New theoretical progress on heavy pentaquarks

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International Workshop on Partial Wave Analyses and Advanced Tools for Hadron Spectroscopy,

CBPF, in Rio de Janeiro, Brazil. **Sep. 02-06, 2019**

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Outline

- Motivation: Why **heavy** pentaquarks ?
- The theoretical prediction before LHCb P_c States
- The discussion of LHCb P_c States
- The progress after LHCb P_c States
- Beyond P_c States
- Summary and Outlook

Motivation

- Why **heavy** pentaquarks ?

$\Longrightarrow$

- Why “ $\bar{c}cqqq$ ” is important to search five quark states ?

Motivation

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Possible Five quark state is studied in many years.

1. $\bar{q}$’qqqq： **Never Confirmed** θ^+ state ??
2. $\bar{q}$’q’qqq: **Various Discussion** Roper, Λ*(1405)

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u,d,s ⇒ **Five-quark state** / **Three-quark excited states** —Close mass / Parameters→ Indistinguishable

Question ?

Motivation

- Why " $\bar{c}cqqq$ " is important to search five quark states ?

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u,d,s ⇒ **Five-quark state** / **Three-quark excited states** → Close mass / Parameters → Indistinguishable

Question ?

Solution !

N*($\bar{c}c$) = uud + $\bar{c}c$ → $\bar{D}\Sigma_c$ -- $\bar{D}\Lambda_c$ / **[ud][uc] $\bar{c}$**

The theoretical prediction before LHCb P_c States

- Before LHCb first announce their results in 2015, there are several theoretical papers about Pc as follows
- Valencia Model：

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

Wu, Zhao and Zou, PLB 709, 70

Oset, etal, IJMP. E21, 1230011 (2012).

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

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

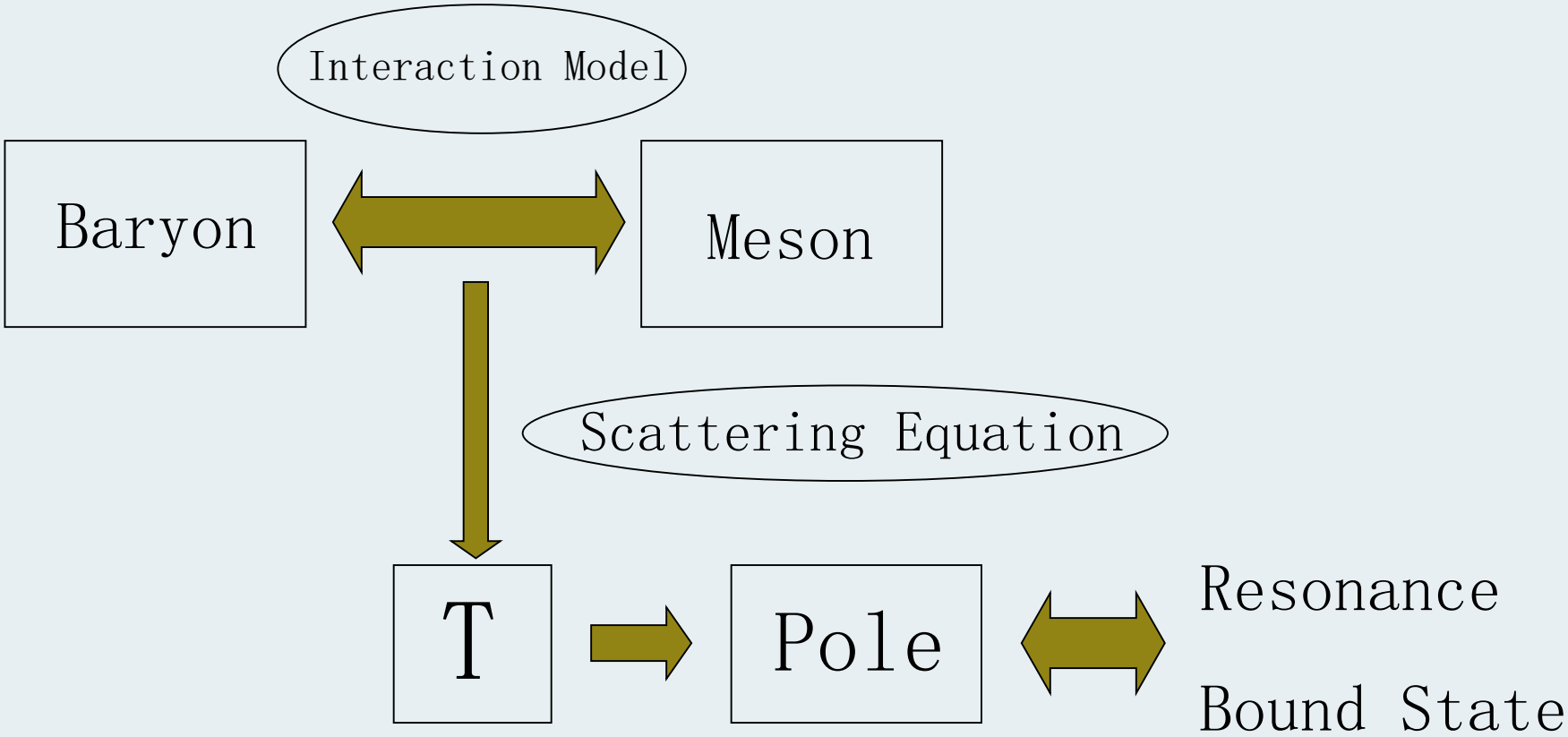
Uchino, Liang, and Oset, EPJA 52, 43(2016)

- EBAC Model： Wu, Lee and Zou, PRC **85**, 044002
- Chiral constituent quark model & a resonating group method equation

  Wang, Huang, Zhang, Zou, PRC 84,015203(2011).
- Schrödinger Equation & One boson exchange：

  Yang, Sun, He, Liu, Zhu, Chin.Phys. C36 (2012) 6-13
- Pentaquark Model： Yuan, Wei, He, Xu and Zou, EPJA 48, 61(2012)

The Prediction of P_c



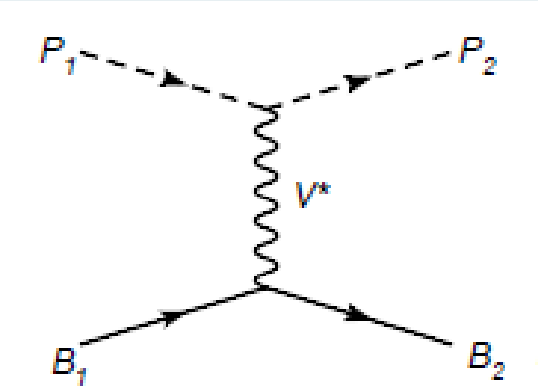
Interaction Model, Chiral Lagrangians

Local Hidden Symmetry and SU(4) Symmetry

Scattering Equation: Valencia and EBAC

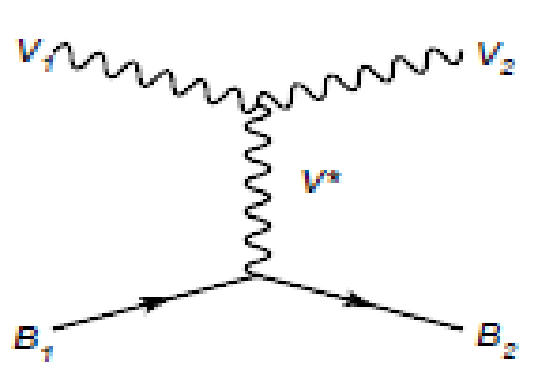
$\bar{D}\Sigma_c$ and $\bar{D}_s\Lambda_c$ bound states

J. J. Wu, R. Molina, E. Oset, B. S. Zou, PRL 105 (2010) 232001



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

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



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

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

	(I,S)	M	Γ	Γ_i						g_a		
N*	$(1/2,0)$			πN	ηN	$\eta' N$	$K\Sigma$		$\eta_c N$	$\bar{D}\Sigma_c$	$\bar{D}\Lambda_c^+$	
		4261	56.9	3.8	8.1	3.9	17.0		23.4	2.85	0	
Λ*	$(0,-1)$			KN	$\pi\Sigma$	$\eta\Lambda$	$\eta'\Lambda$	$K\Xi$	$\eta_c\Lambda$	$\bar{D}_s\Lambda_c^+$	$\bar{D}\Xi_c$	$\bar{D}\Xi_c'$
		4209	32.4	15.8	2.9	3.2	1.7	2.4	5.8	1.37	3.25	0
		4394	43.3	0	10.6	7.1	3.3	5.8	16.3	0	0	2.64

The states from $PB \to PB$, with units in MeV

	(I,S)	M	Γ	Γ_i						g_a		
N*	$(1/2,0)$			ρN	ωN	$K^*\Sigma$			$J/\psi N$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Lambda_c^+$	
		4412	47.3	3.2	10.4	13.7			19.2	2.75	0	
Λ*	$(0,-1)$			K^*N	$\rho\Sigma$	$\omega\Lambda$	$\phi\Lambda$	$K^*\Xi$	$J/\psi\Lambda$	$\bar{D}_s^*\Lambda_c^+$	$\bar{D}^*\Xi_c$	$\bar{D}^*\Xi_c'$
		4368	28.0	13.9	3.1	0.3	4.0	1.8	5.4	1.23	3.14	0
		4544	36.6	0	8.8	9.1	0	5.0	13.8	0	0	2.53

The states from $VB \to VB$, with units in MeV

- Various Predictions for N* $\bar{c}c$
- Valencia Model：

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

$\bar{D}\Sigma_c$ ~ 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

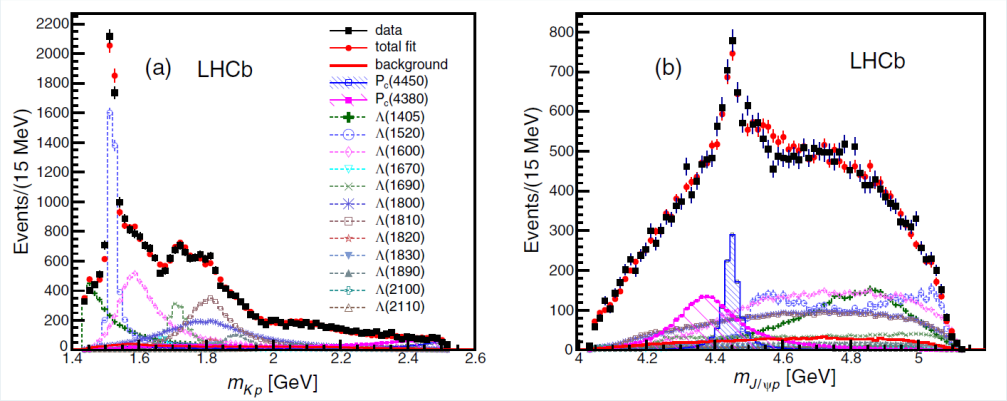
$\bar{D}\Sigma_c - \eta_c N$ coupled channel state and main decay channel ηN ~ 3.5 GeV

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

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

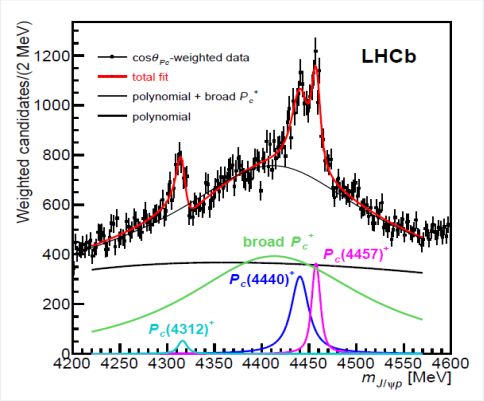
C. Gobbi, D.O. Riska, N.N. Scoccola, Phys. Lett. B 296 (1992) 166

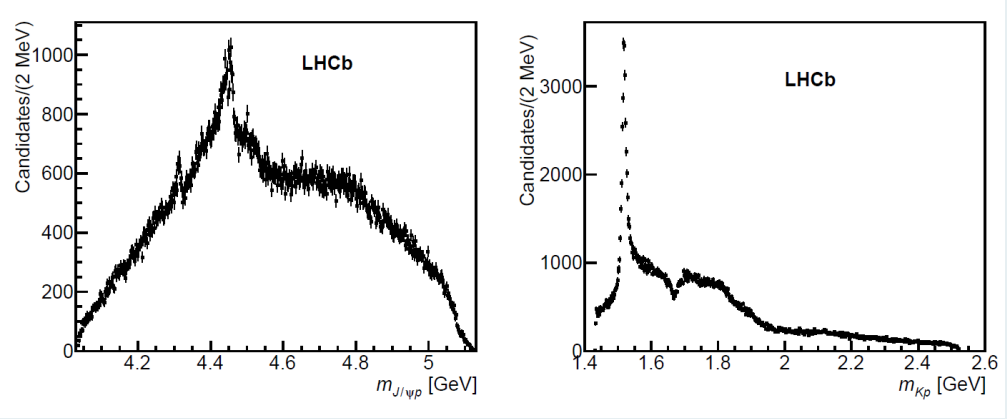
The discussion of LHCb P_c States



$$P_c(4380)\ :\ (m,\Gamma)=(4380\pm8\pm29,\ 205\pm18\pm86)MeV$$
$$P_c(4450)\ :\ (m,\Gamma)=(4449.8\pm1.7\pm2.5,\ 39\pm5\pm19)MeV$$

LHCb, Phys. Rev. Lett. 115 (2015) 072001
LHCb, Phys. Rev. Lett. 122 (2019) 222001



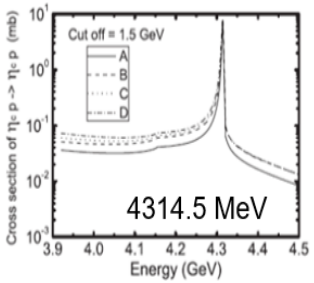


State	M [MeV]	Γ [MeV]
$P_c(4312)^+$	$4311.9\pm0.7^{+6.8}_{-0.6}$	$9.8\pm2.7^{+3.7}_{-4.5}$
$P_c(4440)^+$	$4440.3\pm1.3^{+4.1}_{-4.7}$	$20.6\pm4.9^{+8.7}_{-10.1}$
$P_c(4457)^+$	$4457.3\pm0.6^{+4.1}_{-1.7}$	$6.4\pm2.0^{+5.7}_{-1.9}$

Comparison to numerical predictions

- Many theoretical predictions for $\Sigma_c^+ \bar{D}^{(*)0}$ published before 2015, **some in quantitative agreement with the LHCb data**
  - Wu,Molina,Oset,Zou, PRL105, 232001 (2010),
  - **Wang,Huang,Zhang,Zou, PR C84, 015203 (2011),**
  - **Yang,Sun,He,Liu,Zhu, Chin. Phys. C36, 6 (2012),**
  - **Wu,Lee,Zou, PR C85 044002 (2012),**
  - Karliner,Rosner, PRL 115, 122001 (2015)

PR C85 044002 (2012)



ΔE – binding energy

Example:

Nucleon resonances with hidden charm in coupled-channels models

Jia-Jun Wu, T.-S. H. Lee, and B. S. Zou
Phys. Rev. C **85**, 044002 – Published 17 April 2012

arXiv:1202.1036

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

	PB System		VB System	
$J^P = \frac{1}{2}^-$ Λ	$M - i\Gamma/2$	ΔE	$M - i\Gamma/2$	ΔE
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
$J^P = \frac{3}{2}^-$				
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

$\Delta E(4312) = 5.8^{+1.0}_{-6.8}$ MeV

$\Delta E(4457) = 2.5^{+4.3}_{-4.1}$ MeV

Λ - cut off on exchanged meson mass.

$\Delta E(4440) = 19.5^{+4.9}_{-4.3}$ MeV

Valencia &&&& EBAC

$\bar{D}\Sigma_c$ 4269MeV 4301-4318MeV

$$T = V + VG^{Valencia}T$$

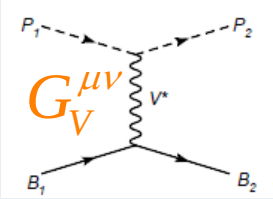
$$T(q_1,q_2) = V + \int q_3^2 dq_3\, V(q_1,q_3) \times G(q_3)T(q_3,q_2)$$

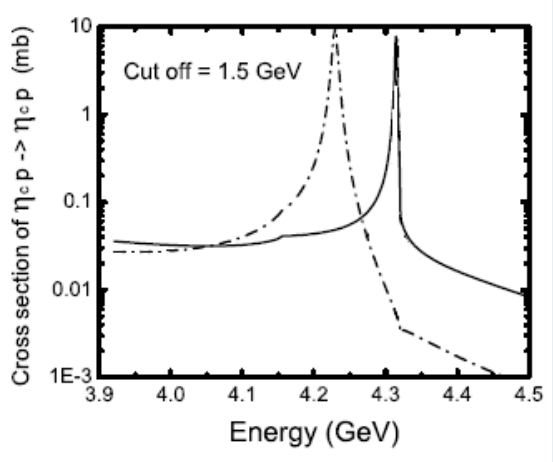
$$G^{Valencia} = \int \frac{dp^4}{(2\pi)^4} \frac{2m_B}{(p^2-m_B^2)((P-p)^2-m_M^2)}$$

$$G(q_3) = \frac{1}{\sqrt{S}-E_M-E_B},$$

$$G_V^{\mu\nu} = \frac{p_V^\mu p_V^\nu / m_V^2 - g^{\mu\nu}}{p_V^2 - m_V^2}$$

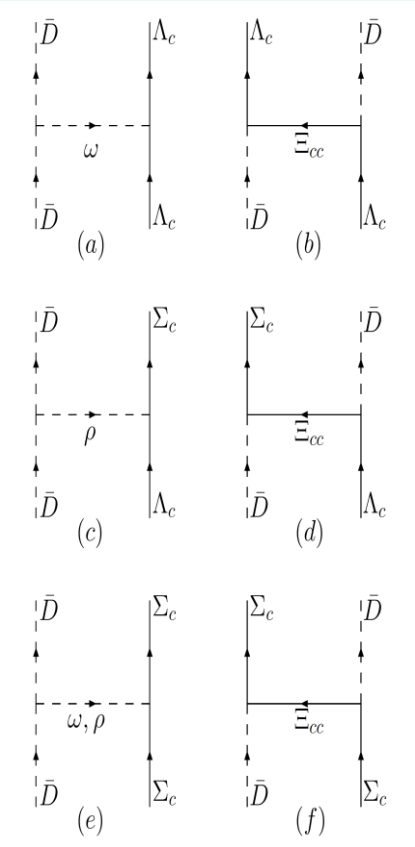
$$\sim \frac{p_V^\mu p_V^\nu / m_V^2 - g^{\mu\nu}}{-m_V^2} \sim \frac{-g^{\mu\nu}}{-m_V^2}$$



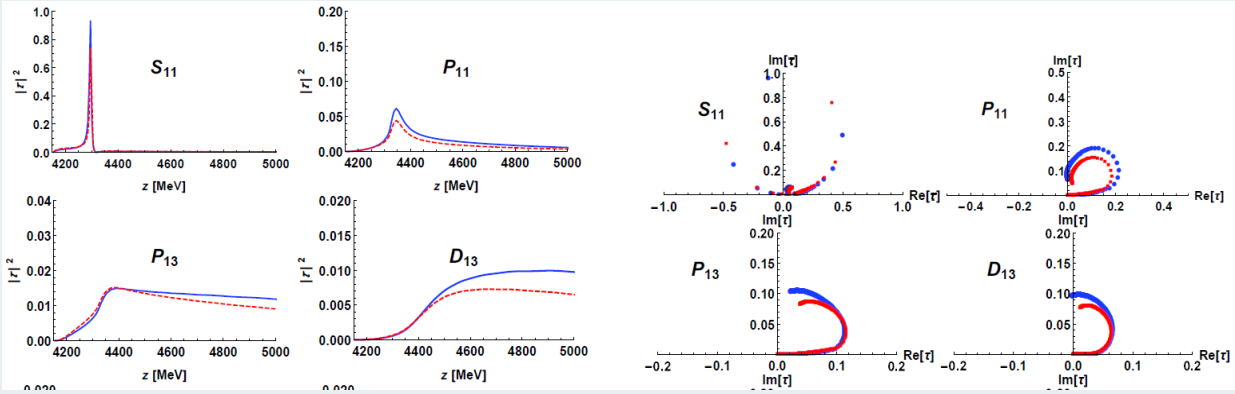


Another dynamical coupled-channel

- Julich-Bonn dynamical coupled-channel



J^P	A			B		
	z_R/MeV	couplings/10^{-3} MeV$^{-\frac{1}{2}}$		z_R/MeV	couplings/10^{-3} MeV$^{-\frac{1}{2}}$	
		$g_{\bar{D}\Lambda_c}$	$g_{\bar{D}\Sigma_c}$		$g_{\bar{D}\Lambda_c}$	$g_{\bar{D}\Sigma_c}$
$\frac{1}{2}^-$	4295−i3.7	1.4+i0.2	13.2+i0.8	4297−i3.0	1.1+i0.2	10.9+i0.6
$\frac{1}{2}^+$	4334−i28	1.1−i1.1	−1.9+i3.6	4334−i30	1.0−i1.0	−1.9+i3.7
$\frac{3}{2}^+$	4325−i54	0.3−i1.1	0.8−i4.5	4325−i54	0.3−i1.0	0.7−i4.6
$\frac{3}{2}^-$	4380−i147	0.5−i1.9	−1.4+i5.6	4378−i146	0.5−i1.7	−1.3+i5.6



C.-W. Shen, D. Ronchen, U.-G. Meissner, and B.-S. Zou, Chin. Phys. **C42**, 023106 (2018), 1710.03885.

The progress after LHCb P_c States

Thresholds $\bar{D}\Sigma_c^*$(4383MeV), $\bar{D}^*\Sigma_c$(4460MeV), $p\chi_{c1}$(4449MeV)

1) $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$, $\bar{D}^*\Sigma_c^*$ molecular states

Chen, Liu, Li, Zhu, PRL115 (2015) 132002;
Roca, Nieves, Oset, PRD92 (2015) 094003;
He, PLB 753 (2016) 547 ;

2) Diquark cu & triquark $\bar{c}$(ud) states

Maiani, Polosa, Riquer, PLB749 (2015) 289;
Lebed, PLB749 (2015) 454;
Li, He, He, JHEP 1512 (2015) 128;
Zhu, Qiao, PLB756 (2016) 259;

3) Kinematic triangle-singularity

Guo, Meißner, Wang, Yang, PRD92 (2015) 071502
Liu, Wang, Zhao, PLB757 (2016) 231

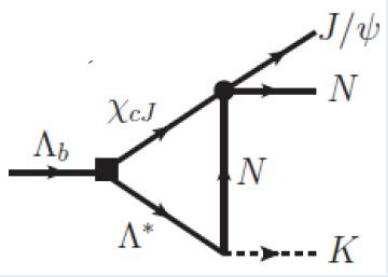
Chen, Chen, Liu, and Zhu, PR **639**, 1 (2016), 1601.02092.

Zhao, AAPPS Bull. **26**, 8.

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.



The progress after LHCb P_c States

After 2019 observation, there are a lot of theoretical studies.

[1] Chen, Sun, Liu, and Zhu (2019), 1903.11013.
[2] Chen, Chen, and Zhu (2019), 1903.11001.
[3] Liu, Pan, Peng, Sanchez, Geng, Hosaka and Valderrama (2019), 1903.11560.
[4] Guo, Jing, Meibner, and Sakai (2019), 1903.11503.
[5] He (2019), 1903.11872.
[6] Liu, Chen, Chen, Liu, and Zhu (2019), 1903.11976.
[7] Huang, He, and Ping (2019), 1904.00221.
[8] Ali and Parkhomenko (2019), 1904.00446. --- Diquark model
[9] Xiao, Huang, Dong, Geng, and Chen (2019), 1904.00872.
[10] Shimizu, Yamaguchi, and Harada (2019), 1904.00587.
[11] Guo and Oller (2019), 1904.00851.
[12] Xiao, Nieves, Oset (2019) 1904.01296
[13] Mutuk (2019) 1904.09756
[14] JPAC Collaboration (2019) 1904.10021 ---possible virtual state: Pc(4312)
[15] Zhu, Liu, Huang and, Qiao (2019) 1904.10285 --- $\bar{c}c$-qqq system
[16] Cheng, Liu (2019) 1904.10285 --- compact pentaquarks 3/2- Pc(4312)
[17] Wang, Chen, Liu, (2019) 1905.03636 ---- $\Sigma_c^{(*)}(\Lambda_c)$ - $\bar{D}_1$($\bar{D}^*_2$)
[18] Yang, Meng, Zhu, (2019) 1906.04956
[19] Liu, Wu, Sanchez, Valderrama, Geng, Xie (2019) 1907.06093
[20] Sakai, Jing, Guo (2019) 1907.03414
[21] Yamaguchi, Tecocoatzi, Giachino, Hosaka, Santopinto, Takeuchi, Takizawa.(2019) 1907.0468

.....

LHCb pentaquark states VS Predictions

Consistence :

Pc(4312)	$\bar{D}\Sigma_c(1/2-)$
Pc(4380)	$\bar{D}\Sigma_c^*(3/2-)$
Pc(4440) & Pc(4457)	$\bar{D}^*\Sigma_c(1/2-,\ 3/2-)$

Problems:

1) Pc(4380)-- much larger decay width than prediction
2) Other Pc states have narrower width than prediction
3) All Pc states have negative parity?

To know the **internal structure** and **quantum number** of these states.

The progress after LHCb P_c States

Two main Problems:

1. What is the spin and partity of observed Pc ?

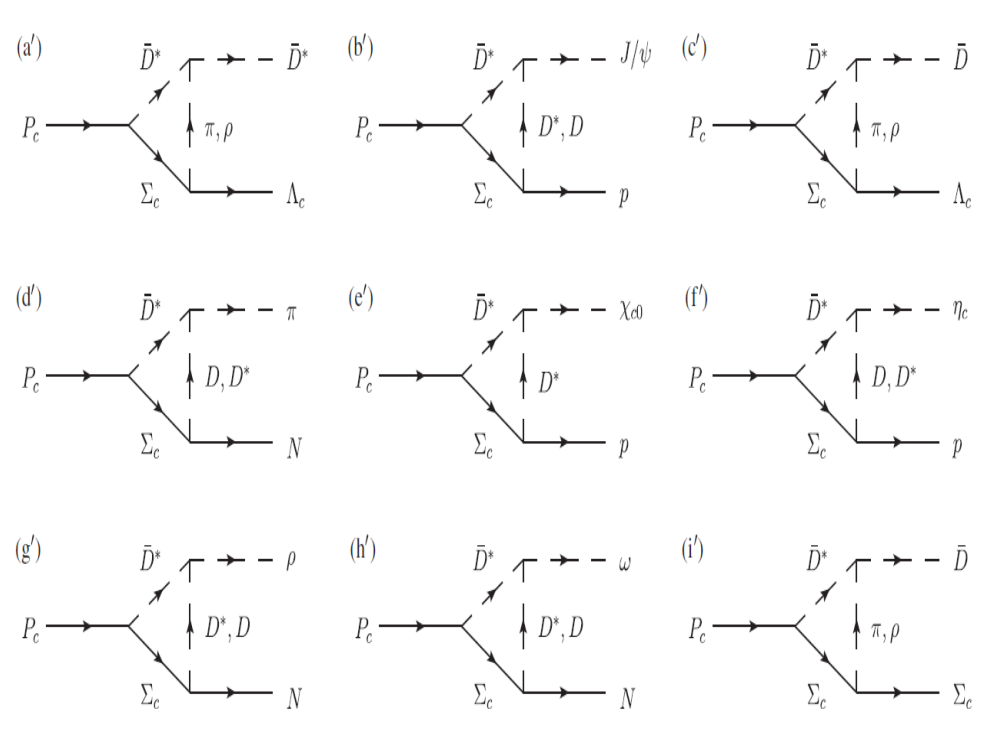
→ Study the decay behiarvior of Pc

2. Is there any other reaction to search Pc ?

→ Study J/ψ photo-production.

Decay Behavior of Pc State

- Y.-H. Lin, C.-W. Shen, F.-K. Guo, and B.-S. Zou, Phys. Rev. **D95**, 114017 (2017), 1703.01045.

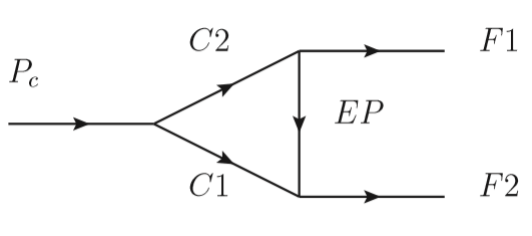


	Widths (MeV)			
	$P_c(4380)$		$P_c(4450)$	
Mode	$\bar{D}\Sigma_c^*(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{5}{2}^+)$
$\bar{D}^*\Lambda_c$	131.3	35.3	72.3	20.5
$J/\psi p$	3.8	16.6	16.3	4.0
$\bar{D}\Lambda_c$	1.2	17.0	41.4	18.8
πN	0.06	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

Decay Behavior of Pc State

- Y.-H. Lin, and B.-S. Zou, 1908.05309

Initial state	Final states	Exchanged particles
$P_c(4312)(\bar{D}\Sigma_c)$	$J/\psi N$, ωp, ρN	D, D^*
	$\bar{D}^*\Lambda_c$	π, ρ
	$\bar{D}\Lambda_c$	ρ
	$\eta_c N$	D^*
	πN	D^*, Λ_c, Σ_c
$P_c(4440)\&P_c(4457)$ $(\bar{D}^*\Sigma_c)$	$\bar{D}^*\Lambda_c$, $\bar{D}\Lambda_c$, $\bar{D}\Sigma_c^*$, $\bar{D}\Sigma_c$	π, ρ
	$J/\psi N$, ωp, ρN, ηN	D^*, D
	πN	D^*, D, Λ_c, Σ_c
	$\chi_{c0}N$	D^*
$P_c(4376)(\bar{D}\Sigma_c^*)$	$\bar{D}^*\Lambda_c$	π, ρ
	$\bar{D}\Lambda_c$, $\bar{D}\Sigma_c$	ρ
	$J/\psi N$, ωp, ρN	D^*, D
	$\eta_c N$	D^*
	πN	D^*, Λ_c, Σ_c
	$\chi_{c0}N$	D
$P_c(4500)\&P_c(4511)$ $\&P_c(4523)(\bar{D}^*\Sigma_c^*)$	$\bar{D}^*\Lambda_c$, $\bar{D}\Lambda_c$, $\bar{D}\Sigma_c^*$, $\bar{D}\Sigma_c$, $\bar{D}\Sigma_c^*$	π, ρ
	$J/\psi N$, ωp, ρN, ηN	D^*, D
	πN	D^*, D, Λ_c, Σ_c
	$\chi_{c0}N$	D^*



Mode	Widths (MeV) with (f_1, f_3)				
	$\bar{D}\Sigma_c$	$\bar{D}^*\Sigma_c$			
	$P_c(4312)$	$P_c(4440)$		$P_c(4457)$	
	$\frac{1}{2}^-$	$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{1}{2}^-$	$\frac{3}{2}^-$
$\bar{D}^*\Lambda_c$	3.8	13.9	6.2	12.5	6.1
$J/\psi p$	0.001	0.03	0.02	0.02	0.01
$\bar{D}\Lambda_c$	0.06	5.6	1.7	3.8	1.5
πN	0.004	0.002	2^{-4}	0.001	1^{-4}
$\chi_{c0}p$	-	8^{-4}	4^{-5}	9^{-4}	3^{-5}
$\eta_c p$	0.01	3^{-4}	8^{-5}	2^{-4}	6^{-5}
ρN	3^{-5}	3^{-4}	4^{-5}	2^{-4}	2^{-5}
ωp	1^{-4}	0.001	2^{-4}	6^{-4}	9^{-5}
$\bar{D}\Sigma_c$	-	3.4	0.5	2.6	1.0
$\bar{D}\Sigma_c^*$	-	0.8	5.4	1.9	6.2
Total	3.9	23.7	13.9	20.7	14.7

$\gamma\, p \rightarrow J/\psi\, p$

- In our 2010 paper, we have mentioned to search Pc in e p → e J/ψ p after update 12 GeV in Jlab experiment, but we did not calculate it in detail at that time.

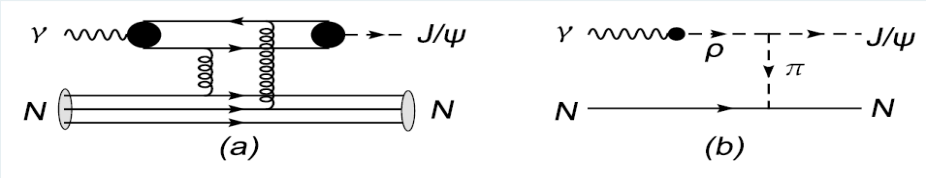
- [1] Y. Huang, J. He, H.-F. Zhang, and X.-R. Chen, JPG **41**, 115004 (2014), 1305.4434.
- [2] Q. Wang, X.-H. Liu, and Q. Zhao, PRD**92**, 034022 (2015), 1508.00339.
- [3] V. Kubarovsky and M. B. Voloshin, PRD**92**, 031502 (2015), 1508.00888.
- [4] M. Karliner and J. L. Rosner, PLB**752**, 329 (2016), 1508.01496.
- [5] A. N. Hiller Blin, C. Fernandez-Ramirez, A. Jackura, V. Mathieu, V. I. Mokeev, A. Pilloni, and A. P. Szczepaniak, PRD**94**, 034002 (2016), 1606.08912.
- [6] E. Ya. Paryev and Yu. T. Kiselev, NPA**978**, 201 (2018), 1810.01715.
- [7] X.-Y. Wang, X.-R. Chen, J. He, arXiv:1904.11706
- [8] Xu Cao and Jian-ping Dai arXiv: 1904.06015
- [9] J.-J. Wu, T.-S.H. Lee, B.-S. Zou arXiv:1906.05375

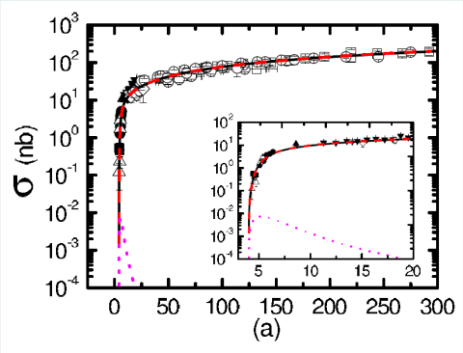
- Last year, Prof. Harry Lee was suggested by the experimentalist collaborates with Jlab in ANL.

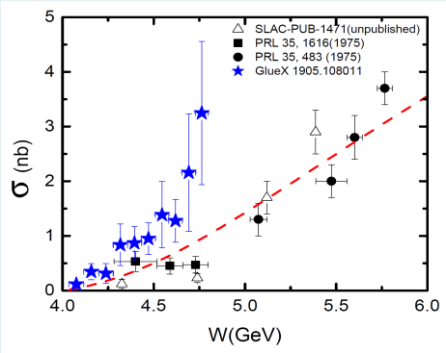
Pin down P_c states from their photo-production

arXiv:1906.05375

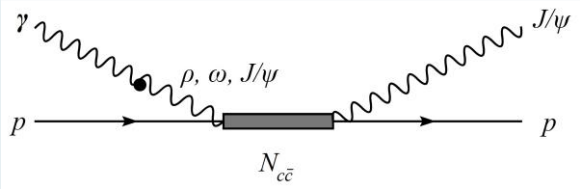
Background

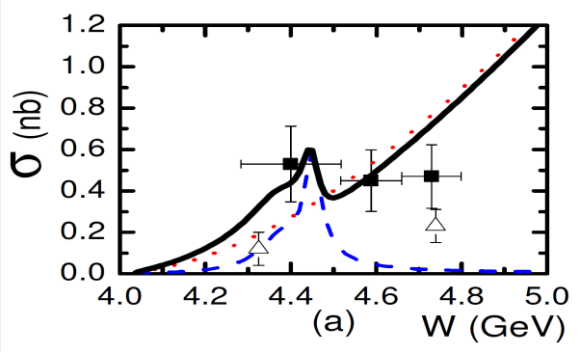




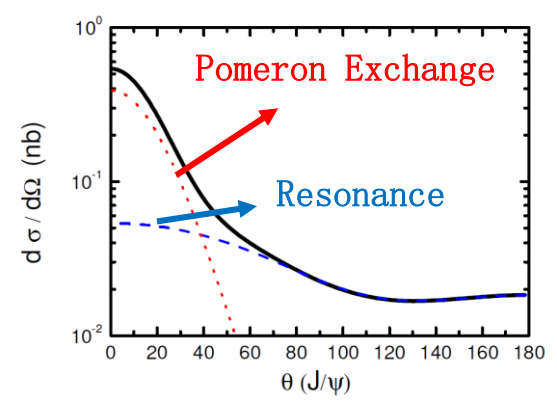


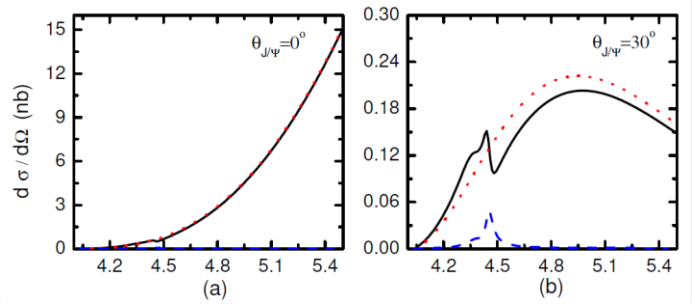
Signal

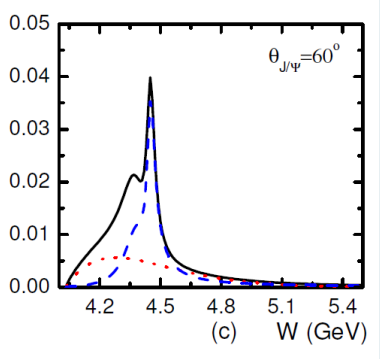




How to extract Signal



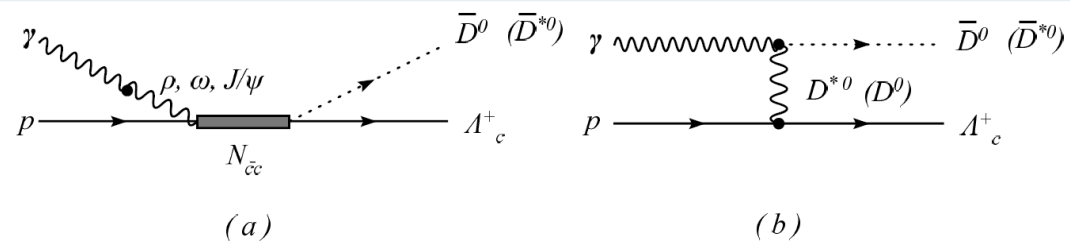


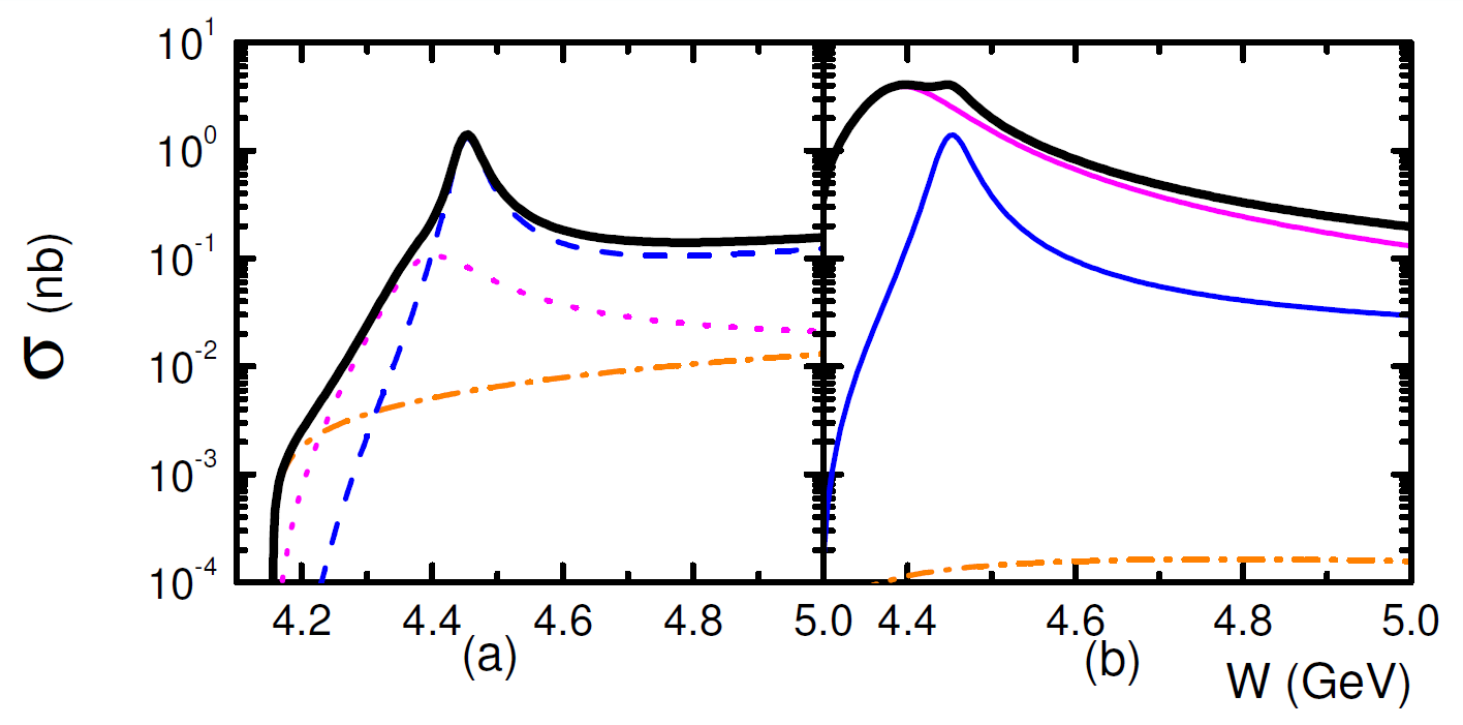


γ p → other final states

arXiv:1906.05375

- $\gamma p \rightarrow \Lambda^+_c \ \bar{D}^0 \ (\ \bar{D}^{*0} \ )$





Beyond P_c States

- From P_c ($\boldsymbol{N_{\bar{c}c}}$) to $\boldsymbol{\Lambda_{\bar{c}c}}$

- From P_c ($\boldsymbol{N_{\bar{c}c}}$) to P_b ($\boldsymbol{N_{\bar{b}b}}$)

Beyond P_c States

- From Pc ($N_{\bar{c}c}$) to $\Lambda_{\bar{c}c}$

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

(I,S)	M	Γ	Γ_i						g_a		
$(1/2,0)$			πN	ηN	$\eta' N$	$K\Sigma$		$\eta_c N$	$\bar{D}\Sigma_c$	$\bar{D}\Lambda_c^+$	
	4261	56.9	3.8	8.1	3.9	17.0		23.4	2.85	0	
$(0,-1)$			KN	$\pi\Sigma$	$\eta\Lambda$	$\eta'\Lambda$	$K\Xi$	$\eta_c\Lambda$	$\bar{D}_s\Lambda_c^+$	$\bar{D}\Xi_c$	$\bar{D}\Xi_c'$
	4209	32.4	15.8	2.9	3.2	1.7	2.4	5.8	1.37	3.25	0
	4394	43.3	0	10.6	7.1	3.3	5.8	16.3	0	0	2.64

The states from $PB \to PB$, with units in MeV

(I,S)	M	Γ	Γ_i						g_a		
$(1/2,0)$			ρN	ωN	$K^*\Sigma$			$J/\psi N$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Lambda_c^+$	
	4412	47.3	3.2	10.4	13.7			19.2	2.75	0	
$(0,-1)$			K^*N	$\rho\Sigma$	$\omega\Lambda$	$\phi\Lambda$	$K^*\Xi$	$J/\psi\Lambda$	$\bar{D}_s^*\Lambda_c^+$	$\bar{D}^*\Xi_c$	$\bar{D}^*\Xi_c'$
	4368	28.0	13.9	3.1	0.3	4.0	1.8	5.4	1.23	3.14	0
	4544	36.6	0	8.8	9.1	0	5.0	13.8	0	0	2.53

The states from $VB \to VB$, with units in MeV

Beyond P_c States

- From Pc ($N_{\bar{c}c}$) to $\Lambda_{\bar{c}c}$

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

(I,S)	M	Γ	Γ_i				g_a				
			$\eta_c\Lambda$	$J/\psi\Lambda$	$\bar{D}\Xi_c$	$\bar{D}_s\Lambda_c$	$\bar{D}\Xi_c'$	$\bar{D}^*\Xi_c$	$\bar{D}_s^*\Lambda_c$	$\bar{D}^*\Xi_c'$	$\bar{D}^*\Xi_c^*$
$(1/2,0)$	4261	$4276.59+i7.67$									
		g_i	$0.17-i0.03$	$0.29-i0.07$	$\mathbf{2.93+i0.08}$	$0.76+i0.31$	$0.00+i0.01$	$0.01+i0.02$	$0.01+i0.04$	$0.01-i0.02$	$0.01-i0.03$
		$\lvert g_i\rvert$	0.17	0.30	**2.93**	0.82	0.01	0.02	0.05	0.02	0.03
$(0,-1)$	4209	$4429.84+i7.92$									
	4394	g_i	$0.29-i0.11$	$0.17-i0.07$	$0.00-i0.00$	$0.00-i0.00$	$0.15-i0.26$	$\mathbf{2.78+i0.01}$	$0.66+i0.32$	$0.01+i0.05$	$0.01+i0.03$
		$\lvert g_i\rvert$	0.31	0.18	0.00	0.00	0.30	**2.78**	0.73	0.05	0.04
		$4436.70+i1.17$									
		g_i	$0.24+i0.03$	$0.14+0.01$	$0.00-i0.00$	$0.00-i0.00$	$\mathbf{1.72-i0.04}$	$0.22-i0.31$	$0.06-i0.01$	$0.01-i0.04$	$0.01-i0.03$
		$\lvert g_i\rvert$	0.24	0.14	0.00	0.00	**1.72**	0.38	0.07	0.04	0.03
(I,S)	M										
$(1/2,0)$	4412	$4580.96+i2.44$									
		g_i	$0.12-i0.00$	$0.37-i0.04$	$0.02-i0.01$	$0.02-i0.01$	$0.03-i0.00$	$0.02-i0.02$	$0.03-i0.02$	$\mathbf{1.57-i0.17}$	$0.00+i0.02$
		$\lvert g_i\rvert$	0.12	0.37	0.02	0.02	0.03	0.03	0.03	**1.58**	0.02
$(0,-1)$	4368	$4650.86+i2.59$									
	4544	g_i	$0.32-i0.05$	$0.19-i0.03$	$0.02-i0.01$	$0.03-i0.02$	$0.02-i0.00$	$0.01-i0.01$	$0.02-i0.01$	$0.01-i0.00$	$\mathbf{1.41-i0.23}$
		$\lvert g_i\rvert$	0.32	0.19	0.03	0.04	0.02	0.02	0.02	0.02	**1.43**

The states from $VB \to VB$, with units in MeV

C. W. Xiao, J. Nieves, E. Oset 1906.09010 (2019)

Beyond P_c States

- From Pc ($N_{\bar{c}c}$) to $\Lambda_{\bar{c}c}$

Chao-Wei Shen, Wu, and Zou, (2019) 1906.03896

Mode	Widths (MeV)									
	$\Lambda_{c\bar{c}}(4213)$		$\Lambda_{c\bar{c}}(4403)$	$\Lambda_{c\bar{c}}(4370)$				$\Lambda_{c\bar{c}}(4490)$	$\Lambda_{c\bar{c}}(4550)$	
	$D_s^-\Lambda_c^+$	$\bar{D}\Xi_c$	$\bar{D}\Xi_c'$	$D_s^{*-}\Lambda_c^+$		$\bar{D}^*\Xi_c$		$\bar{D}\Xi_c^*$	$\bar{D}^*\Xi_c'$	
	$\frac{1}{2}^-$	$\frac{1}{2}^-$	$\frac{1}{2}^-$	$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{3}{2}^-$	$\frac{1}{2}^-$	$\frac{3}{2}^-$
$J/\psi\Lambda$	NA	NA	0.045	3.006	0.766	2.380	0.592	0.464	10.143	2.254
$\eta_c\Lambda$	2.624	1.961	9.126	0.085	0.002	0.076	0.002	0.115	0.485	0.019
$\bar{D}\Xi_c$	NA	NA	NA	1.679	0.002	3.260	0.002	NA	99.134	5.094
$D_s^-\Lambda_c^+$	NA	NA	NA	0.000	0.000	3.862	0.021	NA	4.307	0.316
$\phi\Lambda$	0.269	NA	NA	4.403	0.380	NA	NA	NA	NA	NA
$\rho\Sigma$	NA	1.245	0.248	NA	NA	20.697	1.781	2.837	6.247	0.428
$\omega\Lambda$	NA	0.137	0.243	NA	NA	2.304	0.194	2.824	6.248	0.417
$\pi\Sigma$	NA	2.902	1.008	NA	NA	0.881	0.074	0.165	0.314	0.026
$\eta\Lambda$	0.749	0.114	0.354	0.207	0.017	0.033	0.003	0.056	0.107	0.009
$\eta'\Lambda$	0.438	0.278	0.845	0.100	0.008	0.063	0.005	0.109	0.212	0.017
$\bar{K}N$	4.417	NA	NA	1.359	0.112	NA	NA	NA	NA	NA
$\bar{K}^*N$	1.301	NA	NA	21.103	1.537	NA	NA	NA	NA	NA
$K\Xi$	NA	1.528	0.531	NA	NA	0.410	0.035	0.075	0.149	0.012
$K^*\Xi$	NA	0.501	0.109	NA	NA	8.463	0.824	1.130	2.575	0.204
$D_s^{*-}\Lambda_c^+$	NA	NA	0.112	NA	NA	NA	NA	1.304	2.558	0.327
$\bar{D}^*\Xi_c$	NA	NA	NA	NA	NA	NA	NA	15.709	47.178	4.687
$\bar{D}\Xi_c^*$	NA	NA	NA	NA	NA	NA	NA	NA	1.127	24.421
$\bar{D}\Xi_c'$	NA	NA	NA	NA	NA	NA	NA	0.024	106.219	2.028
Total	9.798	8.666	12.621	31.942	2.824	42.429	3.533	24.812	287.003	40.259

Main decay channels

PB $\Lambda_{\bar{c}c}(4213)$: $\eta_c\Lambda$, $\bar{K}N$.

$\Lambda_{\bar{c}c}(4403)$: $\eta_c\Lambda$.

VB $\Lambda_{\bar{c}c}(4370)$: $\bar{K}^*N$, $\phi\Lambda$, $J/\psi\Lambda$ for $\bar{D}_s\Lambda_c$ molecule & $\rho\Sigma$, $K^*\Xi$, $\bar{D}\Xi_c$, $\bar{D}_s\Lambda_c$ for $\bar{D}^*\Xi_c$ molecule.

$\Lambda_{\bar{c}c}(4550)$: $\bar{D}\Xi^*_c$, $\bar{D}^*\Xi_c$, $\bar{D}\Xi_c$, $\bar{D}\Xi'_c$ because of π exchange.

PD $\Lambda_{\bar{c}c}(4490)$: $\bar{D}^*\Xi c$ because of π exchange

Beyond P_c States

- From P_c $(N_{\bar{c}c})$ to $\Lambda_{\bar{c}c}$
- From P_c $(N_{\bar{c}c})$ to P_b $(N_{\bar{b}b})$

Physics Letters B 709 (2012) 70–76

Contents lists available at SciVerse ScienceDirect

Physics Letters B

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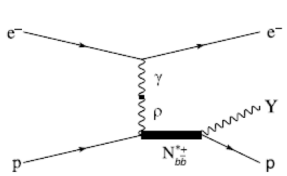
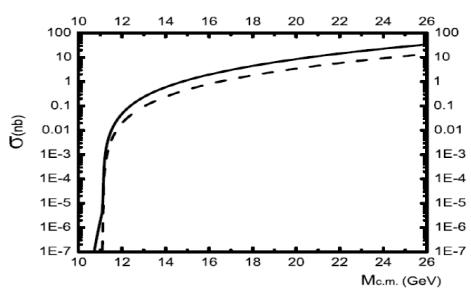
Prediction of super-heavy N^* and Λ^* resonances with hidden beauty

Jia-Jun Wu [a,*], Lu Zhao [a], B.S. Zou [a,b]

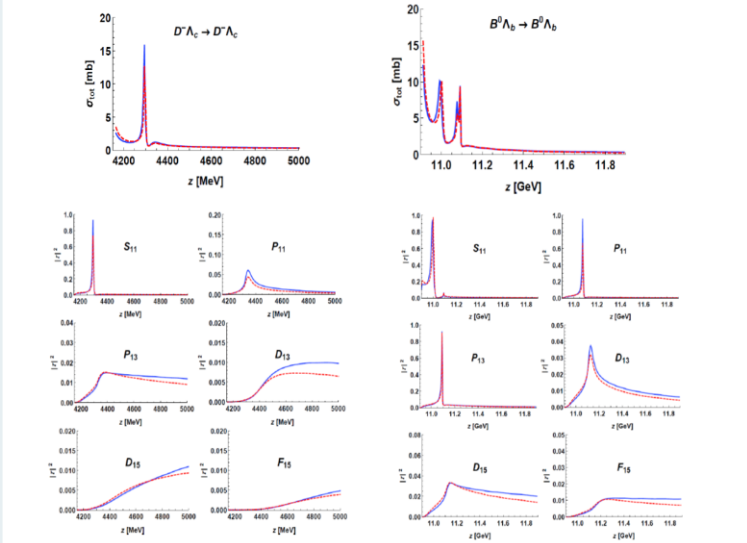
M (MeV)	Γ (MeV)	Γ_i (MeV)					
		πN	ηN	$\eta' N$	$K\Sigma$	$\eta_b N$	
11 052	1.38	0.10	0.21	0.11	0.42	0.52	$1/2^-$
		ρN	ωN	$K^*\Sigma$	ΥN		
11 100	1.33	0.09	0.30	0.39	0.51		$1/2^-$, $3/2^-$





$\bar{D}\Lambda_c - \bar{D}\Sigma_c$ and $B\Lambda_b - B\Sigma_b$ dynamical coupled channel study

C.W.Shen, Roechen, Meissner, Zou, CPC42(2018) 023106



More pentaquarks with hidden beauty than with hidden charm

Mode	Widths (MeV)		
	$J^P = 3/2^-$		$J^P = 1/2^-$
	$B\Sigma_b^*$	$B^*\Sigma_b$	$B^*\Sigma_b$
$B^*\Lambda_b$	271.1	19.9	167.0
Υp	0.3	0.04	0.1
ρN	5.5	0.02	0.1
ωp	20.9	0.07	0.4
$B\Lambda_b$	-	7.3	135.9
$B\Sigma_b$	-	-	-
$\eta_b p$	0.02	0.0001	0.0009
$\chi_{b0} p$	1.4	0.0008	0.2
πN	0.7	0.005	0.003
$B\Sigma_b^*$	-	-	-
Total	299.9	27.4	303.8

Y. H. Lin, C.W. Shen, B.S. Zou NPA980 21 (2018)

Summary and Outlook

- Heavy pentaquarks will not be mixing with 3-quark excited states.
- There are various models to discuss P_c States observed by LHCb grou p. There are various predictions for J^P and internal structure of P_c States.

New penta-quark spectroscopy provides a new ideal platform for understanding multi-quarkdynamics

- And we still wait for the measurement of J^P from experiments. We pin d own Pc from photo-production reaction. Study the decay behavior of P_c states based on various assumption of them.

Further experimental confirmation and extension for whole penta-quark spectroscopy from γN, πN, KN, e+e−, $\bar{\Lambda}_b\Lambda_b$, etc.

ep/γp@JLab, π10/K10@JPARC, BelleII, BESIII, Eic/EicC, PANDA@FAIR, STCF etc. may play important role here!

Thank very much !

中国科学院大学
University of Chinese Academy of Sciences

Backup

Motivation

- In 2010，from this paper，it was the first proposing N*，Λ* with hidden-charm exist above 4 GeV in theory.

PRL **105,** 232001 (2010) PHYSICAL REVIEW LETTERS week ending 3 DECEMBER 2010

Prediction of Narrow N^* and Λ^* Resonances with Hidden Charm above 4 GeV

Jia-Jun Wu,[1,2] R. Molina,[2,3] E. Oset,[2,3] and B. S. Zou[1,3]
[1]*Institute of High Energy Physics, CAS, Beijing 100049, China*
[2]*Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC, Institutos de Investigación de Paterna, Apartado 22085, 46071 Valencia, Spain*
[3]*Theoretical Physics Center for Science Facilities, CAS, Beijing 100049, China*
(Received 5 July 2010; published 29 November 2010)

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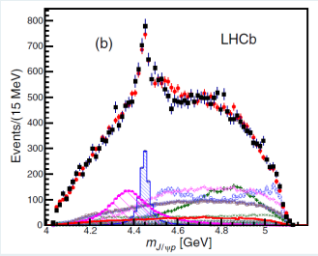
[3]*Theoretical Physics Center for Science Facilities, CAS, Beijing 100049, China*
(Received 5 July 2010; published 29 November 2010)

- In 2015, LHCb group first found two peaks of J/ψp invariant mass spectrum from $\Lambda_b \rightarrow$ J/ψKp reaction.

Selected for a Viewpoint in *Physics*
PRL 115, 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \rightarrow J/\psi K^- p$ Decays

R. Aaij *et al.*[*]
(LHCb Collaboration)
(Received 13 July 2015; published 12 August 2015)



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[3]*Theoretical Physics Center for Science Facilities, CAS, Beijing 100049, China*
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From 2015-Now, there are more than 500 citations for LHCb experimental paper.

- In 2015, LHCb group first found two peaks of J/ψp invariant mass spectrum from $\Lambda_b \rightarrow J/\psi Kp$ reaction.

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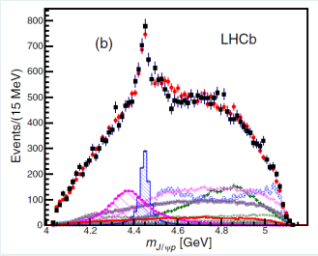
PRL 115, 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \rightarrow J/\psi K^- p$ Decays

R. Aaij *et al.*[*]
(LHCb Collaboration)
(Received 13 July 2015; published 12 August 2015)



Motivation

- In 2010, from this paper, it was the first proposing N*, Λ* with hidden-charm exist above 4 GeV in theory.

PRL 105, 232001 (2010) PHYSICAL REVIEW LETTERS week ending 3 DECEMBER 2010

Prediction of Narrow N^* and Λ^* Resonances with Hidden Charm above 4 GeV

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(Received 5 July 2010; published 29 November 2010)

From 2015-Now, there are more than 500 citations for LHCb experimental paper.

- In 2015, LHCb group first found two peaks of J/ψp invariant mass spectrum from $\Lambda_b \rightarrow$ J/ψKp reaction.

Selected for a Viewpoint in *Physics*
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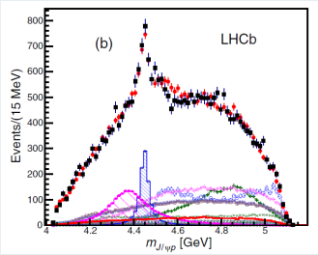
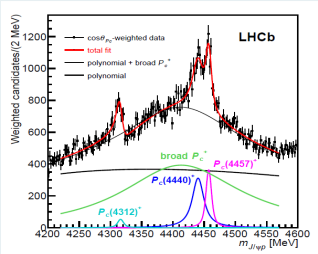


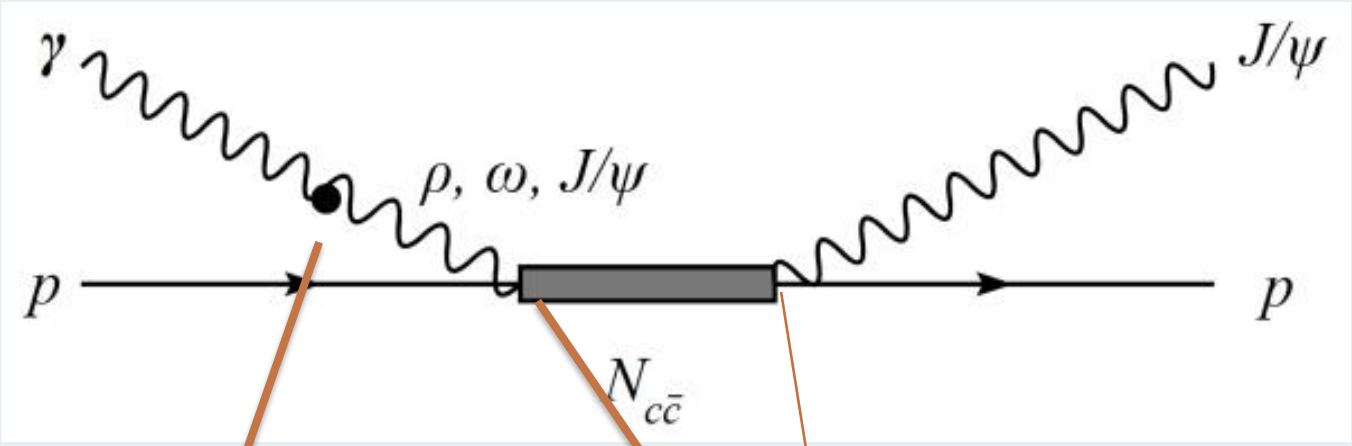
- Two months ago, LHCb group updated the new results.

Observation of a narrow pentaquark state, $P_c(4312)^+$, and of two-peak structure of the $P_c(4450)^+$

arXiv:1904.03947v1 [hep-ex] 8 Apr 2019



$\gamma\, p \rightarrow P_c \rightarrow J/\psi\, p$



Off shell

On shell

VMD vertex

PcVP vertex

PcγP vertex