}(23.8^{+19.4}_{-15.6})$
$\bar{D}^*T^0_{\bar{c}\bar{c}}$	1^-	6042.3	$29.5^{+42.1}_{-26.2}(18.6^{+16.7}_{-13.0})$	$38.2^{+47.6}_{-32.0}(25.6^{+19.9}_{-16.3})$
$\bar{D}^*T^1_{\bar{c}\bar{c}}$	0^-	6120.3	$43.7^{+50.7}_{-35.3}(29.7^{+21.6}_{-18.0})$	$26.1^{+39.6}_{-23.8}(15.6^{+15.2}_{-11.4})$
$\bar{D}^*T^1_{\bar{c}\bar{c}}$	1^-	6120.3	$36.8^{+46.6}_{-31.0}(24.1^{+19.2}_{-15.6})$	$32.4^{+43.8}_{-28.1}(20.6^{+17.6}_{-13.9})$
$\bar{D}^*T^1_{\bar{c}\bar{c}}$	2^-	6120.3	$24.2^{+38.2}_{-22.3}(14.0^{+14.4}_{-10.6})$	$46.1^{+52.1}_{-36.7}(31.6^{+22.4}_{-18.8})$
$\bar{D}^*T^2_{\bar{c}\bar{c}}$	1^-	6179.7	$51.7^{+55.0}_{-39.8}(35.8^{+24.0}_{-20.5})$	$20.9^{+35.7}_{-19.8}(11.2^{+12.8}_{-9.0})$
$\bar{D}^*T^2_{\bar{c}\bar{c}}$	2^-	6179.7	$37.4^{+46.8}_{-31.3}(24.3^{+19.3}_{-15.6})$	$32.9^{+44.0}_{-28.5}(20.8^{+17.7}_{-14.0})$
$\bar{D}^*T^2_{\bar{c}\bar{c}}$	3^-	6179.7	$19.0^{+34.3}_{-18.3}(9.8^{+12.0}_{-8.1})$	$54.3^{+56.4}_{-41.3}(37.8^{+24.8}_{-21.3})$

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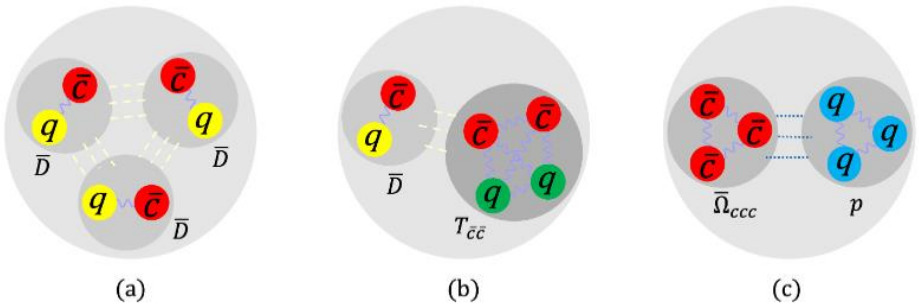
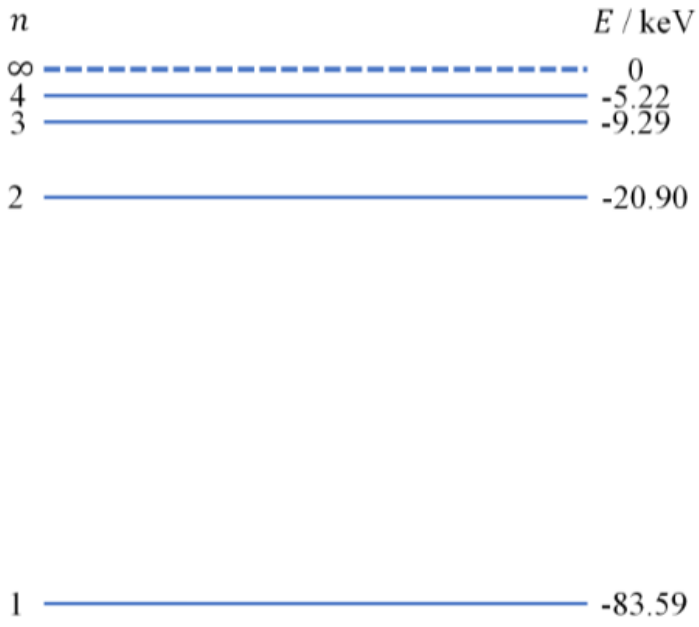
- A new type of hadronic molecules

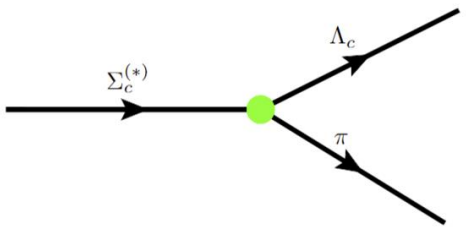


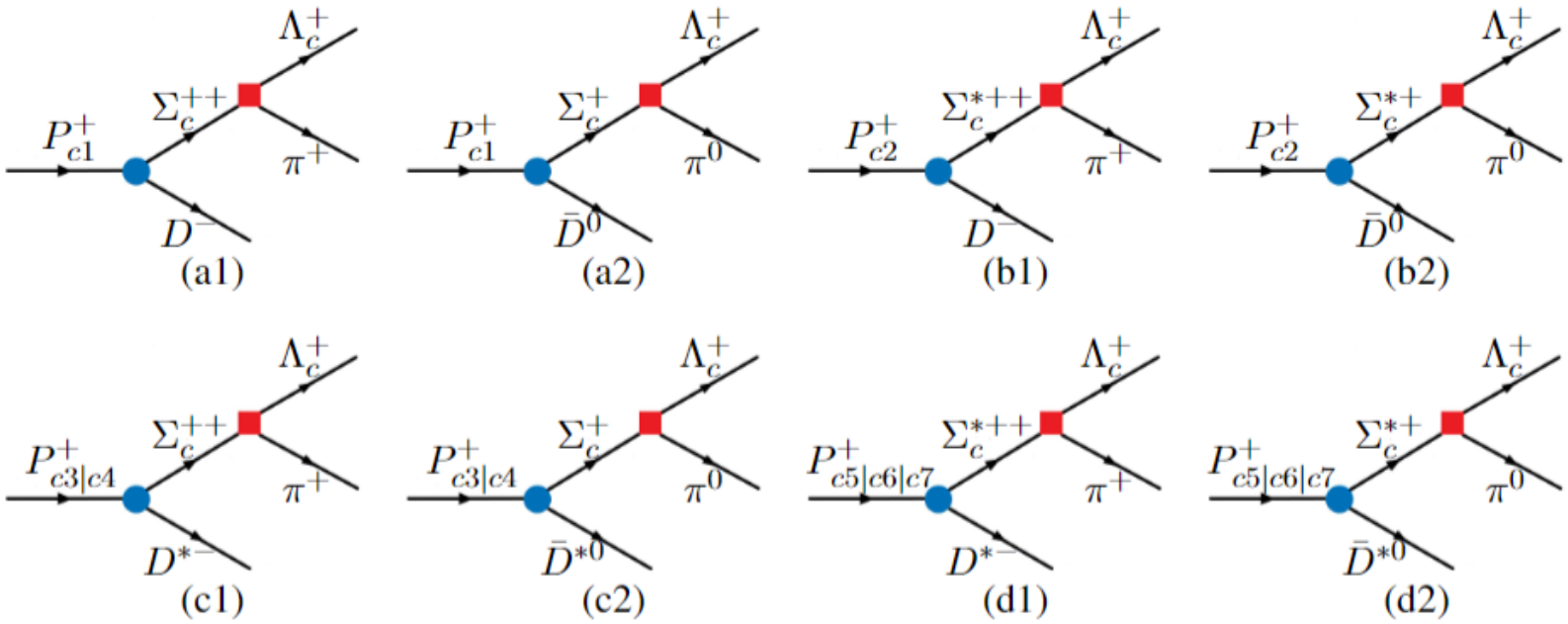
- (a)Molecules made of three charmed mesons
- (c)Molecules bind together by Coulomb force



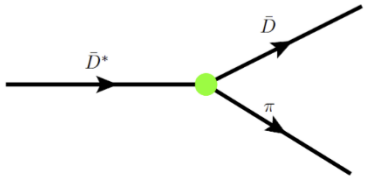
Three-body decay of $\bar{D}^{(*)}\Sigma_c^{(*)}$ molecules

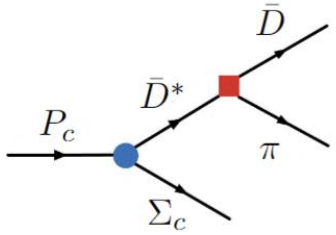
I Decay mechanism of molecules





II Decay mechanism of molecules

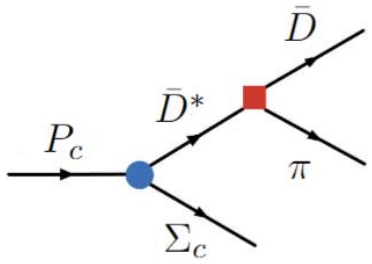




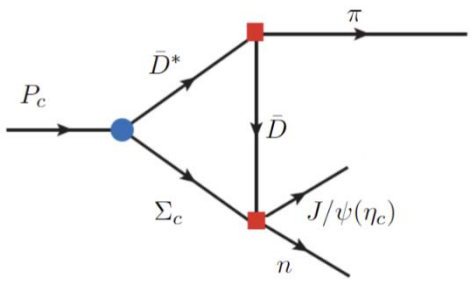
- The masses of $\bar{D}^{(*)}\Sigma_c^{(*)}$ are under the mass threshold 4-20 MeV
- The masses of $\bar{D}\pi\Sigma_c^{(*)}$ are almost in the mass threshold of $\bar{D}^{(*)}\Sigma_c^{(*)}$

No phase space!

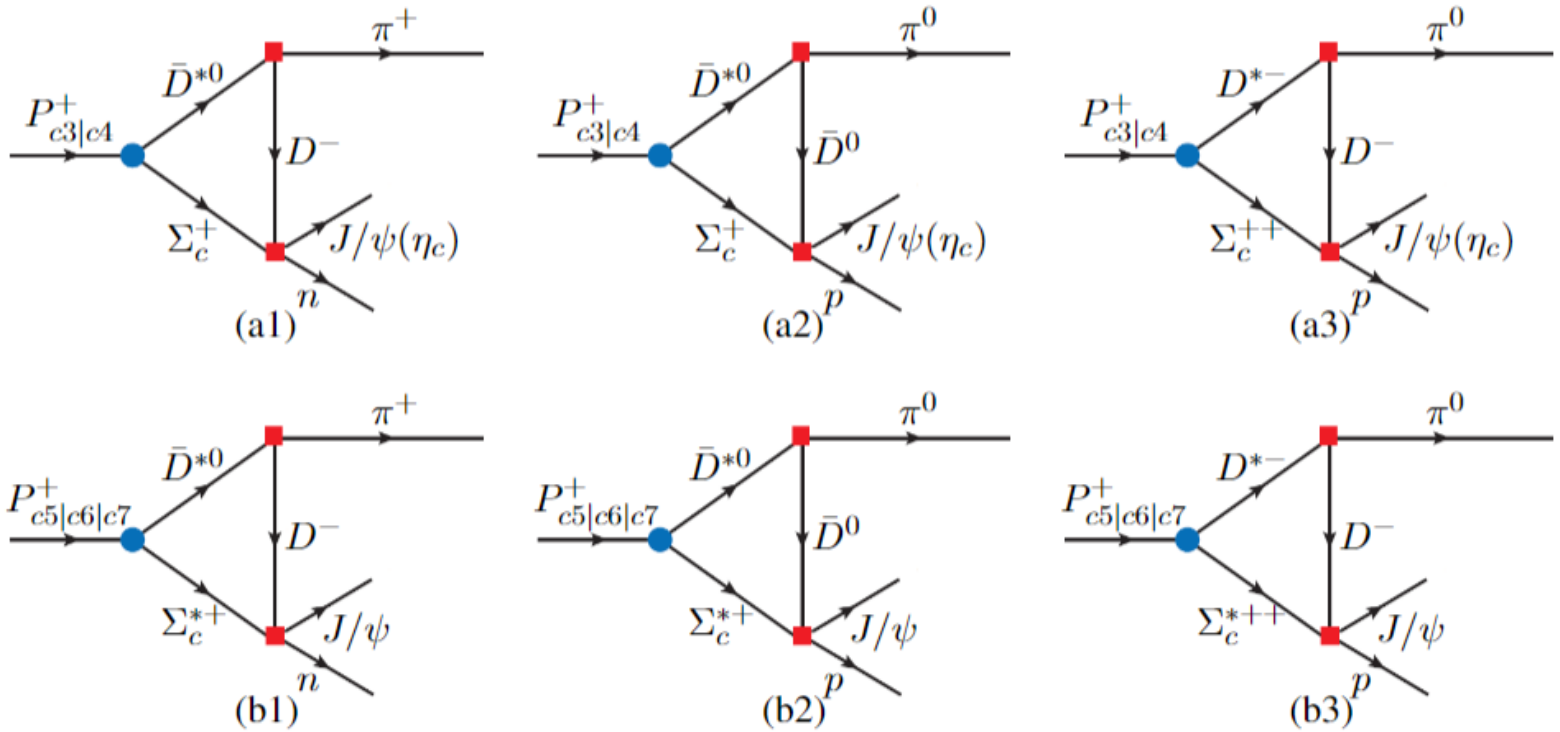
Three-body decay of $\bar{D}^{(*)}\Sigma_c^{(*)}$ molecules



Final states rescattering



Triangle diagrams $P_c \to \eta_c \pi N$

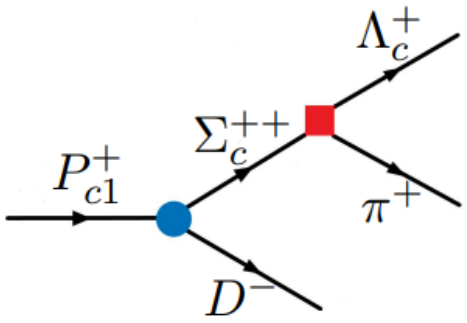


Three-body decay of $\bar{D}^{(*)}\Sigma_c^{(*)}$ molecules

Tree-modes decay

Scenario	A	A	B	B
Mode	$D^{(*)-}\Lambda_c^+\pi^+$	$\bar{D}^{(*)0}\Lambda_c^+\pi^0$	$D^{(*)-}\Lambda_c^+\pi^+$	$\bar{D}^{(*)0}\Lambda_c^+\pi^0$
P_{c1}	0.034	0.141	0.004	0.037
P_{c2}	2.085	2.166	1.468	1.479
P_{c3}	0.002	0.033	0.517	1.793
P_{c4}	0.170	0.591	0.001	0.011
P_{c5}	2.508	2.219	6.906	6.280
P_{c6}	3.087	2.758	3.866	3.529
P_{c7}	2.807	2.578	1.033	0.915

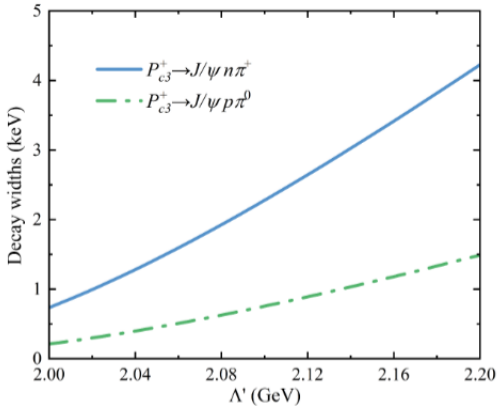
Jia-Ming Xie, et al. arXiv:2204.12356



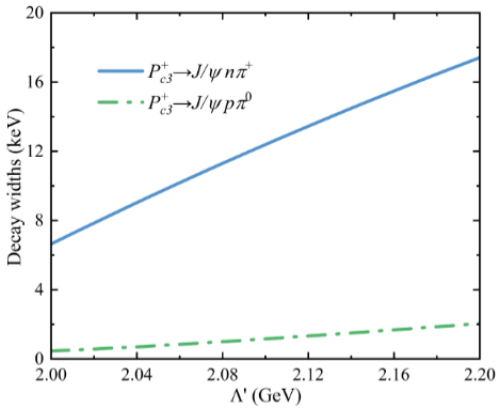
- P_{c2}, $P_c(4457)$, P_{c5}, P_{c6}, P_{c7} decaying into $\bar{D}^{(*)}\Lambda_c\pi$ are up to several MeV.
- $P_c(4312)$ and $P_c(4440)$ decaying into $\bar{D}^{(*)}\Lambda_c\pi$ are less than 1 MeV.
- Search for the pentaquark states in the $\bar{D}^{(*)}\Lambda_c\pi$ invariant mass distribution.
- Search for P_{c7} in the $\bar{D}^*\Lambda_c\pi$ invariant mass distribution

Three-body decay of $\bar{D}^{(*)}\Sigma_c^{(*)}$ molecules

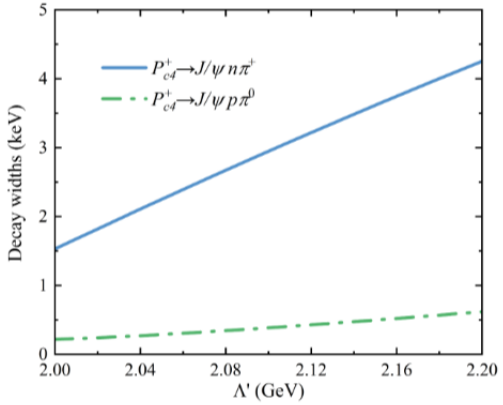
Triangle diagram modes



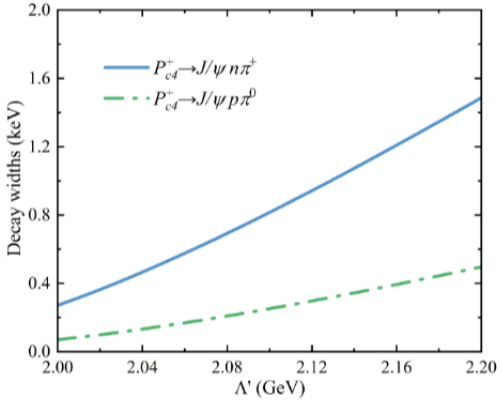
(a) P_{c3}-Scenario A



(b) P_{c3}-Scenario B

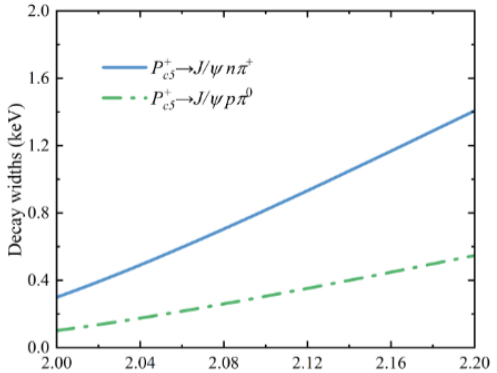


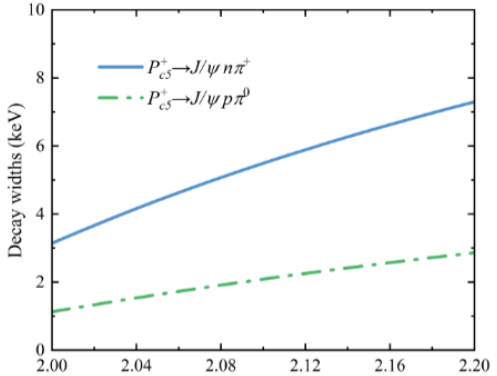
(c) P_{c4}-Scenario A

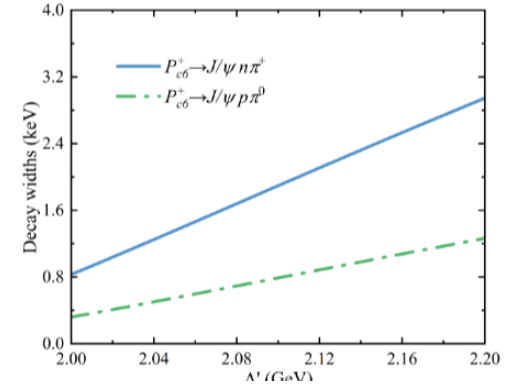


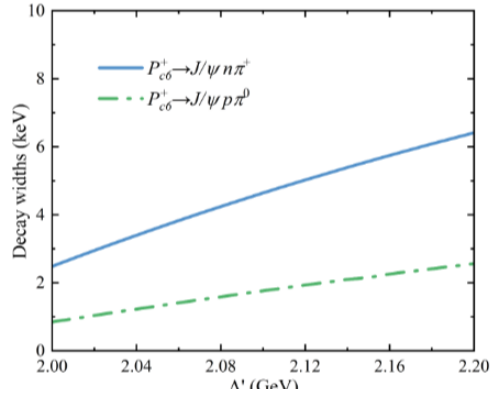
(d) P_{c4}-Scenario B

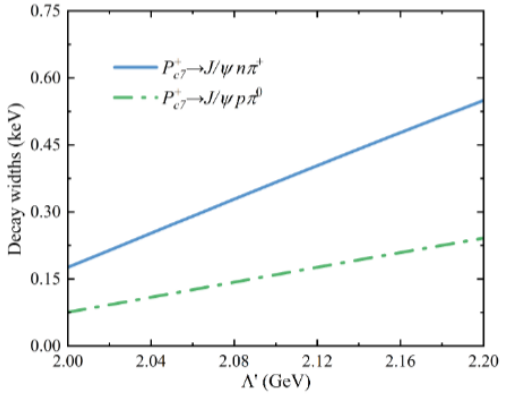
- These partial decay widths are up to be the order of keV.



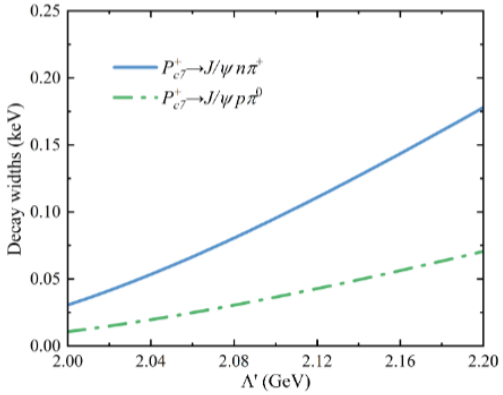








(e) P_{c7}-Scenario A



(f) P_{c7}-Scenario B

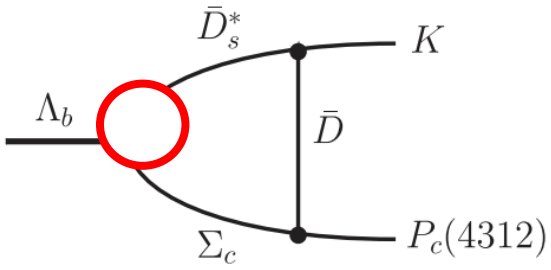
Summary and outlook

- We assigned the $Pc(4312), Pc(4440)$, and $Pc(4457)$ as $\bar{D}^{(*)}\Sigma_c$ molecules as well as obtained a complete HQSS multiplet hadronic molecules $\bar{D}^{(*)}\Sigma_c^{(*)}$. With similar approach, we explained $Pcs(4338)$, $Pcs1(4459)$ and $Pcs2(4459)$ as $\bar{D}^{(*)}\Xi_c$ molecules.

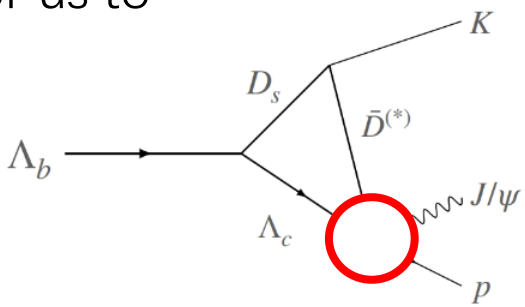
- Based on the existence of $\bar{D}^{(*)}\Sigma_c^{(*)}$ molecules, we predict a series of molecules composed of $\Xi_{cc}^{(*)}\Sigma_c^{(*)}$ and $\bar{D}^{(*)}T_{\bar{c}\bar{c}}^{(*)}$. If they are discovered by experiment or confirmed by Lattice QCD, it will help us understand the molecular nature of pentaquark states.

- Within the molecular picture, we have predicted the three-body partial decay widths of $\bar{D}^{(*)}\Sigma_c^{(*)}$ molecules, which are useful to check the molecular nature of pentaquark states

  - The production rates of $\bar{D}^{(*)}\Sigma_c$ molecules are important for us to understand the natue of pentaquark states.



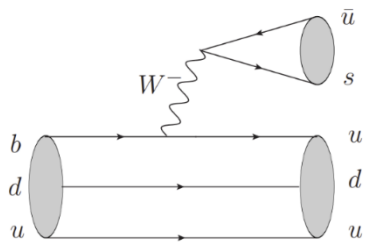
Qi Wu and Dian-Yong Chen. Phys.Rev.D 100 (2019) 11, 114002



T. J. Burns and E. S. Swanson, arXiv:2207.00511

Thanks for your attention!

Backup

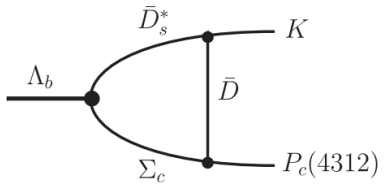


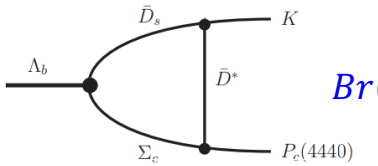
$$Br(\Lambda_b \to \Lambda_c^+ D_s^-) = 2.46\%$$

$$Br(\Lambda_b \to \Lambda_c^+ D_s^{*-}) = 3.65\%$$

Zhen-Xing Zhao. Chin.Phys.C 42 (2018) 9, 093101

$Br(\Lambda_b \to \Lambda_c^+ D_s^-) = 1.10\%$ Experimental data





$Br(\Lambda_b \to \Sigma_c^+ D_s^-) \approx 0.11\%$

Qi Wu and Dian-Yong Chen. Phys.Rev.D 100 (2019) 11, 114002

Resonance	$\lvert g_1\rvert$ (GeV)	$\lvert g_2\rvert$ (GeV)	Γ_1 (MeV)	Γ_2 (MeV)	X_1	X_2
$P_c(4312)$						
$X = 1.0$	$4.0^{+2.0}_{-3.8}$	$10.5^{+1.3}_{-2.5}$	$6.8^{+5.4}_{-6.8}$	$3.0^{+10.6}_{-3.0}$	$0.09^{+0.16}_{-0.09}$	$0.91^{+0.09}_{-0.16}$
$X = 0.8$	$4.2^{+2.0}_{-3.4}$	$9.2^{+1.2}_{-2.0}$	$7.5^{+5.5}_{-7.2}$	$2.3^{+8.1}_{-2.3}$	$0.10^{+0.16}_{-0.10}$	$0.70^{+0.10}_{-0.16}$
$X = 0.5$	$4.5^{+2.0}_{-2.5}$	$6.8^{+0.9}_{-1.2}$	$8.5^{+5.7}_{-6.5}$	$1.3^{+4.3}_{-1.3}$	$0.11^{+0.17}_{-0.09}$	$0.39^{+0.09}_{-0.17}$
$P_c(4440)$						
$X = 1.0$	$3.8^{+0.7}_{-1.0}$	$14.8^{+1.0}_{-1.3}$	$16.4^{+6.8}_{-7.5}$	$4.2^{+9.1}_{-4.2}$	$0.03^{+0.01}_{-0.02}$	$0.97^{+0.02}_{-0.01}$
$X = 0.8$	$3.9^{+0.8}_{-1.1}$	$13.1^{+0.9}_{-1.1}$	$17.3^{+7.7}_{-8.3}$	$3.3^{+7.2}_{-3.3}$	$0.03^{+0.01}_{-0.02}$	$0.77^{+0.02}_{-0.01}$
$X = 0.5$	$4.0^{+1.0}_{-1.2}$	$10.2^{+0.6}_{-0.8}$	$18.6^{+9.2}_{-9.4}$	$2.0^{+4.3}_{-2.0}$	$0.03^{+0.02}_{-0.01}$	$0.47^{+0.01}_{-0.02}$
$P_c(4457)$						
$X = 1.0$	$1.7^{+0.9}_{-1.6}$	$9.4^{+2.3}_{-5.0}$	$3.5^{+3.7}_{-3.5}$	$2.9^{+9.5}_{-2.9}$	$0.005^{+0.007}_{-0.005}$	$0.995^{+0.005}_{-0.007}$
$X = 0.8$	$1.9^{+0.8}_{-1.9}$	$8.4^{+2.0}_{-4.4}$	$4.1^{+4.6}_{-4.1}$	$2.3^{+7.9}_{-2.3}$	$0.006^{+0.008}_{-0.006}$	$0.794^{+0.006}_{-0.008}$
$X = 0.5$	$2.0^{+0.9}_{-2.0}$	$6.6^{+1.6}_{-3.2}$	$5.0^{+5.1}_{-5.0}$	$1.4^{+4.9}_{-1.4}$	$0.008^{+0.008}_{-0.008}$	$0.492^{+0.008}_{-0.008}$

Zhi-Hui Guo, et al. Phys.Lett.B 793 (2019) 144-149

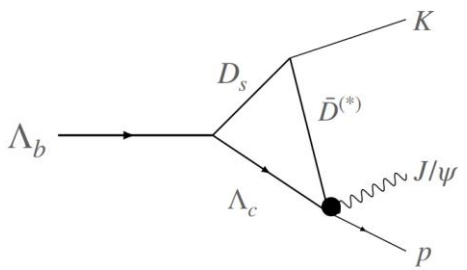
$(4306.0 + i7.0)$ MeV	$\eta_c N$	$J/\psi N$	$\bar{D}\Lambda_c$	$\bar{D}\Sigma_c$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Sigma_c^*$
$\lvert g_i\rvert$	0.59	0.41	0.01	**1.99**	0.10	0.02	0.03
Γ_i	**9.7**	3.9	0.0	–	0.1	–	–
Br	**69.0**%	27.6%	0.0%	–	0.9%	–	–
$(4433.0 + i11.0)$ MeV	$\eta_c N$	$J/\psi N$	$\bar{D}\Lambda_c$	$\bar{D}\Sigma_c$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Sigma_c^*$
$\lvert g_i\rvert$	0.16	0.49	0.03	0.07	0.03	**2.42**	0.06
Γ_i	0.7	**6.4**	0.1	0.2	0.0	–	–
Br	3.4%	**29.0**%	0.3%	1.1%	0.2%	–	–
$(4500.0 + i5.5)$ MeV	$\eta_c N$	$J/\psi N$	$\bar{D}\Lambda_c$	$\bar{D}\Sigma_c$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Sigma_c^*$
$\lvert g_i\rvert$	0.37	0.26	0.05	0.03	0.02	0.02	**2.29**
Γ_i	**4.5**	1.9	0.2	0.1	0.0	0.0	–
Br	**41.2**%	17.7%	1.5%	0.5%	0.3%	0.0%	–

Chun-Wen Xiao, et al, Phys.Rev.D 102 (2020) 5, 056018

The $\bar{D}^{(*)}\Lambda_c$ contribution is minor

Backup

The $\bar{D}^{(*)}\Lambda_c$ contribution is important



T. J. Burns and E. S. Swanson, arXiv:2207.00511

There exist two states near the $\Sigma_c\bar{D}^*$ threshold in our model, which can be related to the experimental $P_c(4440)$ and $P_c(4457)$. The channel above the $\Sigma_c\bar{D}^*$ channel, here $\Sigma_c^*\bar{D}^*$ channel, does not provide the width, that is, the the pole near the $\Sigma_c\bar{D}^*$ threshold from the two-channel calculation with $\Sigma^*\bar{D}^*$ channel is still on the real axis. It reflects that a state $\Sigma\bar{D}^*$ can not decay to $\Sigma^*\bar{D}^*$ which is beyond its mass. Hence, there are only four channels listed. For both $\Sigma_c\bar{D}^*$ states, the $\Lambda\bar{D}^*$ channel is dominant with branching ratio about 70%. Other channels only have branching ratios smaller than 20%. The dominance of the $\Lambda_c\bar{D}^*$ is also found in the $\Sigma_c^*\bar{D}(3/2^-)$ and $\Sigma_c\bar{D}(1/2^-)$ states, where fewer channels are opened in the models considered in the current work. The branching ratio of the $\Sigma_c^*\bar{D}(3/2^-)$ state to the $\Lambda_c\bar{D}$ channel is 100% while the $\Lambda_c\bar{D}$ channel provides about 90% contribution to the $\Sigma_c\bar{D}(1/2^-)$ state.

Jun He, et al. Eur.Phys.J.C 79 (2019) 11, 887

$\Gamma_{J/\psi p}$	$\Gamma_{\eta_c p}$	$\Gamma_{\bar{D}^*\Lambda_c}$	$\Gamma_{\bar{D}\Lambda_c}$	Γ_{Total}	$\Gamma_{Expt.}$
$0.0448^{+0.0197(+0.0309)}_{-0.0161(-0.0287)}$	$0.0892^{+0.0392(+0.0615)}_{-0.0321(-0.0571)}$	$8.36^{+3.68(+5.77)}_{-3.01(-5.35)}$	0	$8.49^{+3.74(+5.86)}_{-3.06(-5.43)}$	$9.8 \pm 2.7^{+3.5}_{-4.5}$

Yubing Dong, et al. Eur.Phys.J.C 80 (2020) 4, 341

Mode	Widths (MeV) with (f_2, f_3)				
	$\bar{D}\Sigma_c$	$\bar{D}^*\Sigma_c$			
	$P_c(4312)$	$P_c(4440)$		$P_c(4457)$	
	$\frac{1}{2}^-$	$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{1}{2}^-$	$\frac{3}{2}^-$
$\bar{D}^*\Lambda_c$	10.7	12.5	6.8	10.8	6.9
$J/\psi p$	0.1	0.6	1.8	0.2	0.6
$\bar{D}\Lambda_c$	0.3	2.7	1.2	2.0	1.2
πN	1.7	0.2	1.9	0.07	0.6
$\chi_{c0}p$	-	0.1	0.009	0.05	0.003
$\eta_c p$	0.4	0.07	0.008	0.02	0.003
ρN	0.0008	0.4	0.3	0.1	0.1
ωp	0.003	1.5	1.2	0.5	0.4
$\bar{D}\Sigma_c$	-	3.4	0.6	2.8	0.9
$\bar{D}\Sigma_c^*$	-	0.9	7.3	2.3	7.2
Total	13.2	22.4	21.0	18.8	17.9

Yong-Hui Lin, et al. Eur.Phys.J.C 80 (2020) 4, 341

Backup

Coupled channel potentials

$$V^{J=5/2}_{\bar{D}^*\Sigma_c^*} = C_a + C_b$$

$$V^{J=1/2}_{\eta_c N - J/\psi N - \bar{D}\Sigma_c} = \begin{pmatrix} 0 & 0 & \frac{1}{2}g \\ 0 & 0 & \frac{1}{2\sqrt{3}}g \\ \frac{1}{2}g & \frac{1}{2\sqrt{3}}g & C_a \end{pmatrix}$$

$$V^{J=1/2}_{\eta_c N - J/\psi N - \bar{D}^*\Sigma_c} = \begin{pmatrix} 0 & 0 & \frac{1}{2\sqrt{3}}g \\ 0 & 0 & \frac{5}{6}g \\ \frac{1}{2\sqrt{3}}g & \frac{5}{6}g & C_a - \frac{4}{3}C_b \end{pmatrix}$$

$$V^{J=1/2}_{\eta_c N - J/\psi N - \bar{D}^*\Sigma_c^*} = \begin{pmatrix} 0 & 0 & \sqrt{\frac{2}{3}}g \\ 0 & 0 & -\frac{\sqrt{2}}{3}g \\ \sqrt{\frac{2}{3}}g & -\frac{\sqrt{2}}{3}g & C_a - \frac{5}{3}C_b \end{pmatrix}$$

$$V^{J=3/2}_{\eta_c N - J/\psi N - \bar{D}\Sigma_c^*} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \frac{1}{\sqrt{3}}g \\ 0 & \frac{1}{\sqrt{3}}g & C_a \end{pmatrix}$$

$$V^{J=3/2}_{\eta_c N - J/\psi N - \bar{D}^*\Sigma_c} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{3}g \\ 0 & -\frac{1}{3}g & C_a + \frac{2}{3}C_b \end{pmatrix}$$

$$V^{J=3/2}_{\eta_c N - J/\psi N - \bar{D}^*\Sigma_c^*} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \frac{\sqrt{5}}{3}g \\ 0 & \frac{\sqrt{5}}{3}g & C_a - \frac{2}{3}C_b \end{pmatrix}$$

Inelastic potential

$$g = \langle \bar{D}^{(*)}\Sigma_c^{(*)} | 1_H \otimes 1/2_L \rangle$$
$$= \langle \bar{D}^{(*)}\Sigma_c^{(*)} | 0_H \otimes 1/2_L \rangle$$

Reproducing widths

Pc(4312)	Pc(4440)	Pc(4457)
	Pc(4457)	Pc(4440)

Scenario	Λ (GeV)	C_a	C_b	g_1	g_3	g_4
A	1.5	-52.750	5.625	7.650	6.760	12.350
B	1.5	-56.447	-5.480	7.350	4.610	18.000

Backup

Single channels

Scenario	Molecule	J^P	B (MeV)	M (MeV)
A	$\bar{D}\Sigma_c$	$\frac{1}{2}^-$	7.8 – 9.0	4311.8 – 4313.0
A	$\bar{D}\Sigma_c^*$	$\frac{3}{2}^-$	8.3 – 9.2	4376.1 – 4377.0
A	$\bar{D}^*\Sigma_c$	$\frac{1}{2}^-$	Input	4440.3
A	$\bar{D}^*\Sigma_c$	$\frac{3}{2}^-$	Input	4457.3
A	$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}^-$	25.7 – 26.5	4500.2 – 4501.0
A	$\bar{D}^*\Sigma_c^*$	$\frac{3}{2}^-$	15.9 – 16.1	4510.6 – 4510.8
A	$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^-$	3.2 – 3.5	4523.3 – 4523.6

Coupled channels

State	Molecule	J^P	Mass (MeV)	$g_{P_c\bar{D}^{(*)}\Sigma_c^{(*)}}$	$g_{P_cJ/\psi N}$	$g_{P_c\eta_c N}$
P_{c1}	$\bar{D}\Sigma_c$	$(1/2)^-$	4309.3+**4.9**i	2.16	0.31	0.53
P_{c2}	$\bar{D}\Sigma_c^*$	$(3/2)^-$	4372.2+4.8i	2.19	0.62	-
P_{c3}	$\bar{D}^*\Sigma_c$	$(1/2)^-$	**4440.3+10.3**i	2.60	0.83	0.29
P_{c4}	$\bar{D}^*\Sigma_c$	$(3/2)^-$	**4457.3+3.2**i	1.70	0.49	-
P_{c5}	$\bar{D}^*\Sigma_c^*$	$(1/2)^-$	4502.7+14.0i	2.68	0.48	0.83
P_{c6}	$\bar{D}^*\Sigma_c^*$	$(3/2)^-$	4510.5+7.2i	2.31	0.71	-
P_{c7}	$\bar{D}^*\Sigma_c^*$	$(5/2)^-$	4522.8	1.49	-	-

- The real part of these Pc for couple channel case change little
- Within the HQSS, we can not well describe the widths of three Pc states
- Reasons
  - The HQSS breaking
  - Other channels contribute to their widths

Backup

One boson exchange model

Molecule	I	J^P	a_2 (fm)	B_2 (MeV)	M (MeV)
$\bar{D}\Sigma_c$	$\frac{1}{2}$	$\frac{1}{2}^-$	$1.9^{+1.0}_{-0.4}$	Input	Input
$\bar{D}\Sigma_c^*$	$\frac{1}{2}$	$\frac{3}{2}^-$	$1.9^{+0.9}_{-0.4}$	$9.3^{+7.7}_{-5.7}$	4376.0
$\bar{D}^*\Sigma_c$	$\frac{1}{2}$	$\frac{1}{2}^-$	$2.5^{+2.3}_{-0.6}$	$4.2^{+5.3}_{-3.4}$	4458.0
$\bar{D}^*\Sigma_c$	$\frac{1}{2}$	$\frac{3}{2}^-$	$1.4^{+0.5}_{-0.3}$	$18.3^{+11.6}_{-9.2}$	4443.9
$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}$	$\frac{1}{2}^-$	$2.6^{+2.5}_{-0.7}$	$2.9^{+4.5}_{-2.6}$	4523.8
$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}$	$\frac{3}{2}^-$	$1.9^{+1.0}_{-0.4}$	$9.2^{+7.9}_{-5.8}$	4517.5
$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}$	$\frac{5}{2}^-$	$1.3^{+0.4}_{-0.3}$	$22.4^{+13.1}_{-10.6}$	4504.3

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- Results of OBE confirmed the conclusion of EFT
- Results of OBE are consistent with Scenario B

$P_c(4440) \to 3/2$
$P_c(4457) \to 1/2$

Effective field theory

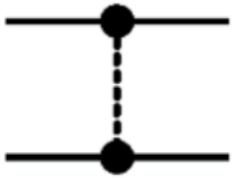
Scenario	Molecule	J^P	B (MeV)	M (MeV)
A	$\bar{D}\Sigma_c$	$\frac{1}{2}^-$	7.8 – 9.0	4311.8 – 4313.0
A	$\bar{D}\Sigma_c^*$	$\frac{3}{2}^-$	8.3 – 9.2	4376.1 – 4377.0
A	$\bar{D}^*\Sigma_c$	$\frac{1}{2}^-$	Input	4440.3
A	$\bar{D}^*\Sigma_c$	$\frac{3}{2}^-$	Input	4457.3
A	$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}^-$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

Backup

Leading order

Contact

One pion exchange



Next to leading order

⋮

OPE is perturbative in charm hadronic interactions

Jun-Xu Lu, et al. Phys.Rev. D99 (2019) 074026

Contact Lagrangian

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

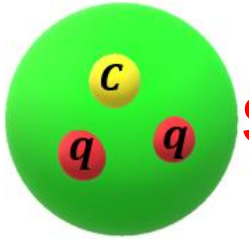
Superfields

$$H_c = \frac{1}{\sqrt{2}}(D + \vec{D}^*\vec{\sigma})$$

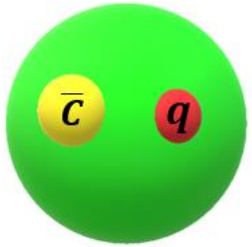
$$\vec{S}_c = \frac{1}{\sqrt{3}}(\Sigma_c\vec{\sigma} + \vec{\Sigma}^*{}_c)$$

⟸ Spin multiplet hadrons

Effective potential

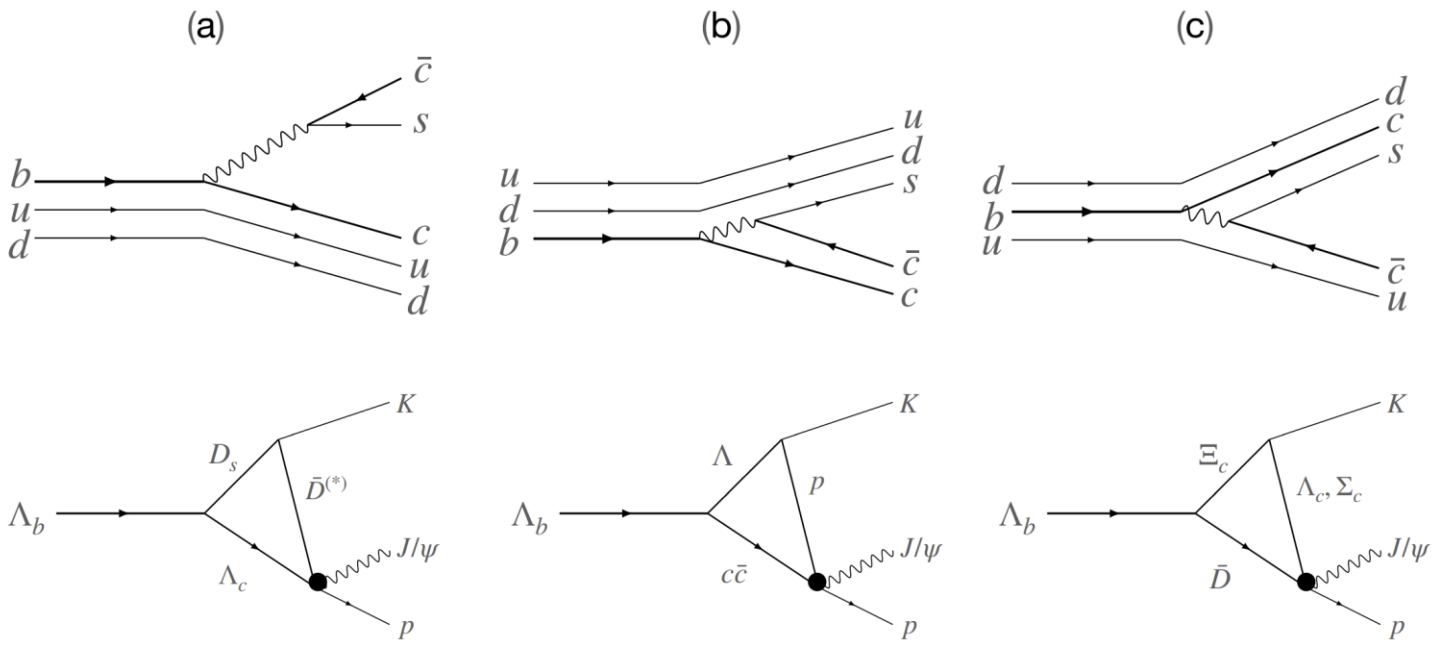


S-wave



Single channel

Backup



Λ_b vertex:	Large	Small	Small
P_c vertex:	Large	Small	Large