第十八届全国中高能核物理大会

On the way of (re)searching pentaquark states

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Outline

Introduction

1. Theoretical Predictions (2010--2014)
2. First Exp./Theo. Findings (2014--2018)
3. New Exp./Theo. Results (2019--)
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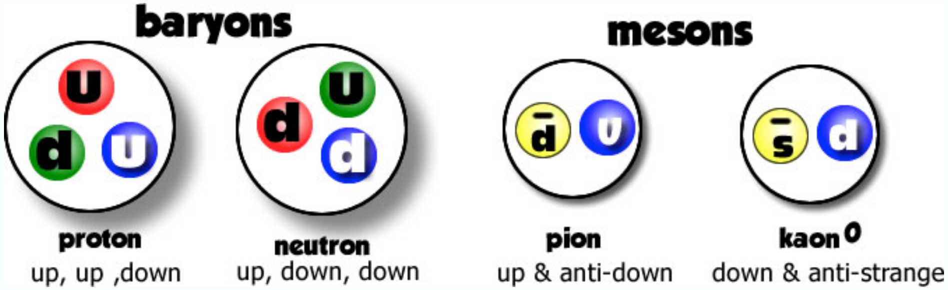
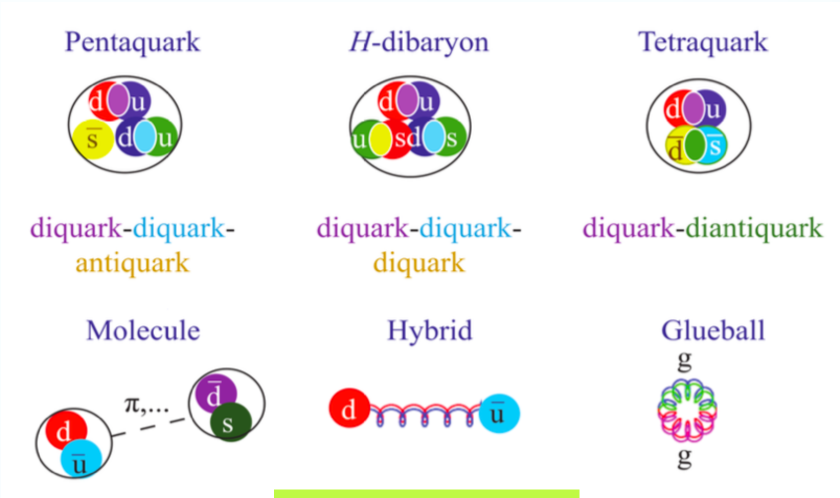
§ Introduction

Quark model





Exotic States

H.-X. Chen, W. Chen, X. Liu and S.-L. Zhu, **Phys. Rept. 639** (2016) 1.
A. Esposito, A. Pilloni and A. D. Polosa, **Phys. Rept. 668** (2016) 1.
F.-K. Guo, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao and B.-S. Zou, **Rev. Mod. Phys. 90** (2018) 0115004.
S. L. Olsen, T. Skwarnicki and D. Zieminska, **Rev. Mod. Phys. 90** (2018) 0115003.

Pentaquark

1. Theoretical Pridictions

$\Theta^+(1540)$ ✗

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]

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

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

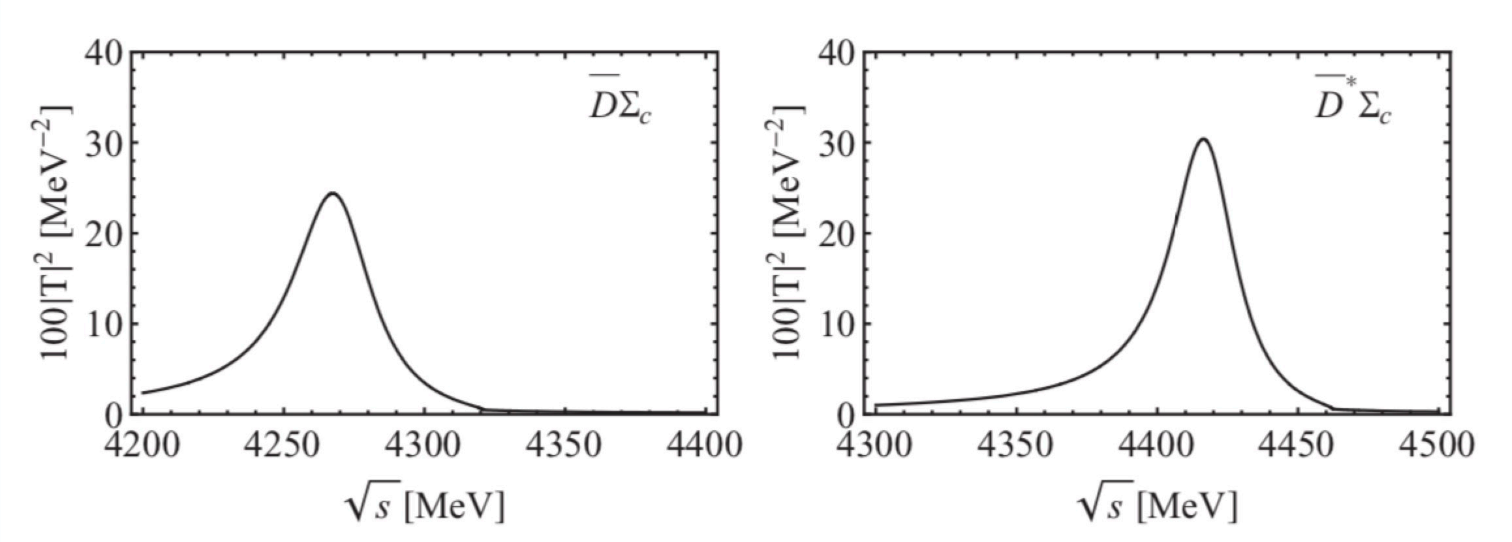
W. L. Wang, F. Huang, Z. Y. Zhang and B. S. Zou, **Phys. Rev. C 84** (2011) 015203.

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

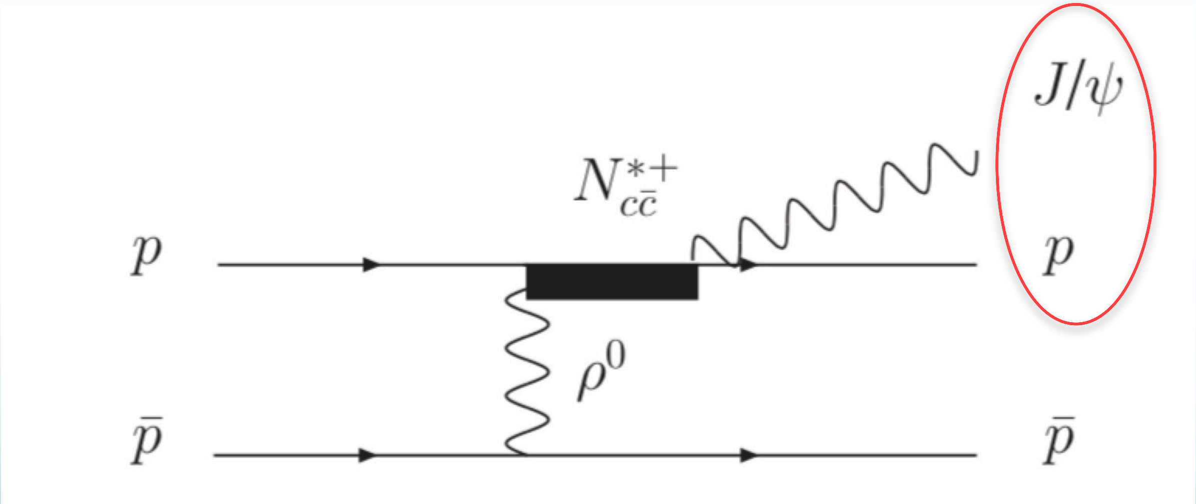
J. J. Wu, T.-S. H. Lee and B. S. Zou, **Phys. Rev. C 85** (2012) 044002.

C. Garcia-Recio, J. Nieves, O. Romanets, L. L. Salcedo and L. Tolos, **Phys. Rev. D 87** (2013) 074034.

*C. W. Xiao, J. Nieves and E. Oset, **Phys. Rev. D 88** (2013) 056012.*

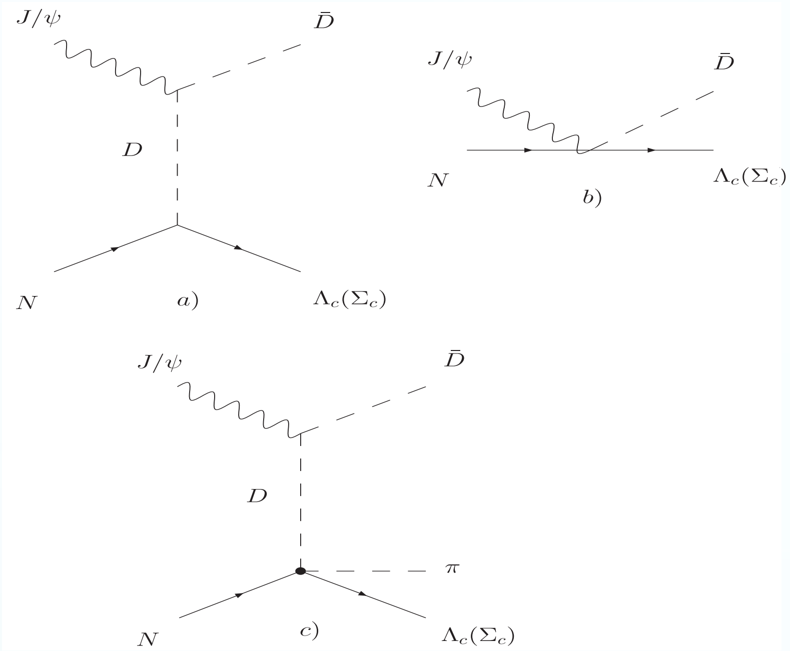


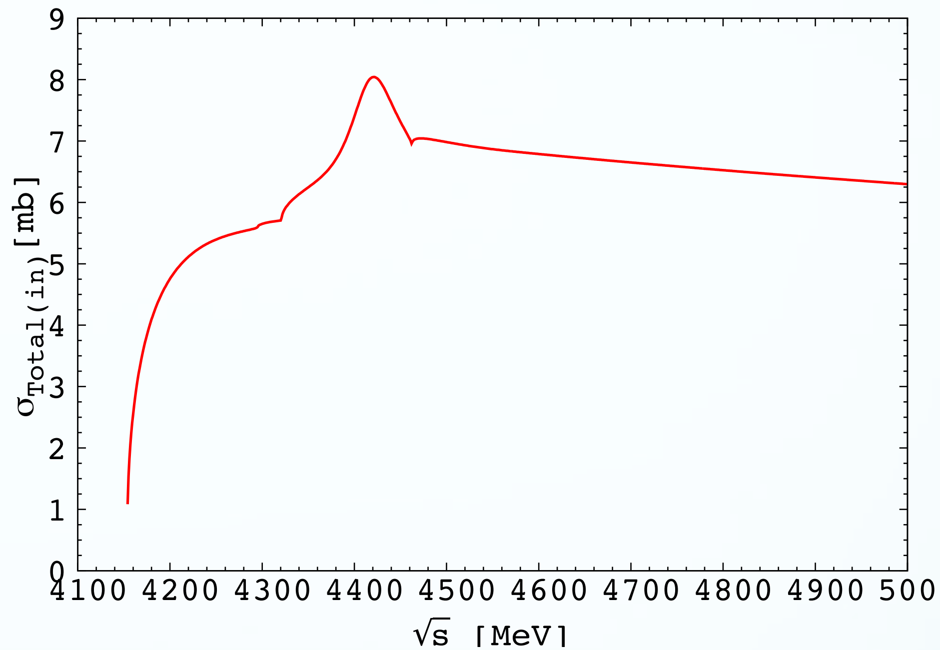
J. J. Wu, R. Molina, E. Oset, and B. S. Zou, **Phys. Rev. Lett. 105**, 232001 (2010)

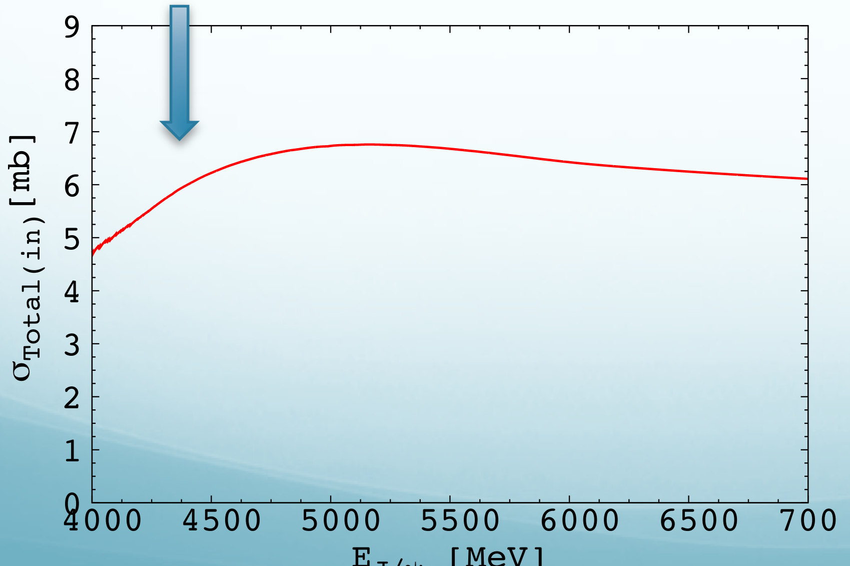


J. J. Wu, R. Molina, E. Oset and B. S. Zou, **Phys. Rev. C 84** (2011) 015202

Test the predictions with nuclear target

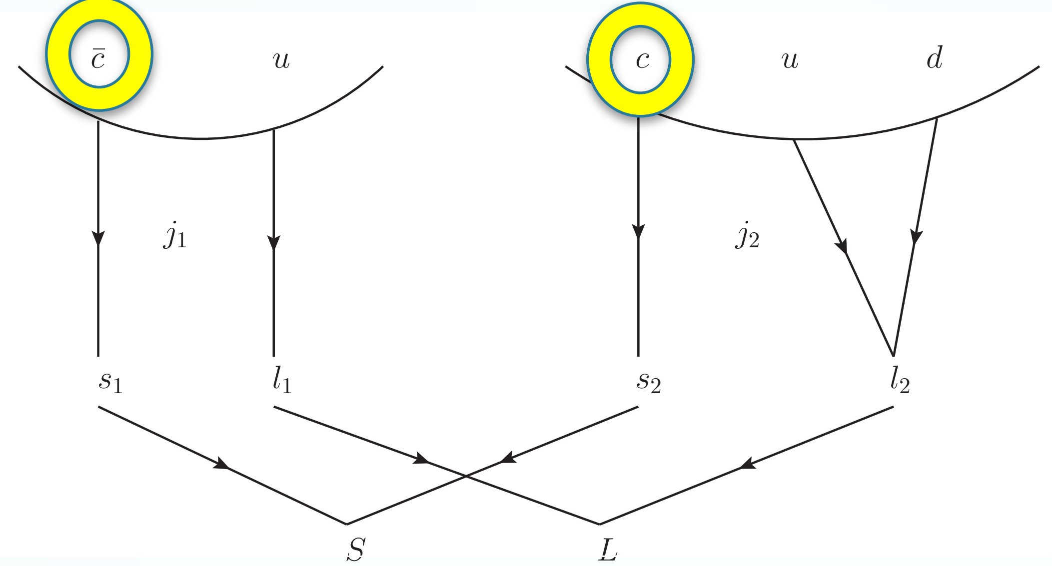






Fermi motion considered

R. Molina, *C. W. Xiao*, E. Oset, **Phys. Rev. C 86,** 014604 (2012)



Considering the heavy quark spin-flavor symmetry

$$_{(\ell'_M,\ell'_B)}\left\langle S'_{c\bar{c}},\, \mathcal{L}';\, J',\, \alpha' \middle| H^{QCD} \middle| S_{c\bar{c}},\, \mathcal{L};\, J,\, \alpha \right\rangle_{(\ell_M,\ell_B)}$$
$$= \delta_{\alpha\alpha'}\delta_{JJ'}\delta_{S'_{c\bar{c}}S_{c\bar{c}}}\delta_{\mathcal{L}\mathcal{L}'}\left\langle \ell'_M\ell'_B\mathcal{L};\alpha \middle|\middle| H^{QCD} \middle|\middle| \ell_M\ell_B\mathcal{L};\alpha \right\rangle.$$

$$|l_1 s_1 j_1; l_2 s_2 j_2; JM\rangle = \sum_{S,L}[(2S+1)(2L+1)(2j_1+1)(2j_2+1)]^{1/2}\begin{Bmatrix} l_1 & l_2 & L \\ s_1 & s_2 & S \\ j_1 & j_2 & J \end{Bmatrix}|l_1 l_2 L; s_1 s_2 S; JM\rangle$$

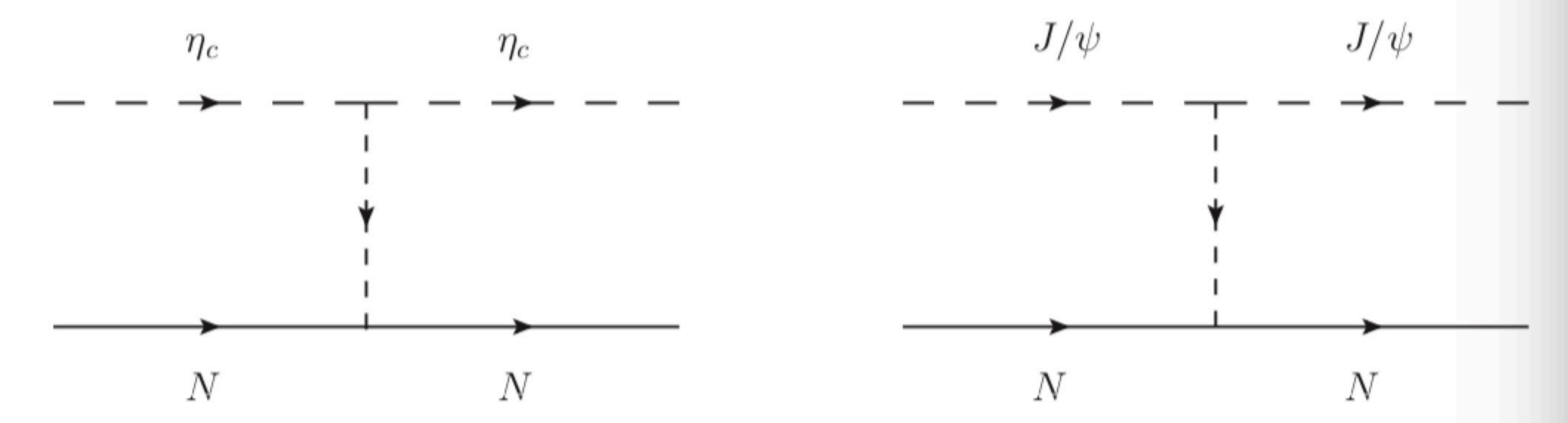
$$|\bar{D}\Sigma_c\rangle = \frac{1}{2}\left|S_{c\bar{c}}=0,\,\mathcal{L}=\frac{1}{2};J=\frac{1}{2}\right\rangle_{(\ell_M=1/2,\ell_B=1)} - \frac{1}{2\sqrt{3}}\left|S_{c\bar{c}}=1,\,\mathcal{L}=\frac{1}{2};J=\frac{1}{2}\right\rangle_{(\ell_M=1/2,\ell_B=1)}$$
$$+\sqrt{\frac{2}{3}}\left|S_{c\bar{c}}=1,\,\mathcal{L}=\frac{3}{2};J=\frac{1}{2}\right\rangle_{(\ell_M=1/2,\ell_B=1)},$$

$$J = 1/2, I = 1/2$$

$$
\begin{array}{ccccccc}
\eta_c N & J_\Psi N & \bar{D}\Lambda_c & \bar{D}\Sigma_c & \bar{D}^*\Lambda_c & \bar{D}^*\Sigma_c & \bar{D}^*\Sigma_c^*
\end{array}
$$

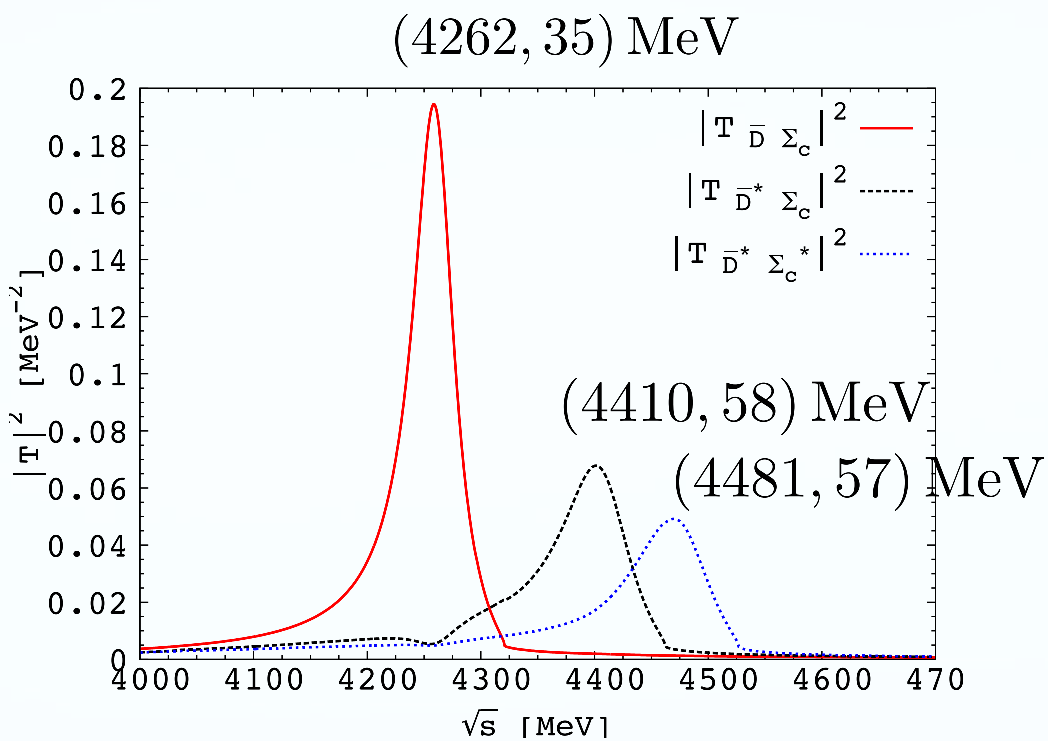
$$
\begin{pmatrix}
\mu_1 & 0 & \frac{\mu_{12}}{2} & \frac{\mu_{13}}{2} & \frac{\sqrt{3}\mu_{12}}{2} & -\frac{\mu_{13}}{2\sqrt{3}} & \sqrt{\frac{2}{3}}\mu_{13} \\
0 & \mu_1 & \frac{\sqrt{3}\mu_{12}}{2} & -\frac{\mu_{13}}{2\sqrt{3}} & -\frac{\mu_{12}}{2} & \frac{5\mu_{13}}{6} & \frac{\sqrt{2}\mu_{13}}{3} \\
\frac{\mu_{12}}{2} & \frac{\sqrt{3}\mu_{12}}{2} & \mu_2 & 0 & 0 & \frac{\mu_{23}}{\sqrt{3}} & \sqrt{\frac{2}{3}}\mu_{23} \\
\frac{\mu_{13}}{2} & -\frac{\mu_{13}}{2\sqrt{3}} & 0 & \frac{1}{3}(2\lambda_2 + \mu_3) & \frac{\mu_{23}}{\sqrt{3}} & \frac{2(\lambda_2 - \mu_3)}{3\sqrt{3}} & \frac{1}{3}\sqrt{\frac{2}{3}}(\mu_3 - \lambda_2) \\
\frac{\sqrt{3}\mu_{12}}{2} & -\frac{\mu_{12}}{2} & 0 & \frac{\mu_{23}}{\sqrt{3}} & \mu_2 & -\frac{2\mu_{23}}{3} & \frac{\sqrt{2}\mu_{23}}{3} \\
-\frac{\mu_{13}}{2\sqrt{3}} & \frac{5\mu_{13}}{6} & \frac{\mu_{23}}{\sqrt{3}} & \frac{2(\lambda_2 - \mu_3)}{3\sqrt{3}} & -\frac{2\mu_{23}}{3} & \frac{1}{9}(2\lambda_2 + 7\mu_3) & \frac{1}{9}\sqrt{2}(\mu_3 - \lambda_2) \\
\sqrt{\frac{2}{3}}\mu_{13} & \frac{\sqrt{2}\mu_{13}}{3} & \sqrt{\frac{2}{3}}\mu_{23} & \frac{1}{3}\sqrt{\frac{2}{3}}(\mu_3 - \lambda_2) & \frac{\sqrt{2}\mu_{23}}{3} & \frac{1}{9}\sqrt{2}(\mu_3 - \lambda_2) & \frac{1}{9}(\lambda_2 + 8\mu_3)
\end{pmatrix}_{I=1/2}
$$

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



$J = 1/2, I = 1/2$

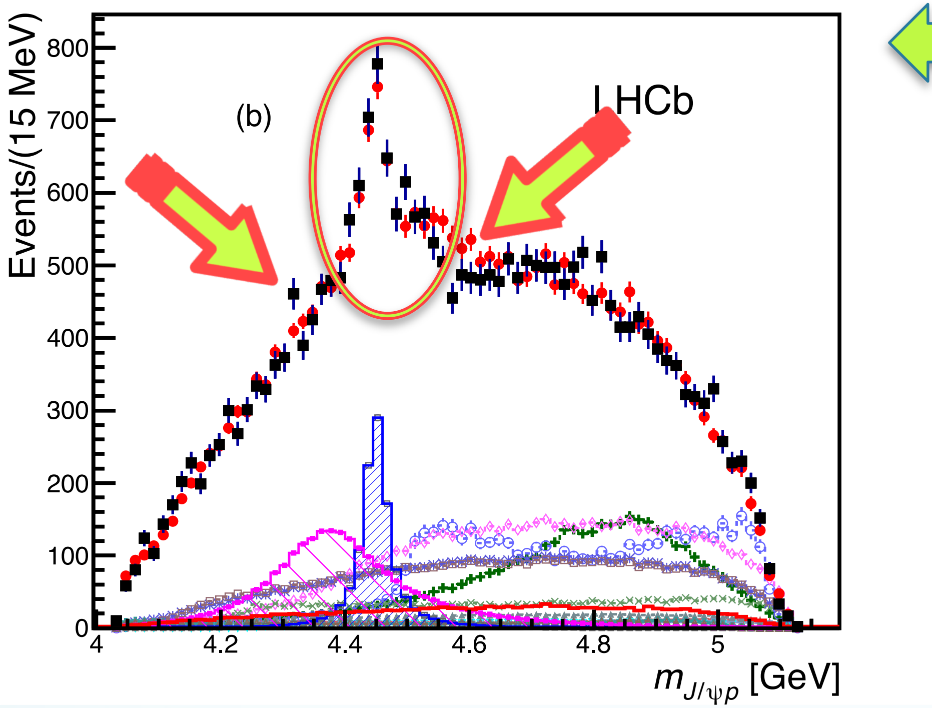
$$\mu_2 = \frac{1}{4f^2}(k^0 + k'^0), \qquad \mu_3 = -\frac{1}{4f^2}(k^0 + k'^0),$$
$$\mu_{12} = -\sqrt{6}\,\frac{m_\rho^2}{p_{D^*}^2 - m_{D^*}^2}\,\frac{1}{4f^2}(k^0 + k'^0), \qquad \mu_1 = 0,$$
$$\mu_{23} = 0, \qquad \lambda_2 = \mu_3, \qquad \mu_{13} = -\mu_{12}.$$



4261.87 + i17.84							
	$\eta_c N$	$J/\psi N$	$\bar{D}\Lambda_c$	$\bar{D}\Sigma_c$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Sigma_c^*$
g_i	*1.04 + i0.05*	*0.76 − i0.08*	0.02 − i0.02	**3.12 − i0.25**	0.14 − i0.48	0.33 − i0.68	0.16 − i0.28
$\|g_i\|$	**1.05**	**0.76**	0.02	**3.13**	0.50	0.75	0.32
4410.13 + i29.44							
	$\eta_c N$	$J/\psi N$	$\bar{D}\Lambda_c$	$\bar{D}\Sigma_c$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Sigma_c^*$
g_i	*0.34 + i0.16*	*1.43 − 0.12*	0.15 − i0.10	0.20 − i0.05	0.17 − i0.11	**3.05 − i0.54**	0.07 − i0.51
$\|g_i\|$	**0.38**	**1.44**	0.18	0.20	0.20	**3.10**	0.51
4481.35 + i28.91							
	$\eta_c N$	$J/\psi N$	$\bar{D}\Lambda_c$	$\bar{D}\Sigma_c$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Sigma_c^*$
g_i	*1.15 − i0.04*	*0.72 + i0.03*	0.18 − i0.08	0.10 − i0.03	0.09 − i0.08	0.09 − i0.06	**2.88 − i0.57**
$\|g_i\|$	**1.15**	**0.72**	0.19	0.10	0.12	0.11	**2.93**

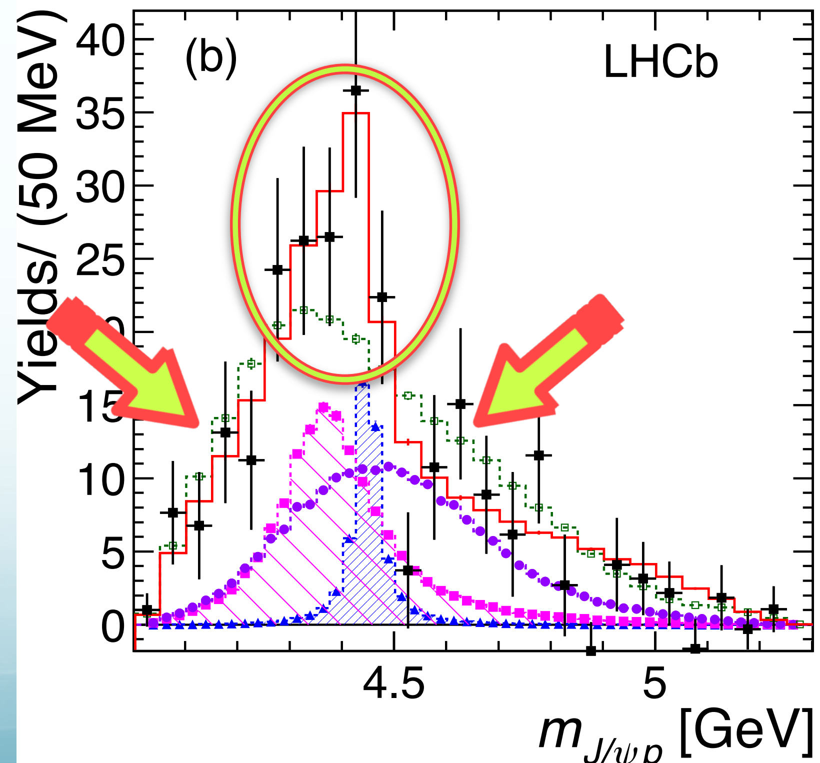
C. W. Xiao, J. Nieves and E. Oset, **Phys. Rev. D 88**, 056012 (2013)

2. First Exp./Theo. Findings



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

R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 117, 082003 (2016)



$$P_c(4380)^+, \Gamma = 205$$

$$P_c(4450)^+, \Gamma = 39$$

J^P ?

◆ diquark state:

L. Maiani, A. D. Polosa and V. Riquer, **Phys. Lett. B 749**, 289 (2015)
R. F. Lebed, **Phys. Lett. B 749,** 454 (2015)
G. N. Li, X. G. He and M. He, **JHEP 1512,** 128 (2015)
Z. G. Wang, **Eur. Phys. J. C 76**, no. 2, 70 (2016)
Z. G. Wang and T. Huang, **Eur. Phys. J. C 76**, no. 1, 43 (2016)
R. Zhu and C. F. Qiao, **Phys. Lett. B 756**, 259 (2016)
Z. G. Wang, **Nucl. Phys. B 913**, 163 (2016)
A. Ali, I. Ahmed, M. J. Aslam and A.Rehman, **Phys. Rev. D 94**, no. 5, 054001 (2016)

◆ a compact pentaquark state:

E. Santopinto and A. Giachino, arXiv:1604.03769 [hep-ph].

◆ a soliton-$\bar{D}$-D bound state:

N. N. Scoccola, D. O. Riska and M. Rho, **Phys. Rev. D 92**, no. 5, 051501 (2015)

◆ a kinematical effect or a cusp effect:

F. K. Guo, U.-G. Meißner, W. Wang and Z. Yang, **Phys. Rev. D 92,** no. 7, 071502 (2015)
X. H. Liu, Q. Wang and Q. Zhao, **Phys. Lett. B 757**, 231 (2016)
M. Mikhasenko, arXiv:1507.06552 [hep-ph].

◆ molecular states (more favored):

R. Chen, X. Liu, X. Q. Li and S. L. Zhu, Phys. Rev. Lett. 115, no. 13, 132002 (2015)

H. X. Chen, W. Chen, X. Liu, T. G. Steele and S. L. Zhu, Phys. Rev. Lett. 115, no. 17, 172001 (2015)

L. Roca, J. Nieves and E. Oset, Phys. Rev. D 92, no. 9, 094003 (2015)

J. He, Phys. Lett. B 753, 547 (2016)

U.-G. Meißner and J. A. Oller, Phys. Lett. B 751, 59 (2015)

C. W. Xiao and U.-G. Meißner, Phys. Rev. D 92 , 114002 (2015)

Q. F. L and Y. B. Dong, Phys. Rev. D 93, no. 7, 074020 (2016)

Y. Shimizu, D. Suenaga and M. Harada, Phys. Rev. D 93, no. 11, 114003 (2016)

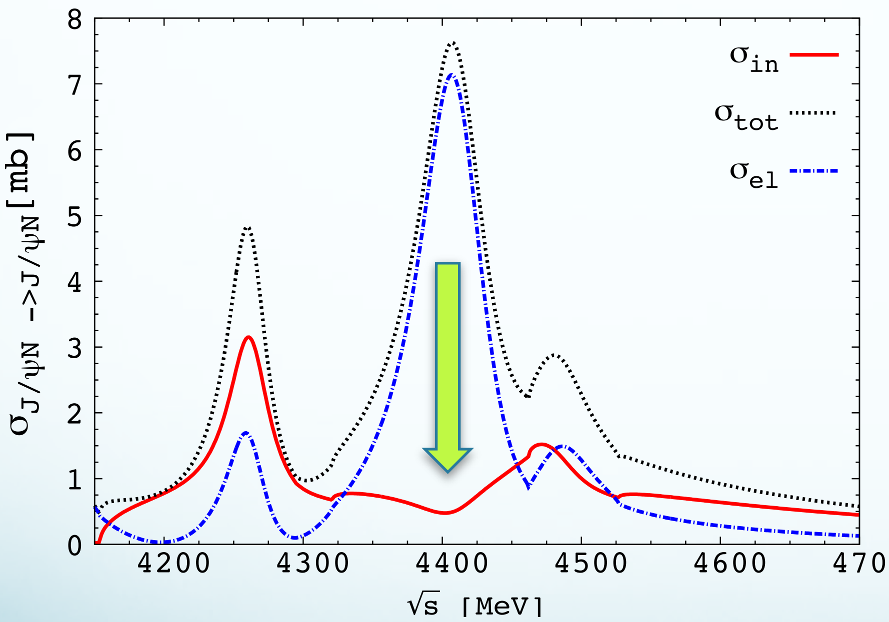
C. W. Shen, F. K. Guo, J. J. Xie and B. S. Zou, Nucl. Phys. A 954, 393 (2016) P. G. Ortega, D. R. Entem and F. Fernndez, **Phys.Lett. B 764,** 207-211 (2017)

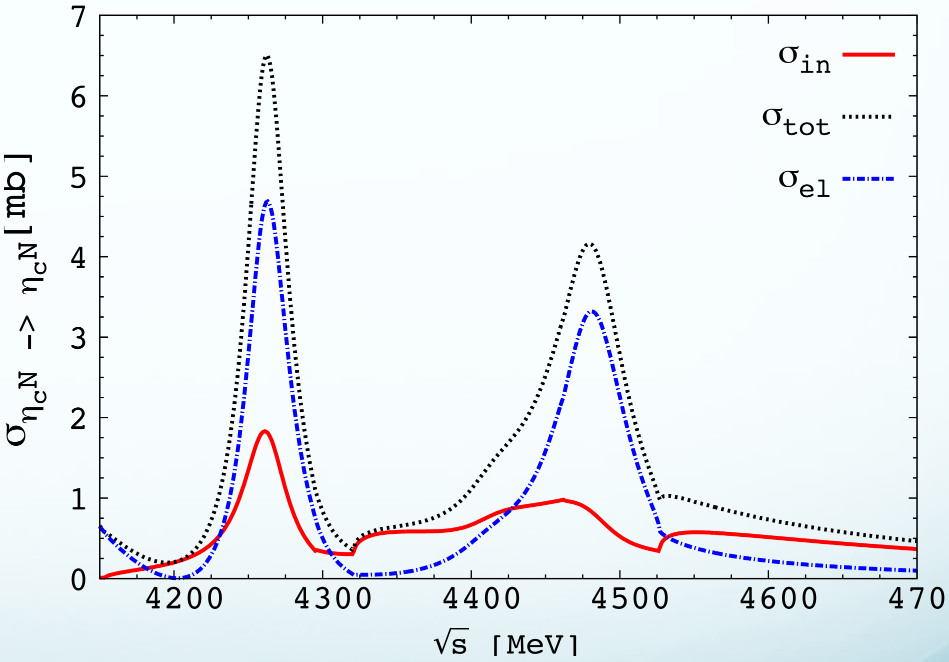
Y. Yamaguchi and E. Santopinto, **Phys.Rev. D 96,** no.1, 014018(2017)

C. W. Xiao, Phys. Rev. D 95, 014006 (2017)

After the experimental findings in the decay of $\Lambda_b^0 \to J/\psi K^- p$

We investigate the inelastic cross sections

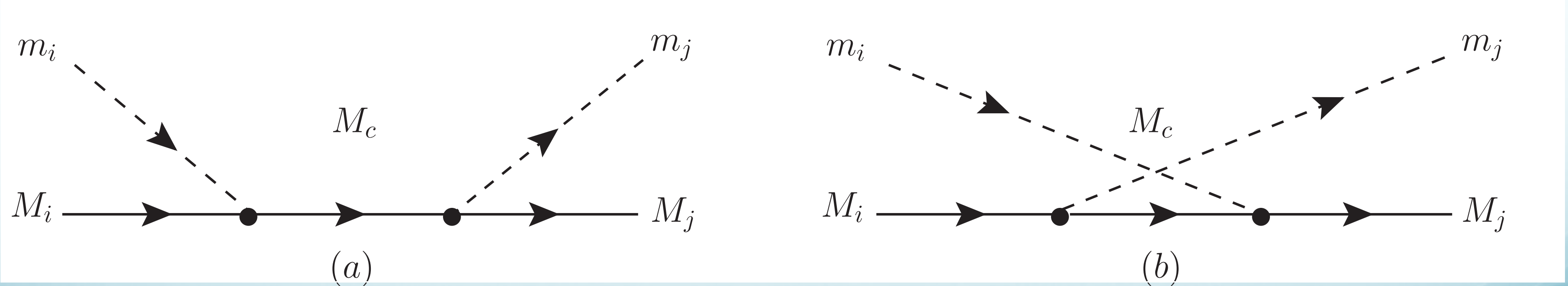


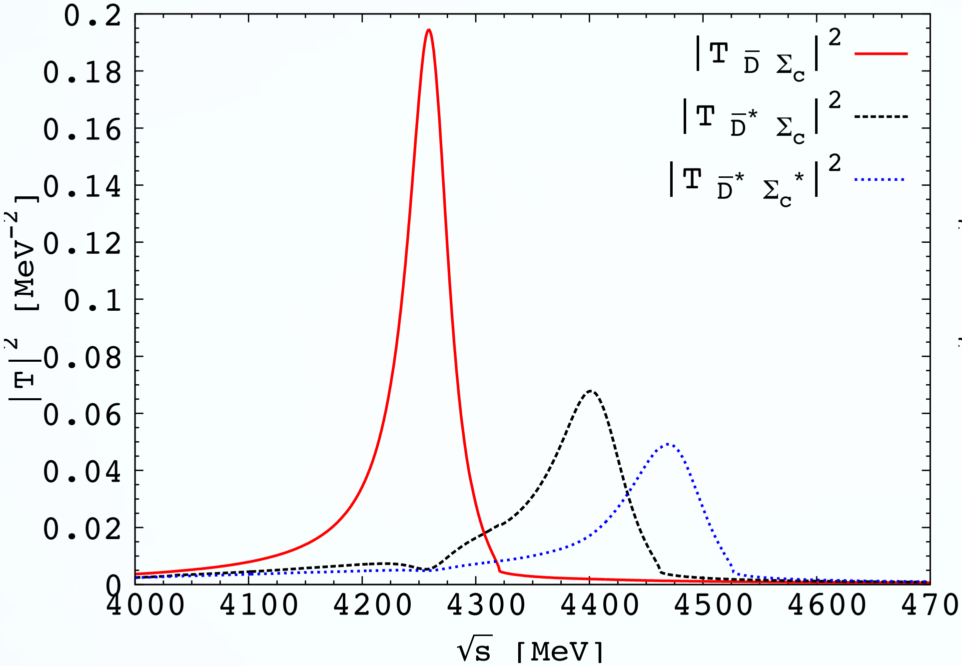


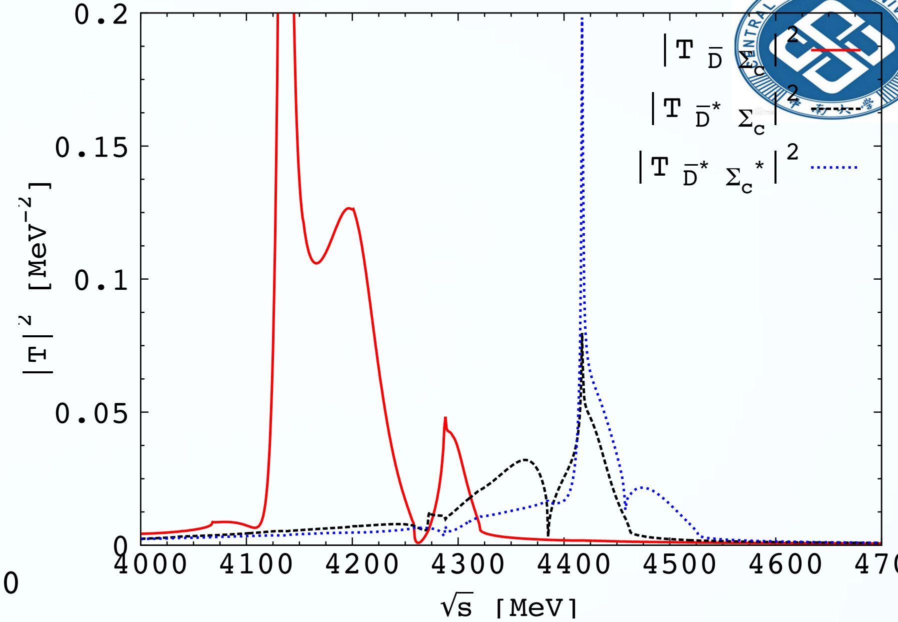
C. W. Xiao and U.-G. Meißner, **Phys. Rev. D 92 ,** 114002 (2015)

We only consider the t channel vector meson exchange diagrams in the former calculations

Next we consider the s- and u- channels contributions

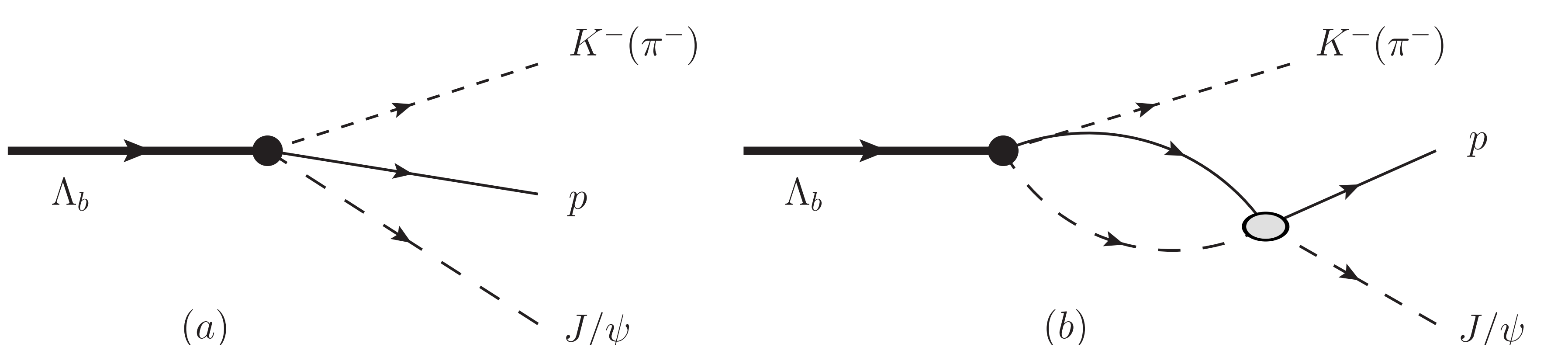






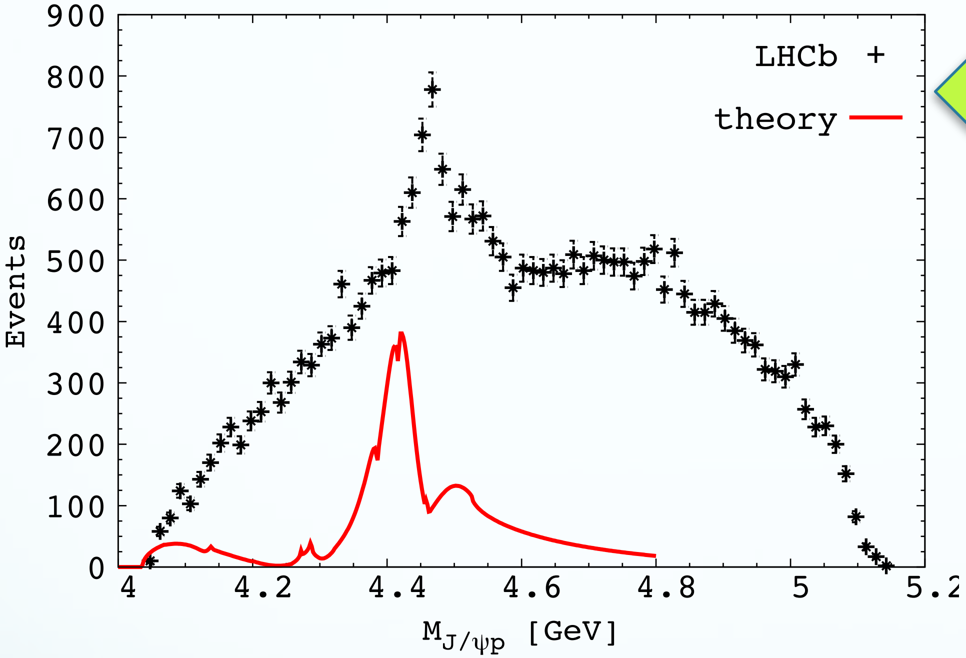
Sectors	Channels	Thresholds	Refs. [10,57]	WT term	WT + s	WT + s + u
	$\bar{D}\Sigma_c$	4320.8	(4262,35)	(4261,44)	(4264,46)	(4291,39)
$J^P = \frac{1}{2}^-$	$\bar{D}^*\Sigma_c$	4462.2	(4410,58)	(4409,74)	(4411,76)	(4427,60)
	$\bar{D}^*\Sigma_c^*$	4526.7	(4481,57)	(4479,80)	(4475,82)	(4482,123)

Finally, we also consider the final state interactions



Results for two decays processes:

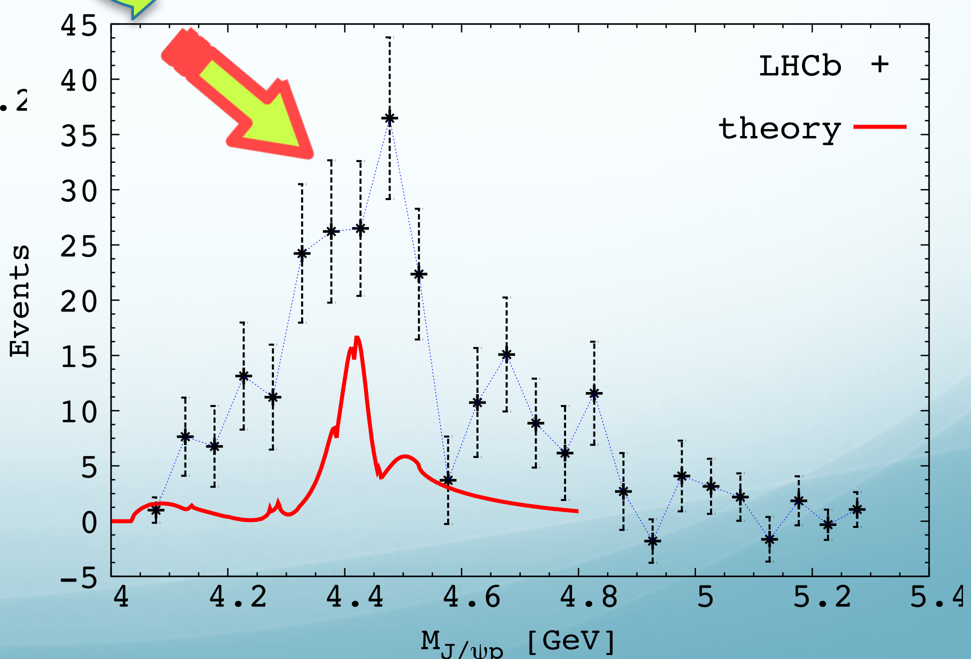
$$\Lambda_b^0 \to J/\psi K^- p$$



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

R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 117, 082003 (2016)

$$\Lambda_b^0 \to J/\psi p \pi^-$$



C. W. Xiao, **Phys. Rev. D 95,** 014006 (2017)

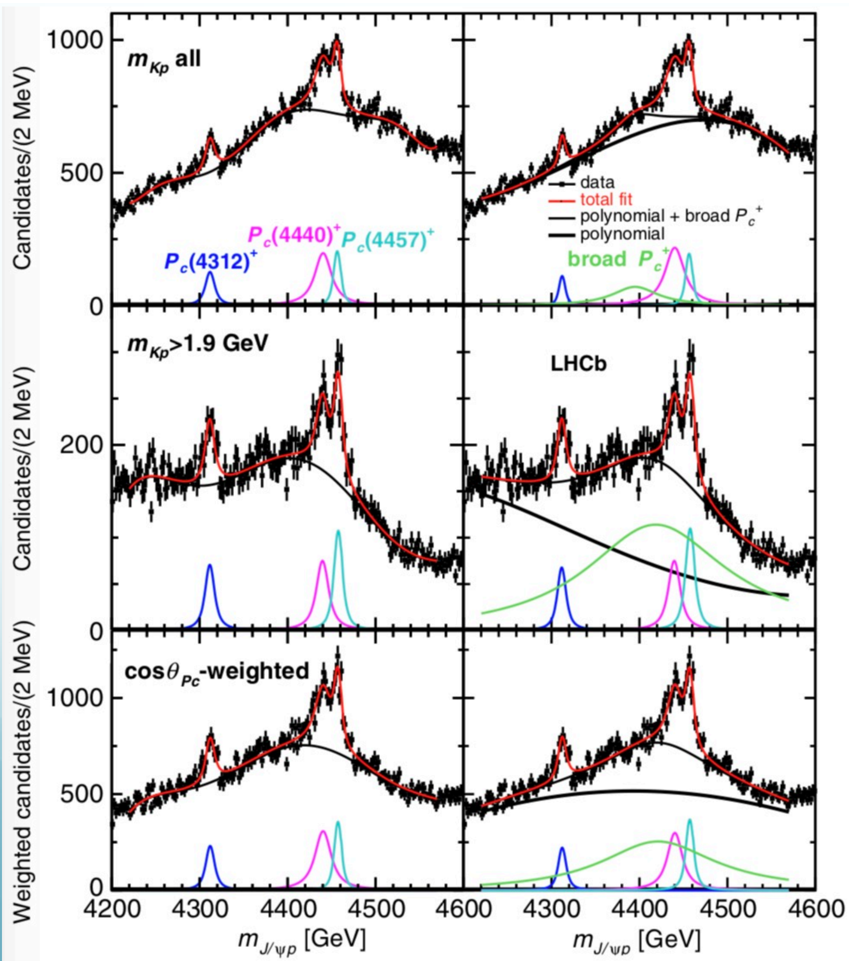
3. New Exp./Theo. Results

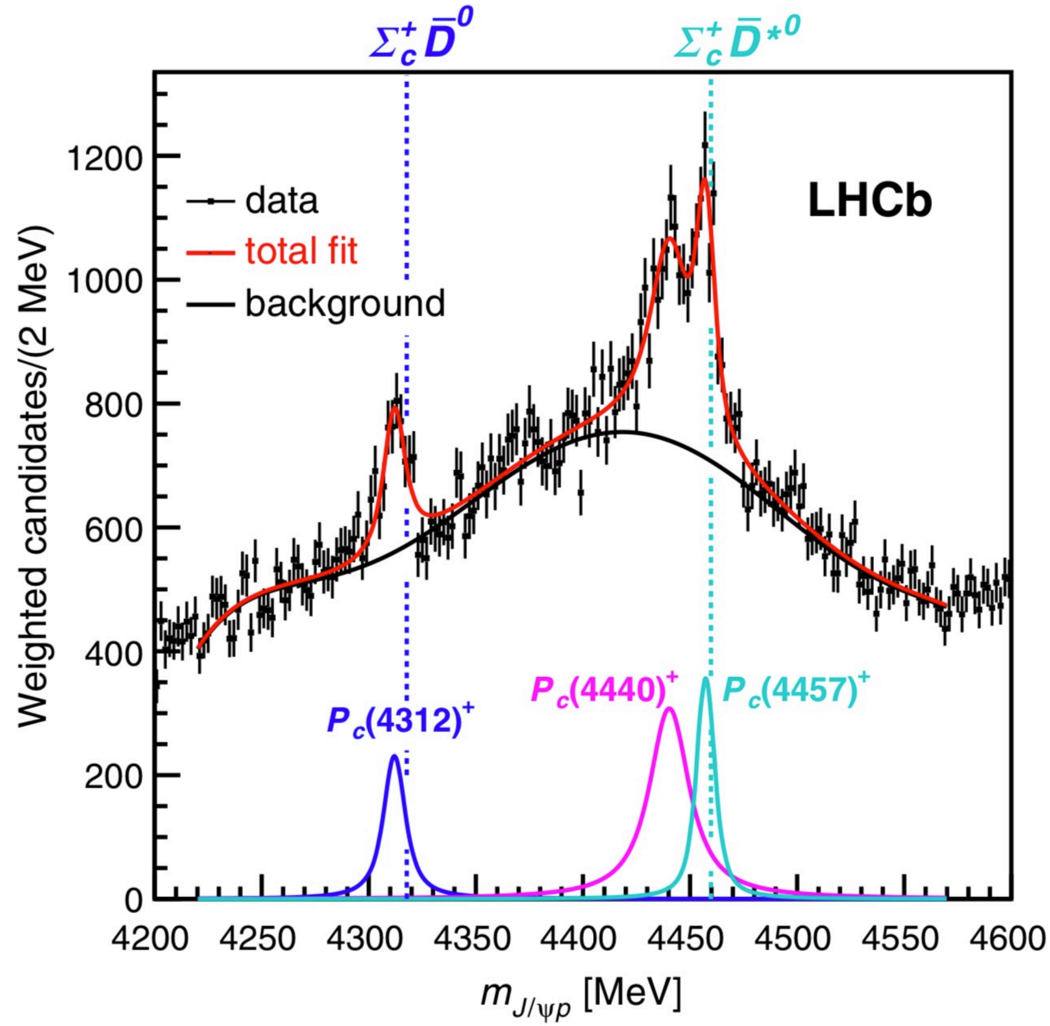
PHYSICAL REVIEW LETTERS **122**, 222001 (2019)

Featured in Physics

Observation of a Narrow Pentaquark State, $P_c(4312)^+$, and of the Two-Peak Structure of the $P_c(4450)^+$

R. Aaij *et al.*[*]
(LHCb Collaboration)





$$M_{P_{c1}} = 4311.9 \pm 0.7^{+6.8}_{-0.6}, \quad \Gamma_{P_{c1}} = 9.8 \pm 2.7^{+3.7}_{-4.5},$$

$$M_{P_{c2}} = 4440.3 \pm 1.3^{+4.1}_{-4.7}, \quad \Gamma_{P_{c2}} = 20.6 \pm 4.9^{+8.7}_{-10.1},$$

$$M_{P_{c3}} = 4457.3 \pm 0.6^{+4.1}_{-1.7}, \quad \Gamma_{P_{c3}} = 6.4 \pm 2.0^{+5.7}_{-1.9}.$$

$P_c(4312)^+$

$4306.38 + i7.62$							
	$\eta_c N$	$J/\psi N$	$\bar{D}\Lambda_c$	$\bar{D}\Sigma_c$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Sigma_c^*$
g_i	$0.67 + i0.01$	$0.46 - i0.03$	$0.01 - i0.01$	$2.07 - i0.28$	$0.03 + i0.25$	$0.06 - i0.31$	$0.04 - i0.15$
$\lvert g_i \rvert$	0.67	0.46	0.01	2.09	0.25	0.31	0.16
$4452.96 + i11.72$							
	$\eta_c N$	$J/\psi N$	$\bar{D}\Lambda_c$	$\bar{D}\Sigma_c$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Sigma_c^*$
g_i	$0.24 + i0.03$	$0.88 - 0.11$	$0.09 - i0.06$	$0.12 - i0.02$	$0.11 - i0.09$	$1.97 - i0.52$	$0.02 + i0.19$
$\lvert g_i \rvert$	0.25	0.89	0.11	0.13	0.14	2.03	0.19
$4520.45 + i11.12$							
	$\eta_c N$	$J/\psi N$	$\bar{D}\Lambda_c$	$\bar{D}\Sigma_c$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Sigma_c^*$
g_i	$0.72 - i0.10$	$0.45 - i0.04$	$0.11 - i0.06$	$0.06 - i0.02$	$0.06 - i0.05$	$0.07 - i0.02$	$1.84 - i0.56$
$\lvert g_i \rvert$	0.73	0.45	0.13	0.06	0.08	0.08	1.92

$P_c(4440)^+$

$4374.33 + i6.87$	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$0.73 - i0.06$	$0.11 - i0.13$	$0.02 - i0.19$	$1.91 - i0.31$	$0.03 - i0.30$
$\lvert g_i \rvert$	0.73	0.18	0.19	1.94	0.30
$4452.48 + i1.49$	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$0.30 - i0.01$	$0.05 - i0.04$	$1.82 - i0.08$	$0.08 - i0.02$	$0.01 - i0.19$
$\lvert g_i \rvert$	0.30	0.07	1.82	0.08	0.19
$4519.01 + i6.86$	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$0.66 - i0.01$	$0.11 - i0.07$	$0.10 - i0.3$	$0.13 - i0.02$	$1.79 - i0.36$
$\lvert g_i \rvert$	0.66	0.13	0.10	0.13	1.82

$P_c(4457)^+$

C. W. Xiao, J. Nieves and E. Oset, **arXiv:1904.01296**

states [MeV]	Widths [MeV]	Main channel	J^P	Experimental state
4306.4	15.2	$\bar{D}\Sigma_c$	$1/2^-$	$P_c(4312)$
4452.9	23.4	$\bar{D}^*\Sigma_c$	$1/2^-$	$P_c(4440)$
4452.5	3.0	$\bar{D}^*\Sigma_c$	$3/2^-$	$P_c(4457)$

$$M_{P_{c1}} = 4311.9 \pm 0.7^{+6.8}_{-0.6}, \quad \Gamma_{P_{c1}} = 9.8 \pm 2.7^{+3.7}_{-4.5},$$
$$M_{P_{c2}} = 4440.3 \pm 1.3^{+4.1}_{-4.7}, \quad \Gamma_{P_{c2}} = 20.6 \pm 4.9^{+8.7}_{-10.1},$$
$$M_{P_{c3}} = 4457.3 \pm 0.6^{+4.1}_{-1.7}, \quad \Gamma_{P_{c3}} = 6.4 \pm 2.0^{+5.7}_{-1.9}.$$

4. Summary

- Our results of bound states:

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

a $\bar{D}\Sigma_c$ state — $P_c(4312)^+$

Having $J = 1/2$.

a $\bar{D}\Sigma_c^*$ state — $P_c(4457)^+$

With $J = 3/2$.

a $\bar{D}^*\Sigma_c$ state — $P_c(4440)^+$

Degenerate in $J = 1/2,\ 3/2$.

a $\bar{D}^*\Sigma_c^*$ state

Degenerate in $J = 1/2,\ 3/2,\ 5/2$.

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Pentaquark states!

We are on the way of

(re)searching……

谢谢大 家！

Thanks for your attention!