Strong decays of the $P_{cs}(4459)$ as a $\Xi_c \bar{D}^*$ molecule

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In this work, we study the strong decay of the newly observed $P_{cs}(4459)$, assuming that it is a pure $\Xi_c \bar{D}^*$ molecular state. Considering two possible spin-parity assignments $J^P = 1/2^−$ and $J^P = 3/2^−$, the partial decay widths of the $\Xi_c \bar{D}^*$ molecular state into $J/\psi \Lambda, D^*_1 \Lambda^*_c$, and $D \Xi_c$ final states through hadronic loops are evaluated with the help of the effective Lagrangians. In comparison with the LHCb data, the $S$-wave $\bar{D}^* \Xi_c$ molecular with $J^P = 1/2^−$ assignment for $P_{cs}(4459)$ is supported by our study, while the $P_{cs}(4459)$ in spin-parity $J^P = 3/2^−$ case may be explained as an $S$-wave coupled bound state with lager $\Xi_c \bar{D}^*$ component. In addition, the calculated partial decay widths with $J^P = 1/2^−$ $\Xi_c \bar{D}^*$ molecular state picture indicate that allowed decay mode, $\bar{D} \Xi_c$, may have the biggest branching ratio. The experimental measurements for this strong decay process could be a crucial test for the molecule interpretation of the $P_{cs}(4459)$.

molecular state, strong decay, effective Lagrangians

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1 Introduction

Thanks to the great progress of the experiment in the past several decades, many baryons that cannot be ascribed into 3-quark(qqq) configurations have been reported [1]. In particular, three narrow hidden-charm pentaquarks, namely $P_c(4312)$, $P_c(4440)$, and $P_c(4450)$, were observed by the LHCb Collaboration in the $J/\psi p$ invariant mass distributions of the $\Lambda_b \rightarrow J/\psi p K$ decay [2]. Very recently, a new possible strange hidden charm pentaquark $P_{cs}(4459)$ was reported by the LHCb Collaboration [3] in the $J/\psi \Lambda$ final state from the $\Xi_b^0 \rightarrow J/\psi \Lambda K^−$ process. The observed resonance masses and widths are

$$M = 4458.8 \pm 2.9^{+4.7}_{-1.1} \text{ MeV},$$
$$\Gamma = 17.3 \pm 6.5^{+8.0}_{-5.7} \text{ MeV},$$

respectively. From the observed decay mode, the isospin of this state is zero. Although the spin and parity remain undetermined, it is very helpful to understand the spectroscopy of the hidden-charm pentaquark.

Before the discovery of the $P_{cs}(4459)$ state, there were already a few theoretical studies on the existence of the strange hidden-charm pentaquarks [4-12]. And refs. [8, 9, 12] proposed to search for these strange hidden-charm pentaquarks states in $\Xi_b(\Lambda_b) \rightarrow J/\psi \Lambda \eta(K)$. In particular, Wang et al. [5] found two isoscalar $\Xi_c \bar{D}^*$ molecular states with the chiral ef-

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fective field theory; the masses were predicted considering the $\Xi_c D^*$ molecules for $J^P = 1/2^-$ and $J^P = 3/2^-$ as 4456.9 and 4463.0 MeV, respectively, which can be associated with the experimental $P_{c^+}(4459)$.

The observation of the $P_{c^+}(4459)$ inspires a large number of theoretical studies about its internal structure. The QCD sum rule suggests that the newly observed state of theoretical studies about its internal structure. The QCD spin of the $S$-wave $\bar{c} s$ antiquark with the spin parity $J^P = 1/2^-$ [13]. Based on the analysis of the two-body allowed strong decays $P_{c^+}(4459) \to J/\psi \Lambda$ with a similar method above but considering different details, the same conclusion was drawn from ref. [14] that $P_{c^+}(4459)$ can be understood as a compact pentaquark nature of diquark-diquark-antiquark form.

Because the mass is just 19 MeV below the $\Xi_c D^*$ threshold, the recent observation of $P_{c^+}(4459)$ also favors the molecular state interpretations of the hidden-charm pentaquarks. Indeed, the $\Xi_c D^*$ molecular explanation for the $P_{c^+}(4459)$ was discussed using effective field formalism, and the spin of the $P_{c^+}(4459)$ state was suggested to be $J = 3/2$ [15]. The molecular explanation for the $P_{c^+}(4459)$ was also studied in ref. [16] using QCD sum rule method, and the results supported its possibility to be a $\Xi_c D^*$ molecular state with either $J^P = 1/2^-$ or $J^P = 3/2^-$. By analyzing the spectroscopy using the one-boson-exchange model, refs. [17, 18] assigned the $P_{c^+}(4459)$ as a coupled bound states with spin-parity $J^P = 3/2^-$ instead of pure $\Xi_c D^*$ molecular. A possible explanation for these results of refs. [15-18] is that the $P_{c^+}(4459)$ has a predominant $\Xi_c D^*$ component and that the lager $\Xi_c D^*$ component makes the interaction between a $D^*$ meson and a $\Xi_c$ baryon strong enough to form a bound state with a mass roughly 4459 MeV [18]. This make it possible to search for the $P_{c^+}(4459)$ in the $\Xi_c^+ \to J/\psi \Lambda K^*$ by assuming the $P_{c^+}(4459)$ is a molecular mainly composed of $D^* \Xi_c$ [19].

Until now, the nature of the observed $P_{c^+}(4459)$ baryon remains unclear. In particular, the quantum numbers of the $P_{c^+}(4459)$ was not determined by the experiment, and from different studies, there are different assumptions for its quantum numbers and substructure. In this work, we will calculate the strong decay pattern of $S$-wave $\Xi_c D^*$ molecular state within the effective Lagrangian approach, and find the relation between the $D^* \Xi_c$ molecular state and the $P_{c^+}(4459)$ state by comparing with the LHCb observation. This idea is inspired by the allowed strong decay that will almost saturate its total decay width.

2 Theoretical formalism

In this work, we study the strong decay widths $P_{c^+} \to J/\psi \Lambda, D\Xi_c^+$, and $D^*_c \Lambda_c^+$ in the molecular scenario with different spin-parity assignments for the $P_{c^+}$. The Feynman diagrams for the hadronic decay of the $\Xi_c D^*$ molecular state into $J/\psi \Lambda, D\Xi_c^+$ and $D^*_c \Lambda_c^+$ mediated by the exchange of the $\pi$, $K^{(*)}$, and $D^{(*)}$ mesons are shown in Figure 1.

To compute the diagrams shown in Figure 1, we need the effective Lagrangian densities for the relevant interaction vertices. As mentioned above, the $P_{c^+}(4459)$ resonance is identified as an $S$-wave $\Xi_c D^*$ molecule. The molecular structure of the $P_{c^+}(4459)$ baryon with $J^P = 1/2^-$ is described by the following Lagrangian [20]:

\[
\mathcal{L}_{P_{c^+},\Xi_c D^*} = g_{P_{c^+}} P_{c^+}(x) y^5 \times \int \phi(y^2) \sum C_i \Xi_c(x + \omega \Lambda y) \xi_p(x - \omega \Xi_c y), \quad (2)
\]

while for $J^P = 3/2^-$ the Lagrangian contains a derivative $D^* \Xi_c$ coupling [20]

\[
\mathcal{L}_{P_{c^+},\Xi_c D^*} = -i g_{P_{c^+}} P_{c^+}(x) \times \int \phi(y^2) \sum C_i \Xi_c(x + \omega \Lambda y) \xi_p(x - \omega \Xi_c y), \quad (3)
\]

where $\omega = m_i/(m_i + m_j)$. In the above Lagrangians, the effective correlation function $\Phi(y^2)$ shows the distribution of the components in the hadronic molecule $P_{c^+}(4459)$ state. Moreover, the role of the correlation function $\Phi(y^2)$ is also to avoid the Feynman diagram’s ultraviolet divergence, and his Fourier transform should vanish quickly in the ultraviolet region in the Euclidean space. We adopt the form as used in refs. [21, 22]

\[
\Phi(-p^2) = \exp(-p_E^2/\Lambda^2), \quad (4)
\]

where $p_E$ is the Euclidean Jacobi momentum. At present, the value of $\Lambda$ still could not be accurately determined from first principles, and therefore, it better determined by experimental data.

The experimental total widths of some states [21-27]
that can be considered as molecules can be well explained with $\Lambda = 1.0$ GeV. We therefore assume $\Lambda = 1.0$ GeV in this work to study whether the $P_{cs}(4459)$ can be interpreted as a molecule composed of $D^* \Xi_c$.

The coupling constants $g_{P_i}$ in eqs. (2) and (3) can be calculated by employing the compositeness condition [28-32]. This condition requires that the renormalization constant of the hadronic molecular wave function is equal to zero

$$1 - \frac{d \Sigma_{P_i}}{dk_0} |_{k_0=m_{P_i}} = 0, \quad j = \frac{1}{2},$$

$$1 - \frac{d \Sigma_{P_i}^*}{dk_0} |_{k_0=m_{P_i}} = 0, \quad j = \frac{3}{2},$$

where $k_0^2 = m_{P_i}^2$ with $m_{P_i}$ denotes the four momenta and the mass of the $P_{cs}(4459)$, respectively. Here, we set $m_{P_{cs}} = m_{\Xi_c} + m_{D^*} - E_0$ with $m_{\Xi_c}$, $m_{D^*}$, with $E_0$ being the mass of the components $\Xi_c$, $D^*$, and the binding energy of $P_{cs}(4459)$, respectively. The $\Sigma_{P_i}$ is the self-energy of the hadronic molecule $P_{cs}(4459)$, and the $\Sigma_{P_i}^*$ is the transverse part of the self-energy operator $\Sigma_{P_i}^*$ related to $\Sigma_{P_i}$ via

$$\Sigma_{P_i}^{\mu\nu} = \left( g_{P_i} \frac{k_0^{\mu} k_0^{\nu}}{k_0^2} \right) \Sigma_{P_i} + \cdots.$$  

(7)

The Feynman diagram describing the self-energy of the $P_{cs}(4459)$ state is presented in Figure 2. With the effective Lagrangians in eqs. (2) and (3), we can compute the Feynman diagrams shown in Figure 2, and obtain the self-energy of the $P_{cs}(4459)$,

$$\Sigma_{P_i}^{1/2} = \sum_i C_i g_{P_i}^2 \int \frac{d^4 k}{(2\pi)^4} \Phi^2 \left[(p_\omega + q_\omega \Xi_c)^2\right] \gamma^\mu \gamma^5$$

$$\times \left[ \frac{i (\bar{\phi} + m_{\Xi_c})^2}{\not{k}^2 - m_{\Xi_c}^2} \gamma^\nu + \frac{i (g^{\mu\nu} + q^{\mu} q^{\nu} / m_{D^*}^2)}{q^2 - m_{D^*}^2} \right],$$  

(8)

$$\Sigma_{P_i}^{3/2} = \sum_i C_i g_{P_i}^2 \int \frac{d^4 q}{(2\pi)^4} \Phi^2 \left[(p_\omega + q_\omega \Xi_c)^2\right]$$

$$\times \left[ \frac{i (\bar{\phi} + m_{\Xi_c})^2}{\not{k}^2 - m_{\Xi_c}^2} \gamma^\nu + \frac{i (g^{\mu\nu} + q^{\mu} q^{\nu} / m_{D^*}^2)}{q^2 - m_{D^*}^2} \right],$$  

(9)

where isospin symmetry implies that

$$C_i = \begin{cases} 
-1 / \sqrt{2}, & \text{if } \Xi_c^0 D^0, \\
1 / \sqrt{2}, & \text{if } \Xi_c^+ D^-, \end{cases}$$

(10)

with the following isospin assignments for the $\Xi_c$ and $D^*$:

$$\begin{pmatrix} \Xi_c^+ \\ \Xi_c^0 \end{pmatrix} \sim \begin{pmatrix} \frac{1}{2}, & \frac{1}{2} \end{pmatrix}, \quad \begin{pmatrix} D^0 \end{pmatrix} \sim \begin{pmatrix} -\frac{1}{2}, & -\frac{1}{2} \end{pmatrix}.$$  

(11)

To compute the amplitudes of the diagrams shown in Figure 1, the effective Lagrangian densities related to the final state are required, which are [33]

$$L_{P_{BB}} = \frac{ig}{2\sqrt{2}} (\bar{\phi}^\mu P_\nu (V_\mu - V_\nu)),$$

(12)

$$L_{V_{BB}} = \frac{g'}{\sqrt{2}} (\bar{\phi}^\mu \partial_\nu (\bar{V}_\mu V_\nu \partial_\lambda V_{\nu\lambda} P_\nu),$$

(13)

$$L_{V_{VV}} = \frac{ig}{2\sqrt{2}} (\bar{\phi}^\mu V^\nu (\bar{V}_\mu V_\nu - V_\nu V_\mu)),$$

(14)

where the coupling constants are $G = 12.00$ and $G' = 55.51$. The symbol $V_\mu$ and $P$ represents the vector and pseudoscalar fields of the 16-plet of the $\rho$ and $\pi$ meson, respectively.

$$P = \begin{pmatrix} \frac{\pi^0 + \eta}{\sqrt{2}} + \frac{\eta'}{\sqrt{2}} & \pi^+ & K^+ & D^0 \\
\pi^- & -\frac{\eta^0}{\sqrt{2}} + \frac{\eta'}{\sqrt{2}} & K^0 & D^- \\
K^- & \bar{K}^0 & \frac{2\eta^0}{\sqrt{2}} + \frac{\eta'}{\sqrt{2}} & D^*_0 \\
D^0 & D^* & D^*_0 & -\frac{3\eta'}{\sqrt{2}} \end{pmatrix},$$

(15)

$$V = \begin{pmatrix} \frac{\rho^0 + \omega}{\sqrt{2}} + \frac{\omega'}{\sqrt{2}} & \rho^+ & K^+ & D^0 \\
\rho^- & -\frac{\omega^0}{\sqrt{2}} + \frac{\omega'}{\sqrt{2}} & K^0 & D^- \\
K^- & \bar{K}^0 & \frac{2\omega^0}{\sqrt{2}} + \frac{\omega'}{\sqrt{2}} & D^*_0 \\
D^0 & D^* & D^*_0 & -\frac{3\omega'}{\sqrt{2}} \end{pmatrix},$$

where $\omega_8 = \omega \cos \theta + \phi \sin \theta$ and $\sin \theta = -0.761$.

The SU(4) invariant interaction Lagrangians between baryons and pseudoscalar mesons as well as between baryons and vector mesons can be written, respectively, as [34]:

$$L_{P_{BB}} = ig_p (c \phi^{\mu\nu\gamma} \gamma_5 P_\mu \phi_{\lambda\nu\gamma} + b \phi^{\mu\nu\gamma} \gamma_5 P_\mu \phi_{\gamma\lambda\nu}),$$

(16)

$$L_{V_{BB}} = ig_c (c \phi^{\mu\nu\gamma} \gamma_5 V_\mu \phi_{\lambda\nu\gamma} + d \phi^{\mu\nu\gamma} \gamma_5 V_\mu \phi_{\gamma\lambda\nu}),$$

(17)

where $g_p$ and $g_c$ are universal baryon-pseudoscalar-meson and baryon-vector-meson coupling constants, and $a, b, c$, and $d$ are constants. In the SU(4) quark model, baryons belong to the 20-plet states [34]. These states can be conveniently expressed by tensors $\phi_{\mu\nu\lambda}$, where $\mu, \nu$, and $\lambda$ run from 1 to 4, and satisfy the conditions

$$\phi_{\mu\nu\lambda} + \phi_{\nu\lambda\mu} + \phi_{\lambda\mu\nu} = 0, \quad \phi_{\mu\nu\lambda} = \phi_{\mu\lambda\nu},$$

(18)

with

$$p = \phi_{112}, \quad n = \phi_{221}, \quad \Lambda = \sqrt{2}/3 (\phi_{121} - \phi_{312}),$$

$$\Sigma^+ = \phi_{113}, \quad \Sigma^0 = \sqrt{2} \phi_{123}, \quad \Sigma^- = \phi_{223},$$

Figure 2 (Color online) Self-energy of the $P_{cs}(4459)$ state.
where we know $c = \left(\frac{\sqrt{2}}{3}(p_2 - k_1)^2 \right)$.

Writing explicitly, we obtain the following interaction Lagrangians,

$$L_{\text{BB}} = \mathcal{L} = \frac{1}{2}\mathcal{F} \left( N \gamma_5 \tau \cdot \pi N \right) + \frac{3\sqrt{3}}{8} \mathcal{F} \left( N \gamma_5 K \Lambda + N \gamma_5 \bar{D} \Lambda_c + \cdots \right),$$

where we have $b/a = 5.3, d/c = 0.5, g_{\pi NN} = 13.5, g_{\pi NN} = 3.25$.

Putting all the pieces together, we obtain the following amplitudes:

$$M^{1/2}_{\text{BB}} = \mathcal{L} \left[ \frac{1}{4} \mathcal{F} \left( N \gamma_5 \tau \cdot \pi N \right) + \frac{3\sqrt{3}}{8} \mathcal{F} \left( N \gamma_5 K \Lambda + N \gamma_5 \bar{D} \Lambda_c + \cdots \right) \right]$$

and

$$M^{0/2}_{\text{BB}} = \mathcal{L} \left[ \frac{1}{4} \mathcal{F} \left( N \gamma_5 \tau \cdot \pi N \right) + \frac{3\sqrt{3}}{8} \mathcal{F} \left( N \gamma_5 K \Lambda + N \gamma_5 \bar{D} \Lambda_c + \cdots \right) \right]$$

where we have $b/a = 5.3, d/c = 0.5, g_{\pi NN} = 13.5, g_{\pi NN} = 3.25$.

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and

$$M^{0/2}_{\text{BB}} = \mathcal{L} \left[ \frac{1}{4} \mathcal{F} \left( N \gamma_5 \tau \cdot \pi N \right) + \frac{3\sqrt{3}}{8} \mathcal{F} \left( N \gamma_5 K \Lambda + N \gamma_5 \bar{D} \Lambda_c + \cdots \right) \right]$$

where we have $b/a = 5.3, d/c = 0.5, g_{\pi NN} = 13.5, g_{\pi NN} = 3.25$.
partial decay widths can be obtained, which read

$$\times \Phi \left( p_0 \omega_{p'} - q_0 \omega_{q'} \right)^2 \frac{1}{k_1^2 - m_{q'}^2} \left( p_2^2 - k_1^2 \right)$$

$$\times \frac{q'' + q' d^2/\left. m_{p''} \right|_{p''} + q'' + m_{q''} \right|_{q''}}{q^2 - m_{p''}^2} \mu^2(k_0), \tag{28}$$

$$\mathcal{M}_i^{P_{cs}^{3/2}} = \mathcal{M}_i \left( g_{P_{cs}^{3/2} \pi^0} \rightarrow g_{P_{cs}^{3/2} \eta} \right) \left( m_{P_{cs}^{3/2}} \rightarrow m_{\Xi^0} \right). \tag{29}$$

Once the amplitudes are determined, the corresponding partial decay widths can be obtained, which read

$$\Gamma(P_{cs} \rightarrow) = \int \frac{1}{2J + 1} \frac{1}{32\pi^2} \frac{1}{m_{P_{cs}}} |\mathcal{M}|^2 d\Omega, \tag{30}$$

where the $J$ is the total angular momentum of the $P_{cs}(4459)$, $|p_i|$ is the three-momenta of the decay products in the center of mass frame, the overline indicates the sum over the polarization vectors of the final hadrons. The $\Omega$ is the angle of the final particle in the rest frame of $P_{cs}(4459)$.

### 3 Results

In this work, we study the strong decays of the $P_{cs}(4459)$ to the two-body final states $J/\psi \Lambda$, $D^* \Lambda'$, and $D \Xi_c^-$, assuming that $P_{cs}(4459)$ is a $D^* \Xi_c$ molecular state. In order to obtain the two-body decay width through the triangle diagrams shown in Figure 1, we first need to compute the coupling constants $g_{P_{cs}}$ relevant to the effective Lagrangians listed in eqs. (2) and (3).

First, the coupling constants $g_{P_{cs}}$ versus the model parameter $\Lambda$ are computed. Taking a value of the cutoff $\Lambda=0.9$-1.1 GeV, the corresponding coupling constants are shown in Figure 3. The finding is that they decrease slowly with the increase of the $\Lambda$, and the coupling constants are almost independent of cutoff $\Lambda$ for the $J^P=1/2^-$ and $J^P=3/2^-$ cases, where the $P_{cs}(4459)$ is an $S$-wave $D^* \Xi_c$ molecular state. This is consistent with the conclusion in refs. [21-27] that for an $S$-wave loosely bound state the effective coupling strength of the bound state to its components is insensitive to its inner structure. The results also show that the coupling constant for $J^P=2/3^-$ case is bigger than that for the case of $J^P=1/2^-$.

According to the discussions in above section and studies in refs. [21-27], a typical value of $\Lambda = 1.0$ GeV is often employed. In this work we thus take $\Lambda = 1.0$ GeV and the corresponding coupling constants are listed in Table 1, which are used to calculate the decay processes of Figure 1.

With the obtained couplings $g_{P_{cs}}$, the total decay width of the $P_{cs}(4459)$ can be calculated straightforwardly. We show the dependence of the total decay width on the cutoff $\Lambda$ in Figure 4. The cyan bands in these plots denote the experimental data. In the present calculation, we vary $\Lambda$ from 0.9 to 1.1 GeV. In this cutoff range, the total decay width increases for the cases of $J^P=1/2^-$ and $J^P=3/2^-$. For the case of $J^P=3/2^-$, the predicted total decay width increases from 28.54 to 39.86 MeV and is slightly bigger than the experimental total width, which disfavors such a spin-parity assignment for the $P_{cs}(4459)$ in the $\Xi_c D^*$ molecular picture. In other words, the decay width of the observed $P_{cs}(4459)$ in $J^P=3/2^-$ case cannot be well reproduced in a pure $D^* \Xi_c$ molecular state picture. Following the strategy in ref. [35], the $P_{cs}(4459)$ may be a meson-baryon molecule with a larger $D^* \Xi_c$ component. This is the same as the results by Chen et al. [17, 18] that the $P_{cs}(4459)$ can be explained as an $S$-wave coupled bound states with spin-parity $J^P=3/2^-$. 

![Figure 3](image-url) (Color online) The coupling constants of the $P_{cs}(4459)$ state with different $J^P$ assignments are as a function of the parameter $\Lambda$.

| $J^P$ | $g_{P_{cs}}$ |
|-------|------------|
| $1/2^-$ | 1.62 |
| $3/2^-$ | 2.81 |

Table 1 Coupling constants $g_{P_{cs}}$ for different $J^P$ states with $\Lambda = 1.0$ GeV.

![Figure 4](image-url) (Color online) Partial decay widths of the $P_{cs}(4459)$ as a function of the parameter $\Lambda$. The cyan bands denote the experimental total width [3].
The $J^P = 1/2^-$ assignment is favored by our study. However, in this case the $D^* \Xi_c$ molecular state should be in an $S$-wave. Hence, only the assignment as an $S$-wave $\Xi_c D^*$ molecular state with $J^P = 1/2^-$ is possible for the $P_{cs}(4459)$, based on the total decay width experimentally measured.

We also show the partial decay widths of the $P_{cs} \to \Xi_c \bar{D}$, $P_{cs} \to J/\psi \Lambda$, $P_{cs} \to \Lambda_c^+ D^*$, and $P_{cs} \to \Xi_c \bar{D}$ as a function of the cutoff $\Lambda$ in Figure 4. The two-body decays are not very sensitive to the cutoff parameter $\Lambda$. We find that the transition $P_{cs} \to \Xi_c \bar{D}$ is the main decay channel for the $J^P = 1/2^-$ case, even though the phase space is small compared with the other three channels. The dominant $P_{cs} \to \Xi_c \bar{D}$ decay can be easily understood because there is an enhancement due to the mass of the $\Xi_c \bar{D}$ very close to the $\Xi_c D^*$ threshold. The more important reason is that the long-range $\pi$-meson exchange plays an indispensable role compared with the other boson exchanges in the interaction between the hadrons. Only a $\pi$-meson exchange contribution is allowed when studying the nuclear force [36].

The interference among the individual contributions is sizable, leading to a total decay width bigger than the partial decay widths in the case of $J^P = 3/2^-$. It is the exact opposite of the case of spin parity $J^P = 1/2^-$. We take the $P_{cs} \to J/\psi \Lambda$ as an example and the results are shown in Figure 5. This also demonstrates that the $\Gamma[P_{cs} \to J/\psi \Lambda]$ is the largest for the $J^P = 3/2^-$ case, while for the $J^P = 1/2^-$ case the transition $P_{cs} \to J/\psi \Lambda$ gives minor contributions.

To sum up, the $S$-wave $D^* \Xi_c$ molecular with $J^P = 1/2^-$ assignment for $P_{cs}(4459)$ is supported by our study, while the $P_{cs}(4459)$ in spin-parity $J^P = 3/2^-$ case may be explained as an $S$-wave coupled bound state with lager $\Xi_c D^*$ component. It is worth noting that the $P_{cs}(4459)$ can also be considered as a compact pentaquark state [13, 14]. Theoretical investigations on other decay modes and further experimental information on its spin parities and partial decay widths will be very helpful to understand the nature of the $P_{cs}(4459)$.

![Figure 5](coloronline) Individual contributions of the $D^*$ and $D^{**}$ exchange for the $P_{cs} \to J/\psi \Lambda$ reaction depending on the parameter $\Lambda$. The red dot and blue dash lines stand for the $D^*$ and $D^{**}$ contributions, respectively.

4 Summary

We studied the strong decays of the newly observed $P_{cs}(4459)$ baryon into $J/\psi \Lambda$, $D^*_c \Lambda_c^+$, and $\bar{D}\Xi_c^{(*)}$ with different spin-parity assignments, assuming that it is a $D^* \Xi_c$ molecular structure. With the coupling constants between the $P_{cs}(4459)$ and its components determined by the composition condition, we calculated the partial decay widths into $J/\psi \Lambda$, $D^*_c \Lambda_c^+$, and $\bar{D}\Xi_c^{(*)}$ final states through triangle diagrams in an effective Lagrangian approach. In such a picture, the decays $P_{cs} \to \Xi_c \bar{D}$, $P_{cs} \to J/\psi \Lambda$, $P_{cs} \to \Lambda_c^+ D^*$, and $P_{cs} \to \Xi_c \bar{D}$ occur by exchanging $\pi$, $D^{(*)}$, and $K^{(*)}$ mesons. We found that the total decay width can be reproduced with the assumption that the $P_{cs}(4459)$ is an $S$-wave $D^* \Xi_c$ molecular with $J^P = 1/2^-$ assignment, while the $P_{cs}(4459)$ in spin-parity $J^P = 3/2^-$ case maybe explained as an $S$-wave coupled bound state with lager $\Xi_c D^*$ component. Our study shows that the experimental measurement of the spin-parity and the $\bar{D}\Xi_c$ decay width of the $P_{cs}(4459)$ will be able to tell whether it is a pure $D^* \Xi_c$ molecular state, coupled bound state with lager $\Xi_c D^*$ component, or a compact pentaquark state.
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