# Heavy hadron interactions and hadronic molecules

## in chiral effective field theory


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- Effective chiral Lagrangians and Feynman diagrams
- Interactions of different systems
  - $BB$, $BB^*$ and $B^*B^*$
  - $\Sigma_c\bar{D}$, $\Sigma_c\bar{D}^*$, $\Sigma_c^*\bar{D}$ and $\Sigma_c^*\bar{D}^*$
  - $\Xi_c\bar{D}^{(*)}$, $\Xi_c'\bar{D}^{(*)}$ and $\Xi_c^*\bar{D}^{(*)}$
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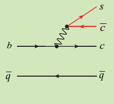
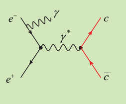
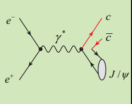
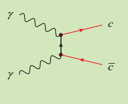
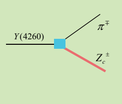
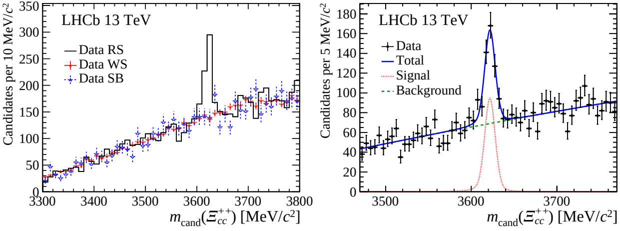
- Heavy quark symmetry breaking effect
- Preliminary results of $D^*N$ interaction
- Summary and conclusion

A poster child in hadron physics: $X(3872)$ [PRL 91, 262001].

|  |  |  |  |  |
|---|---|---|---|---|
| $X(3872)$ | $Y(4260)$ | $X(3940)$ | $X(3915)$ | $Z_c(3900)$ |
| $Y(3940)$ | $Y(4008)$ | $X(4160)$ | $X(4350)$ | $Z_c(4025)$ |
| $Z^+(4430)$ | $Y(4360)$ | | $Z(3930)$ | $Z_c(4020)$ |
| $Z^+(4051)$ | $Y(4630)$ | | | $Z_c(3885)$ |
| $Z^+(4248)$ | $Y(4660)$ | | | |
| $Y(4140)$ | | | | |
| $Y(4274)$ | | | | |
| $Z_c^+(4200)$ | | | | |
| $Z^+(4240)$ | | | | |
| $X(3823)$ | | | | |

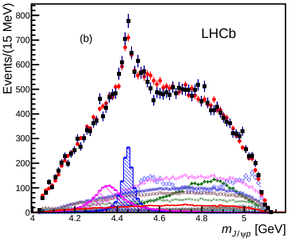
Many exotic states were observed after the $X(3872)$. This table is from [Phys. Rep. 639, 1]

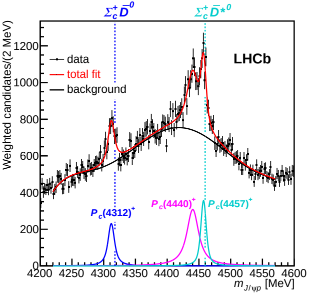
In 2017, the LHCb Collaboration reported the observation of doubly charmed baryon $\Xi_{cc}^{++}$ [PRL 119, 112001], which triggered many discussions on whether the stable $QQ\bar{q}\bar{q}$ tetraquark states can exist in nature [PRL 119, 202001, PRL 119, 202002].




Lattice QCD and quark model all support $0(1^+)$ states [IJMPE 17, 1157], then how about the molecular-like states in $B^{(*)}B^{(*)}$ systems?

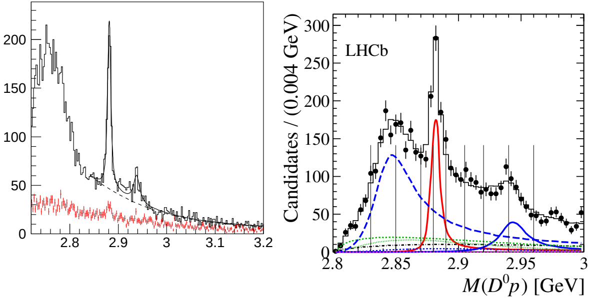
$P_c(4312)$, $P_c(4440)$ and $P_c(4457)$ were reported by LHCb in the April of last year [PRL 122, 222001].




Molecular explanations were proposed by many theoretical works, such as Refs. [PRD 100, 014031; PRL 122, 242001; PRD 100, 011502; PRD 100, 014021; EPJC 79, 393].

What is the nature of $\Lambda_c(2940)$ [PRL 98, 012001, PRL 98, 262001, JHEP05(2017)030]?




$D^*N$ molecule or the conventional excited baryons?

1. The interactions between heavy hadrons are essential to map out the mass spectra of the corresponding molecules.
2. Various methods can be applied to study the heavy hadron interactions.

$$\text{Methods} = \begin{cases} \text{Quark model at the quark level} \\ \text{One-boson-exchange (OBE) model at the hadron level} \\ \text{OBE motivated other ways by solving nonperturbative equations} \\ \text{Effective field theory based on symmetries, pionless or pionful} \end{cases}$$

**Pionful**: Pion is explicitly treated as the light degree of freedom (*dof*) in the Lagrangians. $\rho$ and other high states as the heavy *dof* are integrated out due to the large scale separations.

**Merits**: Consistent power counting, the error is estimable and controllable at the order we are working on. Extensively exploited to study the $N$-$N$ systems with great success [IJMP E4, 193; RMP 81, 1773; PR 503, 1].

We systematically study the heavy hadron interactions with chiral effective field theory up to the one-loop level.

Troubles: Pinch singularity in the loops needs to be carefully tackled.

Surprises: (1)New spin-spin interaction term $(\mathbf{S}_1 \cdot \mathbf{S}_2)^2$ emerges from the loop diagrams for the $B^*B^*$ and $\Sigma_c^*\bar{D}^*$ system. (2) Heavy quark symmetry is not always good for the charm sectors.

Expectation: Chirally motivated effective field theory can give a good description for the $P_c$ and $\Lambda_c(2940)$ states.

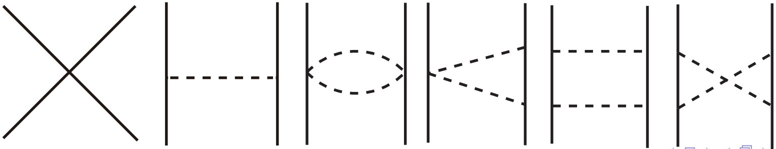
## Lagrangians for $\bar{B}^{(*)}\bar{B}^{(*)}$ systems

Pion interaction:

$$\mathcal{L}^{(1)}_{\mathcal{H}\phi} = -\left\langle (iv\cdot\partial\mathcal{H})\,\bar{\mathcal{H}}\right\rangle + \left\langle \mathcal{H}v\cdot\Gamma\bar{\mathcal{H}}\right\rangle + g\left\langle \mathcal{H}\not{u}\gamma_5\bar{\mathcal{H}}\right\rangle - \frac{1}{8}\Delta\left\langle \mathcal{H}\sigma^{\mu\nu}\bar{\mathcal{H}}\sigma_{\mu\nu}\right\rangle, \quad (3.1)$$

Contact interaction:

$$\begin{aligned}\mathcal{L}^{(0)}_{4\mathcal{H}} = {} & D_a\mathrm{Tr}\left[\mathcal{H}\gamma_\mu\bar{\mathcal{H}}\right]\mathrm{Tr}\left[\mathcal{H}\gamma^\mu\bar{\mathcal{H}}\right] + D_b\mathrm{Tr}\left[\mathcal{H}\gamma_\mu\gamma_5\bar{\mathcal{H}}\right]\mathrm{Tr}\left[\mathcal{H}\gamma^\mu\gamma_5\bar{\mathcal{H}}\right] \\ & + E_a\mathrm{Tr}\left[\mathcal{H}\gamma_\mu\tau^a\bar{\mathcal{H}}\right]\mathrm{Tr}\left[\mathcal{H}\gamma^\mu\tau_a\bar{\mathcal{H}}\right] + E_b\mathrm{Tr}\left[\mathcal{H}\gamma_\mu\gamma_5\tau^a\bar{\mathcal{H}}\right]\mathrm{Tr}\left[\mathcal{H}\gamma^\mu\gamma_5\tau_a\bar{\mathcal{H}}\right], \quad (3.2)\end{aligned}$$



## Lagrangians for $\Sigma_c^{(*)}\bar{D}^{(*)}$ systems

**Pion interaction:**

$$\begin{aligned}\mathcal{L}_{B\phi} &= -\mathrm{Tr}\left(\bar{\psi}^\mu iv\cdot D\psi_\mu\right) + ig_a\epsilon_{\mu\nu\rho\sigma}\mathrm{Tr}\left(\bar{\psi}^\mu u^\rho v^\sigma\psi^\nu\right) + i\frac{\delta_a}{2}\mathrm{Tr}\left(\bar{\psi}^\mu\sigma_{\mu\nu}\psi^\nu\right)\\ &+\frac{1}{2}\mathrm{Tr}\left[\bar{\mathcal{B}}_1(iv\cdot D)\mathcal{B}_1\right] + g_b\mathrm{Tr}\left(\bar{\psi}^\mu u_\mu\mathcal{B}_1 + \mathrm{H.c.}\right), \qquad (3.3)\end{aligned}$$

$$\mathcal{L}_{H\phi} = -i\langle\bar{\tilde{\mathcal{H}}}v\cdot\mathcal{D}\tilde{\mathcal{H}}\rangle - \frac{1}{8}\delta_b\langle\bar{\tilde{\mathcal{H}}}\sigma^{\mu\nu}\tilde{\mathcal{H}}\sigma_{\mu\nu}\rangle + g\langle\bar{\tilde{\mathcal{H}}}\not{u}\gamma_5\tilde{\mathcal{H}}\rangle, \qquad (3.4)$$

**Contact interaction:**

$$\begin{aligned}\mathcal{L}_{HB} &= D_a\langle\bar{\tilde{\mathcal{H}}}\tilde{\mathcal{H}}\rangle\mathrm{Tr}\left(\bar{\psi}^\mu\psi_\mu\right) + iD_b\epsilon_{\sigma\mu\nu\rho}v^\sigma\langle\bar{\tilde{\mathcal{H}}}\gamma^\rho\gamma_5\tilde{\mathcal{H}}\rangle\mathrm{Tr}\left(\bar{\psi}^\mu\psi^\nu\right)\\ &+E_a\langle\bar{\tilde{\mathcal{H}}}\tau^i\tilde{\mathcal{H}}\rangle\mathrm{Tr}\left(\bar{\psi}^\mu\tau_i\psi_\mu\right) + iE_b\epsilon_{\sigma\mu\nu\rho}v^\sigma\langle\bar{\tilde{\mathcal{H}}}\gamma^\rho\gamma_5\tau^i\tilde{\mathcal{H}}\rangle\mathrm{Tr}\left(\bar{\psi}^\mu\tau_i\psi^\nu\right), \qquad (3.5)\end{aligned}$$

where $\psi$ and $\tilde{\mathcal{H}}$ are the super-fields for the charmed baryons and mesons, respectively [NPB 396, 183; PRD 45, 2188R]. $g_a$ and $g_b$ can be determined with the partial decay widths of $\Sigma_c \to \Lambda_c\pi$ and $\Sigma_c^* \to \Lambda_c\pi$, respectively. $g$ is extracted from the partial decay width of $D^{*+} \to D^0\pi^+$. $D_a$, $D_b$, $E_a$ and $E_b$ are four independent low-energy-constants (LECs).

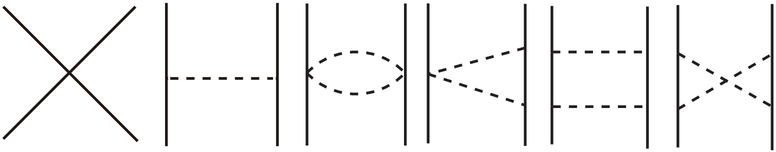


Figure: The possible Feynman diagrams that account for the short-, long- and intermediate-range interactions of the $\Sigma_c^{(*)}\bar{D}^*$ systems.

## Lagrangians for $D^{(*)}N$ systems

Pion interaction:

$$\mathcal{L}_{N\phi} = \bar{N}(iv\cdot D + 2g_A\mathcal{S}\cdot u)N, \tag{3.6}$$

$$\mathcal{L}_{\Delta N\phi} = 2g_\delta(\bar{T}_i^\mu g_{\mu\alpha}\omega_i^\alpha N + \bar{N}\omega_i^{\alpha\dagger}g_{\alpha\mu}T_i^\mu), \tag{3.7}$$

Contact interaction:

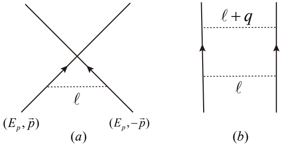
$$\begin{aligned}\mathcal{L}^{(0)}_{\mathcal{H}N} \;=\;& D_a\bar{N}N\mathrm{Tr}\left[\mathcal{H}\gamma^\mu\bar{\mathcal{H}}\right] + D_b\bar{N}\gamma_\mu\gamma_5 N\mathrm{Tr}\left[\mathcal{H}\gamma^\mu\gamma_5\bar{\mathcal{H}}\right]\\ & + E_a\bar{N}\tau_a N\mathrm{Tr}\left[\mathcal{H}\gamma^\mu\tau_a\bar{\mathcal{H}}\right] + E_b\bar{N}\gamma_\mu\gamma_5\tau_a N\mathrm{Tr}\left[\mathcal{H}\gamma^\mu\gamma_5\tau_a\bar{\mathcal{H}}\right],\end{aligned} \tag{3.8}$$

where

$$T^1_\mu = \frac{1}{\sqrt{2}}\begin{pmatrix}\Delta^{++} - \frac{1}{\sqrt{3}}\Delta^0\\ \frac{1}{\sqrt{3}}\Delta^+ - \Delta^-\end{pmatrix}, T^2_\mu = \frac{i}{\sqrt{2}}\begin{pmatrix}\Delta^{++} + \frac{1}{\sqrt{3}}\Delta^0\\ \frac{1}{\sqrt{3}}\Delta^+ + \Delta^-\end{pmatrix}, T^3_\mu = -\sqrt{\frac{2}{3}}\begin{pmatrix}\Delta^+\\ \Delta^0\end{pmatrix}. \tag{3.9}$$

## Weinberg's formalism:

We need the effective potential!




$$i\int \frac{d^D\ell}{(2\pi)^D}\frac{1}{(-\ell_0+i\varepsilon)(\ell_0+i\varepsilon)(\ell^2-m_\pi^2+i\varepsilon)}. \tag{3.10}$$

The integration over $\ell_0$ is ill-defined because it has poles above and below the real axis at $\ell_0 = \pm i\varepsilon$ (which is always called as pinch singularity).

$$\ell_0 = \pm\left(\mathcal{E} - \vec{\ell}^2/2M_N\right) \pm i\varepsilon, \tag{3.11}$$

where $\mathcal{E} = \vec{p}^2/2M_N$, and $M_N$ is the mass of the nucleon.

## Lagrangians and diagrams

Effective potential in momentum space:

$$\mathcal{V}(\boldsymbol{q}) = -\frac{\mathcal{M}(\boldsymbol{q})}{\sqrt{2M_1 2M_2 2M_3 2M_4}}. \tag{3.12}$$

In coordinate space:

$$\mathcal{V}(r) = \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} e^{-i\boldsymbol{q}\cdot\boldsymbol{r}} \mathcal{V}(\boldsymbol{q}) \mathcal{F}(\boldsymbol{q}), \tag{3.13}$$

where the Gauss regulator $\mathcal{F}(\boldsymbol{q}) = \exp(-\boldsymbol{q}^{2n}/\Lambda^{2n})$ [PRC 53, 2086; NPA 671, 295]. As in the $N$-$N$ systems, we set $n = 2$ and $\Lambda = 0.5$ GeV to give predictions [PR 503, 1; EPJA 51, 53; PRC 68, 041001].

## Numerical results of the $\bar{B}^{(*)}\bar{B}^{(*)}$ systems

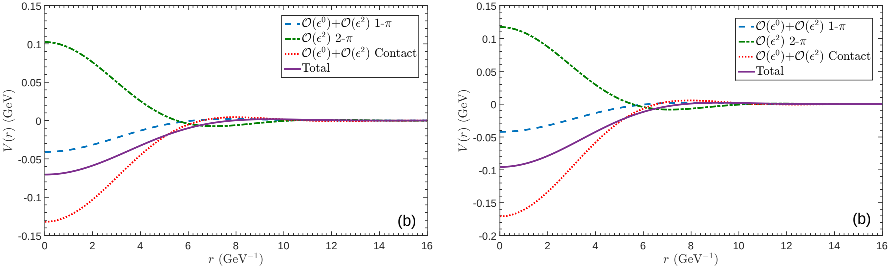



Figure: The potentials of $0(1^+)$ $\bar{B}\bar{B}^*$ (left panel) and $\bar{B}^*\bar{B}^*$ (right panel) systems in coordinate space. The potentials of other channels are all repulsive.

By solving the Schrödinger equation, we get

$$\begin{aligned} \Delta E_{\bar{B}\bar{B}^*} &\simeq -12.6^{+9.2}_{-12.9}\ \mathrm{MeV}, \quad \Delta E_{\bar{B}^*\bar{B}^*} \simeq -23.8^{+16.3}_{-21.5}\ \mathrm{MeV}. \\ m_{\bar{B}\bar{B}^*} &\simeq 10591.4^{+9.2}_{-12.9}\ \mathrm{MeV}, \quad m_{\bar{B}^*\bar{B}^*} \simeq 10625.5^{+16.3}_{-21.5}\ \mathrm{MeV}. \end{aligned} \tag{4.1}$$

The four LECs in eq. (3.5) are still unknown. But we do not have to determine each of them since the forms of the $\mathcal{O}(\varepsilon^0)$ contact potentials are homogeneous for definite isospin states.

$$\mathbb{D}_1 = D_a + 2E_a(\mathbf{I}_1 \cdot \mathbf{I}_2), \qquad \mathbb{D}_2 = D_b + 2E_b(\mathbf{I}_1 \cdot \mathbf{I}_2). \tag{4.2}$$

Therefore, the leading order potential

$$\begin{aligned} \mathcal{V}^{X_{1.1}}_{\Sigma_c\bar{D}} &= -\mathbb{D}_1, & \mathcal{V}^{X_{2.1}}_{\Sigma_c\bar{D}^*} &= -\left[\mathbb{D}_1 + \frac{2}{3}\mathbb{D}_2(\boldsymbol{\sigma}\cdot\boldsymbol{T})\right], \\ \mathcal{V}^{X_{3.1}}_{\Sigma_c^*\bar{D}} &= -\mathbb{D}_1, & \mathcal{V}^{X_{4.1}}_{\Sigma_c^*\bar{D}^*} &= -\left[\mathbb{D}_1 + \mathbb{D}_2(\boldsymbol{\sigma}_{rs}\cdot\boldsymbol{T})\right]. \end{aligned} \tag{4.3}$$

In the scenario II of our previous work [PRD 100, 014031], the LECs are determined by fitting the data of the three $P_c$s, yet the result is unsatisfactory.

## The three $P_c$s without and with the $\Lambda_c$

Table: The experimental and theoretical information of the $P_c(4312)$, $P_c(4440)$, $P_c(4457)$, and $P_c(4380)$. The $I(\mathcal{J}^P)$ quantum numbers are the theoretically favored ones, not the experimental measurements (in units of MeV).

| States | Mass | Width | Threshold | Binding energy | $I(\mathcal{J}^P)$ |
|---|---|---|---|---|---|
| $P_c(4312)$ | $4311.9 \pm 0.7^{+6.8}_{-0.6}$ | $9.8 \pm 2.7^{+3.7}_{-4.5}$ | $\Sigma_c^+ \bar{D}^0$ | $-5.83 \pm 0.7^{+6.8}_{-0.6}$ | $\frac{1}{2}\left(\frac{1}{2}^-\right)$ |
| $P_c(4440)$ | $4440.3 \pm 1.3^{+4.1}_{-4.7}$ | $20.6 \pm 2.7^{+8.7}_{-10.1}$ | $\Sigma_c^+ \bar{D}^{*0}$ | $-19.45 \pm 1.3^{+4.1}_{-4.7}$ | $\frac{1}{2}\left(\frac{1}{2}^-\right)$ |
| $P_c(4457)$ | $4457.3 \pm 0.6^{+4.1}_{-1.7}$ | $6.4 \pm 2.0^{+5.7}_{-1.9}$ | $\Sigma_c^+ \bar{D}^{*0}$ | $-2.45 \pm 0.6^{+4.1}_{-1.7}$ | $\frac{1}{2}\left(\frac{3}{2}^-\right)$ |
| $P_c(4380)$ | $4380 \pm 8 \pm 29$ | $205 \pm 18 \pm 86$ | $\Sigma_c^{*+} \bar{D}^0$ | $-2.33 \pm 8 \pm 29$ | $\frac{1}{2}\left(\frac{3}{2}^-\right)$ |

## The three $P_c$s without and with the $\Lambda_c$

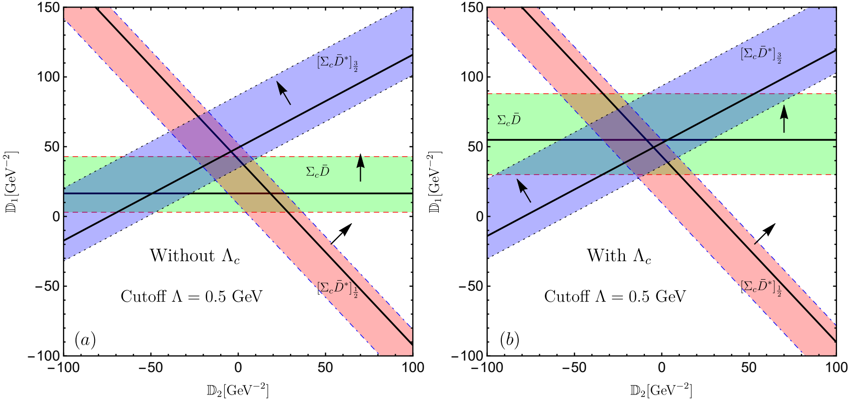



**Figure:** The dependence of the binding energies of the three $P_c$ states on the redefined LECs $\mathbb{D}_1$ and $\mathbb{D}_2$. The boundaries of the bands that are parallel to the corresponding straight lines stand for the regions of parameters with the binding emerges $-30$ MeV and $0$ MeV, respectively. The accompanied arrow shows the direction that the each binding becomes deeper. Figures $(a)$ and $(b)$ illustrate the results without and with the $\Lambda_c$, respectively.

Table: The binding energies $\Delta E$ for the $I=\frac{1}{2}$ hidden-charm $[\Sigma_c^{(*)}\bar{D}^{(*)}]_{\mathcal{J}}$ systems in both cases with and without the $\Lambda_c$, as well as the case with $\mathcal{J}^P=\frac{1}{2}^-$ for $P_c(4457)$ and $\frac{3}{2}^-$ for $P_c(4440)$. "$\times$" means no binding solution (in units of MeV).

| $\Delta E$ | $[\Sigma_c\bar{D}]_{\frac{1}{2}}$ | $[\Sigma_c\bar{D}^*]_{\frac{1}{2}}$ | $[\Sigma_c\bar{D}^*]_{\frac{3}{2}}$ | $[\Sigma_c^*\bar{D}]_{\frac{3}{2}}$ | $[\Sigma_c^*\bar{D}^*]_{\frac{1}{2}}$ | $[\Sigma_c^*\bar{D}^*]_{\frac{3}{2}}$ | $[\Sigma_c^*\bar{D}^*]_{\frac{5}{2}}$ |
|---|---|---|---|---|---|---|---|
| Without $\Lambda_c$ | $-29.05$ | $-6.84$ | $-2.98$ | $-34.30$ | $-0.16$ | $\times$ | $\times$ |
| With $\Lambda_c$ | $-4.60$ | $-22.48$ | $-3.19$ | $-34.51$ | $-14.34$ | $-3.40$ | $-0.30$ |
| I.S. | $-7.24$ | $-1.47$ | $-17.44$ | $-40.88$ | $\times$ | $-0.24$ | $-11.20$ |

## Role of the $\Lambda_c$

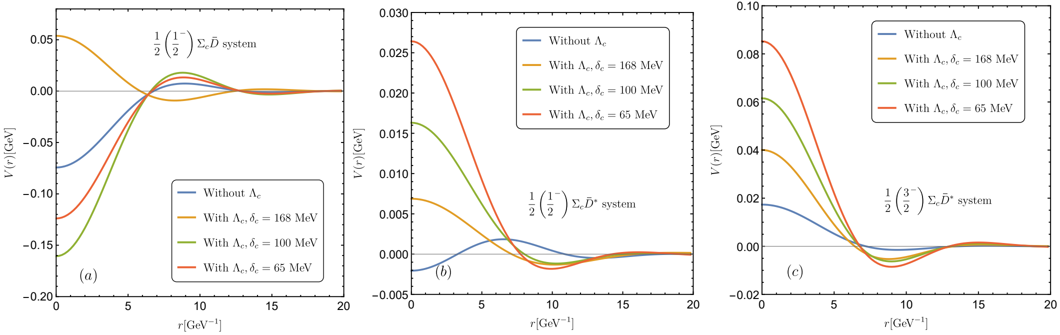



Figure: The variations of the two-pion-exchange potentials for the $\Sigma_c\bar{D}^{(*)}$ systems in the cases of without and with the $\Lambda_c$. The dependence on the mass splitting $\delta_c$ is also illustrated.

## Role of the $\Lambda_c$

Take the two-pion-exchange potential of the $[\Sigma_c\bar{D}]_{\frac{1}{2}}$ system as an example.

$$\mathcal{V}^{2\pi}_{\Sigma_c\bar{D}} = \begin{cases} \text{attractive} & \text{without } \Lambda_c \\ \text{repulsive} & \text{with } \Lambda_c \end{cases}$$

Why $\Lambda_c$ is so important?

1. Strong coupling: The threshold of $\Lambda_c\pi$ lies below the $\Sigma_c^{(*)}$, the coupling is very strong.
2. Accidental degeneration: The mass difference between $\Sigma_c\bar{D}$ and $\Lambda_c\bar{D}^*$ systems is only about $28$ MeV, which is a tiny value compared with the pion mass. Thus the loop diagram that account for the coupled channel effect is largely enhanced.

If only $\Lambda_c$? Negative!

## Interchanging the spins of $P_c(4440)$ and $P_c(4457)$

1. The $\mathcal{J}^P$ quantum numbers of the $P_c(4312)$, $P_c(4440)$ and $P_c(4457)$ are not determined yet [PRL 122, 222001].
2. The theoretically favored $\mathcal{J}^P$ for $P_c(4440)$ and $P_c(4457)$ in our paper and some previous works are $\frac{1}{2}^-$ and $\frac{3}{2}^-$, respectively.
3. In some recent works [arXiv:1907.04684; 1907.05294; 1907.06093], a new conjecture, that the $\mathcal{J}^P = \frac{3}{2}^-$ for $P_c(4440)$ and $\frac{1}{2}^-$ for $P_c(4457)$, is proposed.
4. We investigate the possibility of this spin assignment.

## Interchanging the spins of $P_c(4440)$ and $P_c(4457)$

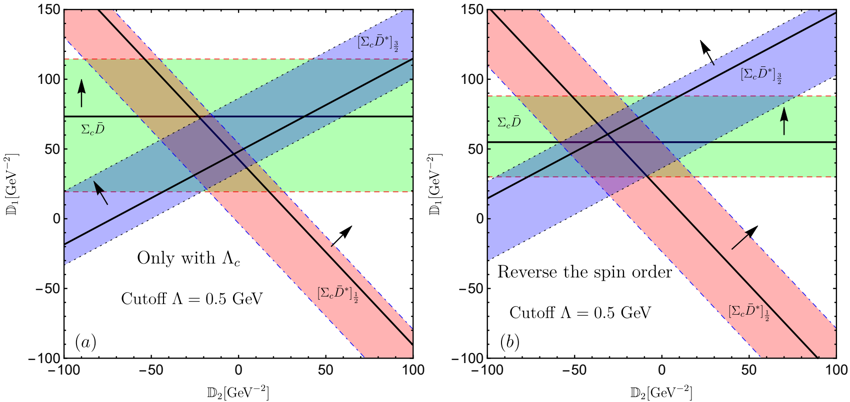



**Figure:** The dependence of the binding energies of the three $P_c$ states on the redefined LECs $\mathbb{D}_1$ and $\mathbb{D}_2$ in different cases. Figure $(a)$ gives the result that only considering the contributions of $\Lambda_c$ in the two-pion-exchange diagrams. Figure $(b)$ shows the result when interchanging the spins of $P_c(4440)$ and $P_c(4457)$. The notations are the same as those in figure 3.

1. The result is comparable with the one in figure 3(b), i.e., it seems this assignment can well describe the experimental data, likewise.
2. But something becomes abnormal. No interchanging: $(\mathbb{D}_1, \mathbb{D}_2) = (52, -4)$ GeV$^{-2}$; interchanging: $(\mathbb{D}_1, \mathbb{D}_2) = (58, -31)$ GeV$^{-2}$.
3. One has to largely enhance the contribution of the $\mathcal{O}(\varepsilon^0)$ spin-spin interaction to reverse the *canonical order* of the spins of $P_c(4440)$ and $P_c(4457)$.
4. Why abnormal? Some hints from the $N$-$N$ scattering data:

$$\mathcal{L}_{NN}^{(0)} = -\frac{1}{2}C_S(\bar{N}N)(\bar{N}N) - \frac{1}{2}C_T(\bar{N}\boldsymbol{\sigma}N)\cdot(\bar{N}\boldsymbol{\sigma}N). \quad (4.4)$$

The next-to-next-to-next-to-leading order fitting gives [PRC 68, 041001]

$$C_S = -100.28\ \mathrm{GeV}^{-2}, \qquad C_T = 5.61\ \mathrm{GeV}^{-2}, \tag{4.5}$$

i.e., the spin-spin interaction only serves as the perturbation.

Other hints from the OBE model:

1. $\rho$ and $\omega$ contribute the $q^2$-dependent spin-spin interaction.
2. The momentum-independent contributions can only come from the axial-vector mesons, such as $(h_1, f_1)$ and $(b_1, a_1)$.
3. The masses of these states reside around $1.2$ GeV, which are much heavier than those of $\omega$ and $\rho$, and suppress the value of $\mathbb{D}_2$.

Looking forward to the last adjudication from the experimental measurements!

1. The above study for the hidden-charm pentaquarks can be extended to the hidden-bottom case.
2. Just the coupling constants and mass splittings are replaced by the bottomed ones.
3. The axial coupling $g$ of the $B$ mesons cannot be directly derived from the experiments due to absence of phase space for $B^* \to B\pi$, so we adopt the average value from the lattice calculations [PRD 77, 094509; PRD 85, 114508].
4. The coupling constants for the bottom baryons can be determined by

$$\Gamma(\Sigma_b \to \Lambda_b \pi) = \frac{g_2^2}{4\pi f_\pi^2}\frac{m_{\Lambda_b}}{m_{\Sigma_b}}|\boldsymbol{q}_\pi|^3, \qquad \Gamma(\Sigma_b^* \to \Lambda_b \pi) = \frac{g_4^2}{12\pi f_\pi^2}\frac{m_{\Lambda_b}}{m_{\Sigma_b^*}}|\boldsymbol{q}_\pi|^3. \quad (5.1)$$

## Hidden-bottom ones

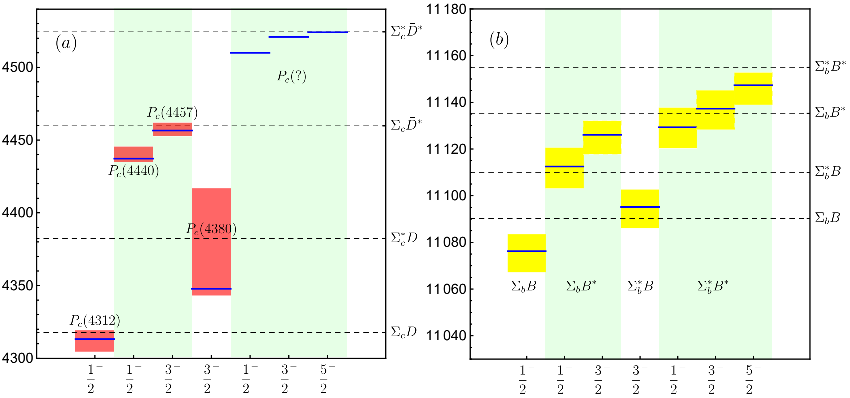



**Figure:** The mass spectra of the hidden-charm $(a)$ and hidden-bottom $(b)$ molecular pentaquarks. The red and yellow regions in figures $(a)$ and $(b)$ denote the mass ranges obtained from the experimental measurements and theoretical estimations, respectively. The blue solid lines represent the central values in our calculations. The black dashed lines are the corresponding thresholds.

1. We set the $(52, -4)$ GeV$^{-2}$ as the limits of $(\mathbb{D}_1, \mathbb{D}_2)$ for the bottom case, which deviate $17\%$ from the central value. Approximately, we have

$$\mathbb{D}_1 = 43 \pm 9\,\mathrm{GeV}^{-2}, \qquad \mathbb{D}_2 = -3.3 \mp 0.7\,\mathrm{GeV}^{-2}. \tag{5.2}$$

2. The hidden-bottom ones are the tightly bound molecules due to the large masses of their components. There is plenty of room at the 'bottom'.

Table: The binding energies $\Delta E$ for the $I = \frac{1}{2}$ hidden-bottom $[\Sigma_b^{(*)} B^{(*)}]_J$ systems with the contribution of the $\Lambda_b$ (in units of MeV).

| $\Delta E$ | $[\Sigma_b B]_{\frac{1}{2}}$ | $[\Sigma_b B^*]_{\frac{1}{2}}$ | $[\Sigma_b B^*]_{\frac{3}{2}}$ | $[\Sigma_b^* B]_{\frac{3}{2}}$ | $[\Sigma_b^* B^*]_{\frac{1}{2}}$ | $[\Sigma_b^* B^*]_{\frac{3}{2}}$ | $[\Sigma_b^* B^*]_{\frac{5}{2}}$ |
|---|---|---|---|---|---|---|---|
| With $\Lambda_b$ | $-14.04^{+7.36}_{-8.92}$ | $-22.72^{+8.03}_{-9.34}$ | $-9.12^{+6.06}_{-8.34}$ | $-14.74^{+7.54}_{-9.05}$ | $-25.75^{+8.38}_{-9.06}$ | $-17.76^{+7.91}_{-9.07}$ | $-7.81^{+5.56}_{-8.41}$ |

1. QCD Lagrangian has heavy quark symmetry (HQS) when $m_Q \to \infty$.
2. But, the physical masses of the heavy quarks are finite, such as $m_c \sim 1.5$ GeV, $m_b \sim 5$ GeV.
3. The breaking effect is explicit, $g_{B^*B\pi} \simeq 17\% g_{D^*D\pi}$, $m_{D^*} - m_D \simeq 142$ MeV, $m_{B^*} - m_B \simeq 45$ MeV.
4. The $S$-wave effective potentials between $\Sigma_c^{(*)}$ and $\bar{D}^{(*)}$ at the quark level

$$\text{Quark level}: V^{\text{HQS}} = V_c + V_s \boldsymbol{l}_1 \cdot \boldsymbol{l}_2. \tag{6.1}$$

$$\text{Hadron level}: \begin{cases} \mathcal{V}_{\Sigma_c\bar{D}} = \mathcal{V}_1 & \mathcal{V}_{\Sigma_c\bar{D}^*} = \mathcal{V}_2 + \mathcal{V}_2' \boldsymbol{S}_1 \cdot \boldsymbol{S}_2 \\ \mathcal{V}_{\Sigma_c^*\bar{D}} = \mathcal{V}_3 & \mathcal{V}_{\Sigma_c^*\bar{D}^*} = \mathcal{V}_4 + \mathcal{V}_4' \boldsymbol{S}_1 \cdot \boldsymbol{S}_2 \end{cases}. \tag{6.2}$$

$$\mathcal{V}_1 = \mathcal{V}_2 = \mathcal{V}_3 = \mathcal{V}_4 = V_c; \qquad \mathcal{V}_2' = \frac{2}{3} V_s, \quad \mathcal{V}_4' = \frac{1}{3} V_s. \tag{6.3}$$

## HQS breaking

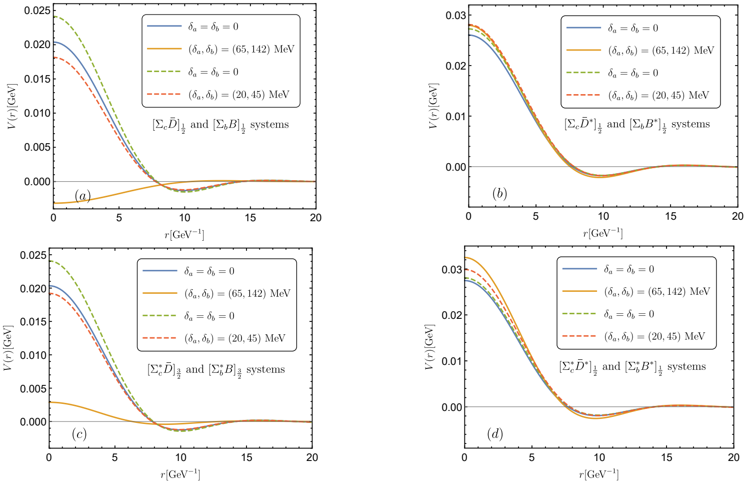



**Figure:** The heavy quark symmetry breaking phenomena in the two-pion-exchange diagrams. The solid lines denote the $\Sigma_c^{(*)}\bar{D}^{(*)}$ systems with vanishing mass splittings and physical mass splittings. The dashed lines represent the same cases but for the $\Sigma_b^{(*)}B^{(*)}$ systems.

Based on above work, we further study the effective potentials of six systems, i.e., $\Xi_c\bar{D}^{(*)}$, $\Xi_c'\bar{D}^{(*)}$ and $\Xi_c^*\bar{D}^{(*)}$. They all contain one strange quark.

Table: The predicted binding energies $\Delta E$ and masses $M$ for the $[\Xi_c'\bar{D}^{(*)}]_{\mathcal{J}}$, $[\Xi_c^*\bar{D}^{(*)}]_{\mathcal{J}}$ and $[\Xi_c\bar{D}^{(*)}]_{\mathcal{J}}$ systems in $I=0$ channel, where the subscript "$\mathcal{J}$" denotes the total spin of the system.

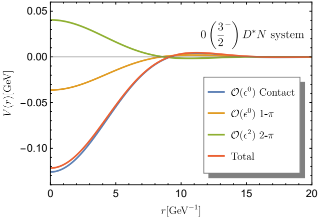
| System | $[\Xi_c'\bar{D}]_{\frac{1}{2}}$ | $[\Xi_c'\bar{D}^*]_{\frac{1}{2}}$ | $[\Xi_c'\bar{D}^*]_{\frac{3}{2}}$ | $[\Xi_c^*\bar{D}]_{\frac{3}{2}}$ | $[\Xi_c^*\bar{D}^*]_{\frac{1}{2}}$ | $[\Xi_c^*\bar{D}^*]_{\frac{3}{2}}$ | $[\Xi_c^*\bar{D}^*]^{\sharp}_{\frac{5}{2}}$ | $[\Xi_c\bar{D}]_{\frac{1}{2}}$ | $[\Xi_c\bar{D}^*]_{\frac{1}{2}}$ | $[\Xi_c\bar{D}^*]_{\frac{3}{2}}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $\Delta E$ | $-18.5^{+6.4}_{-6.8}$ | $-15.6^{+6.4}_{-7.2}$ | $-2.0^{+1.8}_{-3.3}$ | $-7.5^{+4.2}_{-5.3}$ | $-17.0^{+6.7}_{-7.5}$ | $-8.0^{+4.5}_{-5.6}$ | $-0.7^{+0.7}_{-2.2}$ | $-13.3^{+2.8}_{-3.0}$ | $-17.8^{+3.2}_{-3.3}$ | $-11.8^{+2.8}_{-3.0}$ |
| $M$ | $4423.7^{+6.4}_{-6.8}$ | $4568.7^{+6.4}_{-7.2}$ | $4582.3^{+1.8}_{-3.3}$ | $4502.9^{+4.2}_{-5.3}$ | $4635.4^{+6.7}_{-7.5}$ | $4644.4^{+4.5}_{-5.6}$ | $4651.7^{+0.7}_{-2.2}$ | $4319.4^{+2.8}_{-3.0}$ | $4456.9^{+3.2}_{-3.3}$ | $4463.0^{+2.8}_{-3.0}$ |

The predicted states can be reconstructed from the $J/\psi\Lambda$ final states in the decay modes $\Lambda_b(\Xi_b)\to J/\psi\Lambda K(\eta)$ [PRD 93, 094009; PRC 93, 065203].

## Preliminary results

$D^*N$ potential: short-, intermediate- and long-range interactions are simultaneously considered ($\Delta(1232)$ is included in the loops).

With the quark model: $NN$ interaction as the input to determine the LECs.




Only the $0\left(\frac{3}{2}^-\right)$ channel has binding solution, $\Delta E \simeq -5.7$ MeV, i.e., $m_{D^*N} \simeq 2939.4$, which is in good agreement with the Babar, Belle and LHCb data of $\Lambda_c(2940)$. For another possible explanation, see recent work: arXiv:1910.14545.

## Summary

- We predicted two $0(1^+)$ bound states in the $\bar{B}\bar{B}^*$ and $\bar{B}^*\bar{B}^*$ systems.
- LHCb reported three pentaquark states $P_c(4312)$, $P_c(4440)$ and $P_c(4457)$.
- We systematically investigate the $\Sigma_c^{(*)}$ and $\bar{D}^{(*)}$ interactions in chiral effective field theory without and with considering the $\Lambda_c$ contribution in the loop diagrams.
- Our calculation supports the $P_c(4312)$, $P_c(4440)$ and $P_c(4457)$ to be the $S$-wave hidden-charm $[\Sigma_c\bar{D}]^{I=1/2}_{\mathcal{J}=1/2}$, $[\Sigma_c\bar{D}^*]^{I=1/2}_{\mathcal{J}=1/2}$ and $[\Sigma_c\bar{D}^*]^{I=1/2}_{\mathcal{J}=3/2}$ hadronic molecules.
- Our calculation disfavors the spin assignment $\mathcal{J}^P = \frac{1}{2}^-$ for $P_c(4457)$ and $\mathcal{J}^P = \frac{3}{2}^-$ for $P_c(4440)$.
- We also study the hidden-bottom $\Sigma_b^{(*)}B^{(*)}$ systems, and predict seven bound molecular states.

- HQS breaking effect is nonnegligible in predicting the effective potentials between the charmed hadrons.
- Strange hidden-charm molecular pentaquarks are predicted.
- We find a isoscalar $[D^*N]_{3/2}$ bound state, which might correspond to the observed $\Lambda_c(2940)$.

**Thank you and happy new year!**