The spin structure of three new pentaquarks

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arXiv:1907.06093
arXiv:1907.11220

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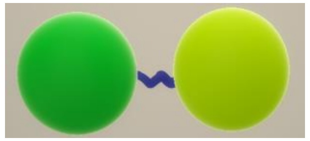
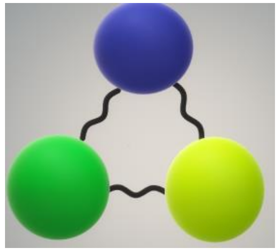
Background of hadronic molecule

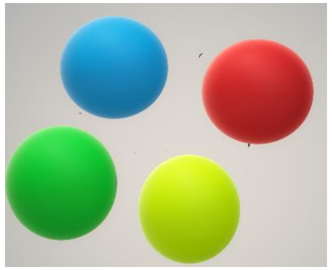
Meson and baryon

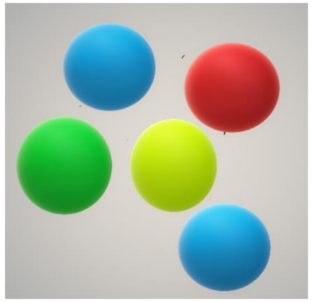


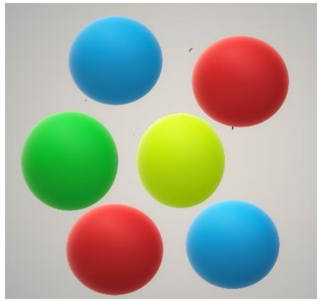


Pentaquark

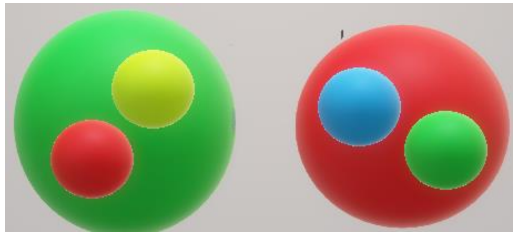
Multiquark

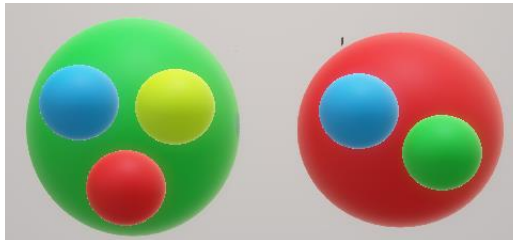


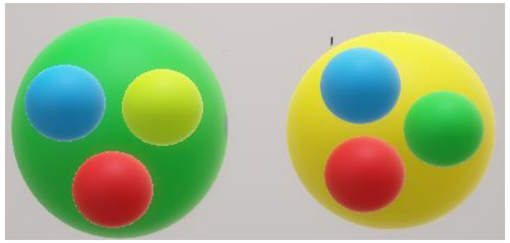




Hadronic molecule







Background of hadronic molecule

Possible hadronic molecules

$D_{s0}(2317)$ $0(0^+)$ DK

Phys.Rev.Lett. 111 (2013) 222001 Daniel Mohler, C. B. Lang, Luka Leskovec, et. al Lattice QCD

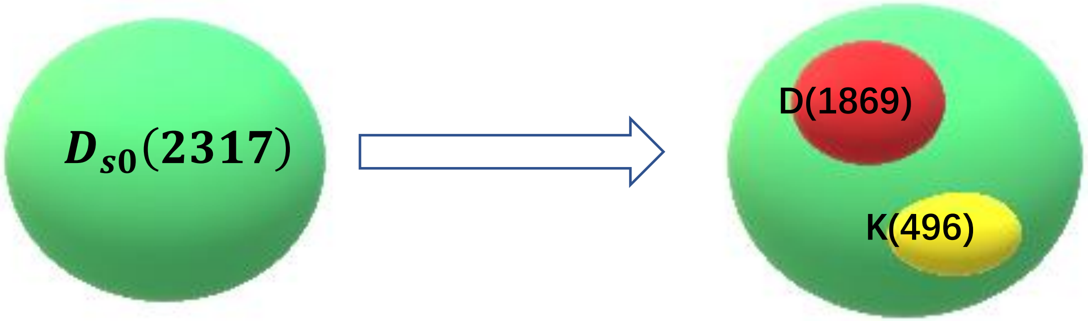
$\Lambda(1405)$ $0(1/2)^-$ $N\bar{K}$

Phys.Rev.Lett. 114 (2015) 132002 Jonathan M. M. Hall, Waseem Kamleh, et. al Lattice QCD

$X(3872)$ $0^+(1^{++})$ $\bar{D}D^*$

Phys.Rev.Lett. 111 (2013) 192001 Sasa Prelovsek and Luka Leskovec Lattice QCD

Molecular pictures



Mass relationship

$$m_D + m_K - m_{Ds0} = 48\ MeV$$

Isospin conservation

$$I_D \otimes I_K = 1 \oplus 0 \qquad I_{Ds0} = 0$$

Angular momentum and party

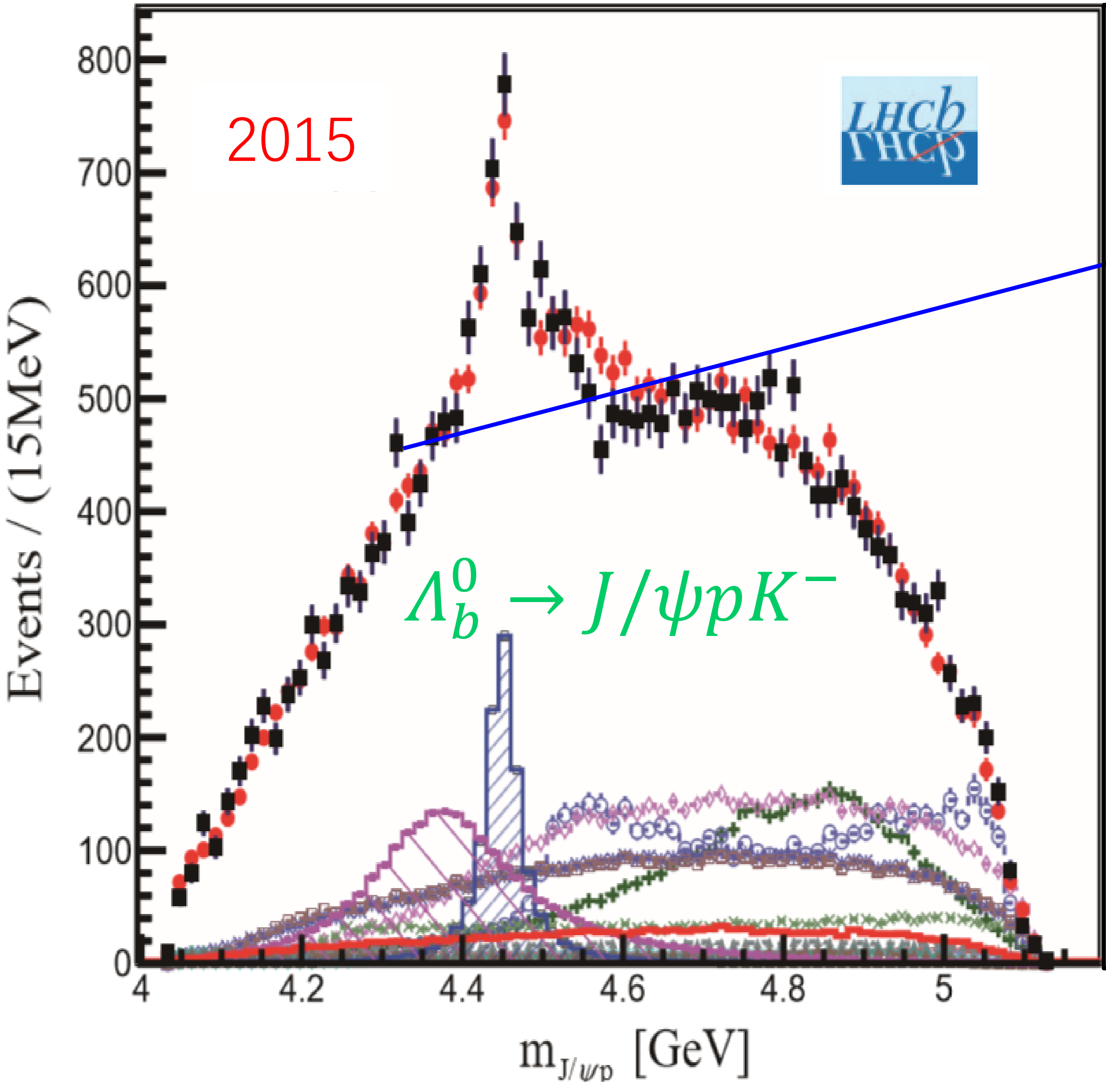
$$S_D \otimes S_K = S = 0 \qquad S \otimes L = J = L$$

$$(-1)^L P_{D,K} = (-1)^L = P_{Ds0}$$

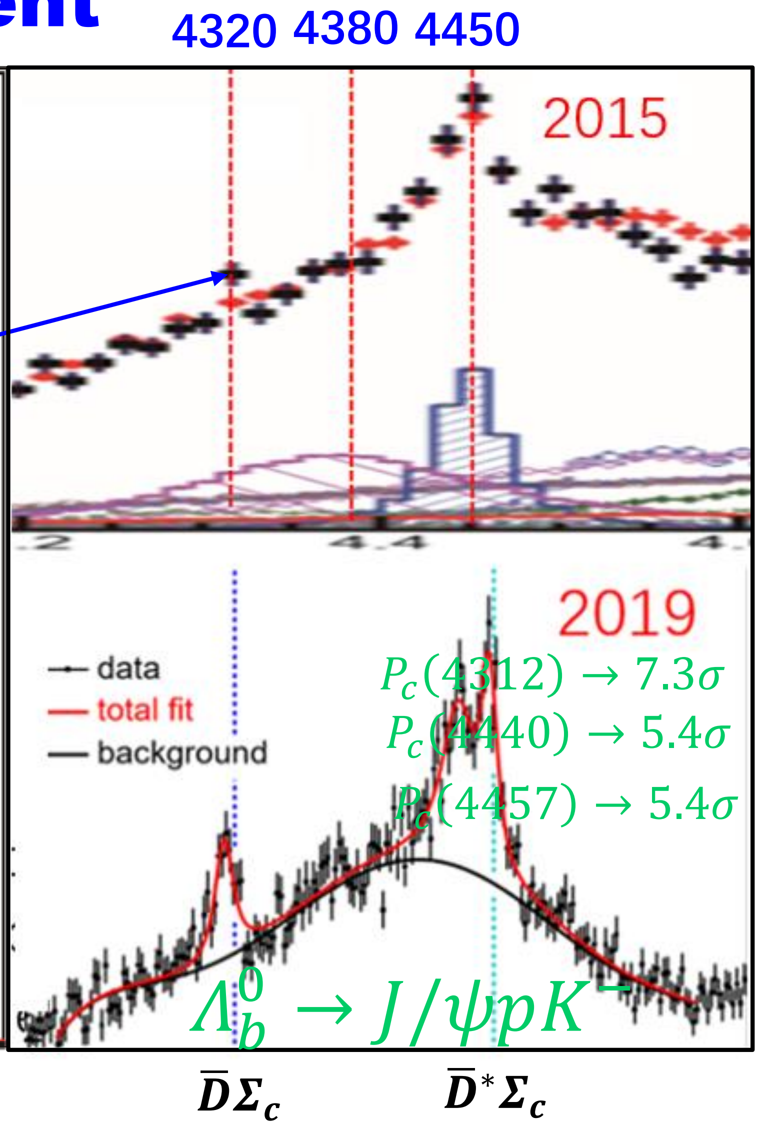
$$L = S$$

Background of hadronic molecule

2015 and 2019 experiment



Phys.Rev.Lett. 115 (2015) 072001



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

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

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

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

Heavy quark symmetry

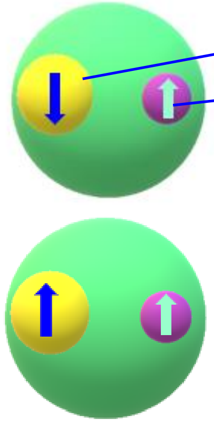
Heavy quark spin symmetry(HQSS)

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

Heavy quark **light quark**

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

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



HQSS is broken in charm and bottom sector

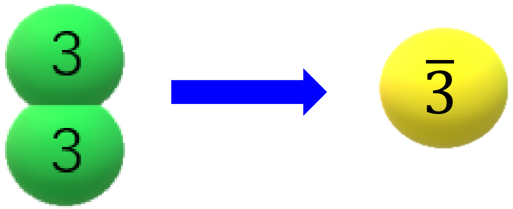
$$m_{D^*} - m_D = 142MeV \qquad m_{\Sigma_c^*} - m_{\Sigma_c} = 64MeV$$

$$m_{B^*} - m_B = 46MeV \qquad m_{\Sigma_b^*} - m_{\Sigma_b} = 21MeV$$

Heavy Anti-quark Di-quark symmetry(HADS)

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

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

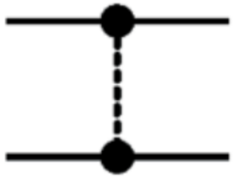


$$m_{\Xi_{cc\,3/2}} - m_{\Xi_{cc\,1/2}} = \frac{3}{4}(m_{D*} - m_D) \approx 106.5MeV$$

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

Phys.Lett. B248 (1990) 177-180 Phys.Rev. D73 (2006) 054003

Effective field theory

Leading order
- Contact 
- One pion exchange 

Next to leading order

⋮

OPE is perturbative in charm hadronic interactions

Phys.Rev. D99 (2019) 074026

Phys.Rev. D100 (2019) 014031

Contact Lagrangian

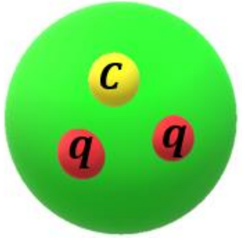
$$L = C_a Tr[H_c^{\dagger} H_c]\vec{S}_c \cdot \vec{S}_c^{\dagger} + C_b \sum_{i=1}^{3} Tr[H_c^{\dagger}\sigma_i H_c]\vec{S}_c \cdot (J_i \vec{S}_c^{\dagger})$$

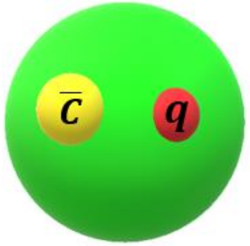
Superfields

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

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

HQSS ⟸ Spin multiplet hadrons

Effective potential 

S-wave 

Single channel

arXiv:1907.03414

Contact potential constraint by heavy quark spin symmetry

Results and Discussion

Lippmann-Schwinger Equation

$$\langle \vec{k}' | T | \vec{k} \rangle = \langle \vec{k}' | T | \vec{k} \rangle + \int \frac{d^3\vec{q}}{(2\pi)^3} \langle \vec{k}' | V | \vec{q} \rangle \frac{1}{E - \frac{\vec{q}^2}{2\mu}} \langle \vec{q} | T | \vec{k} \rangle$$

Integral Equation

$$1 + \int \frac{d^3\vec{q}}{(2\pi)^3} \frac{C(\Lambda)\theta^2(\Lambda - |\vec{q}|)}{B + \frac{\vec{q}^2}{2\mu}} = 0$$

Experimental data

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

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

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

Input in two Scenarios A and B

A	$(3/2^-)\ Pc(4457)$	$(1/2^-)\ Pc(4440)$
B	$(1/2^-)\ Pc(4457)$	$(3/2^-)\ Pc(4440)$

Separated potential

$$\langle \vec{k} | V | \vec{q} \rangle = C(\Lambda)\theta(\Lambda - |\vec{k}|)\theta(\Lambda - |\vec{q}|)$$

Contact-range potential

Input

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

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

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

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

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

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

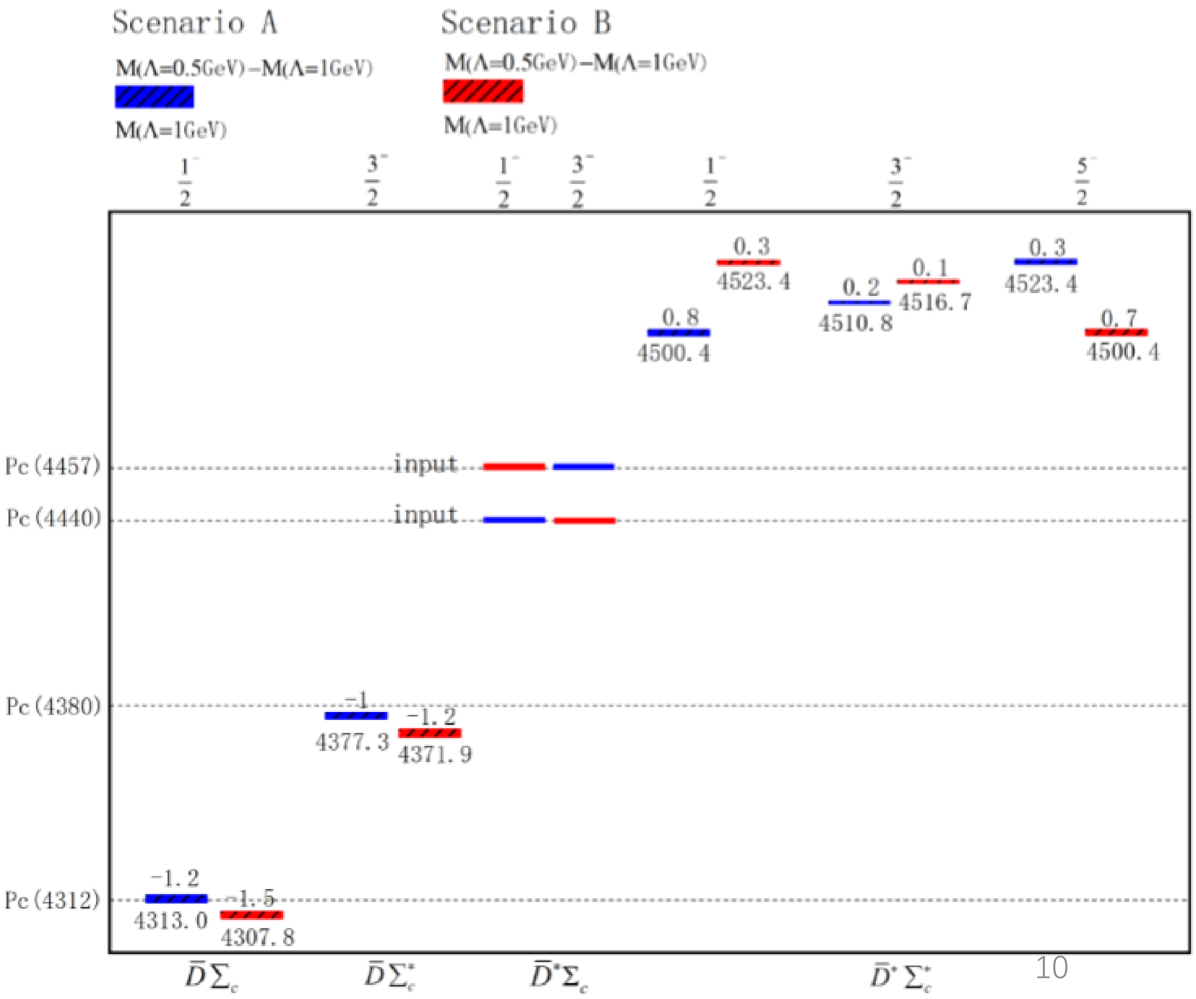
$$V(5/2^-, \Sigma_c^* \bar{D}^*) = C_a + C_b$$

Results and Discussion

7 hadronic molecules in light of Pc(4440) and Pc(4457)

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	$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^-$	$25.7-26.5$	$4500.2-4501.0$

Multiplet hadronic molecular picture



Spin of Pc(4440) and Pc(4457) by OBE model

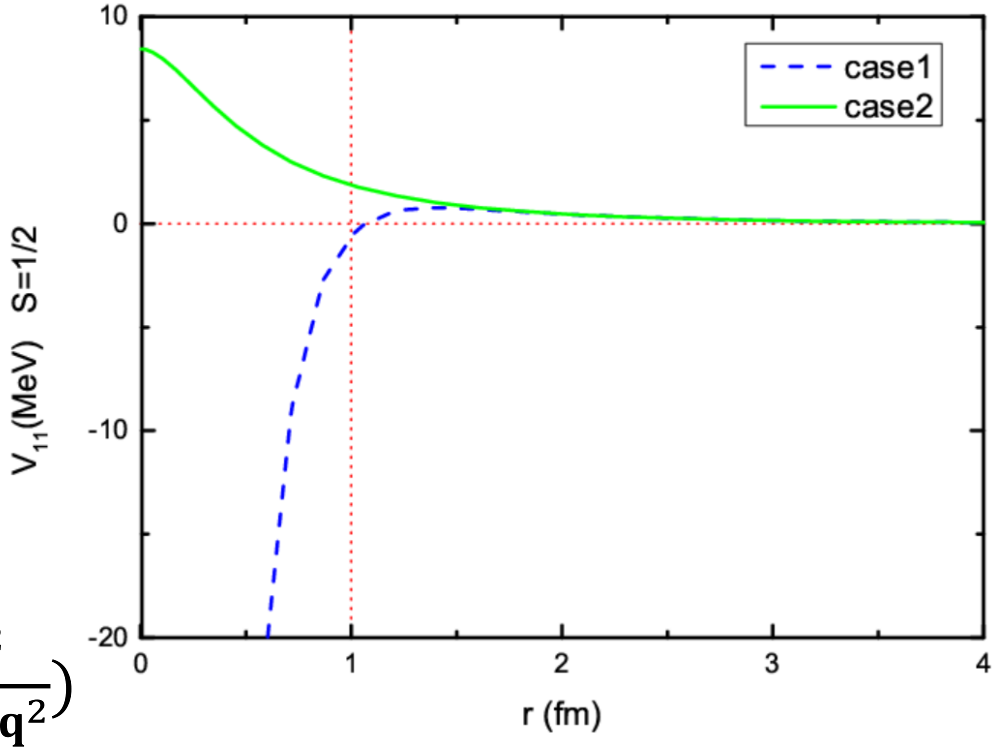
Results and Discussion

Three main kind of potentials in OBE model

Yukawa $\Longrightarrow$ $\dfrac{1}{m^2+\boldsymbol{q}^2}$

Spin-Spin $\Longrightarrow$ $\boldsymbol{\sigma}_1\boldsymbol{\sigma}_2\dfrac{\boldsymbol{q}^2}{m^2+\boldsymbol{q}^2}$

Tensor $\Longrightarrow$ $\dfrac{\boldsymbol{\sigma}_1\boldsymbol{q}\boldsymbol{\sigma}_2\boldsymbol{q}-\frac{1}{3}\boldsymbol{\sigma}_1\boldsymbol{\sigma}_2\boldsymbol{q}^2}{m^2+\boldsymbol{q}^2}$



Spin-Spin interaction

$$\boldsymbol{\sigma}_1\boldsymbol{\sigma}_2\ \frac{\mathbf{q}^2}{\mathbf{m}^2+\mathbf{q}^2}\rightarrow\boldsymbol{\sigma}_1\boldsymbol{\sigma}_2\ \frac{\mathbf{q}^2+\mathbf{m}^2-\mathbf{m}^2}{\mathbf{m}^2+\mathbf{q}^2}\rightarrow\boldsymbol{\sigma}_1\boldsymbol{\sigma}_2\left(1-\frac{\mathbf{m}^2}{\mathbf{m}^2+\mathbf{q}^2}\right)$$

$1 \rightarrow \delta(r)$

Discussion about removing delta potential

Case 1: Do not remove any delta potential

Case 2: Remove pion delta potential and keep vector delta potential

Case 3: Remove both pion and vector delta potential

Results and Discussion

One parameter in one boson exchange model

Pc(4312) ⟹ $\frac{\Lambda^2 - m^2}{\Lambda^2 - q^2}$

Results in different cases

Case 1： Keeping pion and vector delta potential B(1/2)=74; B(3/2)=3

Case 2： Removing only pion delta potential B(1/2)=13; B(3/2)=12

Case 3： Removing pion and vector delta potential B(1/2)=4; B(3/2)=19

Experimental data

Pc(4457) ⟹ B=5

Pc(4440) ⟹ B=22

Compared with the experimental data, case 3 is more favored

The spin of Pc(4440) and Pc(4457) on one boson exchange model

Pc(4440) ⟹ S=3/2

Pc(4457) ⟹ S=1/2

Results and Discussion

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

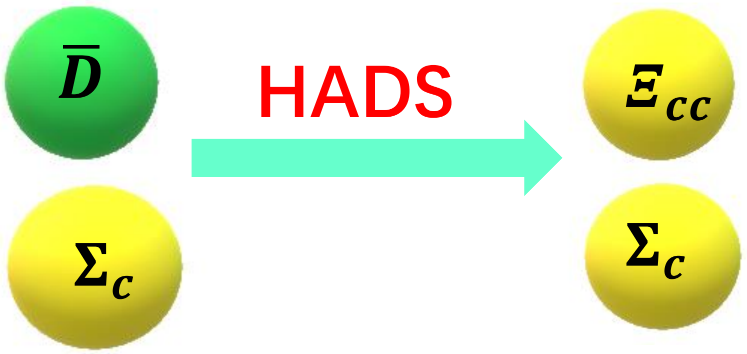
Effective field theory

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

The results are similar to the scenario B of effective field theory scheme

Contact potential constraint by HQSS and HADS

Results and Discussion



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

$$L_{\Xi_{cc}\Sigma_c} = C_a Tr[\vec{T}_{cc}^{\dagger} \vec{T}_{cc}]\vec{S}_c \cdot \vec{S}_c^{\,\dagger} + C_b \sum_{i=1}^{3} Tr[\vec{T}_{cc}^{\dagger}\sigma_i \vec{T}_{cc}]\vec{S}_c \cdot (J_i \vec{S}_c^{\,\dagger})$$

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

Superfield

$$\vec{T}_{cc} = \frac{1}{\sqrt{3}}(\Xi_{cc}\vec{\sigma} + \vec{\Xi}^{*}{}_{cc})$$

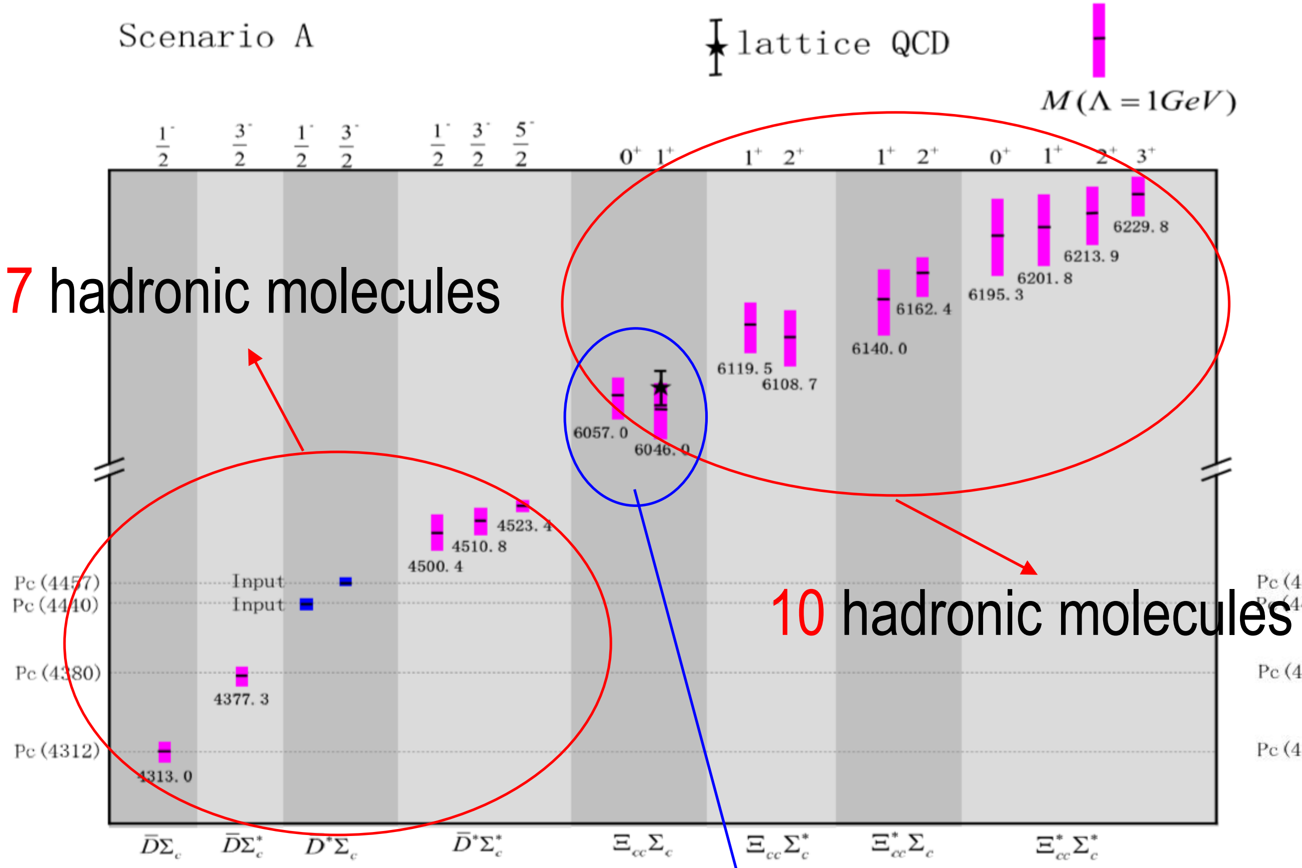
LHCb data → C_a, C_b

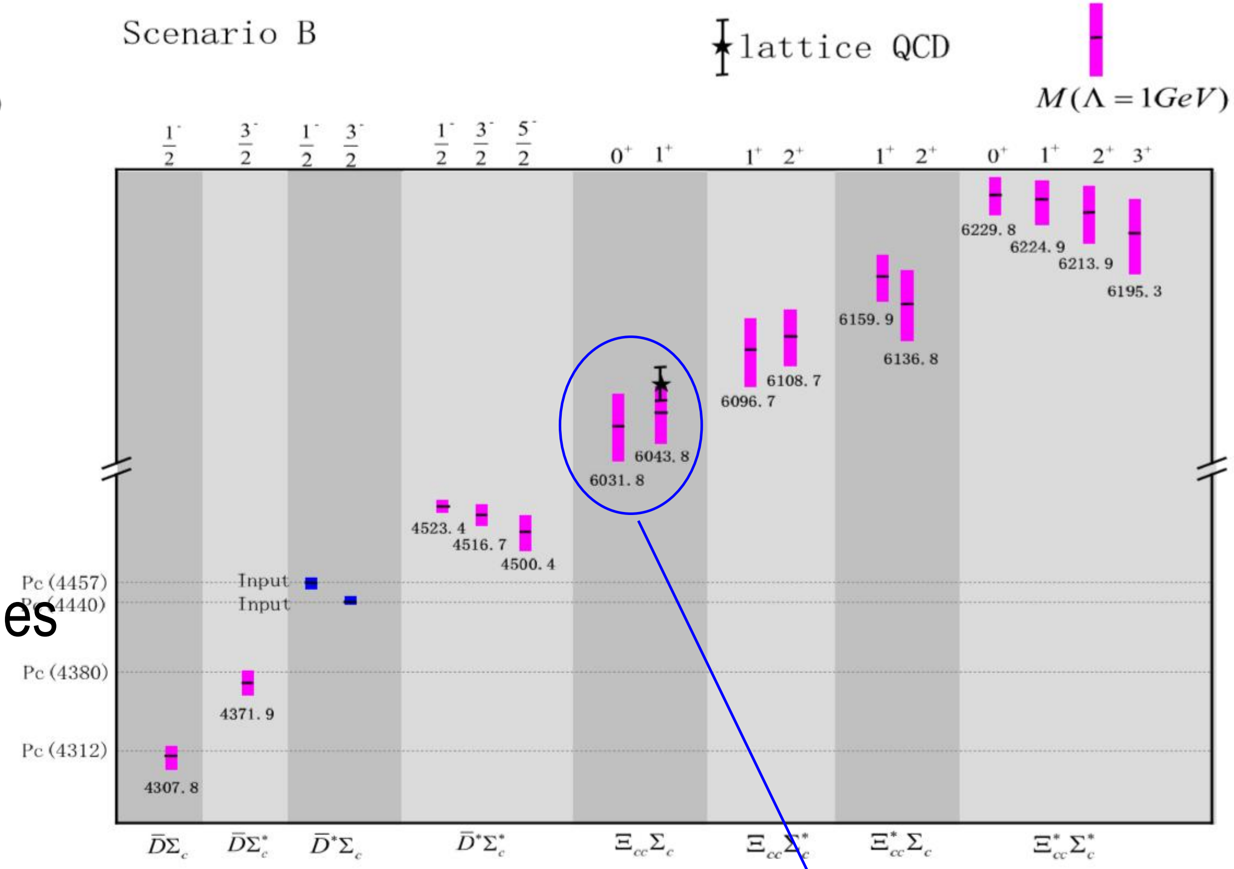
Predict 10 hadronic molecular states

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^+	$C_a + C_b$

Results and Discussion

A more complete multiplet hadronic molecular picture



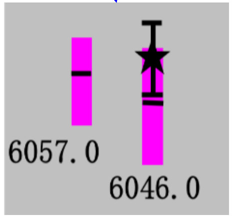


Mass splitting of $\Xi_{cc}\Sigma_c$ system

Lattice QCD

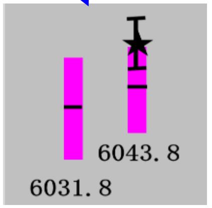
$$1^+ - 0^+ = -9MeV$$

$$\Delta_m < 0$$



$$1^+ - 0^+ = 12MeV$$

$$\Delta_m > 0$$



Summary

- We employ the effective field theory and one boson exchange model to show a complete multiplet hadronic molecules.

- We adopt one boson exchange model and a model-independent scheme to discuss the spin of Pc(4440) and Pc(4457).

Thanks for your attention!