第十一届 XYZ 粒子研讨会

Study of multi-quarks states with the ChUA

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  Jing-Zhi Cao , Huan-Yu Wei , Jiao-Xue Yang, Jian Sun

2026.7. 贵阳

Outline

1. Introduction
2. Formalism
3. Pentaquark states
4. Tetraquark states
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§1. Introduction

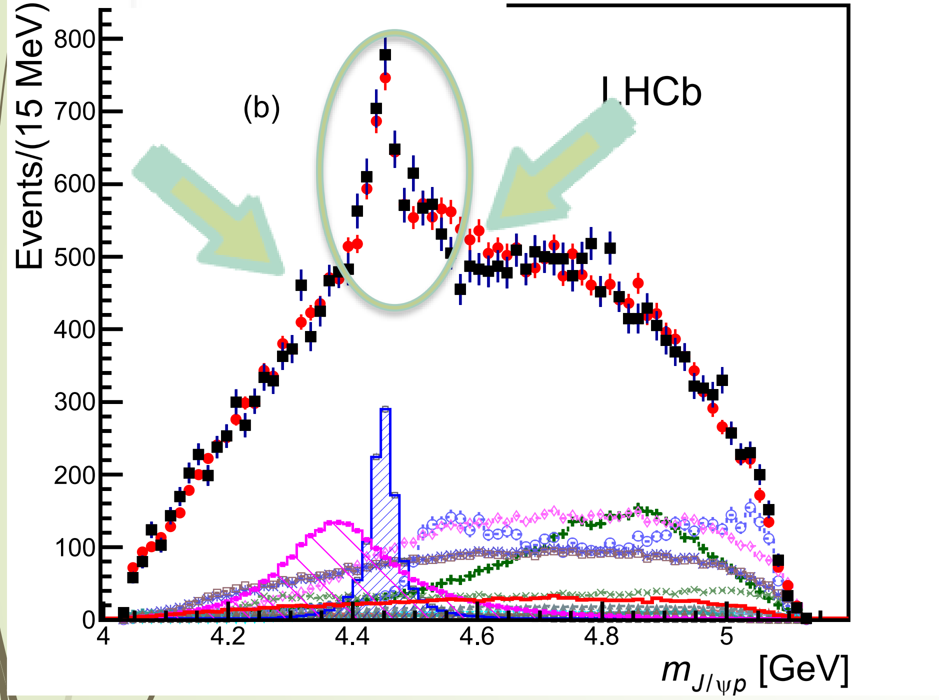
PHYSICAL REVIEW LETTERS **122,** 222001 (2019)

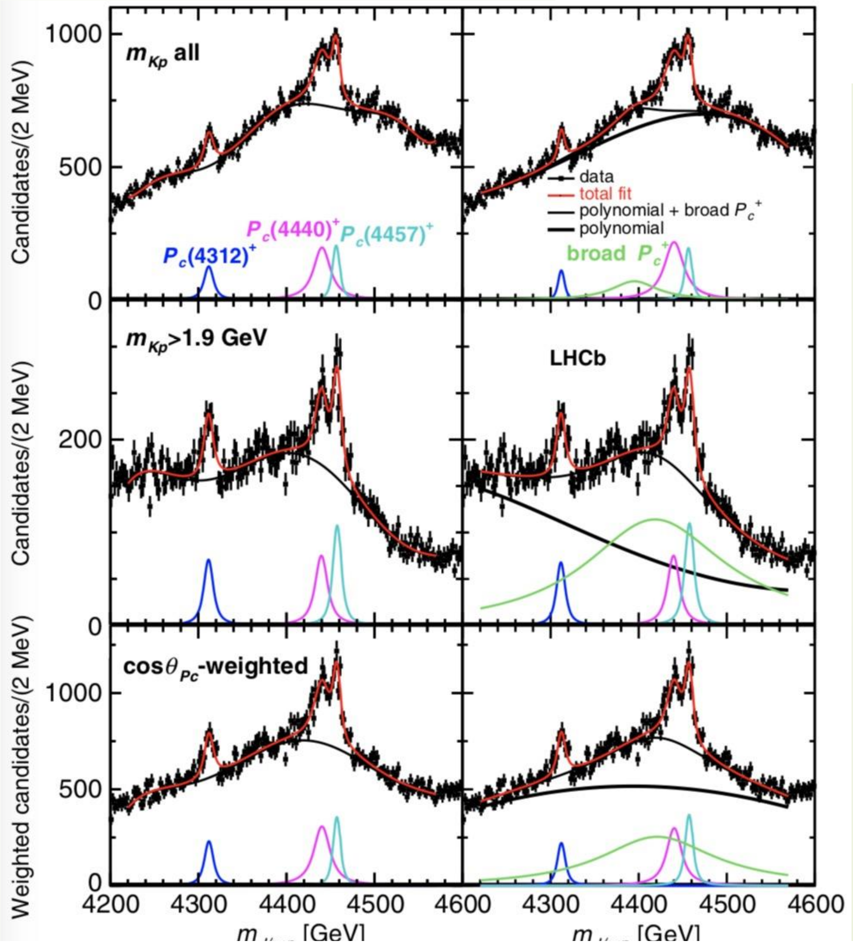
Featured in Physics

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)

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





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

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

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

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

J^P ?

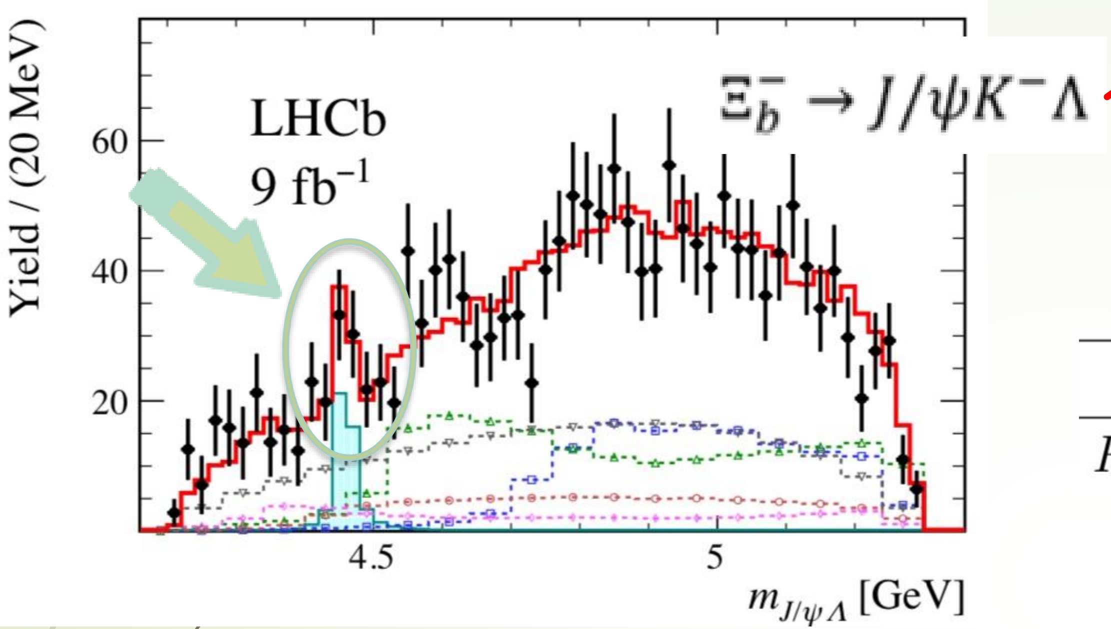
R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 115, 072001 (2015)

H.-X. Chen, W. Chen, X. Liu and S.-L. Zhu, Phys. Rept. 639, 1 (2016)
A. Esposito, A. Pilloni and A. D. Polosa, Phys. Rept. 668, 1 (2016)
A. Hosaka, T. Iijima, K. Miyabayashi, Y. Sakai and S. Yasui, PTEP 2016, 062C01 (2016)
H. X. Chen, W. Chen, X. Liu, Y. R. Liu and S. L. Zhu, Rept. Prog. Phys. 80, 076201 (2017)
R. F. Lebed, R. E. Mitchell and E. S. Swanson, Prog. Part. Nucl. Phys. 93, 143 (2017)
A. Ali, J. S. Lange and S. Stone, Prog. Part. Nucl. Phys. 97, 123 (2017)
F.-K. Guo, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao and B.-S. Zou, Rev. Mod. Phys. 90, 015004 (2018)
R. A. Bricen˜o, J. J. Dudek and R. D. Young, Rev. Mod. Phys. 90, 025001 (2018)
S. L. Olsen, T. Skwarnicki and D. Zieminska, Rev. Mod. Phys. 90, 015003 (2018)
M. Karliner, J. L. Rosner and T. Skwarnicki, Ann. Rev. Nucl. Part. Sci. 68, 17 (2018)
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, 1 (2020)

Bing-Song Zou, Sci. Bull 66, 1258 (2021)

Findings for the Pcs state

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

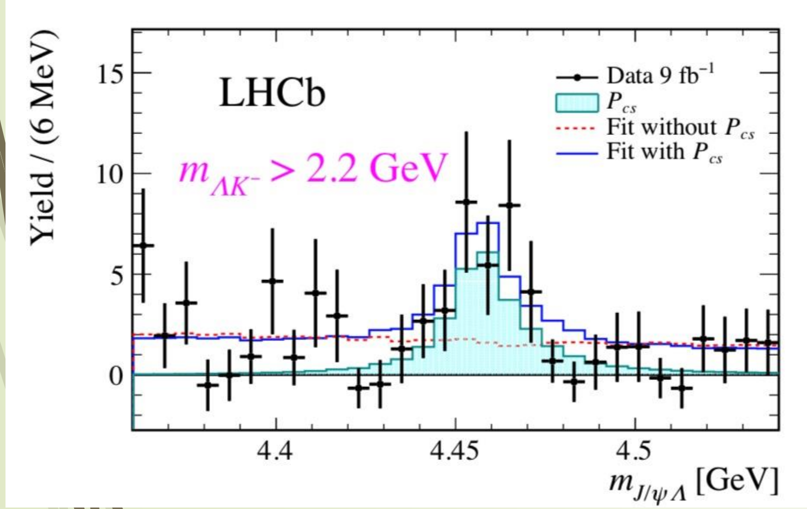


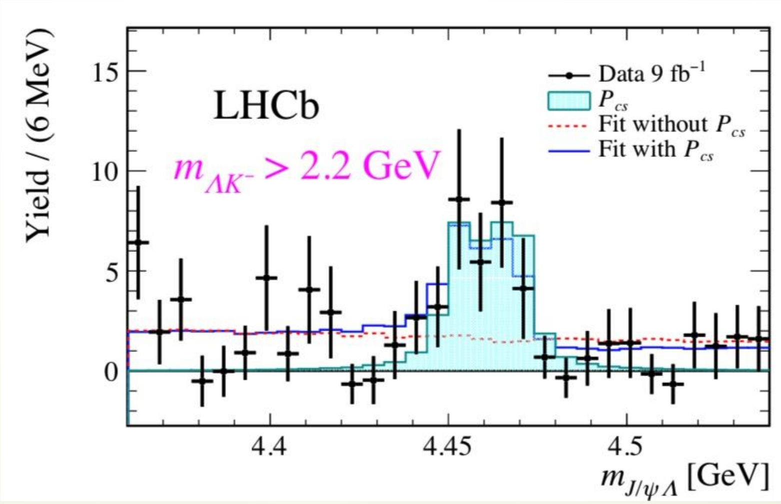
R. Aaij et al. (LHCb Collaboration), **Sci. Bull. 66** (2021) 1278-1287

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.

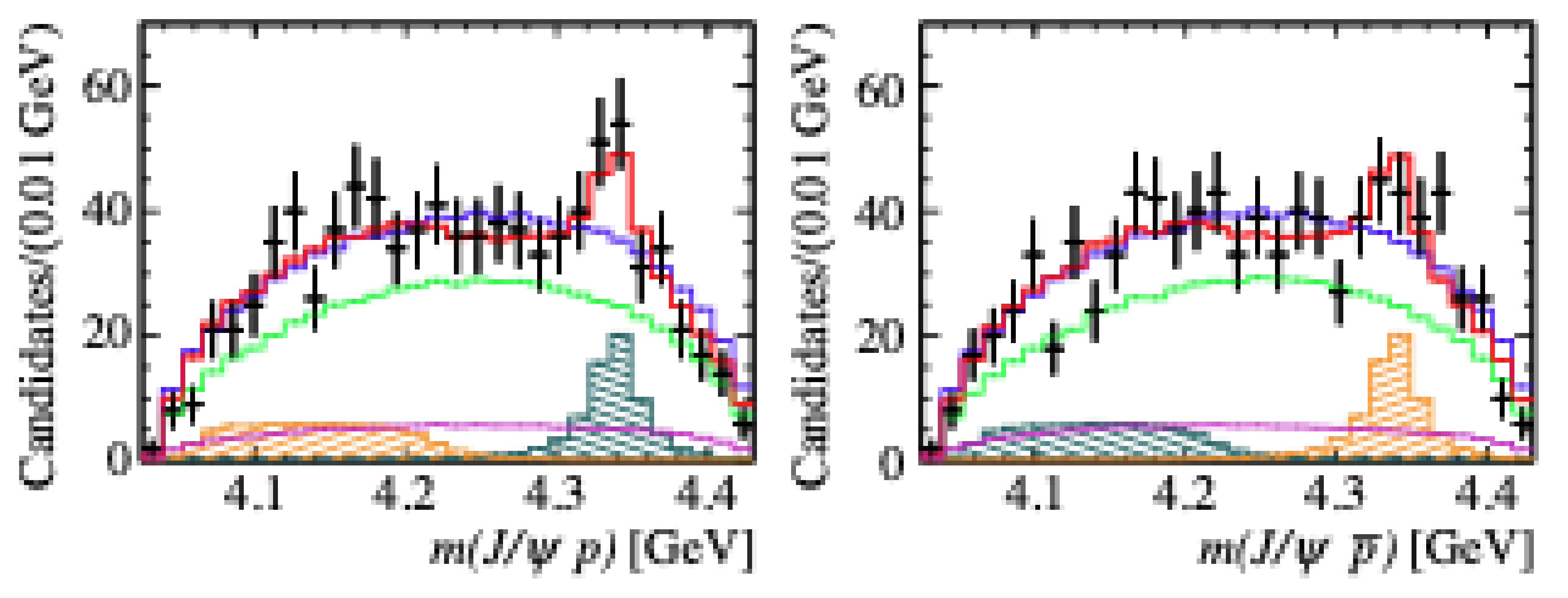
The data cannot confirm or refute the two-peak hypothesis.

PHYSICAL REVIEW LETTERS **128,** 062001 (2022)

Editors' Suggestion

Evidence for a New Structure in the $J/\psi p$ and $J/\psi\bar{p}$ Systems in $B_s^0 \to J/\psi p\bar{p}$ Decays

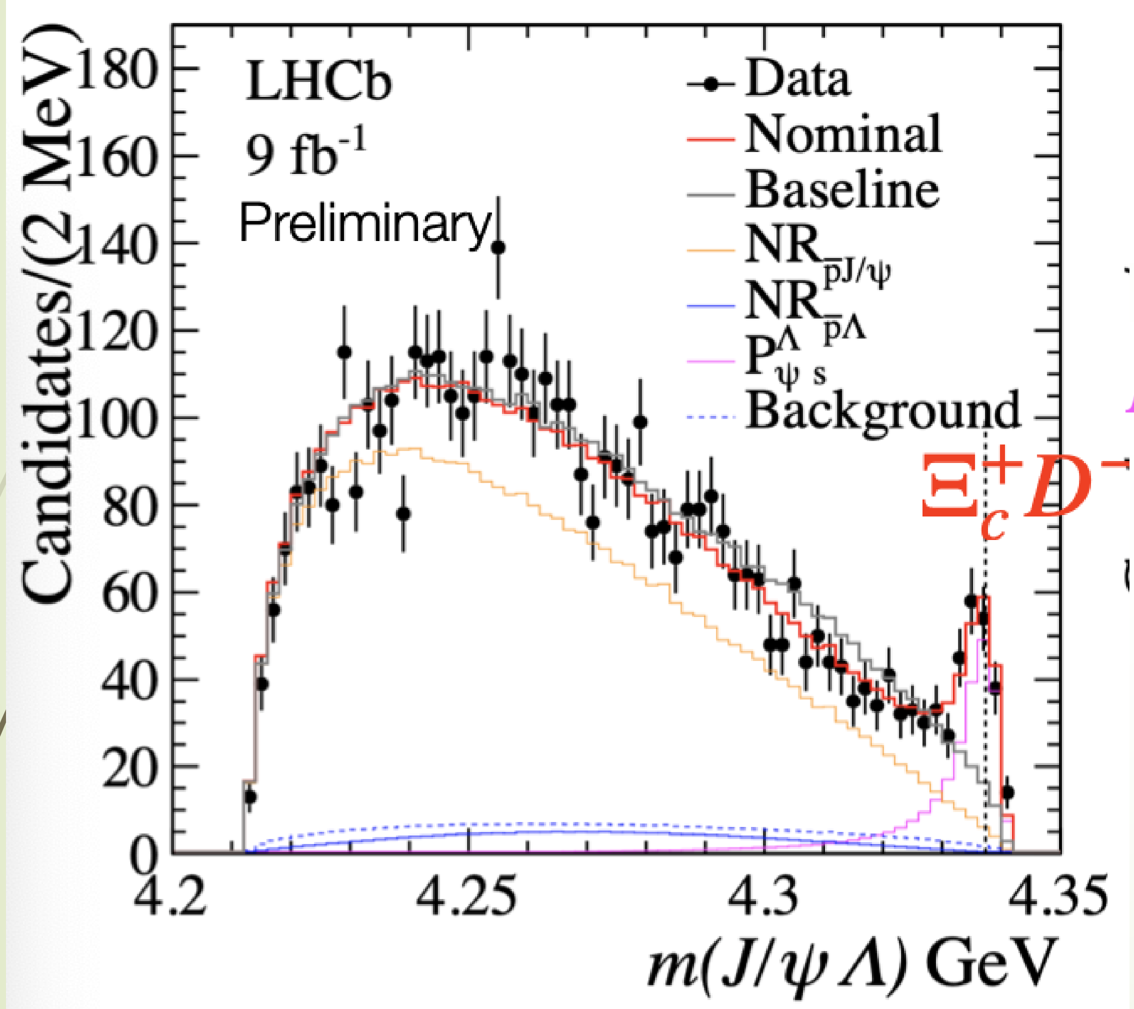
R. Aaij *et al.*[*]
(LHCb Collaboration)



$$M_{P_c} = 4337^{+7}_{-4}\,{}^{+2}_{-2}\ \text{MeV},$$

$$\Gamma_{P_c} = 29^{+26}_{-12}\,{}^{+14}_{-14}\ \text{MeV},$$

$B^- \to (J/\psi\Lambda)\bar{p}$



$m(P_{\psi s}^{\Lambda})$=4338.3±0.7±0.4 MeV

$\Gamma(P_{\psi s}^{\Lambda})$=7.0±1.2±1.3 MeV

$P_{\psi s}^{\Lambda}(4338)^0$

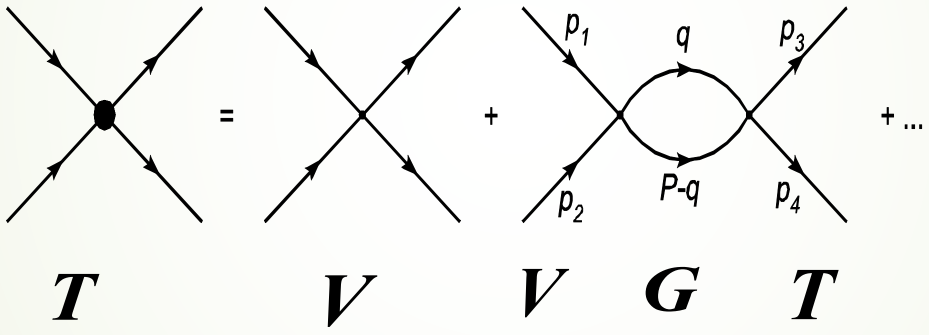
Significance: >10σ

LHCb, Phys. Rev. Lett. 131, 031901 (2023)

§2. Formalism

➨ **Coupled Channel Unitary Approach**： solving Bethe-Salpeter equations, which take on-shell approximation for the loops.

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



D. L. Yao, L. Y. Dai, H. Q. Zheng and Z. Y. Zhou, Rept. Prog. Phys. 84, 076201 (2021)

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:

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

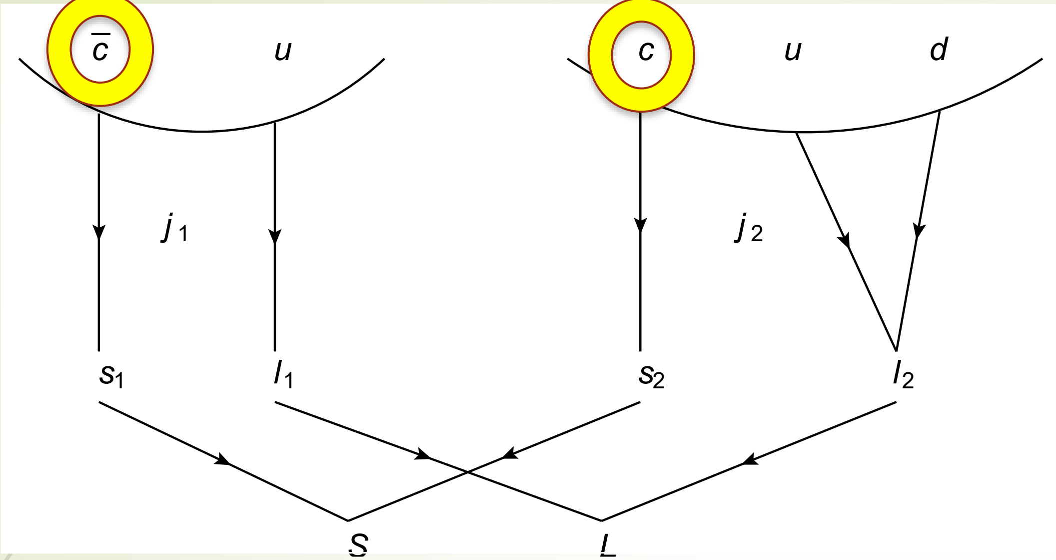
The coupled channel scattering amplitudes **T matrix satisfy the unitary**：

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

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

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 symmetry

$\bar{D} \Rightarrow \bar{D}^*$

$\Sigma_c \Rightarrow \Sigma_c^*$

$\Xi_c \Rightarrow \Xi_c^*$

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

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

X. K. Dong, F. K. Guo and B. S. Zou, *Progr. Phys.* 41 (2021) 65; *Commun. Theor. Phys.* 73 (2021) 125201.

§3. Pentaquark states

Pcs states

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.

Bing-Song Zou, Sci. Bull 66, 1258 (2021)

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

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

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	4336.61	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%	–	–

$P_{\psi s}^{\Lambda}(4338)^0$

F. L. Wang and X. Liu, **Phys. Lett. B 835,** 137583 (2022).

X.-W. Wang, Z.-G. Wang, Chin. Phys. C 47 (2023) 013109
L. Meng, B. Wang, S.-L. Zhu, Phys. Rev. D 107 (2023) 014005
J.-T. Zhu, S.-Y. Kong, J. He, Phys. Rev. D 107 (2023) 3, 034029

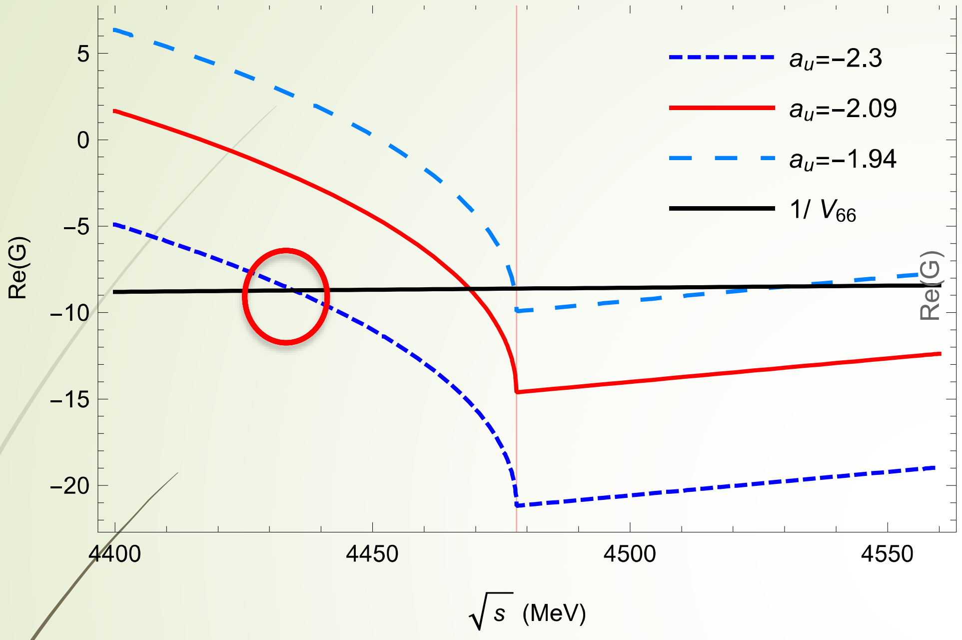
$P_{cs}(4459)$

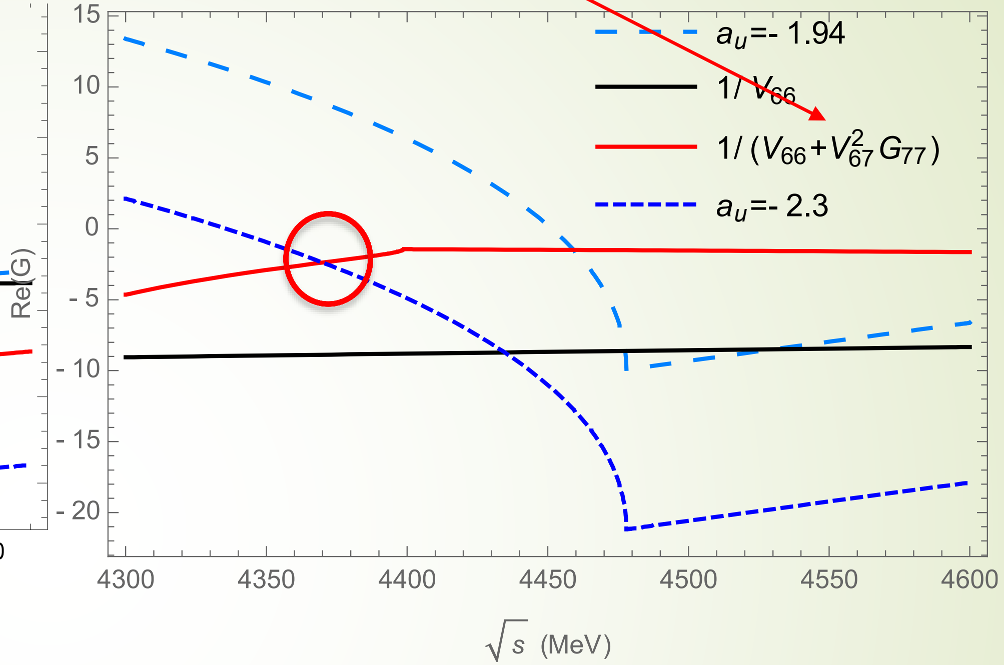
- $J = 3/2,\ I = 0$

H.-X. Chen, W. Chen, X. Liu, X.-H. Liu, Eur. Phys. J. C 81 (2021) 409
K. Azizi, Y. Sarac, H. Sundu, Phys. Rev. D 103 (2021) 094033
F.-Z. Peng, M.-J. Yan, M. Sánchez Sánchez, M.P. Valderrama, Eur. Phys. J. C 81 (2021) 666
R. Chen, Phys. Rev. D 103 (2021) 054007
M.-Z. Liu, Y.-W. Pan, L.-S. Geng, Phys. Rev. D 103 (2021) 034003
W.-Y. Liu, W. Hao, G.-Y. Wang, Y.-Y. Wang, E. Wang, D.-M. Li, Phys. Rev. D 103 (2021) 034019

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

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





	$J/\psi\Lambda$	$\bar{D}_s^*\Lambda_c$	$\bar{D}^*\Xi_c$	$\bar{D}^*\Xi_c'$
$J/\psi\Lambda$	0	$-\frac{1}{\sqrt{3}}\lambda$	$\frac{1}{\sqrt{6}}\lambda$	$-\frac{1}{\sqrt{2}}\lambda$
$\bar{D}_s^*\Lambda_c$		0	$-\sqrt{2}$	0
$\bar{D}^*\Xi_c$			-1	0
$\bar{D}^*\Xi_c'$				-1

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

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

Noting the results for Pc

$$
\begin{array}{ccccccc}
\eta_c N & J/\psi N & \bar{D}\Lambda_c & \bar{D}\Sigma_c & \bar{D}^*\Lambda_c & \bar{D}^*\Sigma_c & \bar{D}^*\Sigma_c^* \\
\end{array}
$$

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

$$
\mu_1 = 0, \quad \mu_{23} = 0, \quad \lambda_2 = \mu_3, \quad \mu_{13} = -\mu_{12},
$$

$$
\mu_2 = \frac{1}{4f^2}(k^0 + k'^0), \quad \mu_3 = -\frac{1}{4f^2}(k^0 + k'^0),
$$

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

Recalling the results in Pc states

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	$\bar{D}^*\Sigma_c$	$3/2^-$	$P_c(4457)$

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

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

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

$$M_{P_{c2}} = 4440.3 \pm 1.3^{+4.1}_{-4.7},$$

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

$P_c : \bar{D}\Sigma_c, \bar{D}\Lambda_c$ and $\bar{D}^*\Sigma_c, \bar{D}^*\Lambda_c$

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

Further investigation

$PB(1/2^+)$ sector with $J^P = \frac{1}{2}^-$

Poles		$\eta_c \Lambda$	$\bar{D}_s \Lambda_c$	$\bar{D}\Xi_c$	$\bar{D}\Xi_c'$
$\boxed{4198.94 + i0.11}$	g_i	$0.12 - i0.00$	$3.01 - i0.01$	**4.85+i0.01**	$0.01 - i0.03$
	$g_i G_i^{II}$	$-0.35 + i1.01$	$-19.24 + i0.05$	**−20.35−i0.07**	$-0.03 + i0.09$
$4422.79 + i7.75$	g_i	$0.71 - i0.08$	$0.05 + i0.00$	$-0.06 + i0.04$	**2.79−i0.35**
	$g_i G_i^{II}$	$1.14 + i10.71$	$0.76 + i1.82$	$-0.43 - i1.53$	**−26.54+i0.64**

$P_{cs}(4459)$

$VB(1/2^+)$ sector with $J^P = \frac{1}{2}^-, \frac{3}{2}^-$

Poles		$J/\psi \Lambda$	$\bar{D}_s^* \Lambda_c$	$\bar{D}^*\Xi_c$	$\bar{D}^*\Xi_c'$
$\boxed{4337.98 + i0.12}$	g_i	$0.11 - i0.00$	$3.17 - i0.01$	**5.07+i0.01**	$0.00 - i0.04$
	$g_i G_i^{II}$	$-0.13 + i1.07$	$-18.57 + i0.06$	**−19.94−i0.07**	$-0.01 + i0.10$
$4565.73 + i15.58$	g_i	$0.70 - i0.16$	$0.09 - i0.03$	$-0.10 + i0.09$	**2.84−i0.72**
	$g_i G_i^{II}$	$6.24 + i21.04$	$2.07 + i3.40$	$-1.37 - i2.81$	**−26.31+i1.15**

$P_{\psi s}^{\Lambda}(4338)^0$

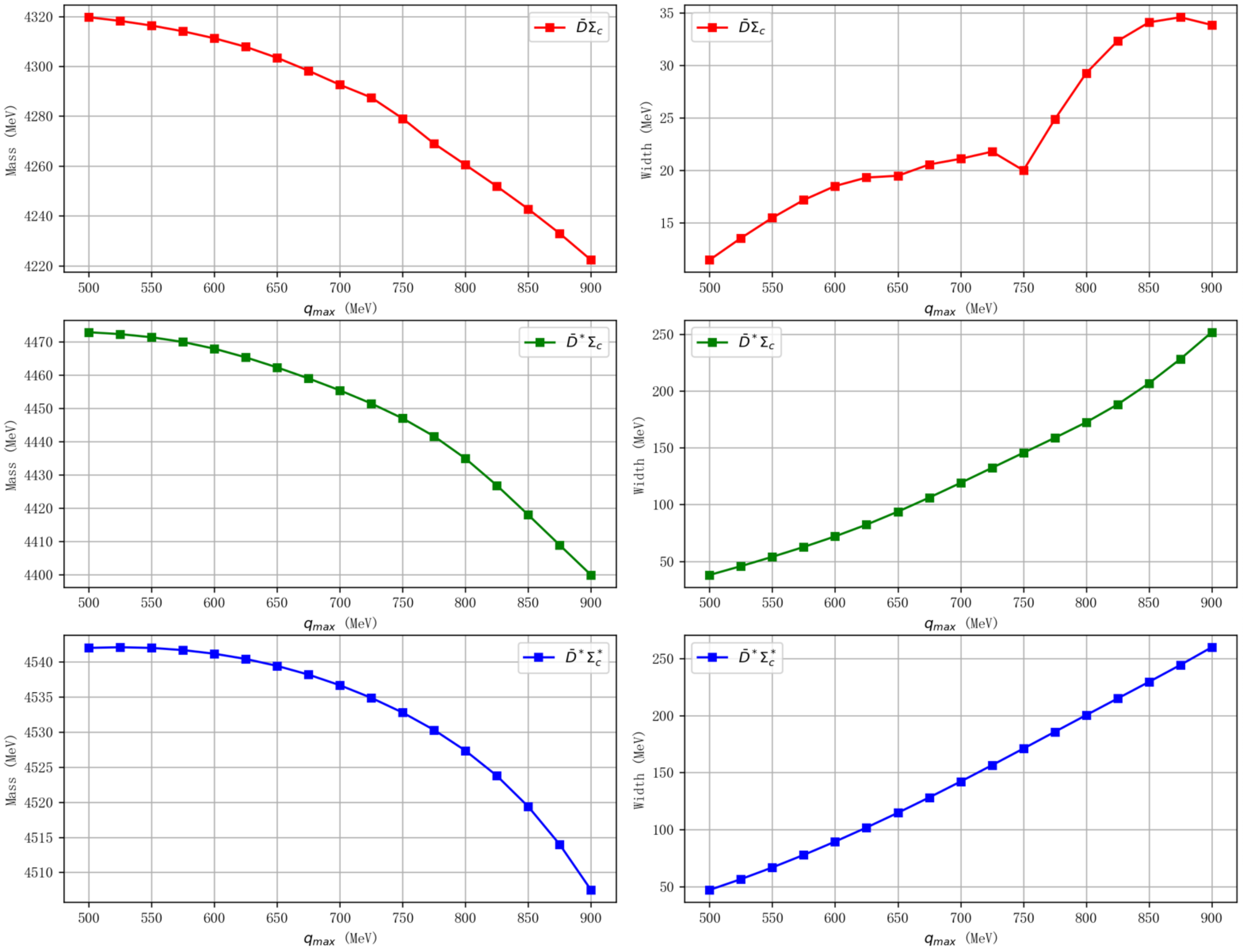
$P_c : \bar{D}\Sigma_c, \bar{D}\Lambda_c$ and $\bar{D}^*\Sigma_c, \bar{D}^*\Lambda_c$

$\cancel{P_{cs} : \bar{D}\Xi_c, \bar{D}_s\Lambda_c \text{ and } \bar{D}^*\Xi_c, \bar{D}_s^*\Lambda_c}$

A. Feijoo, W. F. Wang, **CWX**, J. J. Wu, E. Oset, J. Nieves, B. S. Zou, Phys. Lett. B 839 (2023) 137760

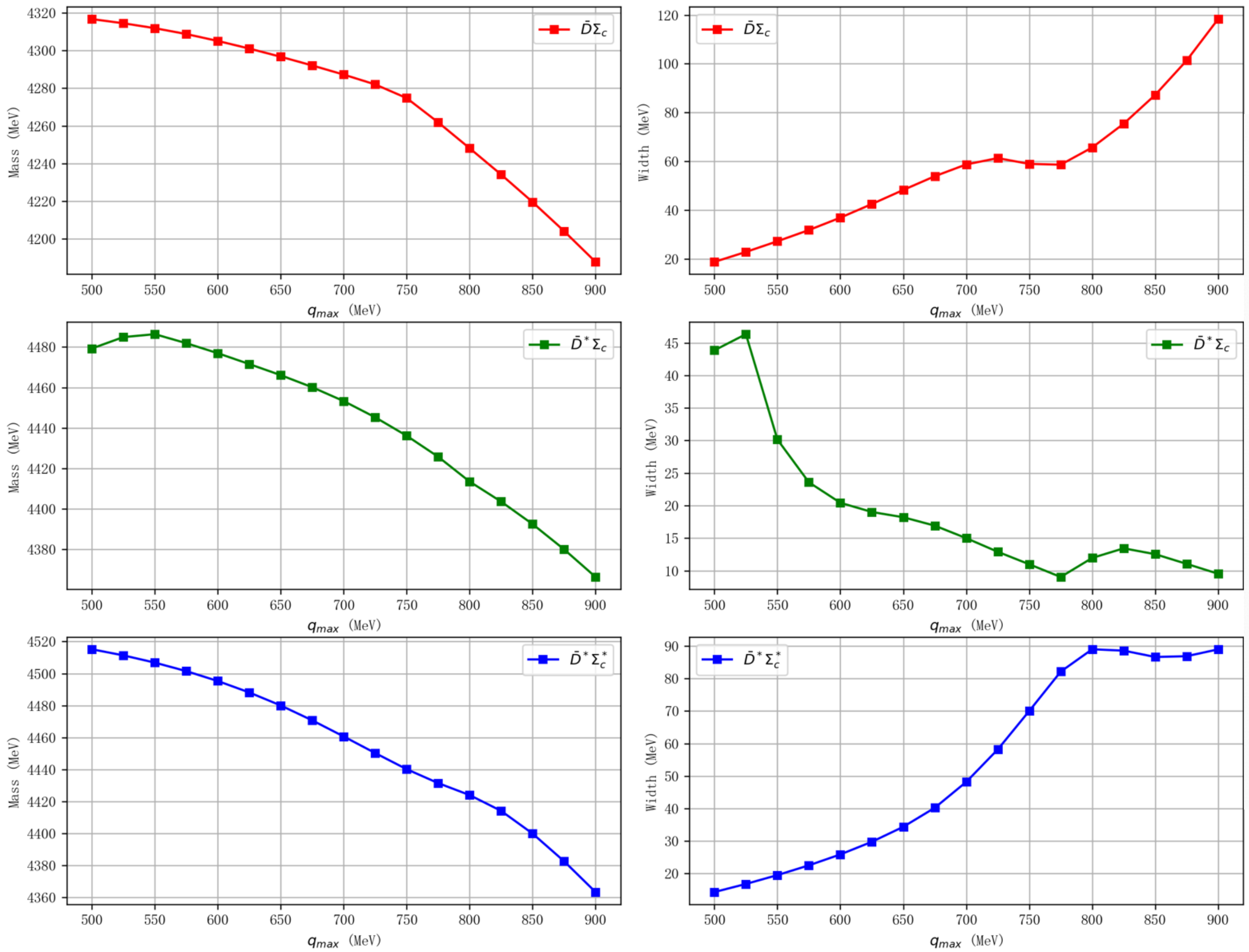
Further Results-1

(1) $J^P = 1/2^-$ Pc poles: full coupled channels



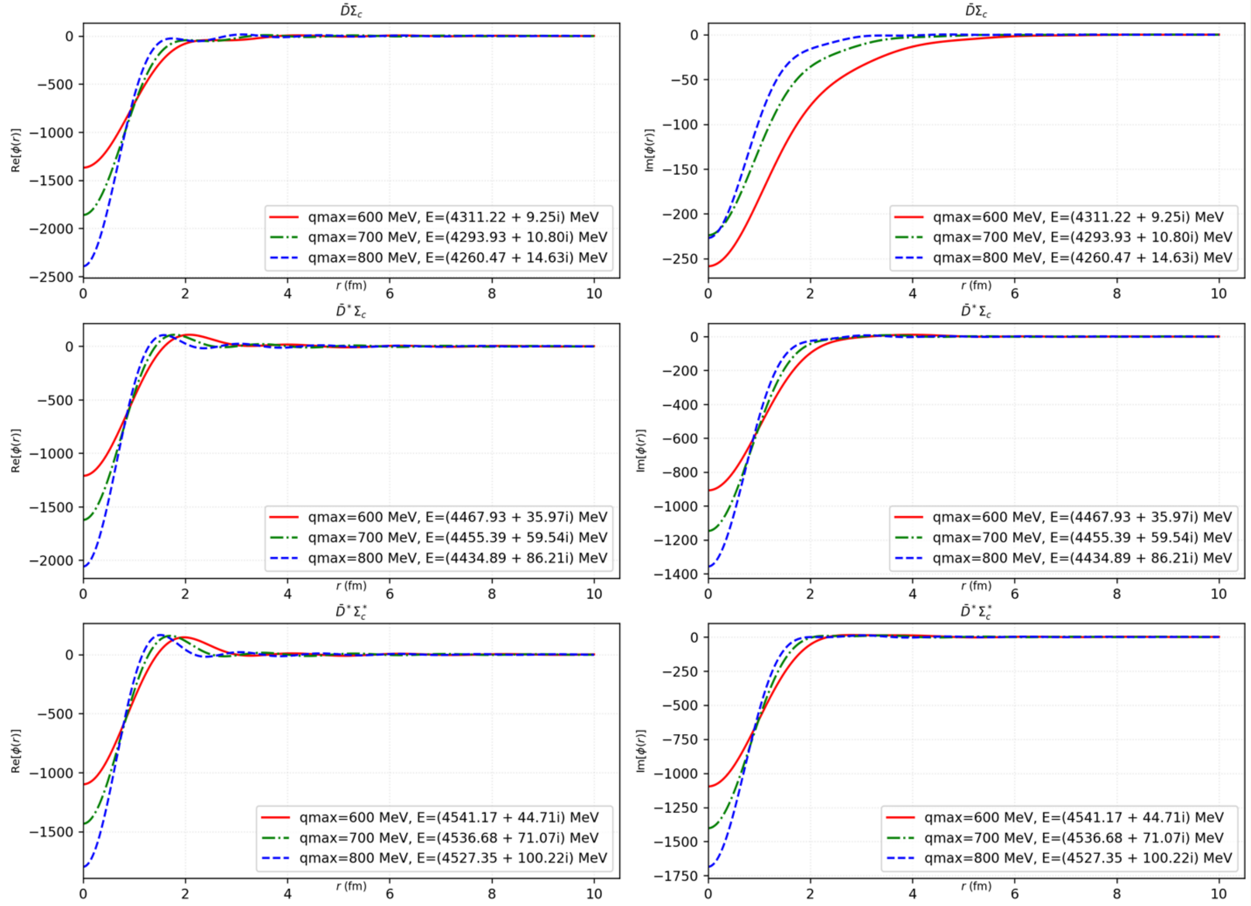
q_{max} [MeV]	Mass [MeV]	Width [MeV]	Main channel	J^P	Experimental states
600	4311.22	18.50	$\bar{D}\Sigma_c$	$1/2^-$	$P_c(4312)$
700	4293.93	21.60	$\bar{D}\Sigma_c$	$1/2^-$	
800	4260.47	29.26	$\bar{D}\Sigma_c$	$1/2^-$	
600	4467.93	71.95	$\bar{D}^*\Sigma_c$	$1/2^-$	
700	4455.39	119.08	$\bar{D}^*\Sigma_c$	$1/2^-$	$P_c(4440)$
800	4434.89	172.42	$\bar{D}^*\Sigma_c$	$1/2^-$	
600	4541.17	89.41	$\bar{D}^*\Sigma_c^*$	$1/2^-$	–
700	4536.68	142.14	$\bar{D}^*\Sigma_c^*$	$1/2^-$	–
800	4527.35	200.45	$\bar{D}^*\Sigma_c^*$	$1/2^-$	–

Pc poles : PB and VB sectors

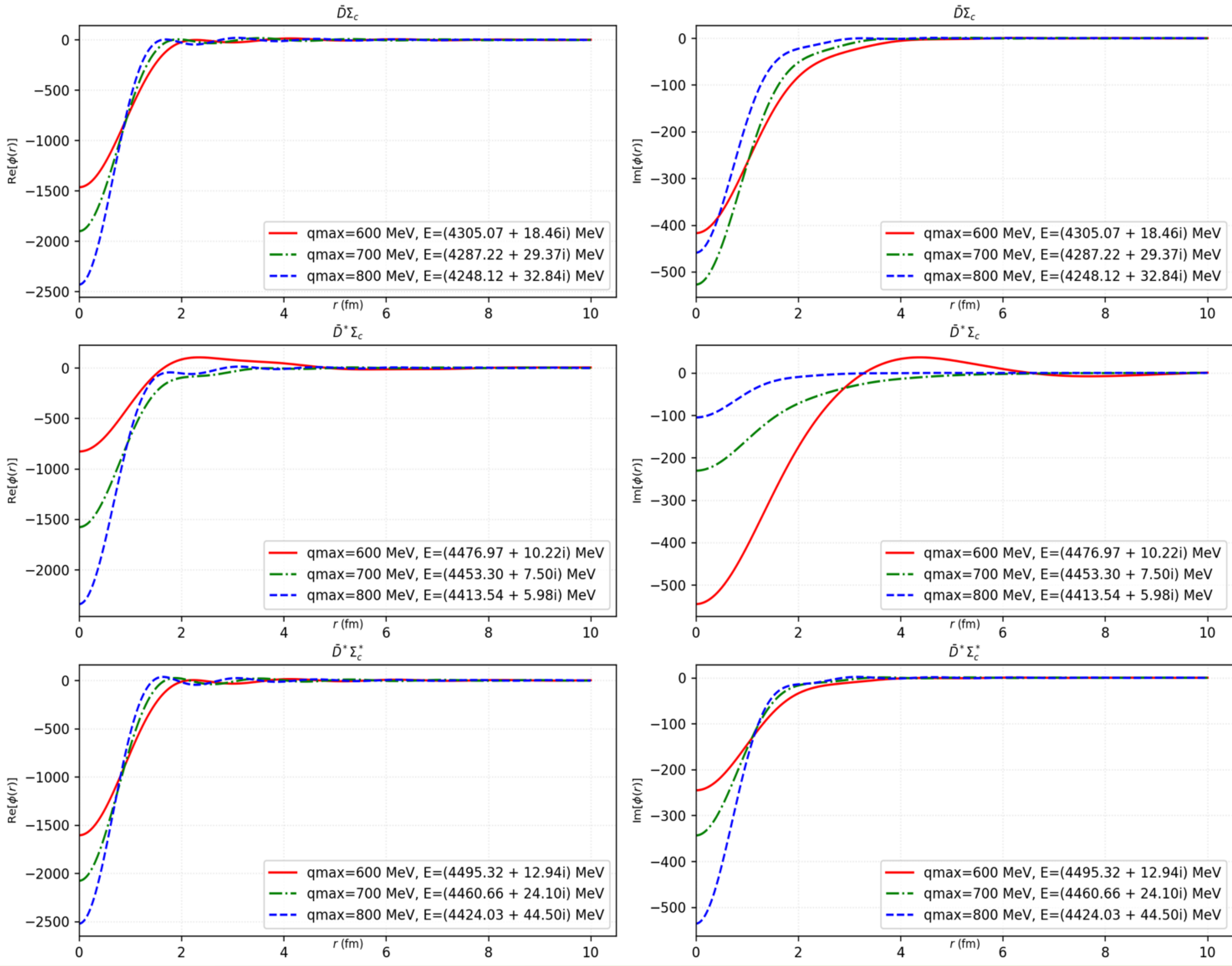


q_{max} [MeV]	Mass [MeV]	Width [MeV]	Main channel	Sector	J^P	Experimental states
600	4305.07	36.92	$\bar{D}\Sigma_c$	PB	$1/2^-$	$P_c(4312)$
700	4287.22	58.75	$\bar{D}\Sigma_c$	PB	$1/2^-$	
800	4248.12	65.69	$\bar{D}\Sigma_c$	PB	$1/2^-$	
600	4476.97	20.44	$\bar{D}^*\Sigma_c$	VB	$1/2^-$	
700	4453.30	15.00	$\bar{D}^*\Sigma_c$	VB	$1/2^-$	$P_c(4440)$
800	4413.54	11.96	$\bar{D}^*\Sigma_c$	VB	$1/2^-$	
600	4495.32	25.88	$\bar{D}^*\Sigma_c^*$	VB	$1/2^-$	–
700	4460.66	48.19	$\bar{D}^*\Sigma_c^*$	VB	$1/2^-$	–
800	4424.03	89.01	$\bar{D}^*\Sigma_c^*$	VB	$1/2^-$	–

(2) Pc wave functions : full coupled channels

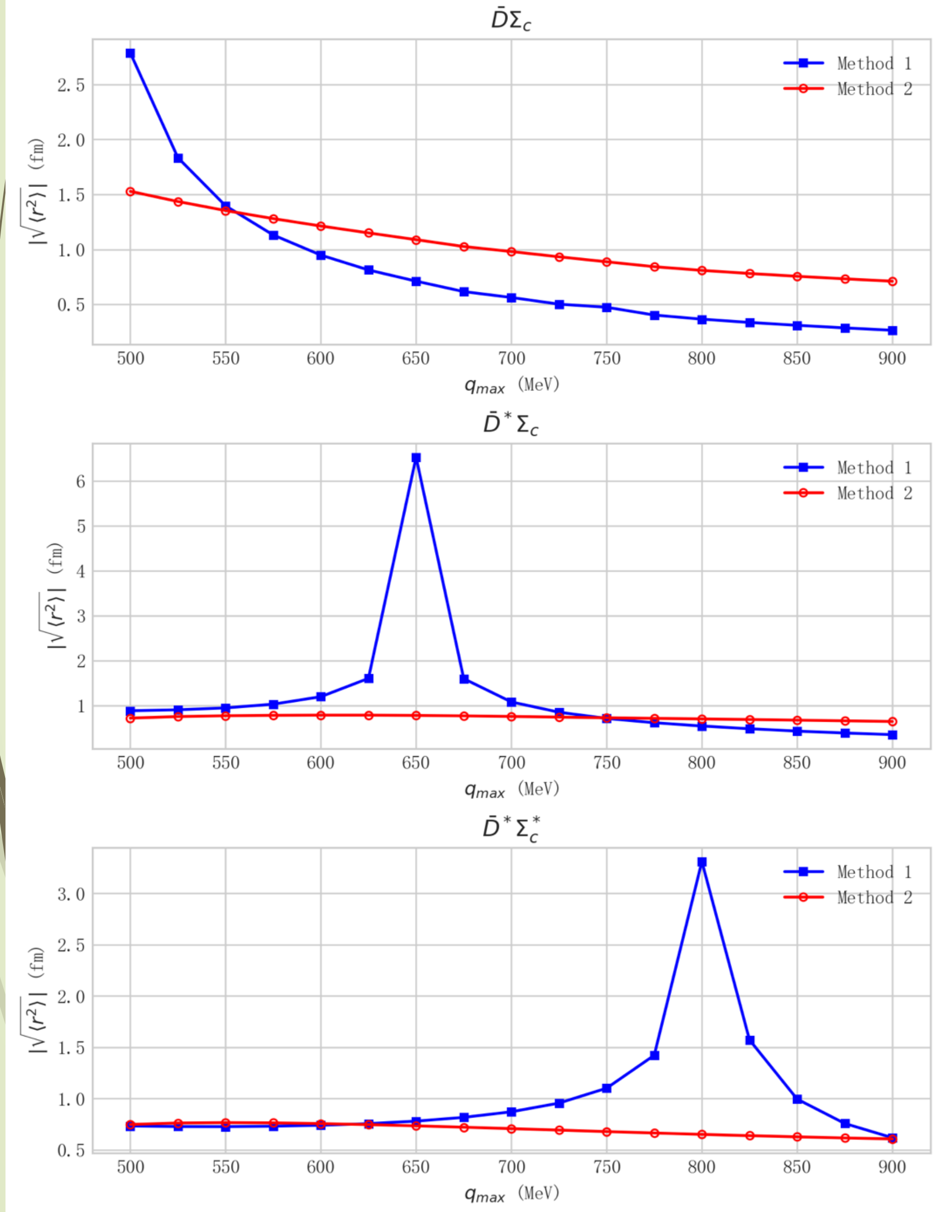


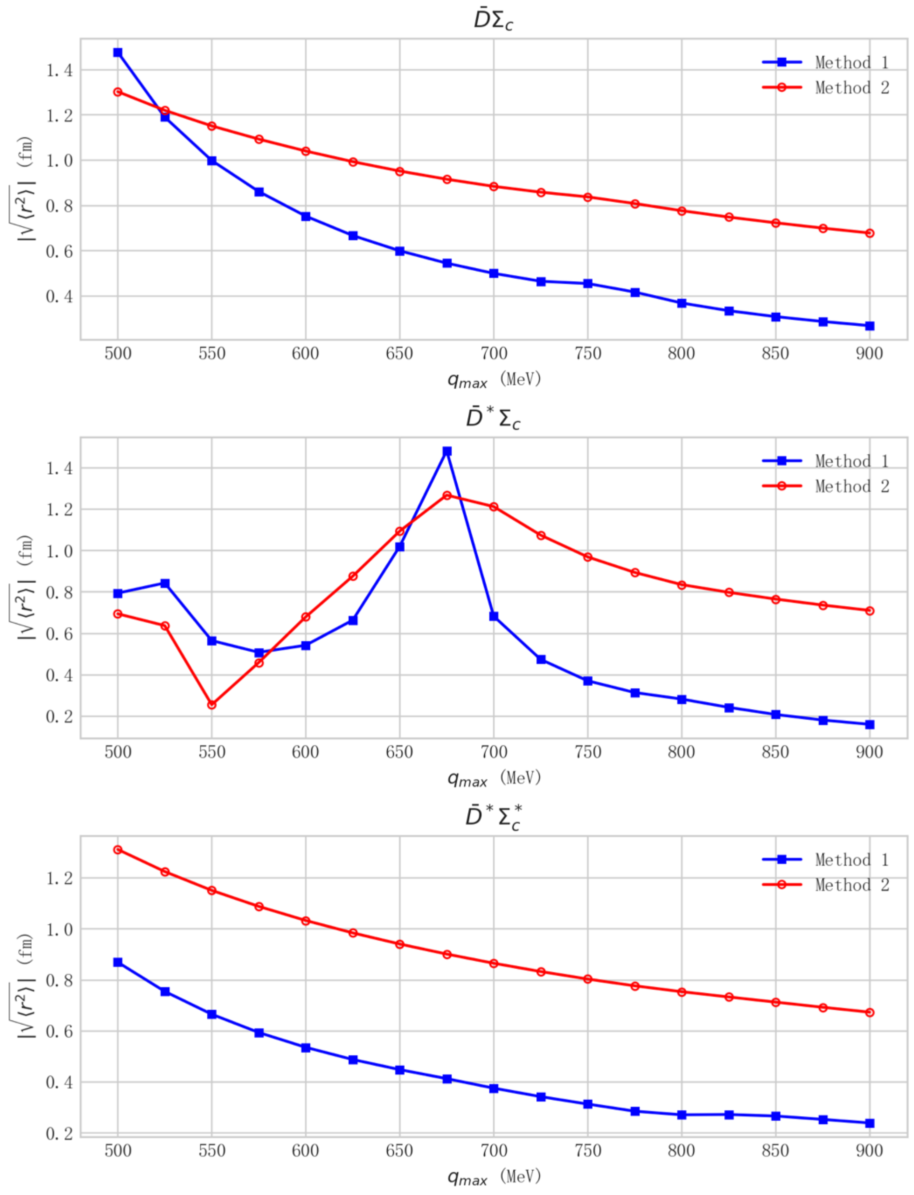
PB and VB sectors



(3) Pc radii: full coupled channels

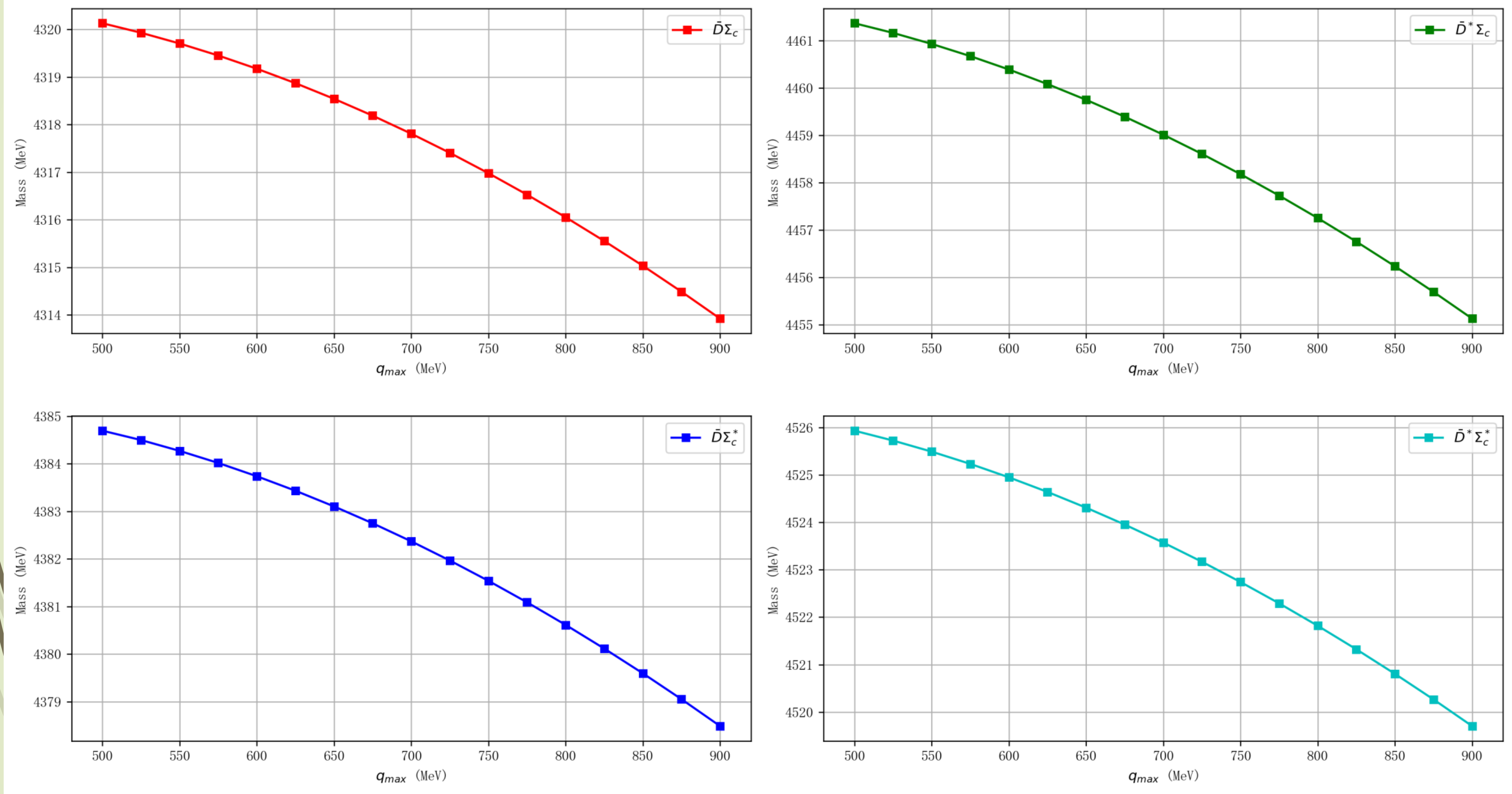
PB and VB sectors



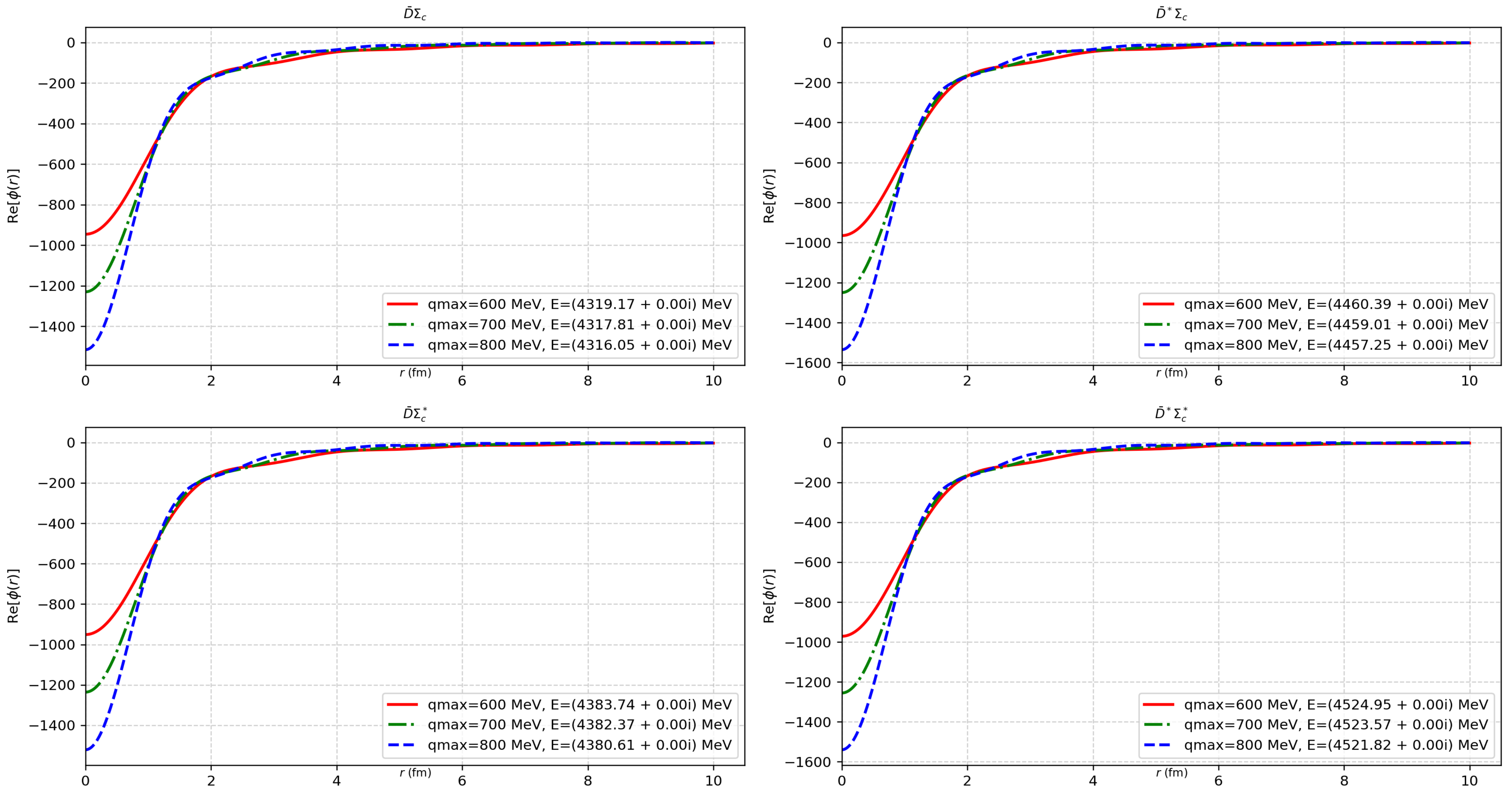


(4) Single *channel interaction* poles:

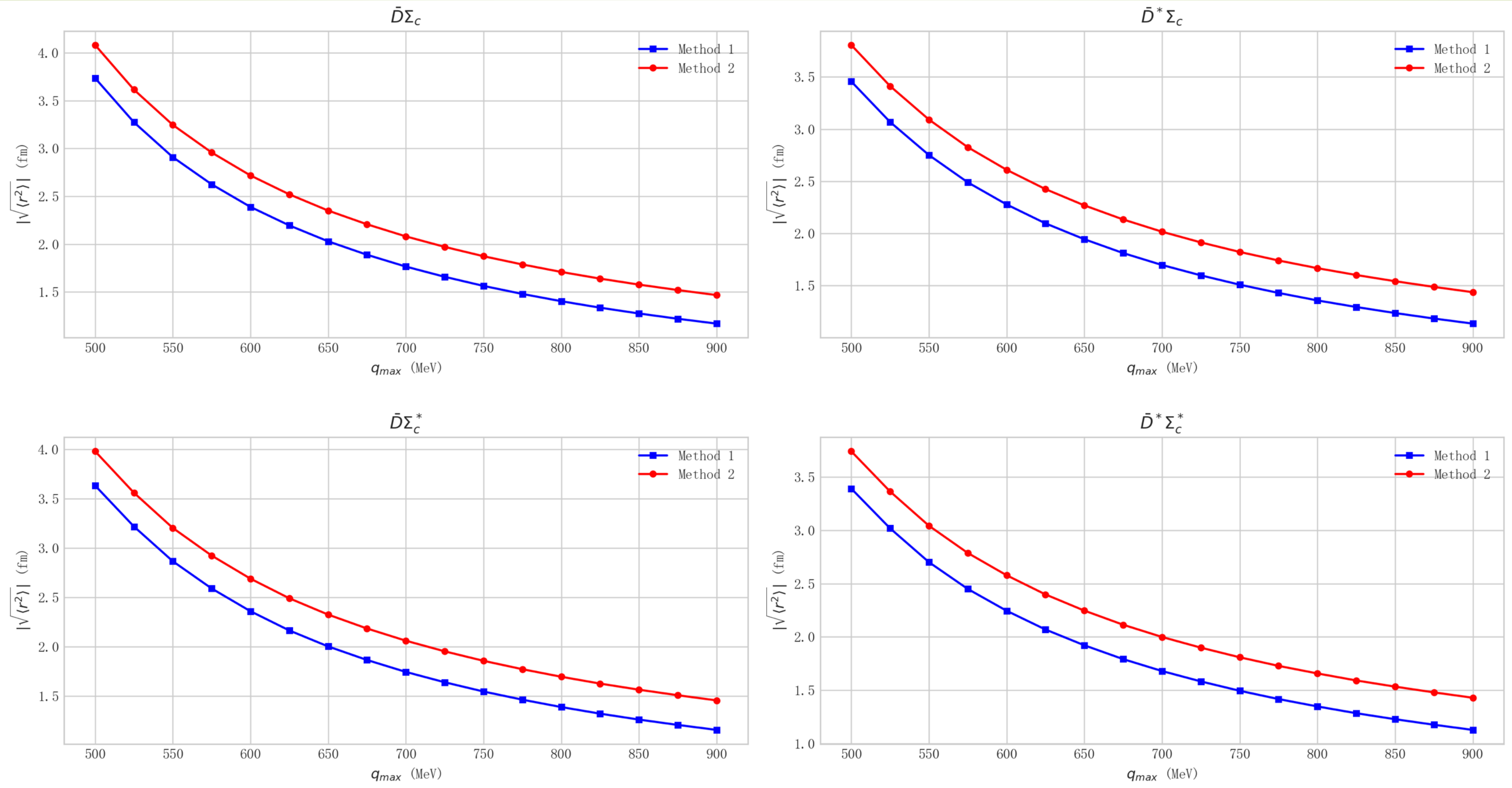
$J^P = 3/2^-$ ***Pc states***



Wave functions:

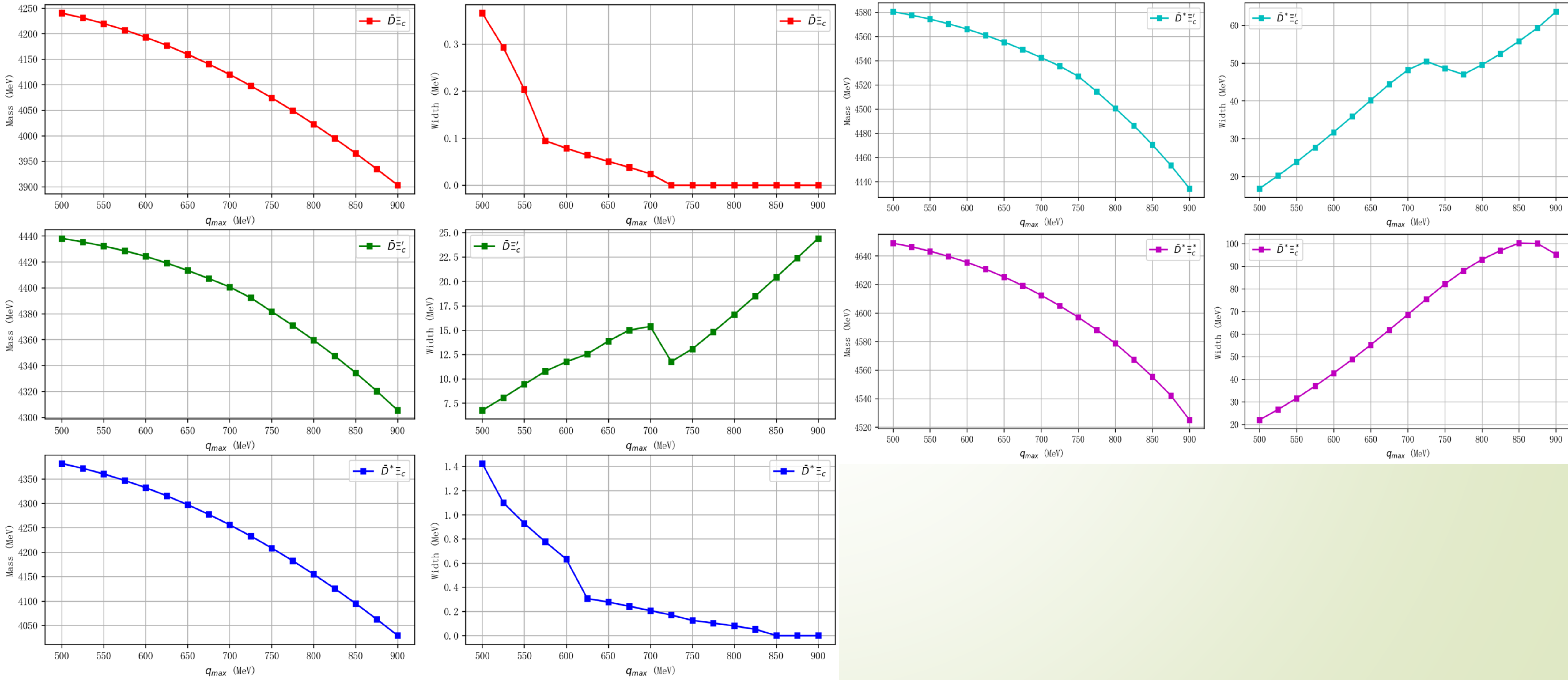


Radii:


$\bar{D}\Sigma_c$
$\bar{D}^*\Sigma_c$
$\bar{D}\Sigma_c^*$
$\bar{D}^*\Sigma_c^*$
Method 1
Method 2
$|\sqrt{\langle r^2 \rangle}|$ (fm)
q_{max} (MeV)
500 550 600 650 700 750 800 850 900
1.0 1.5 2.0 2.5 3.0 3.5 4.0

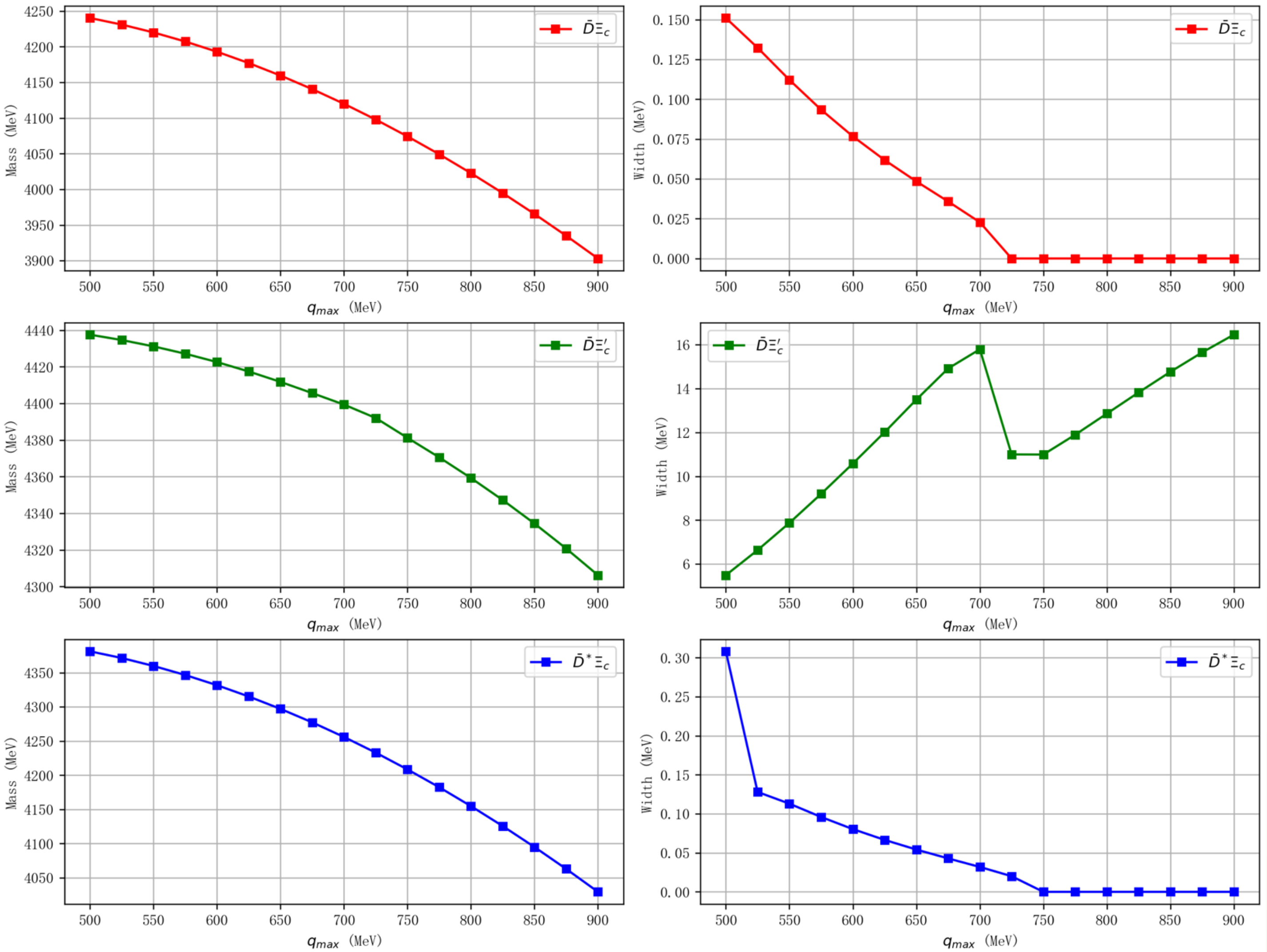
Further Results-2

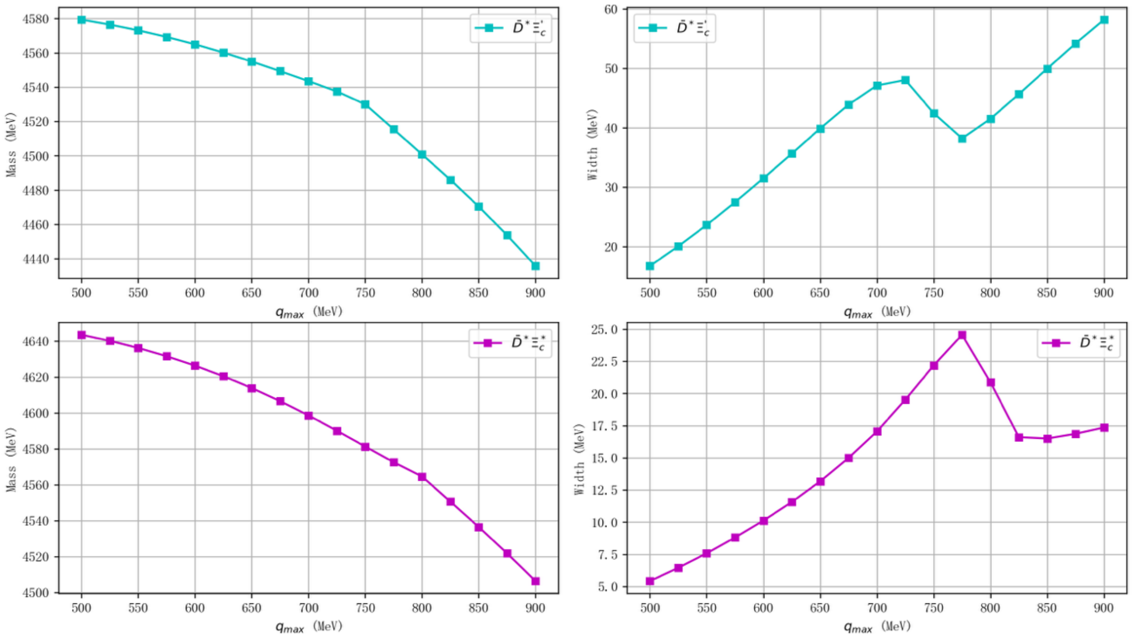
(1) $J^P = 1/2^-$ Pcs poles: full coupled channels



q_{max} [MeV]	Mass [MeV]	Width [MeV]	Main channel	J^P	Experimental states
600	4192.91	0.08	$\bar{D}\Xi_c$	$1/2^-$	–
700	4119.91	0.02	$\bar{D}\Xi_c$	$1/2^-$	–
800	4022.66	0.00	$\bar{D}\Xi_c$	–	
600	4331.89	0.63	$\bar{D}^*\Xi_c$	$1/2^-$	$P_{cs}(4338)$
700	4255.98	0.21	$\bar{D}^*\Xi_c$	$1/2^-$	–
800	4154.76	0.08	$\bar{D}^*\Xi_c$	$1/2^-$	–
600	4424.27	11.75	$\bar{D}\Xi_c'$	$1/2^-$	$P_{cs}(4459)$
700	4400.58	15.38	$\bar{D}\Xi_c'$	$1/2^-$	–
800	4359.59	16.61	$\bar{D}\Xi_c'$	$1/2^-$	–
600	4565.96	31.73	$\bar{D}^*\Xi_c'$	$1/2^-$	–
700	4542.46	48.20	$\bar{D}^*\Xi_c'$	$1/2^-$	–
800	4500.58	49.56	$\bar{D}^*\Xi_c'$	$1/2^-$	–
600	4635.46	42.75	$\bar{D}^*\Xi_c^*$	$1/2^-$	–
700	4612.43	68.66	$\bar{D}^*\Xi_c^*$	$1/2^-$	–
800	4578.71	93.02	$\bar{D}^*\Xi_c^*$	$1/2^-$	–

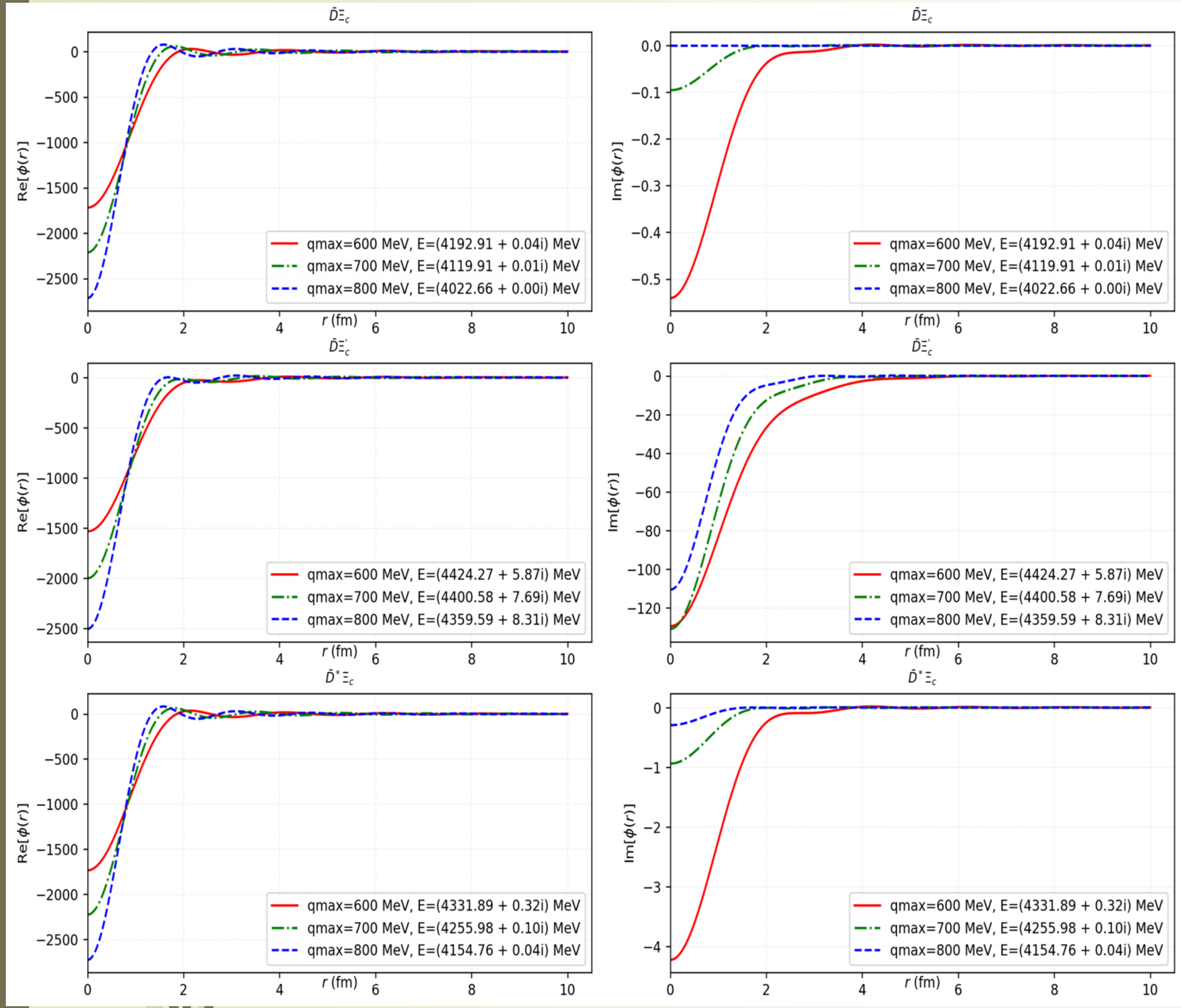
Pcs poles : PB and VB sectors

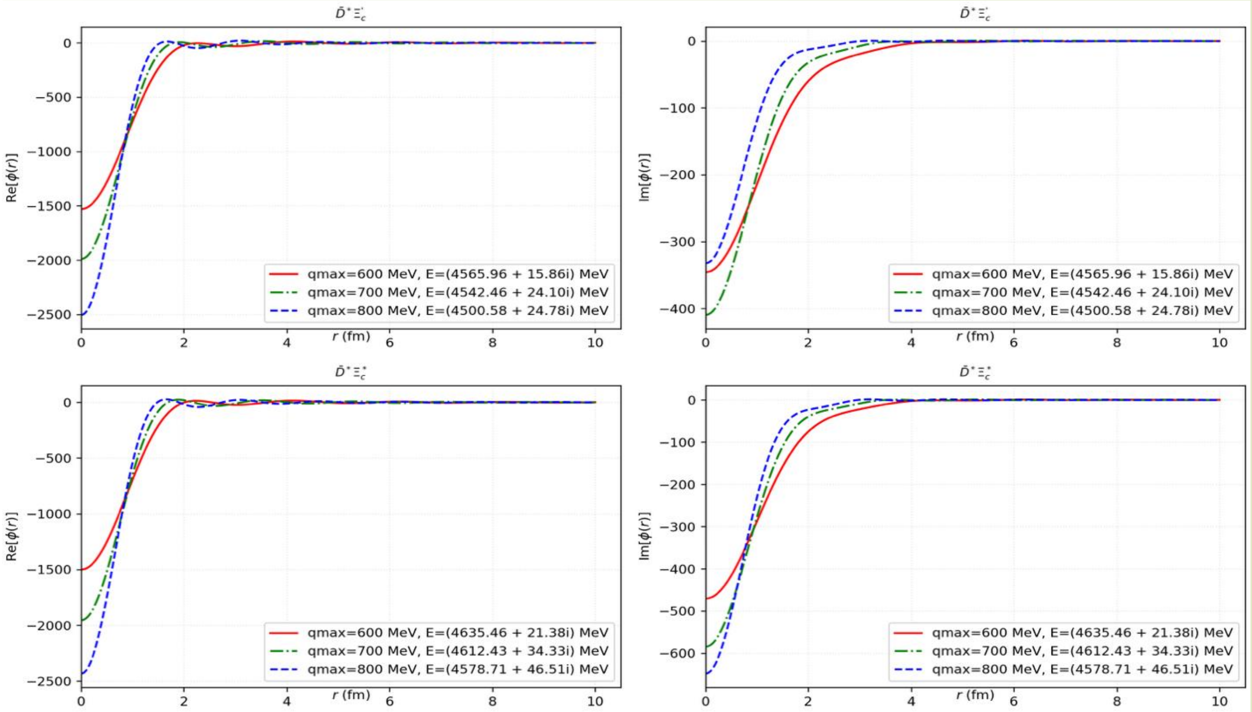




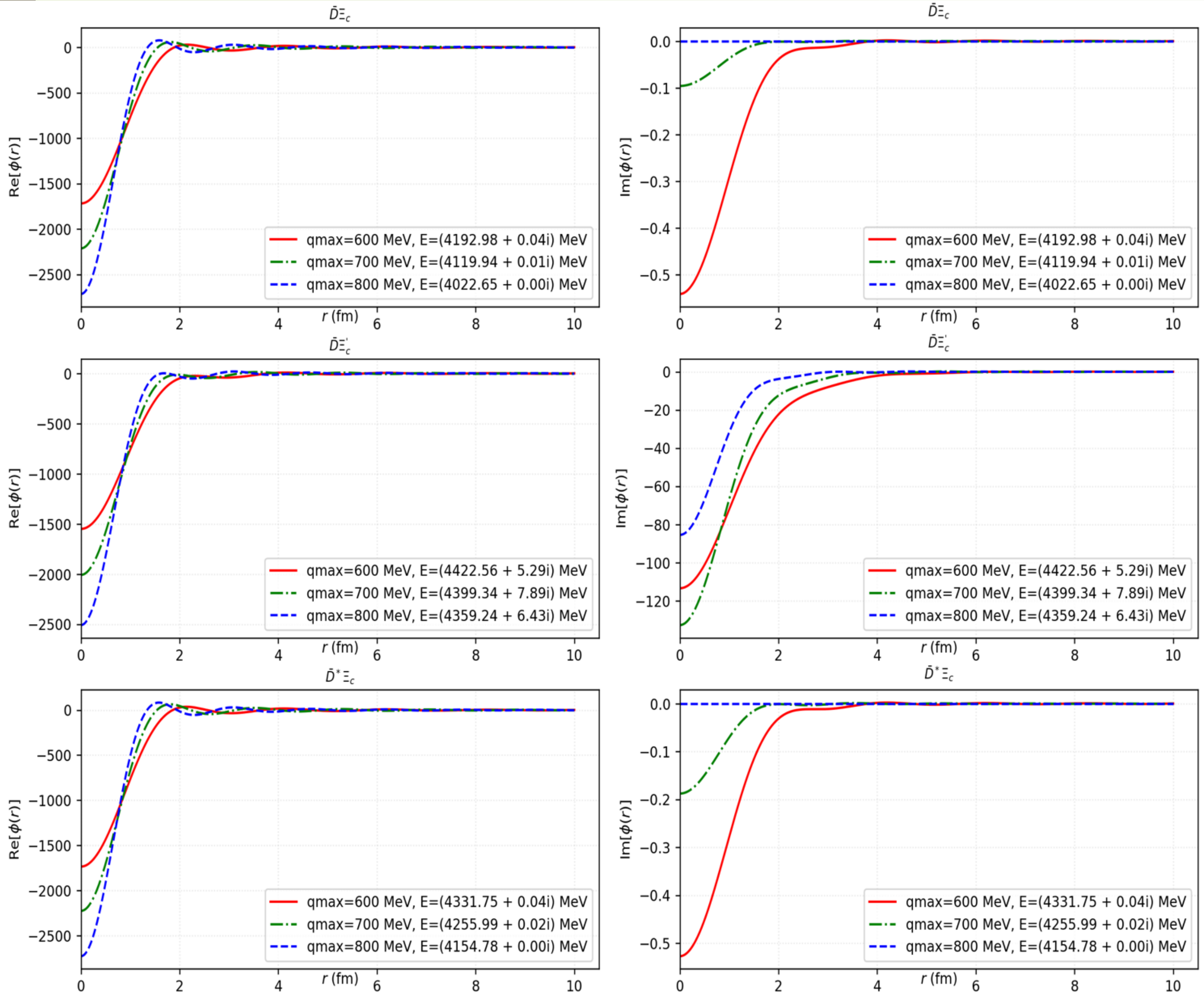
q_{max} [MeV]	Mass [MeV]	Width [MeV]	Main channel	Sector	J^P	Experimental state
600	4192.98	0.08	$\bar{D}\Xi_c$	PB	$1/2^-$	–
700	4119.94	0.02	$\bar{D}\Xi_c$	PB	$1/2^-$	–
800	4022.65	0.00	$\bar{D}\Xi_c$	PB	$1/2^-$	–
600	4331.75	0.08	$\bar{D}^*\Xi_c$	VB	$1/2^-$	$P_{cs}(4338)$
700	4255.99	0.03	$\bar{D}^*\Xi_c$	VB	$1/2^-$	–
800	4154.78	0.00	$\bar{D}^*\Xi_c$	VB	$1/2^-$	–
600	4422.56	10.58	$\bar{D}\Xi'_c$	PB	$1/2^-$	$P_{cs}(4459)$
700	4399.34	15.79	$\bar{D}\Xi'_c$	PB	$1/2^-$	–
800	4359.24	12.85	$\bar{D}\Xi'_c$	PB	$1/2^-$	–
600	4564.95	31.49	$\bar{D}^*\Xi'_c$	VB	$1/2^-$	–
700	4543.50	47.12	$\bar{D}^*\Xi'_c$	VB	$1/2^-$	–
800	4500.82	41.50	$\bar{D}^*\Xi'_c$	VB	$1/2^-$	–
600	4626.34	10.12	$\bar{D}^*\Xi^*_c$	VB	$1/2^-$	–
700	4598.59	17.05	$\bar{D}^*\Xi^*_c$	VB	$1/2^-$	–
800	4564.59	20.87	$\bar{D}^*\Xi^*_c$	VB	$1/2^-$	–

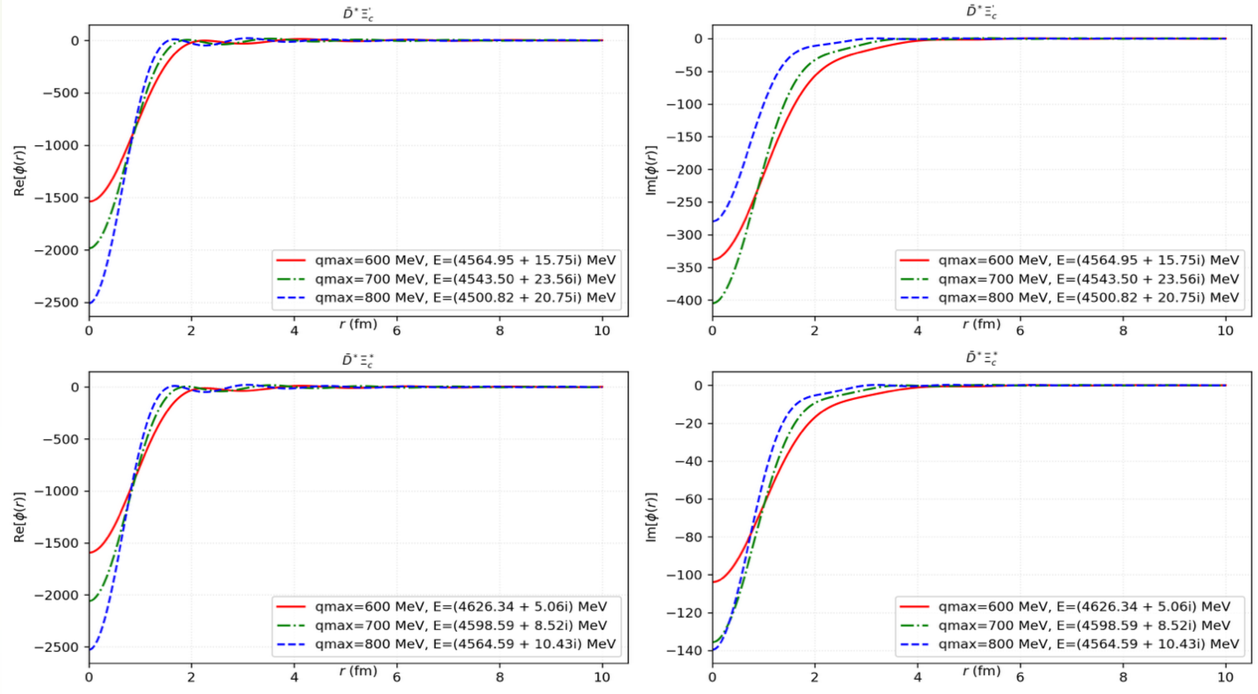
(2) Pcs wave functions : full coupled channels



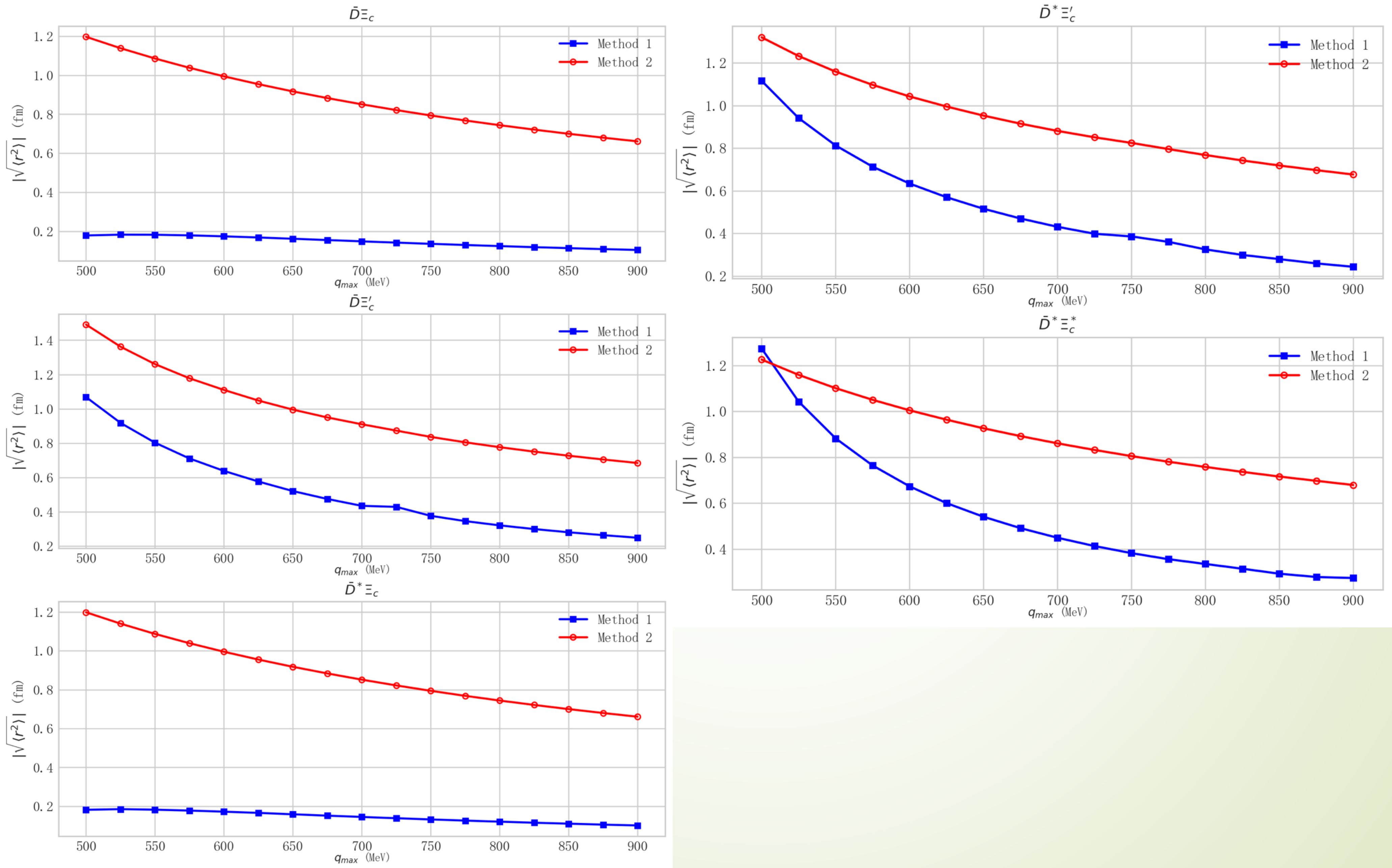


Pcs wave functions : PB and VB sectors

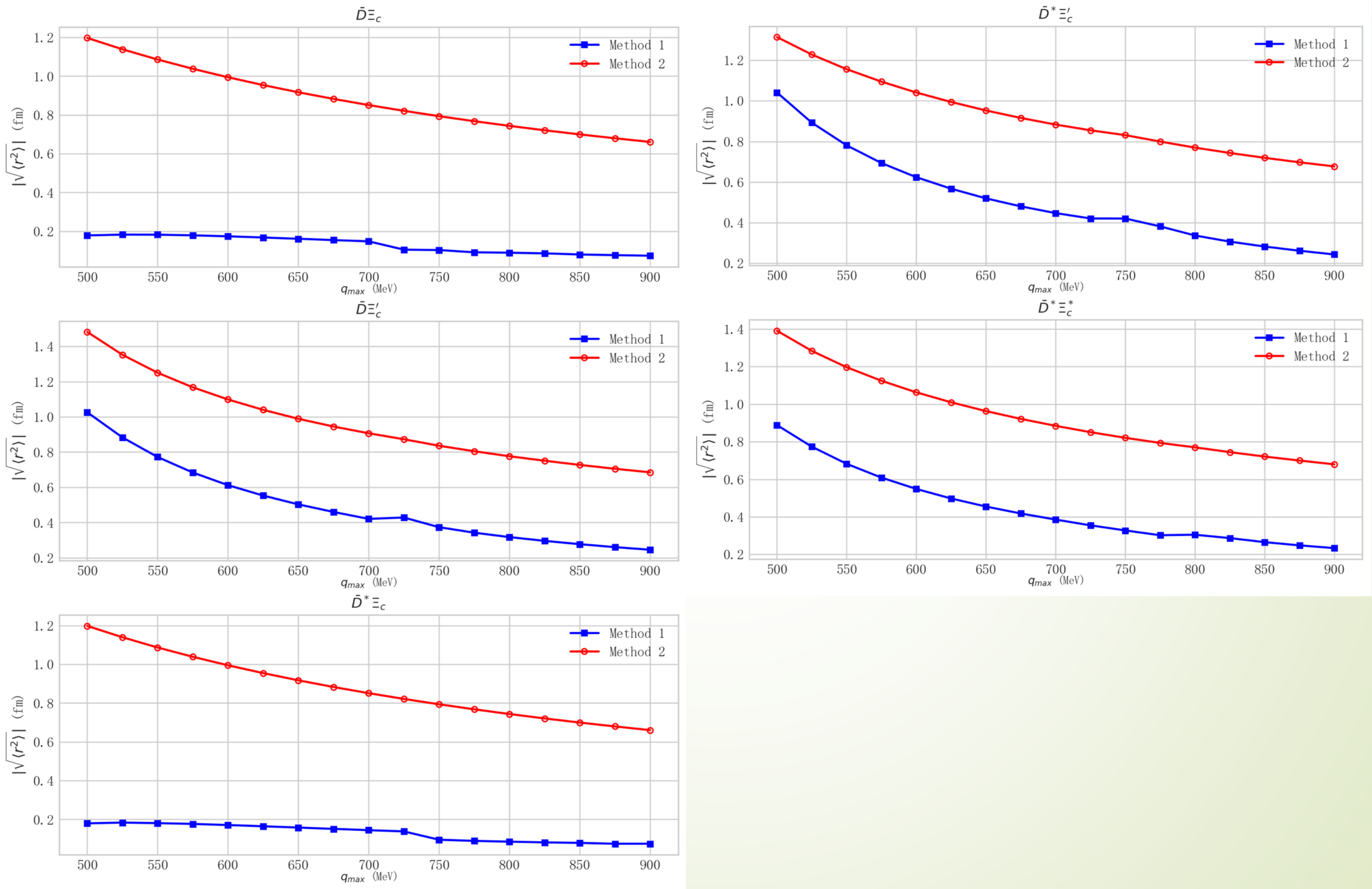




(3) Pcs radii: full coupled channels

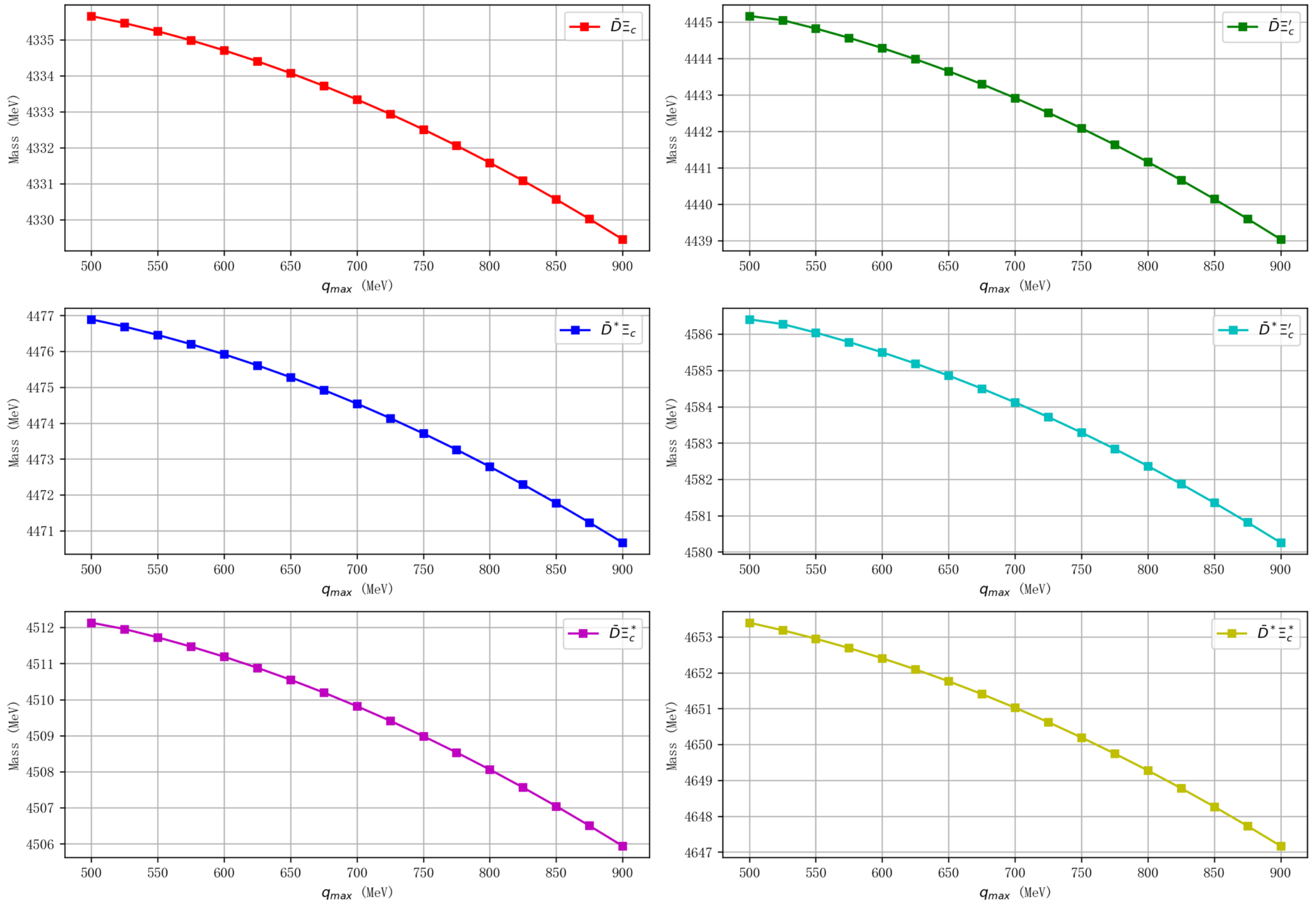


(3) Pcs radii: PB and VB sectors

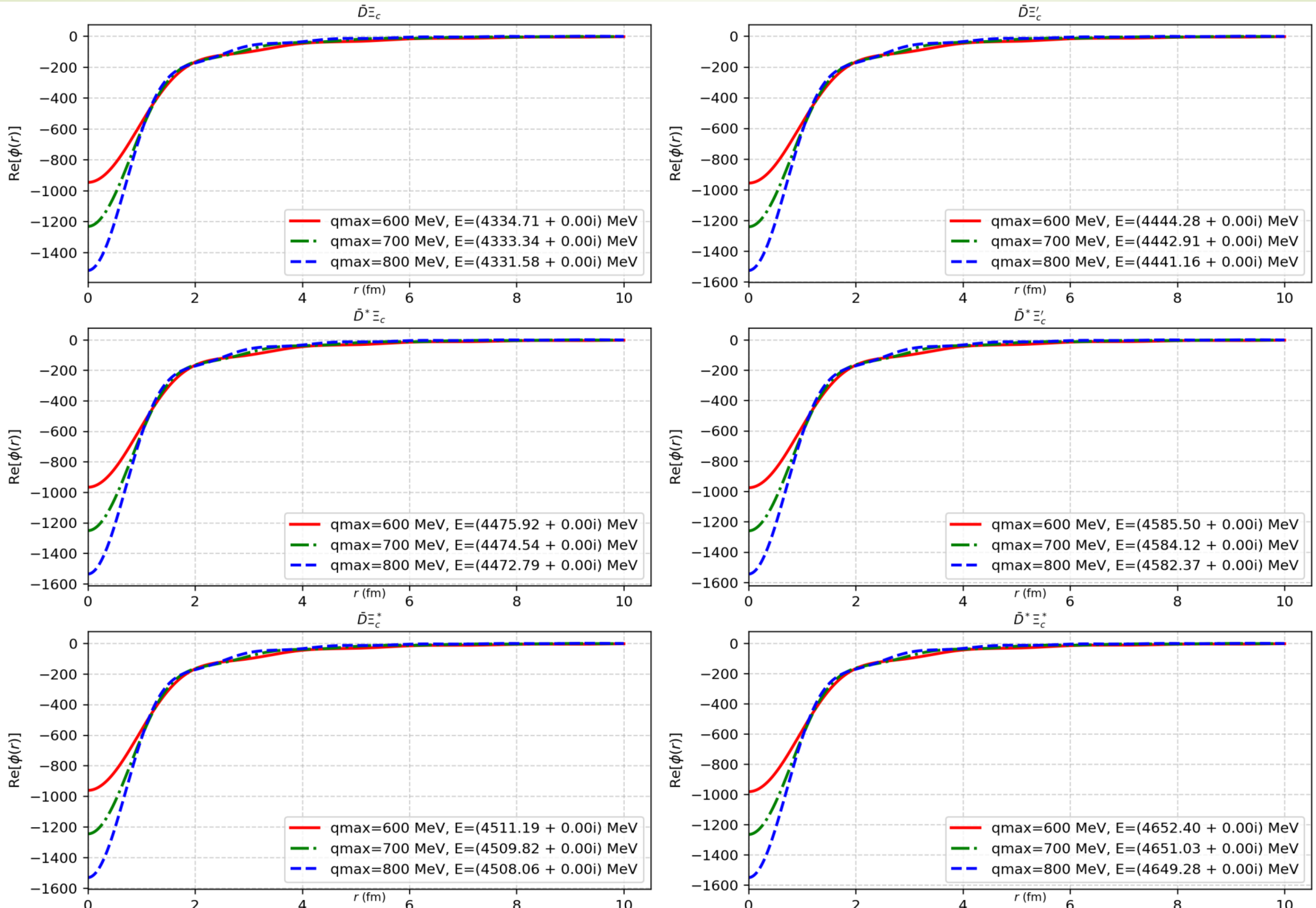


(4) Single channel interaction poles:

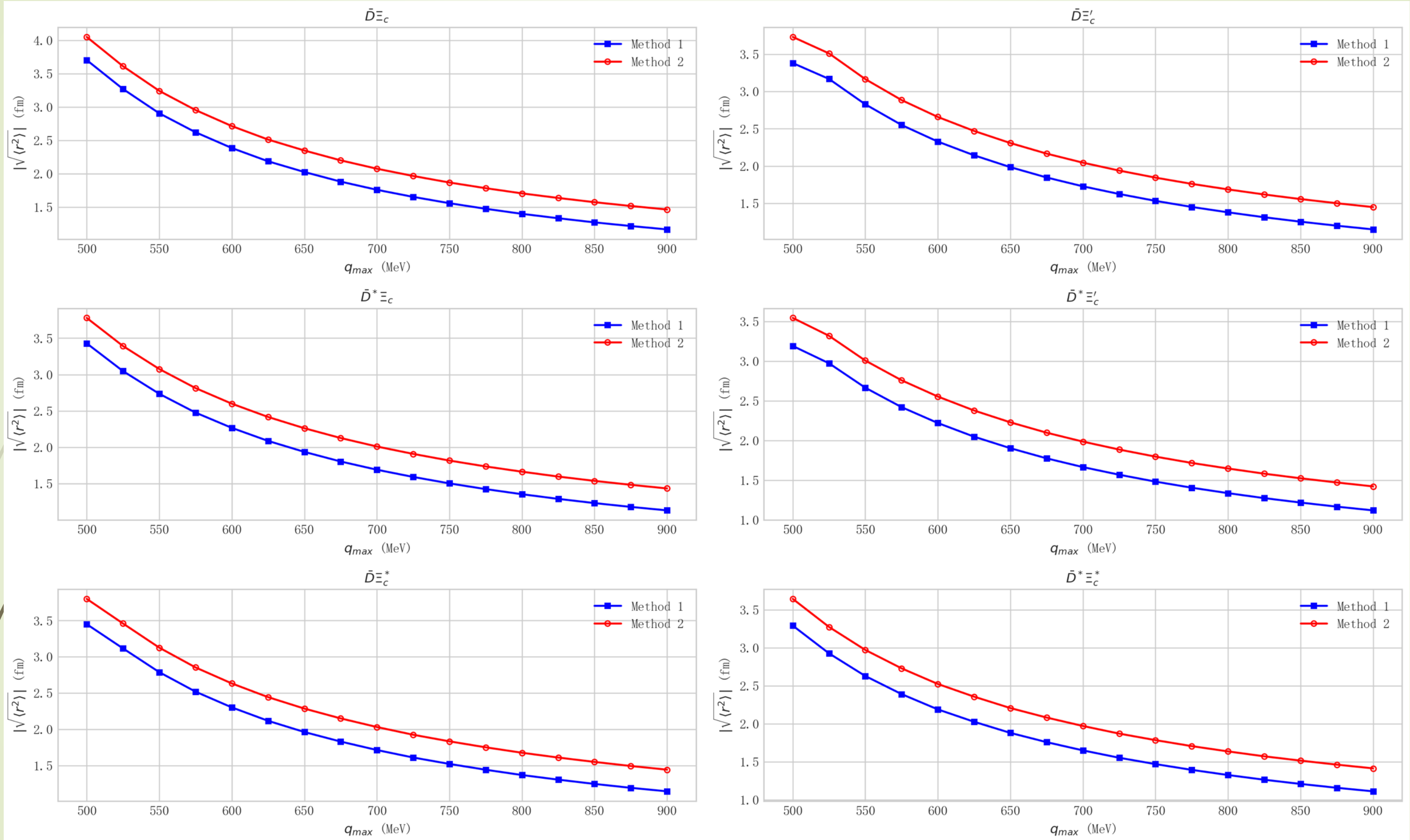
$J^P = 3/2^-$ ***Pcs states***



Wave functions:



Radii:



J. Z. Cao, H. Y. Wei, J. X. Yang, CWX, J. Sun, **arXiv:** 2604.04821

§4. Tetraquark states

BESIII Collaboration

PHYSICAL REVIEW LETTERS **126**, 102001 (2021)

Editors' Suggestion | Featured in Physics

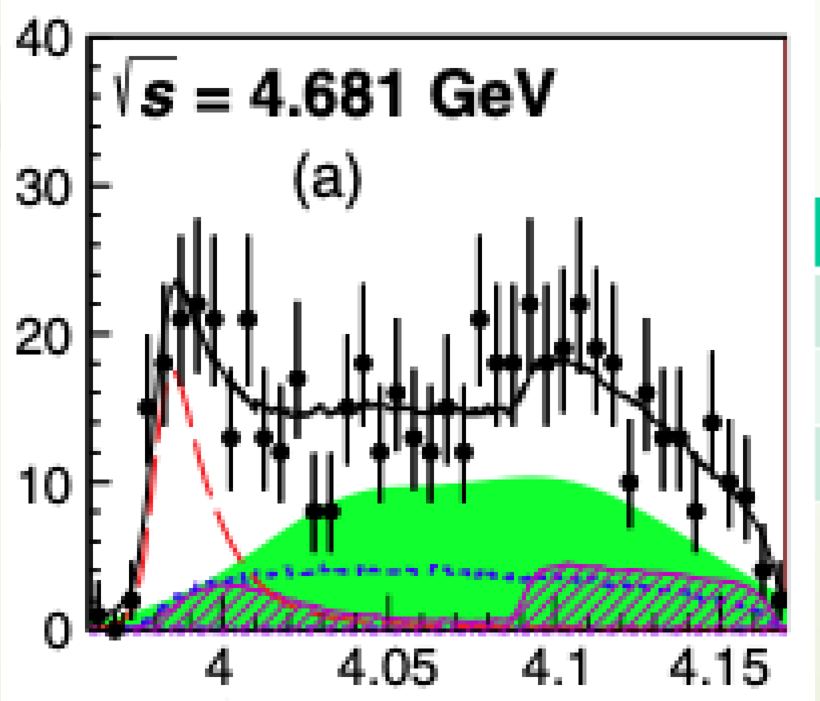
Observation of a Near-Threshold Structure in the K^+ Recoil-Mass Spectra in $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$

PHYSICAL REVIEW LETTERS **127**, 082001 (2021)

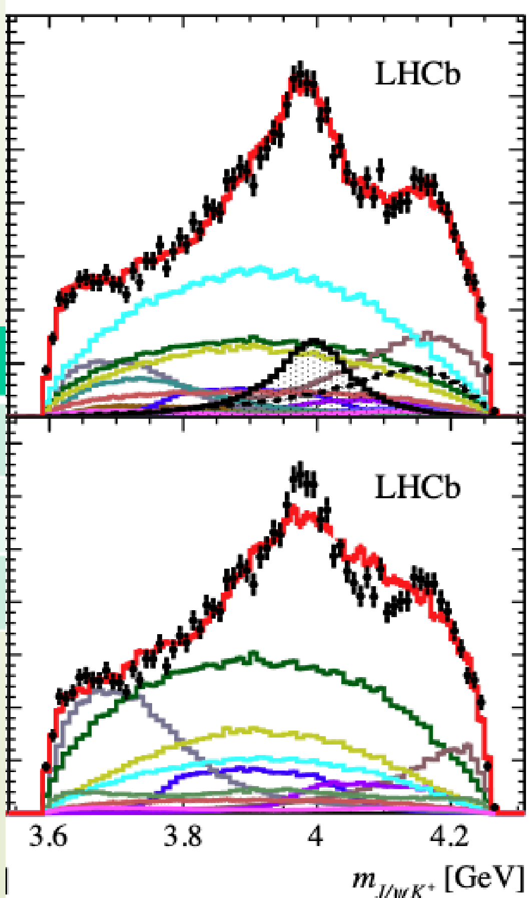
Editors' Suggestion

Observation of New Resonances Decaying to $J/\psi K^+$ and $J/\psi\phi$

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



State	Signif.	JP	Mass (MeV)	Width (MeV)
$Z_{cs}(3985)$	5.3σ	??	$3982.5^{+1.8}_{-2.6} \pm 2.1$	$12.8^{+5.3}_{-4.4} \pm 3.0$
$Z_{cs}(4000)$	15σ	1+	$4003 \pm 6^{+4}_{-14}$	131±15±26
$Z_{cs}(4220)$	5.9σ	1+	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$



第 41 卷 第 2 期
2021 年 04 月
物 理 学 进 展
PROGRESS IN PHYSICS

A survey of heavy-antiheavy hadronic molecules

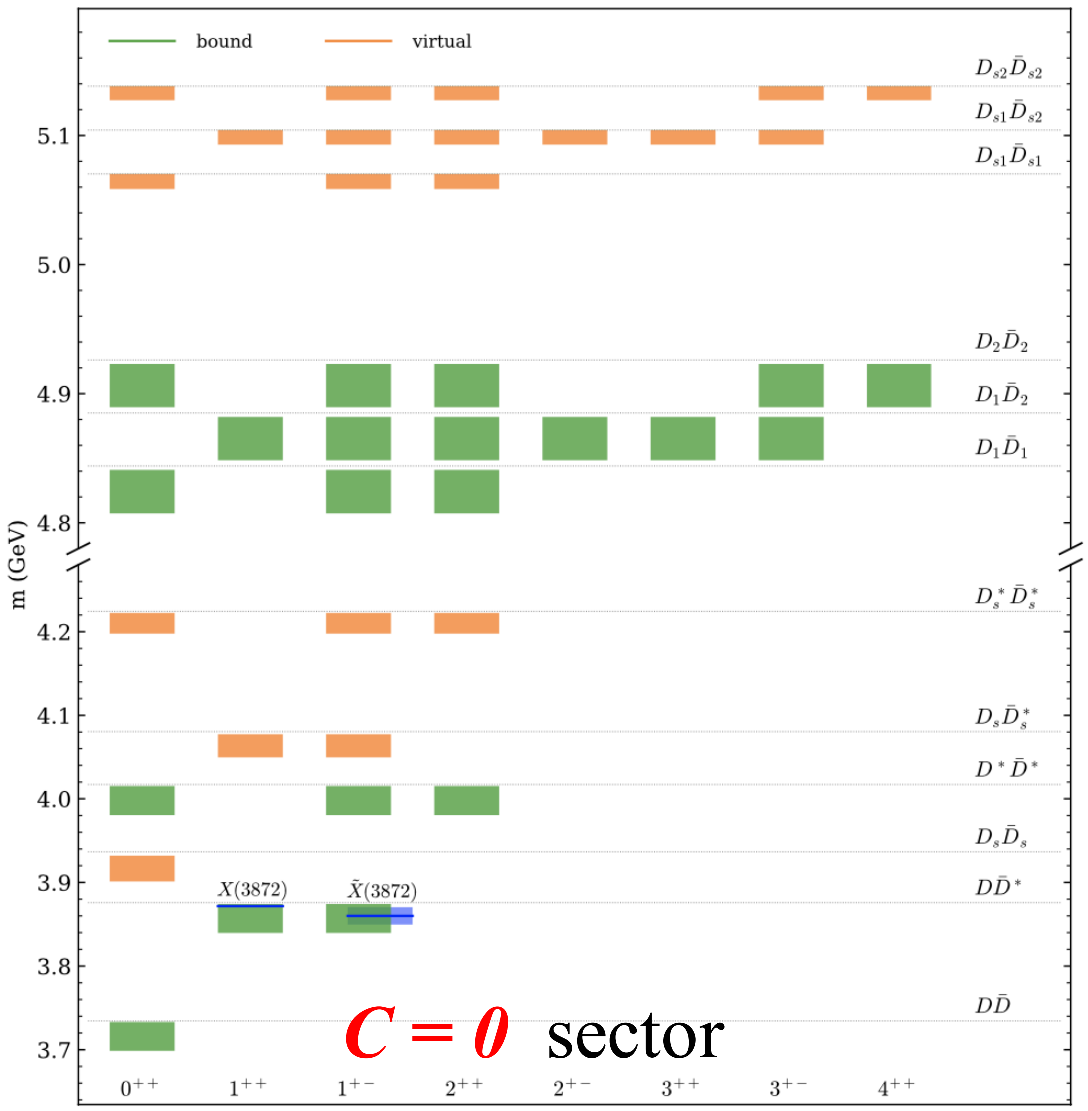
Dong Xiang-Kun [1,2*], Guo Feng-Kun [1,2†], Zou Bing-Song [1,2,3‡]

Progr. Phys. **41** (2021) 65

A survey of heavy-antiheavy hadronic molecules

Xiang-Kun Dong[1,2,*] Feng-Kun Guo[1,2,†] and Bing-Song Zou[1,2,3‡]

System	$E_{\rm th}$	J^{PC}	Pole (0.5)	Pole (1.0)
$D\bar{D}$	3734	0^{++}	(1, 1.31)	(1, 35.8)
$D\bar{D}^*$	3876	$1^{+\pm}$	(1, 1.56)	(1, 36.2)
$D_s\bar{D}_s$	3937	0^{++}	(2, 35.5)	(2, 4.72)
$D^*\bar{D}^*$	4017	$(0,2)^{++},1^{+-}$	(1, 1.82)	(1, 36.6)
$D_s\bar{D}_s^*$	4081	$1^{+\pm}$	(2, 31.0)	(2, 3.15)
$D_s^*\bar{D}_s^*$	4224	$(0,2)^{++},1^{+-}$	(2, 26.7)	(2, 1.92)
$D\bar{D}_2$	4330	$2^{-\pm}$	(1, 2.2)	(1, 36.7)
$D_s\bar{D}_{s2}$	4537	$2^{-\pm}$	(2, 21.3)	(2, 0.713)
$D_1\bar{D}_1$	4844	$(0,2)^{++},1^{+-}$	(1, 3.01)	(1, 36.7)
$D_1\bar{D}_2$	4885	$(1,2,3)^{+\pm}$	(1, 3.06)	(1, 36.6)
$D_2\bar{D}_2$	4926	$(0,2,4)^{++},(1,3)^{+-}$	(1, 3.1)	(1, 36.6)
$D_{s1}\bar{D}_{s1}$	5070	$(0,2)^{++},1^{+-}$	(2, 11.7)	(1, 0.074)
$D_{s1}\bar{D}_{s2}$	5104	$(1,2,3)^{+\pm}$	(2, 11.3)	(1, 0.104)
$D_{s2}\bar{D}_{s2}$	5138	$(0,2,4)^{++},(1,3)^{+-}$	(2, 10.9)	(1, 0.139)



Molecular nature

PHYSICAL REVIEW LETTERS **126,** 152001 (2021)

Explaining the Many Threshold Structures in the Heavy-Quark Hadron Spectrum

Xiang-Kun Dong,[1,2] Feng-Kun Guo,[1,2,*] and Bing-Song Zou[1,2,3]

F.-K. Guo, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao and B.-S. Zou, Rev. Mod. Phys. 90, 015004 (2018)
H.-X. Chen, W. Chen, X. Liu and S.-L. Zhu, Phys. Rept. 639, 1 (2016)
N. Brambilla, S. Eidelman, C. Hanhart, A. Nefediev, C. P. Shen, C. E. Thomas, A. Vairo and C. Z. Yuan, Phys. Rept. 873, 1 (2020)

ELSEVIER Nuclear Physics A 620 (1997) 438–456

Chiral symmetry amplitudes
in the S-wave isoscalar and isovector channels
and the σ, $f_0(980)$, $a_0(980)$ scalar mesons

J.A. Oller, E. Oset

$f_0(1710)$ and $a_0(1710)$ states

L. S. Geng and E. Oset, Phys. Rev. D 79, 074009 (2009): Coupled channel approach

$K\bar{K}$ molecular state → **$K^*\bar{K}^*$ molecular state**

$S = 0$ sector $S \neq 0$ sector ?

We try to investigate……

	Systems	Coefficients $I=0$	Coes. $I=1,\ (\frac{1}{2})$	Exp.
$S=2,\ C=0$	KK	$\frac{1}{2}(-3V_t^\rho + V_t^\omega + 2V_t^\phi)g^2$ $-\frac{1}{2}(-3V_u^\rho + V_u^\omega + 2V_u^\phi)g^2$	$\frac{1}{2}(V_t^\rho + V_t^\omega + 2V_t^\phi)g^2$ $+\frac{1}{2}(V_u^\rho + V_u^\omega + 2V_u^\phi)g^2$	
	KK^*	$\frac{1}{2}(-3V_t^\rho + V_t^\omega + 2V_t^\phi)g^2$	$\frac{1}{2}(V_t^\rho + V_t^\omega + 2V_t^\phi)g^2$	
	K^*K^*	$\frac{1}{2}(-3V_t^\rho + V_t^\omega + 2V_t^\phi)g^2$ $-\frac{1}{2}(-3V_u^\rho + V_u^\omega + 2V_u^\phi)g^2$	$\frac{1}{2}(V_t^\rho + V_t^\omega + 2V_t^\phi)g^2$ $+\frac{1}{2}(V_u^\rho + V_u^\omega + 2V_u^\phi)g^2$	
$S=-1,\ C=1$	$\bar{K}D$	$\frac{1}{2}(-3V_t^\rho + V_t^\omega - 2V_u^{D_s^*})g^2$	$\frac{1}{2}(V_t^\rho + V_t^\omega + 2V_u^{D_s^*})g^2$	$X(2900)$
	$\bar{K}D^*$	$\frac{1}{2}(-3V_t^\rho + V_t^\omega)g^2$	$\frac{1}{2}(V_t^\rho + V_t^\omega)g^2$	
	$\bar{K}^*D$	$\frac{1}{2}(-3V_t^\rho + V_t^\omega)g^2$	$\frac{1}{2}(V_t^\rho + V_t^\omega)g^2$	
	$\bar{K}^*D^*$	$\frac{1}{2}(-3V_t^\rho + V_t^\omega - 2V_u^{D_s^*})g^2$	$\frac{1}{2}(V_t^\rho + V_t^\omega + 2V_u^{D_s^*})g^2$	$X_0(2866)$
$S=1,\ C=1$	KD	$\frac{1}{2}(-3V_t^\rho - V_t^\omega)g^2$	$\frac{1}{2}(V_t^\rho - V_t^\omega)g^2$	$D_{s0}^*(2317)$
	KD^*	$\frac{1}{2}(-3V_t^\rho - V_t^\omega)g^2$	$\frac{1}{2}(V_t^\rho - V_t^\omega)g^2$	$D_{s1}(2460),\ D_{s1}(2536)$
	K^*D	$\frac{1}{2}(-3V_t^\rho - V_t^\omega)g^2$	$\frac{1}{2}(V_t^\rho - V_t^\omega)g^2$	
	K^*D^*	$\frac{1}{2}(-3V_t^\rho - V_t^\omega)g^2$	$\frac{1}{2}(V_t^\rho - V_t^\omega)g^2$	$D_{s2}^*(2573)$

$S=2,\ C=1$

KD_s	$(V_t^{\phi}+V_u^{D^*})g^2$	
KD_s^*	$\cancel{V_t^{\phi}g^2}$	
K^*D_s	$\cancel{V_t^{\phi}g^2}$	
$K^*D_s^*$	$(V_t^{\phi}+V_u^{D^*})g^2$	
$\bar{D}D_s$	$-V_t^{J/\psi}g^2$	
$\bar{D}D_s^*$	$-V_t^{J/\psi}g^2$	$Z_{cs}(3985)$
$\bar{D}^*D_s$	$-V_t^{J/\psi}g^2$	
$\bar{D}^*D_s^*$	$-V_t^{J/\psi}g^2$	$Z_{cs}(4000)$

$S=1,\ C=0$

$S=1,\ C=2$

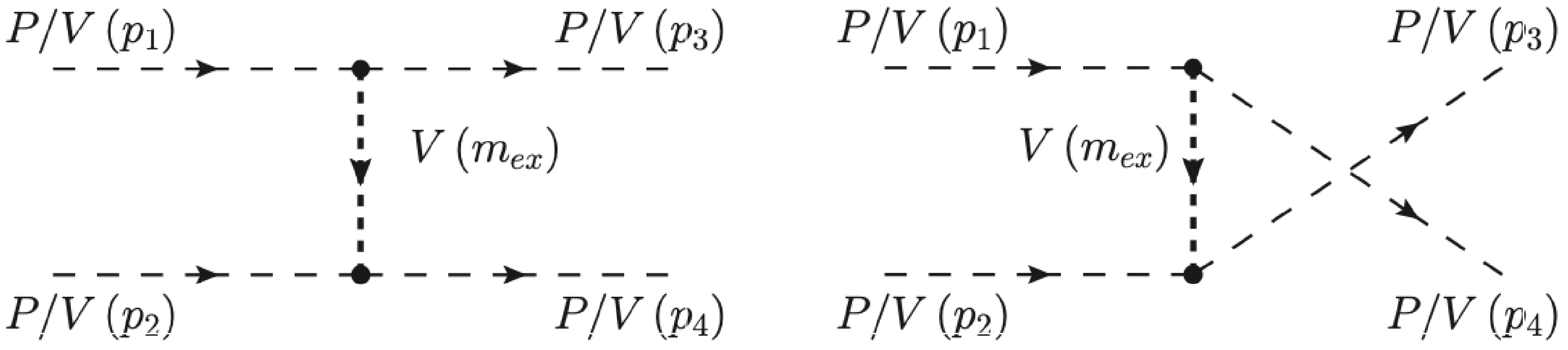
DD_s	$(V_t^{J/\psi}+V_u^{K^*})g^2$
DD_s^*	$\cancel{V_t^{J/\psi}g^2}$
D^*D_s	$\cancel{V_t^{J/\psi}g^2}$
$D^*D_s^*$	$(V_t^{J/\psi}+V_u^{K^*})g^2$
D_sD_s	$(V_t^{J/\psi}+V_t^{\phi})g^2$ $+(V_u^{J/\psi}+V_u^{\phi})g^2$
$D_sD_s^*$	$\cancel{(V_t^{J/\psi}+V_t^{\phi})g^2}$
$D_s^*D_s^*$	$(V_t^{J/\psi}+V_t^{\phi})g^2$ $+(V_u^{J/\psi}+V_u^{\phi})g^2$

$S=2,\ C=2$

$$V_{t(u)}^{ex} = \frac{-V_{t(u)}}{t(u) - m_{ex}^2},$$

$$V_t = (k_1 + k_3) \cdot (k_2 + k_4)$$

$$V_u = (k_1 + k_4) \cdot (k_2 + k_3)$$



(a) t-channel (b) u-channel

$$\frac{1}{2}\int_{-1}^{+1} \mathrm{d}\cos\theta \frac{-V_t}{t - m_{ex}^2}$$

$$= -\frac{s}{\sqrt{\lambda\left(s, m_1^2, m_2^2\right)\lambda\left(s, m_3^2, m_4^2\right)}}\left(m_1^2 + m_2^2 + m_3^2 + m_4^2 - 2s - m_{ex}^2\right)$$

$$\times \log \frac{m_1^2 + m_3^2 - \frac{\left(s+m_1^2-m_2^2\right)\left(s+m_3^2-m_4^2\right)}{2s} - \frac{\sqrt{\lambda\left(s,m_1^2,m_2^2\right)\lambda\left(s,m_3^2,m_4^2\right)}}{2s} - m_{ex}^2}{m_1^2 + m_3^2 - \frac{\left(s+m_1^2-m_2^2\right)\left(s+m_3^2-m_4^2\right)}{2s} + \frac{\sqrt{\lambda\left(s,m_1^2,m_2^2\right)\lambda\left(s,m_3^2,m_4^2\right)}}{2s} - m_{ex}^2} - 1,$$

Systems	Ours-new ($q_{max}=883$)	Oset's ($q_{max}=1100$)	Ours-new2 ($q_{max}=760$)	Oset's-2 ($q_{max}=843$)	Exp.
$\bar{K}D$ (2362.89)	2354.10	2346.74	2362.40	2362.82	
$\bar{K}D^*$ (2504.20)	–	2502.68	–	–	
$\bar{K}^*D$ (2760.86)	$2694.17+i42.94$	2689.01	2747.40	2741.24	
$\bar{K}^*D^*$, $J=0$ (2902.17)	2866.14	2866.38	2897.82	2897.02	$X_0(2866)$
$\bar{K}^*D^*$, $J=1$ (2902.17)	2894.66	2859.98	2902.06	2895.50	
$\bar{K}^*D^*$, $J=2$ (2902.17)	$2813.41-i135.96$	2745.76	$2807.55\pm i66.51$	2837.49	
KD (2362.89)	2258.22	2262.15	2317.36	2317.14	$D^*_{s0}(2317)$
KD^* (2504.20)	2391.78	2400.22	24555.06	2456.29	$D_{s1}(2460)$
K^*D (2760.86)	$2698.42-i237.63$	2504.39	$2684.60\pm i170.50$	2620.27	
K^*D^*, $J=0$ (2902.17)	$2874.93+i192.31$	2713.15	$2849.62+i135.30$	2804.40	
K^*D^*, $J=1$ (2902.17)	$2866.91+i164.04$	2748.72	$2857.40\pm i112.55$	2826.76	
K^*D^*, $J=2$ (2902.17)	$2824.87+i259.85$	2600.70	$2817.27+i189.09$	2732.68	$D^*_{s2}(2573)$

CWX, J. J. Wu, Eur. Phys. J. A 61 (2025) 179

§5. Summary

- To generate the Pc states, the full coupled channel interactions with the heavy quark spin symmetry are important, which affect seriously the widths of the corresponding poles.
- it is not so necessary to reproduce the Pcs state using the full coupled channel interactions with the heavy quark spin symmetry, showing that the results of the splitting PB and VB sectors are not much differences.
- all the main bound channels have similar binding energies for the single channel interactions.

§5. Summary

- We dynamically generate the resonances:

$$X_0(2866),\ D_{s0}^*(2317)\ \text{and}\ D_{s1}(2460)$$

- We find some attractive interactions, which would be more molecular (tetraquark) states with strangeness as our predictions?

Hope future experiments and theories bring more clarifications on these issues…….

第八届粒子物理天问论坛

Aug 27 – 31, 2026
广西桂林
Asia/Shanghai timezone

会议计划于2026年8月27---31日（27日下午报道，31日离会）在桂林市大公馆酒店召开。会议统一安排食宿，费用自理。会议收取注册费，教师及博士后1500元/人，学生1000元/人。

会议网址：https://indico.ihep.ac.cn/event/29685/ 。

Thanks for your attention!

感谢大家的聆听！