Is Pc(4457) a positive parity state?

Jia-Jun Wu (UCAS)

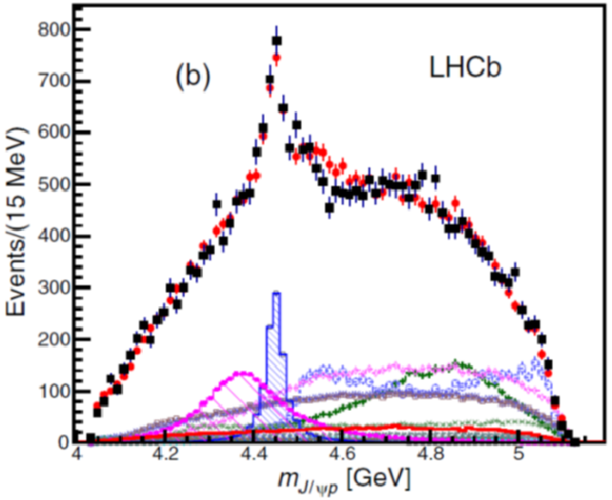
Collaborator: Jinzi Wu, Jinyi Pang

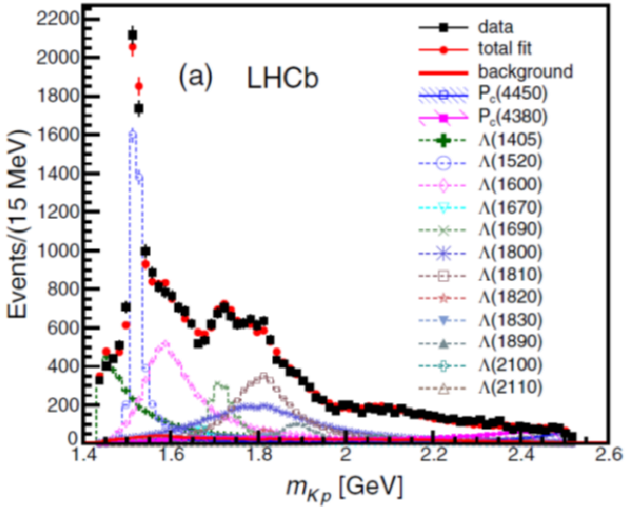
2407.05743 [hep-ph](Chin. Phys. 41 (2024) 9, 091201)

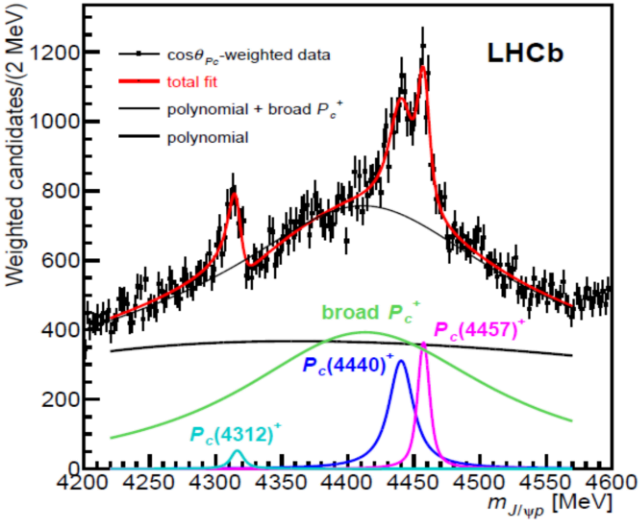
Outline

- Introduction of P_c states
- $\bar{\mathrm{D}}\Lambda_{\mathrm{c}1}(2595)$ channel
- $\bar{\mathrm{D}}\Lambda_{\mathrm{c}1}(2595) - P_c(4312)\pi$ coupled channel
- Discussion and Summary

Introduction of Pc states







$\bar{D}\Sigma_c$ threshold: 4320 MeV

$\bar{D}^*\Sigma_c$ threshold: 4465 MeV

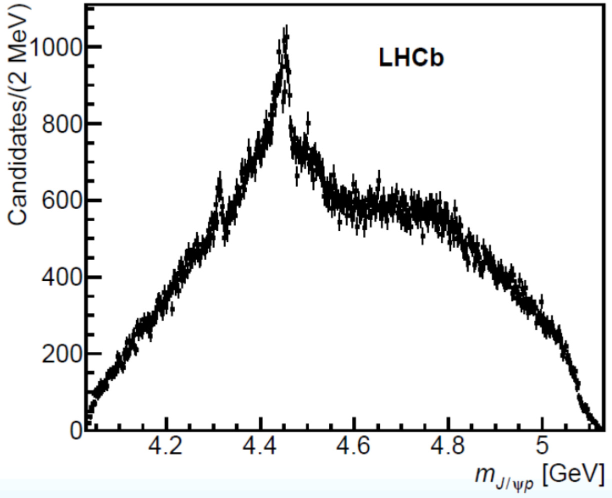
LHCb

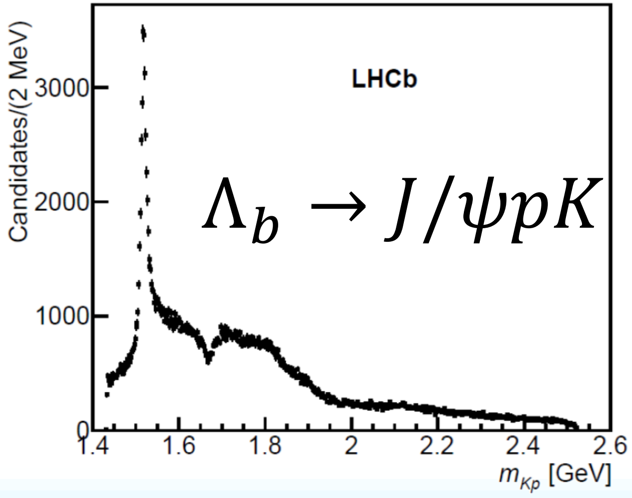
PRL 115 (2015) 072001

1849 Citations

PRL 122 (2019) 222001

815 Citations



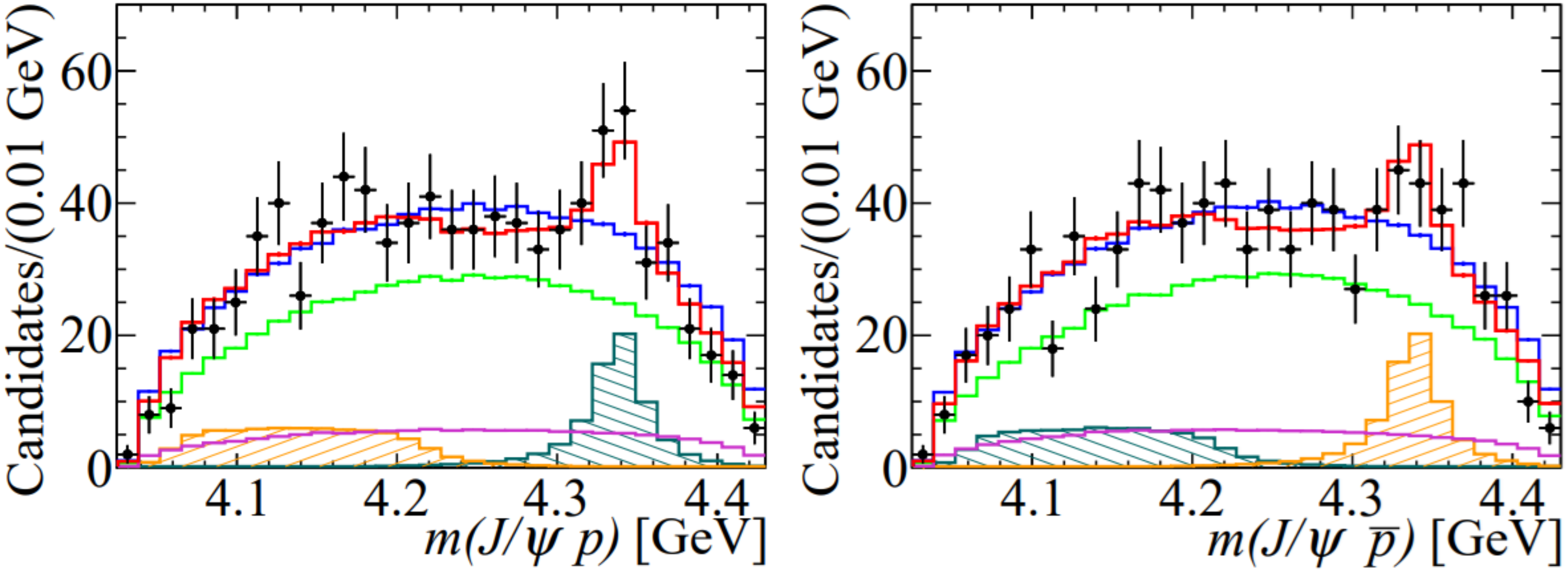


Pc(4380)	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$
Pc(4450)	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$

Pc(4312)	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$
Pc(4440)	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.5}$
Pc(4457)	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$

Unit: MeV

Introduction of Pc states



LHCb PRL 128 (2022) 6, 062001

115 Citations

$\bar{D}\Sigma_c$ threshold: 4320 MeV

$$M_{P_c} = 4337 \,^{+7}_{-4}\,^{+2}_{-2}\,\mathrm{MeV},$$
$$\Gamma_{P_c} = 29 \,^{+26}_{-12}\,^{+14}_{-14}\,\mathrm{MeV},$$

$3.1 - 3.7\sigma$

$B_s^0 \to J/\psi p\bar{p}$

University of Chinese Academy of Sciences

Introduction of Pc states

1) Molecular states: P_c -- $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$, $\bar{D}^*\Sigma_c^*$

……,too many papers !

2) Compact Pentaquark: $cu + \bar{c}(ud)$ **states**

Maiani,Polosa,Riquer, PLB749 (2015) 289;
Lebed, PLB749 (2015) 454;
Li,He,He, JHEP 1512 (2015) 128;
Zhu,Qiao, PLB756 (2016) 259;
Yuan, An, Wei, Zou, Xu,PRC87(2013) 025205;
Yuan, He, Xu, Zou, Eur.Phys.J.A 48 (2012) 61; ……

3) Kinematic triangle-singularity

Guo, Meißner, Wang, Yang, PRD92 (2015) 071502;
Liu, Wang, Zhao, PLB757 (2016) 231;
Bayar, Aceti, Guo and Oset, PRD94(2016) 074039; ……

Chen, Chen, Liu, and Zhu, PR 639, 1 (2016),1601.02092.

Dong, Faessler, and Lyubovitskij, PPNP 94, 282 (2017).

Guo, Hanhart, Meissner, Wang, Zhao, and Zou, RMP 90, 015004 (2018), 1705.00141.

Ali, Lange, and Stone, PPNP 97, 123 (2017), 1706.00610.

Introduction of Pc states

1) Molecular states: P_c—— $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$, $\bar{D}^*\Sigma_c^*$

……,too many papers !

- Valencia Model：

  Wu, Molina, Oset and Zou, PRL 105, 232001, PRC 84, 015202 (2010)

  Garcia-Recio, Nieves, Romanets, Salcedo, and Tolos, PRD87, 074034(2013)

  Xiao, Nieves, and Oset, PRD88, 056012(2013)

  Uchino, Liang, and Oset, EPJA 52, 43(2016)

  $\bar{D}\Sigma_c$ ~ 4.3 GeV $\bar{D}\Sigma_c^*$ ~ 4.35 GeV $\bar{D}^*\Sigma_c$ ~ 4.4 GeV $\bar{D}^*\Sigma_c^*$ ~ 4.5 GeV

- EBAC Model： **Wu, Lee and Zou, PRC 85, 044002 (2012)**

  $\bar{D}\Sigma_c$ ~ 4.3 GeV $\bar{D}^*\Sigma_c$ ~ 4.4 GeV

- Chiral constituent quark model & a resonating group method equation

  Wang, Huang, Zhang, Zou, PRC 84,015203(2011). $\bar{D}\Sigma_c$ ~ 4.3 GeV

- Schrödinger Equation & One boson exchange：

  Yang, Sun, He, Liu, Zhu, Chin.Phys. C36 (2012) 6-13

  $\bar{D}\Sigma_c$(I=3/2) ~ 4.3 GeV $\bar{D}^*\Sigma_c$ ~ 4.4 GeV

- Pentaquark Model： **Yuan, Wei, He, Xu and Zou, EPJA 48, 61(2012)**~ 4.3-4.5 GeV

$\bar{D}\Sigma_c - \eta_c N - \eta N$ coupled channel state ~ 3.5 GeV

J. Hofmann, M.F.M. Lutz, Nucl. Phys. A 763 (2005) 90

$c\bar{c}$-N bound states in topological soliton model **~ 3.9 GeV**

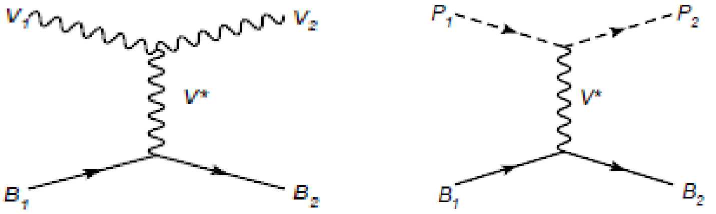
C. Gobbi, D.O. Riska, N.N. Scoccola, Phys. Lett. B 296 (1992) 166

Introduction of Pc states

$J^P = 1/2^-,\ \ 3/2^-$

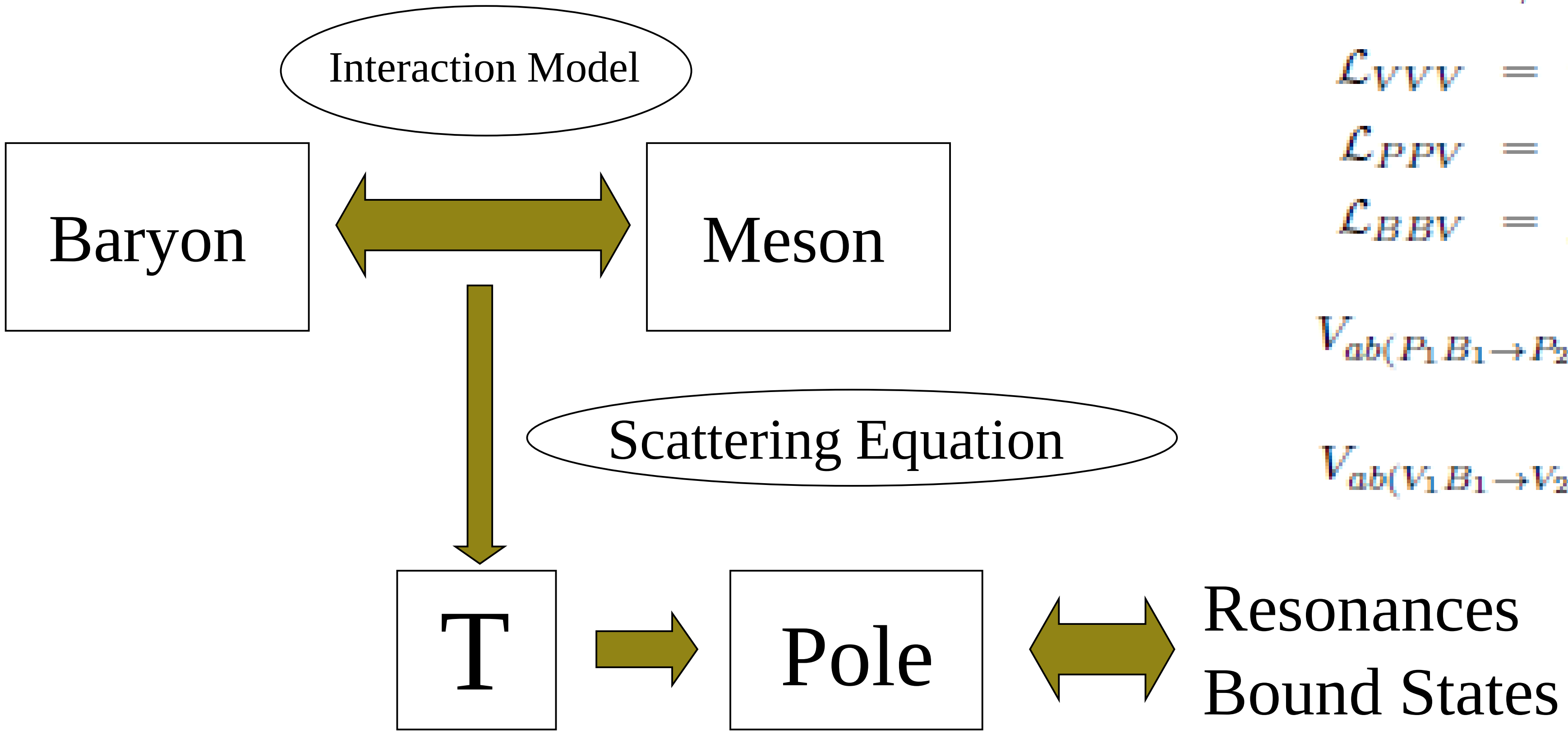
1) Molecular states: P_c -- $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$, $\bar{D}^*\Sigma_c^*$

Wu, Molina, Oset and Zou, PRL 105, 232001，PRC 84, 015202 (2010)



$$\mathcal{L}_{VVV} = ig\langle V^\mu [V^\nu, \partial_\mu V_\nu]\rangle$$
$$\mathcal{L}_{PPV} = -ig\langle V^\mu [P, \partial_\mu P]\rangle$$
$$\mathcal{L}_{BBV} = g(\langle \bar{B}\gamma_\mu [V^\mu, B]\rangle + \langle \bar{B}\gamma_\mu B\rangle\langle V^\mu\rangle$$

$$V_{ab(P_1B_1\to P_2B_2)} = \frac{C_{ab}}{4f^2}(E_{P_1}+E_{P_2}),$$
$$V_{ab(V_1B_1\to V_2B_2)} = \frac{C_{ab}}{4f^2}(E_{V_1}+E_{V_2})\vec{\epsilon}_1\cdot\vec{\epsilon}_2,$$



$$T = [1 - VG]^{-1}V$$

$$T_{ab} = \frac{g_a g_b}{\sqrt{s} - z_R}$$

$\bar{D}\Lambda_{c1}(2595)$ channel

The threshold of $\bar{D}\Lambda_c(2595)$ is 1865+2595=4460 MeV, just above the Pc(4457)!

$\bar{D}\Lambda_{c1}(2595)$ channel

The threshold of $\bar{D}\Lambda_c(2595)$ is 1865+2595=4460 MeV, just above the Pc(4457)!

Before Pc(4457), just Pc(4450)

Geng, Lu, and Valderrama. PRD, 97 094036,

Scale invariance in heavy hadron molecules

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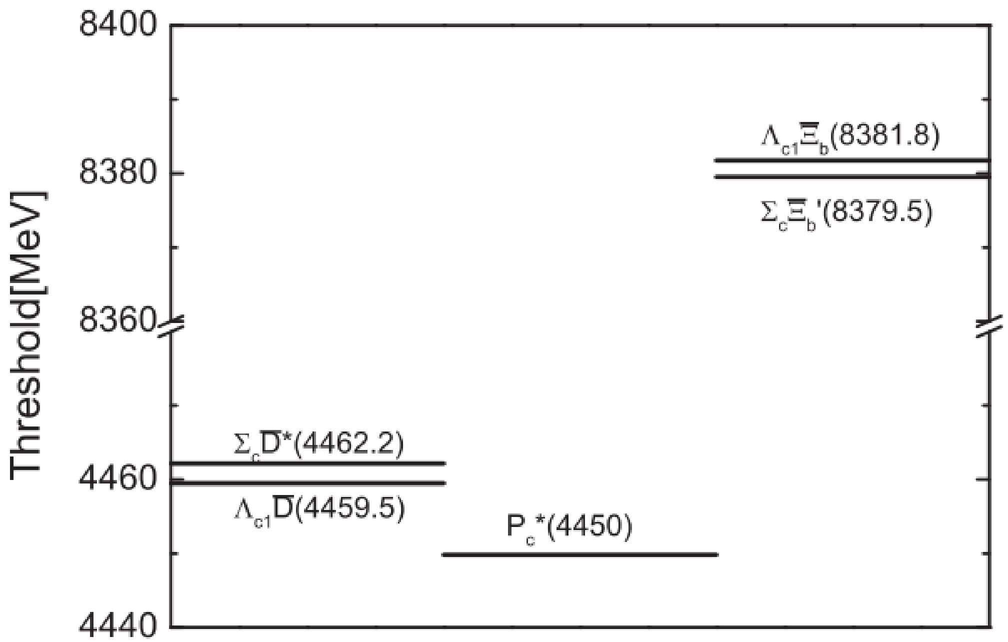
We discuss a scenario in which the $P_c(4450)^+$ heavy pentaquark is a $\Sigma_c\bar{D}^*$-$\Lambda_c(2595)\bar{D}$ molecule. The $\Lambda_{c1}\bar{D} \to \Sigma_c\bar{D}^*$ transition is mediated by the exchange of a pion almost on the mass shell that generates a long-range $1/r^2$ potential. This is analogous to the effective force that is responsible for the Efimov spectrum in three-boson systems interacting through short-range forces. The equations describing this molecule exhibit approximate scale invariance, which is anomalous and broken by the solutions. If the $1/r^2$ potential is strong enough this symmetry survives in the form of discrete scale invariance, opening the prospect of an Efimov-like geometrical spectrum in two-hadron systems. For a molecular pentaquark with quantum numbers $\frac{3}{2}^-$ the attraction is not enough to exhibit discrete scale invariance, but this prospect might very well be realized in a $\frac{1}{2}^+$ pentaquark or in other hadron molecules involving transitions between particle channels with opposite intrinsic parity and a pion near the mass shell. A very good candidate is the $\Lambda_c(2595)\bar{\Xi}_b - \Sigma_c\bar{\Xi}_b'$ molecule. Independently of this, the $1/r^2$ force is expected to play a very important role in the formation of this type of hadron molecule, which points to the existence of $\frac{1}{2}^+$ $\Sigma_c D^*$-$\Lambda_c(2595)D$ and 1^+ $\Lambda_c(2595)\Xi_b - \Sigma_c\Xi_b'$ molecules and $0^+/1^-$ $\Lambda_c(2595)\bar{\Xi}_b - \Sigma_c\bar{\Xi}_b'$ baryonia.



After Pc(4457)

$\bar{D}\Lambda_{c1}(2595)$ channel

After Pc(4457)

Burns and Swanson PRD 100 114033,2019

Molecular interpretation of the $P_c(4440)$ and $P_c(4457)$ states

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(Received 23 August 2019; published 20 December 2019)

A molecular model of the $P_c(4457)$ and $P_c(4440)$ LHCb states is proposed. The model relies on channels coupled by long-range pion-exchange dynamics with features that depend crucially on the novel addition of the $\Lambda_c(2595)\bar{D}$ channel. A striking prediction of the model is the unusual combination of quantum numbers $J^P(4457) = 1/2^+$ and $J^P(4440) = 3/2^-$. Unlike in other models, a simultaneous description of both states is achieved without introducing additional short-range interactions. The model also gives a natural explanation for the relative widths of the states. We show that the usual molecular scenarios cannot explain the production rate of P_c states in Λ_b decays and that this can be resolved by including $\Lambda_c(2595)\bar{D}$ and related channels. Experimental tests and other states are discussed in the conclusions.

Yalikun, Lin, Guo, Kamiya, and Zou PRD 104,094039,2021.

Coupled-channel effects of the $\Sigma_c^{(*)}\bar{D}^{(*)}$–$\Lambda_c(2595)\bar{D}$ system and molecular nature of the P_c pentaquark states from one-boson exchange model

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[4] *School of Physics and Electronics, Central South University, Changsha 410083, China*

The effects of the $\Sigma_c\bar{D}^*$-$\Lambda_c(2595)\bar{D}$ coupled-channel dynamics and various one-boson-exchange (OBE) forces for the LHCb pentaquark states, $P_c(4440)$ and $P_c(4457)$, are reinvestigated. Both the pion and ρ-meson exchanges are considered for the $\Sigma_c\bar{D}^*$-$\Lambda_c(2595)\bar{D}$ coupled-channel dynamics. It is found that the role of the $\Lambda_c(2595)\bar{D}$ channel in the descriptions of the $P_c(4440)$ and $P_c(4457)$ states is not significant with the OBE parameters constrained by other experimental sources. The naive OBE models with the short-distance $\delta(\vec{r})$ term of the one-pion exchange (OPE) keep failing to reproduce the $P_c(4440)$ and $P_c(4457)$ states simultaneously. The OPE potential with the full $\delta(\vec{r})$ term results in a too large mass splitting for the $J^P = 1/2^-$ and $3/2^-$ $\Sigma_c\bar{D}^*$ bound states with total isospin $I = 1/2$. The OBE model with only the OPE $\delta(\vec{r})$ term dropped may fit the splitting much better but somewhat underestimates the splitting. Since the $\delta(\vec{r})$ potential is from short-distance physics, which also contains contributions from the exchange of mesons heavier than those considered explicitly, we vary the strength of the $\delta(\vec{r})$ potential and find that the masses of the $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$ can be reproduced simultaneously with the $\delta(\vec{r})$ term in the OBE model reduced by about 80%. While two different spin assignments are possible to produce their masses, in the preferred description, the spin parities of the $P_c(4440)$ and $P_c(4457)$ are $3/2^-$ and $1/2^-$, respectively.

$\bar{D}\Lambda_{c1}(2595)$ channel

After Pc(4457)

Burns and Swanson PRD 100 114033,2019

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Yalikun

Coupled-channel effects of the $\Sigma_c^{(*)}\bar{D}^{(*)}$–$\Lambda_c(2595)\bar{D}$ system and molecular nature of the P_c pentaquark states from one-boson exchange model

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Kamiya, and Zou PRD 104,094039,2021.

Universität Bonn, D-53115 Bonn, Germany
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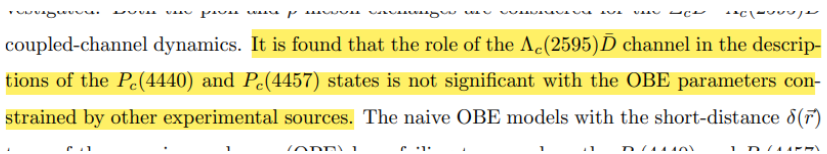
$\bar{D}\Lambda_{c1}(2595) - P_c(4312)\pi$ coupled channel

Another coupled channel $P_c(4312)\pi$, the threshold is 4312+135 = 4447 MeV, also very close to $P_c(4457)$.

Furthermore, the spin-parity is $1/2^-$ and 0^-, if we assume $P_c(4312)$ is bound state of $\bar{D}\Sigma_c$, then the quantum number of J^P for the S-wave state is also $1/2^+$.

Then we consider $\bar{D}\Lambda_{c1}(2595) - P_c(4312)\pi$ couple channel.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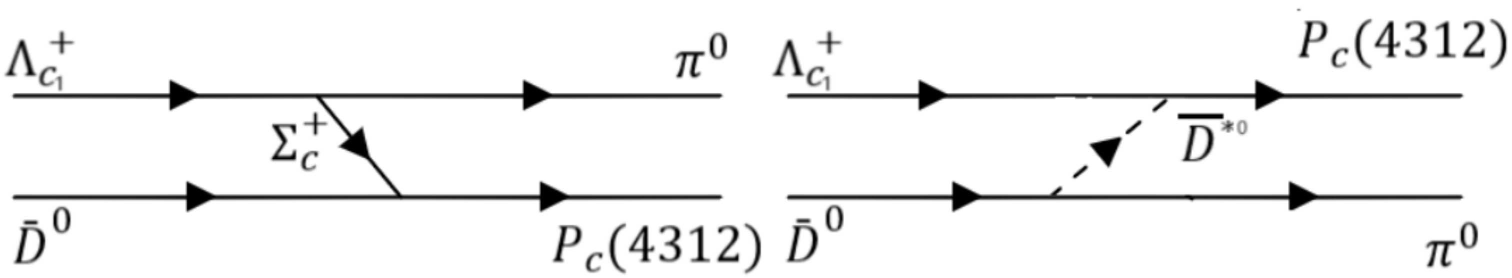
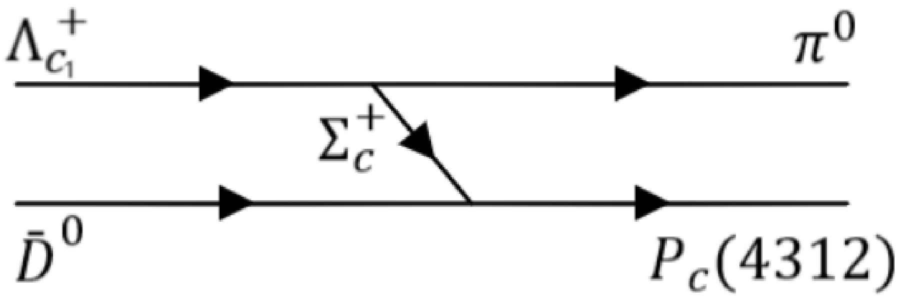


The diagonal term of potential is neglect! While the off-diagonal term will have two mechanisms.

Σ_C^+ is almost on-shell !

$\bar{D}\Lambda_{c1}(2595) - P_c(4312)\pi$: **$\bar{D}\pi\Sigma_c^+$** three-body

$\bar{D}\Lambda_{c1}(2595) - P_c(4312)\pi$ coupled channel



$$\mathcal{U}_i(\boldsymbol{p},\lambda_i) = \sqrt{\frac{\omega_i(\boldsymbol{p})+m_i}{2m_i}}\begin{pmatrix}\Phi^{\lambda_i}\\ \frac{\boldsymbol{\sigma}\cdot\boldsymbol{p}}{\omega_i(\boldsymbol{p})+m_i}\Phi^{\lambda_i}\end{pmatrix},$$

$$\Gamma = g_1^2\frac{q_{on}}{4\pi}\frac{\left(\omega_{\Sigma_c^+}(q_{on})+m_{\Sigma_c^+}\right)}{m_{\Lambda_{c1}^+}}$$

$$g_2^2 = \frac{4\pi}{4m_{P_c}m_{\Sigma_c}}\frac{(m_{\Sigma_c}+m_D)^{\frac{5}{2}}}{(m_{\Sigma_c}m_D)^{\frac{1}{2}}}\sqrt{32\,|m_{\Sigma_c}+m_D-m_{P_c}|}$$

Weinberg PR 137(1965) B672
Baru, et.al. PLB586(2004) 53
Lin, Shen, Guo, and Zou. PRD95(2017) 114017

$$\mathcal{V}_{\alpha\beta}(\boldsymbol{p},\,\boldsymbol{q},\,\lambda_{\alpha_B},\,\lambda_{\beta_B}) = g_1 g_2\bar{\mathcal{U}}_{\beta_B}(\boldsymbol{q},\lambda_{\beta_B})G^{\alpha\beta}_{\Sigma_c^+}(\boldsymbol{p},\boldsymbol{q})\mathcal{U}_{\alpha_B}(\boldsymbol{p},\lambda_{\alpha_B}).$$

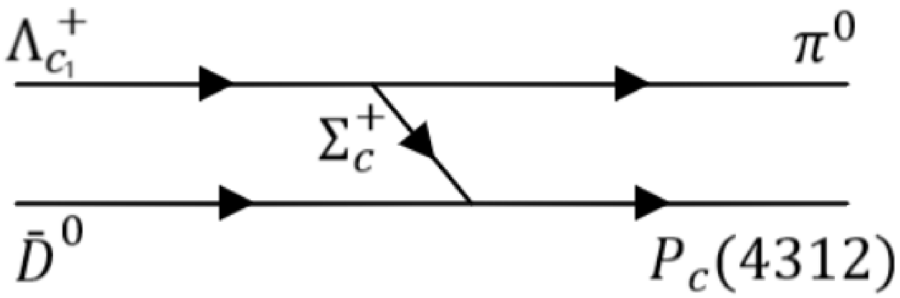
$$G^{\alpha\beta}_{\Sigma_c^+}(\boldsymbol{p},\boldsymbol{q},E) = \frac{1}{2}\left\{\frac{(\omega_{\alpha_B}(\boldsymbol{p})-\omega_{\beta_M}(\boldsymbol{q}))\gamma_0-(\boldsymbol{p}+\boldsymbol{q})\cdot\vec{\gamma}+m_{\Sigma_c^+}}{(\omega_{\beta_M}(\boldsymbol{q})-\omega_{\alpha_B}(\boldsymbol{p}))^2-\omega^2_{\Sigma_c^+}(\boldsymbol{p}+\boldsymbol{q})}+\frac{(\omega_{\beta_B}(\boldsymbol{q})-\omega_{\alpha_M}(\boldsymbol{p}))\gamma_0-(\boldsymbol{p}+\boldsymbol{q})\cdot\vec{\gamma}+m_{\Sigma_c^+}}{(\omega_{\beta_B}(\boldsymbol{q})-\omega_{\alpha_M}(\boldsymbol{p}))^2-\omega^2_{\Sigma_c^+}(\boldsymbol{p}+\boldsymbol{q})}\right\}.$$

Wu, Lee, and Zou. PRC85(2012) 044002

$$V_{\alpha\beta}(p,q) = \frac{F(p,q)}{2(2\pi)^3}\sqrt{\frac{m_{\Lambda_{c1}^+}m_{P_c}}{\omega_{\Lambda_{c1}^+}(p)\omega_{P_c}(q)2\omega_{D^0}(p)2\omega_\pi(q)}}\sum_{\lambda_{\alpha_B},\lambda_{\beta_B}}2\pi\int_{-1}^{1}d\cos\theta\, d^{1/2}_{\lambda_{\alpha_B}\lambda_{\beta_B}}(\theta)\,\mathcal{V}_{\alpha\beta}(\boldsymbol{p},\,\boldsymbol{q},\,\lambda_{\alpha_B},\,\lambda_{\beta_B}).$$

$$F(p,q) = \frac{\Lambda^2}{p^2+\Lambda^2}\frac{\Lambda^2}{q^2+\Lambda^2},$$

$\bar{D}\Lambda_{c1}(2595) - P_c(4312)\pi$ coupled channel



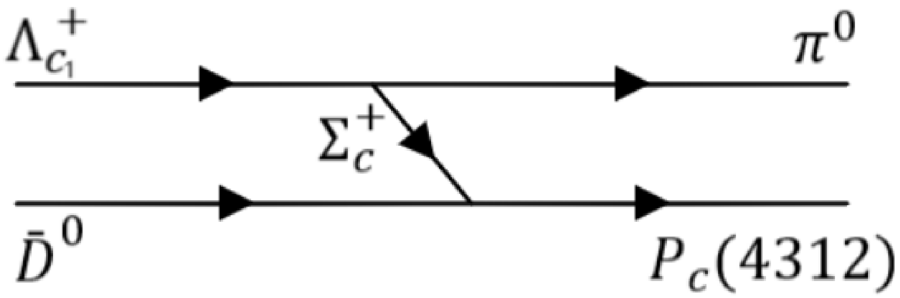
$$\mathcal{G}_\gamma(q;E) = \frac{1}{E - \omega_{\gamma_B}(q) - \omega_{\gamma_M}(q) + i\epsilon}$$

$$T_{\alpha\beta}(p,p';E) = V_{\alpha\beta}(p,p') + \sum_\gamma \int dq q^2 V_{\alpha\gamma}(p,q) G_\gamma(q;E) T_{\gamma\beta}(q,p';E)$$

Usual method: change to a matrix equation ! Then we will find the routines of p and p' are the same as integral variable q !

$$\det(\mathbb{I} - VG) = 0.$$

$\bar{D}\Lambda_{c1}(2595)-P_c(4312)\pi$ coupled channel



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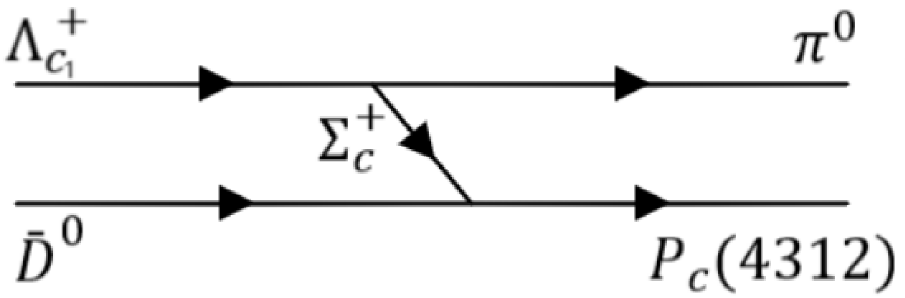
Usual method: change to a matrix equation ! Then we will find the routines of p and p' are the same as integral variable q !

Key problem: $V(p,q)$ will have a pole of integral variable q when p changed.

Left hand cut

$$\det\left(\mathbb{I}-VG\right)=0.$$

$\bar{D}\Lambda_{c1}(2595) - P_c(4312)\pi$ coupled channel



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Usual method: change to a matrix equation ! Then we will find the routines of p and p' are the same as integral variable q !

$$\det(\mathbb{I} - VG) = 0.$$

Key problem: $V(p,q)$ will have a pole of integral variable q when p changed.

Left hand cut

Solution: Find a special integral routine which will not touch the singularity because of integral routine.

$\bar{D}\Lambda_{c1}(2595) - P_c(4312)\pi$ coupled channel

Integral routine

Key problem: $V(p,q)$ **will have a pole of integral variable q when p changed.**

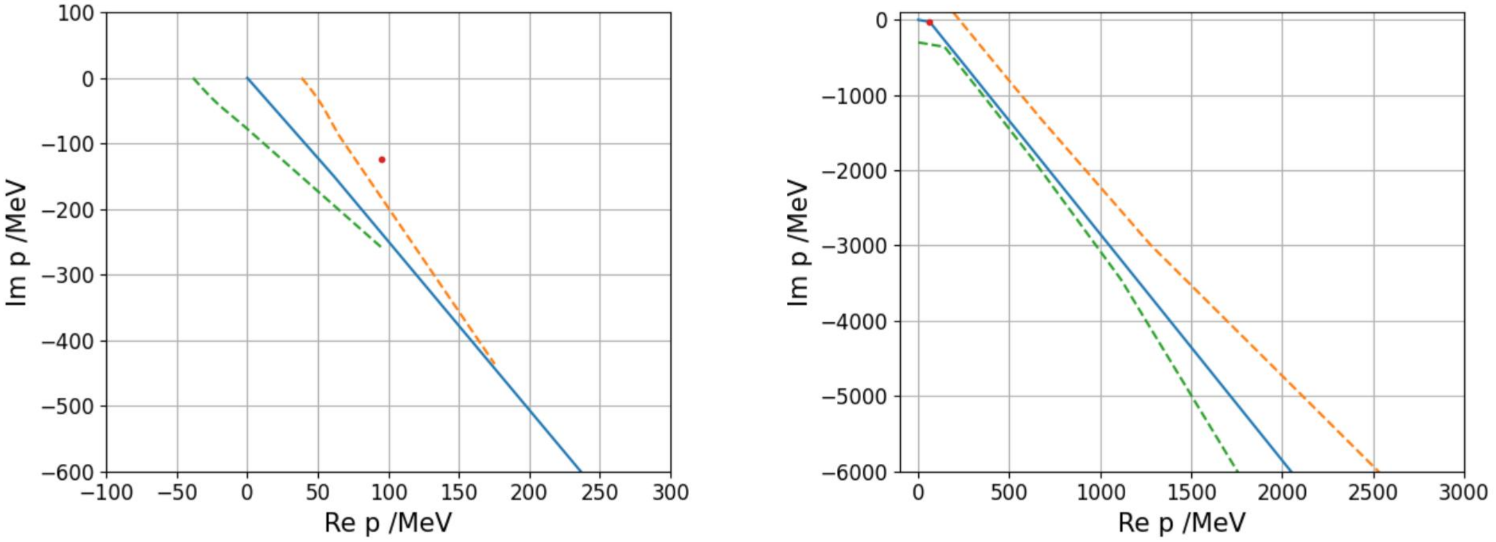


Figure 2: Two paths of integrate momenta for $\pi^0 P_c(4312)$(left) and $\bar{D}^0\Lambda_{c1}^+$(right).

Table 1. The pole position of T−matrix in the complex plain for different cutoffs.

	M_{P_c}/ MeV	$\Gamma_{P_c}/2$ MeV
$\Lambda = 0.8$ GeV	4456.7428	10.7337
$\Lambda = 1.0$ GeV	4456.7667	10.7293
$\Lambda = 1.2$ GeV	4456.7861	10.7238

the second Riemann sheet of $P_c(4312)\pi$
the first Riemann sheet of $\bar{D}\Lambda_{c1}(2595)$

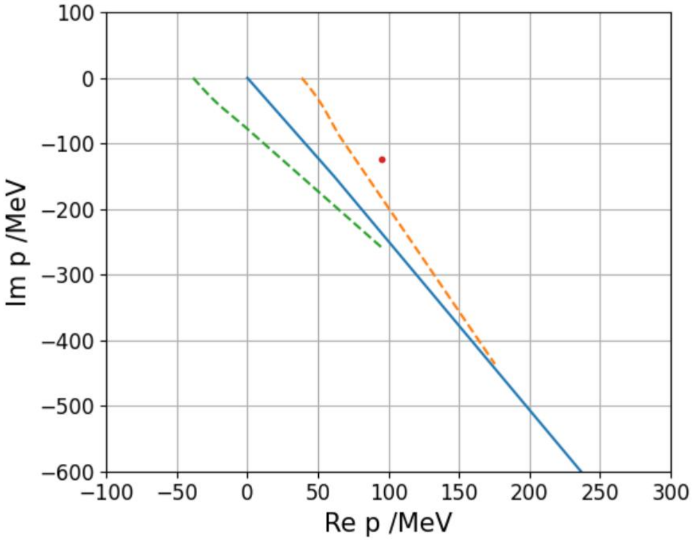
A bound state of $\bar{D}\Lambda_{c1}(2595)$ with $J^P = \frac{1}{2}^+$

Typical property: Large decay width to $P_c(4312)\pi$.

$\bar{D}\Lambda_{c1}(2595) - P_c(4312)\pi$ coupled channel

Integral routine

Key problem: $V(p,q)$ **will have a pole of integral variable q when p changed.**



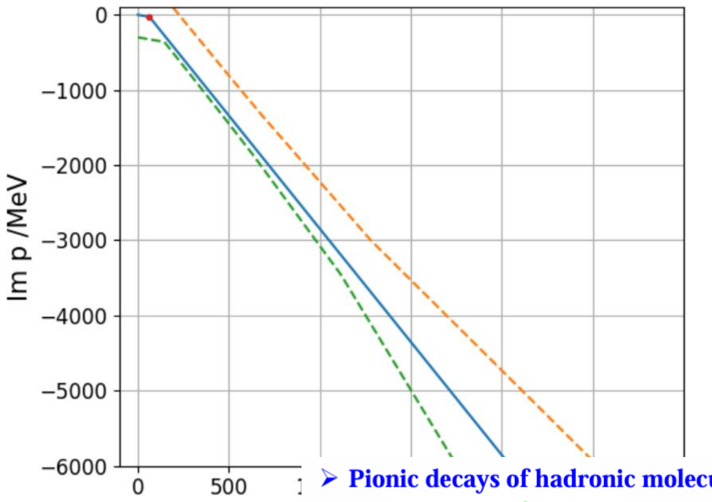


Figure 2: Two paths of integrate momenta for $\pi^0 P_c(4312)$(left)

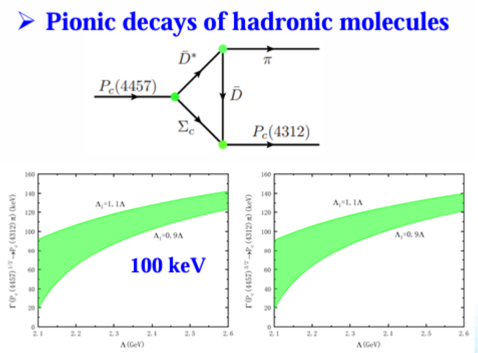


Table 1. The pole position of $T-$matrix in the complex plain for different cutoffs.

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the second Riemann sheet of $P_c(4312)\pi$
the first Riemann sheet of $\bar{D}\Lambda_{c1}(2595)$

A bound state of $\bar{D}\Lambda_{c1}(2595)$ with $J^P = \frac{1}{2}^+$

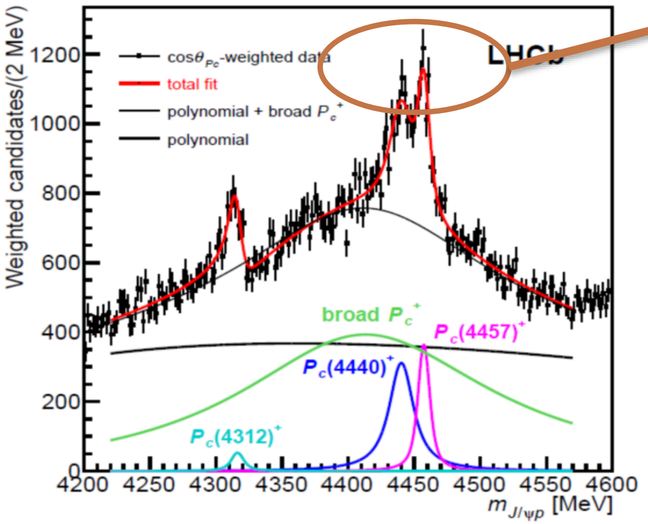
Typical property: **Large decay width to $P_c(4312)\pi$. While for $\frac{1}{2}^-$ state, the width of $Pc(4457) \to P_c(4312)\pi$ is only 100 keV.**

Minzhu Liu' s talk at第九届手征有效场论研讨会

University of Chinese Academy of Sciences

Discussion

$\Lambda_b^0 \rightarrow K^- P_c(4457) \rightarrow K^- J/\psi P$ √



How many states here ?
Maybe more !

Possible new processes

$$\Lambda_b^0 \rightarrow K^- P_c(4457) \rightarrow K^- P_c(4312)\pi^0 \rightarrow K^- J/\psi P \pi^0$$

$$\Lambda_b^0 \rightarrow K_s P_c^0(4457) \rightarrow K_s P_c(4312)\pi^- \rightarrow K_s J/\psi P \pi^-$$

$$\Lambda_b^0 \rightarrow K^- J/\psi P \pi^+ \pi^-$$

Summary

We based on $\bar{D}\Lambda_{c1}(2595)-P_c(4312)\pi$ coupled channel, by exchanging Σ_c^+, it will exist a $J^P=1/2^+$ $P_c(4457)$ state!

$$\Lambda_b^0 \to K^- P_c(4457) \to K^- P_c(4312)\pi^0 \to K^- J/\psi P \pi^0$$

$$\Lambda_b^0 \to K_s P_c^0(4457) \to K_s P_c(4312)\pi^- \to K_s J/\psi P \pi^-$$

$$\Lambda_b^0 \to K^- J/\psi P \pi^+ \pi^-$$

Thanks for attention !