



全国第十八届重味物理和 CP 破坏研讨会

Study of $P_{cs}(4459)$ state

Chu-Wen Xiao (肖楮文)

Central South University (中南大学)

Collaborators: Jia-Jun Wu, Bing-Song Zou,

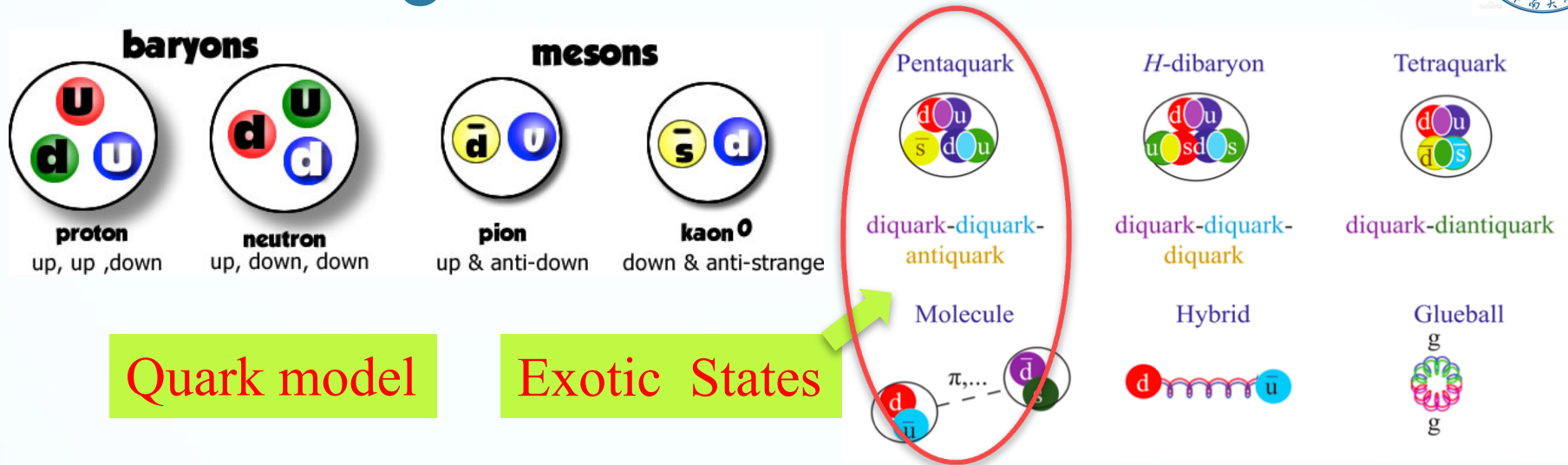
Juan Nieves, Eulogio Oset

2021. 广州

Outline

1. Introduction
2. Formalism
3. Results
4. Summary

§1. Introduction



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.

Predictions on the 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.

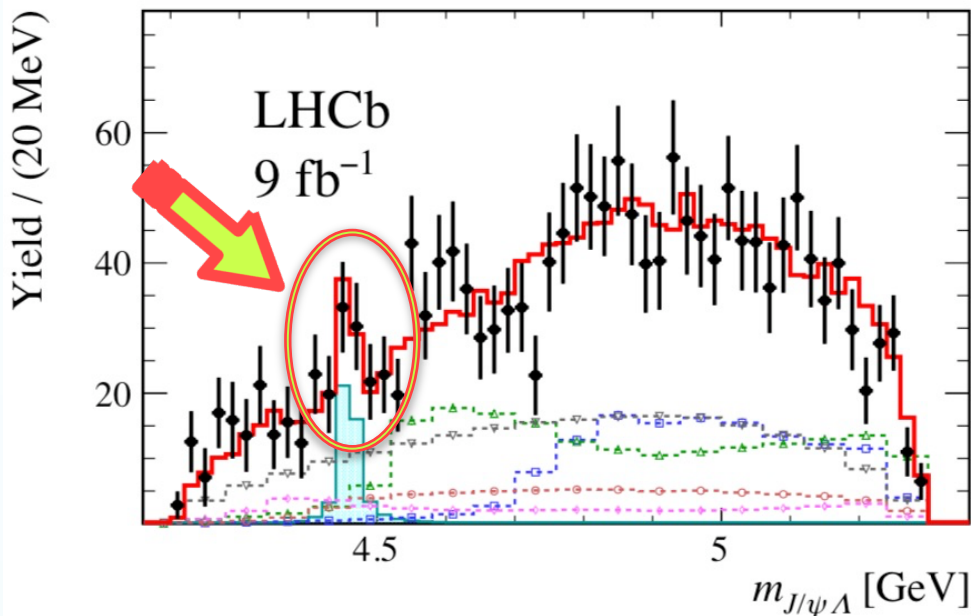
E. Santopinto and A. Giachino, **Phys. Rev. D** **96** (2017) 014014.

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.

New findings for the Pcs state

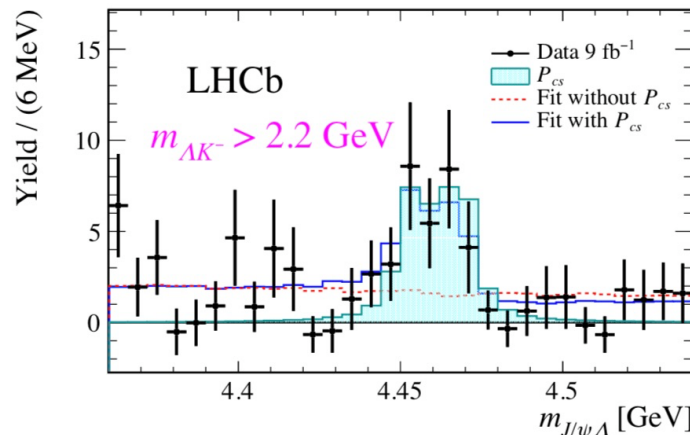
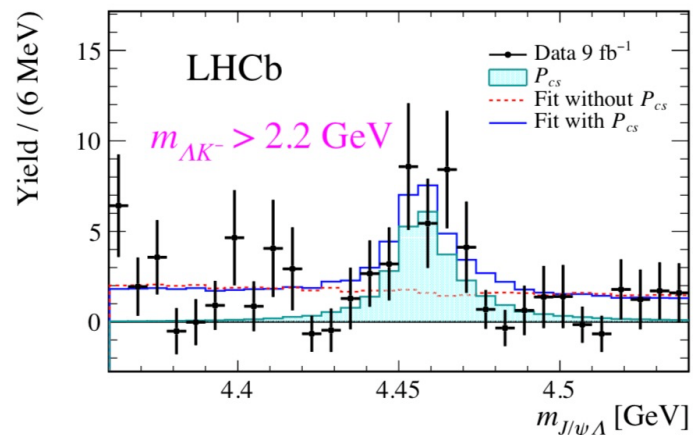


R. Aaij et al. (LHCb Collaboration),
Sci. Bull. 66 (2021) 1278-1287

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

$J^P ?$

mass difference of about 6 MeV



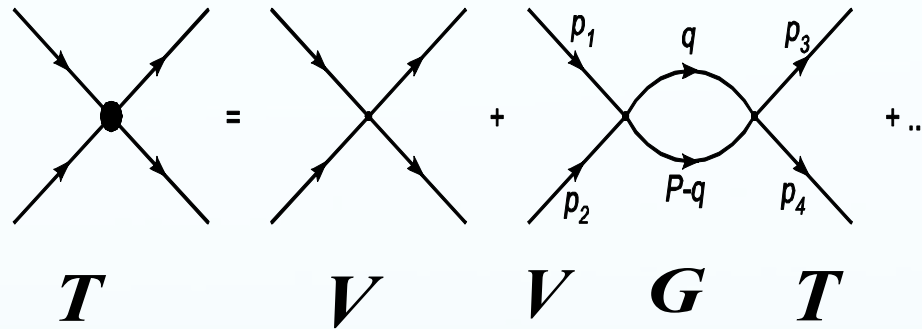
B. Wang, L. Meng and S. L. Zhu, **Phys. Rev. D** **101** (2020) 034018.

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:

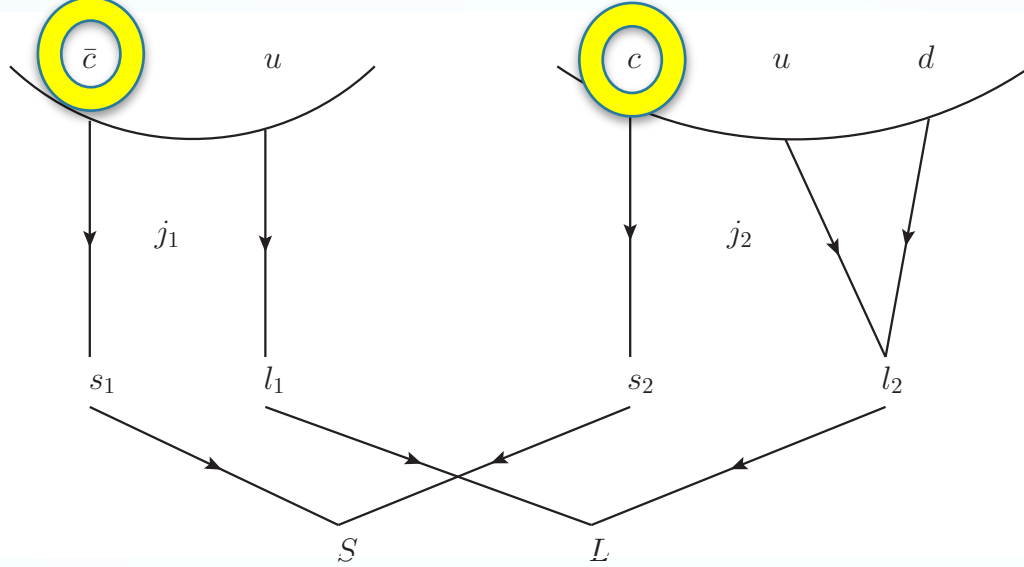
$$G_{ll}(s) = i \int \frac{d^4 q}{(2\pi)^4} \frac{1}{(P-q)^2 - m_{l1}^2 + i\varepsilon} \frac{1}{q^2 - m_{l2}^2 + i\varepsilon}$$

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

$$\begin{aligned} \text{Im } T_{ij} &= T_{in} \sigma_{nn} T_{nj}^* \\ \sigma_{nn} &\equiv \text{Im } G_{nn} = - \frac{q_{cm}}{8\pi\sqrt{s}} \theta(s - (m_1 + m_2)^2) \end{aligned}$$

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

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



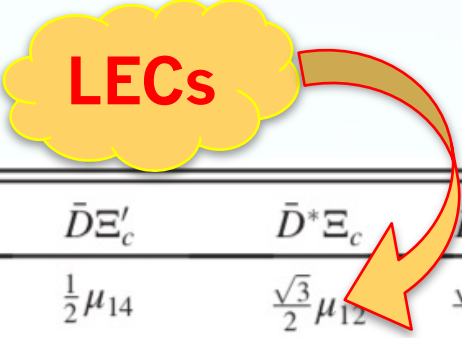
Considering the heavy quark spin symmetry

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

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

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

$J = 1/2, I = 0$



$\eta_c \Lambda$	$J/\psi \Lambda$	$\bar{D}\Xi_c$	$\bar{D}_s \Lambda_c$	$\bar{D}\Xi'_c$	$\bar{D}^* \Xi_c$	$\bar{D}_s^* \Lambda_c$	$\bar{D}^* \Xi'_c$	$\bar{D}^* \Xi_c^*$
μ_1	0	$-\frac{1}{2}\mu_{12}$	$-\frac{1}{2}\mu_{13}$	$\frac{1}{2}\mu_{14}$	$\frac{\sqrt{3}}{2}\mu_{12}$	$\frac{\sqrt{3}}{2}\mu_{13}$	$\frac{1}{2\sqrt{3}}\mu_{14}$	$\sqrt{\frac{2}{3}}\mu_{14}$
	μ_1	$\frac{\sqrt{3}}{2}\mu_{12}$	$\frac{\sqrt{3}}{2}\mu_{13}$	$\frac{1}{2\sqrt{3}}\mu_{14}$	$\frac{1}{2}\mu_{12}$	$\frac{1}{2}\mu_{13}$	$\frac{5}{6}\mu_{14}$	$-\frac{\sqrt{2}}{3}\mu_{14}$
		μ_2	μ_{23}	0	0	0	$\frac{1}{\sqrt{3}}\mu_{24}$	$-\sqrt{\frac{2}{3}}\mu_{24}$
			μ_3	0	0	0	$\frac{1}{\sqrt{3}}\mu_{34}$	$-\sqrt{\frac{2}{3}}\mu_{34}$
				$\frac{1}{3}(2\lambda + \mu_4)$	$\frac{1}{\sqrt{3}}\mu_{24}$	$\frac{1}{\sqrt{3}}\mu_{34}$	$-\frac{2}{3\sqrt{3}}(\lambda - \mu_4)$	$\frac{1}{3}\sqrt{\frac{2}{3}}(\mu_4 - \lambda)$
					μ_2	μ_{23}	$\frac{2}{3}\mu_{24}$	$\frac{\sqrt{2}}{3}\mu_{24}$
						μ_3	$\frac{2}{3}\mu_{34}$	$\frac{\sqrt{2}}{3}\mu_{34}$
							$\frac{1}{9}(2\lambda + 7\mu_4)$	$\frac{\sqrt{2}}{9}(\lambda - \mu_4)$
								$\frac{1}{9}(\lambda + 8\mu_4)$

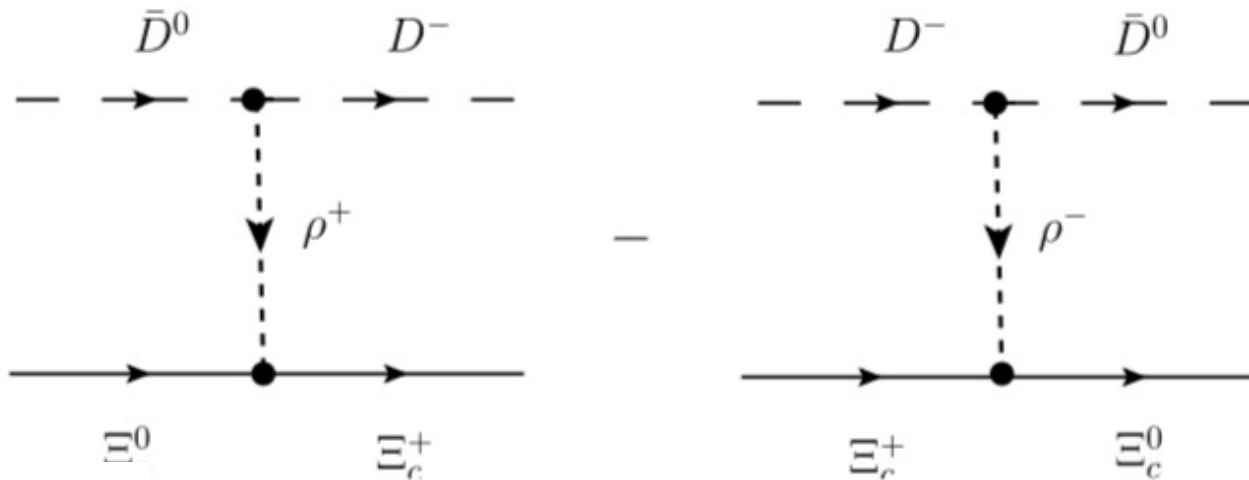
$J = 3/2, I = 0$

$J/\psi \Lambda$	$\bar{D}^* \Xi_c$	$\bar{D}_s^* \Lambda_c$	$\bar{D}^* \Xi'_c$	$\bar{D}\Xi_c^*$	$\bar{D}^* \Xi_c^*$
μ_1	μ_{12}	μ_{13}	$-\frac{1}{3}\mu_{14}$	$\frac{1}{\sqrt{3}}\mu_{14}$	$\frac{\sqrt{5}}{3}\mu_{14}$
	μ_2	μ_{23}	$-\frac{1}{3}\mu_{24}$	$\frac{1}{\sqrt{3}}\mu_{24}$	$\frac{\sqrt{5}}{3}\mu_{24}$
		μ_3	$-\frac{1}{3}\mu_{34}$	$\frac{1}{\sqrt{3}}\mu_{34}$	$\frac{\sqrt{5}}{3}\mu_{34}$
			$\frac{1}{9}(8\lambda + \mu_4)$	$\frac{1}{3\sqrt{3}}(\lambda - \mu_4)$	$\frac{\sqrt{5}}{9}(\lambda - \mu_4)$
				$\frac{1}{3}(2\lambda + \mu_4)$	$\frac{1}{3}\sqrt{\frac{5}{3}}(\mu_4 - \lambda)$
					$\frac{1}{9}(4\lambda + 5\mu_4)$

$$\mathcal{L}_{VVV} = ig \langle [V_\nu, \partial_\mu V_\nu] V^\mu \rangle,$$

$$\mathcal{L}_{PPV} = -ig \langle [P, \partial_\mu P] V^\mu \rangle,$$

$$\mathcal{L}_{BBV} = g (\langle \bar{B} \gamma_\mu [V^\mu, B] \rangle + \langle \bar{B} \gamma_\mu B \rangle \langle V^\mu \rangle)$$



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

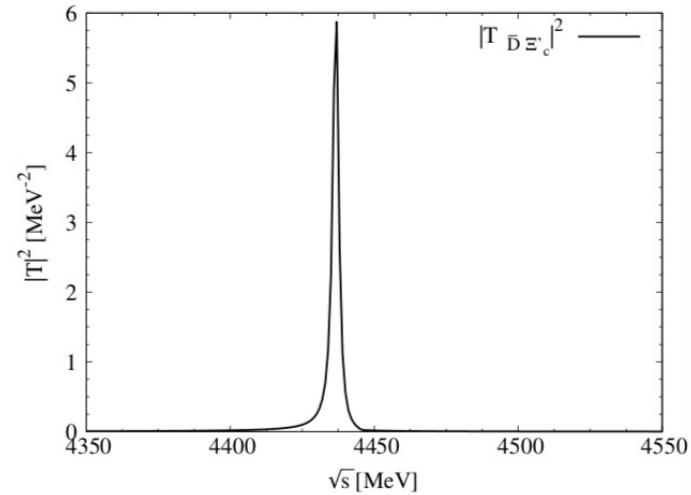
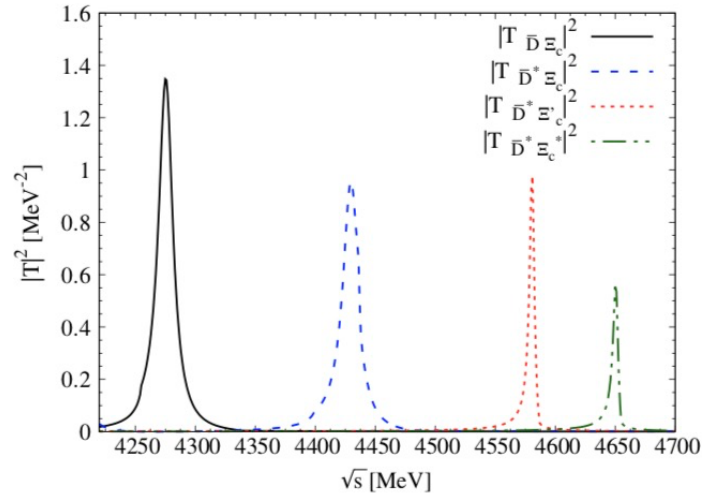
$$\hat{\mu}_1 = \hat{\mu}_3 = \hat{\mu}_{24} = \hat{\mu}_{34} = 0$$

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

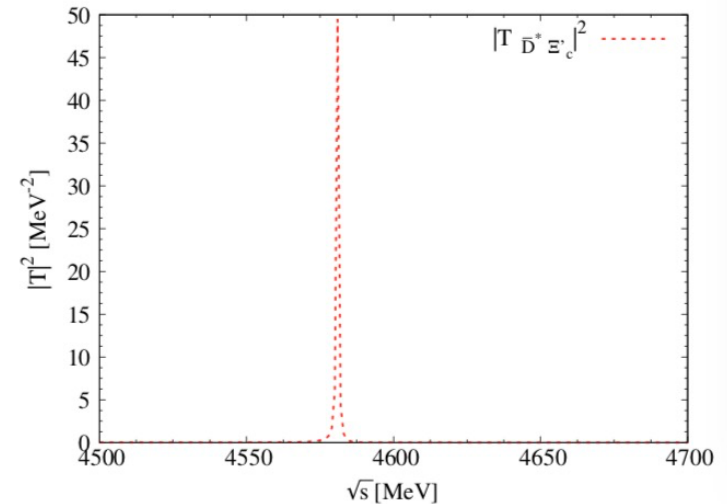
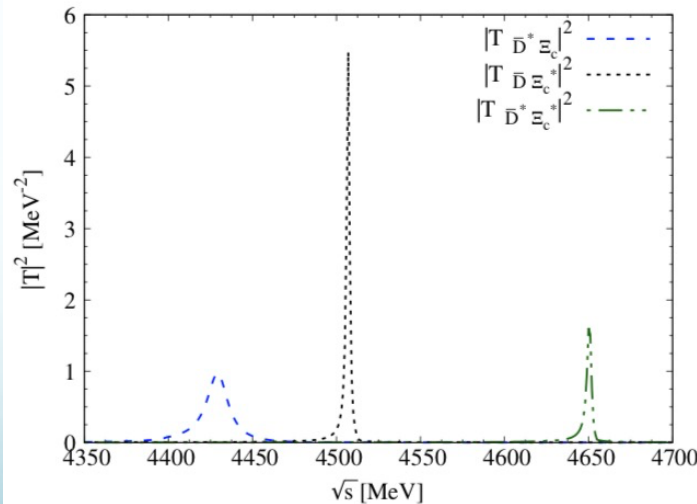
$$\hat{\mu}_{12} = -\hat{\mu}_{13}/\sqrt{2} = \hat{\mu}_{14}/\sqrt{3} = -\sqrt{\frac{2}{3}} \frac{m_V^2}{m_{D^*}^2} F,$$

§3. Results

$J = 1/2, I = 0$



$J = 3/2, I = 0$



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

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

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

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

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	$0.17 - i0.03$	$0.29 - i0.07$	$2.93 + i0.08$	$0.76 + i0.31$	$0.00 + i0.01$	$0.01 + i0.02$	$0.01 + i0.04$	$0.01 - i0.02$	$0.01 - i0.03$
$ g_i $	0.17	0.30	2.93	0.82	0.01	0.02	0.05	0.02	0.03
	$4429.84 + i7.92$								
g_i	$0.29 - i0.11$	$0.17 - i0.07$	$0.00 - i0.00$	$0.00 - i0.00$	$0.15 - i0.26$	$2.78 + i0.01$	$0.66 + i0.32$	$0.01 + i0.05$	$0.01 + i0.03$
$ g_i $	0.31	0.18	0.00	0.00	0.30	2.78	0.73	0.05	0.04
	$4436.70 + i1.17$								
g_i	$0.24 + i0.03$	$0.14 + i0.01$	$0.00 - i0.00$	$0.00 - i0.00$	$1.72 - i0.04$	$0.22 - i0.31$	$0.06 - i0.01$	$0.01 - i0.04$	$0.01 - i0.03$
$ g_i $	0.24	0.14	0.00	0.00	1.72	0.38	0.07	0.04	0.03
	$4580.96 + i2.44$								
g_i	$0.12 - i0.00$	$0.37 - i0.04$	$0.02 - i0.01$	$0.02 - i0.01$	$0.03 - i0.00$	$0.02 - i0.02$	$0.03 - i0.02$	$1.57 - i0.17$	$0.00 + i0.02$
$ g_i $	0.12	0.37	0.02	0.02	0.03	0.03	0.03	1.58	0.02
	$4650.86 + i2.59$								
g_i	$0.32 - i0.05$	$0.19 - i0.03$	$0.02 - i0.01$	$0.03 - i0.02$	$0.02 - i0.00$	$0.01 - i0.01$	$0.02 - i0.01$	$0.01 - i0.00$	$1.41 - i0.23$
$ g_i $	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 + i0.002	0.00 - i0.06	0.00 + i0.004
$ 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

• $J = 1/2, I = 0$

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

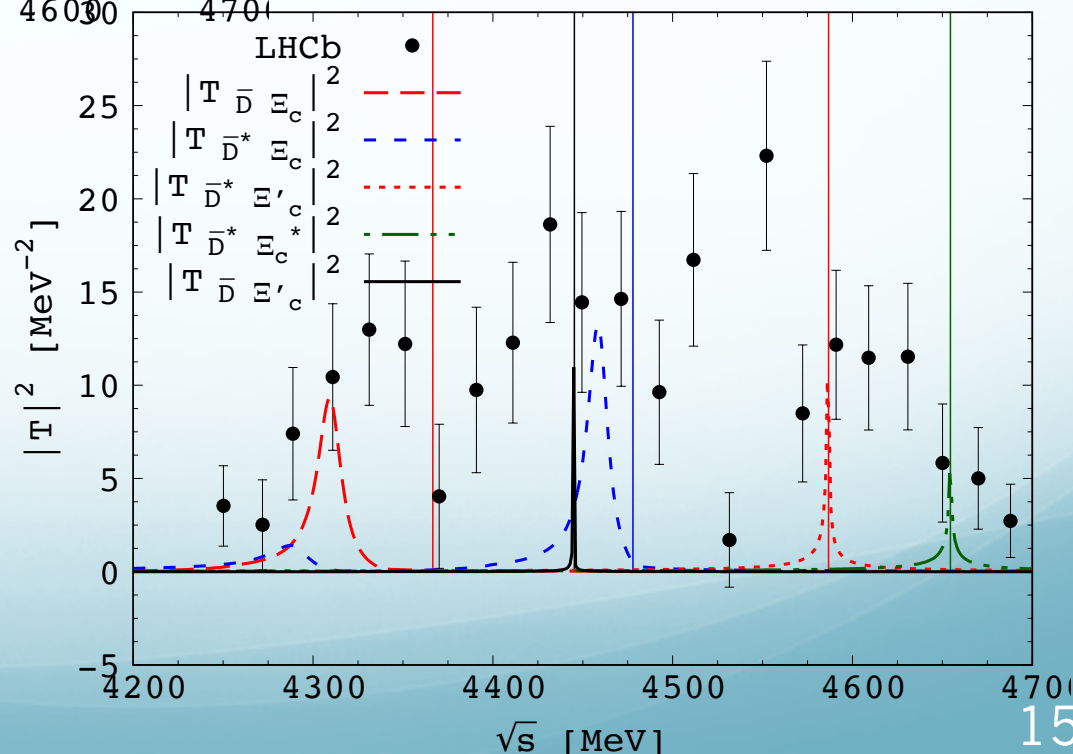
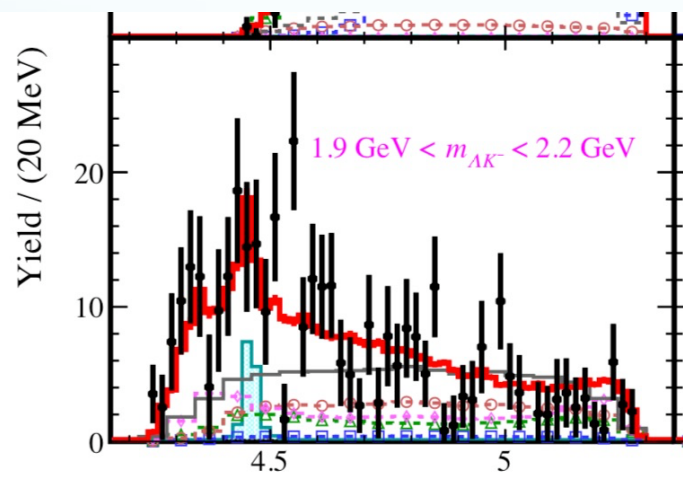
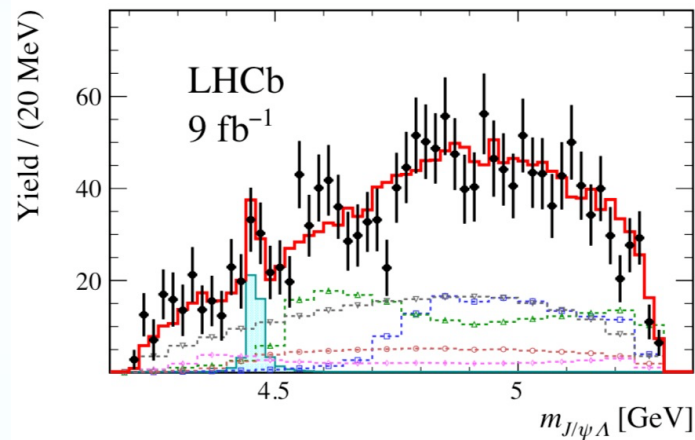
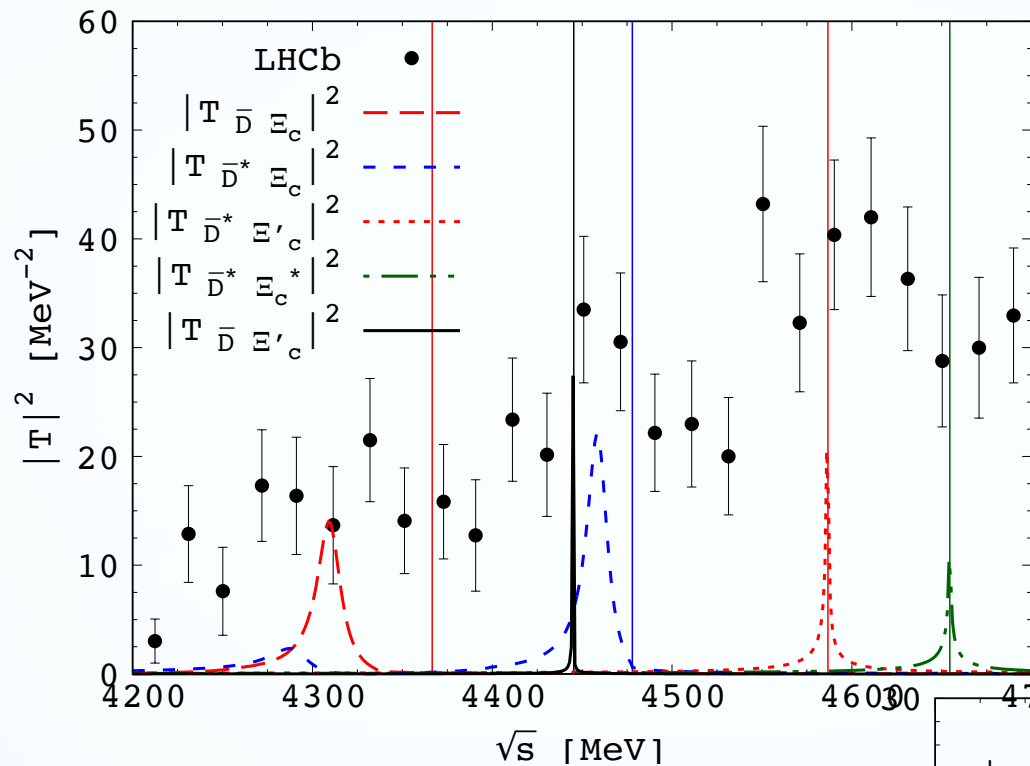


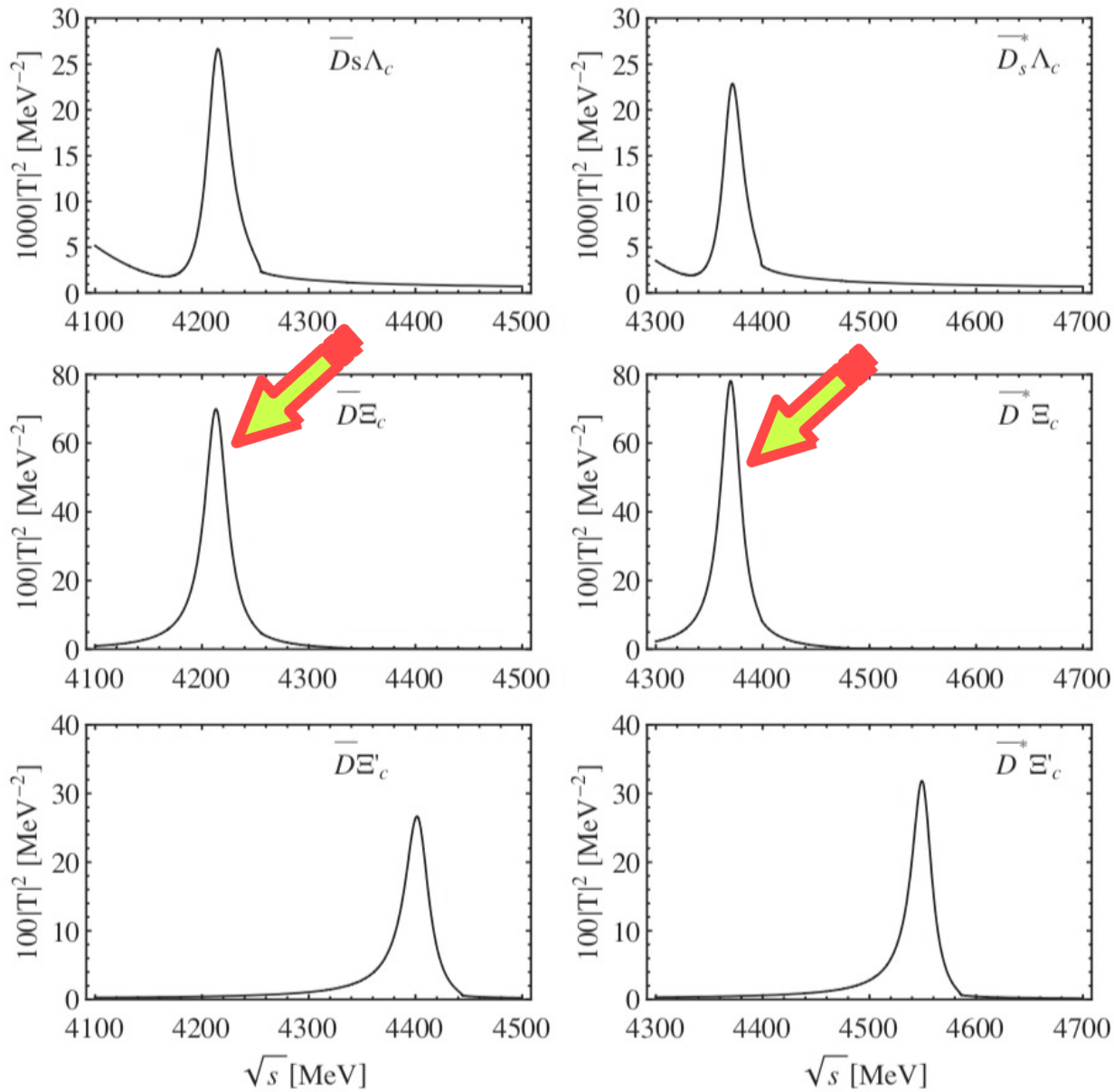
Chan.	$\eta_c \Lambda$	$J/\psi \Lambda$	$\bar{D}\Xi_c$	$\bar{D}_s \Lambda_c$	$\bar{D}\Xi'_c$	$\bar{D}^* \Xi_c$	$\bar{D}_s^* \Lambda_c$	$\bar{D}^* \Xi'_c$	$\bar{D}^* \Xi_c^*$
Thres.	4099.58	4212.58	4366.61	4254.80	4445.34	4477.92	4398.66	4586.66	4654.48
$4310.53 + i8.23$									
$ g_i $	0.15	0.27	2.33	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%	—	—	—	—	—
$4445.12 + i0.19$									
$ g_i $	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%	—	—
$4459.07 + i6.89$ $P_{cs}(4459)$									
$ g_i $	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?									
$ g_i $	—	—	—	—	—	—	—	—	—
4654.48?									
$ g_i $	—	—	—	—	—	—	—	—	—

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

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	$P_{cs}(4459)$				
$ g_i $	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?					
$ g_i $	—	—	—	—	—	—
	4513.17?					
$ g_i $	—	—	—	—	—	—
	4654.48?					
$ g_i $	—	—	—	—	—	—







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

states from $P B \rightarrow P B$. The units :

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

for the states from $V B \rightarrow V B$.

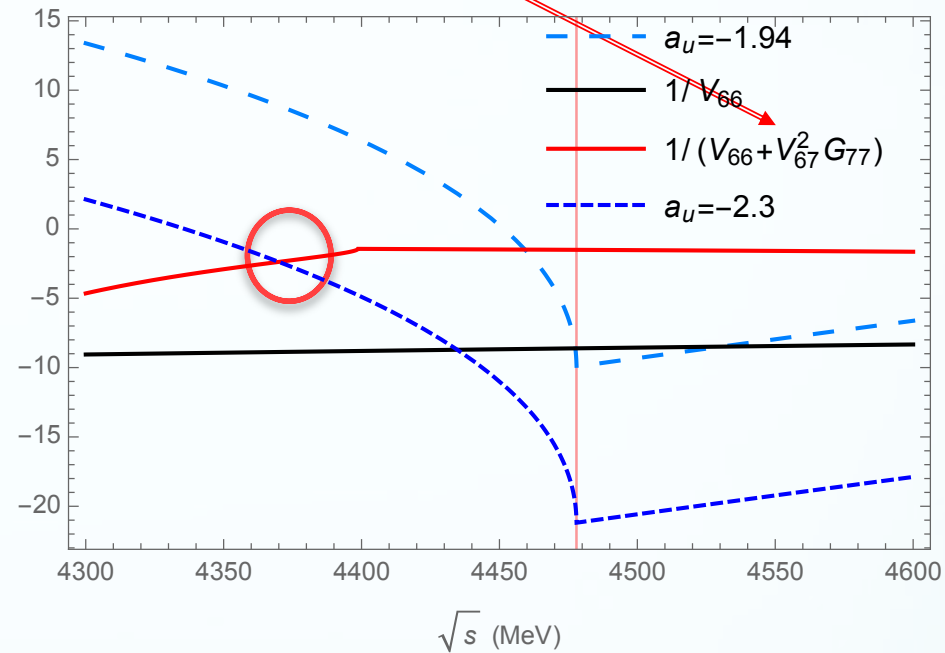
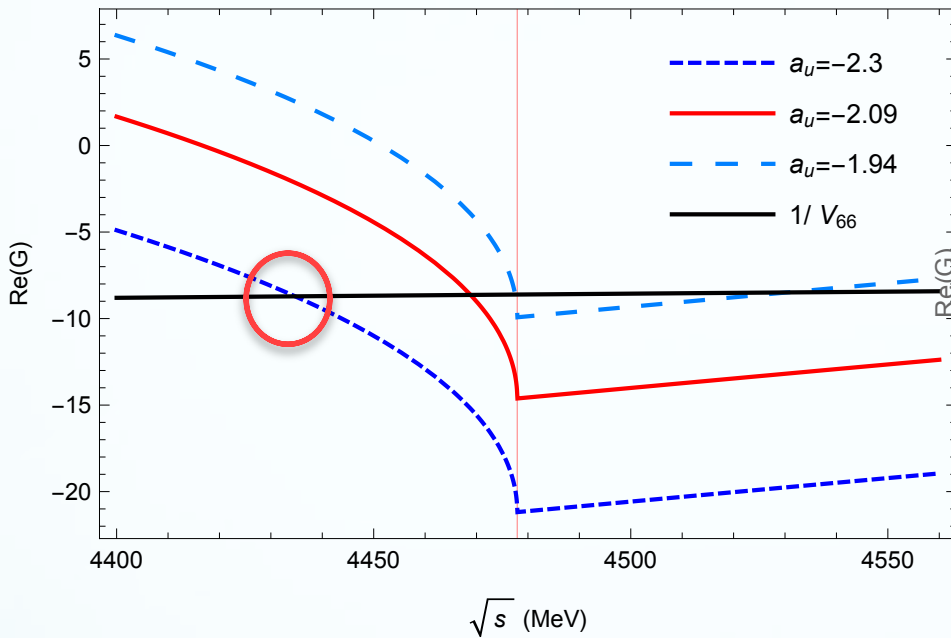
(I, S)	z_R	Real Axis	
		M	Γ
$(1/2, 0)$	4418	4416	28.4
	4370	4371	23.3
$(0, -1)$	4550	4549	23.7

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

$$\mu = 1000 \text{ MeV}$$

$$a(\mu) = -2.3$$

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



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

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

§4. Summary

- Our results of bound states —molecular states

a $\bar{D}\Xi_c$ state $\bar{D}\Xi'_c$?

Having $J = 1/2$.

a $\bar{D}\Xi_c^*$ state ?

With $J = 3/2$.

a $\bar{D}^*\Xi_c$ state $\bar{D}^*\Xi'_c$?

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

$P_{cs}(4459)$

Two states?

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!

谢谢大家！

Thanks for your attention!