Hadron 2021

Is $P_{cs}(4459)$ one state or two?

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2021. Mexico

Outline

1. Introduction
2. Formalism
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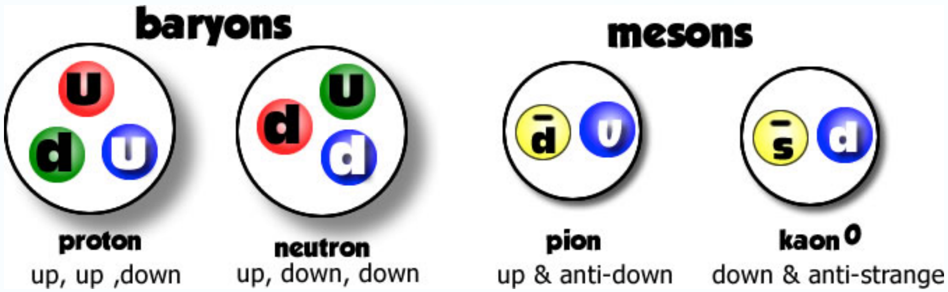
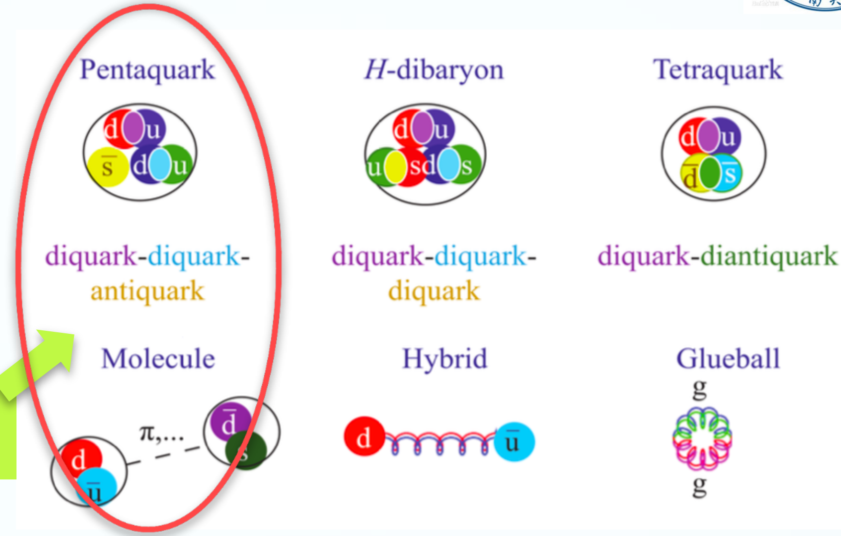
§1. Introduction



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.

C. Z. Yuan, **Int. J. Mod. Phys. A 33**,1830018 (2018).

Y. R. Liu, H. X. Chen, W. Chen, X. Liu and S. L. Zhu, **Prog. Part. Nucl. Phys. 107**, 237 (2019) .

N. Brambilla, S. Eidelman, C. Hanhart, A. Nefediev, C. P. Shen, C. E. Thomas, A. Vairo and C. Z. Yuan, **Phys. Rept. 873** (2020) 1.

Pridictions

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

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.

H. X. Chen, L. S. Geng, W. H. Liang, E. Oset, E. Wang and J. J. Xie, **Phys. Rev. C 93** (2016) 065203.

R. Chen, J. He and X. Liu, **Chin. Phys. C 41** (2017) 103105.

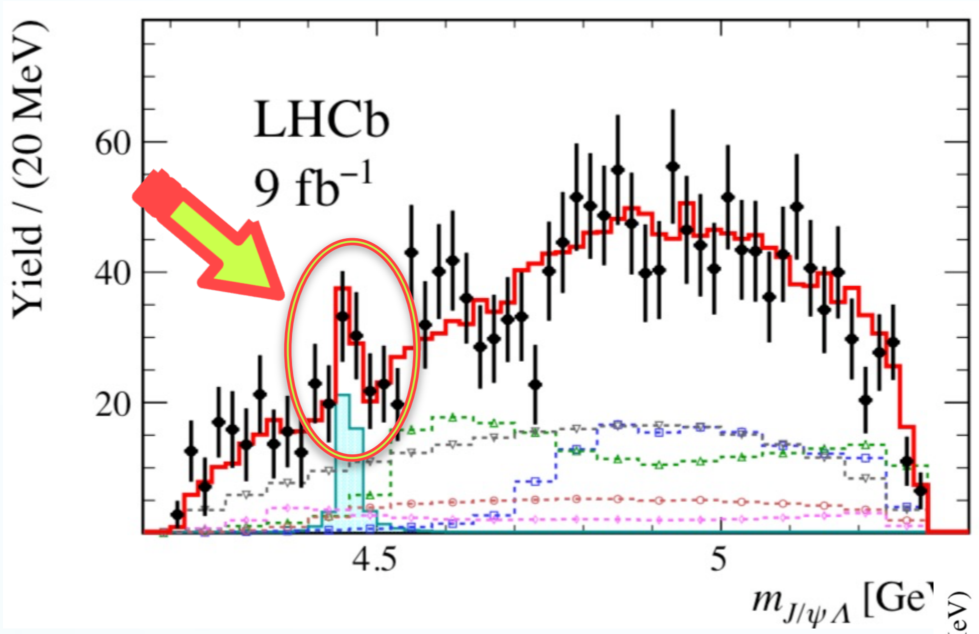
E. Santopinto and A. Giachino, **Phys. Rev. D 96** (2017) 014014.

C. W. Shen, J. J. Wu and B. S. Zou, **Phys. Rev. D 100** (2019) 056006.

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

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

Experimental Findings for Pcs

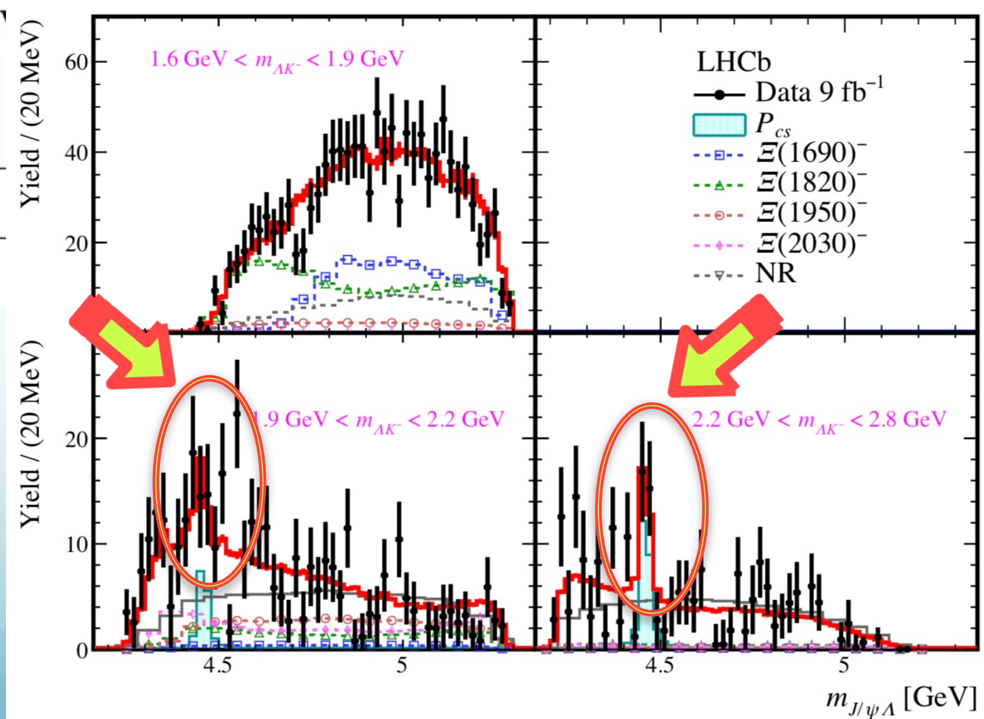


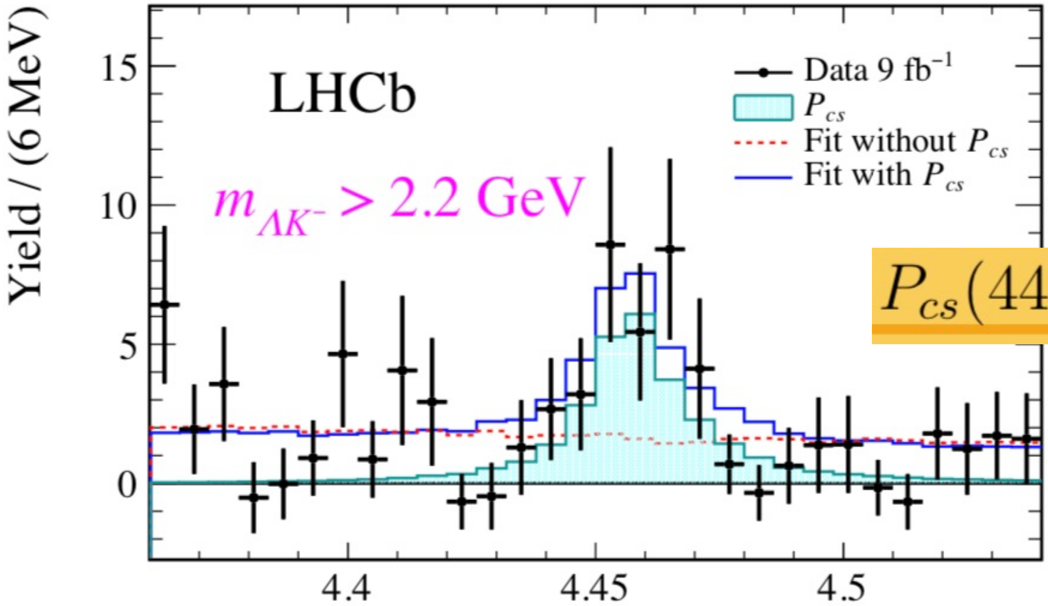
R. Aaij et al. (LHCb Collaboration), arXiv:2012.10380

$$\Xi_b^- \to J/\psi \Lambda K^-$$

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

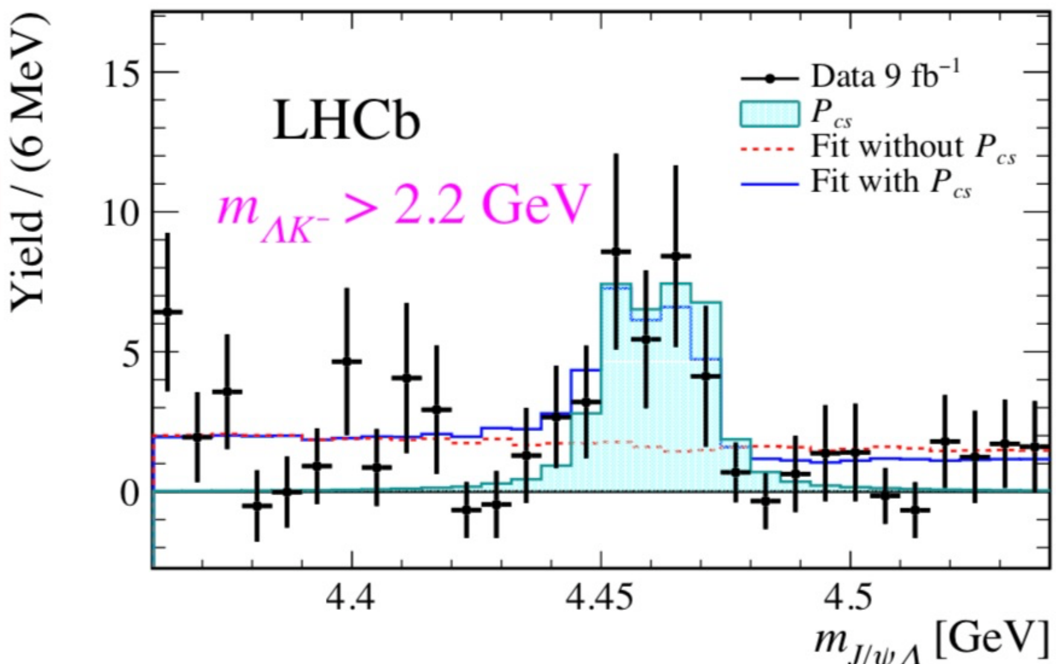
J^P ?





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

mass difference of about 6 MeV



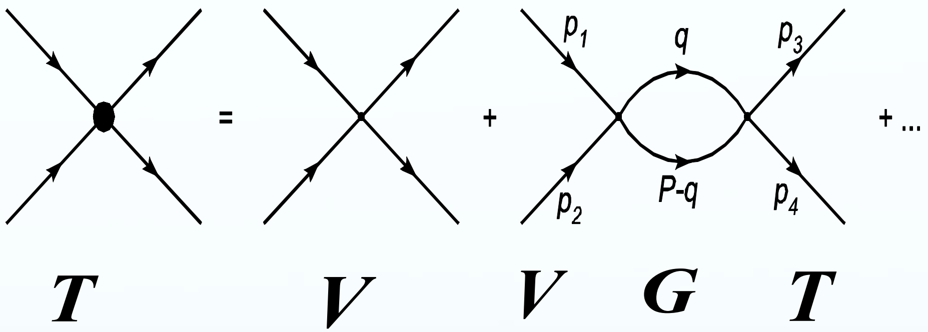
B. Wang, L. Meng and S. L. Zhu, **Phys. Rev. D 101** (2020) 034018.

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

§2. Formalism

- Coupled Channel Unitary Approach (CCUA)：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 the interaction 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:

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

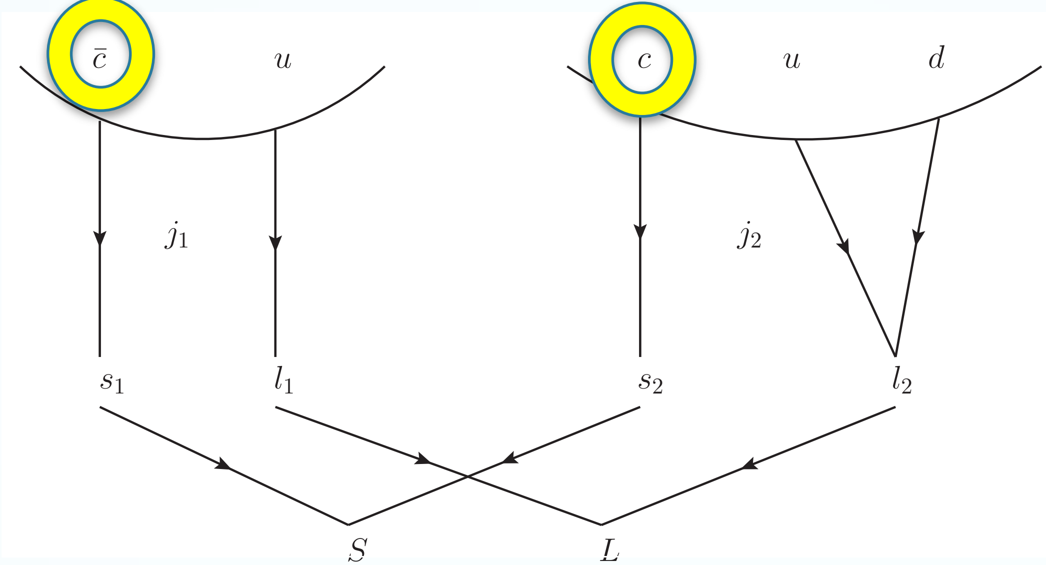
The coupled channel scattering amplitudes **T matrix satisfy the unitary** :

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

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

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

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



Considering the heavy quark spin symmetry

$\bar{D} \longrightarrow \bar{D}^*$ $\quad \Xi_c \longrightarrow \Xi_c^*$

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

$$|\ell_M s_M j_M S; \ell_B s_B j_B; J\rangle = \sum_{\mathcal{L}, S_{c\bar{c}}} [(2S_{c\bar{c}}+1)(2\mathcal{L}+1)(2j_M+1)(2j_B+1)]^{\frac{1}{2}} \times \begin{Bmatrix} \ell_M & \ell_B & \mathcal{L} \\ s_M & s_B & S_{c\bar{c}} \\ j_M & j_B & J \end{Bmatrix} |\mathcal{L} S_{c\bar{c}}; J\rangle_{(\ell_M \ell_B S)}$$

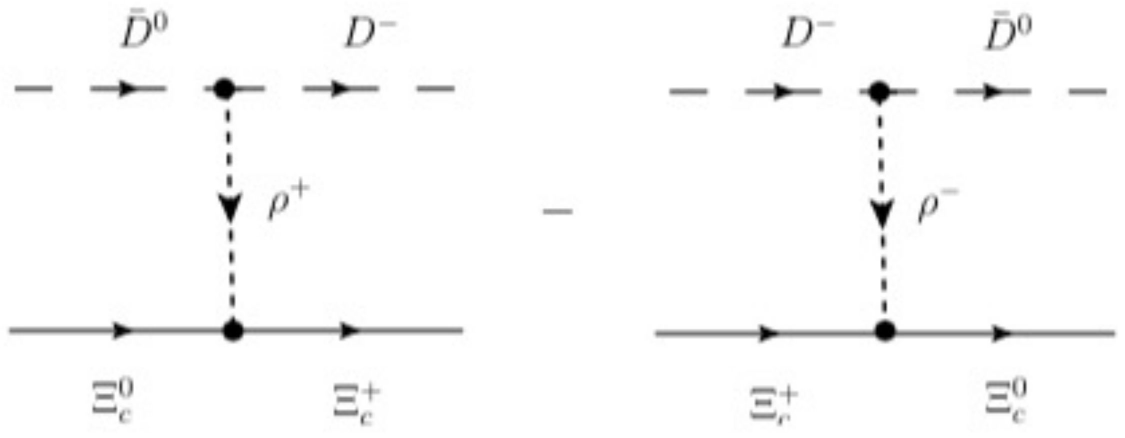
$J = 1/2,\ I = 0$

$$
\begin{array}{ccccccccc}
\eta_c\Lambda & J/\psi\Lambda & \bar{D}\Xi_c & \bar{D}_s\Lambda_c & \bar{D}\Xi_c' & \bar{D}^*\Xi_c & \bar{D}_s^*\Lambda_c & \bar{D}^*\Xi_c' & \bar{D}^*\Xi_c^*
\end{array}
$$

$$
\begin{pmatrix}
\hat{\mu}_1 & 0 & -\frac{\hat{\mu}_{12}}{2} & -\frac{\hat{\mu}_{13}}{2} & \frac{\hat{\mu}_{14}}{2} & \frac{\sqrt{3}\hat{\mu}_{12}}{2} & \frac{\sqrt{3}\hat{\mu}_{13}}{2} & \frac{\hat{\mu}_{14}}{2\sqrt{3}} & \sqrt{\frac{2}{3}}\hat{\mu}_{14} \\
0 & \hat{\mu}_1 & \frac{\sqrt{3}\hat{\mu}_{12}}{2} & \frac{\sqrt{3}\hat{\mu}_{13}}{2} & \frac{\hat{\mu}_{14}}{2\sqrt{3}} & \frac{\hat{\mu}_{12}}{2} & \frac{\hat{\mu}_{13}}{2} & \frac{5\hat{\mu}_{14}}{6} & -\frac{\sqrt{2}\hat{\mu}_{14}}{3} \\
-\frac{\hat{\mu}_{12}}{2} & \frac{\sqrt{3}\hat{\mu}_{12}}{2} & \hat{\mu}_2 & \hat{\mu}_{23} & 0 & 0 & 0 & \frac{\hat{\mu}_{24}}{\sqrt{3}} & -\sqrt{\frac{2}{3}}\hat{\mu}_{24} \\
-\frac{\hat{\mu}_{13}}{2} & \frac{\sqrt{3}\hat{\mu}_{13}}{2} & \hat{\mu}_{23} & \hat{\mu}_3 & 0 & 0 & 0 & \frac{\hat{\mu}_{34}}{\sqrt{3}} & -\sqrt{\frac{2}{3}}\hat{\mu}_{34} \\
\frac{\hat{\mu}_{14}}{2} & \frac{\hat{\mu}_{14}}{2\sqrt{3}} & 0 & 0 & \frac{1}{3}(2\hat{\lambda}+\hat{\mu}_4) & \frac{\hat{\mu}_{24}}{\sqrt{3}} & \frac{\hat{\mu}_{34}}{\sqrt{3}} & -\frac{2(\hat{\lambda}-\hat{\mu}_4)}{3\sqrt{3}} & \frac{1}{3}\sqrt{\frac{2}{3}}(\hat{\mu}_4-\hat{\lambda}) \\
\frac{\sqrt{3}\hat{\mu}_{12}}{2} & \frac{\hat{\mu}_{12}}{2} & 0 & 0 & \frac{\hat{\mu}_{24}}{\sqrt{3}} & \hat{\mu}_2 & \hat{\mu}_{23} & \frac{2\hat{\mu}_{24}}{3} & \frac{\sqrt{2}\hat{\mu}_{24}}{3} \\
\frac{\sqrt{3}\hat{\mu}_{13}}{2} & \frac{\hat{\mu}_{13}}{2} & 0 & 0 & \frac{\hat{\mu}_{34}}{\sqrt{3}} & \hat{\mu}_{23} & \hat{\mu}_3 & \frac{2\hat{\mu}_{34}}{3} & \frac{\sqrt{2}\hat{\mu}_{34}}{3} \\
\frac{\hat{\mu}_{14}}{2\sqrt{3}} & \frac{5\hat{\mu}_{14}}{6} & \frac{\hat{\mu}_{24}}{\sqrt{3}} & \frac{\hat{\mu}_{34}}{\sqrt{3}} & -\frac{2(\hat{\lambda}-\hat{\mu}_4)}{3\sqrt{3}} & \frac{2\hat{\mu}_{24}}{3} & \frac{2\hat{\mu}_{34}}{3} & \frac{1}{9}(2\hat{\lambda}+7\hat{\mu}_4) & \frac{1}{9}\sqrt{2}(\hat{\lambda}-\hat{\mu}_4) \\
\sqrt{\frac{2}{3}}\hat{\mu}_{14} & -\frac{\sqrt{2}\hat{\mu}_{14}}{3} & -\sqrt{\frac{2}{3}}\hat{\mu}_{24} & -\sqrt{\frac{2}{3}}\hat{\mu}_{34} & \frac{1}{3}\sqrt{\frac{2}{3}}(\hat{\mu}_4-\hat{\lambda}) & \frac{\sqrt{2}\hat{\mu}_{24}}{3} & \frac{\sqrt{2}\hat{\mu}_{34}}{3} & \frac{1}{9}\sqrt{2}(\hat{\lambda}-\hat{\mu}_4) & \frac{1}{9}(\hat{\lambda}+8\hat{\mu}_4)
\end{pmatrix}
$$

LECs

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



$$\hat{\mu}_1 = \hat{\mu}_3 = \hat{\mu}_{24} = \hat{\mu}_{34} = 0$$

$$\hat{\mu}_2 = \hat{\mu}_{23}/\sqrt{2} = \hat{\mu}_4 = \hat{\lambda} = -F, \qquad F = \frac{1}{4f^2}(p^0 + p'\,)$$

$$\hat{\mu}_{12} = -\hat{\mu}_{13}/\sqrt{2} = \hat{\mu}_{14}/\sqrt{3} = -\sqrt{\frac{2}{3}}\,\frac{m_V^2}{m_{D^*}^2}\,F,$$

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

§3. Results

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

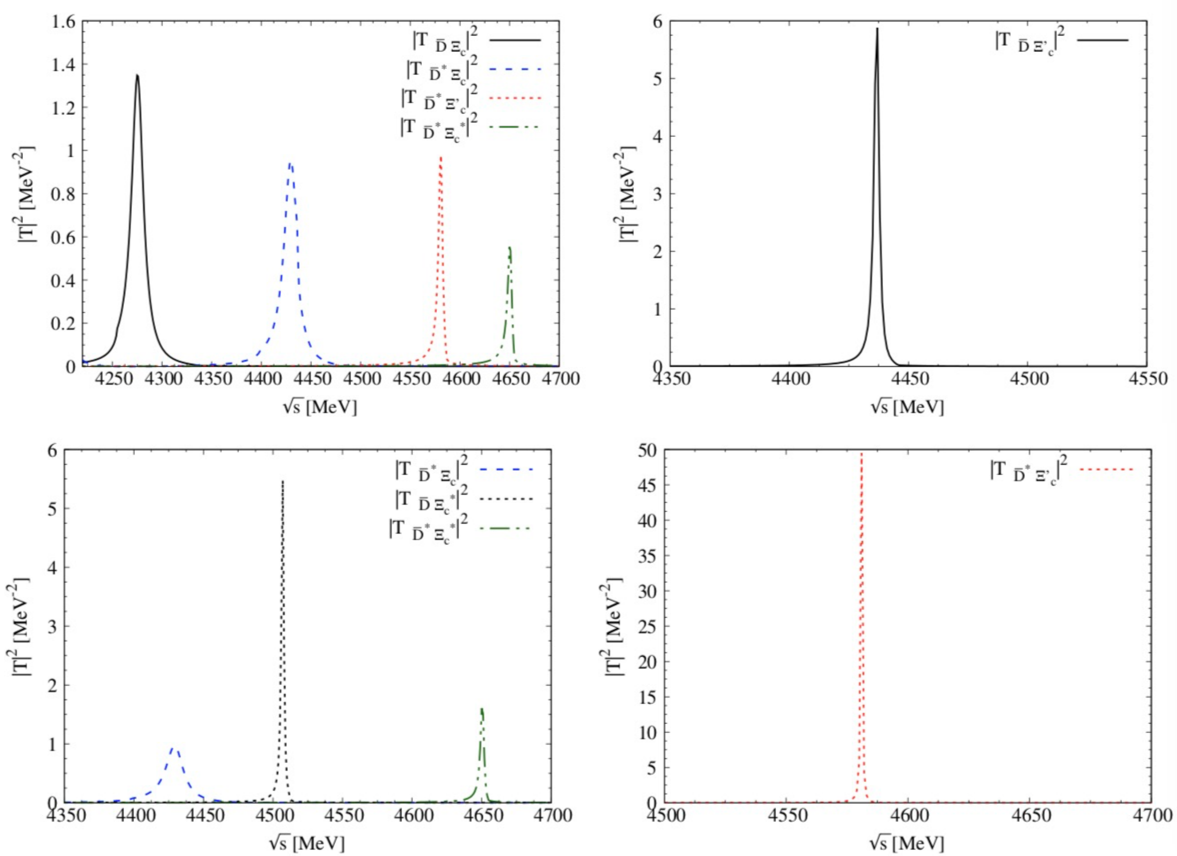
$\eta_c\Lambda,\ J/\psi\Lambda,\ \bar{D}\Xi_c,\ \bar{D}_s\Lambda_c,\ \bar{D}\Xi'_c,\ \bar{D}^*\Xi_c,\ \bar{D}^*_s\Lambda_c,\ \bar{D}^*\Xi'_c,\ \bar{D}^*\Xi^*_c.$

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

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

HQSS

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



CWX, J. Nieves and E. Oset, Phys. Rev. D 100 (2019) 014021

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

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

Thres.	4099.58	4212.58	4366.61	4254.80	4445.34	4477.92	4398.66	4586.66	4654.48
	$\eta_c\Lambda$	$J/\psi\Lambda$	$\bar{D}\Xi_c$	$\bar{D}_s\Lambda_c$	$\bar{D}\Xi_c'$	$\bar{D}^*\Xi_c$	$\bar{D}_s^*\Lambda_c$	$\bar{D}^*\Xi_c'$	$\bar{D}^*\Xi_c^*$
$4276.59+i7.67$									
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	$0.31 - i0.10$	$\mathbf{2.77 - i0.02}$	$0.67 + i0.32$	$0.00 + i0.0.02$	$0.00 - i0.06$	$0.00 + i0.0.04$
$\lvert g_i\rvert$	0.32	**2.77**	0.74	0.02	0.06	0.04
$4506.99 + i1.03$						
g_i	$0.27 - i0.02$	$0.02 - i0.03$	$0.02 - i0.02$	$0.00 - i0.03$	$\mathbf{1.56 - i0.07}$	$0.00 - i0.05$
$\lvert g_i\rvert$	0.27	0.03	0.03	0.03	**1.56**	0.05
$4580.96 + i0.34$						
g_i	$0.14 - i0.01$	$0.01 - i0.01$	$0.01 - i0.01$	$\mathbf{1.54 - i0.02}$	$0.02 - i0.00$	$0.00 - i0.04$
$\lvert g_i\rvert$	0.14	0.01	0.02	**1.54**	0.02	0.04
$4650.58 + i1.48$						
g_i	$0.29 - i0.02$	$0.02 - i0.01$	$0.03 - i0.02$	$0.03 - i0.01$	$0.03 - i0.00$	$\mathbf{1.40 - i0.13}$
$\lvert g_i\rvert$	0.29	0.03	0.03	0.03	0.03	**1.41**

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

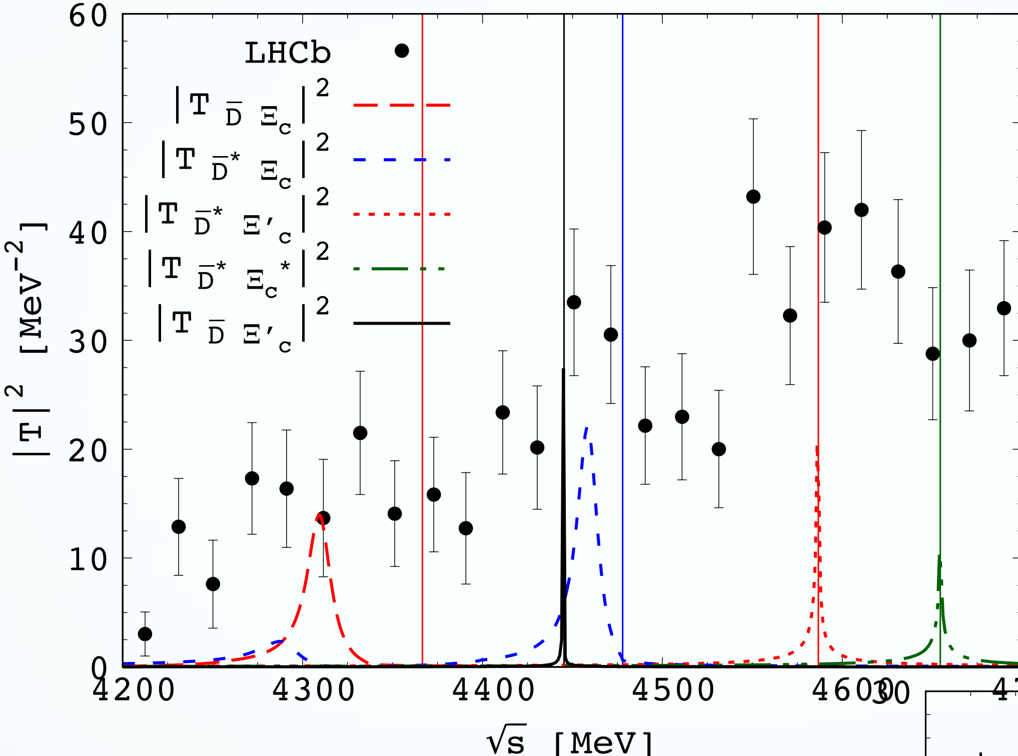
- $J = 1/2,\ I = 0$

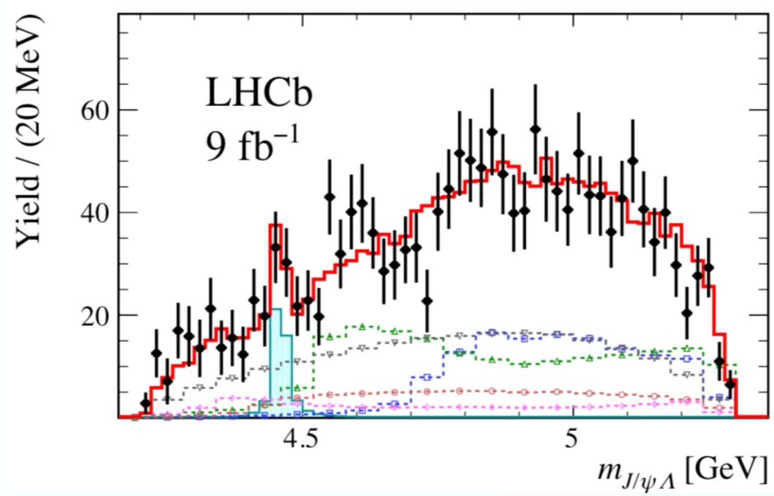
$a_\mu(\mu = 1\ \text{GeV}) = -1.94$

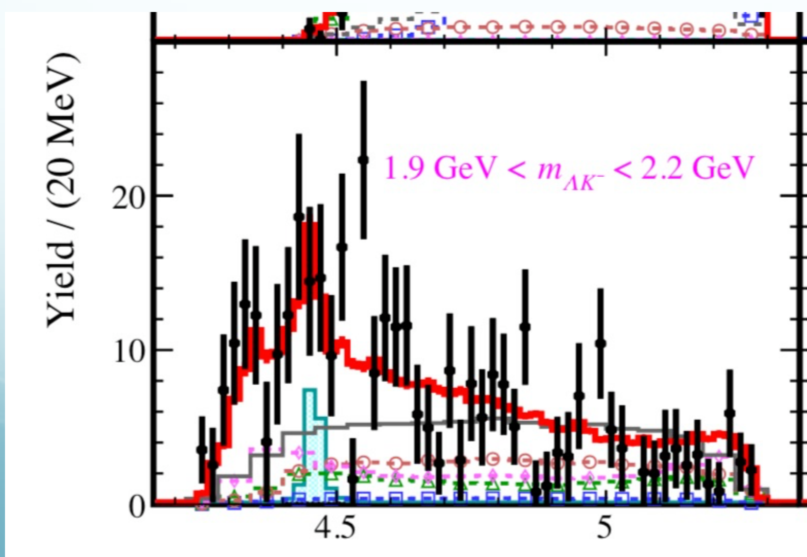
Chan.	$\eta_c\Lambda$	$J/\psi\Lambda$	$\bar{D}\Xi_c$	$\bar{D}_s\Lambda_c$	$\bar{D}\Xi'_c$	$\bar{D}^*\Xi_c$	$\bar{D}^*_s\Lambda_c$	$\bar{D}^*\Xi'_c$	$\bar{D}^*\Xi^*_c$
Thres.	4099.58	4212.58	4366.61	4254.80	4445.34	4477.92	4398.66	4586.66	4654.48
$4310.53 + i8.23$									
$\lvert g_i \rvert$	0.15	0.27	**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%	–	–
$4459.07 + i6.89$	$P_{cs}(4459)$								
$\lvert g_i \rvert$	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%	–	–
4586.66?									
$\lvert g_i \rvert$	–	–	–	–	–	–	–	–	–
4654.48?									
$\lvert g_i \rvert$	–	–	–	–	–	–	–	–	–

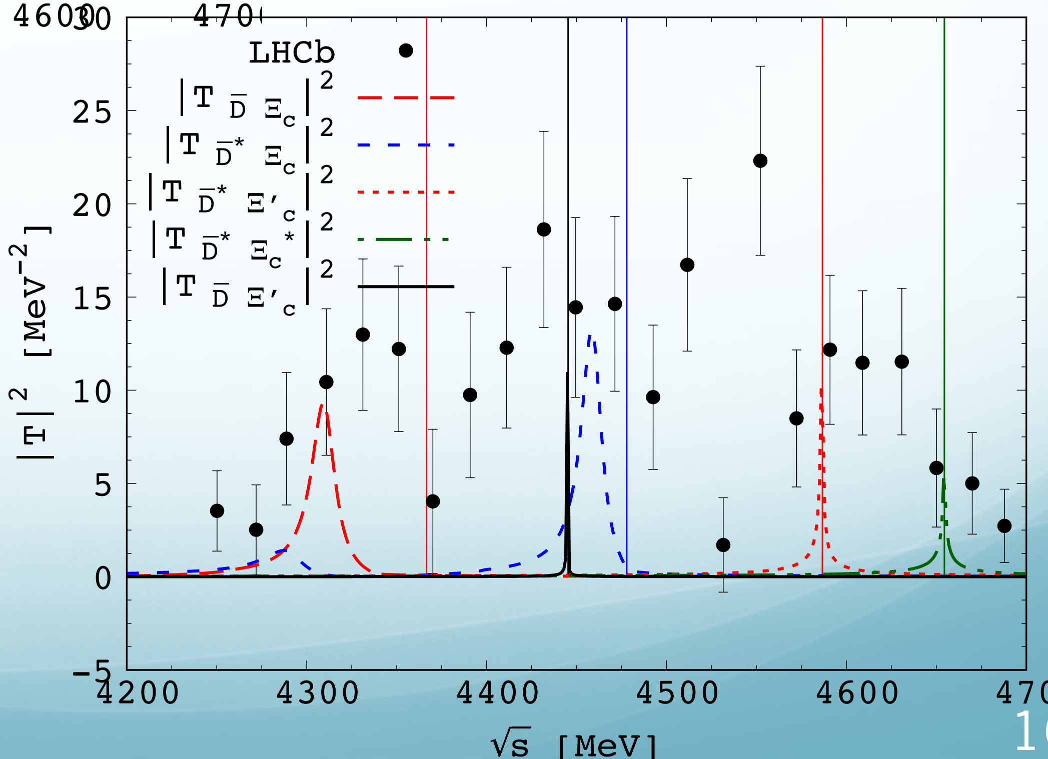
- $J = 3/2,\ I = 0$

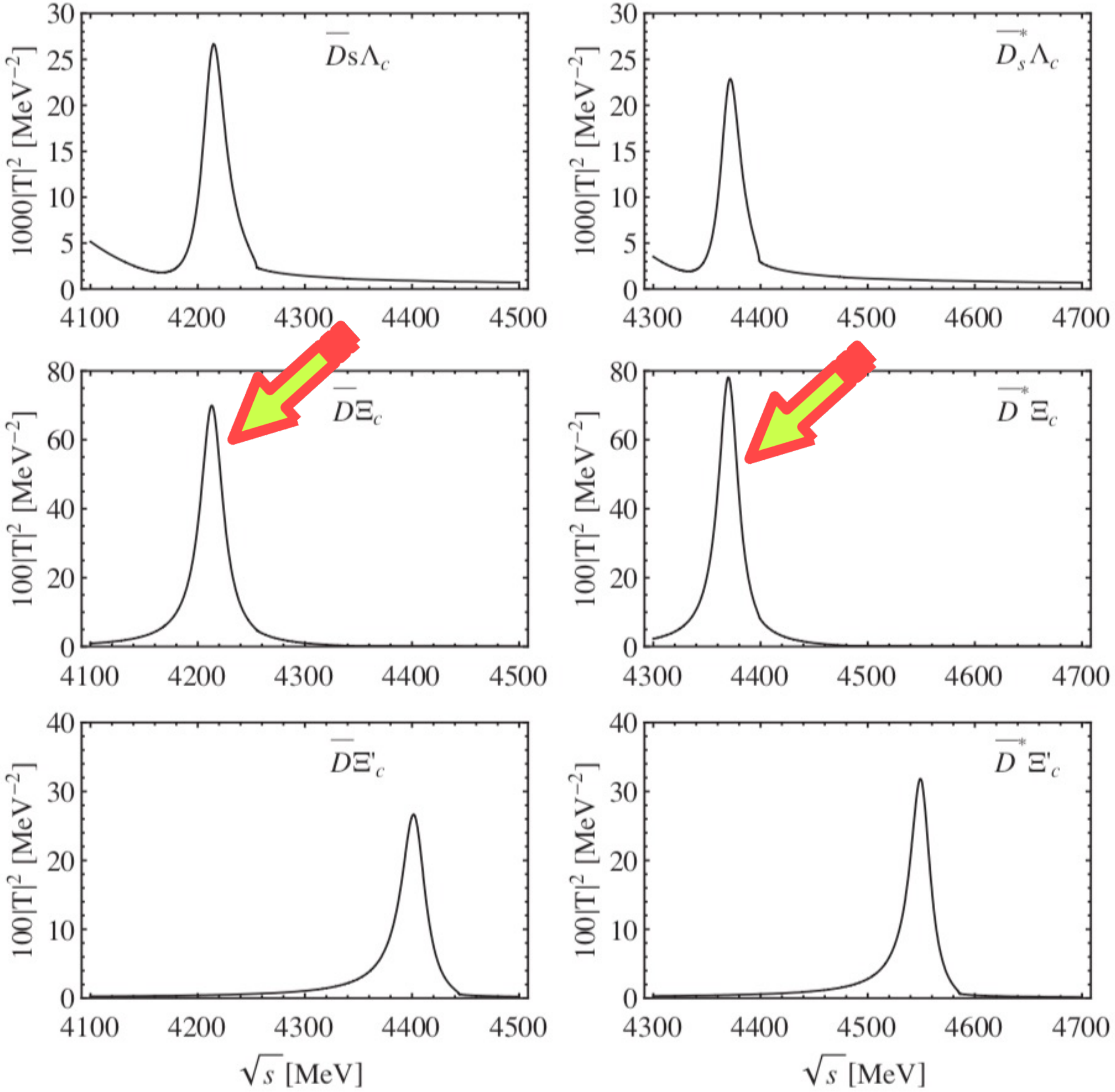
Chan.	$J/\psi\Lambda$	$\bar{D}^*\Xi_c$	$\bar{D}_s^*\Lambda_c$	$\bar{D}^*\Xi_c'$	$\bar{D}\Xi_c^*$	$\bar{D}^*\Xi_c^*$
Thres.	4212.58	4477.92	4398.66	4586.66	4513.17	4654.48
$4459.02 + i6.83$		$P_{cs}(4459)$				
$\lvert g_i \rvert$	0.28	**2.16**	0.61	0.02	0.04	0.03
Γ_i	2.00	–	11.15	–	–	–
Br.	14.68%	–	81.64%	–	–	–
4586.66?						
$\lvert g_i \rvert$	–	–	–	–	–	–
4513.17?						
$\lvert g_i \rvert$	–	–	–	–	–	–
4654.48?						
$\lvert g_i \rvert$	–	–	–	–	–	–


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]


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


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


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]



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

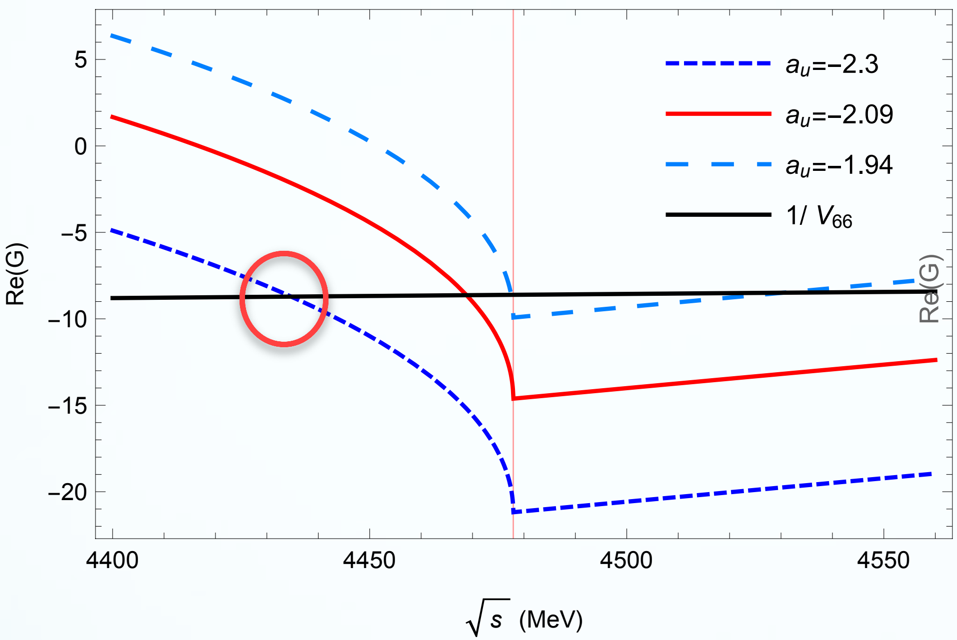
$\Lambda_{c\bar{c}}(4213)$		$\Lambda_{c\bar{c}}(4403)$		$\Lambda_{c\bar{c}}(4370)$	$\Lambda_{c\bar{c}}(4490)$	$\Lambda_{c\bar{c}}(4550)$
$D_s^- \Lambda_c^+(4255)$	$\bar{D}\Xi_c(4337)$	$\bar{D}\Xi_c'(4445)$	$D_s^{*-}\Lambda_c^+(4399)$	$\bar{D}^*\Xi_c(4478)$	$\bar{D}\Xi_c^*(4513)$	$\bar{D}^*\Xi_c'(4587)$

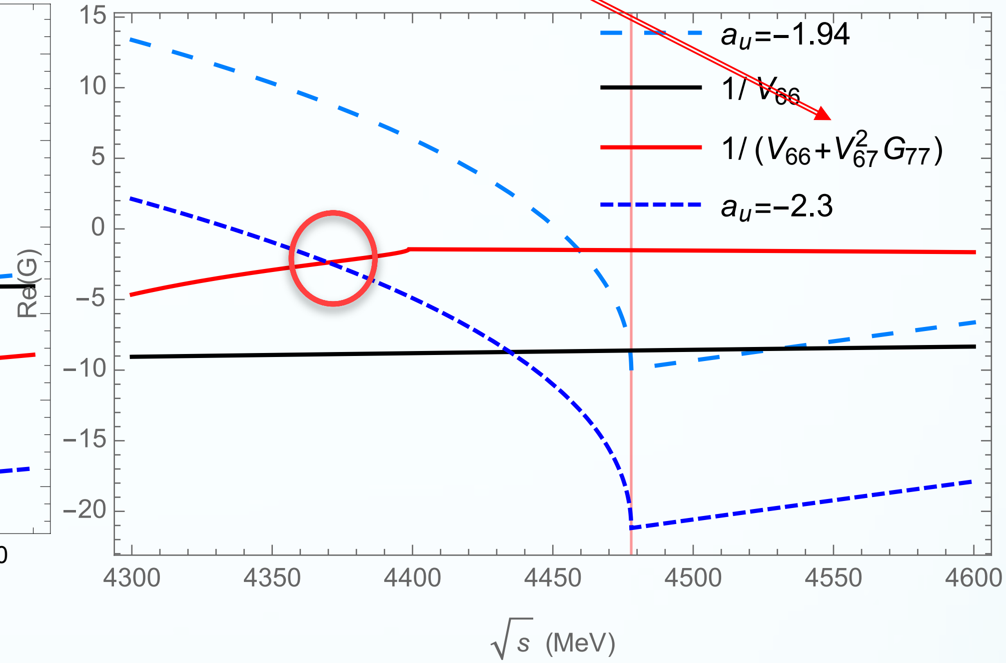
$\mu = 1000$ MeV

$a(\mu) = -2.3$

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

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





CWX, J. J. Wu and B. S. Zou, Phys. Rev. D 103 (2021) 054016.

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

§4. Summary

- Our results of bound states ——molecular states

a $\bar{D}\Xi_c$ state
Having $J = 1/2$.

4310.53 $\bar{D}\Xi_c'$ $P_c(4312)^+$

a $\bar{D}\Xi_c^*$ state
With $J = 3/2$.

$P_c(4450)$

?

a $\bar{D}^*\Xi_c$ state
Degenerate in $J = 1/2,\ 3/2$.

$P_{cs}(4459)$ $\bar{D}^*\Xi_c'$ $P_c(4440)^+$ $P_c(4457)^+$

a $\bar{D}^*\Xi_c^*$ state
Degenerate in $J = 1/2,\ 3/2,\ 5/2$.

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

Thanks for your attention!