Decay behaviors of the P_c hadronic molecules

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Modern problems in nuclear and elementary particle physics

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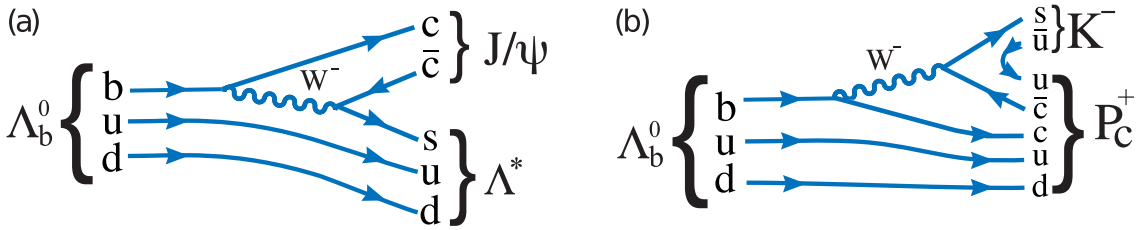
Overview

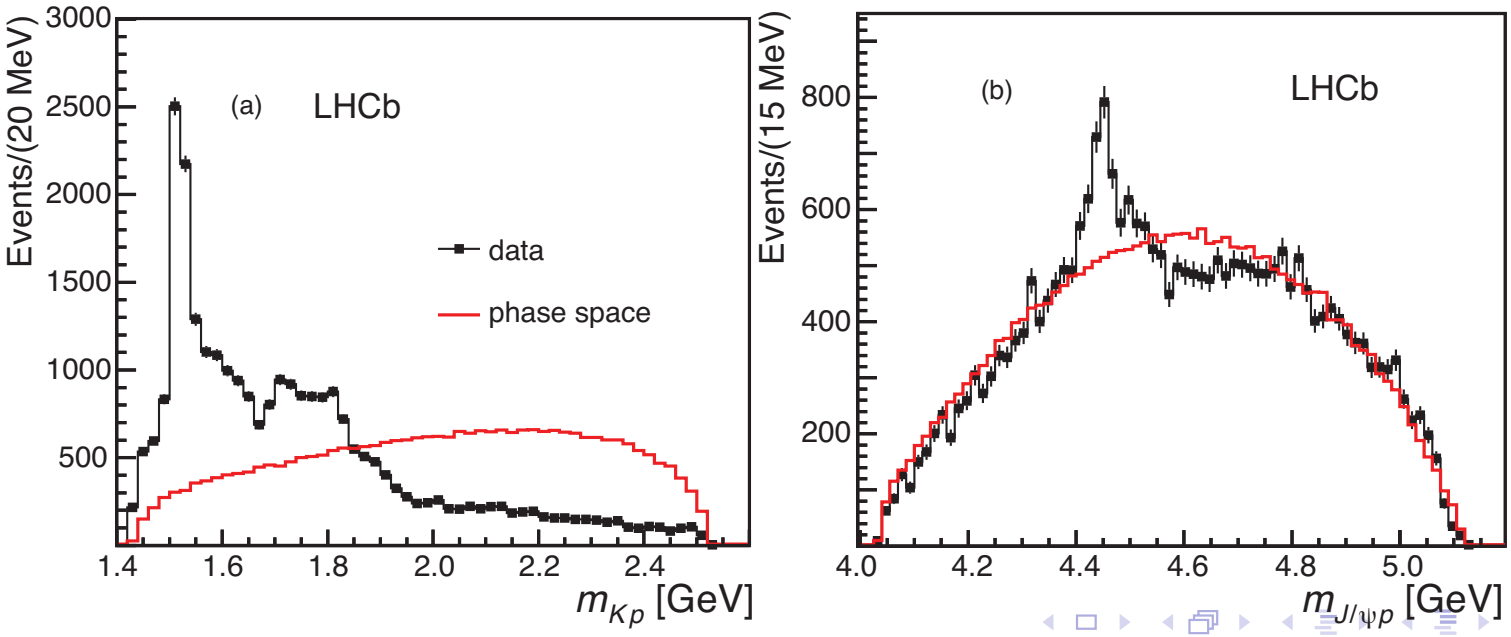
1. Disentangling the hadronic molecule nature of the pentaquark-like structure
   - LHCb's observation of pentaquark states
   - Predictions prior to LHCb observation
   - Explanations after LHCb observation

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
   - Problems and prospects

LHCb's observation of pentaquark states

LHCb Collaboration, Phys.Rev.Lett. 115 (2015) 072001
Observation of $J/\psi p$ resonances consistent with pentaquark states in $\Lambda_b^0 \to J/\psi K p$ Decays





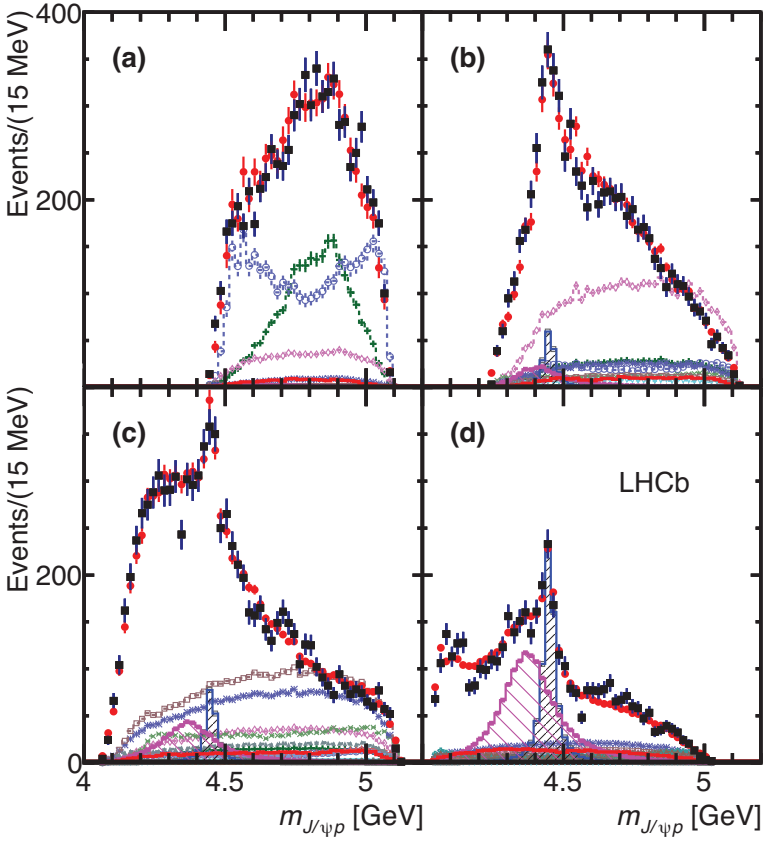


Figure: (d) $m_{Kp} > 2.00$ GeV

- 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

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, B.S. Zou
Phys.Rev.Lett. 105 (2010) 232001, Phys.Rev. C84 (2011) 015202.

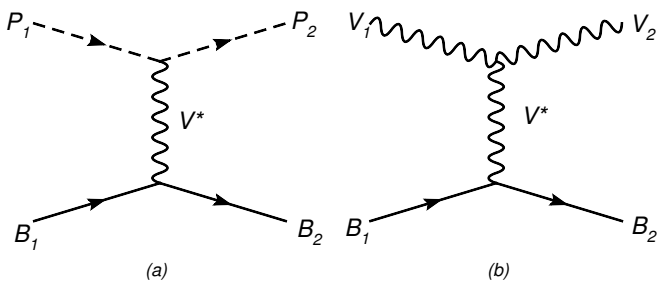


Figure: The Feynman diagrams of pseudoscalar-baryon (a) or vector- baryon (b) interaction via the exchange of a vector meson. P_1, P_2 is D^-, $\bar{D}^0$ or D_s^-, and V_1, V_2 is D^{*-}, $\bar{D}^{*0}$ or D_s^{*-}, and B_1, B_2 is Σ_c, Λ_c^+, Ξ_c, Ξ_c' or Ω_c, and V^* is ρ, K^*, ϕ or ω.

(I,S)	M	Γ	Γ_i					
$(1/2,0)$			πN	ηN	$\eta' N$	$K\Sigma$		$\eta_c N$
	4261	56.9	3.8	8.1	3.9	17.0		23.4
$(0,-1)$			$\bar{K}N$	$\pi\Sigma$	$\eta\Lambda$	$\eta'\Lambda$	$K\Xi$	$\eta_c\Lambda$
	4209	32.4	15.8	2.9	3.2	1.7	2.4	5.8
	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 $PB \to PB$, with units in MeV.

(I,S)	M	Γ	Γ_i					
$(1/2,0)$			ρN	ωN	$K^*\Sigma$			$J/\psi N$
	4412	47.3	3.2	10.4	13.7			19.2
$(0,-1)$			$\bar{K}^*N$	$\rho\Sigma$	$\omega\Lambda$	$\phi\Lambda$	$K^*\Xi$	$J/\psi\Lambda$
	4368	28.0	13.9	3.1	0.3	4.0	1.8	5.4
	4544	36.6	0	8.8	9.1	0	5.0	13.8

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

Explanations after LHCb observation

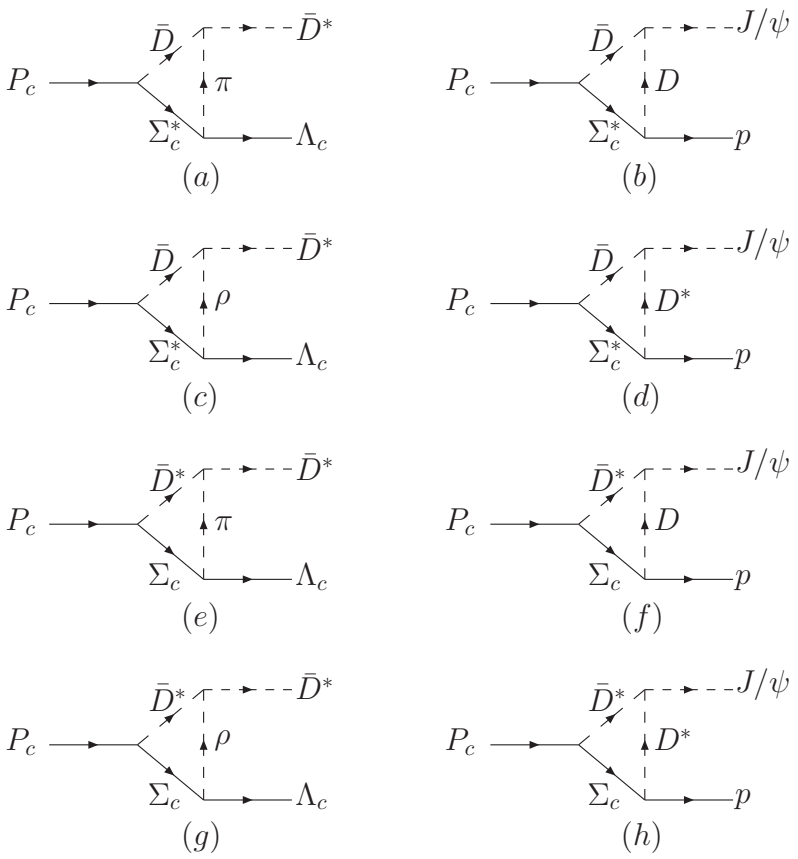
Three possible molecular states' thresholds

1. $\bar{D}\Sigma_c^*$ (4387 MeV)
2. $\bar{D}^*\Sigma_c$ (4461 MeV)
3. $\bar{D}^*\Sigma_c^*$ (4525 MeV)

LHCb experiment claims that the two states have opposite parity, which is against that both states are S-wave molecules with spin-parity $3/2^-$. And the preferred spin is one having spin-3/2 and the other 5/2.

The observed decay width of $P_c(4380)$ state is about a few times larger than the predicted one.

C.W. Shen, F.K. Guo, J.J. Xie, B.S. Zou, Nucl.Phys. A954 (2016) 393-405



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

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

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

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

where q_E is the Euclidean Jacobi momentum.

$$
\begin{aligned}
\mathcal{L}_{PPV} &= g_{PPV}\phi_P(x)\partial_\mu\phi_P(x)\phi_V^\mu(x), \\
\mathcal{L}_{VVP} &= g_{VVP}\, i\varepsilon_{\mu\nu\alpha\beta}\partial^\mu\phi_V^\nu(x)\partial^\alpha\phi_V^\beta(x)\phi_P(x), \\
\mathcal{L}_{VVV} &= g_{VVV}\, i\left[\partial_\mu\phi_{V\nu}(x) - \partial_\nu\phi_{V\mu}(x)\right]\phi_V^\mu(x)\phi_V^\nu(x), \\
\mathcal{L}_{BPB^*} &= g_{BPB^*}\left[\bar{\psi}_{B^*\mu}(x)\psi_B(x) + \bar{\psi}_B(x)\psi_{B^*\mu}(x)\right]\partial^\mu\phi_P(x), \\
\mathcal{L}_{BVB^*} &= g_{BVB^*}\, i\left[\bar{\psi}_{B^*\nu}(x)\gamma^5\gamma_\mu\psi_B(x) - \bar{\psi}_B(x)\gamma^5\gamma_\mu\psi_{B^*\nu}(x)\right] \\
&\quad \left[\partial^\mu\phi_V^\nu(x) - \partial^\nu\phi_V^\mu(x)\right], \\
\mathcal{L}_{BBP} &= g_{BBP}\bar{\psi}_B(x)i\gamma^5\psi_B(x)\phi_P(x), \\
\mathcal{L}_{BBV} &= g_{BBV}\left[\bar{\psi}_B(x)\gamma_\mu\psi_B(x)\phi_V^\mu(x)\right. \\
&\quad \left. +2f_{BBV}\bar{\psi}_B(x)\sigma_{\mu\nu}\psi_B(x)\left(\partial^\mu\phi_V^\nu(x) - \partial^\nu\phi_V^\mu(x)\right)\right],
\end{aligned}
$$

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

$$R_{\rm I} = \frac{\Gamma(P_c(4380) \to \bar{D}\Sigma_c^* \to \bar{D}^*\Lambda_c)}{\Gamma(P_c(4380) \to \bar{D}\Sigma_c^* \to J/\psi p)} \sim 10$$

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

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

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

where $\bar{H}_a = -\vec{\bar{D}}^*_a\cdot\vec{\sigma} + \bar{D}_a$, $\vec{u}_{ab} = -\sqrt{2}\vec{\partial}\phi_{ab}/F + \mathcal{O}(\phi^3)$,
$S^i_{ab} = B^{*i}_{6,ab} + \frac{1}{\sqrt{3}}\sigma^i B_{6,ab}$ 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

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

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

$$\begin{aligned} \sum_{\omega,\alpha,\lambda} \left|\mathcal{A}^{\rm OPE}_{\bar{D}\Sigma_c^*}\right|^2 &= 144 N^2 g_{P_c}^2 m_{\Lambda_c} m_{P_c} m_{\Sigma_c^*}^2 \times \\ &\quad \left[2\left|I_D(m_D, m_{\Sigma_c^*}, m_\pi, \vec{q}^{\,2})\right|^2 + \left|I_S(m_D, m_{\Sigma_c^*}, m_\pi, \vec{q}^{\,2})\right|^2\right], \\ \sum_{\omega,\alpha,\lambda} \left|\mathcal{A}^{\rm OPE}_{\bar{D}^*\Sigma_c}\right|^2 &= 48 N^2 g_{P_c}'^2 m_{\Lambda_c} m_{P_c} m_{\Sigma_c}^2 \times \\ &\quad \left[5\left|I_D(m_D, m_{\Sigma_c^*}, m_\pi, \vec{q}^{\,2})\right|^2 + \left|I_S(m_D, m_{\Sigma_c^*}, m_\pi, \vec{q}^{\,2})\right|^2\right]. \end{aligned}$$

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

$$g^2 = \frac{4\pi}{4Mm_2}\frac{(m_1+m_2)^{5/2}}{(m_1m_2)^{1/2}}\sqrt{32\epsilon},$$

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.

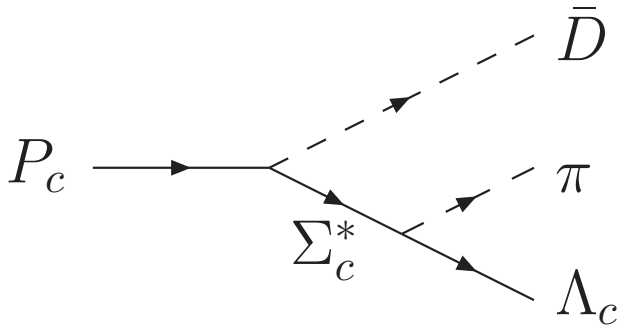


Figure: The three-body decay for $P_c(4380)$ being a $\bar{D}\Sigma_c^*$ hadronic molecule.

The three-body decay $P_c \to \bar{D}\pi\Lambda_c$ 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, B.S.Zou, Phys.Rev.D95(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
$P_c(4380)(\bar{D}\Sigma_c^*)$	$\bar{D}^*\Lambda_c$, $J/\psi p$, $\bar{D}\Lambda_c$, πN, $\chi_{c0}p$, $\eta_c p$, ρN, ωp, $\bar{D}\Sigma_c$
$P_c(4380)(\bar{D}^*\Sigma_c)$	$\bar{D}^*\Lambda_c$, $J/\psi p$, $\bar{D}\Lambda_c$, πN, $\chi_{c0}p$, $\eta_c p$, ρN, ωp, $\bar{D}\Sigma_c$
$P_c(4450)(\bar{D}^*\Sigma_c)$	$\bar{D}^*\Lambda_c$, $J/\psi p$, $\bar{D}\Lambda_c$, πN, $\chi_{c0}p$, $\eta_c p$, ρN, ωp, $\bar{D}\Sigma_c$, $\bar{D}\Sigma_c^*$

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

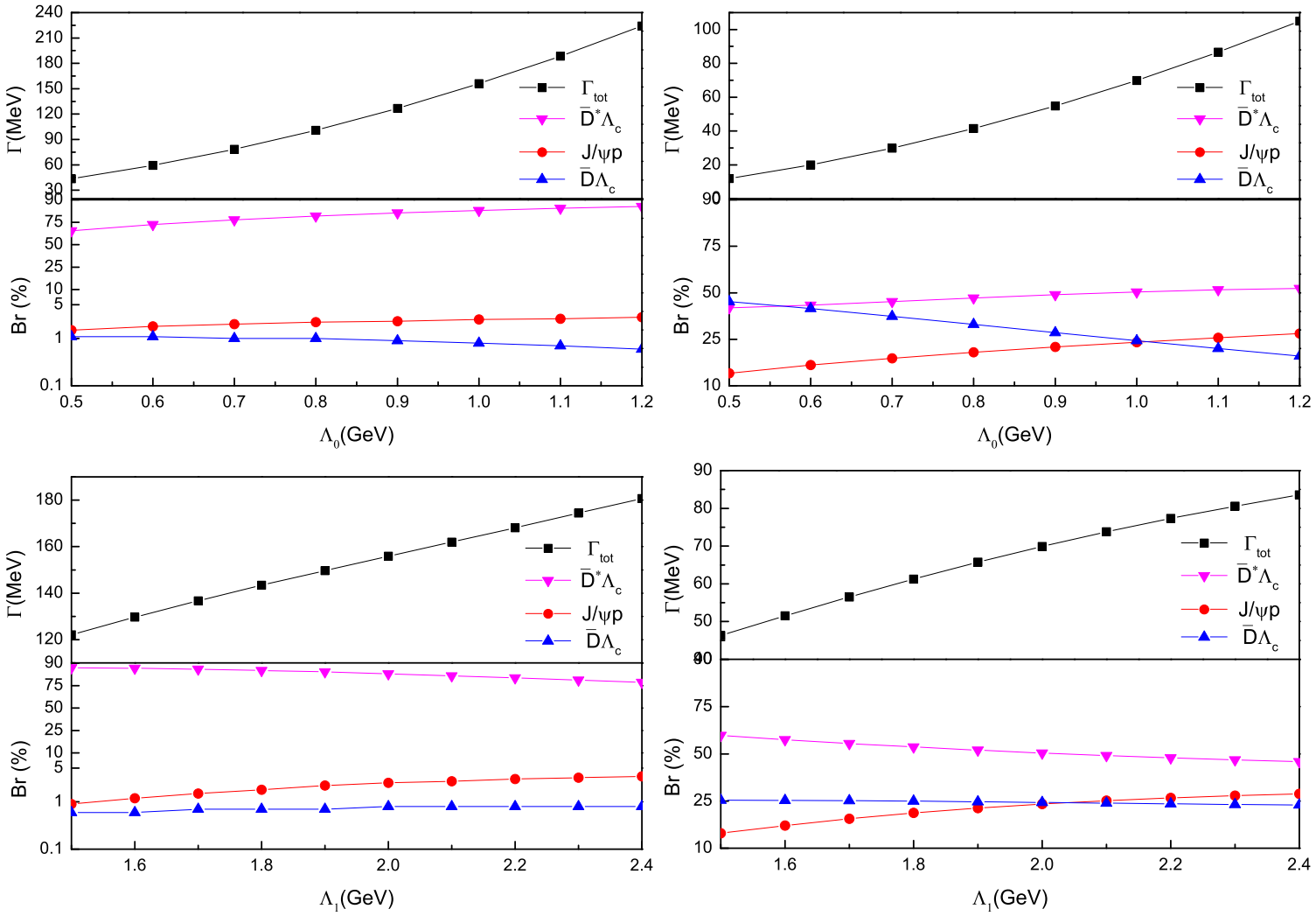

Figure: Dependence of the $P_c(4380)$ total width and branching fractions of $\bar{D}^*\Lambda_c$, $\bar{D}\Lambda_c$ and $J/\psi p$ on the cutoff Λ_0 and Λ_1 in different scenarios for the $P_c(4380)$: (left) S-wave $\bar{D}\Sigma_c^*$ molecule with $J^P = \frac{3}{2}^-$; (right) S-wave $\bar{D}^*\Sigma_c$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

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

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

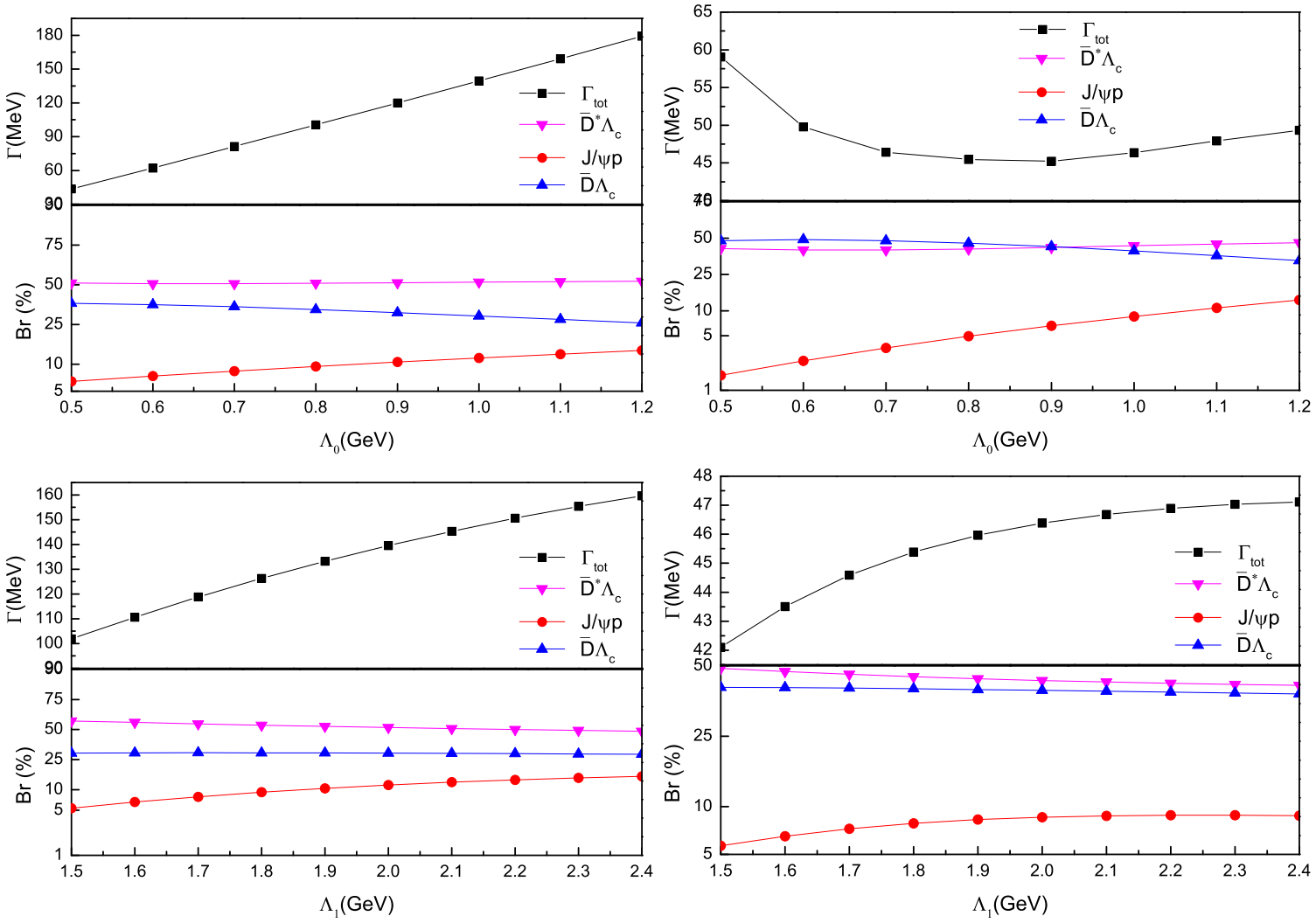

Figure: Dependence of the $P_c(4450)$ total width and branching fractions of $\bar{D}^*\Lambda_c$, $\bar{D}\Lambda_c$ and $J/\psi p$ on the cutoff Λ_0 and Λ_1 in different scenarios for the $P_c(4380)$: (left) S-wave $\bar{D}^*\Sigma_c$ molecule with $J^P = \frac{3}{2}^-$; (right) P-wave $\bar{D}^*\Sigma_c$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

Mode	Widths (MeV)			
	$P_c(4380)$		$P_c(4450)$	
	$\bar{D}\Sigma_c^*(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{5}{2}^+)$
$\bar{D}^*\Lambda_c$	131.3	35.3	72.3	20.5
$J/\psi p$	3.8	16.6	16.3	4.0
$\bar{D}\Lambda_c$	1.2	17.0	41.4	18.8
πN	0.06	0.07	0.07	0.2
$\chi_{c0} p$	0.9	0.004	0.02	0.002
$\eta_c p$	0.2	0.09	0.1	0.04
ρN	1.4	0.15	0.14	0.3
ωp	5.3	0.6	0.5	0.3
$\bar{D}\Sigma_c$	0.01	0.1	1.2	0.8
$\bar{D}\Sigma_c^*$	-	-	7.7	1.4
$\bar{D}\Lambda_c\pi$	11.6	-	-	-
Total	144.3	69.9	139.8	46.4

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

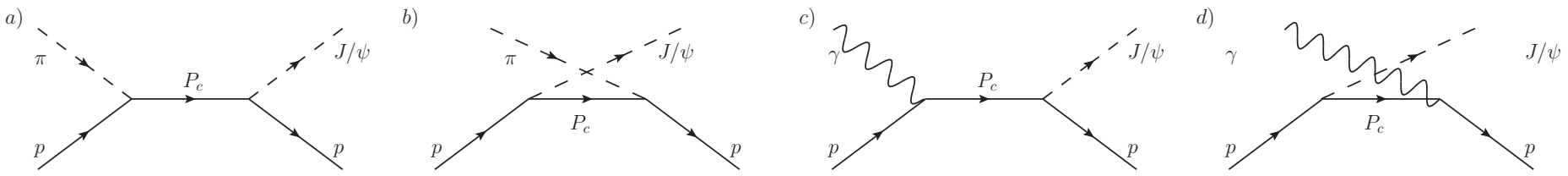

Figure: The s and u-channel contributions of the P_c states for the scattering processes $\pi p \to J/\psi p$ (a&b) and $\gamma p \to J/\psi p$ (c&d).

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 (GeV^{-1})
πp	0.06	0.0053 (GeV^{-2})	0.2	0.00695 (GeV^{-3})
γp	0.0007	0.00239	0.00113	0.00123 (GeV^{-1})

Blatt-Weisskopf barrier factor

We introduce a Blatt-Weisskopf barrier factor $B_L(q, q_R)$ for each s-channel L-wave coupling vertex. The explicit forms are as the following:

$$
\begin{aligned}
B_{L=1}(q, q_R) &= 1, \\
B_{L=2}(q, q_R) &= \sqrt{\frac{1 + (\frac{|q_R|}{\Lambda})^2}{1 + (\frac{|q|}{\Lambda})^2}}, \\
B_{L=3}(q, q_R) &= \sqrt{\frac{((\frac{|q_R|}{\Lambda})^2 - 3)^2 + 9 \times (\frac{|q_R|}{\Lambda})^2}{((\frac{|q|}{\Lambda})^2 - 3)^2 + 9 \times (\frac{|q|}{\Lambda})^2}}, \\
B_{L=4}(q, q_R) &= \sqrt{\frac{(\frac{|q_R|}{\Lambda})^2 \times ((\frac{|q_R|}{\Lambda})^2 - 15)^2 + 9 \times (2(\frac{|q_R|}{\Lambda})^2 - 5)^2}{(\frac{|q|}{\Lambda})^2 \times ((\frac{|q|}{\Lambda})^2 - 15)^2 + 9 \times (2(\frac{|q|}{\Lambda})^2 - 5)^2}}.
\end{aligned}
$$

where q is the incident or exit three momentum in the center-of-mass system and q_R is the value of q at the peak of the relevant P_c state. The Λ parameter takes a typical value of 0.2 GeV in our calculation.

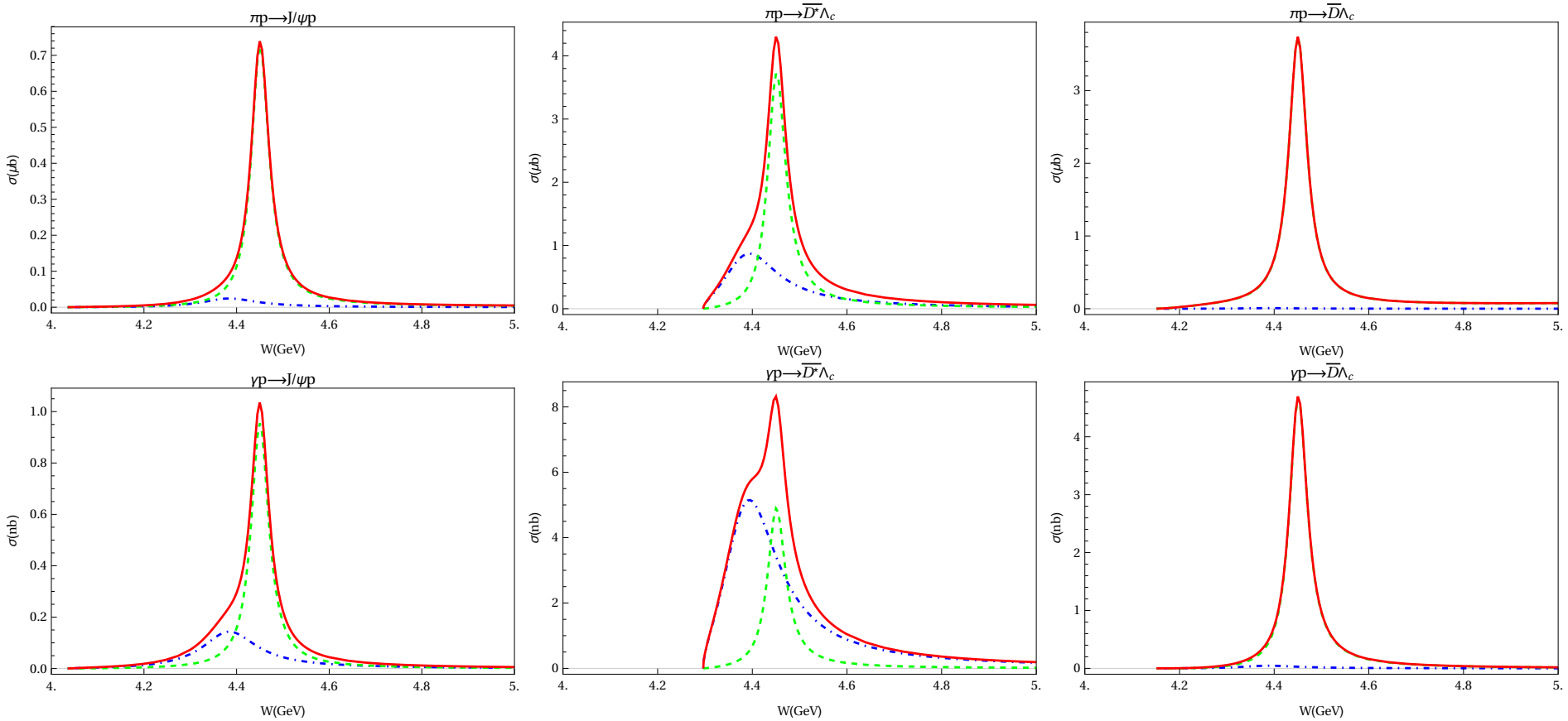

Figure: Dependence of the total cross sections on the center-of-mass energy W for the different processes. The blue dot-dashed, green dashed and red solid lines stand for the spin-parity-$\frac{3}{2}^-$ $P_c(4380)$, spin-parity-$\frac{5}{2}^+$ $P_c(4450)$ intermediate states and total contribution, respectively.

Problems and prospects

The $\mathrm{P_c}(1/2^-)$ state.

The mass difference between these two pentaquark-like states.

Systematic theoretical study of the pentaquark spectroscopy
$\bar{\mathrm{c}}\mathrm{cuud}$ & $\bar{\mathrm{c}}\mathrm{cuds}$ $\rightarrow$ sss $-$ $\bar{\mathrm{q}}\mathrm{qsss}$ $\rightarrow$ light baryons
$\bar{\mathrm{c}}\mathrm{c}\ \bar{\mathrm{u}}\mathrm{d}$ & $\bar{\mathrm{c}}\mathrm{s}\ \bar{\mathrm{u}}\mathrm{d}$ $\rightarrow$ $\bar{\mathrm{c}}\mathrm{c}$ $-$ $\bar{\mathrm{q}}\mathrm{q}\ \bar{\mathrm{c}}\mathrm{c}$ $\rightarrow$ light mesons

THANK YOU
FOR
WATCHING

My Conquest is the Sea of Stars