The effect of the short-range contribution of one-boson model on the hadronic molecular picture for pentaquarks

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In collaborating with X.-K. Dong, Y.-H. Lin, F.-K. Guo, K. Yuki and B.-S. Zou

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Outline

- Review of works for P_c pentaquarks
- Theoretical framework
  - Scattering matrix from Schrödinger equation
  - One-boson exchange model
- Results
  - P_c
  - $P_{\bar{c}s}$
  - $P_{ccs\bar{s}}$
- Summary

Earlier Predictions of P_c

- In 2010-2012, hidden-charm pentaquarks were predicted in the charmed meson-baryon interaction.

- Masses below the $\overline{D}\Sigma_c, \overline{D}^*\Sigma_c$ thresholds.
- $\overline{D}^{(*)}\Sigma_c^{(*)}, \overline{D}^{(*)}\Lambda_c, \eta_c N, J/\psi N$ channels relevant due to having the same quark flavors.
- Unstable bound states in $\overline{D}^{(*)}\Sigma_c^{(*)}$ system produced via strong interaction parameterized by light-meson exchange.
- $J/\psi p$ channel is the lowest decay channel and appropriate for detecting P_c.

- J.-J. Wu, R. Molina, E. Oset, and B. S. Zou, Phys.Rev.Lett. 105 (2010) 232001
- J.-J. Wu, T. S. H. Lee, and B. S. Zou, Phys. Rev. C 85, 044002 (2012)

TABLE III. The pole position ($M - i\Gamma/2$) and "binding energy" ($\Delta E = E_{\rm thr} - M$) for different cutoff parameters Λ and spin-parity J^P. The threshold $E_{\rm thr}$ is 4320.79 MeV of $\bar{D}\Sigma_c$ in the *PB* system and 4462.18 MeV of $\bar{D}^*\Sigma_c$ in the *VB* system. The unit for the listed numbers is MeV.

J^P	Λ	*PB* system		*VB* system	
		$M - i\Gamma/2$	ΔE	$M - i\Gamma/2$	ΔE
$\frac{1}{2}^-$	650	–	–	–	–
	800	–	–	$4462.178 - 0.002i$	0.002
	1200	$4318.964 - 0.362i$	1.826	$4459.513 - 0.417i$	2.667
	1500	$4314.531 - 1.448i$	6.259	$4454.088 - 1.662i$	8.092
	2000	$4301.115 - 5.835i$	19.68	$4438.277 - 7.115i$	23.90
$\frac{3}{2}^-$	650	–	–	–	–
	800	–	–	$4462.178 - 0.002i$	0.002
	1200	–	–	$4459.507 - 0.420i$	2.673
	1500	–	–	$4454.057 - 1.681i$	8.123
	2000	–	–	$4438.039 - 7.268i$	23.14

- Z.-C. Yang, Z.-F. Sun, J. He, X. Liu, and S.-L. Zhu, Chin. Phys.C 36, 6 (2012)

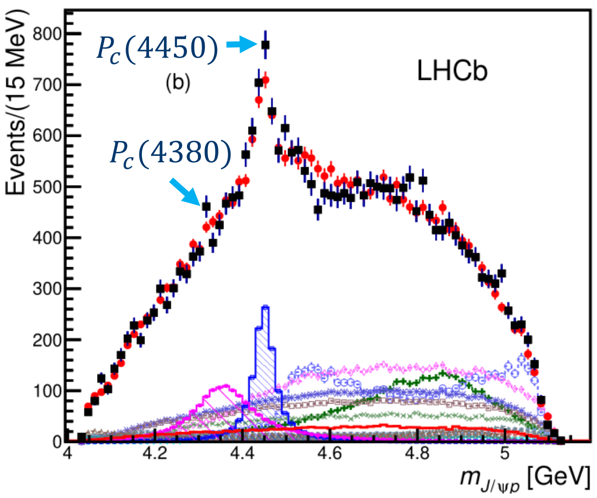
Abstract: Using the one-boson-exchange model, we studied the possible existence of very loosely bound hidden-charm molecular baryons composed of an anti-charmed meson and a charmed baryon. Our numerical results indicate that the $\Sigma_c\bar{D}^*$ and $\Sigma_c\bar{D}$ states exist, but that the $\Lambda_c\bar{D}$ and $\Lambda_c\bar{D}^*$ molecular states do not.

P_c in the experiment

- In 2015, the first evidence of P_c captured by LHCb in the analysis of $J/\psi p$ invariant mass spectrum in $\Lambda_b^0 \to K^- J/\psi p$ decay.

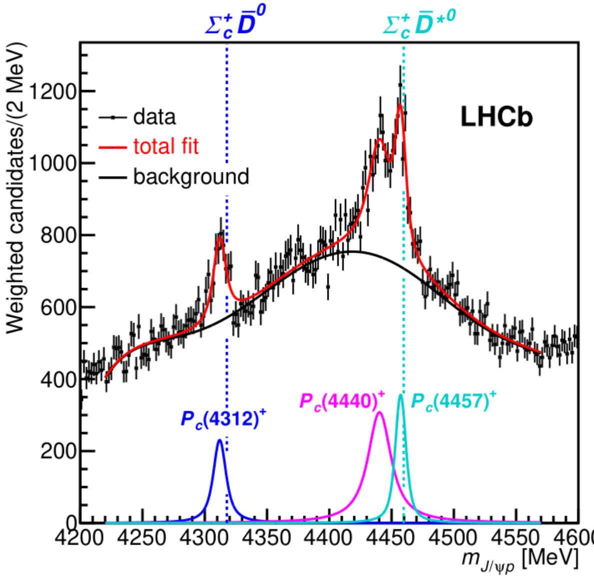
R. Aaij et al. (LHCb), Phys. Rev. Lett. 115, 072001 (2015)

State	Mass [MeV]	Width [MeV]
$P_c(4380)$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 89$
$P_c(4450)$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$



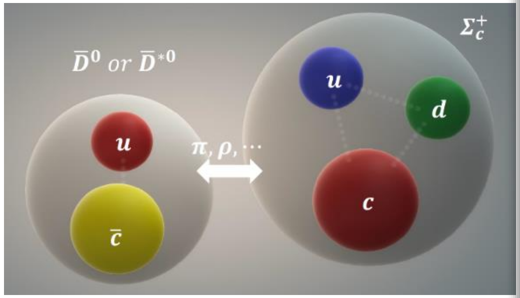
- In 2019, both of $P_c(4380)$ & $P_c(4450)$ could not survive at the LHCb experiment with higher luminosity. Another 3 new P_c states are reported. R. Aaij et al. (LHCb), Phys. Rev. Lett. 122, 222001 (2019)

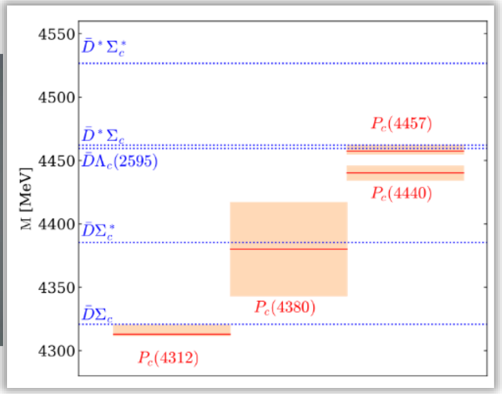
State	Mass [MeV]	Width [MeV]
$P_c(4312)$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$
$P_c(4440)$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$
$P_c(4457)$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$



Interpretation of P_c

- Hadronic molecules
  - Loosely unstable bound state, binding energy about 2-20 MeV, light mesons transmit the strong interaction.
  - Mass region covers several thresholds, coupled channel dynamics may be important for binding.
  - Spin-parity assignment: $1/2^-(\bar{D}\Sigma_c)$ for $P_c(4312)$, $1/2^-$ or $3/2^-$ $(\bar{D}\Sigma_c)$ for $P_c(4440)$ and $P_c(4457)$.





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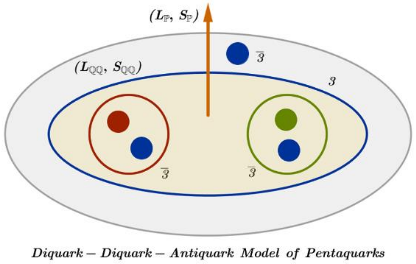

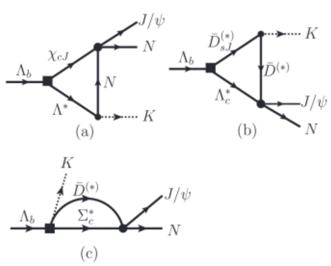

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Our related works

- P_c $qqqc\bar{c}$ q stands u or d
  - $\bar{D}\Sigma_c$, $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$, $\bar{D}^*\Sigma_c^*$, $\bar{D}\Lambda_c(2595)$
  - Mass region at $M \sim 4.3 - 4.5$GeV

N. Yalikun, Y.-H. Lin, F.-K. Guo K. Yuki and B.-S. Zou, *"Coupled-channel effects of the $\Sigma_c^{(*)}\bar{D}^{(*)} - \Lambda_c(2595)\bar{D}$ system and molecular nature of the Pc pentaquark states from one-boson exchange model"*, Phys.Rev.D 104 (2021) 9, 094039

- $P_{\bar{c}s}$ $qqqs\bar{c}$
  - $D_s^- N$, $\bar{D}\Lambda$, $\bar{D}^*\Lambda$, $\bar{D}^*\Sigma$, $\bar{D}\Sigma$
  - Mass region at $M \sim 3.0 - 3.2$GeV

N. Yalikun and B.-S. Zou, *"Anticharmed strange pentaquarks from the one-boson-exchange model"*, Phys.Rev.D 105 (2022) 9, 094026

- $P_{ccs\bar{s}}$ $qccs\bar{s}$
  - $D_s^+\Xi_c$, $D_s^{*+}\Xi_c$, $D_s^+\Xi_c'$, $D_s^{*+}\Xi_c'$, $D_s^+\Xi_c^*$, $D_s^{*+}\Xi_c^*$
  - Mass region at $M \sim 4.4 - 4.7$GeV

N. Yalikun and B.-S. Zou, *"Molecular states in $D_s^{(*)}\Xi_c^{(\prime,*)}$ systems"*, e-Print: 2303.03629

Theoretical framework

- Scattering matrix from Schrödinger equation
- One-boson exchange model

Non-relativistic scattering

- Scattering described by time-independent Schrödinger equation:

$$\left[-\frac{\hbar^2}{2\mu}\frac{d^2}{dr^2}+\frac{\hbar^2 l(l+1)}{2\mu r^2}+W\right]u+Vu=Eu$$

1. J. R. Taylor, Scattering Theory: *The Quantum Theory on Non-relativistic Collisions* (New York, 1972)
2. J. J. Sakurai, *Modern Quantum Mechanics*, 2ed addison(Wesley, 2011)

- For given energy E, solution can be expressed as a superposition of in and out plane waves,

$$u(r)=A(q)h^-(qr)+B(q)h^+(qr)$$

Hankel function

	$l=0$	$l=1$	$l=2$
$h_l^+(z)$	e^{iz}	$(1+i/z)\,e^{i(z-\pi/2)}$	$(1+3i/z-3/z^2)\,e^{i(z-\pi)}$
$h_l^-(z)$	e^{-iz}	$(1-i/z)\,e^{-i(z-\pi/2)}$	$(1-3i/z-3/z^2)\,e^{-i(z-\pi)}$

- For the potential $V(r\to\infty)\to 0$, asymptotic form of the wave function:

$$u(r)\xrightarrow{r\to\infty}h^-(qr)-S(q)h^+(qr)$$

Scattering matrix $S(q)=-\frac{B(q)}{A(q)}$

- Channel momentum $q=\sqrt{2\mu(E-W)}$.

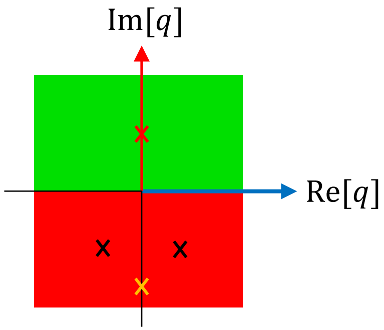
Analytic S matrix

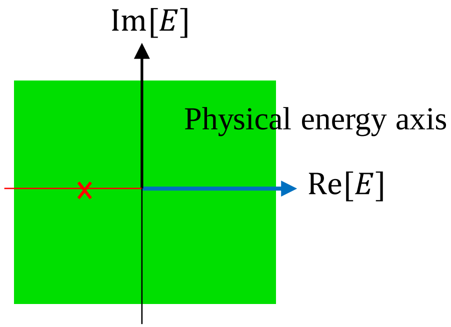
- $q = \sqrt{2\mu(E - W)}$ is multi-valued function of E, each E corresponds to two value of q, thus scattering matrix $S(q)$ can be analytically continued to two complex energy plane

- Distinguish the two Riemann sheets(RSs) by imaginary part of q, i.e. $\text{Im}[q] \geq 0$ corresponds to 1st RS, $\text{Im}[q] < 0$ corresponds to 2nd RS.

- Thus, S matrix at two RSs defined by

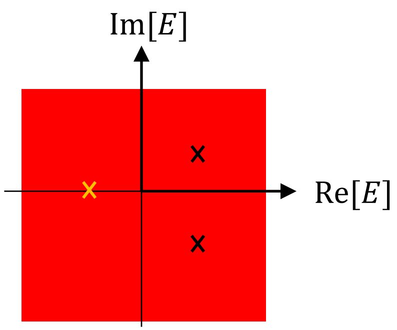
$$S^{\text{RS-I}} = S(q),$$
$$S^{\text{RS-II}} = S(-q).$$





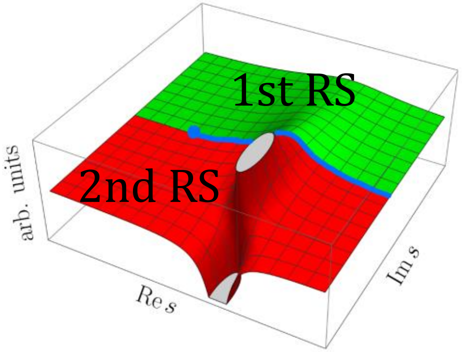
1st RS

X Bound state
X Resonance
X Virtual state



2nd RS

- Above the threshold, lower-half plane of 2nd RS is smoothly connected to physical energy axis, and resonance pole on it can cause a structure of the scattering amplitude.



Coupled channel S matrix

- For multi-channel scattering, coupled-channel Schrödinger equation is

$$\left[-\frac{\hbar^2}{2\mu_j}\frac{d^2}{dr^2}+\frac{\hbar^2 l_j(l_j+1)}{2\mu_j r^2}+W_j\right]u_j+\sum_{k\leq j}V_{jk}\,u_k=Eu_j\,.$$

J. R. Taylor, Scattering Theory: *The Quantum Theory on Non-relativistic Collisions* (New York, 1972)

- Wave functions of jth channel satisfying the αth boundary condition:

$$u_j^\alpha(r)=A_j^\alpha(q_j)h^-(q_j r)+B_j^\alpha(q_j)h^+(q_j r),$$

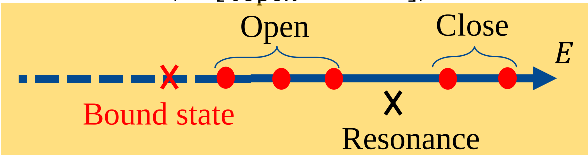
with αth boundray condition: $u_j^\alpha(0)=0,\ \frac{\partial}{\partial r}u_j^\alpha(r)\Big|_{r=0}=\delta_j^\alpha.$

- Asymptotic form:

$$u_j^\alpha(r)\xrightarrow{r\to\infty}h^-(q_j r)-S_j^\alpha(q_j)h^+(q_j r),$$

$$S(q)=-A(q)^{-1}B(q)$$

- For n channels system, each channel momentum $q_j(E)=\sqrt{2\mu_j(E-W_j)}$ defines two RSs, thus there are 2^n RSs in this case.
  - Bound state corresponds to the pole at the 1st RS (all $q_j(E)$ take positive values).
  - Resonance corresponds to the pole between open-channels ($\mathrm{Im}[q_{\mathrm{open}}(E)<0]$) and close-channels ($\mathrm{Im}[q_{\mathrm{close}}(E)<0]$)
  - Virtual state corresponds to other pole.



One-boson exchange model

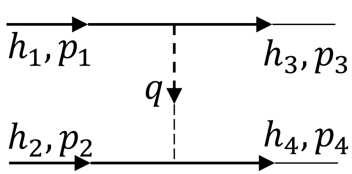
- Strong interaction at low energy parameterized by light meson exchange:

$$\sigma,\quad \mathbb{P}=\begin{pmatrix} \frac{\pi^0}{\sqrt{2}}+\frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}}+\frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix},\quad \mathbb{V}=\begin{pmatrix} \frac{\rho^0}{\sqrt{2}}+\frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}}+\frac{\omega}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}$$

$J^P=0^+$ $\quad$ $J^P=0^-$ $\quad$ $J^P=1^-$

- Potential from t-channel scattering amplitude

$$V(\boldsymbol{q})=-\frac{M^{h_1h_2\to h_3h_4}}{\sqrt{2m_1 2m_2 2m_3 2m_4}},$$



Chen H X, Chen W, Liu X, et al. Phys.Rept. 639 (2016) 1-121

Kinematics

$p_1=(E_1,\boldsymbol{p}), p_2=(E_2,-\boldsymbol{p}),$

$p_3=(E_3,\boldsymbol{p}'), p_4=(E_4,-\boldsymbol{p}')$

$q=\mathrm{p}_3-p_1=p_2-p_4=(q^0,\boldsymbol{q})$

$$\frac{|\boldsymbol{p}|}{m_i}\ll 1\to q^0=\frac{m_2^2-m_1^2+m_3^2-m_4^2}{2(m_3+m_4)}$$

- For the meson-baryon system each containing a heavy quark

$$\begin{aligned}\mathcal{L}_{\rm eff}=&\ l_S\bar{S}_{a\mu}\sigma S_a^\mu-\frac{3}{2}g_1\varepsilon_{\mu\nu\lambda\kappa}v^\kappa\bar{S}_{ab}^\mu A_{bc}^\nu S_{ca}^\lambda+i\beta_S\bar{S}_{ab\mu}v_\alpha(\Gamma_{bc}^\alpha-\rho_{bc}^\alpha)S_{ca}^\mu+\lambda_S\bar{S}_{ab\mu}F^{\mu\nu}(\rho_{bc})S_{ca\nu}\\ &-ih_2[\bar{S}_{ab}^\mu v\cdot A_{bc}R_{ca\mu}+\bar{R}_{ab}^\mu v\cdot A_{cb}S_{ca\mu}]+h_3\varepsilon_{\mu\nu\lambda\kappa}iv^\kappa[\bar{S}_{ab}^\mu(\Gamma_{bc}^\nu-\rho_{bc}^\nu)R_{ca}^\lambda+\bar{R}_{ab}^\mu(\Gamma_{bc}^\nu-\rho_{bc}^\nu)S_{ca}^\lambda]\\ &+g_S{\rm Tr}[\bar{H}_a^{\bar{Q}}\sigma H_a^{\bar{Q}}]+ig{\rm Tr}[\bar{H}_a^{\bar{Q}}\gamma\cdot A_{ab}\gamma^5H_b^{\bar{Q}}]-i\beta{\rm Tr}[\bar{H}_a^{\bar{Q}}v_\mu(\Gamma_{ab}^\mu-\rho_{ab}^\mu)H_b^{\bar{Q}}]\\ &+i\lambda{\rm Tr}\left[\bar{H}_a^{\bar{Q}}\frac{i}{2}[\gamma_\mu,\gamma_\nu]F^{\mu\nu}(\rho_{ab})H_b^{\bar{Q}}\right],\end{aligned}$$

- P. L. Cho, Phys. Rev. D 50, 3295 (1994).
- D. Pirjol and T.-M. Yan, Phys. Rev. D 56, 5483 (1997).
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OBE potentials: $V_{\rm s}+V_{\rm ps}+V_{\rm v}$

$$V_{\rm s}(\boldsymbol{q})\to\frac{\boldsymbol{O}_1\cdot\boldsymbol{O}_2}{\boldsymbol{q}^2+m^2}$$

$$V_{\rm ps}(\boldsymbol{q})\to\frac{\boldsymbol{O}_1\cdot\boldsymbol{q}\boldsymbol{O}_2\cdot\boldsymbol{q}}{\boldsymbol{q}^2+m^2}$$

$$V_{\rm v}(\boldsymbol{q})\to\frac{\boldsymbol{O}_1\cdot\boldsymbol{O}_2}{\boldsymbol{q}^2+m^2}-\frac{(\boldsymbol{O}_1\times\boldsymbol{q})\cdot(\boldsymbol{O}_2\times\boldsymbol{q})}{\boldsymbol{q}^2+m^2}$$

Short-range contribution

F.-L. Wang and X. Liu, Phys. Rev. D 102, 094006 (2020)

- Position space potentials by Fourier transformation

$$V_{\rm ex}(\boldsymbol{r},\Lambda) = \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} V_{\rm ex}(\boldsymbol{q}) F^2(\boldsymbol{q},\Lambda) e^{i\boldsymbol{q}\cdot\boldsymbol{r}},$$

The form factor $F(q,\Lambda) = \frac{\Lambda^2 - m^2}{\Lambda^2 - q^2}$ describes the size of the vertex, where Λ phenomenological parameter.

$$\frac{\boldsymbol{O}_1 \cdot \boldsymbol{O}_2}{\boldsymbol{q}^2 + m^2} \xrightarrow{F} \mathrm{Y}(\mathrm{r},\Lambda,m)\boldsymbol{O}_1 \cdot \boldsymbol{O}_2$$

$S(O_1,O_2,\boldsymbol{q}) = 3\boldsymbol{O}_1 \cdot \boldsymbol{q}\boldsymbol{O}_2 \cdot \boldsymbol{q} - \boldsymbol{q}^2\boldsymbol{O}_1 \cdot \boldsymbol{O}_2)$

$$\frac{\boldsymbol{O}_1 \cdot \boldsymbol{q}\boldsymbol{O}_2 \cdot \boldsymbol{q}}{\boldsymbol{q}^2 + m^2} = \frac{1}{3}\left[\frac{\boldsymbol{q}^2}{\boldsymbol{q}^2 + m^2}\boldsymbol{O}_1 \cdot \boldsymbol{O}_2 + \frac{\boldsymbol{1}}{\boldsymbol{q}^2 + m^2} S(\boldsymbol{O}_1,\boldsymbol{O}_2,\boldsymbol{q})\right] \xrightarrow{F} \mathrm{C}(\mathrm{r},\Lambda,m,a)\boldsymbol{O}_1 \cdot \boldsymbol{O}_2 + \mathrm{T}(r,\Lambda,m) S(\boldsymbol{O}_1,\boldsymbol{O}_2,\hat{r})$$

$$1 - \frac{m^2}{\boldsymbol{q}^2 + m^2} \to 1 - a - \frac{m^2}{\boldsymbol{q}^2 + m^2}$$

Leads $\delta(r)$-term after Fourier transformation

$$\frac{(\boldsymbol{O}_1 \times \boldsymbol{q}) \cdot (\boldsymbol{O}_2 \times \boldsymbol{q})}{\boldsymbol{q}^2 + m^2} \xrightarrow{F} 2\mathrm{C}(\mathrm{r},\Lambda,m,a)\boldsymbol{O}_1 \cdot \boldsymbol{O}_2 - \mathrm{T}(r,\Lambda,m) S(\boldsymbol{O}_1,\boldsymbol{O}_2,\hat{r})$$

OBE potentials: $V_{\rm s} + V_{\rm ps} + V_{\rm v}$

$$V_{\rm s} \to \mathrm{Y}(\mathrm{r},\Lambda,m_s)\boldsymbol{O}_1 \cdot \boldsymbol{O}_2$$

$$V_{\rm ps} \to \mathrm{C}(\mathrm{r},\Lambda,m_{\rm ps},a)\boldsymbol{O}_1 \cdot \boldsymbol{O}_2 + \mathrm{T}(r,\Lambda,m_{\rm ps}) S(\boldsymbol{O}_1,\boldsymbol{O}_2,\hat{r})$$

$$V_{\rm v} \to \mathrm{Y}(\mathrm{r},\Lambda,m_{\rm v})\boldsymbol{O}_1 \cdot \boldsymbol{O}_2 - 2\mathrm{C}(\mathrm{r},\Lambda,m_{\rm v},a)\boldsymbol{O}_1 \cdot \boldsymbol{O}_2 + \mathrm{T}(r,\Lambda,m_{\rm v}) S(\boldsymbol{O}_1,\boldsymbol{O}_2,\hat{r})$$

Short-range contribution

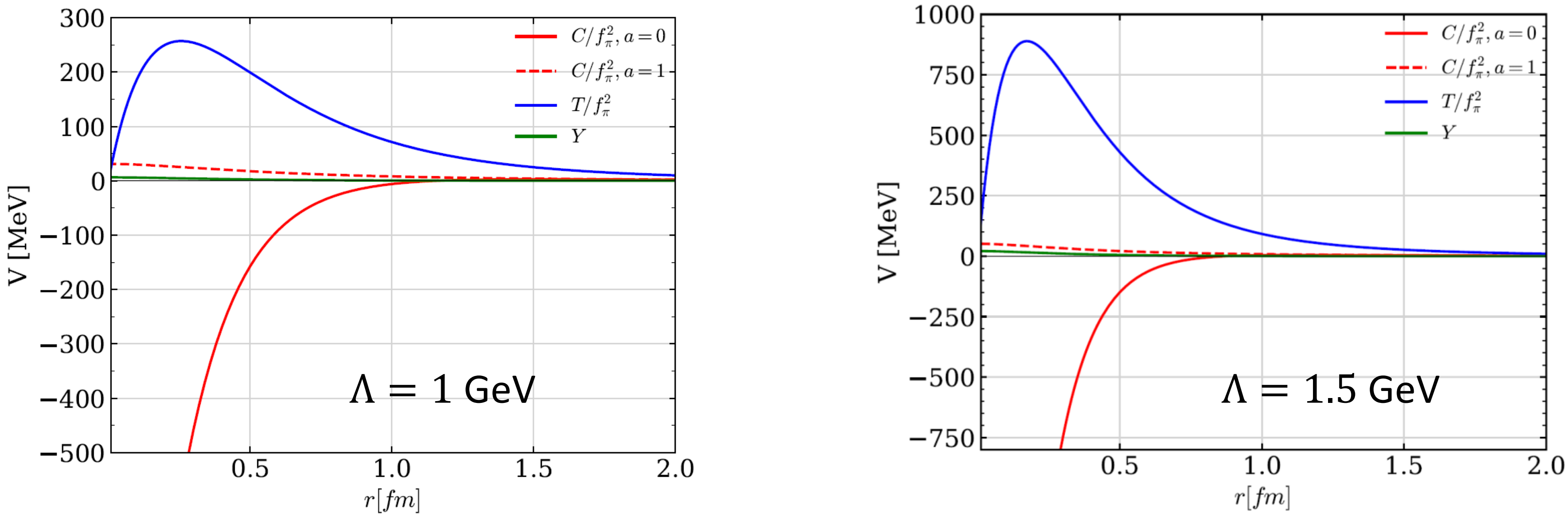
OBE potentials: $V_s + V_{ps} + V_v$

$V_s \to \mathrm{Y}(r, \Lambda, m_s)\boldsymbol{O}_1 \cdot \boldsymbol{O}_2$

$V_{ps} \to \mathrm{C}(r, \Lambda, m_{ps}, a)\boldsymbol{O}_1 \cdot \boldsymbol{O}_2 + \mathrm{T}(r, \Lambda, m_{ps})S(\boldsymbol{O}_1, \boldsymbol{O}_2, \hat{r})$

$V_v \to \mathrm{Y}(r, \Lambda, m_v)\boldsymbol{O}_1 \cdot \boldsymbol{O}_2 - 2\mathrm{C}(r, \Lambda, m_v, a)\boldsymbol{O}_1 \cdot \boldsymbol{O}_2 + \mathrm{T}(r, \Lambda, m_v)S(\boldsymbol{O}_1, \boldsymbol{O}_2, \hat{r})$

- Short-range behaviour of the potential is not fully captured by Λ, but by parameter a



- Repulsive or attractive property of the $C(r, \Lambda, m, a)$ near the origin is quantitatively determined by parameter a, which is not accommodated by Λ.

Results

- P_c
- $P_{\bar{c}s}$
- $P_{ccs\bar{s}}$

P_c states: Single channel bound states

- Binding energy by varying the cutoff, binding energy and Λ in MeV unit

Other $P_c(> 4457)$

Λ	$1/2^-(\Sigma_c\bar{D})$ $a=0$	$1/2^-(\Sigma_c\bar{D})$ $a=1$	$3/2^-(\Sigma_c^*\bar{D})$ $a=0$	$3/2^-(\Sigma_c^*\bar{D})$ $a=1$	$1/2^-(\Sigma_c\bar{D}^*)$ $a=0$	$1/2^-(\Sigma_c\bar{D}^*)$ $a=1$	$3/2^-(\Sigma_c\bar{D}^*)$ $a=0$	$3/2^-(\Sigma_c\bar{D}^*)$ $a=1$	$1/2^-(\Sigma_c^*\bar{D}^*)$ $a=0$	$1/2^-(\Sigma_c^*\bar{D}^*)$ $a=1$	$3/2^-(\Sigma_c^*\bar{D}^*)$ $a=0$	$3/2^-(\Sigma_c^*\bar{D}^*)$ $a=1$	$5/2^-(\Sigma_c^*\bar{D}^*)$ $a=0$	$5/2^-(\Sigma_c^*\bar{D}^*)$ $a=1$
1000	...		...		−23.12	...	...	...	−50.13	...	−2.44	...	...	−0.48
1200	...		...		−117.27	...	...	−4.99	−351.24	...	−27.15	...	...	−10.03
1400	−0.28		−0.36		−325.26	...	−0.04	−19.42	< -500	...	−88.16	−0.21	−0.24	−31.65
1600	−3.73		−4.03		< -500	...	−0.98	−41.04	< -500	...	< -500	−2.07	−1.78	−215.79

$P_c(4312)$ B. E.~ -9 MeV

$P_c(4380)$ B. E.~-5 MeV

$P_c(4440)$ & $P_c(4457)$ B. E.~-22 MeV & ~-5 MeV

→ Mass gap between $1/2^-$ and $3/2^-$ bound states in $\bar{D}^*\Sigma_c$ is controlled by adjusting the partameter a.

- Adjusting the parameter a

J^P(channel)	M [MeV] ($a = 0.58, \Lambda = 1.4$ GeV)	M [MeV] ($a = 0.78, \Lambda = 1.6$ GeV)
$1/2^-(\bar{D}\Sigma_c)$	-	4317.38
$3/2^-(\bar{D}\Sigma_c^*)$	-	4381.34
$1/2^-(\bar{D}^*\Sigma_c)$	**4437.8**	**4458.44**
$3/2^-(\bar{D}^*\Sigma_c)$	**4457.1**	**4441.0**
$1/2^-(\bar{D}^*\Sigma_c^*)$	4480.5	4518.17
$3/2^-(\bar{D}^*\Sigma_c^*)$	4513.7	4514.67
$5/2^-(\bar{D}^*\Sigma_c^*)$	4520.4	4498.19

P_c states: Coupled channel results

- Consider $\bar{D}\Sigma_c - \bar{D}\Sigma_c^* - \bar{D}^*\,\Sigma_c - \bar{D}^*\,\Sigma_c^*$ channels, $P_c(4312)$, $P_c(4440)$ and $P_c(4457)$ as input, fit a and Λ,

J^P (dominant channel)	$(\Lambda, a) =$ (1.23 GeV, 0.55)	$(\Lambda, a) =$ (1.4 GeV, 0.79)
$1/2^-(\Sigma_c\bar{D})$	4317.1	4312.8
$3/2^-(\Sigma_c^*\bar{D})$	$4379.8 - 0.0i$	$4375.6 - 0.1i$
$1/2^-(\Sigma_c\bar{D}^*)$	$4441.0 - 8.0i$	$4458.8 - 1.3i$
$3/2^-(\Sigma_c\bar{D}^*)$	$4456.9 - 5.9i$	$4439.4 - 4.2i$
$1/2^-(\Sigma_c^*\bar{D}^*)$	$4498.6 - 6.6i$	$4525.0 - 0.8i$
$3/2^-(\Sigma_c^*\bar{D}^*)$	$4511.1 - 16.6i$	$4518.0 - 4.2i$
$5/2^-(\Sigma_c^*\bar{D}^*)$	$4521.9 - 5.1i$	$4498.3 - 6.3i$

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Experimental data

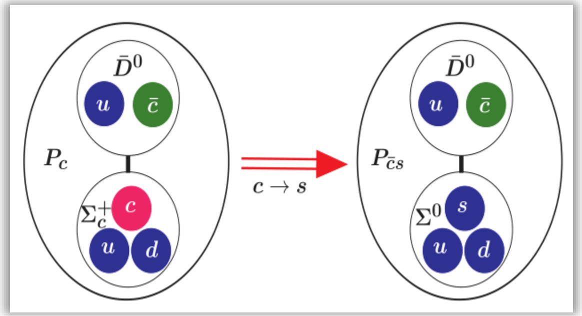
Pentaquarks	Mass [MeV]	width [MeV]
$P_c(4312)$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$
$P_c(4380)$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$
$P_c(4440)$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$
$P_c(4457)$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$

- $a = 0.79$ case prefered due to the smaller decay width

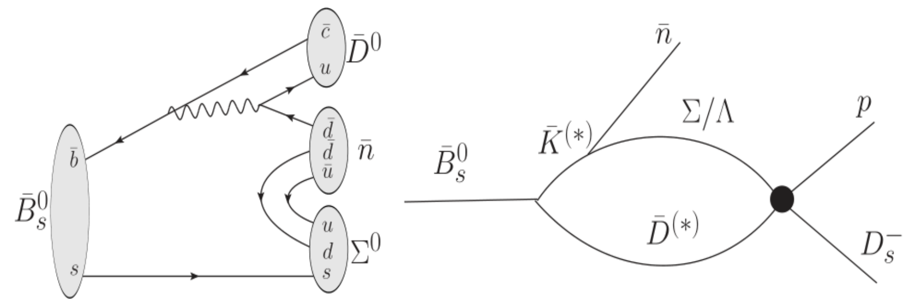
$$P_c(4312):\quad J^P = 1/2^-(\Sigma_c\bar{D}),$$
$$P_c(4380):\quad J^P = 3/2^-(\Sigma_c^*\bar{D}),$$
$$P_c(4440):\quad J^P = 3/2^-(\Sigma_c\bar{D}^*),$$
$$P_c(4457):\quad J^P = 1/2^-(\Sigma_c\bar{D}^*),$$

$P_{\bar{c}s}$ states: Molecular picture

- Binding mechanism similar with P_c pentqaurks



Molecular picture



Production mechanism

- Relevant channels

道	$D_s^- p$	$\bar{D}\Lambda$	$\bar{D}\Sigma$	$\bar{D}^*\Lambda$	$\bar{D}^*\Sigma$
W_j[MeV]	2907.3	2982.9	3060.4	3124.2	3201.7
$J^P = 1/2^-$	$^2S_{1/2}$	$^2S_{1/2}$	$^2S_{1/2}$	$^2S_{1/2}, {}^4D_{1/2}$	$^2S_{1/2}, {}^4D_{1/2}$
$J^P = 3/2^-$	$^2D_{3/2}$	$^2D_{3/2}$	$^2D_{3/2}$	$^4S_{3/2}, {}^2D_{3/2}, {}^4D_{3/2}$	$^4S_{3/2}, {}^2D_{3/2}, {}^4D_{3/2}$

All channels have the same quark configuration-$uuds\bar{c}$

$P_{\bar{c}s}$ states: $D_s^- p$-$\bar{D}\Lambda$-$\bar{D}\Sigma$-$\bar{D}^*\Lambda$-$\bar{D}^*\Sigma$

- Two poles with $J^P = 1/2^-$ and a pole with $J^P = 3/2^-$ are found at the complex energy plane S(E) closet to the physical region, they can be parametrized as $E_{\text{pole}} = M - i\Gamma/2$

$a = 0.58$

Mass(M)、decay width(Γ) and partial decay width(Γ_i) in unit of MeV

Λ[GeV]	$J^P = 1/2^-(\bar{D}\Sigma)$			$J^P = 1/2^-(\bar{D}^*\Sigma)$						$J^P = 3/2^-(\bar{D}^*\Sigma)$						
	$M - i\Gamma/2$	Γ_i		$M - i\Gamma/2$	Γ_i					$M - i\Gamma/2$	Γ_i					
1.2	$3060.3 - i0.3$	0.6	0.1	$3197.3 - i3.9$	0.3	0.7	6.1	0.7	0.6	$3201.2 - i2.8$	0.0	1.9	2.3	1.2	0.2	1.4
1.25	$3059.0 - i1.2$	2.3	0.3	$3190.2 - i7.1$	0.7	1.1	11.3	1.2	0.5	$3199.3 - i3.7$	0.0	2.2	2.7	1.7	0.2	1.5
1.3	$3055.8 - i3.0$	5.7	0.7	$3179.0 - i12.1$	1.5	1.8	18.8	2.1	0.3	$3196.9 - i4.5$	0.0	2.5	3.0	2.3	0.2	1.5
1.35	$3049.6 - i6.2$	11.5	1.4	$3162.0 - i20.1$	3.5	3.1	29.1	3.5	0.1	$3194.0 - i5.1$	0.0	2.7	3.2	2.9	0.2	1.5
1.4	$3036.8 - i10.6$	18.9	2.5	$3136.1 - i32.1$	7.8	5.5	38.7	3.8	0.2	$3190.6 - i5.6$	0.0	2.9	3.4	3.5	0.1	1.4

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- Decay channels

1. $1/2^-(\bar{D}\Sigma)$: $D_s^- p(^2S_{1/2})$, $\bar{D}\Lambda(^2S_{1/2})$
2. $1/2^-(\bar{D}^*\Sigma)$: $D_s^- p(^2S_{1/2})$, $\bar{D}\Lambda(^2S_{1/2})$, $\bar{D}\Sigma(^2S_{1/2})$, $\bar{D}^*\Lambda(^2S_{1/2})$, $\bar{D}^*\Lambda(^4D_{1/2})$
3. $3/2^-(\bar{D}^*\Sigma)$: $D_s^- p(^2D_{3/2})$, $\bar{D}\Lambda(^2D_{3/2})$, $\bar{D}\Sigma(^2D_{3/2})$, $\bar{D}^*\Lambda(^4S_{3/2})$, $\bar{D}^*\Lambda(^2D_{3/2})$, $\bar{D}^*\Lambda(^4D_{3/2})$

$P_{\bar{c}s}$ states: $D_s^- p$-$\bar{D}\Lambda$-$\bar{D}\Sigma$-$\bar{D}^*\Lambda$-$\bar{D}^*\Sigma$

- Two poles with $J^P = 1/2^-$ and a pole with $J^P = 3/2^-$ are found at the complex energy plane S(E) closet to the physical region, they can be parametrized as $E_{\text{pole}} = M - i\Gamma/2$

$a = 0.78$

Mass(M)、decay width(Γ) and partial decay width(Γ_i) in unit of MeV

Λ[GeV]	$J^P=1/2^-(\bar{D}\Sigma)$			$J^P=1/2^-(\bar{D}^*\Sigma)$						$J^P=3/2^-(\bar{D}^*\Sigma)$						
	$M-i\Gamma/2$	Γ_i		$M-i\Gamma/2$	Γ_i					$M-i\Gamma/2$	Γ_i					
1.2	$3060.4-i0.1$	0.2	0.0	⋯	⋯	⋯	⋯	⋯	⋯	$3199.0-i4.9$	0.0	2.4	2.6	4.4	0.2	1.6
1.3	$3058.5-i1.3$	2.4	0.3	⋯	⋯	⋯	⋯	⋯	⋯	$3191.8-i7.5$	0.0	2.9	3.0	7.9	0.2	1.5
1.4	$3053.9-i4.2$	7.8	1.0	⋯	⋯	⋯	⋯	⋯	⋯	$3181.5-i9.6$	0.0	3.2	3.2	11.6	0.1	1.2
1.55	$3044.6-i13.4$	23.7	4.2	$3200.6-i21.1$	0.3	23.6	1.6	30.1	0.6	$3160.9-i11.2$	0.1	3.1	3.2	14.9	0.0	0.5
1.6	$3041.9-i17.7$	30.6	6.2	$3193.6-i26.5$	0.1	28.9	2.0	32.2	0.5	$3152.5-i11.2$	0.1	3.0	3.4	14.7	0.0	0.3

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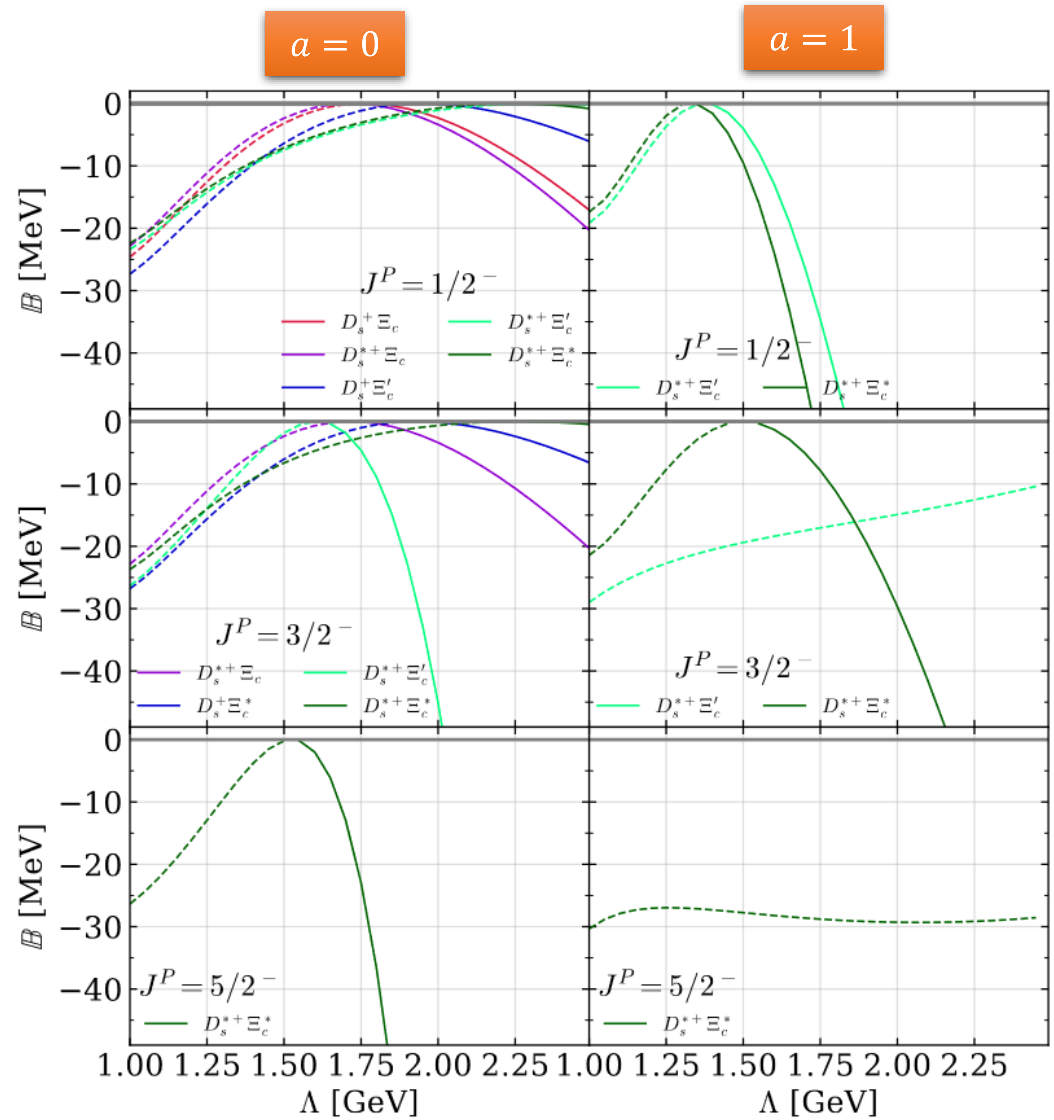
- Decay channels

1. $1/2^-(\bar{D}\Sigma)$: $D_s^- p(^2S_{1/2})$, $\bar{D}\Lambda(^2S_{1/2})$
2. $1/2^-(\bar{D}^*\Sigma)$: $D_s^- p(^2S_{1/2})$, $\bar{D}\Lambda(^2S_{1/2})$, $\bar{D}\Sigma(^2S_{1/2})$, $\bar{D}^*\Lambda(^2S_{1/2})$, $\bar{D}^*\Lambda(^4D_{1/2})$
3. $3/2^-(\bar{D}^*\Sigma)$: $D_s^- p(^2D_{3/2})$, $\bar{D}\Lambda(^2D_{3/2})$, $\bar{D}\Sigma(^2D_{3/2})$, $\bar{D}^*\Lambda(^4S_{3/2})$, $\bar{D}^*\Lambda(^2D_{3/2})$, $\bar{D}^*\Lambda(^4D_{3/2})$

$P_{ccs\bar{s}}$ states: Single channel results

- Energy of the bound states(solid curves) or virtual states states(dashed curves) in single channels calculated by varying the cutoff.
- Virtual states turn to bound states as the cutoff increases
- The results including ($a = 0$) and excluding($a = 1$) the δ-term compared
- Binding requires the larger cutoff Λ



$P_{ccs\bar{s}}$ states: $D_s^+\Xi_c - D_s^+\Xi_c' - D_s^{*+}\Xi_c - D_s^+\Xi_c^* - D_s^{*+}\Xi_c' - D_s^{*+}\Xi_c^*$

- Resonsces and bound state in the coupled-channel calculation as the cutoff $\Lambda = 1.5$ GeV

J^P	Nearby channel	Threshold [MeV]	E_{pole} [MeV]	$\Gamma_i(D_s^+\Xi_c/D_s^+\Xi_c'/D_s^{*+}\Xi_c/D_s^+\Xi_c^*/D_s^{*+}\Xi_c/D_s^{*+}\Xi_c^*)$ [MeV]
$1/2^-$	$D_s^+\Xi_c$	4437.76	4437.71	$\cdots$
	$D_s^+\Xi_c'$	4547.14	$4547.04 - i0.01^\Delta$	$\cdots$
	$D_s^{*+}\Xi_c$	4581.62	$4564.26 - i1.00$	$0.18/1.81/\cdots/\cdots/\cdots/\cdots$
	$D_s^{*+}\Xi_c'$	4691.00	$4687.07 - i3.97^\Delta$	$\cdots$
	$D_s^{*+}\Xi_c^*$	4758.17	$4754.05 - i4.27^\Delta$	$\cdots$
$3/2^-$	$D_s^{*+}\Xi_c$	4581.62	$4569.56 - i0.02$	$0.01/0.04/\cdots/\cdots/\cdots/\cdots$
	$D_s^+\Xi_c^*$	4614.31	$4614.29 - i0.05$	$0.00/0.02/0.10/\cdots/\cdots/\cdots$
	$D_s^{*+}\Xi_c'$	4691.00	$4689.01 - i2.58$	$3.36/0.06/1.9/0.36/\cdots/\cdots$
	$D_s^{*+}\Xi_c^*$	4758.17	$4769.34 - i9.95^\Delta$	$\cdots$
$5/2^-$	$D_s^{*+}\Xi_c^*$	4758.17	$4727.40 - i13.37$	$7.82/0.19/19.27/0.33/0.02/\cdots$

- 5 narrow resonances and an unstable bound states are found
- 4 virtual state poles are found at the other RSs, some of them may cause clear cusp (peak- or dip-like) structure of the amplitude at the threshold

$P_{ccs\bar{s}}$ states: $D_s^+\Xi_c - D_s^+\Xi_c' - D_s^{*+}\Xi_c - D_s^+\Xi_c^* - D_s^{*+}\Xi_c' - D_s^{*+}\Xi_c^*$

- Resonances and bound state in the coupled-channel calculation as the cutoff $\Lambda = 1.5$ GeV

Without δ-term

J^P	Nearby channel	Threshold [MeV]	E_{pole} [MeV]	$\Gamma_i(D_s^+\Xi_c/D_s^+\Xi_c'/D_s^{*+}\Xi_c/D_s^+\Xi_c^*/D_s^{*+}\Xi_c'/D_s^{*+}\Xi_c^*)$ [MeV]
$1/2^-$	$D_s^+\Xi_c$	4437.76	4437.73	$\cdots$
	$D_s^+\Xi_c'$	4547.14	$4547.14 - i0.00^\Delta$	$\cdots$
	$D_s^{*+}\Xi_c$	4581.62	$4565.34 - i2.68$	$0.18/4.98/\cdots/\cdots/\cdots/\cdots$
	$D_s^{*+}\Xi_c'$	4691.00	$4686.30 - i4.49$	$1.20/6.41/2.02/0.01/\cdots/\cdots$
	$D_s^{*+}\Xi_c^*$	4758.17	$4742.51 - i6.44$	$2.81/2.57/6.26/0.05/1.46/\cdots$
$3/2^-$	$D_s^{*+}\Xi_c$	4581.62	$4570.09 - i0.02$	$0.00/0.04/\cdots/\cdots/\cdots/\cdots$
	$D_s^+\Xi_c^*$	4614.31	$4614.26 - i0.22^\Delta$	$\cdots$
	$D_s^{*+}\Xi_c'$	4691.00	$4689.71 - i6.38^\Delta$	$\cdots$
	$D_s^{*+}\Xi_c^*$	4758.17	$4747.06 - i16.76$	$2.29/0.02/24.51/7.32/3.89/\cdots$
$5/2^-$	$D_s^{*+}\Xi_c^*$	4758.17	$4763.39 - i11.20^\Delta$	$\cdots$

- 5 narrow resonances and an unstable bound states are found
- 4 virtual state poles are found at the othe RSs, some of them may cause clear cusp (peak- or dip-like) structure of the amplitude at the threshold

Summary

- P_c
  - Coupled channel system $\bar{D}\Sigma_c$-$\bar{D}\Sigma_c^*$-$\bar{D}^*\Sigma_c$-$\bar{D}^*\Sigma_c^*$ are studied in the one-boson-exchange model. Our study suggests contribution of short range δ-term is important for simultaneous interpretation of $P_c(4312)$, $P_c(4380)$, $P_c(4440)$ and $P_c(4457)$ pentaquarks as the hadronic molecules.
  - Another three pentaquarks $P_c(?)$ are predicted in the $4.49 - 4.53$ GeV mass region.
- $P_{\bar{c}s}$
  - Coupled channel system D_s^-p- $\bar{D}\Lambda$- $\bar{D}\Sigma$- $\bar{D}^*\Lambda$- $\bar{D}^*\Sigma$ are studied and three pentaquarks $P_{\bar{c}s}$ are predicted.
  - It is suggested that the $D_s^- p$ invariant mass spectrum at the 3.0-3.2 GeV energy region in the $\bar{B}_s^0 \to \bar{n}D_s^- p$ decay is an appropriate place to detect the $P_{\bar{c}s}^-$ pentaquarks.
- $P_{ccs\bar{s}}$
  - 5 resonances and an unstable bound state in $D_s^+\Xi_c - D_s^+\Xi_c' - D_s^{*+}\Xi_c - D_s^+\Xi_c^* - D_s^{*+}\Xi_c' - D_s^{*+}\Xi_c^*$ coupled channel system are predicted.
  - suggesting the $D\Lambda_c$ invariant mass spectrum at the energy region of $4.43 \sim 4.76$ GeV to explore the nature of $P_{ccs\bar{s}}$ pentaquarks.

Thanks for you attention!

Back up

P_c states: Related channels

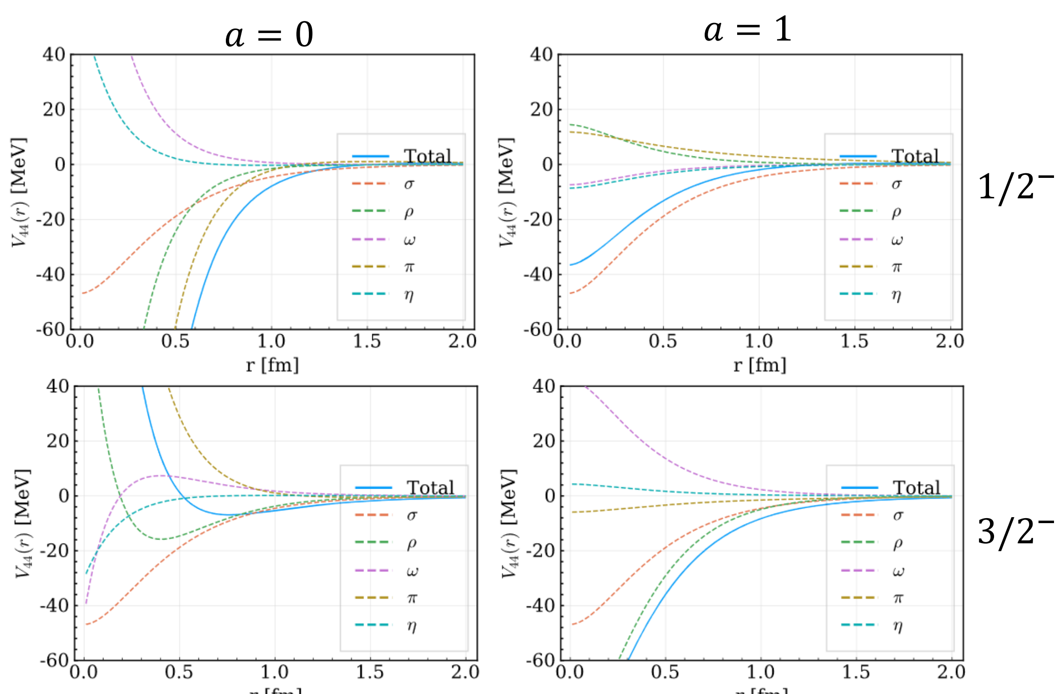
- Partial waves of channels: $^{2S+1}L_J$, $\mathrm{J} = |\mathrm{L}+\mathrm{S}|, |\mathrm{L}+\mathrm{S}-1|, \cdots, |L-S|$

Channels	$\bar{D}\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Sigma_c^*$
Threshold [MeV]	4321.11	4385.37	4462.42	4526.68
$J^P = 1/2^-$	$^2S_{1/2}$	$^4D_{1/2}$	$^2S_{1/2}, {}^4D_{1/2}$	$^2S_{1/2}, {}^4D_{1/2}, {}^6D_{1/2}$
$J^P = 3/2^-$	$^2D_{3/2}$	$^4S_{3/2}$	$^4S_{3/2}, {}^2D_{3/2}, {}^4D_{3/2}$	$^4S_{3/2}, {}^2D_{3/2}, {}^4D_{3/2}, {}^6D_{1/2}$
$J^P = 5/2^-$	$^2D_{5/2}$	$^4D_{5/2}$	$^2D_{5/2}, {}^4D_{5/2}$	$^6S_{5/2}, {}^2D_{5/2}, {}^4D_{5/2}, {}^6D_{5/2}$

- OBE potentials in S wave
  - Partial wave projection

$$^{J^P}V^{ij}(r) =_f \langle ^{2s'+1}L'_J|V^{ij}(r)|^{2s+1}L_J\rangle_i$$

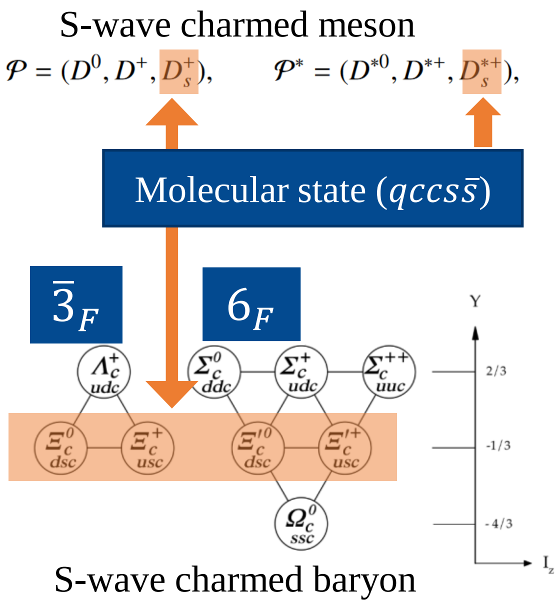
  - Total potentials of $\bar{D}\Sigma_c$ and $\bar{D}\Sigma_c^*$ channels inependent of a
  - In the $\bar{D}^*\Sigma_c$ system, $1/2^-$ is more attractive than $3/2^-$ with $a = 0$, and the stuation interchanges with $a = 1$



S wave potential of $\bar{D}^*\Sigma_c$ with $\Lambda = 1.0$ GeV

$P_{ccs\bar{s}}$ states: considered channels

- Channels consisted of S wave charmed-strange mesons and baryons



Mass region 4.43 ~ 4.76 GeV

Channels	$D_s^+\Xi_c$	$D_s^{*+}\Xi_c$	$D_s^+\Xi_c'$	$D_s^+\Xi_c^*$	$D_s^{*+}\Xi_c'$	$D_s^{*+}\Xi_c^*$
Threshold [MeV]	4437.76	4581.62	4547.14	4614.31	4691.00	4758.17
$J^P = 1/2^-$	$\|^2S_{1/2}\rangle$	$\begin{pmatrix} \|^2S_{1/2}\rangle \\ \|^4D_{1/2}\rangle \end{pmatrix}$	$\|^2S_{1/2}\rangle$	$\|^4D_{1/2}\rangle$	$\begin{pmatrix} \|^2S_{1/2}\rangle \\ \|^4D_{1/2}\rangle \end{pmatrix}$	$\begin{pmatrix} \|^2S_{1/2}\rangle \\ \|^4D_{1/2}\rangle \\ \|^6D_{1/2}\rangle \end{pmatrix}$
$J^P = 3/2^-$	$\|^2D_{3/2}\rangle$	$\begin{pmatrix} \|^4S_{3/2}\rangle \\ \|^2D_{3/2}\rangle \\ \|^4D_{3/2}\rangle \end{pmatrix}$	$\|^2D_{3/2}\rangle$	$\begin{pmatrix} \|^4S_{3/2}\rangle \\ \|^4D_{3/2}\rangle \end{pmatrix}$	$\begin{pmatrix} \|^4S_{3/2}\rangle \\ \|^2D_{3/2}\rangle \\ \|^4D_{3/2}\rangle \end{pmatrix}$	$\begin{pmatrix} \|^4S_{3/2}\rangle \\ \|^2D_{3/2}\rangle \\ \|^4D_{1/2}\rangle \\ \|^6D_{3/2}\rangle \end{pmatrix}$
$J^P = 5/2^-$	$\|^2D_{5/2}\rangle$	$\begin{pmatrix} \|^2D_{5/2}\rangle \\ \|^4D_{5/2}\rangle \end{pmatrix}$	$\|^2D_{5/2}\rangle$	$\|^4D_{5/2}\rangle$	$\begin{pmatrix} \|^2D_{5/2}\rangle \\ \|^4D_{5/2}\rangle \end{pmatrix}$	$\begin{pmatrix} \|^6S_{5/2}\rangle \\ \|^2D_{5/2}\rangle \\ \|^4D_{5/2}\rangle \\ \|^6D_{5/2}\rangle \end{pmatrix}$

- How the effects of OBE and coupled channel dynamics?

Ten more virtual states are found in S-wave sigle channels with vector meson exchange potential

X.-K. Dong, F.-K. Guo, and B.-S. Zou, Commun. Theor.Phys. 73, 125201 (2021)