

Decay behaviors of the P_c hadronic molecules

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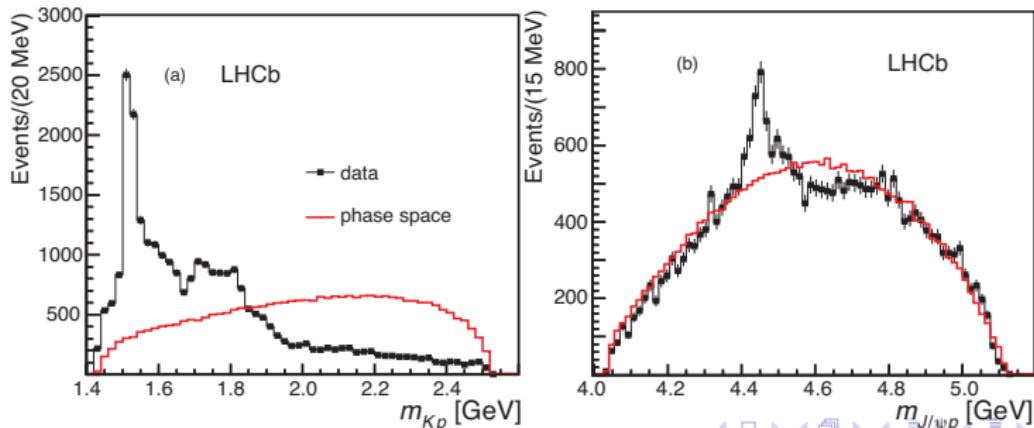
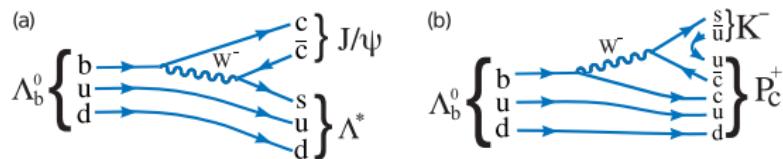
Overview

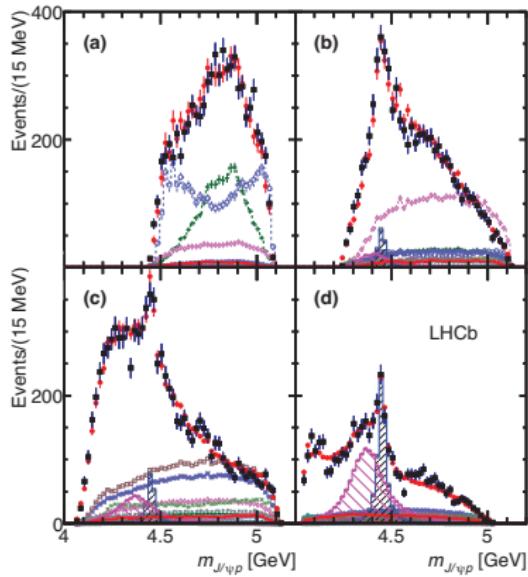
- 1 Disentangling the hadronic molecule nature of the pentaquark-like structure
 - LHCb's observation of pentaquark states
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- 2 Decay behaviors of the P_c hadronic molecules
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- 4 Summary and prospects

LHCb's observation of pentaquark states

R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **115** (2015) 072001

Observation of $J/\psi p$ resonances consistent with pentaquark states in
 $\Lambda_b^0 \rightarrow J/\psi K p$ Decays





- $M = 4380 \pm 8 \pm 29$ MeV,
 $\Gamma = 205 \pm 18 \pm 86$ MeV
- $M = 4450 \pm 2 \pm 3$ MeV,
 $\Gamma = 39 \pm 5 \pm 19$ MeV
- Significances $> 9\sigma$ for both
- The two states have opposite parity.
- The preferred spin is one having spin-3/2 and the other 5/2.

Figure: $m_{J/\psi p}$ in m_{Kp} intervals for the fit with two P_c^+ states: (d) $m_{Kp} > 2$ GeV

Listed in C. Patrignani *et al.* [Particle Data Group],
 Chin. Phys. C **40** no.10, 100001 (2016) and 2017 update.

Predictions prior to LHCb observation

Theoretical groups

ITP, IHEP, IMP, Peking U., UCAS, Valencia U., Georgia U., Bonn U., etc.

J. J. Wu, R. Molina, E. Oset and B. S. Zou,
Phys. Rev. Lett. **105** (2010) 232001, Phys. Rev. C **84** (2011) 015202.

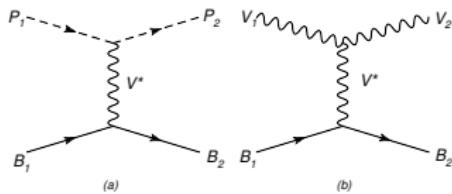


Figure: The Feynman diagrams of pseudoscalar-baryon (a) or vector- baryon (b) interaction via the exchange of a vector meson. P_1, P_2 is D^- , \bar{D}^0 or D_s^- , and V_1, V_2 is D^{*-} , \bar{D}^{*0} or D_s^{*-} , and B_1, B_2 is Σ_c , Λ_c^+ , Ξ_c , Ξ_c' or Ω_c , and V^* is ρ , K^* , ϕ or ω .

Dynamically generated $\bar{D}^{(*)}\Sigma_c$, $\bar{D}_s^{(*)}\Sigma_c$ and $\bar{D}^{(*)}\Xi_c^{(')}$ bound states.

	(I, S)	z_R (MeV)	g_a	
$N_{c\bar{c}}^*$	$(1/2, 0)$		$\bar{D}\Sigma_c$	$\bar{D}\Lambda_c^+$
		4269	2.85	0
$\Lambda_{c\bar{c}}^*$	$(0, -1)$		$\bar{D}_s\Lambda_c^+$	$\bar{D}\Xi_c$
		4213	1.37	3.25
		4403	0	0
				2.64

Table: Pole positions z_R and coupling constants g_a for the states from $PB \rightarrow PB$.

	(I, S)	z_R (MeV)	g_a	
$N_{c\bar{c}}^*$	$(1/2, 0)$		$\bar{D}^*\Sigma_c$	$\bar{D}^*\Lambda_c^+$
		4418	2.75	0
$\Lambda_{c\bar{c}}^*$	$(0, -1)$		$\bar{D}_s^*\Lambda_c^+$	$\bar{D}^*\Xi_c$
		4370	1.23	3.14
		4550	0	0
				2.53

Table: z_R and g_a for the states from $VB \rightarrow VB$.

(I, S)	M	Γ	Γ_i					
$N_{c\bar{c}}^*$	$(1/2, 0)$		πN	ηN	$\eta' N$	$K\Sigma$		$\eta_c N$
		4261	56.9	3.8	8.1	3.9	17.0	23.4
$\Lambda_{c\bar{c}}^*$	$(0, -1)$		$\bar{K}N$	$\pi\Sigma$	$\eta\Lambda$	$\eta'\Lambda$	$K\Xi$	$\eta_c\Lambda$
		4209	32.4	15.8	2.9	3.2	1.7	2.4
		4394	43.3	0	10.6	7.1	3.3	5.8
								16.3

Table: Mass (M), total width (Γ), and the partial decay width (Γ_i) for the states from $PB \rightarrow PB$, with units in MeV.

(I, S)	M	Γ	Γ_i					
$N_{c\bar{c}}^*$	$(1/2, 0)$		ρN	ωN	$K^*\Sigma$			$J/\psi N$
		4412	47.3	3.2	10.4	13.7		19.2
$\Lambda_{c\bar{c}}^*$	$(0, -1)$		\bar{K}^*N	$\rho\Sigma$	$\omega\Lambda$	$\phi\Lambda$	$K^*\Xi$	$J/\psi\Lambda$
		4368	28.0	13.9	3.1	0.3	4.0	1.8
		4544	36.6	0	8.8	9.1	0	5.0
								13.8

Table: M , Γ and Γ_i for the states from $VB \rightarrow VB$.

Explanations after LHCb observation

Theoretical interpretations of the hidden-charm pentaquark states

(H. X. Chen, W. Chen, X. Liu and S. L. Zhu, Phys. Rept. **639** (2016) 1)

① The molecular scheme: bound molecular states of $\bar{D}^{(*)}\Sigma_c^{(*)}$

- R. Chen, X. Liu, X. Q. Li and S. L. Zhu, Phys. Rev. Lett. **115** (2015) 132002
- L. Roca, J. Nieves and E. Oset, Phys. Rev. D **92** (2015) no.9, 094003
- J. He, Phys. Lett. B **753** (2016) 547
- Q. F. Lü and Y. B. Dong, Phys. Rev. D **93** (2016) no.7, 074020

② Diquark-diquark-antiquark state with $\bar{c}[cu][ud]$ configuration

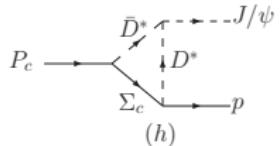
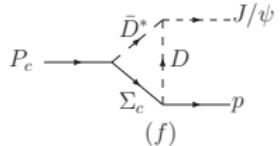
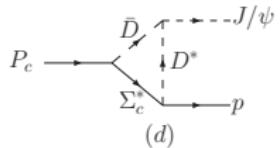
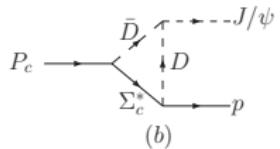
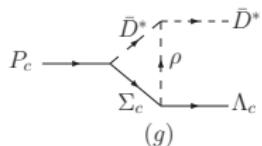
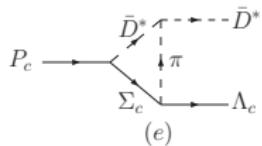
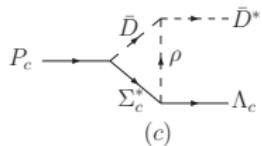
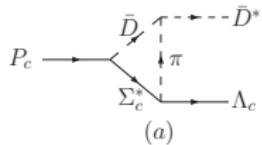
- L. Maiani, A. D. Polosa and V. Riquer, Phys. Lett. B **749** (2015) 289
- V. V. Anisovich *et al.*, arXiv:1507.07652 [hep-ph]

③ Diquark-triquark state with $[cu][ud\bar{c}]$ configuration

- R. F. Lebed, Phys. Lett. B **749** (2015) 454
- R. Zhu and C. F. Qiao, Phys. Lett. B **756** (2016) 259

④ Kinematic effects

- F. K. Guo, U. G. Meißner, W. Wang and Z. Yang, Phys. Rev. D **92** (2015) 071502
- X. H. Liu, Q. Wang and Q. Zhao, Phys. Lett. B **757** (2016) 231



Assuming that the P_c is an S -wave hadronic molecular state of either $\bar{D}^* \Sigma_c$ or $\bar{D} \Sigma_c^*$.

Using the Lorentz covariant orbital-spin (L-S) scheme, we have the effective Lagrangians for the first vertices:

$$\mathcal{L}_{P_c(\frac{3}{2}^-)\Sigma_c\bar{D}^*} = g_{P_c\Sigma_c\bar{D}^*}\bar{\Sigma}_c P_{c\mu}\bar{D}^{*\mu},$$

$$\mathcal{L}_{P_c(\frac{3}{2}^-)\Sigma_c^*\bar{D}} = g_{P_c\Sigma_c^*\bar{D}}\bar{\Sigma}_c^{*\mu} P_{c\mu}\bar{D},$$

A Gaussian regulator is added in the first vertex:

$$\Phi_{P_c}(q_E^2/\Lambda^2) \equiv \exp(-q_E^2/\Lambda^2),$$

where q_E is the Euclidean Jacobi momentum.

The effective Lagrangian involved:

$$\mathcal{L}_{PPV} = g_{PPV} \phi_P(x) \partial_\mu \phi_P(x) \phi_V^\mu(x),$$

$$\mathcal{L}_{VVP} = g_{VVP} i \varepsilon_{\mu\nu\alpha\beta} \partial^\mu \phi_V^\nu(x) \partial^\alpha \phi_V^\beta(x) \phi_P(x),$$

$$\mathcal{L}_{VVV} = g_{VVV} i [\partial_\mu \phi_{V\nu}(x) - \partial_\nu \phi_{V\mu}(x)] \phi_V^\mu(x) \phi_V^\nu(x),$$

$$\mathcal{L}_{BPB^*} = g_{BPB^*} [\bar{\psi}_{B^*\mu}(x) \psi_B(x) + \bar{\psi}_B(x) \psi_{B^*\mu}(x)] \partial^\mu \phi_P(x),$$

$$\begin{aligned} \mathcal{L}_{BVB^*} = & g_{BVB^*} i [\bar{\psi}_{B^*\nu}(x) \gamma^5 \gamma_\mu \psi_B(x) - \bar{\psi}_B(x) \gamma^5 \gamma_\mu \psi_{B^*\nu}(x)] \\ & [\partial^\mu \phi_V^\nu(x) - \partial^\nu \phi_V^\mu(x)], \end{aligned}$$

$$\mathcal{L}_{BBP} = g_{BBP} \bar{\psi}_B(x) i \gamma^5 \psi_B(x) \phi_P(x),$$

$$\begin{aligned} \mathcal{L}_{BBV} = & g_{BBV} [\bar{\psi}_B(x) \gamma_\mu \psi_B(x) \phi_V^\mu(x) \\ & + 2f_{BBV} \bar{\psi}_B(x) \sigma_{\mu\nu} \psi_B(x) (\partial^\mu \phi_V^\nu(x) - \partial^\nu \phi_V^\mu(x))], \end{aligned}$$

The partial decay width is proportional to $g_{P_c \Sigma_c^* \bar{D}}^2$ and $g_{P_c \Sigma_c \bar{D}^*}^2$. However, the ratio R has no relates with the partial the first vertexes' coupling constants.

$$R_I = \frac{\Gamma(P_c(4380) \rightarrow \bar{D}\Sigma_c^* \rightarrow \bar{D}^*\Lambda_c)}{\Gamma(P_c(4380) \rightarrow \bar{D}\Sigma_c^* \rightarrow J/\psi p)} \sim 10$$
$$R_{II} = \frac{\Gamma(P_c(4380) \rightarrow \bar{D}^*\Sigma_c \rightarrow \bar{D}^*\Lambda_c)}{\Gamma(P_c(4380) \rightarrow \bar{D}^*\Sigma_c \rightarrow J/\psi p)} \sim 1$$

The dependence of both ratios on the cutoff is rather weak.

This ratio can be employed to tell the nature of the P_c resonances in the future experiments, such as experiments at LHCb, the γp experiments at JLab, or the πp experiments at JPARC.

We also analyzed in details using the nonrelativistic formalism taking heavy quark spin symmetry into account.

Nonrelativistic formalism

$$\begin{aligned}\mathcal{L}_{HH\pi} &= -\frac{g}{2} \left\langle H_a^\dagger H_b \vec{\sigma} \cdot \vec{u}_{ba} \right\rangle + \frac{g}{2} \left\langle \bar{H}_a^\dagger \vec{\sigma} \cdot \vec{u}_{ab} \bar{H}_b \right\rangle, \\ \mathcal{L}_{SB_{\bar{3}}\pi} &= -\frac{\sqrt{3}}{2} g_2 B_{\bar{3},ab}^\dagger \vec{u}_{bc} \cdot \vec{S}_{ca} + \text{h.c..} \\ \mathcal{L}_{P_c} &= -\sqrt{\frac{2}{3}} \left(g_{P_c} \bar{D}_a^\dagger \vec{\Sigma}_{c,ab}^{*\dagger} \cdot \vec{P}_{c,b} + g'_{P_c} \bar{D}_a^{*i\dagger} \Sigma_{c,ab}^\dagger P_{c,b}^i \right).\end{aligned}$$

where $\bar{H}_a = -\vec{\bar{D}}_a^* \cdot \vec{\sigma} + \bar{D}_a$, $\vec{u}_{ab} = -\sqrt{2} \partial \phi_{ab} / F + \mathcal{O}(\phi^3)$,

$S_{ab}^i = B_{6,ab}^{*i} + \frac{1}{\sqrt{3}} \sigma^i B_{6,ab}$ and

$$B_{\bar{3}} = \begin{pmatrix} 0 & \Lambda_c^+ & \Xi_c^+ \\ -\Lambda_c^+ & 0 & \Xi_c^0 \\ -\Xi_c^+ & -\Xi_c^0 & 0 \end{pmatrix}, B_6 = \begin{pmatrix} \Sigma_c^{++} & \frac{1}{\sqrt{2}} \Sigma_c^+ & \frac{1}{\sqrt{2}} \Xi_c'^+ \\ \frac{1}{\sqrt{2}} \Sigma_c^+ & \Sigma_c^0 & \frac{1}{\sqrt{2}} \Xi_c'^0 \\ \frac{1}{\sqrt{2}} \Xi_c'^+ & \frac{1}{\sqrt{2}} \Xi_c'^0 & \Omega_c^0 \end{pmatrix}.$$

Nonrelativistic formalism

$$I^{ij} \equiv \frac{i}{4m_1 m_2} \int \frac{d^4 l}{(2\pi)^4} \frac{l^i l^j}{(q^0 - l^0 - \omega_1 + i\epsilon)(k^0 + l^0 - \omega_2 + i\epsilon)(l^2 - m_3^2 + i\epsilon)},$$

$$I_S(m_1, m_2, m_3, \vec{q}^2) = I^{ii}(m_1, m_2, m_3, \vec{q}),$$

$$I_D(m_1, m_2, m_3, \vec{q}^2) = \frac{3}{2} I^{ij}(m_1, m_2, m_3, \vec{q}) \left(\frac{q_i q_j}{\vec{q}^2} - \frac{1}{3} \delta^{ij} \right).$$

$$\sum_{\omega, \alpha, \lambda} \left| \mathcal{A}_{\bar{D}\Sigma_c^*}^{\text{OPE}} \right|^2 = 144 N^2 g_{P_c}^2 m_{\Lambda_c} m_{P_c} m_{\Sigma_c^*}^2 \times \\ \left[2 \left| I_D(m_D, m_{\Sigma_c^*}, m_\pi, \vec{q}^2) \right|^2 + \left| I_S(m_D, m_{\Sigma_c^*}, m_\pi, \vec{q}^2) \right|^2 \right],$$

$$\sum_{\omega, \alpha, \lambda} \left| \mathcal{A}_{\bar{D}^*\Sigma_c}^{\text{OPE}} \right|^2 = 48 N^2 g_{P_c}^{\prime 2} m_{\Lambda_c} m_{P_c} m_{\Sigma_c}^2 \times \\ \left[5 \left| I_D(m_D, m_{\Sigma_c^*}, m_\pi, \vec{q}^2) \right|^2 + \left| I_S(m_D, m_{\Sigma_c^*}, m_\pi, \vec{q}^2) \right|^2 \right].$$

Then we evaluated the value of the coupling $g_{P_c \Sigma_c^* \bar{D}}$ and $g_{P_c \Sigma_c \bar{D}^*}$ using:

$$g^2 = \frac{4\pi}{4Mm_2} \frac{(m_1 + m_2)^{5/2}}{(m_1 m_2)^{1/2}} \sqrt{32\epsilon},$$

where M , m_1 and m_2 are the masses of P_c , $\bar{D}(\bar{D}^*)$ and $\Sigma_c^*(\Sigma_c)$, respectively, and ϵ is the binding energy, which is valid for an S -wave shallow bound state.

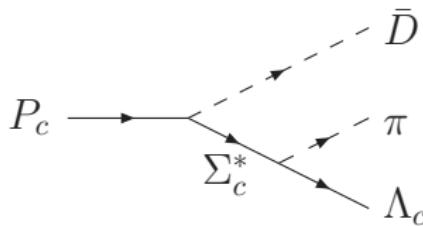


Figure: The three-body decay for $P_c(4380)$ being a $\bar{D}\Sigma_c^*$ hadronic molecule.

The three-body decay $P_c \rightarrow \bar{D}\pi\Lambda_c$ leads to a width of only about 10 MeV, much smaller than the reported width of the $P_c(4380)$.

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The decay width of the P_c to all possible final states

Y. H. Lin, C. W. Shen, F. K. Guo and B. S. Zou, Phys. Rev. D **95** (2017) no.11, 114017

All possible final states for the decay of $P_c(4380)$ with $J^P = \frac{3}{2}^-$ and $P_c(4450)$ with $J^P = \frac{3}{2}^-$ or $\frac{5}{2}^+$.

Initial state	Final states
$P_c(4380)(\bar{D}\Sigma_c^*)$	$\bar{D}^*\Lambda_c, J/\psi p, \bar{D}\Lambda_c, \pi N, \chi_{c0}p, \eta_c p, \rho N, \omega p, \bar{D}\Sigma_c$
$P_c(4380)(\bar{D}^*\Sigma_c)$	$\bar{D}^*\Lambda_c, J/\psi p, \bar{D}\Lambda_c, \pi N, \chi_{c0}p, \eta_c p, \rho N, \omega p, \bar{D}\Sigma_c$
$P_c(4450)(D^*\Sigma_c)$	$D^*\Lambda_c, J/\psi p, \bar{D}\Lambda_c, \pi N, \chi_{c0}p, \eta_c p, \rho N, \omega p, \bar{D}\Sigma_c, \bar{D}\Sigma_c^*$

More diagrams and Lagrangians are needed and used here.

The value of Λ_0 is varied from 0.5 GeV to 1.2 GeV for an estimate of the two-body partial widths, since it denotes a hard momentum scale which suppresses the contribution of the two constituents at short distances $\sim 1/\Lambda_0$.

In addition, an off-shell form factor for the exchanged meson with mass m , momentum q needs to be introduced, and we take the form

$$F(q^2) = \frac{\Lambda_1^4}{(m^2 - q^2)^2 + \Lambda_1^4},$$

The parameter Λ_1 for the off-shell form factor varies for different system, and we will vary it in the range of $1.5 \sim 2.4$ GeV

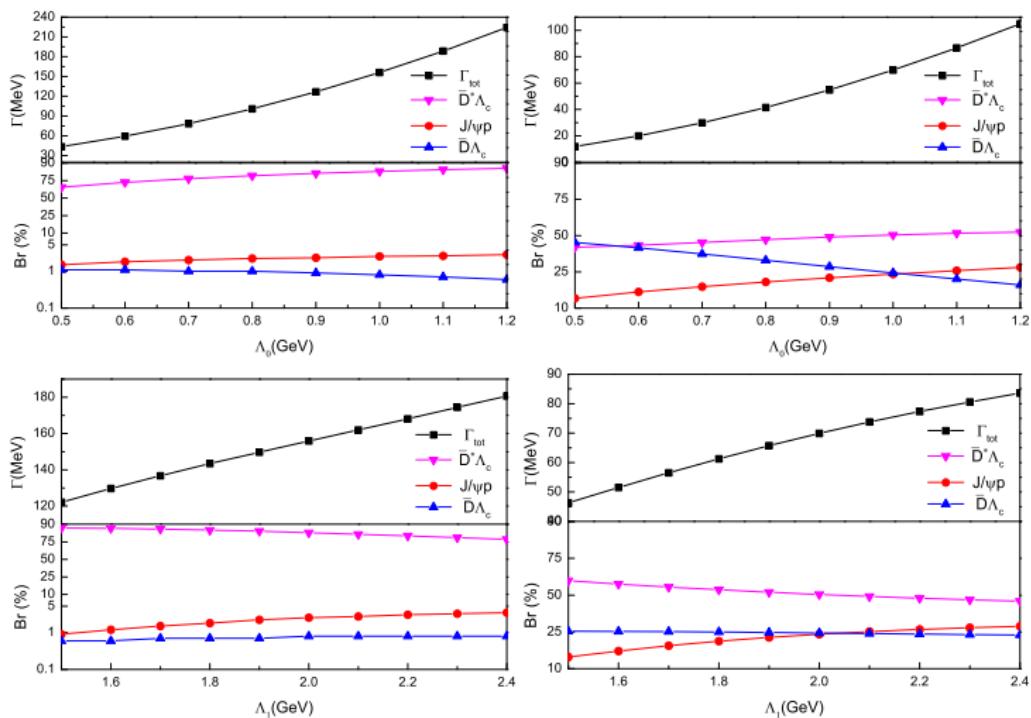


Figure: Dependence of the $P_c(4380)$ total width and branching fractions of $\bar{D}^*\Lambda_c$, $\bar{D}\Lambda_c$ and $J/\psi p$ on the cutoff Λ_0 and Λ_1 in different scenarios for the $P_c(4380)$: (left) S -wave $\bar{D}\Sigma_c^*$ molecule with $J^P = \frac{3}{2}^-$; (right) S -wave $\bar{D}^*\Sigma_c$ molecule with $J^P = \frac{3}{2}^-$. Upper Λ_1 is fixed at 2.0 GeV, and bottom Λ_0 is fixed at 1.0 GeV.

To estimate the partial widths of the $J^P = \frac{5}{2}^+$ $P_c(4450)$ state, we use the effective Lagrangian for the P -wave interaction among $P_c(4450)$, \bar{D}^* and Σ_c :

$$\mathcal{L}_{\bar{D}^*\Sigma_c P_c} = g_{\bar{D}^*\Sigma_c P_c} \left(-g^{\nu\alpha} + \frac{p^\nu p^\alpha}{p^2} \right) (\partial_\alpha \bar{\Sigma}_c \bar{D}^{*\mu} - \bar{\Sigma}_c \partial_\alpha \bar{D}^{*\mu}) P_{c\mu\nu} + H.c.,$$

with p the momentum of the P_c state. The coupling constant $g_{\bar{D}^*\Sigma_c P_c}$ may be obtained from the compositeness condition.

However, being in a P -wave, the obtained coupling strength relies much more on the cutoff Λ_0 . Thus, we can only make a rough estimate for the widths in this case.

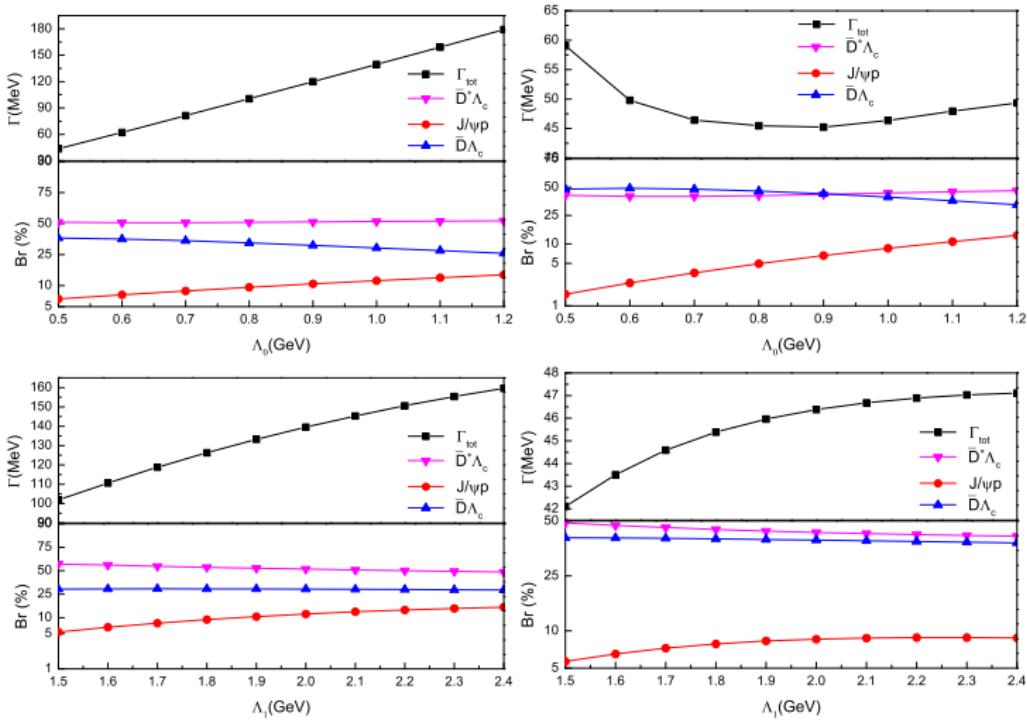


Figure: Dependence of the $P_c(4450)$ total width and branching fractions of $\bar{D}^*\Lambda_c$, $\bar{D}\Lambda_c$ and $J/\psi p$ on the cutoff Λ_0 and Λ_1 in different scenarios for the $P_c(4380)$: (left) S -wave $\bar{D}^*\Sigma_c$ molecule with $J^P = \frac{3}{2}^-$; (right) P -wave $\bar{D}^*\Sigma_c$ molecule with $J^P = \frac{5}{2}^+$. Upper Λ_1 is fixed at 2.0 GeV and bottom Λ_0 is fixed at 1.0 GeV.

The corresponding numerical results are obtained with $\Lambda_0 = 1.0$ GeV and $\Lambda_1 = 2.0$ GeV.

Mode	Widths (MeV)			
	$P_c(4380)$		$P_c(4450)$	
	$\bar{D}\Sigma_c^*(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{5}{2}^+)$
$D^*\Lambda_c$	110.4	28.6	63.8	16.3
$J/\psi p$	2.7	19.8	17.7	2.6
$\bar{D}\Lambda_c$	1.2	13.7	36.0	14.9
πN	0.08	0.06	0.06	0.03
$\chi_{c0}p$	0.8	0.002	0.01	0.001
$\eta_c p$	0.2	0.05	0.1	0.02
ρN	1.6	0.4	0.2	0.1
ωp	6.1	1.3	0.8	0.4
$\bar{D}\Sigma_c$	0.01	0.09	1.1	0.2
$\bar{D}\Sigma_c^*$	-	-	8.9	0.5
$\bar{D}\Lambda_c\pi$	7.5	-	-	-
Total	130.6	64.0	128.7	35.0

Production of P_c states in photo- and pion- induced reactions

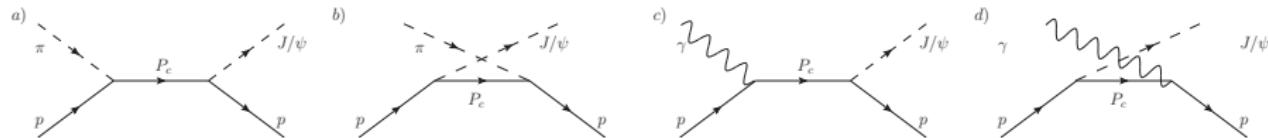


Figure: The s and u -channel contributions of the P_c states for the scattering processes $\pi p \rightarrow J/\psi p$ (a&b) and $\gamma p \rightarrow J/\psi p$ (c&d).

Mode	$P_c(4380)(\frac{3}{2}^-)$		$P_c(4450)(\frac{5}{2}^+)$	
	Widths(MeV)	Couplings	Widths(MeV)	Couplings
$J/\psi p$	3.8	0.36	4.0	$0.368 (\text{GeV}^{-1})$
πp	0.06	$0.0053 (\text{GeV}^{-2})$	0.2	$0.00695 (\text{GeV}^{-3})$
γp	0.0007	0.00239	0.00113	$0.00123 (\text{GeV}^{-1})$

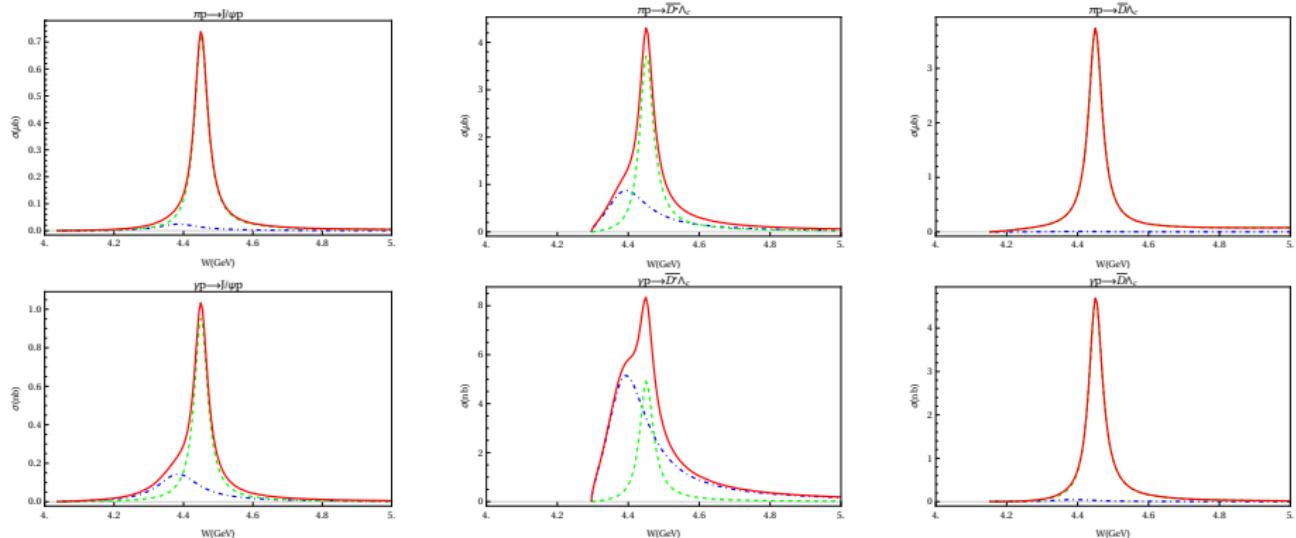


Figure: Dependence of the total cross sections on the center-of-mass energy for different processes. The blue dot-dashed, green dashed and red solid lines stand for the $P_c(4380)^{3-}_{\frac{3}{2}}$, $P_c(4450)^{5+}_{\frac{5}{2}}$ states and total contribution, respectively.

From this point of view, it should be easier to search for the hidden-charm pentaquark states in the $\bar{D}^*\Lambda_c$ and $\bar{D}\Lambda_c$ production than the $J/\psi p$ production.

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$\bar{D}\Lambda_c - \bar{D}\Sigma_c$ interactions in Jülich-Bonn model

Shen, Rönchen, Meißner and Zou:

We use Jülich-Bonn dynamical coupled-channel formalism to calculate the $\bar{D}\Lambda_c - \bar{D}\Sigma_c$ interactions.

The t-channel meson exchange and u-channel doubly-charmed baryon exchange are considered.

The T-matrix of the interaction of a baryon and a meson is formulated as

$$\begin{aligned} T_{\mu\nu}(p'', p', z) &= V_{\mu\nu}(p'', p', z) + \sum_{\kappa} \int_0^{\infty} dp p^2 V_{\mu\kappa}(p'', p, z) \\ &\quad \times G_{\kappa}(p, z) T_{\kappa\nu}(p, p', z) \end{aligned}$$

with

$$G_{\kappa}(p, z) = \frac{1}{z - E_a(p) - E_b(p) + i\epsilon}.$$

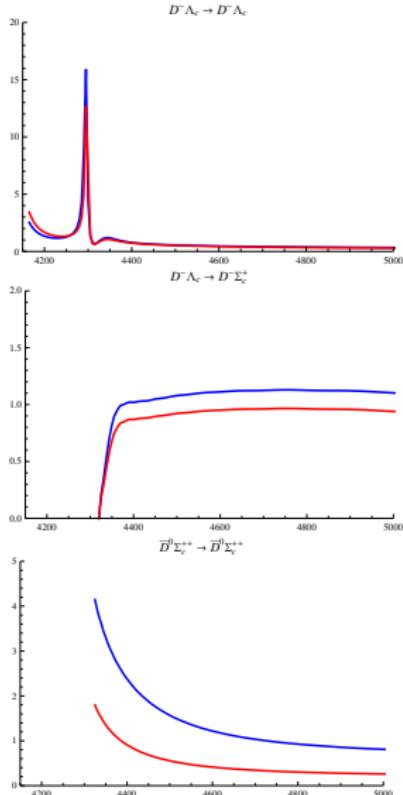
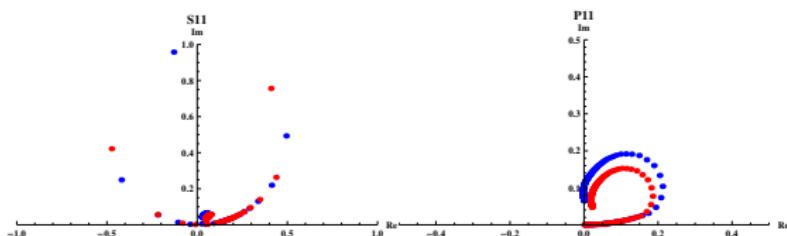


Figure: Total cross sections[mb].

Table: The states from $\bar{D}\Lambda_c \rightarrow \bar{D}\Lambda_c$ with $I = \frac{1}{2}$.



J^P	A	B
	z_R [MeV]	z_R [MeV]
$\frac{1}{2}^-$	4295-i3.713	4297-i2.954
$\frac{1}{2}^+$	4334-i28.20	4334-i29.65
$\frac{3}{2}^+$	4325-i54.00	4325-i53.84
$\frac{3}{2}^-$	4380-i147.0	4378-i146.0
$\frac{5}{2}^-$	4295-i185.5	4298-i183.0
$\frac{5}{2}^+$	4429-i338.5	4425-i329.8

We then applied it to the bottom case, $B\Lambda_b - B\Sigma_b$ interactions.

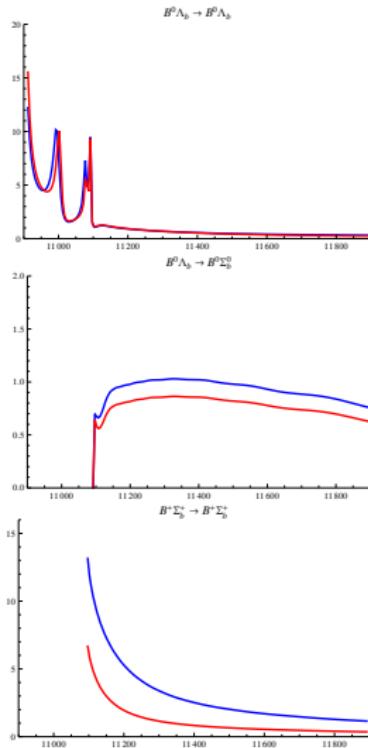
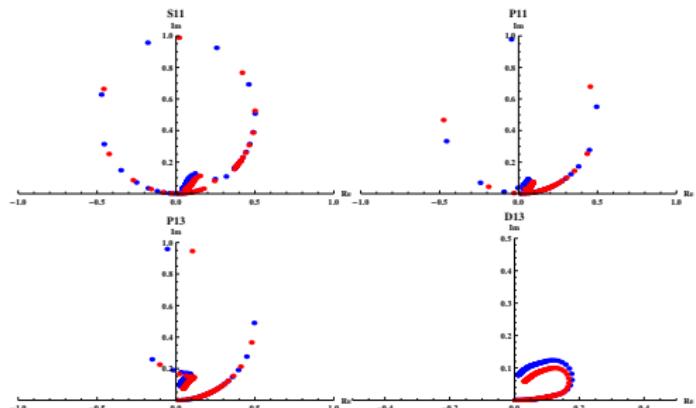


Figure: Total cross sections[mb].



z_R [MeV]	10997	11077
J^P	$\frac{1}{2}^-$	$\frac{1}{2}^+$
11092	11092	11127
$\frac{1}{2}^-$	$\frac{3}{2}^+$	$\frac{3}{2}^-$

Table: Pole positions z_R and spin-paritys for the states from $B\Lambda_b \rightarrow B\Lambda_b$ with $I = \frac{1}{2}$.

Overview

- 1 Disentangling the hadronic molecule nature of the pentaquark-like structure
 - LHCb's observation of pentaquark states
 - Predictions prior to LHCb observation
 - Explanations after LHCb observation
- 2 Decay behaviors of the P_c hadronic molecules
 - The decay width of the P_c to all possible final states
 - Production of P_c states in photo- and pion- induced reactions
- 3 $\bar{D}\Lambda_c - \bar{D}\Sigma_c$ interactions in Jülich-Bonn model
- 4 Summary and prospects

Summary and prospects

The relative ratio of the decays of $P_c^+(4380)$ to $\bar{D}^*\Lambda_c$ and $J/\psi p$ is very different for P_c being a $\bar{D}^*\Sigma_c$ or $\bar{D}\Sigma_c^*$ bound state with $J^P = \frac{3}{2}^-$.

From the total decay width, $P_c(4380)$ being a $\bar{D}\Sigma_c^*$ molecule state with $J^P = \frac{3}{2}^-$ and $P_c(4450)$ being a $\bar{D}^*\Sigma_c$ molecule state with $J^P = \frac{5}{2}^+$ is more reasonable.

More channels like $\bar{D}^*\Lambda_c$ and $\bar{D}^*\Sigma_c$ are taken into consideration in the Jülich-Bonn model calculations. (\leftarrow in progress.)

Searching in the $\bar{D}^*\Lambda_c$ and $\bar{D}\Lambda_c$ system in the forthcoming γp experiment at JLAB and πp experiment at JPARC can be used to disentangle the nature of these P_c states.

More pentaquark states, e.g. P_c states, $\Lambda_{c\bar{c}}$ states, are expected in further experimental results.

THANK YOU
FOR
WATCHING

My Conquest is the Sea of Stars