第五届强子谱和强子结构研讨会

Study of the pentaquark states

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Outline

1. Introduction
2. Formalism
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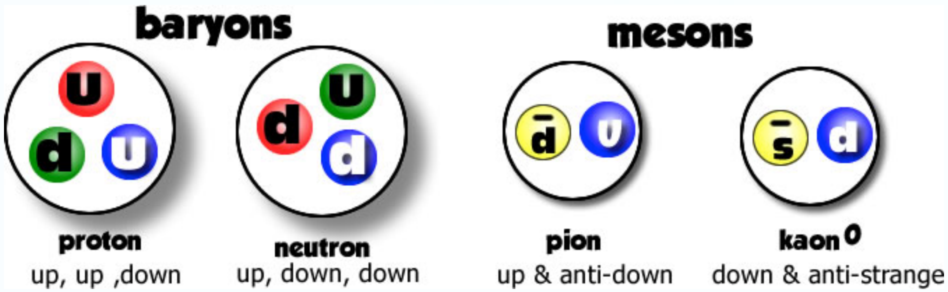
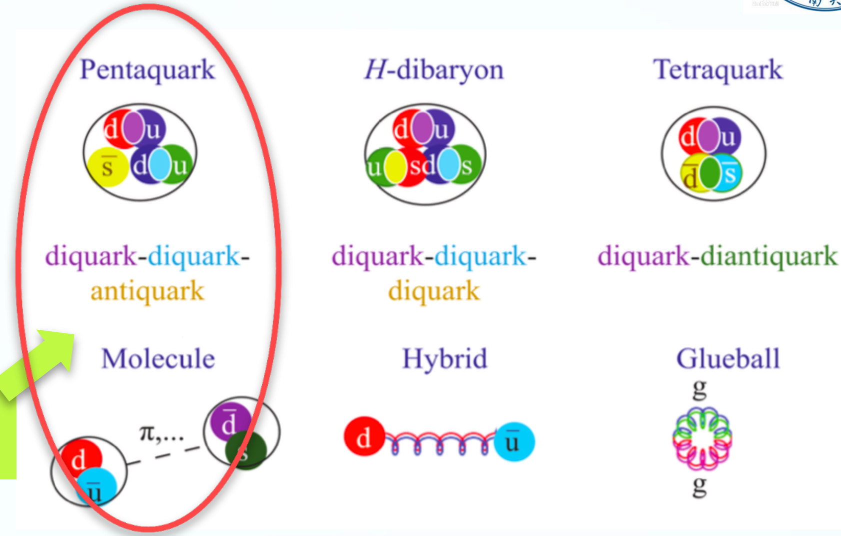
4. Summary

§1. Introduction



Quark model

Exotic States



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Pridictions

$\Theta^+(1540)$ X

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.

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

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

In hidden charm strangeness sector

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

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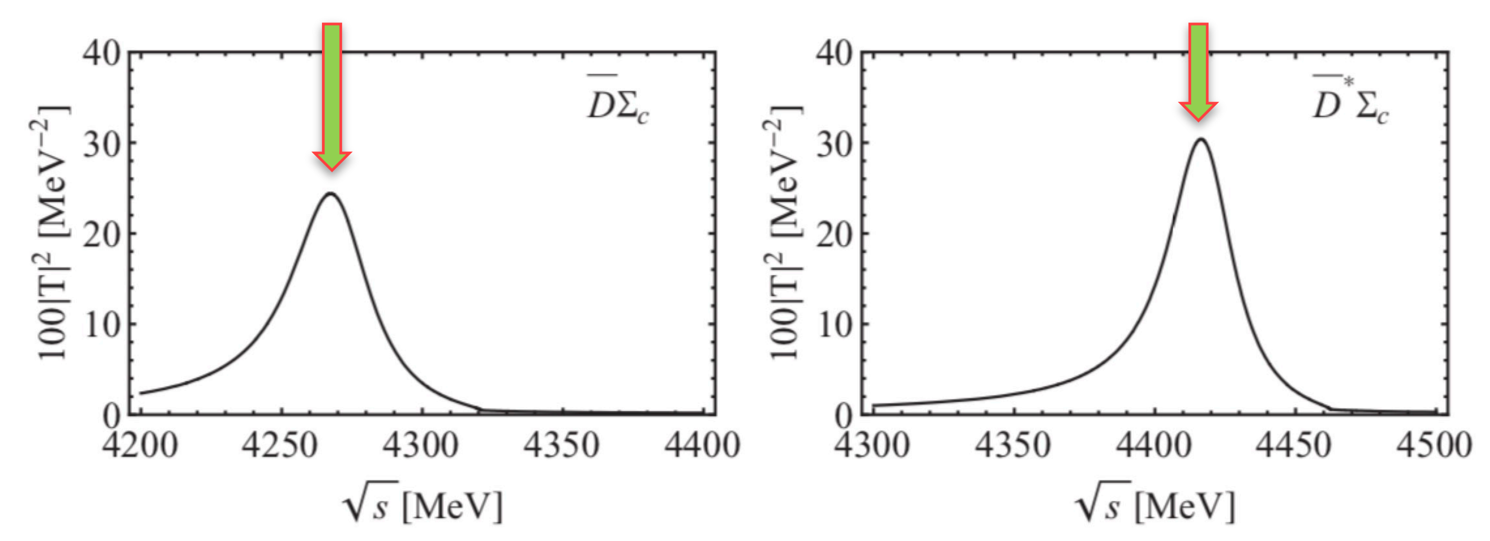
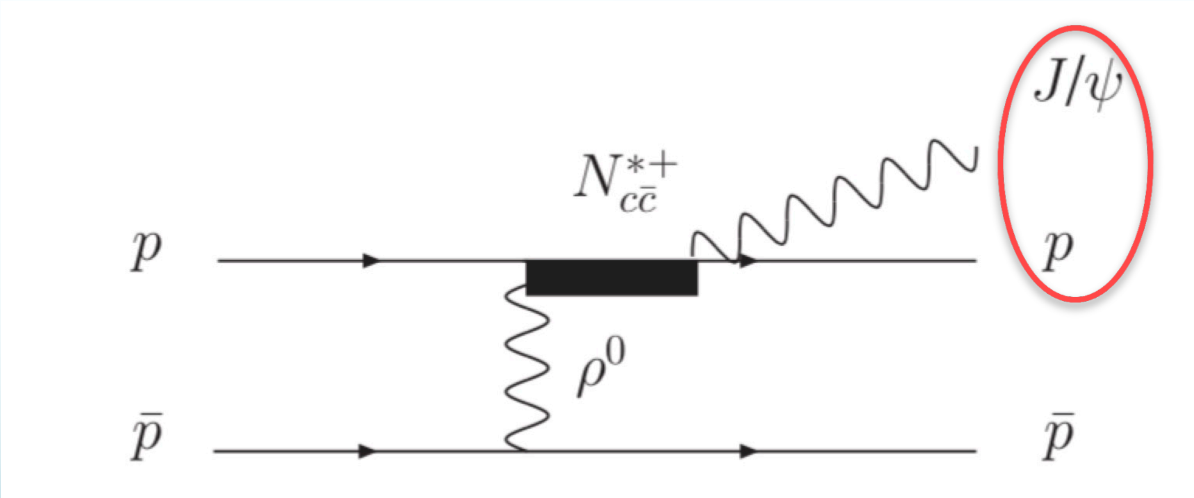
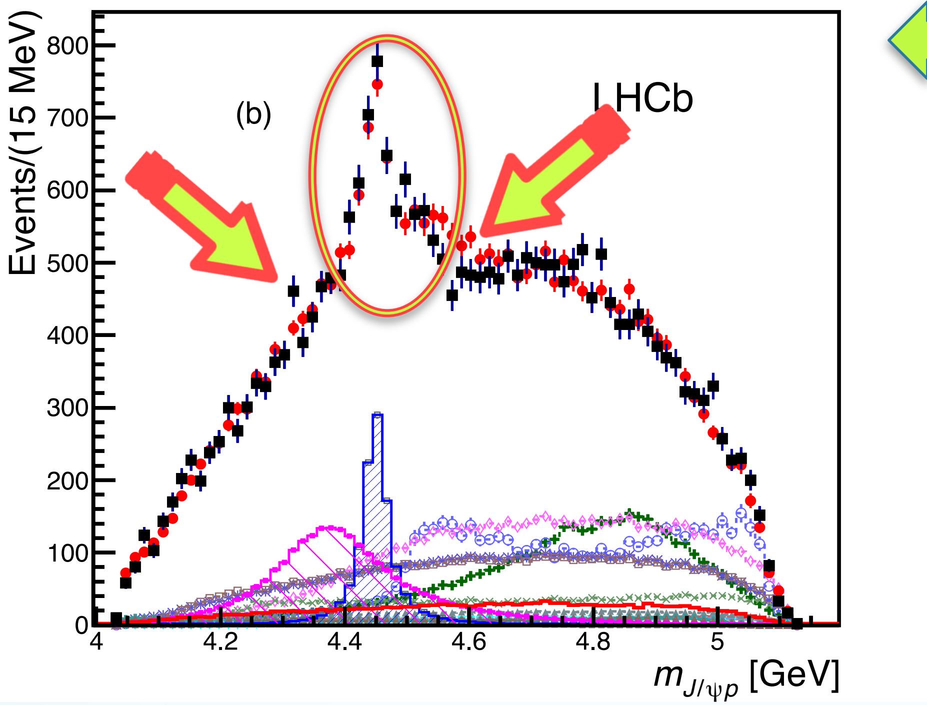


J. J. Wu, R. Molina, E. Oset, and B. S. Zou, Phys. Rev. Lett. 105, 232001 (2010)



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

First Experimental Findings for Pc



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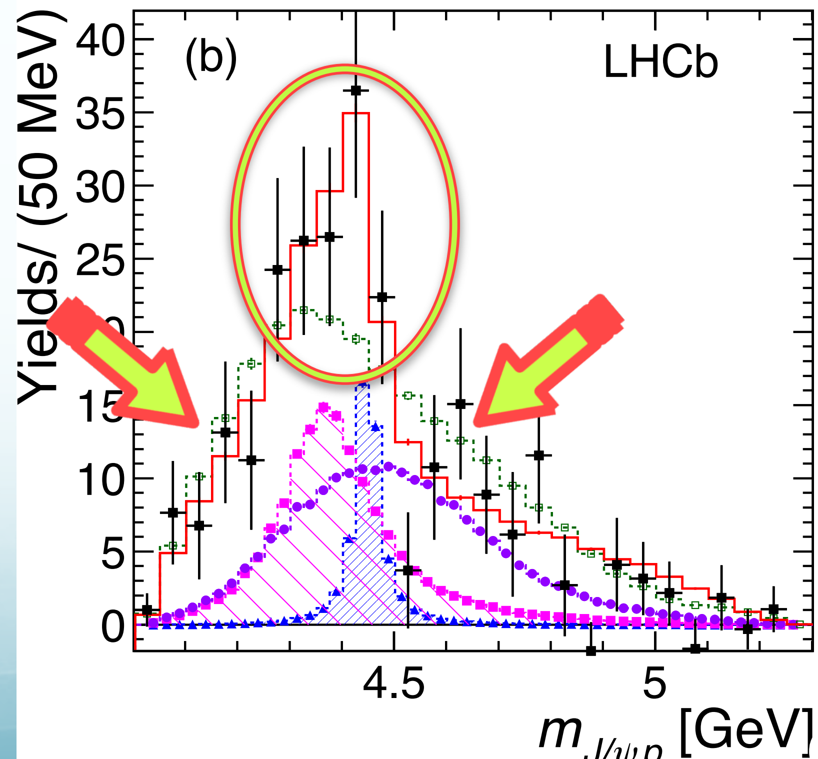


$$P_c(4380)^+, \Gamma = 205$$

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

J^P ?

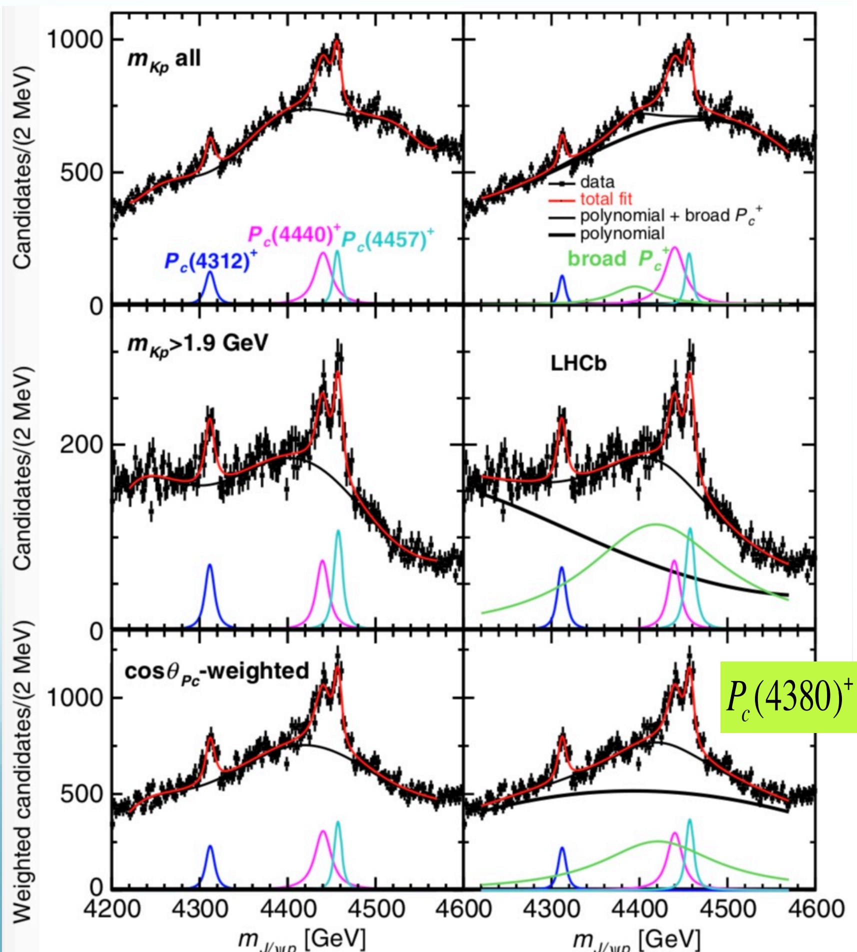
New Experimental Results for Pc

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

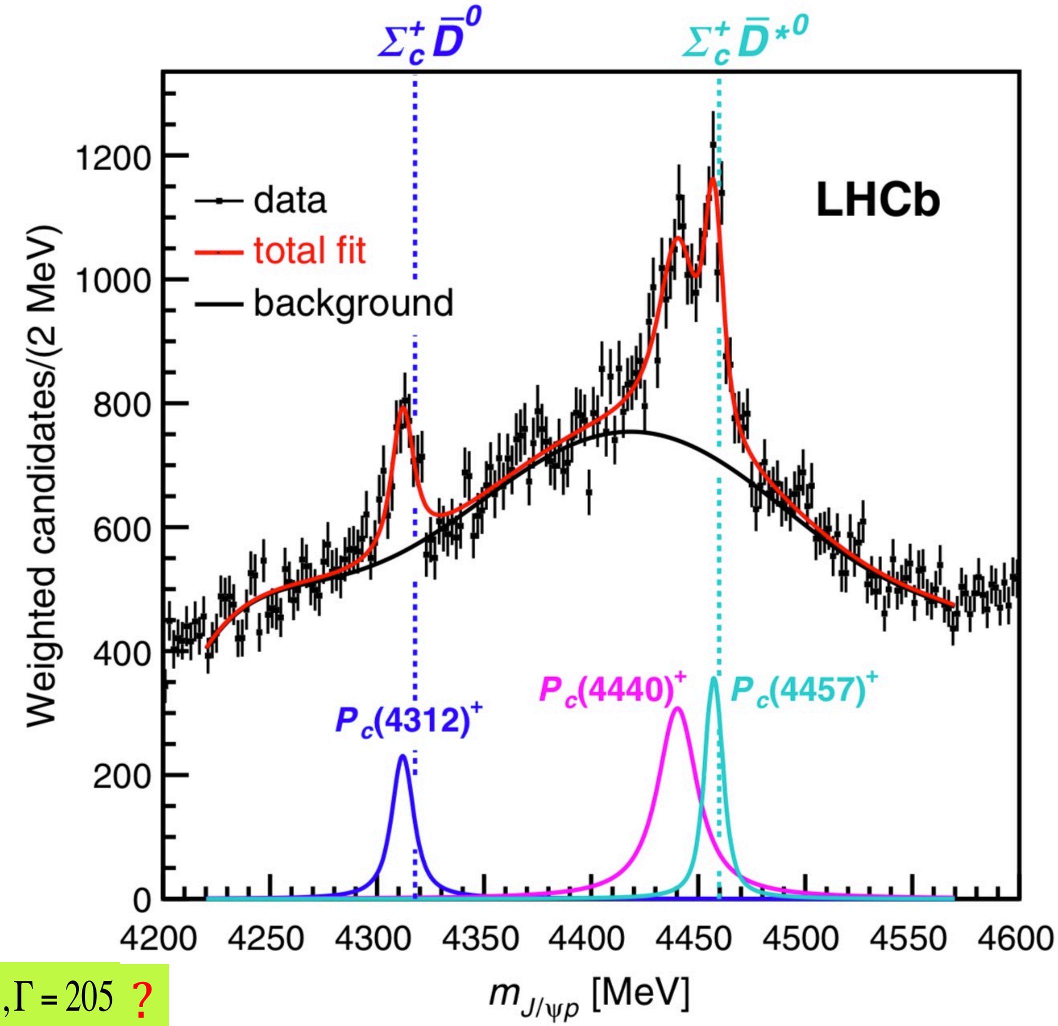
Featured in Physics

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)

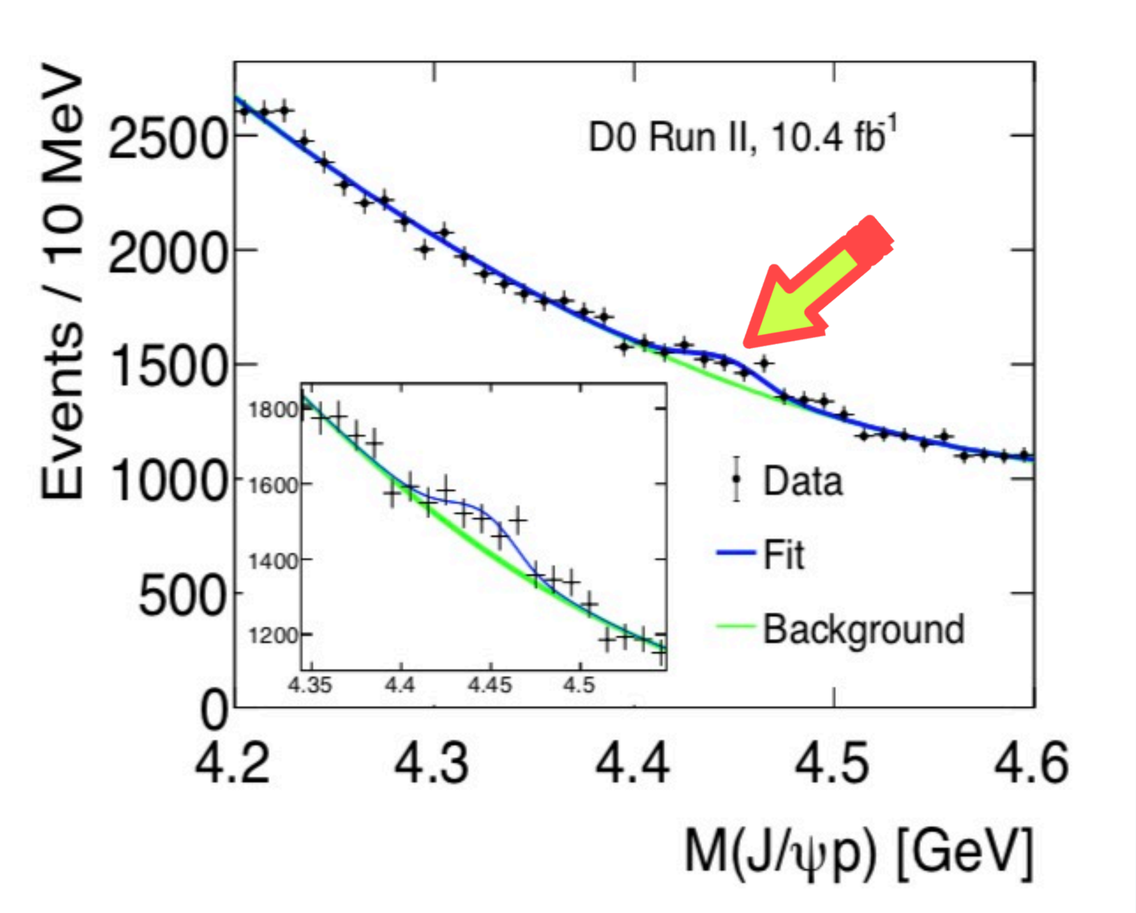


$P_c(4380)^+, \Gamma = 205$?



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

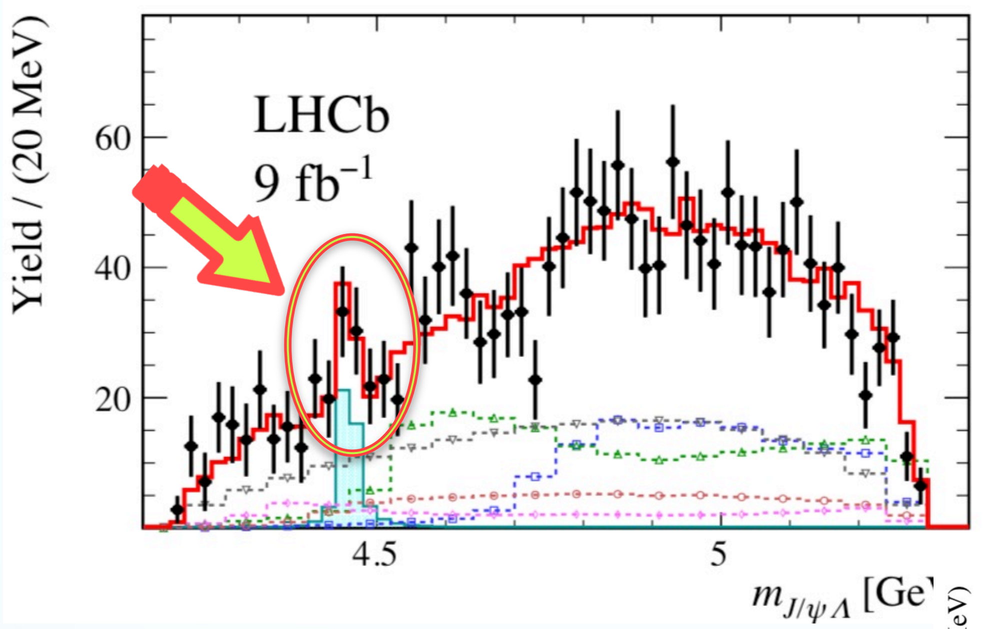
Confirmation from D0 Results



Using a sample of candidates originating from decays of b-flavored hadrons, we find an enhancement in the $J/\psi p$ invariant mass distribution consistent with a sum of $P_c(4440)$ and $P_c(4457)$. The significance, with the input parameters set to the LHCb values, is 3.3σ. This is the first confirmatory evidence for these pentaquark states. We measure the ratio $N_{\text{prompt}}/N_{\text{nonprompt}} = 0.05 \pm 0.39$ and

arXiv:1910.11767

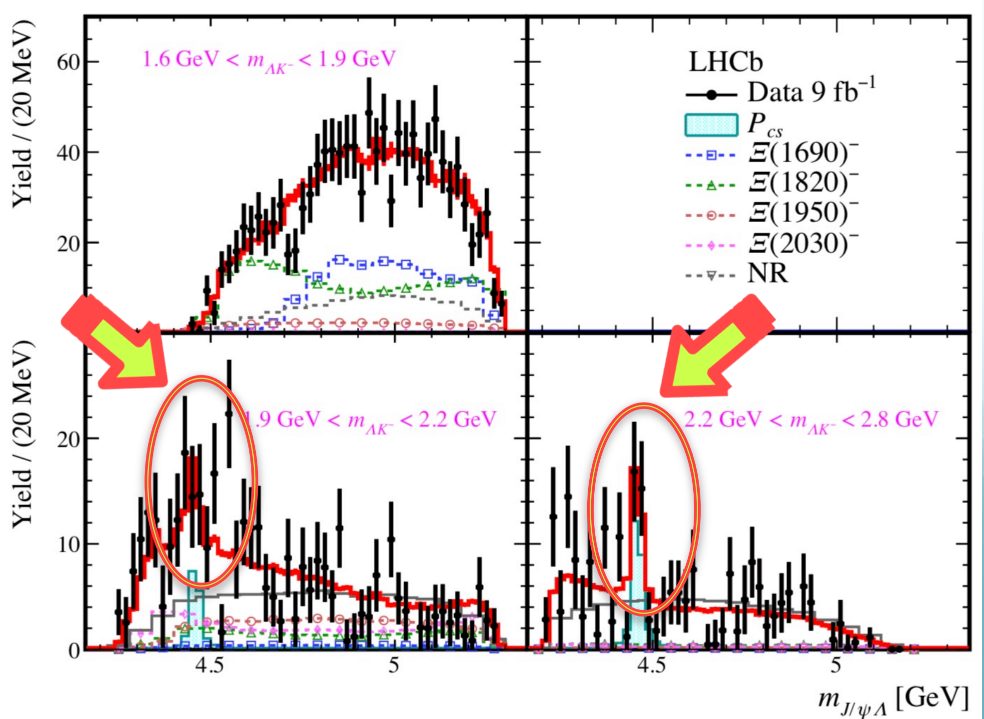
Experimental Findings for Pcs

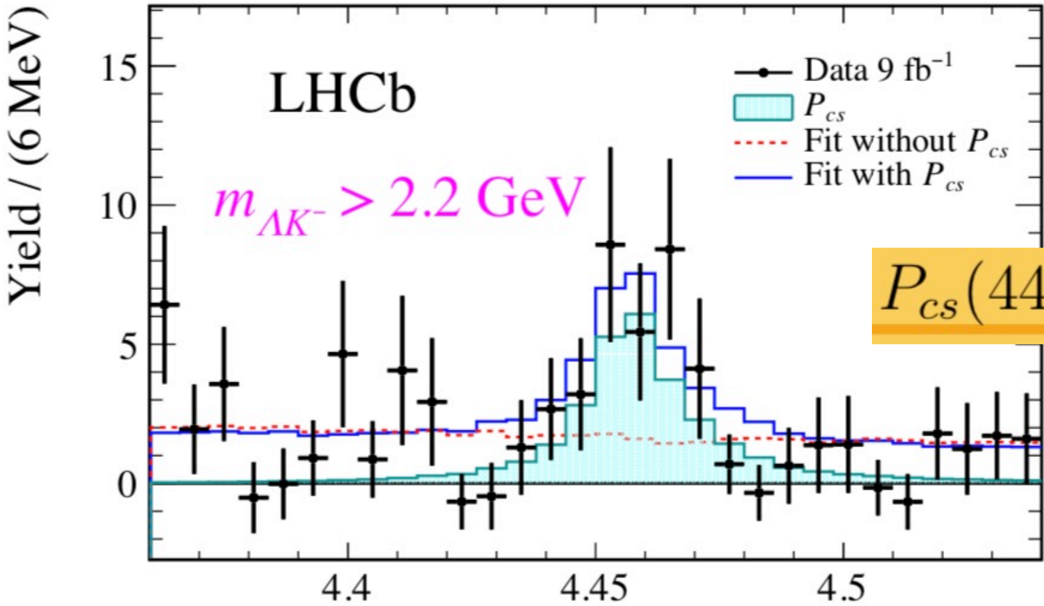


R. Aaij et al. (LHCb Collaboration), arXiv:2012.10380

State	M_0 [MeV]	Γ_0 [MeV]
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$

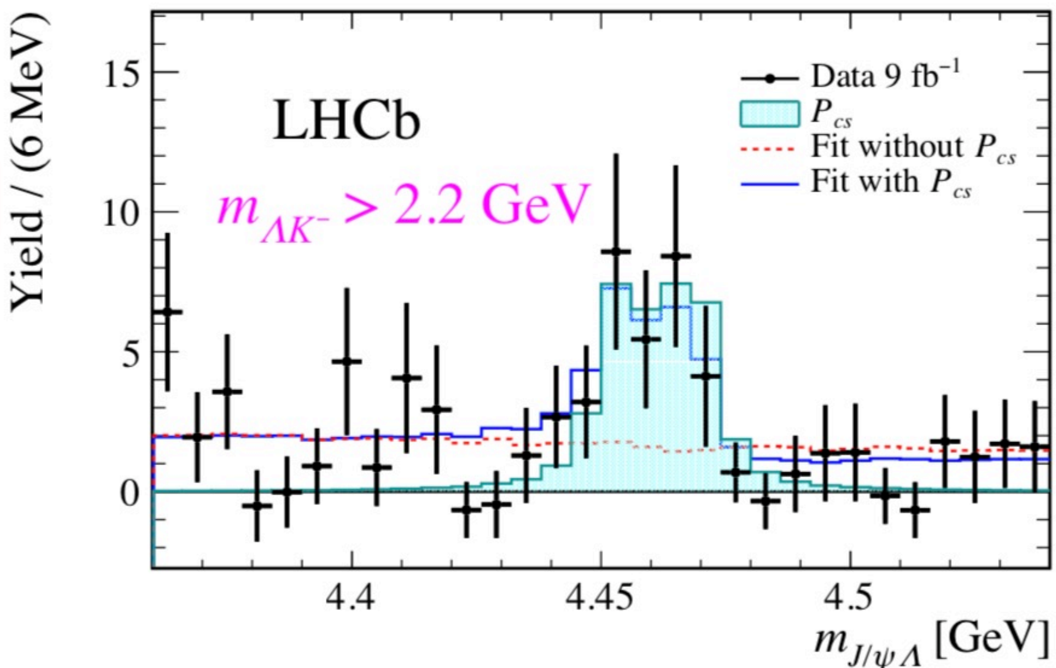
J^P ?





$P_{cs}(4459)^0$ state is more visible

mass difference of about 6 MeV



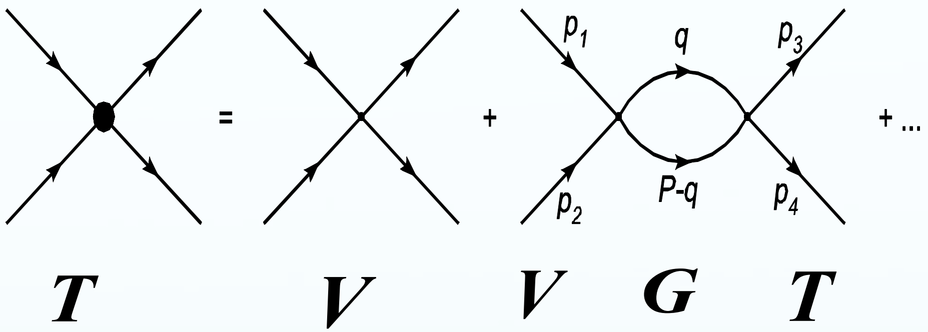
B. Wang, L. Meng and S. L. Zhu, **Phys. Rev. D 101** (2020) 034018.

The data cannot confirm or refute the two-peak hypothesis.

§2. Formalism

- Chiral Unitary Approach (ChUA)：coupled channel approach, solving Bethe-Salpeter (BS) equations, which take on-shell approximation to loops.

$$T = V + V\,G\,T,\; T = [1 - V\,G]^{-1}\,V$$



where V matrix (potentials) can be evaluated from chiral Lagrangians.

J. A. Oller and E. Oset, Nucl. Phys. A 620 (1997) 438

E. Oset and A. Ramos, Nucl. Phys. A 635 (1998) 99

J. A. Oller and U. G. Meißner, Phys. Lett. B 500 (2001) 263

G is a diagonal matrix with the loop functions of each channels:

$$G_{ll}(s) = i \int \frac{d^4q}{(2\pi)^4} \frac{1}{(P-q)^2 - m_{l1}^2 + i\varepsilon} \frac{1}{q^2 - m_{l2}^2 + i\varepsilon}$$

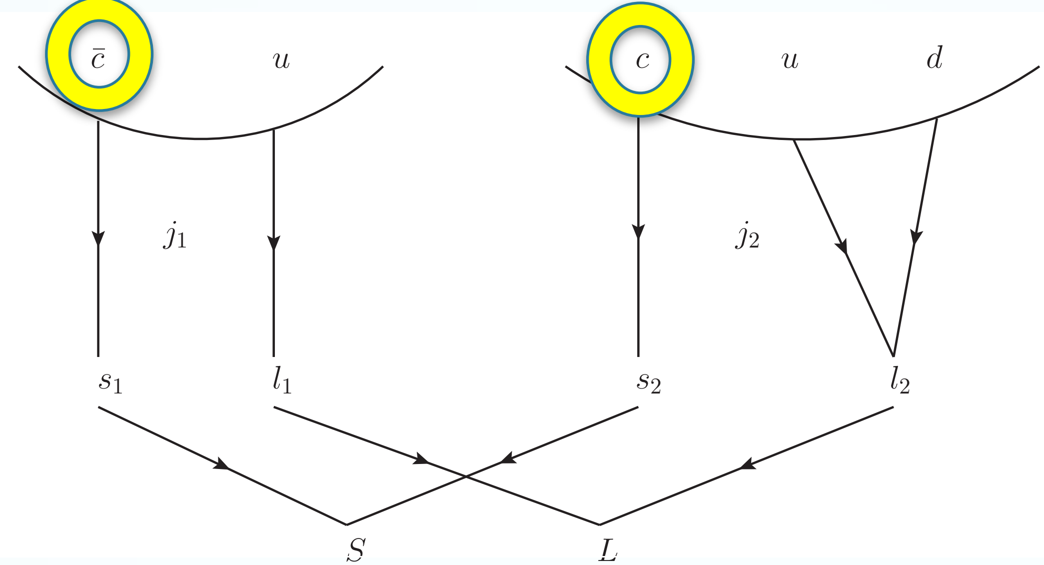
The coupled channel scattering amplitudes **T matrix satisfy the unitary** :

$$\mathrm{Im}\, T_{ij} = T_{in}\, \sigma_{nn}\, T_{nj}^*$$

$$\sigma_{nn} \equiv \mathrm{Im}\, G_{nn} = -\frac{q_{cm}}{8\pi\sqrt{s}} \theta(s - (m_1 + m_2)^2))$$

To search the poles of the resonances, we should extrapolate the scattering amplitudes to the second Riemann sheets:

$$G_{ll}^{II}(s) = G_{ll}^{I}(s) + i\, \frac{q_{cm}}{4\pi\sqrt{s}}$$



Considering the heavy quark spin-flavor symmetry

$\bar{D} \rightarrow \bar{D}^*$ $\quad \Sigma_c \rightarrow \Sigma_c^*$

$\bar{c}$-quark $\rightarrow$ $\bar{b}$-quark.

$\bar{D} \rightarrow B$

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

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

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

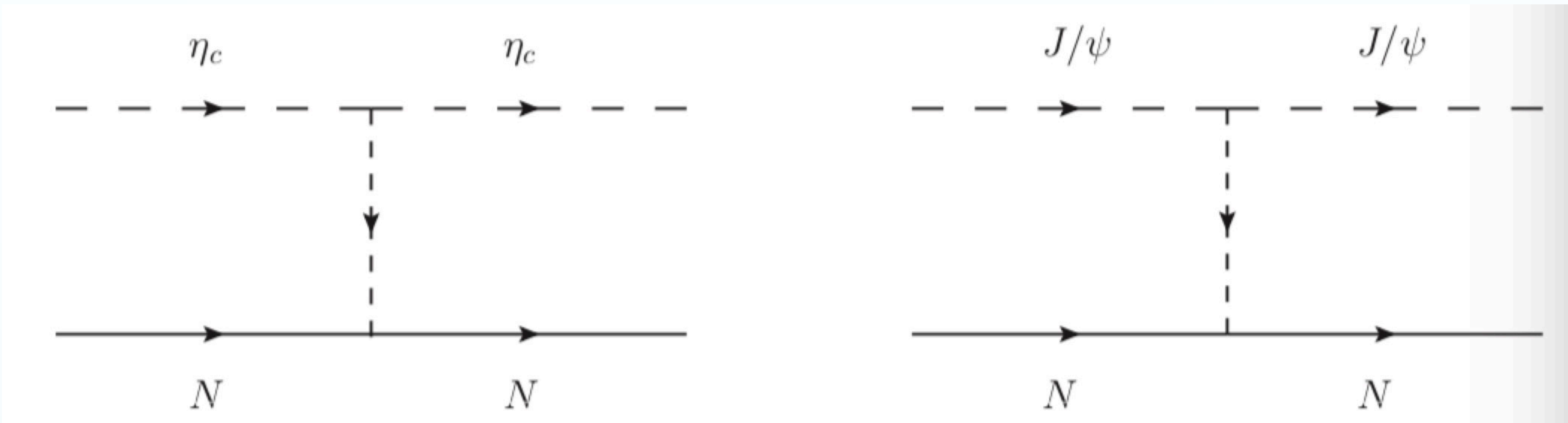
$J = 1/2, I = 1/2$

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

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

LECs

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

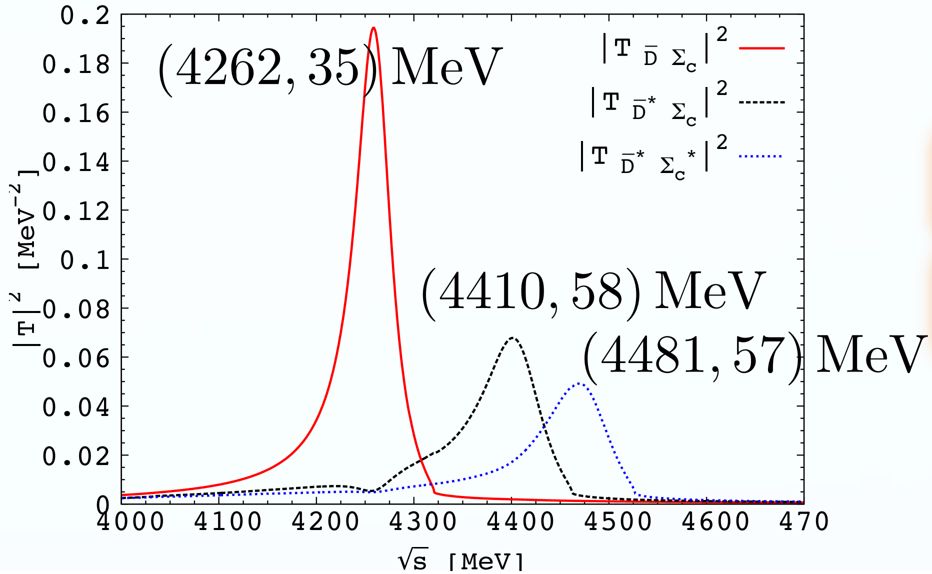


$J = 1/2, I = 1/2$

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

§3. Results

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



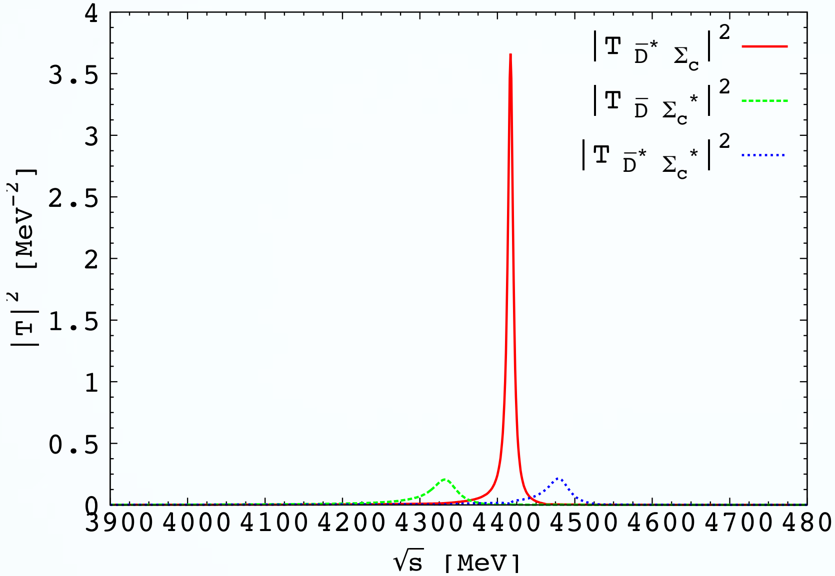
$\mu = 1000$ MeV

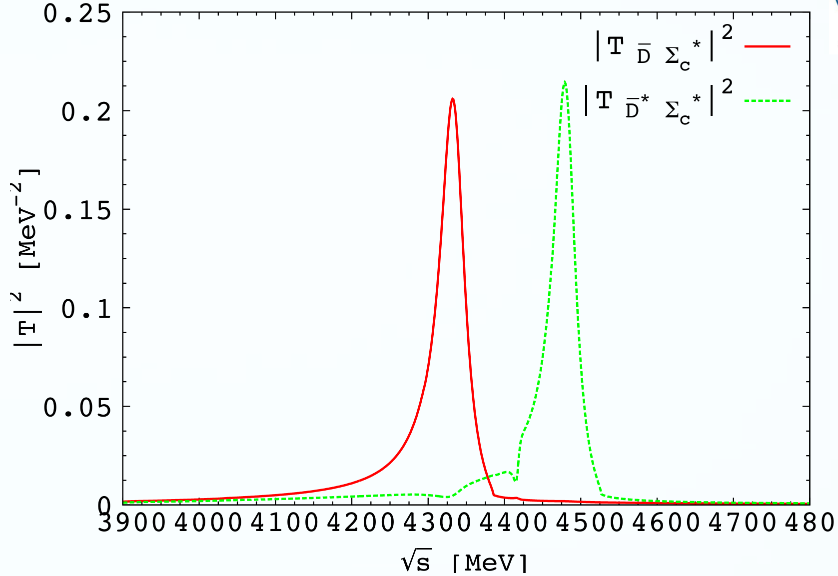
$a(\mu) = -2.3$

J. J. Wu, et.al

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**

$J = 3/2, I = 1/2$





$4334.45 + i19.41$	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$1.31 - i0.18$	$0.16 - i0.23$	$0.20 - i0.48$	$2.97 - i0.36$	$0.24 - i0.76$
$\lvert g_i \rvert$	1.32	0.28	0.52	2.99	0.80
$4417.04 + i4.11$	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$0.53 - i0.07$	$0.08 - i0.07$	$2.81 - i0.07$	$0.12 - i0.10$	$0.11 - i0.51$
$\lvert g_i \rvert$	0.53	0.11	2.81	0.16	0.52
$4481.04 + i17.38$	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$1.05 + i0.10$	$0.18 - i0.09$	$0.12 - i0.10$	$0.22 - i0.05$	$2.84 - i0.34$
$\lvert g_i \rvert$	1.05	0.20	0.16	0.22	2.86

CWX, J. Nieves and E. Oset, Phys. Rev. D 88, 056012 (2013)

The former exercises have shown that the changes produced by using different couplings obtained in other approaches to QCD, with a certain amount of SU(4) or HQSS breaking, induce changes of the order of 20–30 MeV in bindings estimated in our approach to be of the order of 50 MeV. These uncertainties are in line with other systematic uncertainties that we must also admit from our partial ignorance in the regularization scale of the loops. Yet, with all these uncertainties, the binding of the states remains a solid conclusion, as does the order of magnitude of the binding energies; the maximum one can hope without further experimental information to constrain the input in our theory.

$P_c(4312)^+$ $a(\mu = 1\,\mathrm{GeV}) = -2.09$

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	$0.67 + i0.01$	$0.46 - i0.03$	$0.01 - i0.01$	$2.07 - i0.28$	$0.03 + i0.25$	$0.06 - i0.31$	$0.04 - i0.15$
$\|g_i\|$	0.67	0.46	0.01	2.09	0.25	0.31	0.16
4452.96 + i11.72 ($P_c(4440)^+$)							
	$\eta_c N$	$J/\psi N$	$\bar{D}\Lambda_c$	$\bar{D}\Sigma_c$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Sigma_c^*$
g_i	$0.24 + i0.03$	$0.88 - 0.11$	$0.09 - i0.06$	$0.12 - i0.02$	$0.11 - i0.09$	$1.97 - i0.52$	$0.02 + i0.19$
$\|g_i\|$	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	$0.72 - i0.10$	$0.45 - i0.04$	$0.11 - i0.06$	$0.06 - i0.02$	$0.06 - i0.05$	$0.07 - i0.02$	$1.84 - i0.56$
$\|g_i\|$	0.73	0.45	0.13	0.06	0.08	0.08	1.92

4261.87 + i17.84
g_i
$\|g_i\|$
4410.13 + i29.44
g_i
$\|g_i\|$
4481.35 + i28.91
g_i
$\|g_i\|$

$a(\mu) = -2.3$

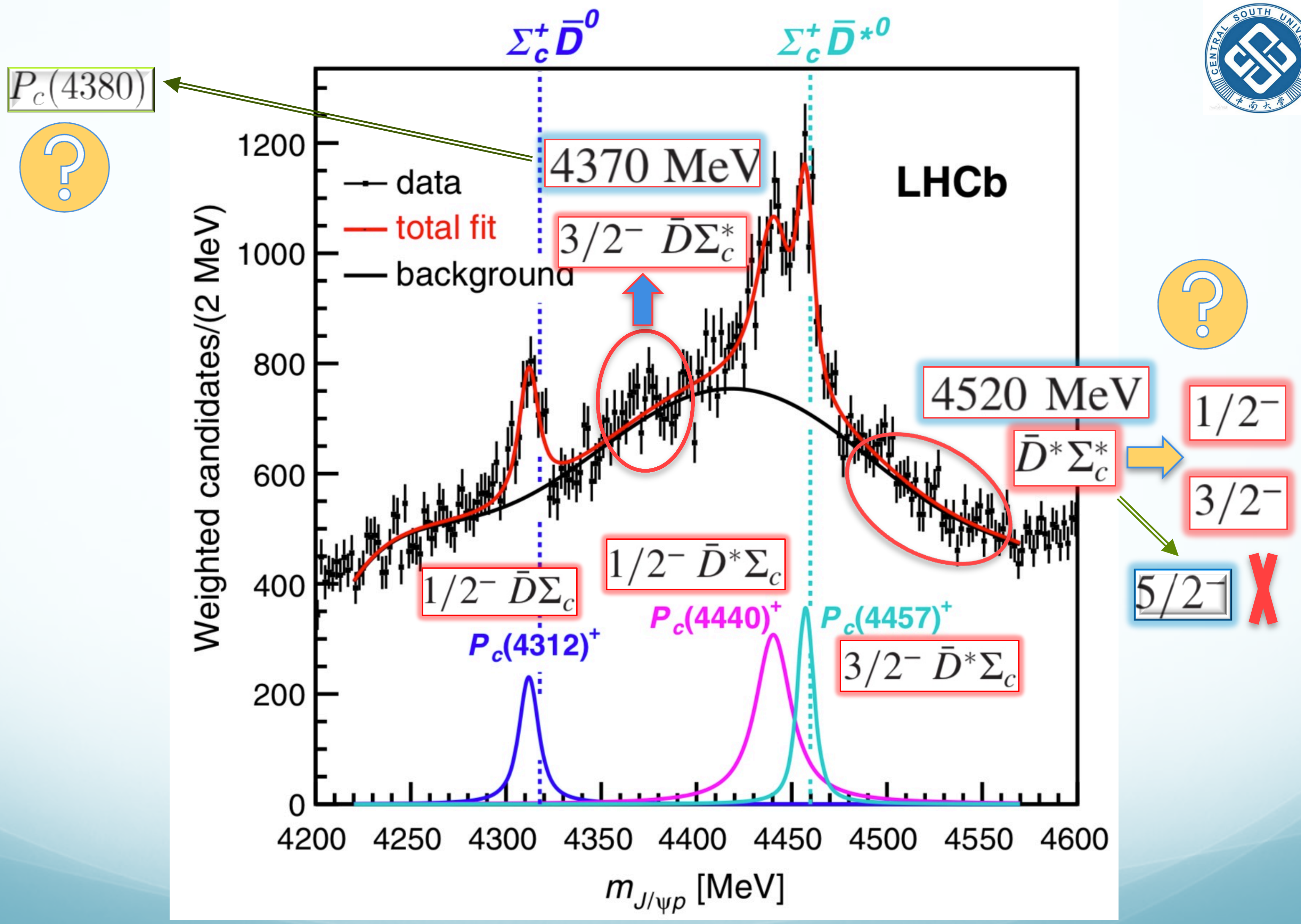
4374.33 + i6.87	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i ($P_c(4457)^+$)	$0.73 - i0.06$	$0.11 - i0.13$	$0.02 - i0.19$	$1.91 - i0.31$	$0.03 - i0.30$
$\|g_i\|$	0.73	0.18	0.19	1.94	0.30
4452.48 + i1.49	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$0.30 - i0.01$	$0.05 - i0.04$	$1.82 - i0.08$	$0.08 - i0.02$	$0.01 - i0.19$
$\|g_i\|$	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	$0.66 - i0.01$	$0.11 - i0.07$	$0.10 - i0.3$	$0.13 - i0.02$	$1.79 - i0.36$
$\|g_i\|$	0.66	0.13	0.10	0.13	1.82

4334.45 + i19.41
g_i
$\|g_i\|$
4417.04 + i4.11
g_i
$\|g_i\|$
4481.04 + i17.38
g_i
$\|g_i\|$

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. Z. Liu, Y. W. Pan, F. Z. Peng, M. S. Sanchez, L. S. Geng, A. Hosaka, and M. P. Valderrama, Phys. Rev. Lett. 122 (2019) 242001

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



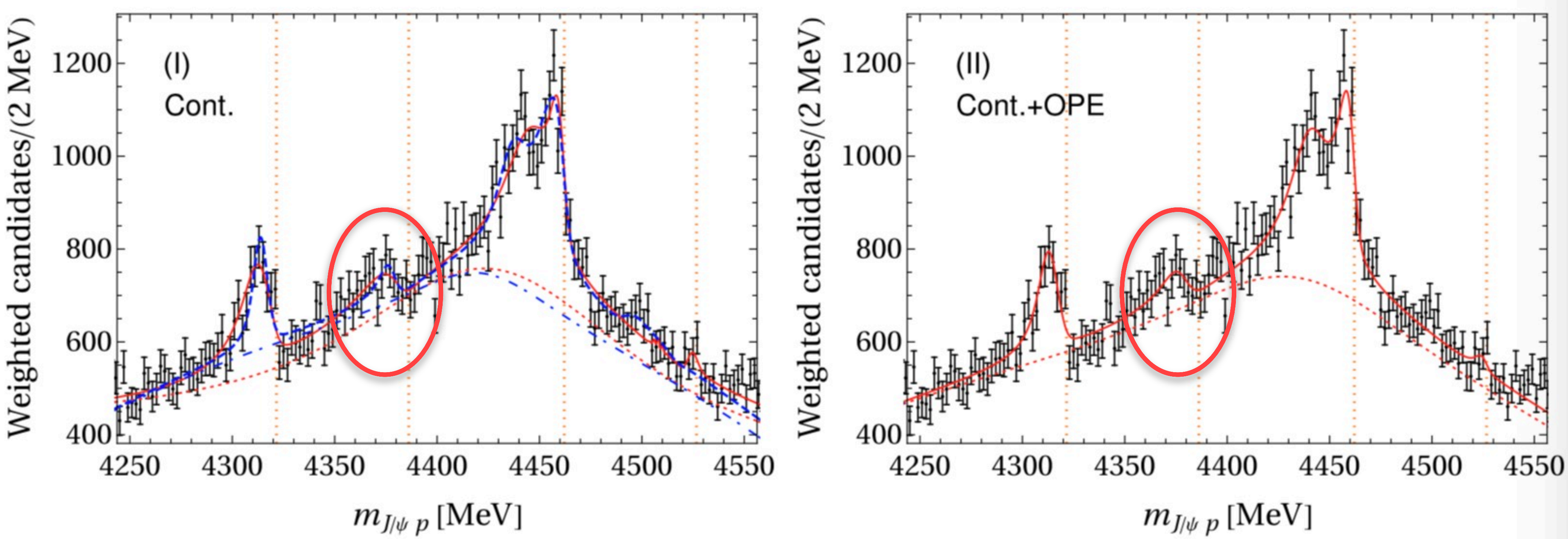
CWX, J. Nieves and E. Oset, Phys. Rev. D100 (2019) 014021

PHYSICAL REVIEW LETTERS **124**, 072001 (2020)

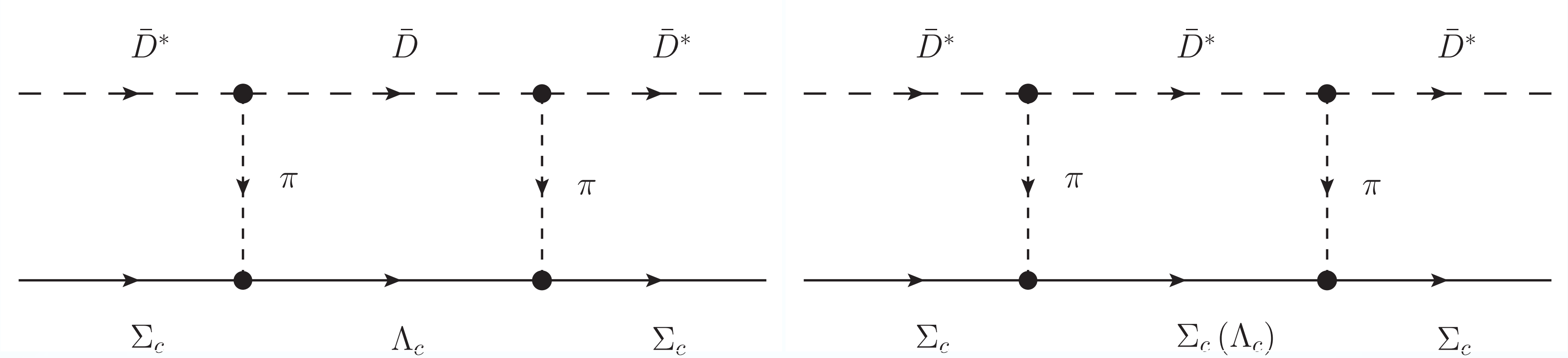
Evidence that the LHCb P_c states are hadronic molecules and the existence of a narrow $P_c(4380)$

Meng-Lin Du,[1,*] Vadim Baru,[1,2,3,†] Feng-Kun Guo,[4,5,‡] Christoph Hanhart,[6,§]
Ulf-G. Meißner,[1,6,7,¶] José A. Oller,[8,**] and Qian Wang[9,10,††]

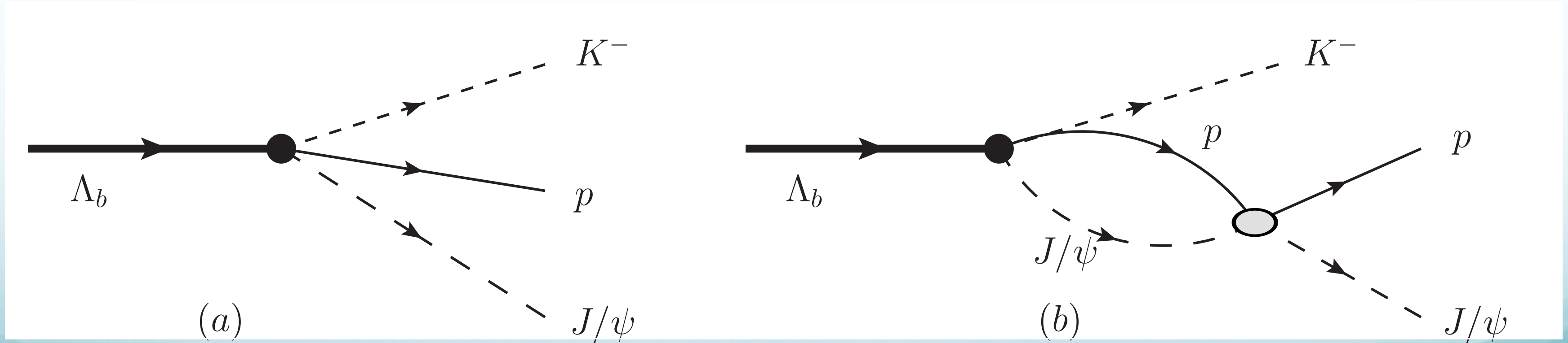
We also show that there is clear evidence for a narrow $\Sigma_c^* \bar{D}$ bound state in the data which we call $P_c(4380)$, different from the broad one reported by LHCb in 2015. With this state established, all

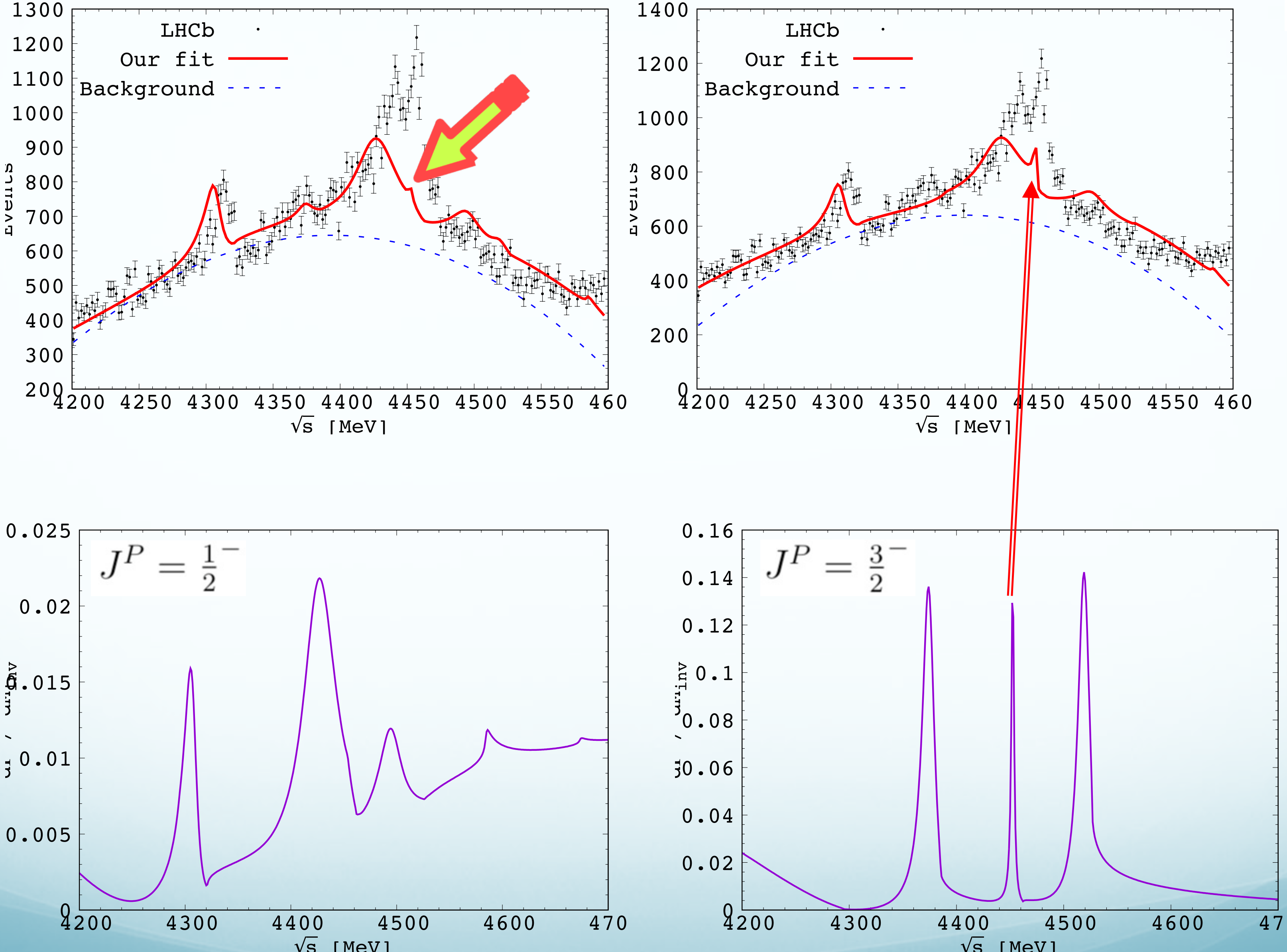


Next, we try to make a further investigation......



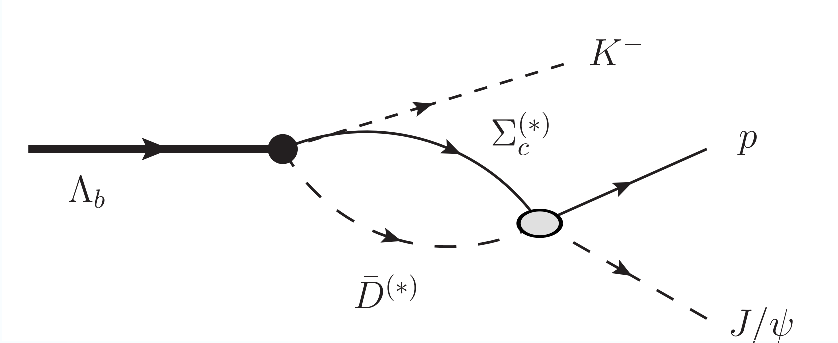
Consider $J/\psi p$ produced directly and final state interactions

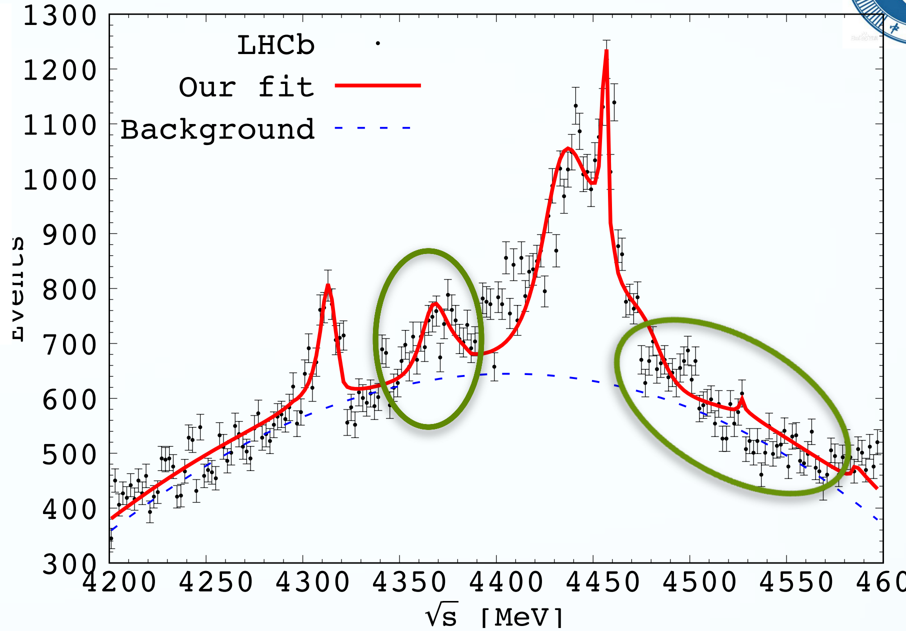




Indeed, this direct production is OZI suppressed!

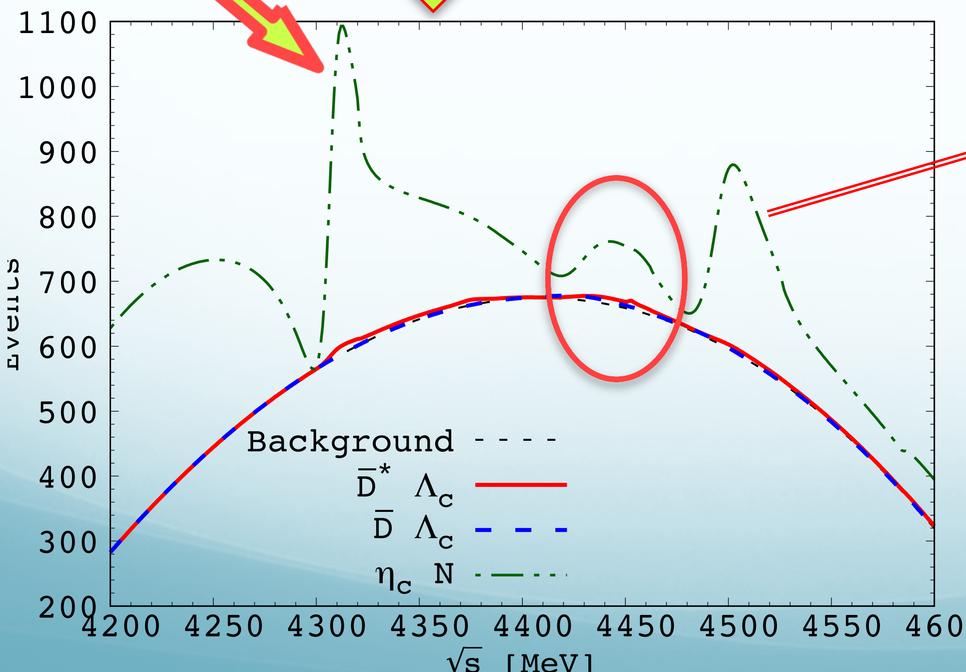
Consider $J/\psi p$ produced indirectly





$a(\mu = 1\,\mathrm{GeV}) = -2.09$

$P_c(4312)$



$J^P = \frac{1}{2}^-$

$P_c(4440)$ and $P_c(4457)$

CWX, J. X. Lu, J. J. Wu, and L. S. Geng, Phys. Rev. D102 (2020) 056018

We make further study on the hidden charm strange sectors:

HQSS

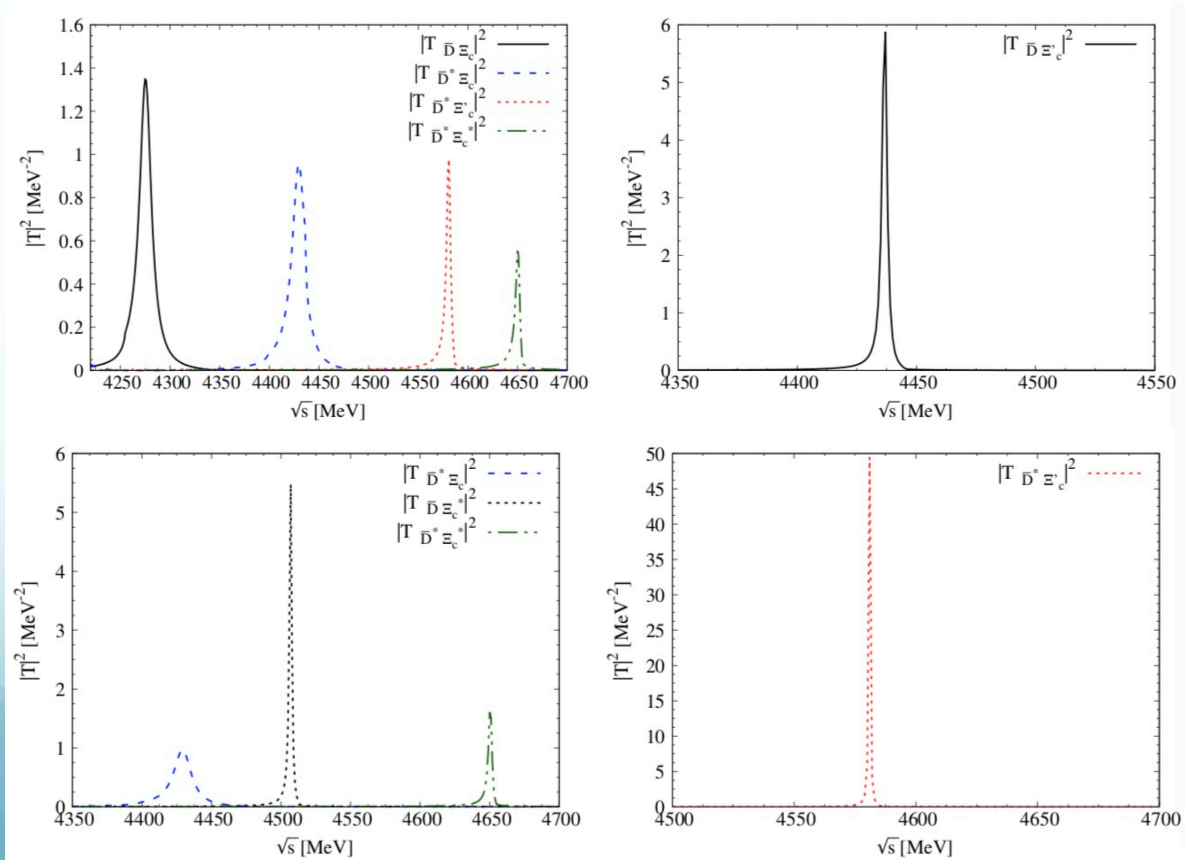
i) $J = 1/2,\ I = 0$

$\eta_c\Lambda,\ J/\psi\Lambda,\ \bar{D}\Xi_c,\ \bar{D}_s\Lambda_c,\ \bar{D}\Xi_c',\ \bar{D}^*\Xi_c,\ \bar{D}_s^*\Lambda_c,\ \bar{D}^*\Xi_c',\ \bar{D}^*\Xi_c^*.$

ii) $J = 3/2,\ I = 0$

$J/\psi\Lambda,\ \bar{D}^*\Xi_c,\ \bar{D}_s\Lambda_c,\ \bar{D}^*\Xi_c',\ \bar{D}\Xi_c^*,\ \bar{D}^*\Xi_c^*.$

$a(\mu = 1\,\mathrm{GeV}) = -2.09$



- $J = 1/2,\ I = 0$

$a(\mu = 1\,\text{GeV}) = -2.09$

	$\eta_c\Lambda$	$J/\psi\Lambda$	$\bar{D}\Xi_c$	$\bar{D}_s\Lambda_c$	$\bar{D}\Xi_c'$	$\bar{D}^*\Xi_c$	$\bar{D}_s^*\Lambda_c$	$\bar{D}^*\Xi_c'$	$\bar{D}^*\Xi_c^*$
Thres.	4099.58	4212.58	4366.61	4254.80	4445.34	4477.92	4398.66	4586.66	4654.48
$4276.59 + i7.67$									
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
$4429.84 + i7.92$									
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
$4580.96 + i2.44$									
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
$4650.86 + i2.59$									
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**

- $J = 3/2,\ I = 0$

Thres.	4212.58	4477.92	4398.66	4586.66	4513.17	4654.48
	$J/\psi\Lambda$	$\bar{D}^*\Xi_c$	$\bar{D}_s^*\Lambda_c$	$\bar{D}^*\Xi_c'$	$\bar{D}\Xi_c^*$	$\bar{D}^*\Xi_c^*$
$4429.52 + i7.67$						
g_i	$0.31 - i0.10$	**2.77 − i0.02**	$0.67 + i0.32$	$0.00 + i0.0.02$	$0.00 - i0.06$	$0.00 + i0.0.04$
$\|g_i\|$	0.32	**2.77**	0.74	0.02	0.06	0.04
$4506.99 + i1.03$						
g_i	$0.27 - i0.02$	$0.02 - i0.03$	$0.02 - i0.02$	$0.00 - i0.03$	**1.56 − i0.07**	$0.00 - i0.05$
$\|g_i\|$	0.27	0.03	0.03	0.03	**1.56**	0.05
$4580.96 + i0.34$						
g_i	$0.14 - i0.01$	$0.01 - i0.01$	$0.01 - i0.01$	**1.54 − i0.02**	$0.02 - i0.00$	$0.00 - i0.04$
$\|g_i\|$	0.14	0.01	0.02	**1.54**	0.02	0.04
$4650.58 + i1.48$						
g_i	$0.29 - i0.02$	$0.02 - i0.01$	$0.03 - i0.02$	$0.03 - i0.01$	$0.03 - i0.00$	**1.40 − i0.13**
$\|g_i\|$	0.29	0.03	0.03	0.03	0.03	**1.41**

CWX, J. Nieves and E. Oset, Phys. Lett. B 799 (2019) 135051.

- $J = 1/2,\ I = 0$

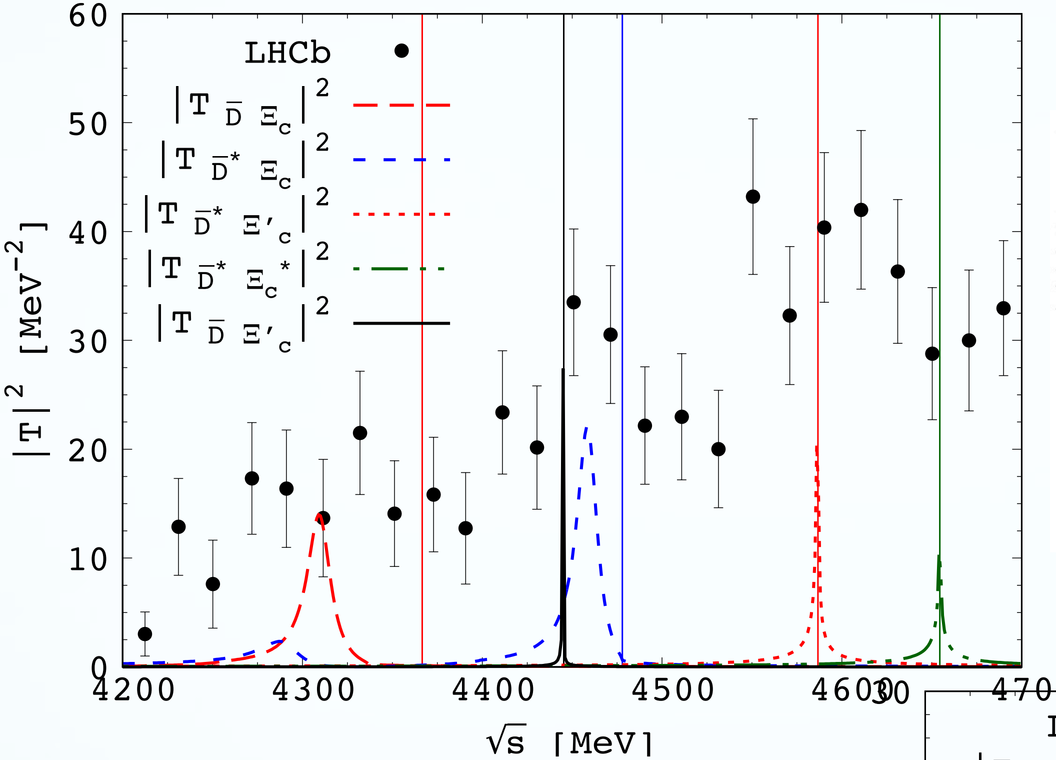
$a_\mu(\mu = 1\ \text{GeV}) = -1.94$

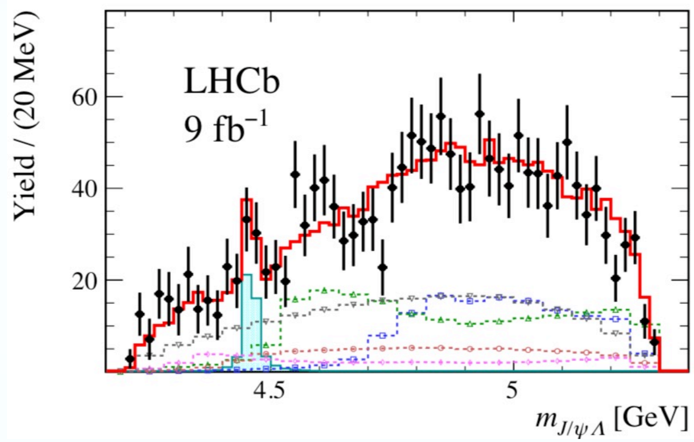
$P_{cs}(4459)$

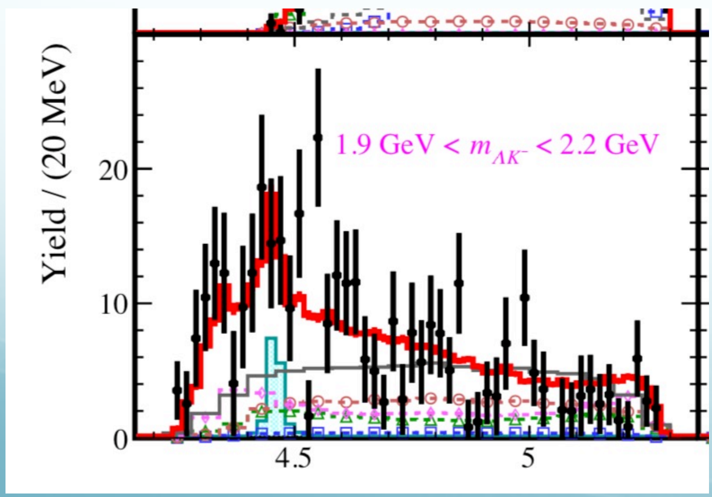
Chan.	$\eta_c\Lambda$	$J/\psi\Lambda$	$\bar{D}\Xi_c$	$\bar{D}_s\Lambda_c$	$\bar{D}\Xi'_c$	$\bar{D}^*\Xi_c$	$\bar{D}^*_s\Lambda_c$	$\bar{D}^*\Xi'_c$	$\bar{D}^*\Xi^*_c$
Thres.	4099.58	4212.58	4366.61	4254.80	4445.34	4477.92	4398.66	4586.66	4654.48
$4310.53 + i8.23$									
$\lvert g_i \rvert$	0.15	0.27	**2.33**	0.69	0.00	0.04	0.09	0.01	0.02
Γ_i	0.57	1.18	–	13.86	–	–	–	–	–
Br.	3.47%	7.16%	–	84.21%	–	–	–	–	–
$4445.12 + i0.19$									
$\lvert g_i \rvert$	0.10	0.06	0.00	0.00	**0.72**	0.08	0.04	0.01	0.01
Γ_i	0.29	0.08	0.00	0.00	–	–	0.04	–	–
Br.	74.74%	21.22%	0.01%	0.01%	–	–	10.62%	–	–
$4459.07 + i6.89$									
$\lvert g_i \rvert$	0.22	0.13	0.00	0.00	0.07	**2.16**	0.61	0.03	0.02
Γ_i	1.59	0.46	0.00	0.00	0.01	–	11.14	–	–
Br.	11.57%	3.31%	0.00%	0.00%	0.70%	–	80.86%	–	–
$4586.65 + i0.51?$									
$\lvert g_i \rvert$	0.01	0.02	0.02	0.02	0.02	0.02	0.02	**0.09**	0.02
Γ_i	0.00	0.02	0.02	0.02	0.02	0.02	0.02	–	–
Br.	0.26%	1.51%	1.80%	1.76%	1.85%	1.72%	1.68%	–	–
$4654.48 + i0.55?$									
$\lvert g_i \rvert$	0.02	0.01	0.02	0.02	0.02	0.03	0.02	0.03	**0.09**
Γ_i	0.02	0.01	0.03	0.03	0.03	0.03	0.03	0.03	–
Br.	1.50%	0.56%	3.11%	3.05%	3.15%	3.03%	2.96%	3.02%	–

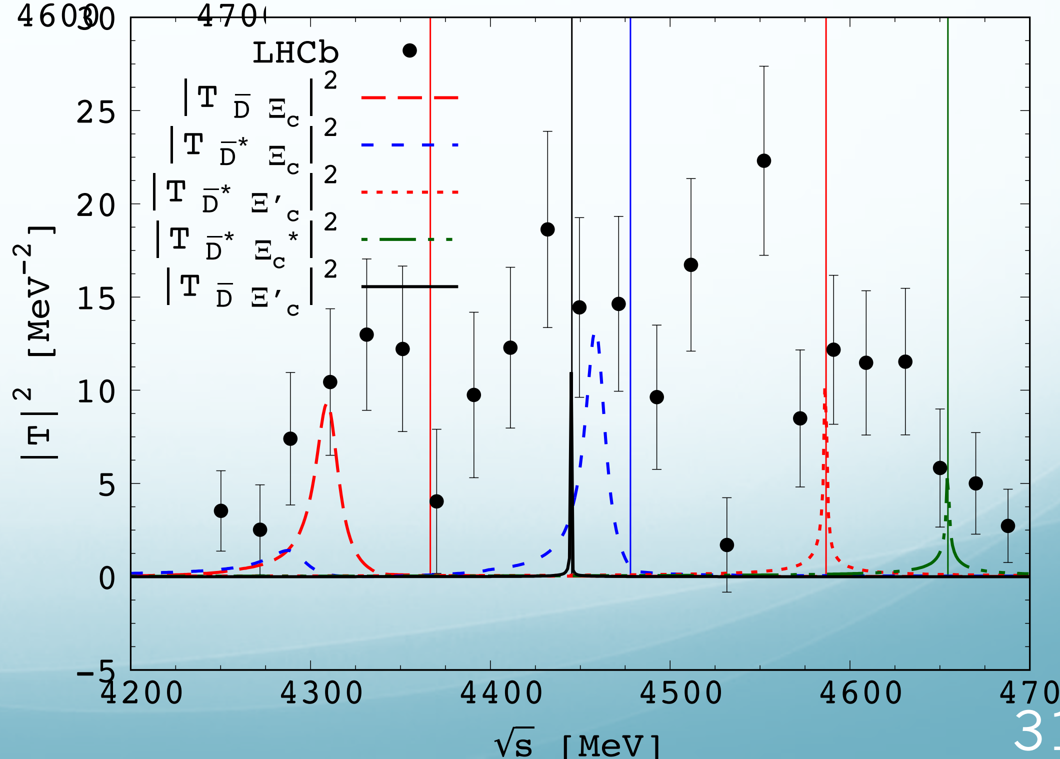
- $J = 3/2,\ I = 0$

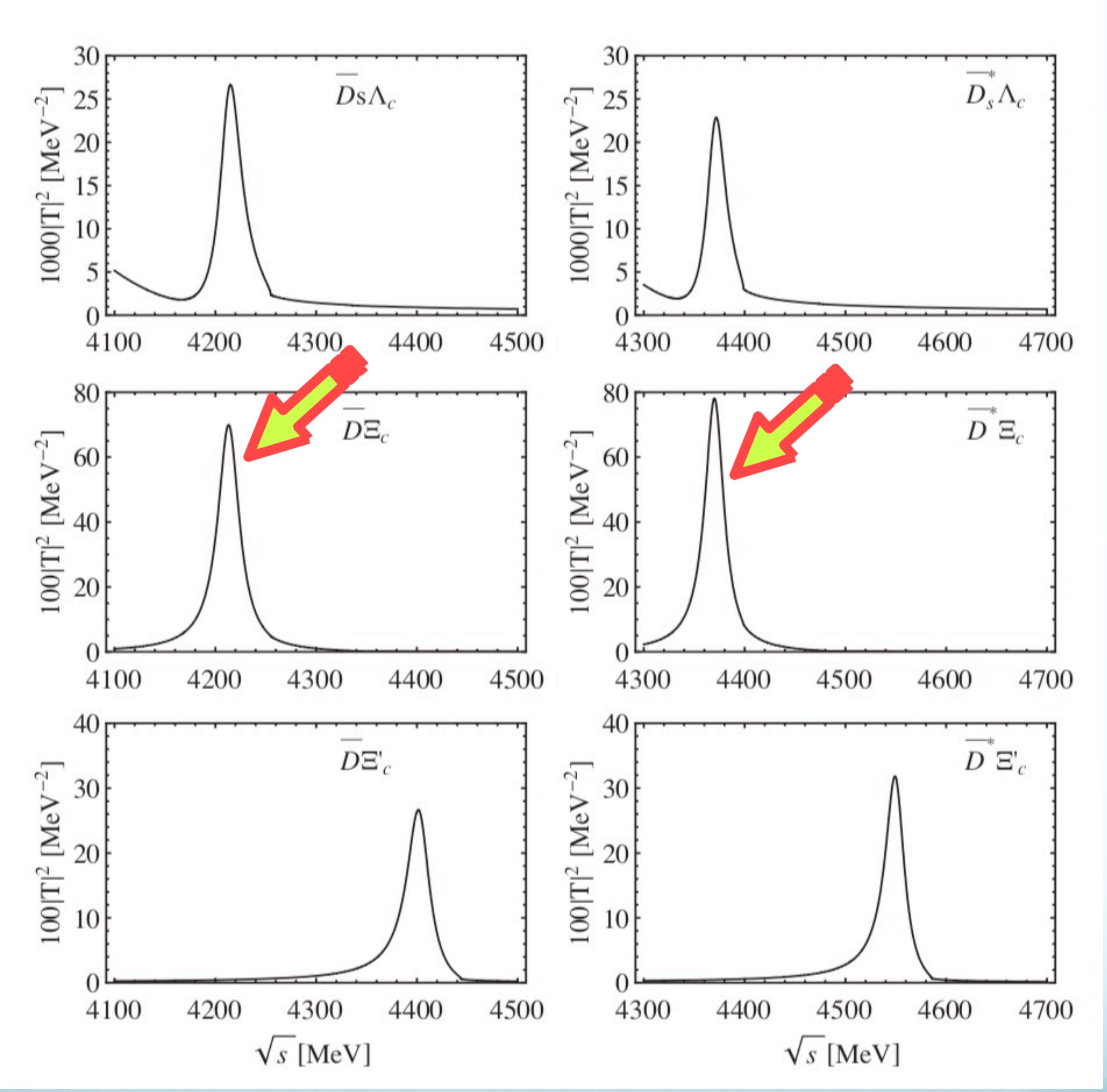
Chan.	$J/\psi\Lambda$	$\bar{D}^*\Xi_c$	$\bar{D}_s^*\Lambda_c$	$\bar{D}^*\Xi_c'$	$\bar{D}\Xi_c^*$	$\bar{D}^*\Xi_c^*$
Thres.	4212.58	4477.92	4398.66	4586.66	4513.17	4654.48
$4459.02 + i6.83$						
$\lvert g_i\rvert$	0.28	**2.16**	0.61	0.02	0.04	0.03
Γ_i	2.00	–	11.15	–	–	–
Br.	14.68%	–	81.64%	–	–	–
$4586.65 + i0.00?$						
$\lvert g_i\rvert$	0.03	0.03	0.03	**0.26**	0.03	0.03
Γ_i	–	–	–	–	–	–
Br.	–	–	–	–	–	–
$4513.21 + i0.03?$						
$\lvert g_i\rvert$	0.06	0.08	0.07	0.08	**0.34**	0.07
Γ_i	–	–	–	–	–	–
Br.	–	–	–	–	–	–
$4654.48 + i0.22?$						
$\lvert g_i\rvert$	0.02	0.03	0.03	0.04	0.03	**0.12**
Γ_i	0.02	0.04	0.04	0.04	0.04	–
Br.	4.04%	8.85%	8.65%	9.25%	9.12%	–


LHCb
$|T_{\bar{D}\Xi_c}|^2$
$|T_{\bar{D}^*\Xi_c}|^2$
$|T_{\bar{D}^*\Xi'_c}|^2$
$|T_{\bar{D}^*\Xi_c^*}|^2$
$|T_{\bar{D}\Xi'_c}|^2$
$|T|^2$ [MeV^{-2}]
$\sqrt{s}$ [MeV]
0
10
20
30
40
50
60
4200
4300
4400
4500
4600
4700


LHCb
9 fb^{-1}
Yield / (20 MeV)
$m_{J/\psi\Lambda}$ [GeV]
20
40
60
4.5
5


1.9 GeV < $m_{\Lambda K^-}$ < 2.2 GeV
Yield / (20 MeV)
0
10
20
4.5
5


LHCb
$|T_{\bar{D}\Xi_c}|^2$
$|T_{\bar{D}^*\Xi_c}|^2$
$|T_{\bar{D}^*\Xi'_c}|^2$
$|T_{\bar{D}^*\Xi_c^*}|^2$
$|T_{\bar{D}\Xi'_c}|^2$
$|T|^2$ [MeV^{-2}]
$\sqrt{s}$ [MeV]
−5
0
5
10
15
20
25
30
4200
4300
4400
4500
4600
4700



J. J. Wu, R. Molina, E. Oset and B. S. Zou, Phys. Rev. C 84 (2011) 015202 states from $PB \to PB$. The units

(I, S)	z_R	Real axis	
		M	Γ
(1/2, 0)			
	4269	4267	34.3
(0, −1)			
	4213	4213	26.4
	4403	4402	28.2

for the states from $VB \to VB$.

(I, S)	z_R	Real Axis	
		M	Γ
(1/2, 0)			
	4418	4416	28.4
(0, −1)			
	4370	4371	23.3
	4550	4549	23.7

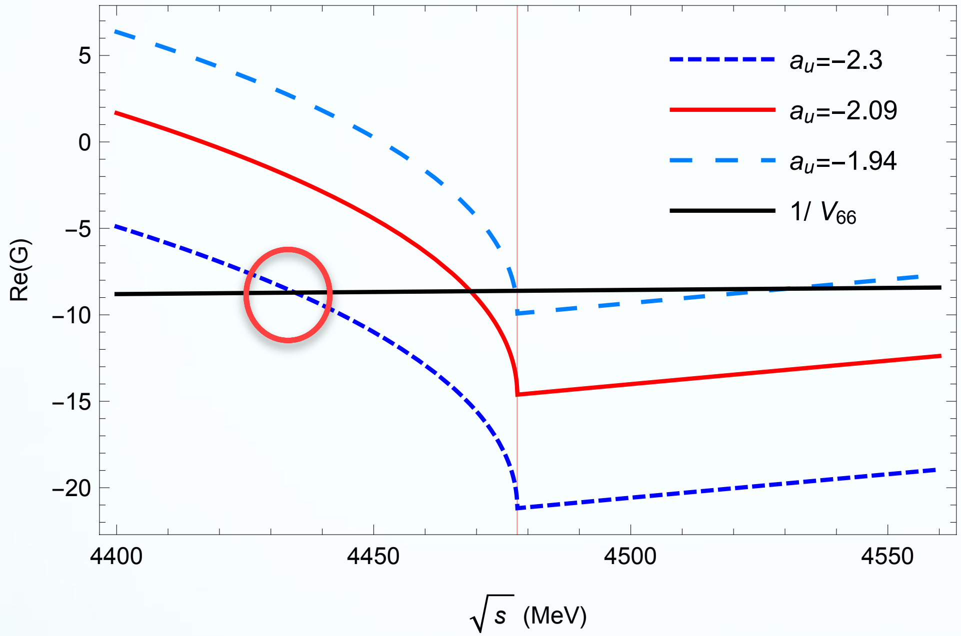
$\Lambda_{c\bar{c}}(4213)$		$\Lambda_{c\bar{c}}(4403)$	$\Lambda_{c\bar{c}}(4370)$		$\Lambda_{c\bar{c}}(4490)$	$\Lambda_{c\bar{c}}(4550)$
$D_s^- \Lambda_c^+(4255)$	$\bar{D}\Xi_c(4337)$	$\bar{D}\Xi_c'(4445)$	$D_s^{*-}\Lambda_c^+(4399)$	$\bar{D}^*\Xi_c(4478)$	$\bar{D}\Xi_c^*(4513)$	$\bar{D}^*\Xi_c'(4587)$

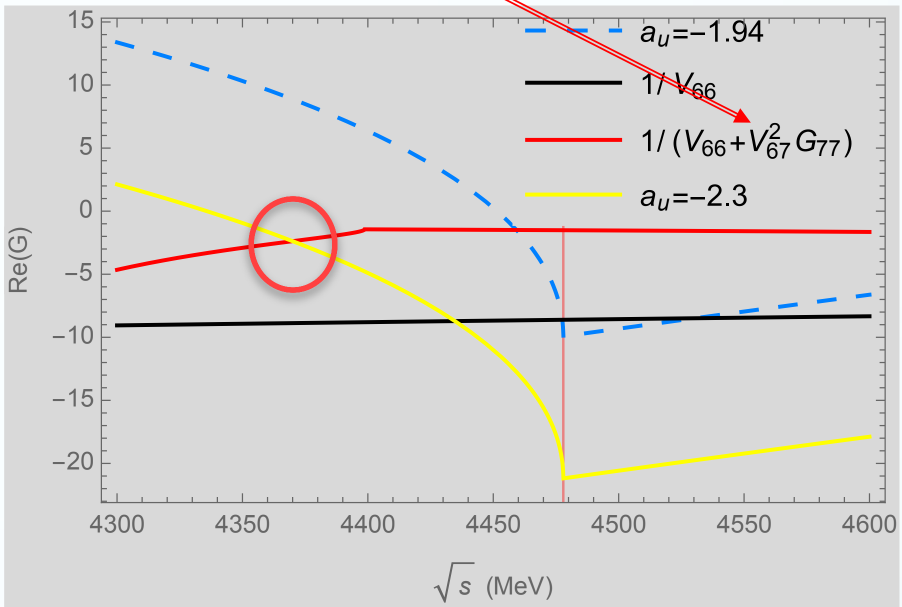
$\mu = 1000$ MeV

$a(\mu) = -2.3$

for the $\bar{D}^*\Xi_c$ channel

$\bar{D}^*_s\Lambda_c$





$\bar{D}\Xi_c$ $\bar{D}_s\Lambda_c$

CWX, J. J. Wu and B. S. Zou, in preparing.

§4. Summary

- Our results of bound states ——molecular states

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

Having $J = 1/2$.

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

With $J = 3/2$.

a $\bar{D}^*\Sigma_c$ state — $P_c(4440)^+$ $P_c(4457)^+$ — $\bar{D}^*\Xi_c$ $\bar{D}^*\Xi'_c$

Degenerate in $J = 1/2,\ 3/2$. — $P_{cs}(4459)$

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

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

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

Hope that our predictions can be found in the future experiments!

谢谢大家！

Thanks for your attention!