

# 15th International Workshop on the Physics of Excited Nucleons

## Study of the $P_c$ and $P_{cs}$ states

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Jia-Jun Wu, Wei-Fei Wang, Albert Feijoo

Juan Nieves , Eulogio Oset, Bing-Song Zou



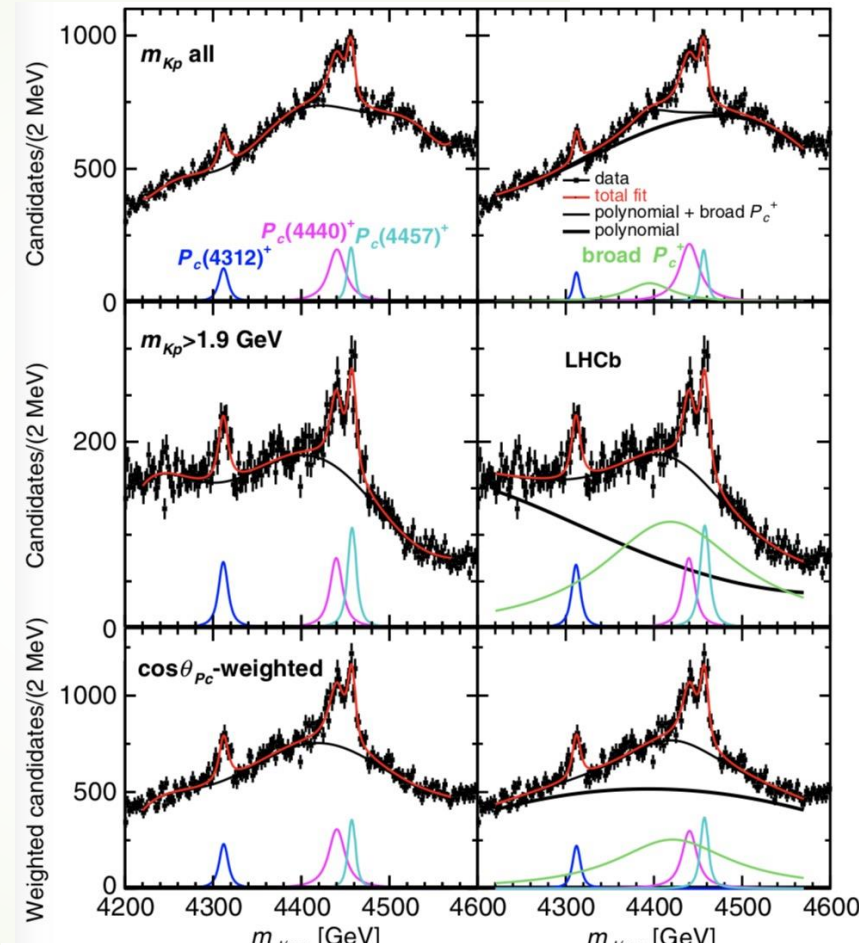
# Outline

1. Introduction
2. Formalism
3. Pentaquark states
4. Summary

# § 1. Introduction

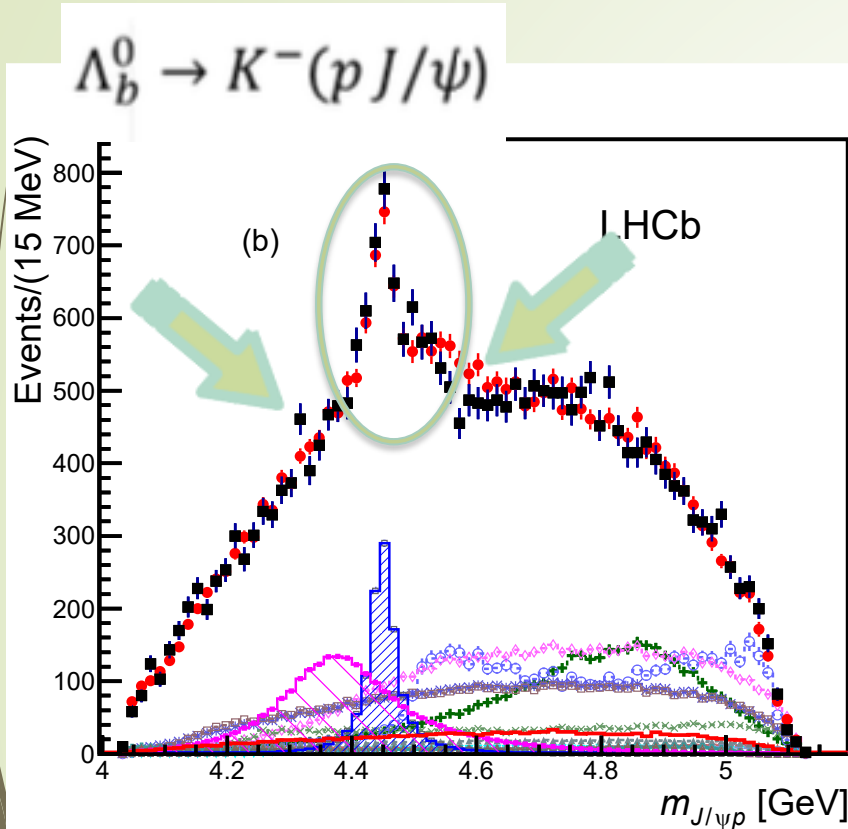
Observation of a Narrow Pentaquark State,  $P_c(4312)^+$ ,  
and of the Two-Peak Structure of the  $P_c(4450)^+$

R. Aaij *et al.*\*  
(LHCb Collaboration)



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

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



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

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

$J^P$  ?

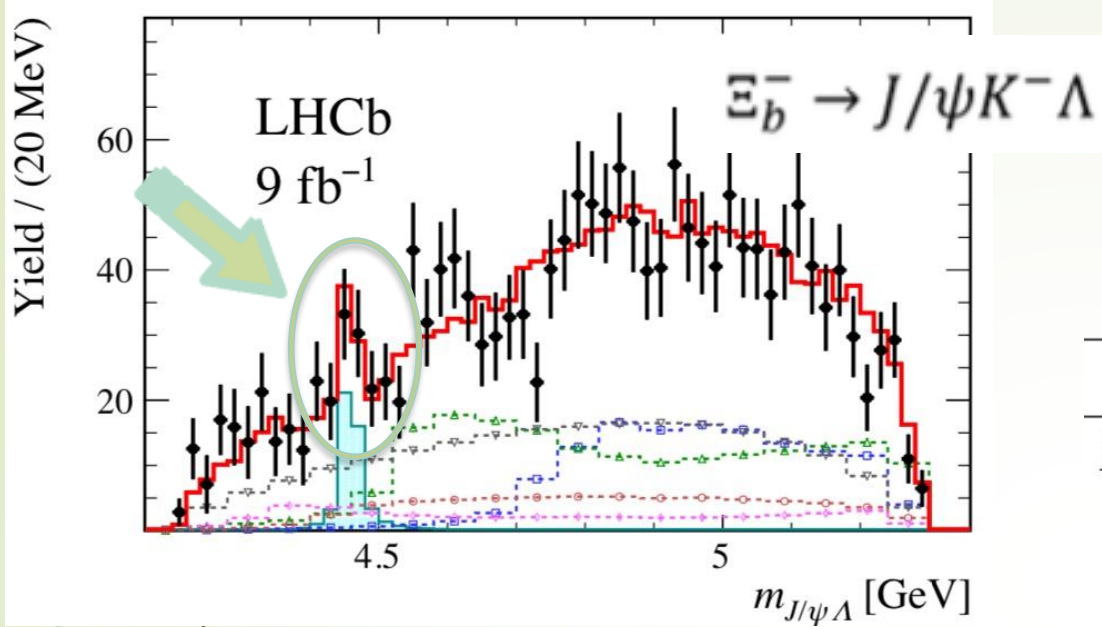
R. Aaij *et al.* (LHCb  
Collaboration), Phys. Rev.  
Lett. 115, 072001 (2015)



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- 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)
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- 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

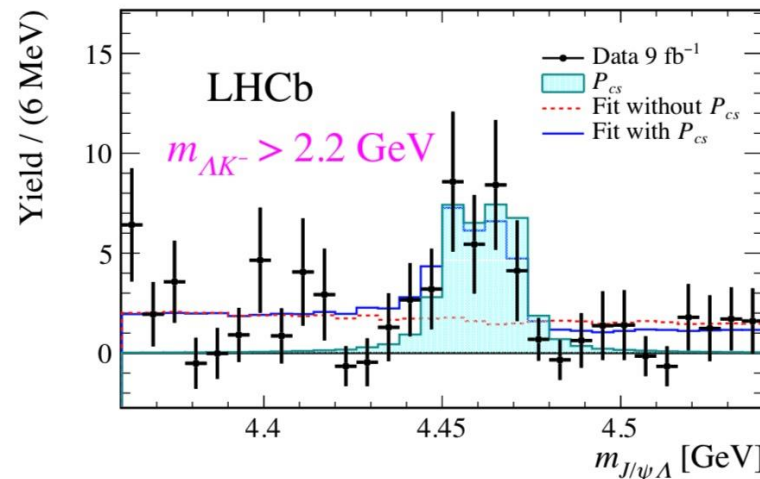
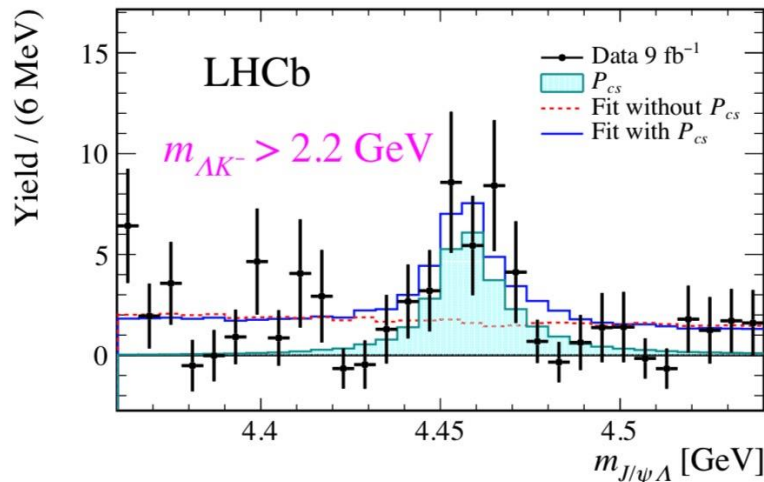


R. Aaij et al. (LHCb Collaboration),  
**Sci. Bull. 66 (2021) 1278-1287**

| State            | $M_0$ [MeV]                    | $\Gamma_0$ [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



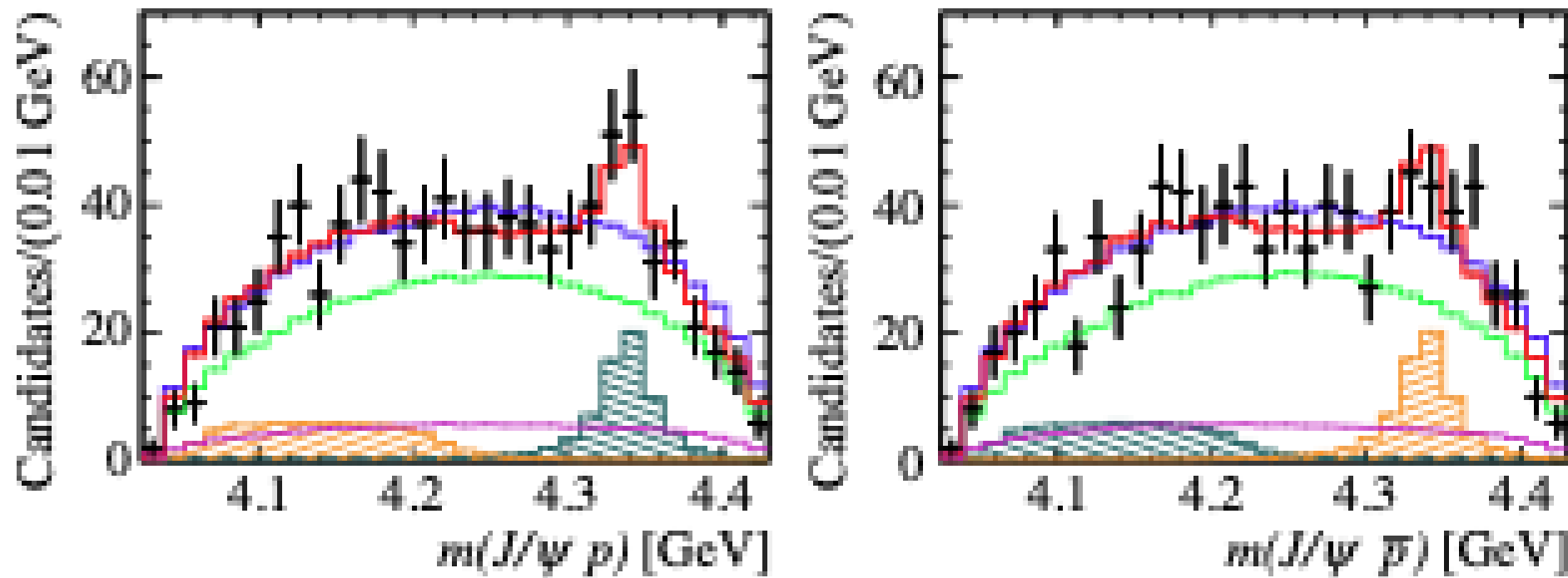
B. Wang, L. Meng and S. L. Zhu, **Phys. Rev. D 101 (2020) 034018.**

Belle + Belle II, **Phys. Rev. Lett. 135, 041901 (2025)**

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

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

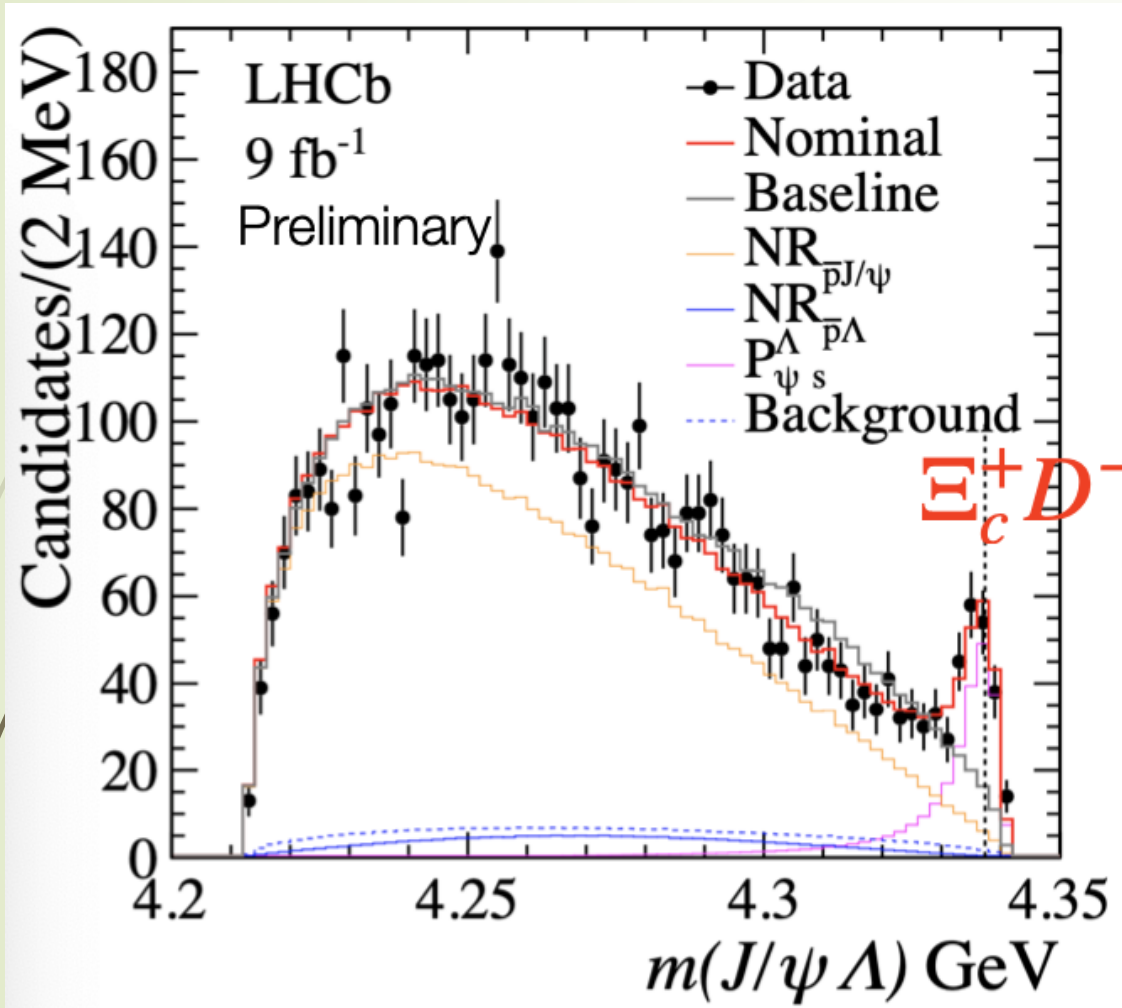
R. Aaij *et al.*<sup>\*</sup>  
(LHCb Collaboration)



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

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

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



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

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

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

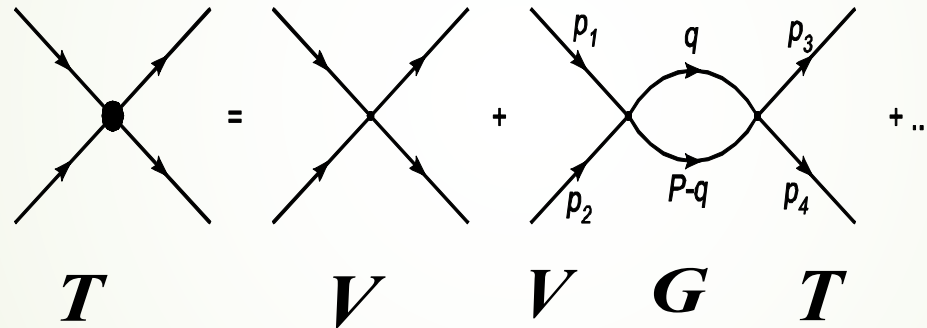
Significance:  $>10\sigma$

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:

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

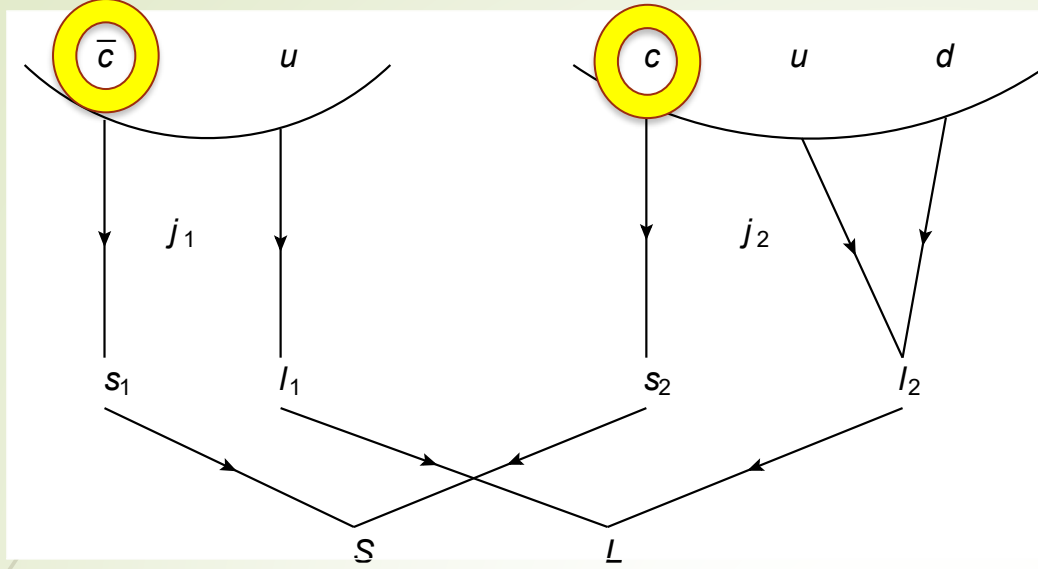
The coupled channel scattering amplitudes **T matrix satisfy the unitary** :

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

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

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

$$G_{ll}^{II}(s) = G_{ll}^I(s) + \boxed{\frac{i}{2\pi} \frac{M_l q_{cml}(s)}{\sqrt{s}}}$$



Considering the heavy quark spin symmetry

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

$$\Sigma_c \longrightarrow \Sigma_c^*$$

$$\Xi_c \longrightarrow \Xi_c^*$$

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

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

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 $\Lambda^*$ Resonances with Hidden Charm above 4 GeV

Jia-Jun Wu,<sup>1,2</sup> R. Molina,<sup>2,3</sup> E. Oset,<sup>2,3</sup> and B. S. Zou<sup>1,3</sup>

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             |
|            | $4310.53 + i8.23$ | $P_{\psi s}^\Lambda(4338)^0$ |                |                       |                 |                   |                         |                    |                     |
| $ g_i $    | 0.15              | 0.27                         | <b>2.33</b>    | 0.69                  | 0.00            | 0.04              | 0.09                    | 0.01               | 0.02                |
| $\Gamma_i$ | 0.57              | 1.18                         | —              | 13.86                 |                 |                   |                         |                    |                     |
| Br.        | 3.47%             | 7.16%                        | —              | <b>84.21%</b>         |                 |                   |                         |                    |                     |
|            | $4445.12 + i0.19$ |                              |                |                       |                 |                   |                         |                    |                     |
| $ g_i $    | 0.10              | 0.06                         | 0.00           | 0.00                  | <b>0.72</b>     | 0.08              | 0.04                    | 0.01               | 0.01                |
| $\Gamma_i$ | 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            | <b>2.16</b>       | 0.61                    | 0.03               | 0.02                |
| $\Gamma_i$ | 1.59              | 0.46                         | 0.00           | 0.00                  | 0.01            | —                 | 11.14                   | —                  | —                   |
| Br.        | 11.57%            | 3.31%                        | 0.00%          | 0.00%                 | 0.70%           | —                 | <b>80.86%</b>           | —                  | —                   |

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

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

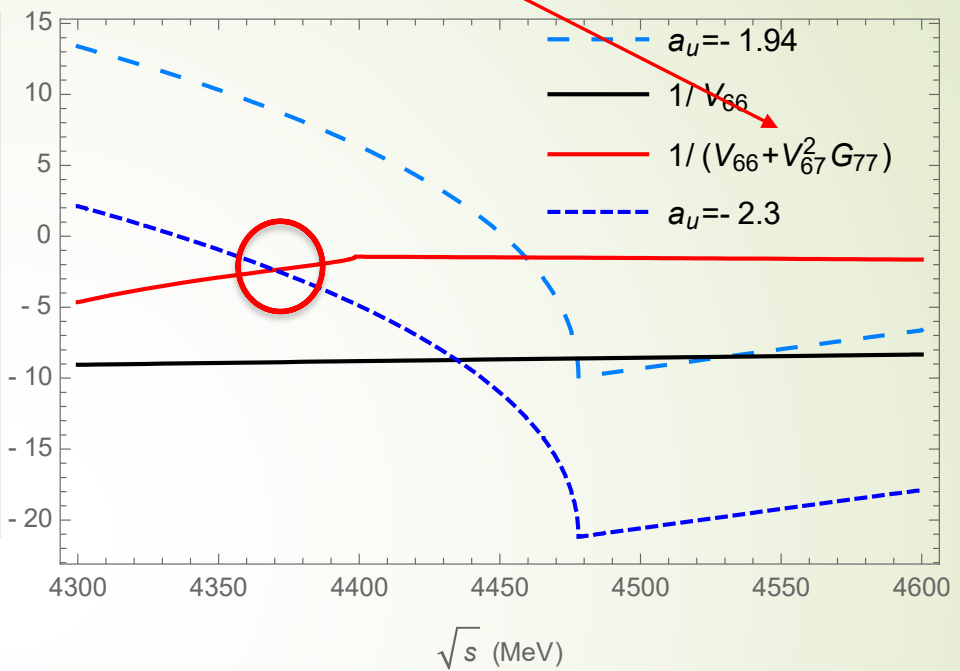
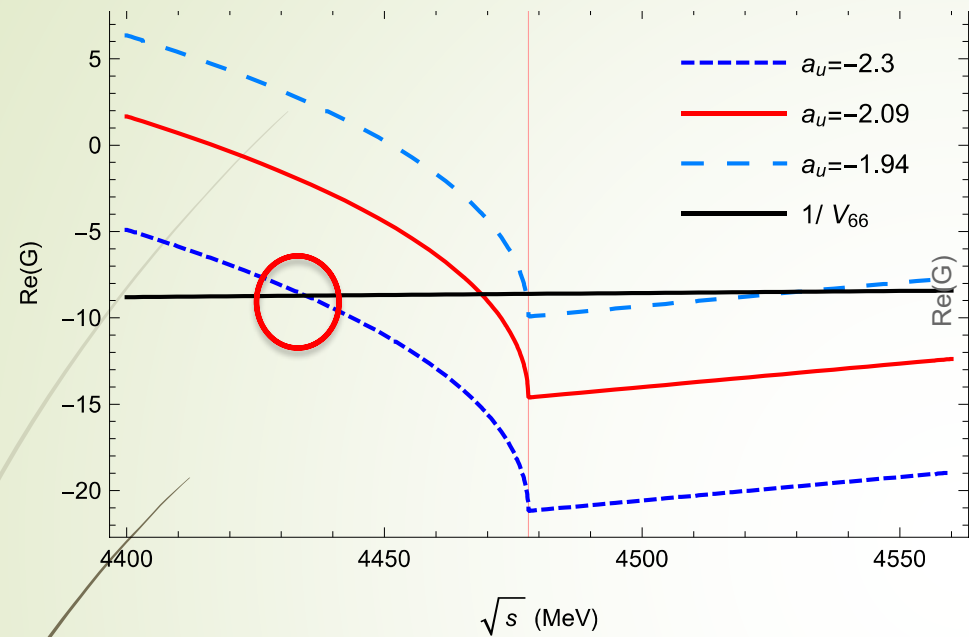
M.-Z. Liu, Y.-W. Pan, L.-S. Geng, *Phys. Rev. D* **103** (2021) 034003

W.-Y. Liu, W. Hao, G.-Y. Wang, Y.-Y. Wang, E. Wang, D.-M. Li, *Phys. Rev. D* **103** (2021) 034019

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



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



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

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

# Noting the results for Pc

$$\begin{pmatrix}
 \eta_c N & J/\psi N & \bar{D}\Lambda_c & \bar{D}\Sigma_c & \bar{D}^*\Lambda_c & \bar{D}^*\Sigma_c & \bar{D}^*\Sigma_c^* \\
 \mu_1 & 0 & \frac{\mu_{12}}{2} & \frac{\mu_{13}}{2} & \frac{\sqrt{3}\mu_{12}}{2} & -\frac{\mu_{13}}{2\sqrt{3}} & \sqrt{\frac{2}{3}}\mu_{13} \\
 0 & \mu_1 & \frac{\sqrt{3}\mu_{12}}{2} & -\frac{\mu_{13}}{2\sqrt{3}} & -\frac{\mu_{12}}{2} & \frac{5\mu_{13}}{6} & \frac{\sqrt{2}\mu_{13}}{3} \\
 \frac{\mu_{12}}{2} & \frac{\sqrt{3}\mu_{12}}{2} & \mu_2 & 0 & 0 & \frac{\mu_{23}}{\sqrt{3}} & \sqrt{\frac{2}{3}}\mu_{23} \\
 \frac{\mu_{13}}{2} & -\frac{\mu_{13}}{2\sqrt{3}} & 0 & \frac{1}{3}(2\lambda_2 + \mu_3) & \frac{\mu_{23}}{\sqrt{3}} & \frac{2(\lambda_2 - \mu_3)}{3\sqrt{3}} & \frac{1}{3}\sqrt{\frac{2}{3}}(\mu_3 - \lambda_2) \\
 \frac{\sqrt{3}\mu_{12}}{2} & -\frac{\mu_{12}}{2} & 0 & \frac{\mu_{23}}{\sqrt{3}} & \mu_2 & -\frac{2\mu_{23}}{3} & \frac{\sqrt{2}\mu_{23}}{3} \\
 -\frac{\mu_{13}}{2\sqrt{3}} & \frac{5\mu_{13}}{6} & \frac{\mu_{23}}{\sqrt{3}} & \frac{2(\lambda_2 - \mu_3)}{3\sqrt{3}} & -\frac{2\mu_{23}}{3} & \frac{1}{9}(2\lambda_2 + 7\mu_3) & \frac{1}{9}\sqrt{2}(\mu_3 - \lambda_2) \\
 \sqrt{\frac{2}{3}}\mu_{13} & \frac{\sqrt{2}\mu_{13}}{3} & \sqrt{\frac{2}{3}}\mu_{23} & \frac{1}{3}\sqrt{\frac{2}{3}}(\mu_3 - \lambda_2) & \frac{\sqrt{2}\mu_{23}}{3} & \frac{1}{9}\sqrt{2}(\mu_3 - \lambda_2) & \frac{1}{9}(\lambda_2 + 8\mu_3)
 \end{pmatrix}_{I=1/2}$$

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

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

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

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

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

$$\begin{aligned}
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 M_{P_{c2}} &= 4440.3 \pm 1.3^{+4.1}_{-4.7}, & \Gamma_{P_{c2}} &= 20.6 \pm 4.9^{+8.7}_{-10.1}, \\
 M_{P_{c3}} &= 4457.3 \pm 0.6^{+4.1}_{-1.7}, & \Gamma_{P_{c3}} &= 6.4 \pm 2.0^{+5.7}_{-1.9}.
 \end{aligned}$$

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

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

$P_{cs}(4459)$

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

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

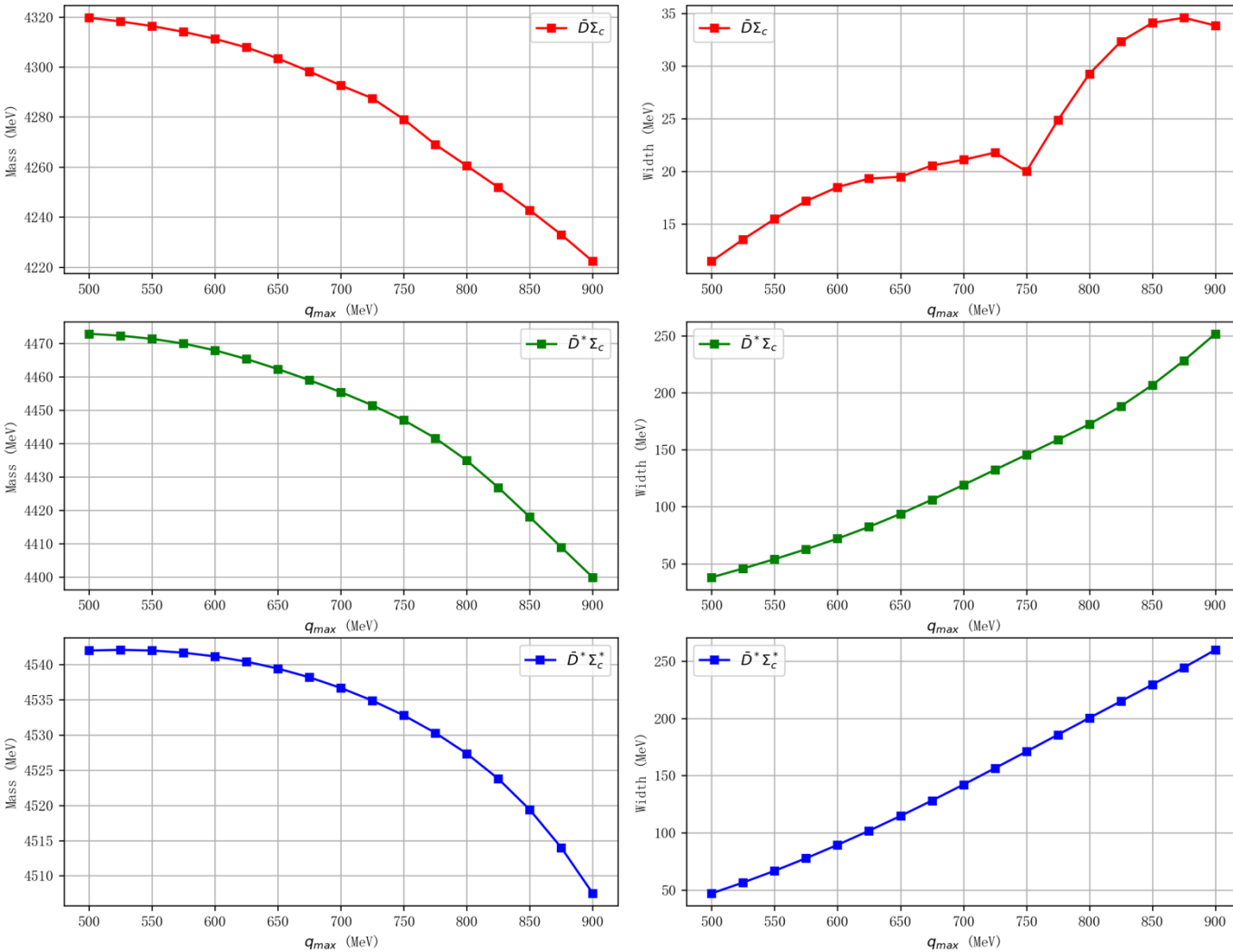
$P_{\psi s}^\Lambda(4338)^0$

$P_c : \bar{D} \Sigma_c, \bar{D} \Lambda_c$  and  $\bar{D}^* \Sigma_c, \bar{D}^* \Lambda_c$   
 ~~$P_{cs} : \bar{D} \Xi_c, \bar{D}_s \Lambda_c$  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

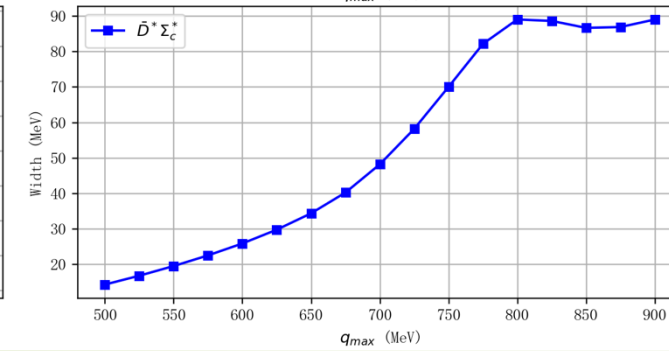
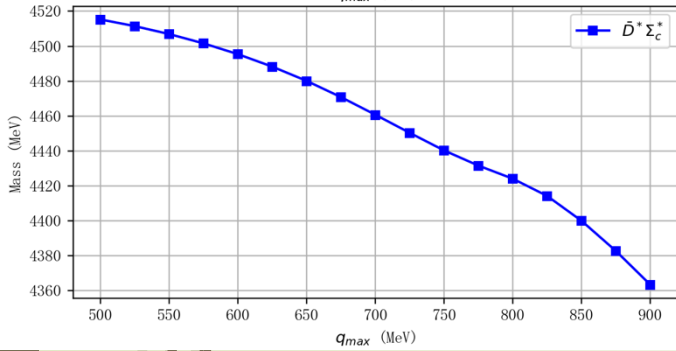
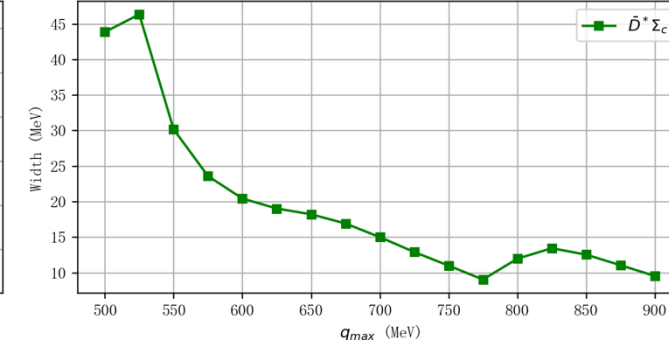
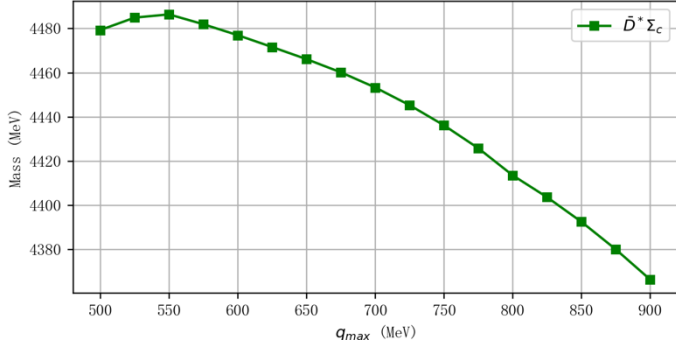
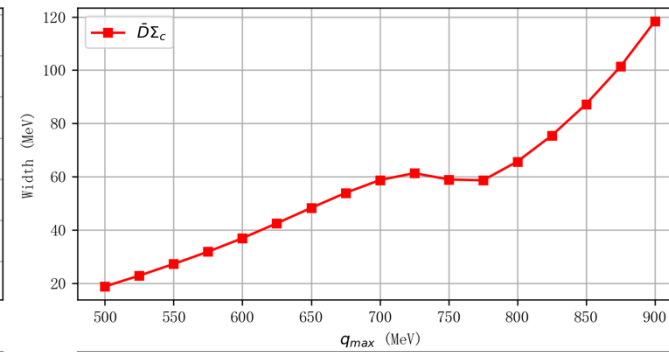
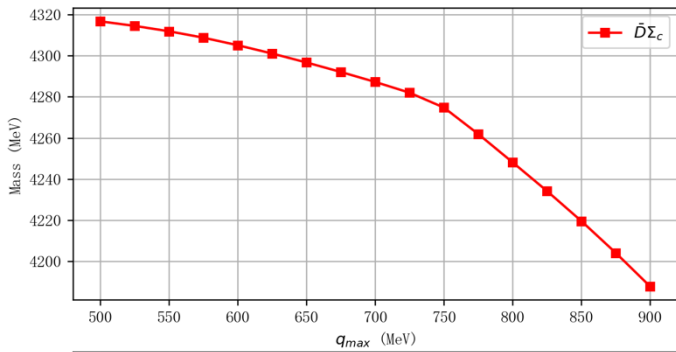
# Further Results-1

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



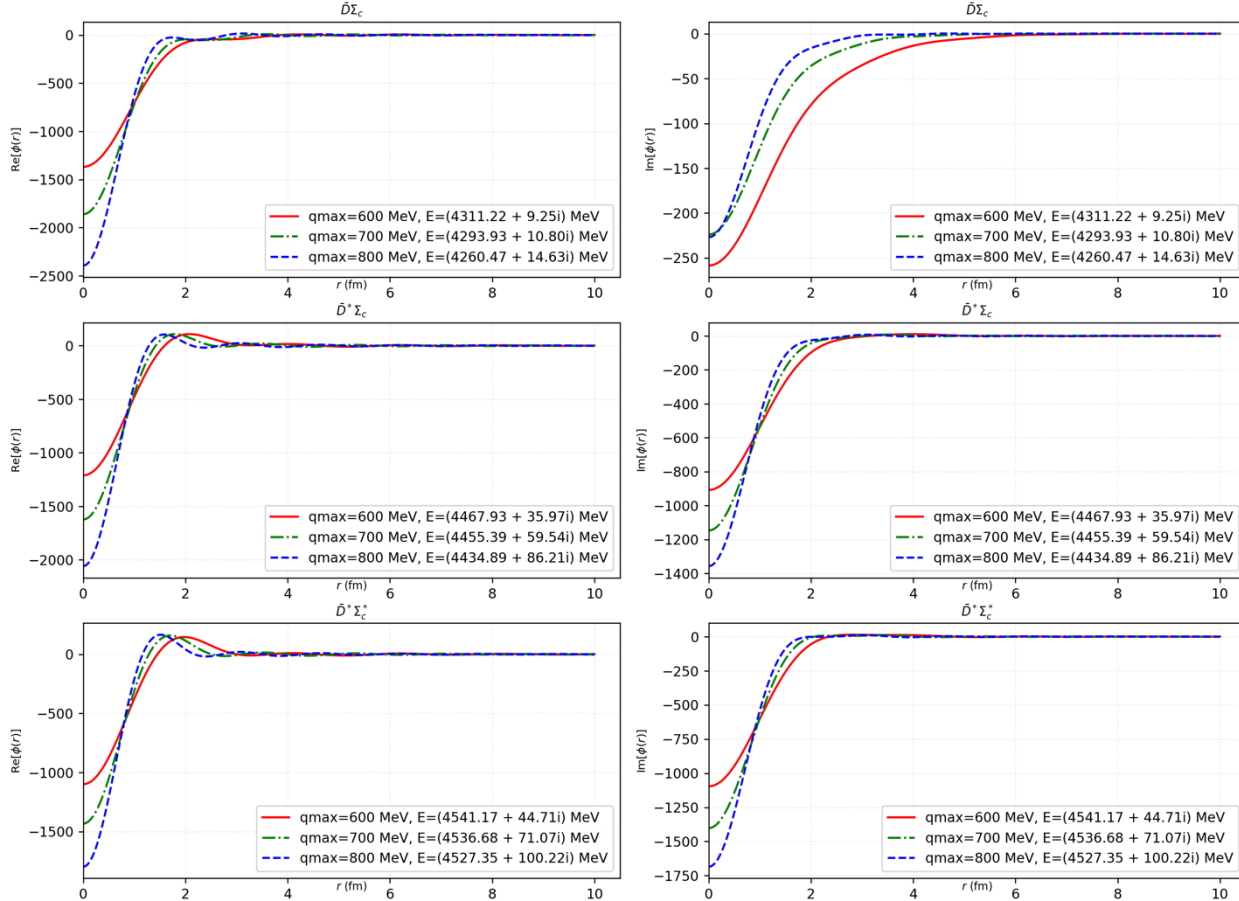
| $q_{max}$<br>[MeV] | Mass<br>[MeV] | Width<br>[MeV] | Main<br>channel       | $J^P$   | Experimental<br>states |
|--------------------|---------------|----------------|-----------------------|---------|------------------------|
| 600                | 4311.22       | 18.50          | $\bar{D}\Sigma_c$     | $1/2^-$ | $P_c(4312)$            |
| 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          | $\bar{D}^*\Sigma_c$   | $1/2^-$ | $P_c(4440)$            |
| 700                | 4455.39       | 119.08         | $\bar{D}^*\Sigma_c$   | $1/2^-$ |                        |
| 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

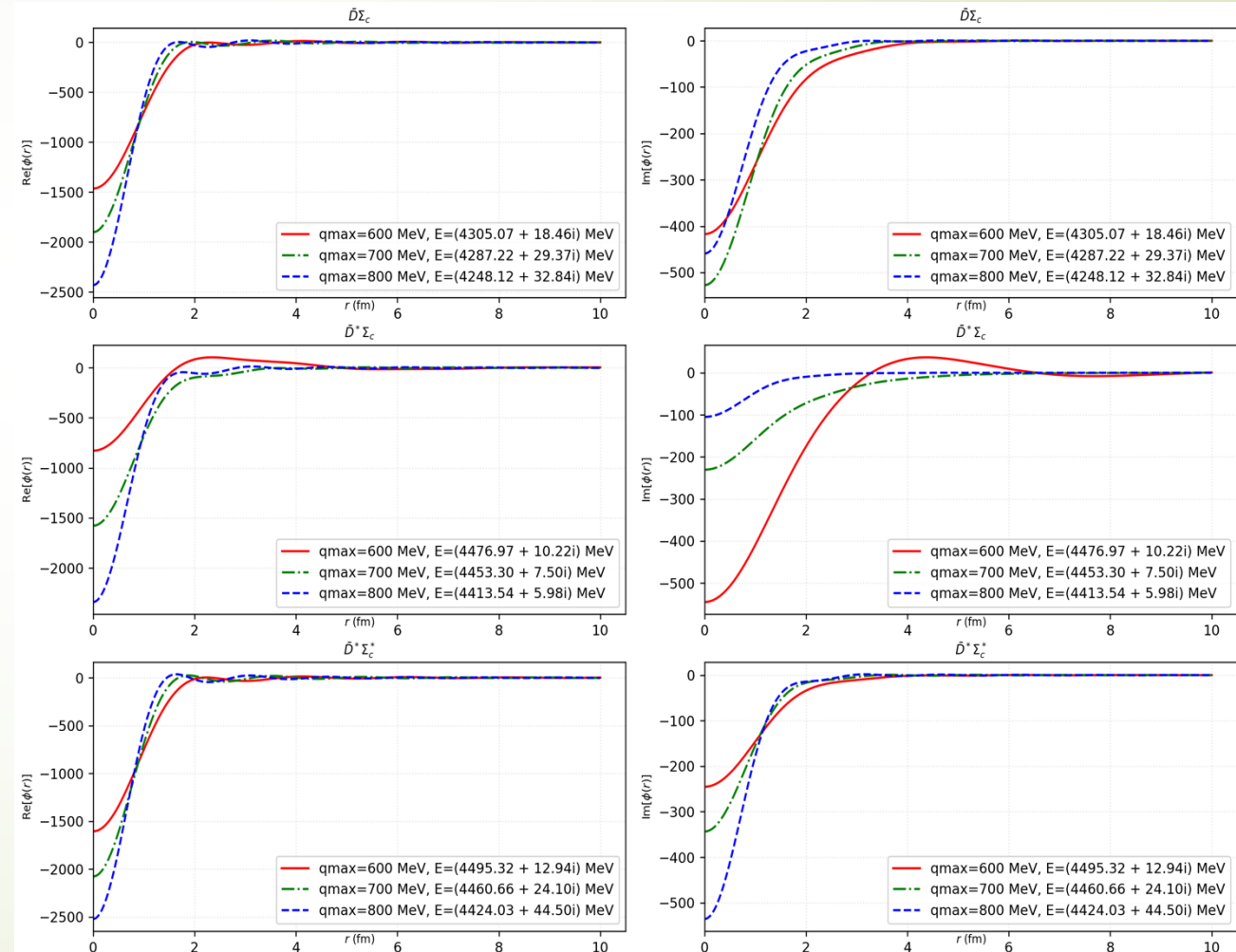


| $q_{max}$<br>[MeV] | Mass<br>[MeV] | Width<br>[MeV] | Main<br>channel       | Sector | $J^P$   | Experimental<br>states |
|--------------------|---------------|----------------|-----------------------|--------|---------|------------------------|
| 600                | 4305.07       | 36.92          | $\bar{D}\Sigma_c$     | 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     | $1/2^-$ | $P_c(4440)$            |
| 700                | 4453.30       | 15.00          | $\bar{D}^*\Sigma_c$   | VB     | $1/2^-$ |                        |
| 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     | $1/2^-$ | —                      |

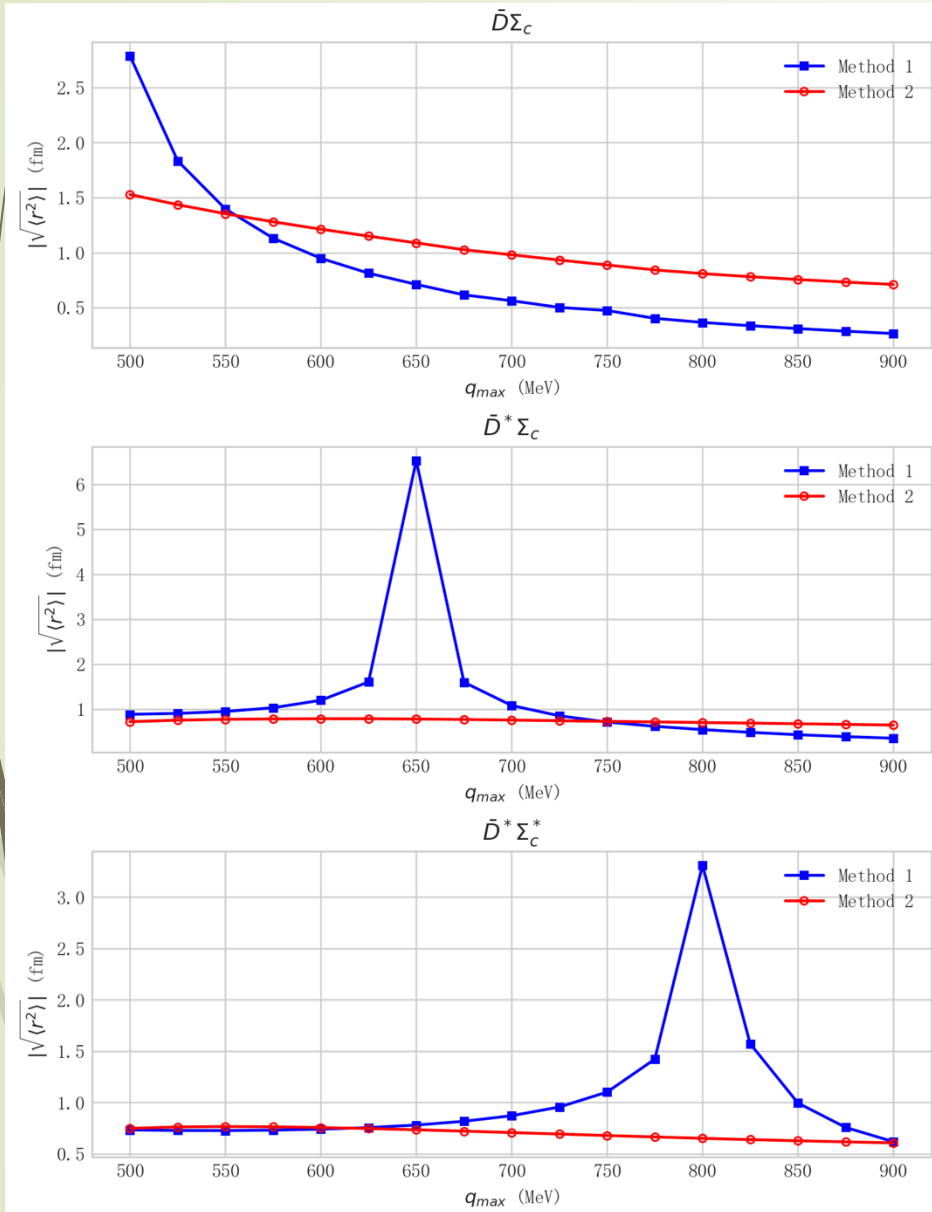
## (2) Pc wave functions : full coupled channels



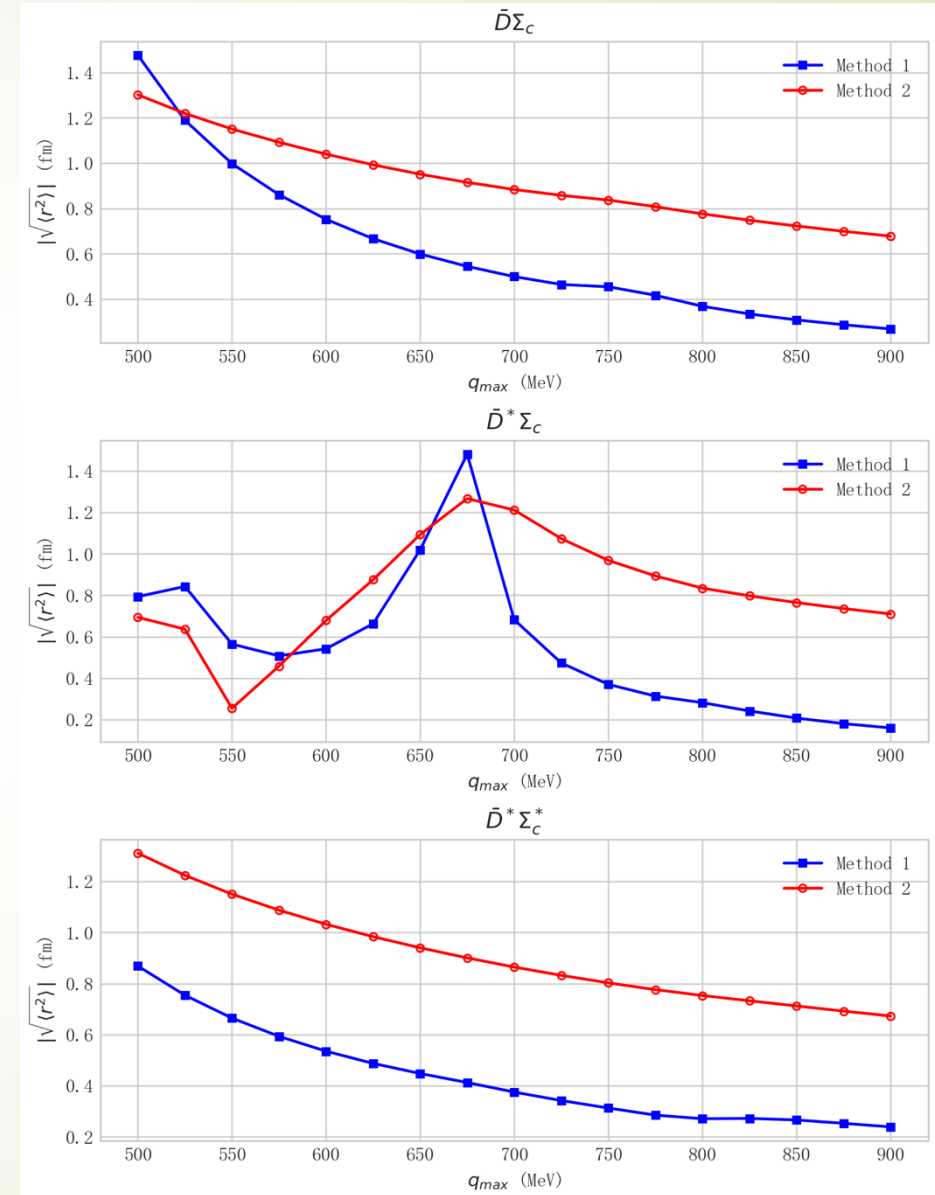
## PB and VB sectors



### (3) $P_c$ radii: full coupled channels

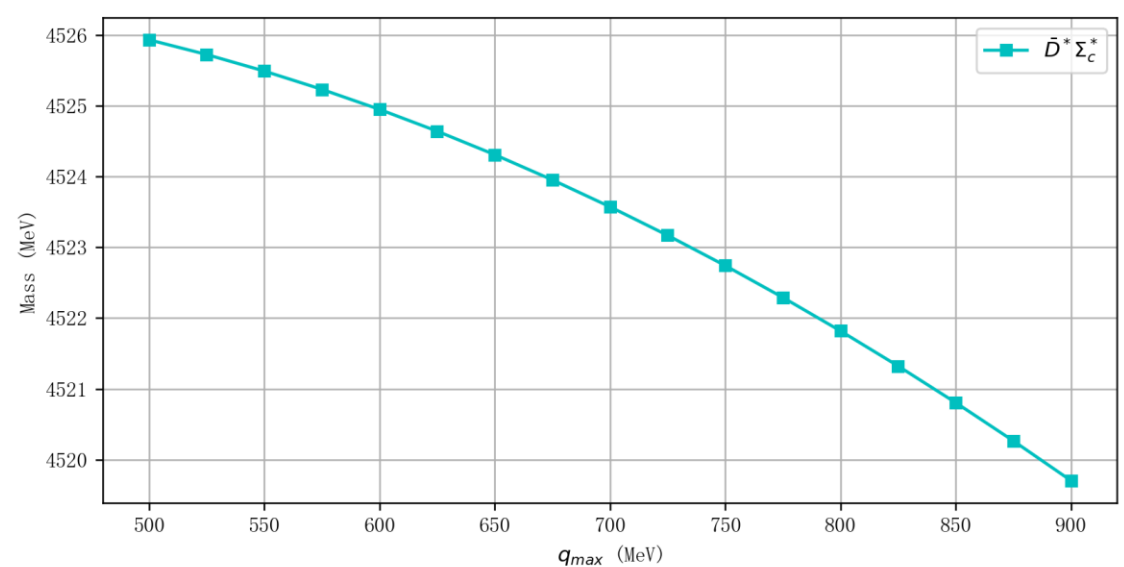
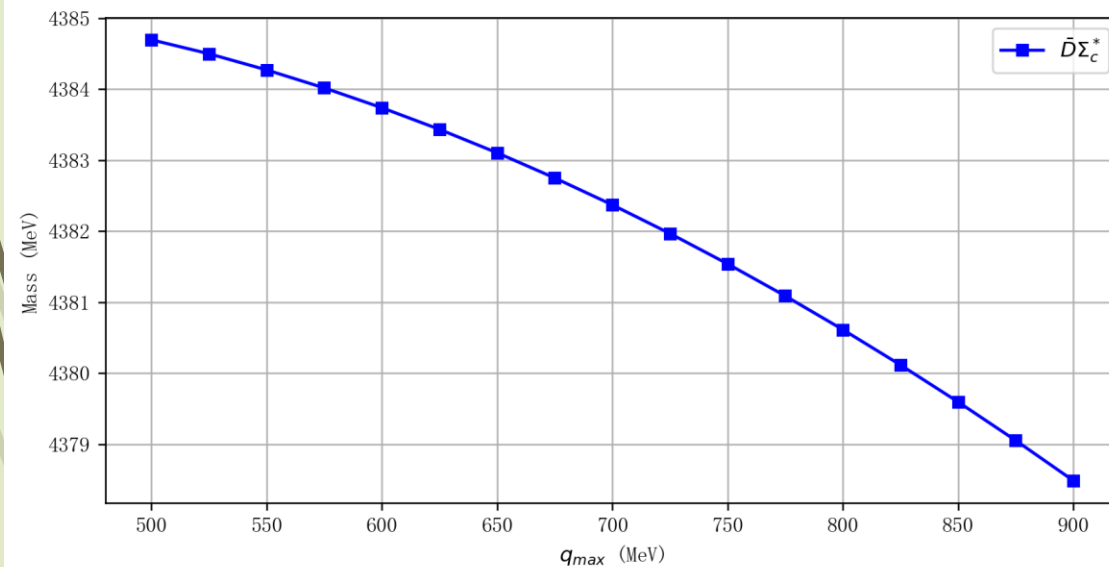
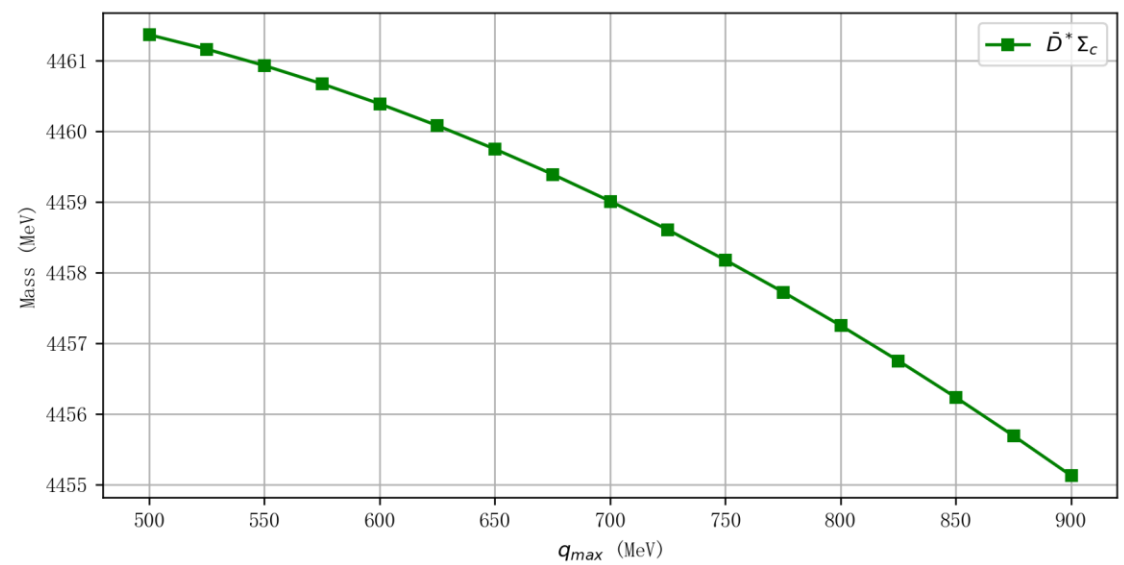
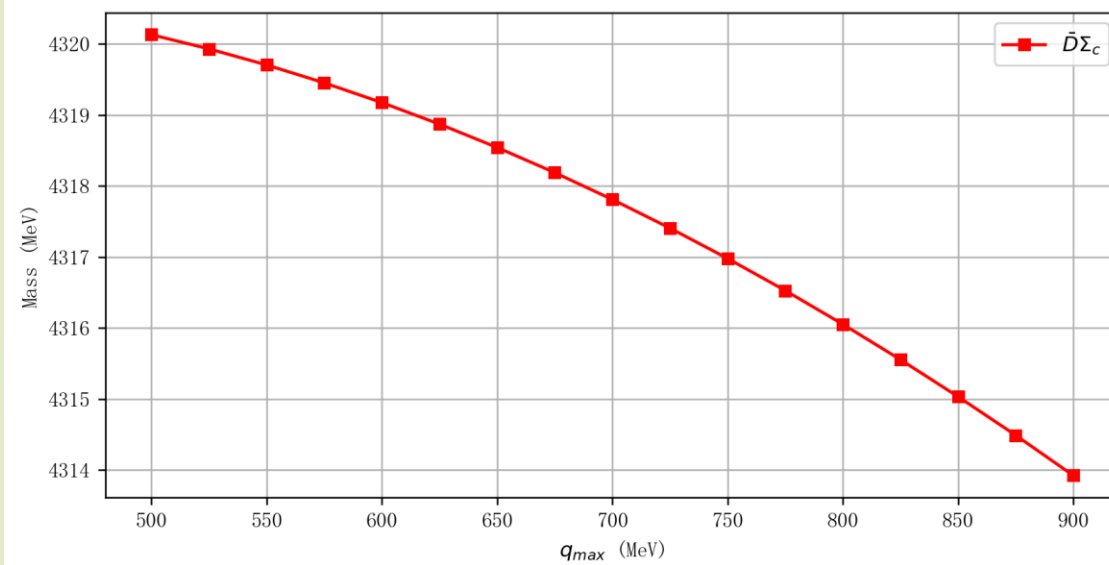


### PB and VB sectors

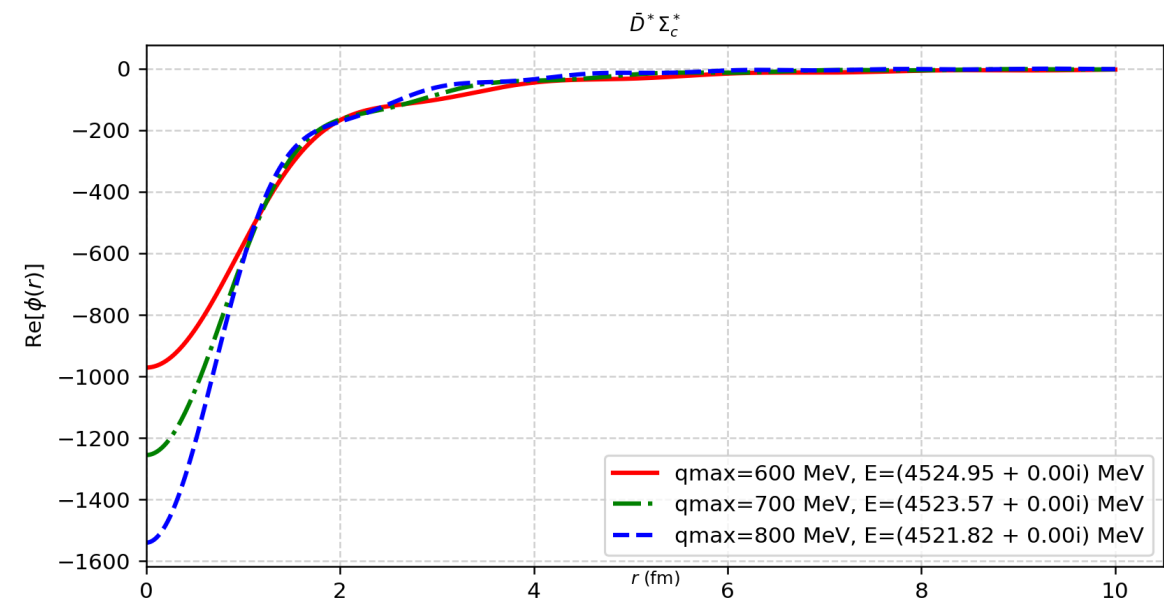
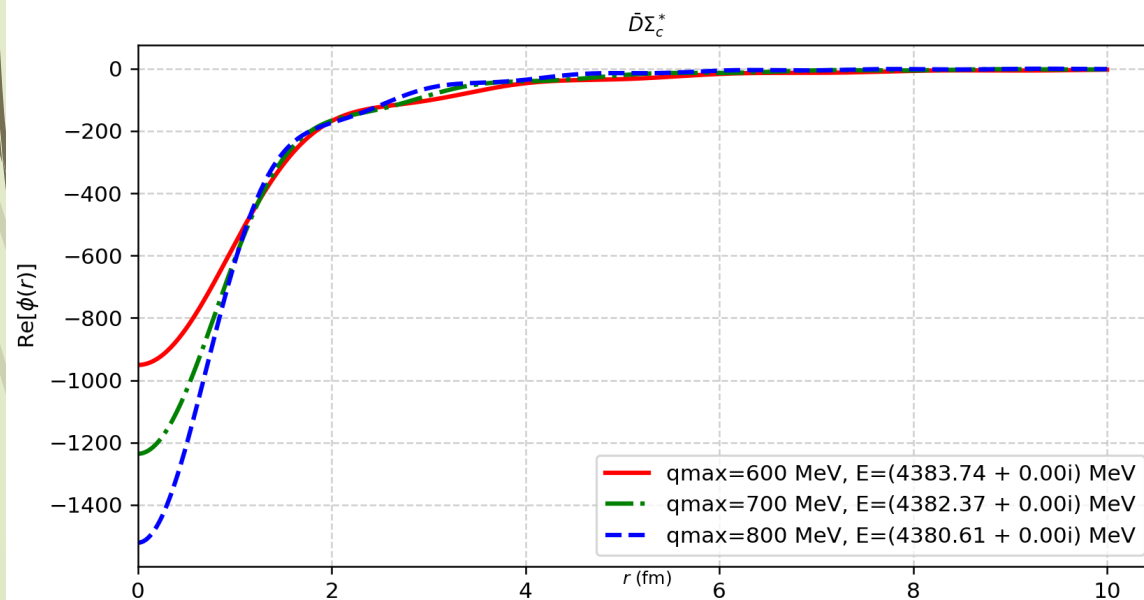
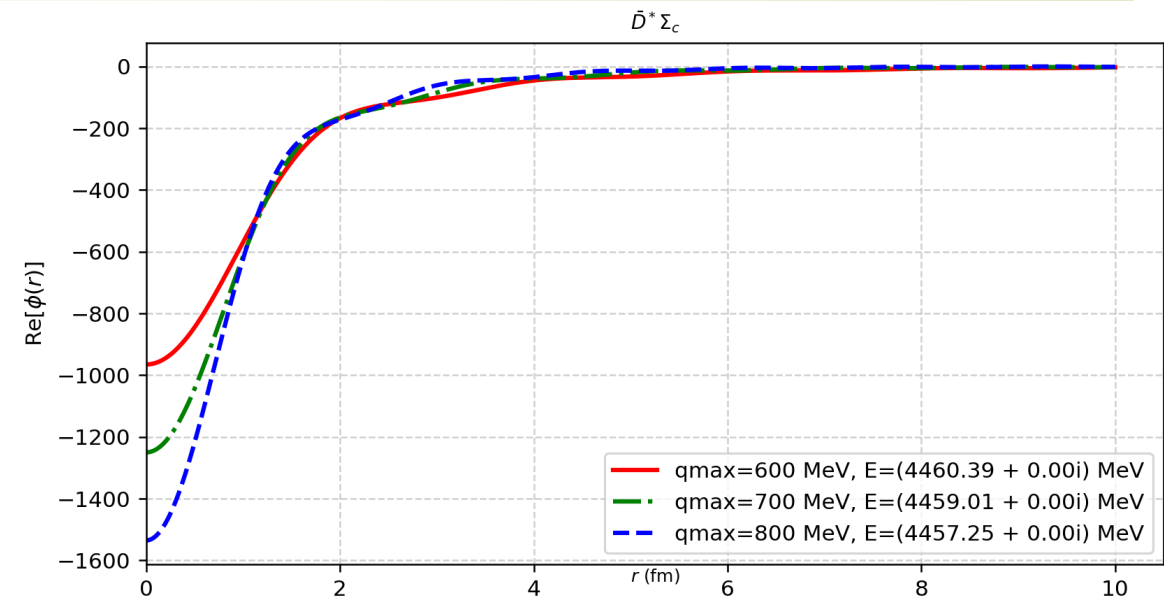
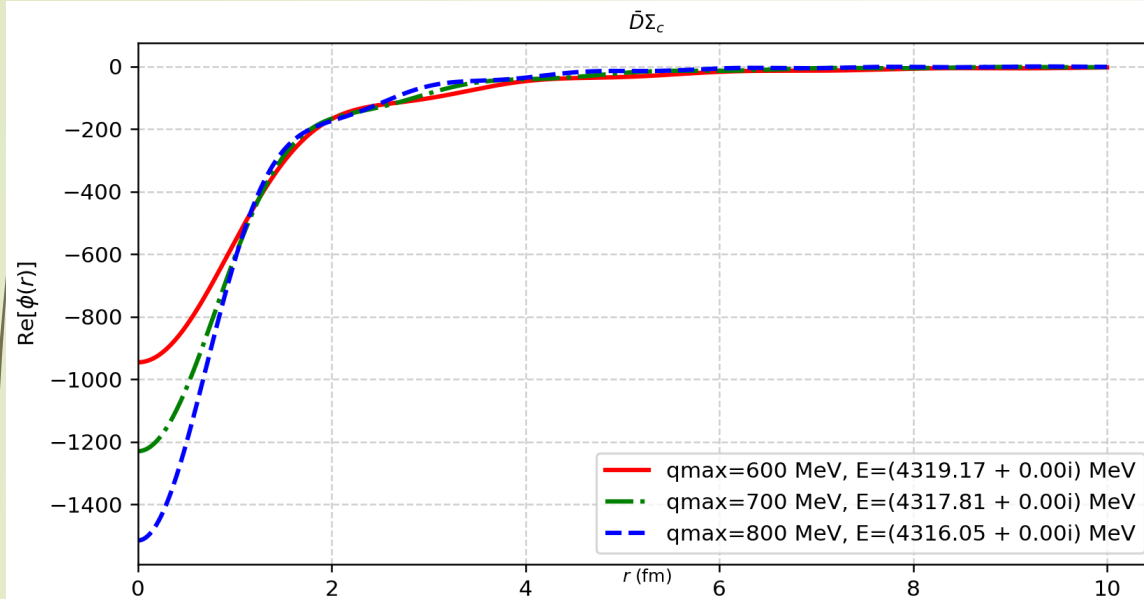


## (4) Single channel interaction poles:

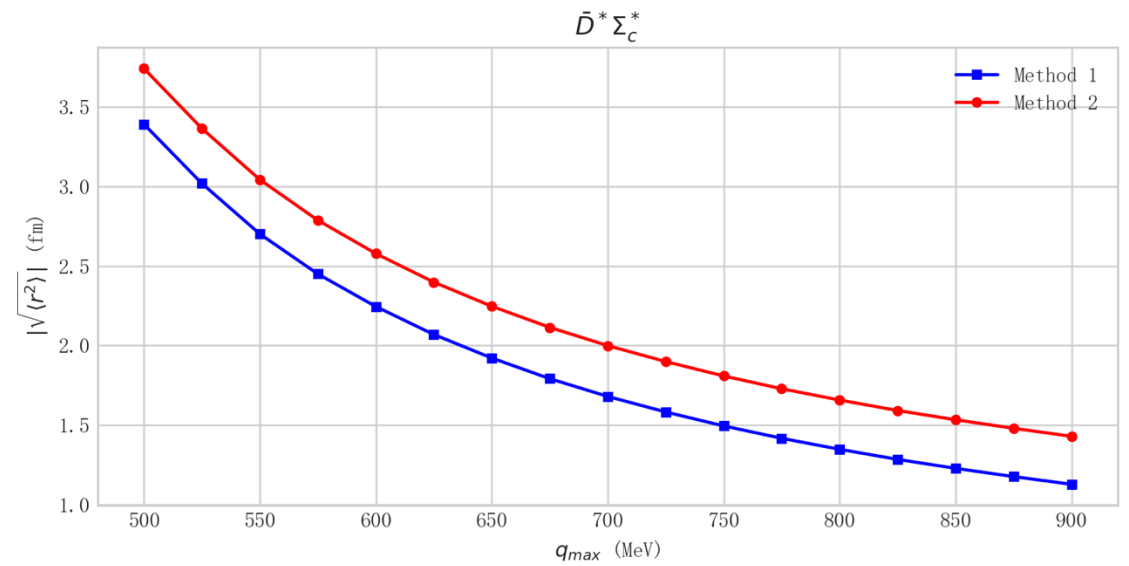
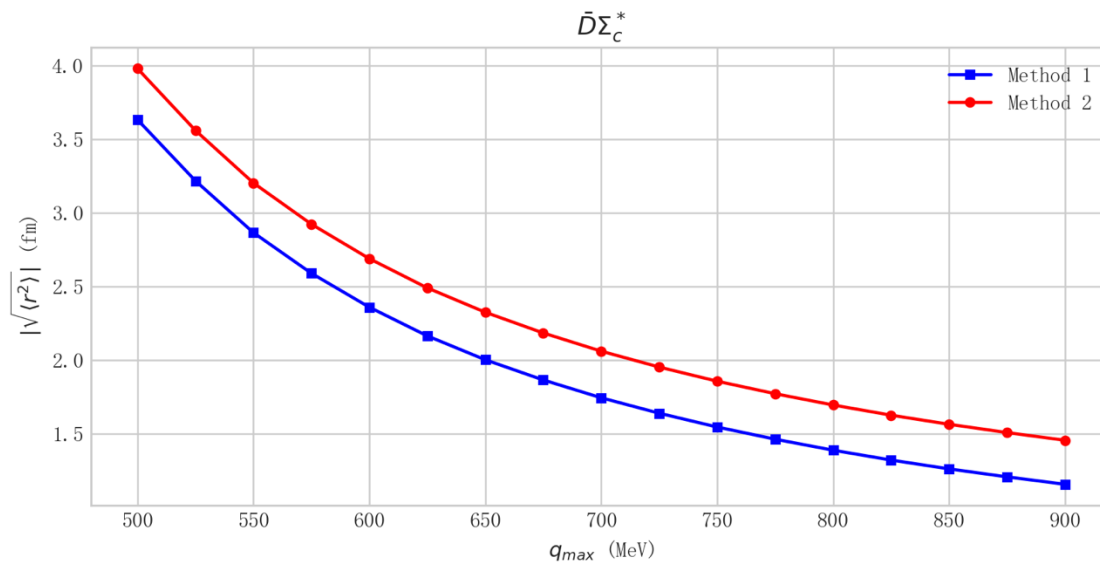
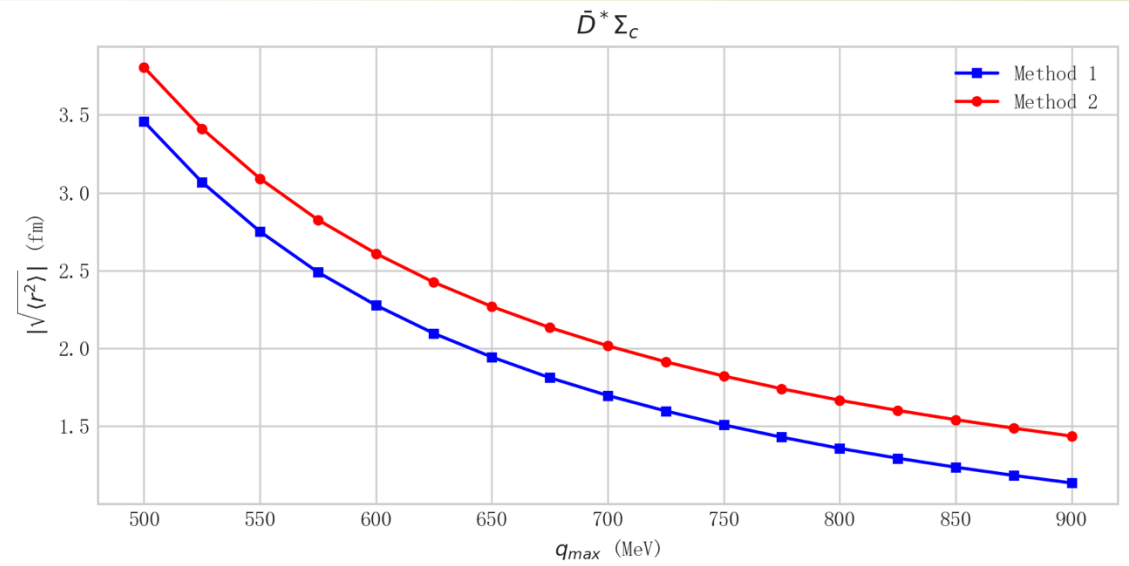
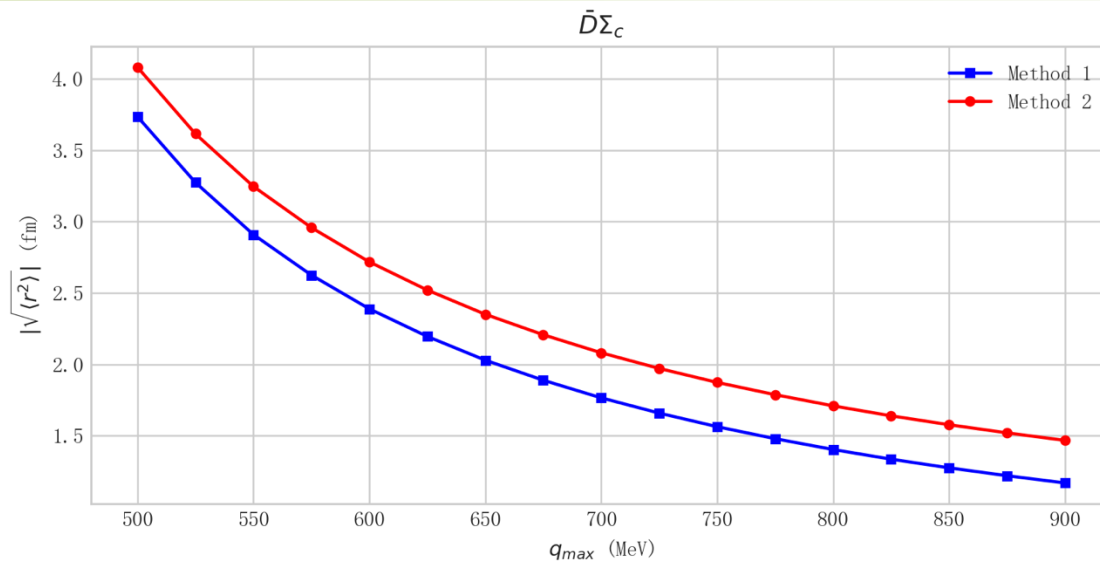
$J^P = 3/2^-$   $P_c$  states



# Wave functions:



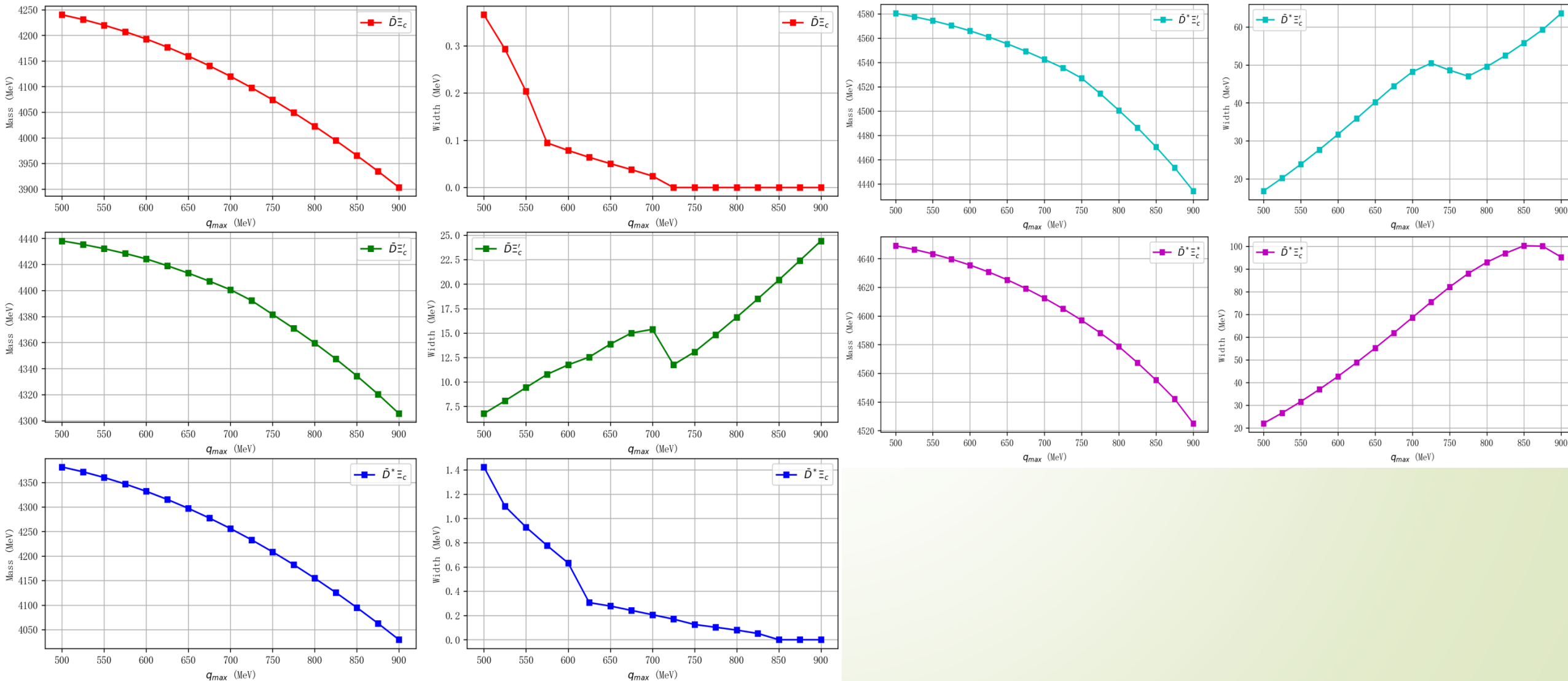
**Radii:**



# Further Results-2

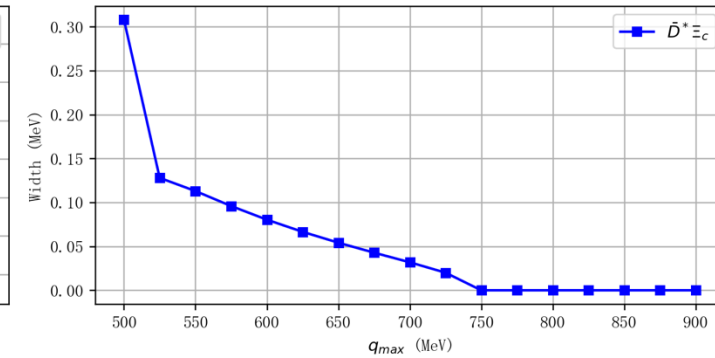
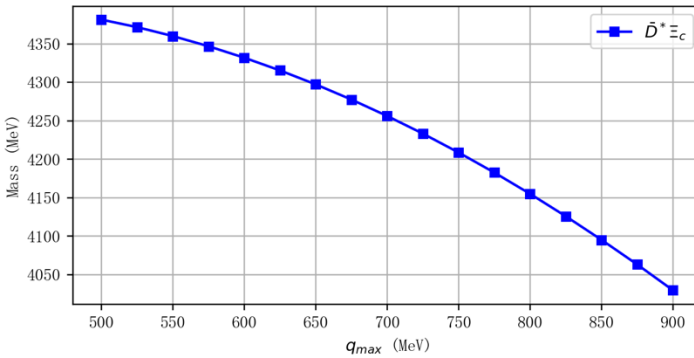
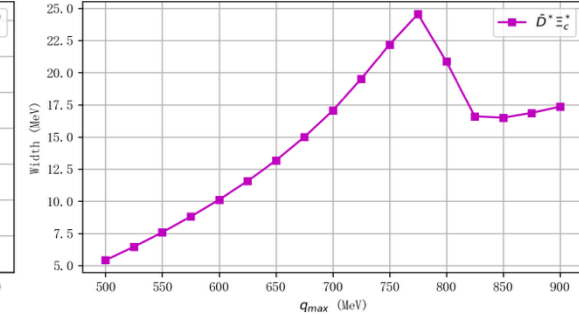
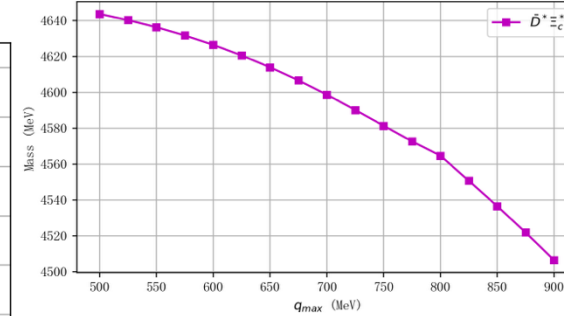
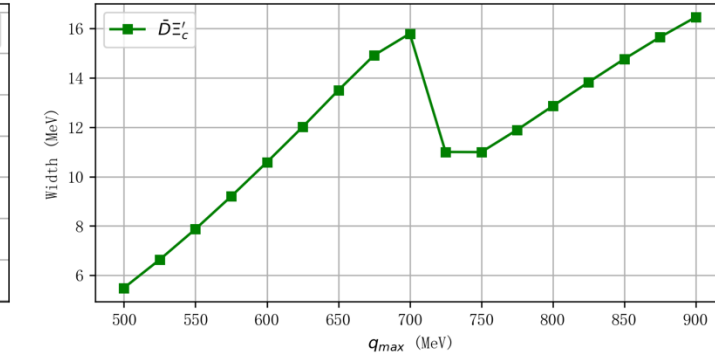
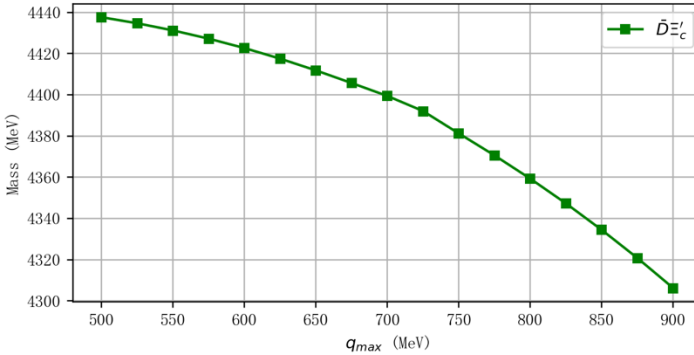
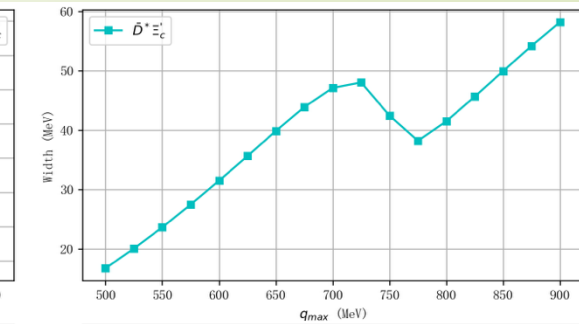
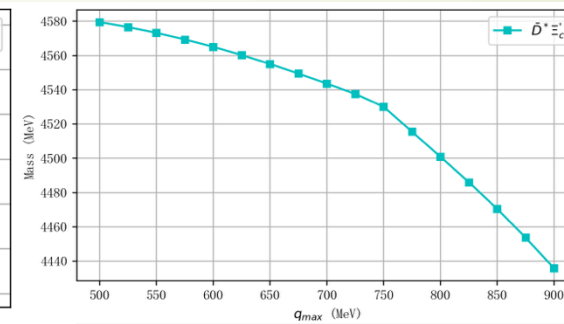
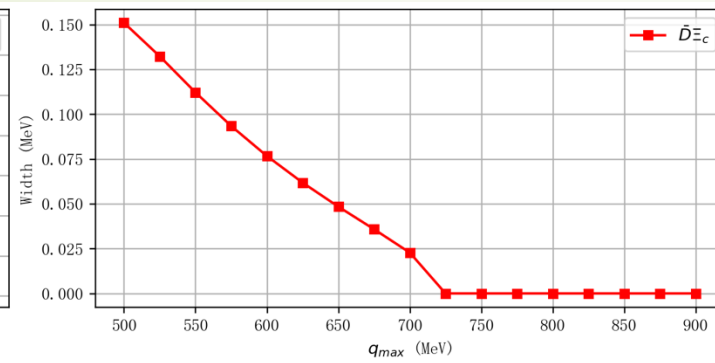
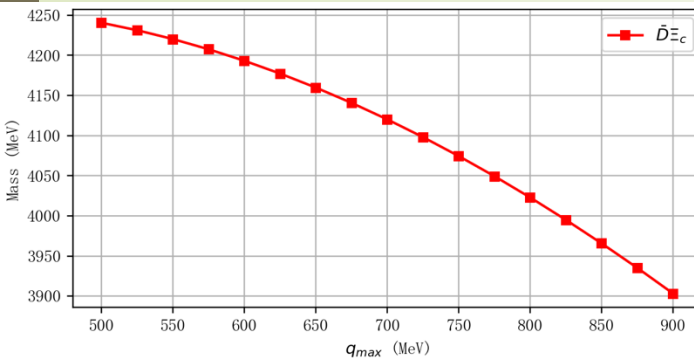


## (1) $J^P = 1/2^-$ Pcs poles: full coupled channels



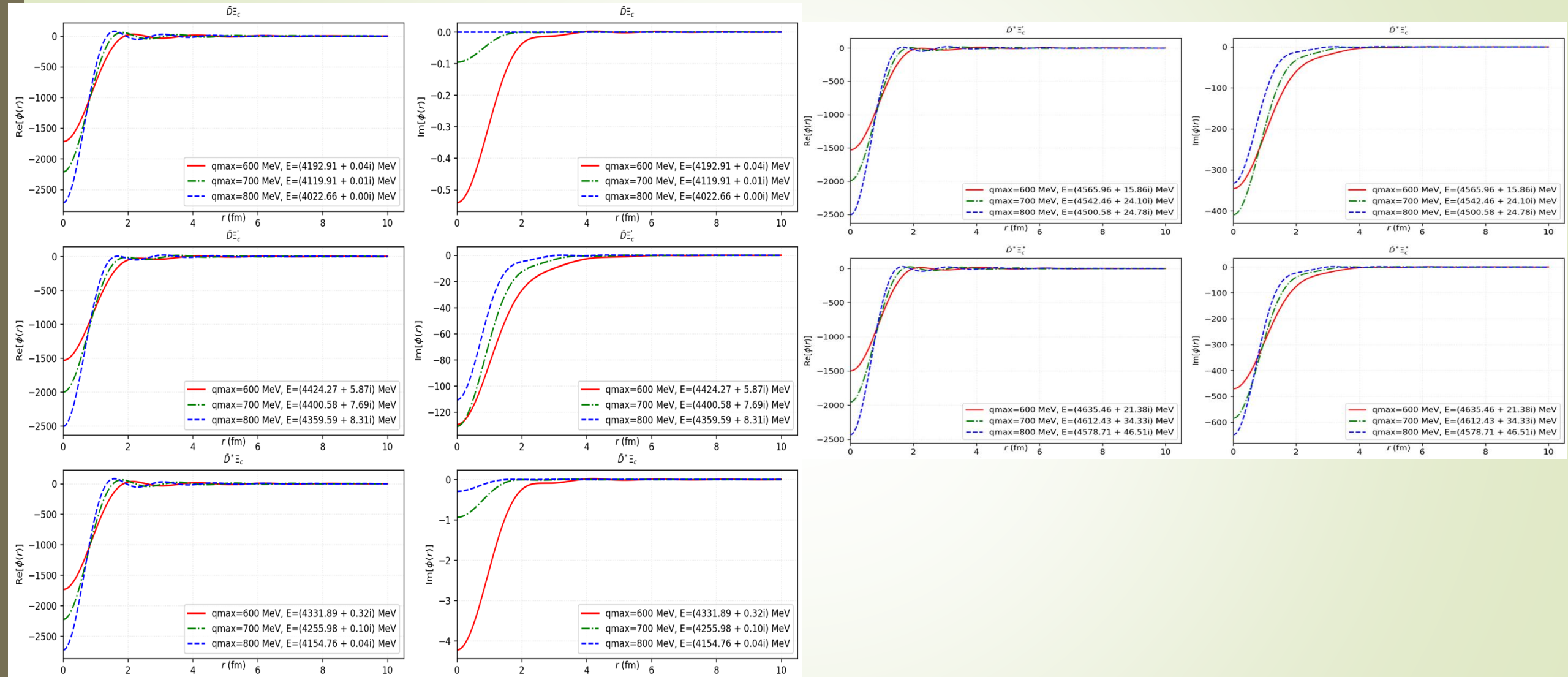
| $q_{max}$<br>[MeV] | Mass<br>[MeV] | Width<br>[MeV] | Main<br>channel    | $J^P$   | Experimental<br>states |
|--------------------|---------------|----------------|--------------------|---------|------------------------|
| 600                | 4192.91       | 0.08           | $\bar{D}\Xi_c$     | $1/2^-$ | —                      |
| 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



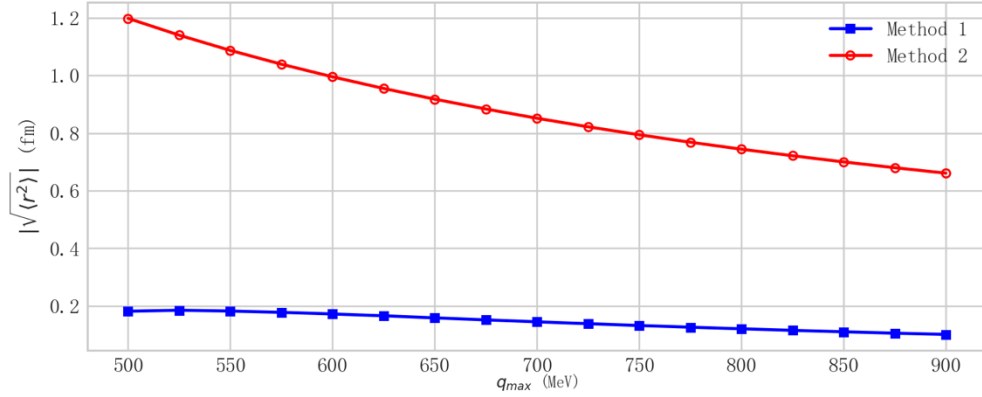
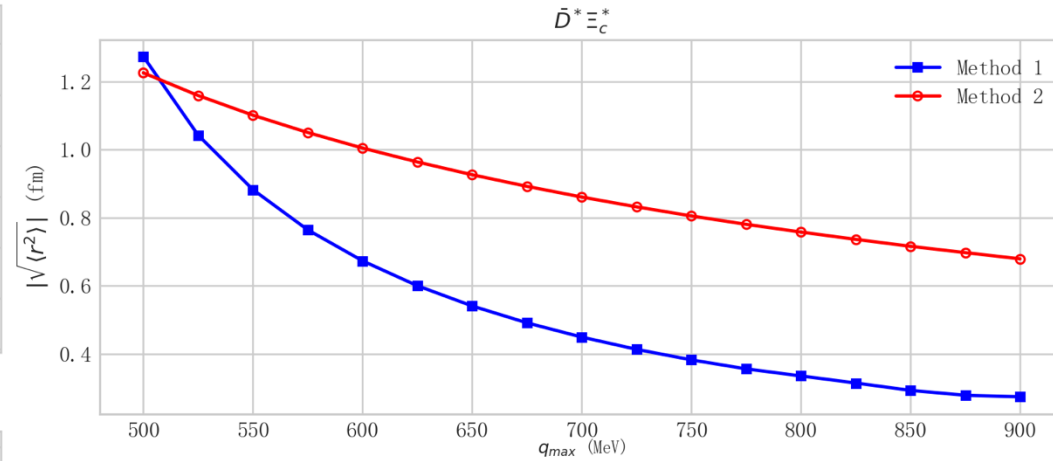
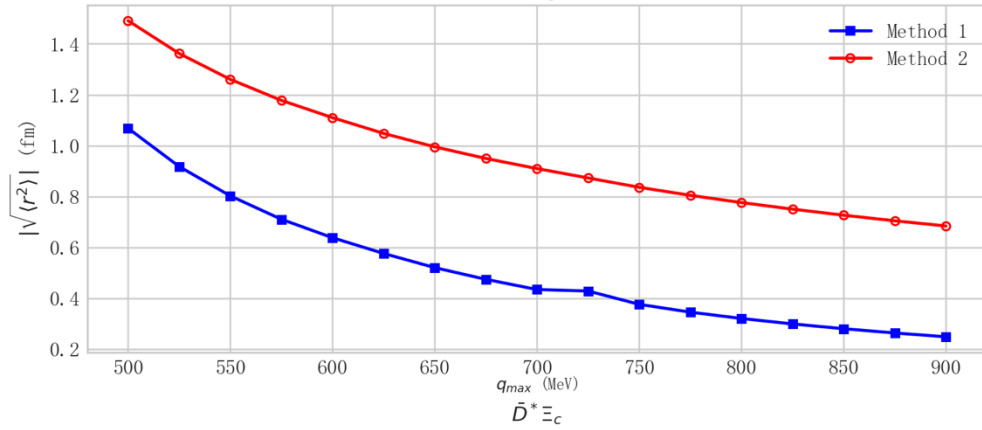
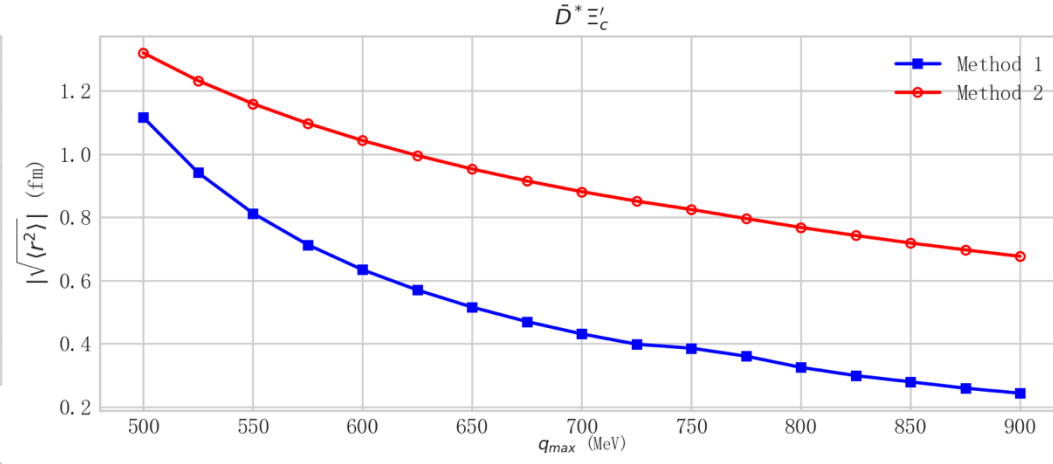
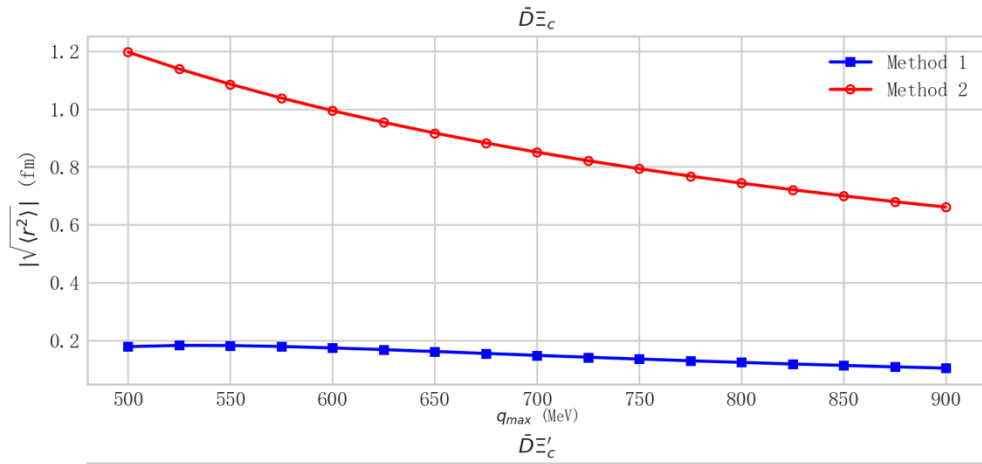
| $q_{max}$<br>[MeV] | Mass<br>[MeV] | Width<br>[MeV] | Main<br>channel    | Sector | $J^P$   | Experimental<br>state |
|--------------------|---------------|----------------|--------------------|--------|---------|-----------------------|
| 600                | 4192.98       | 0.08           | $\bar{D}\Xi_c$     | 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

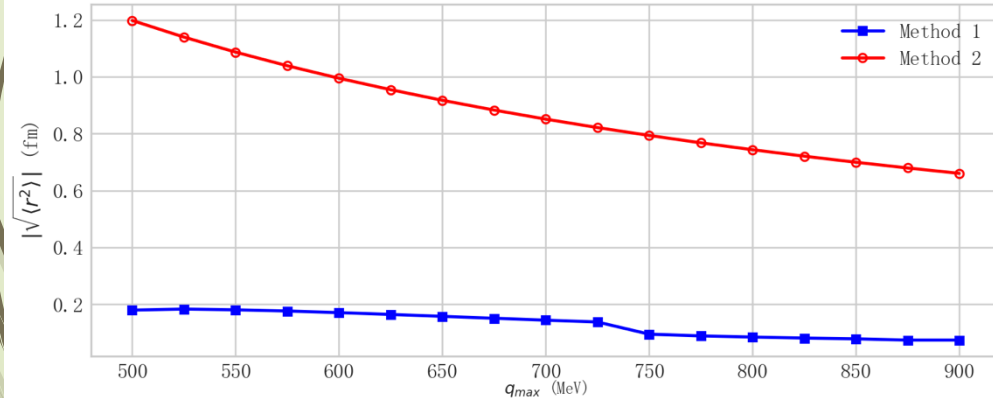
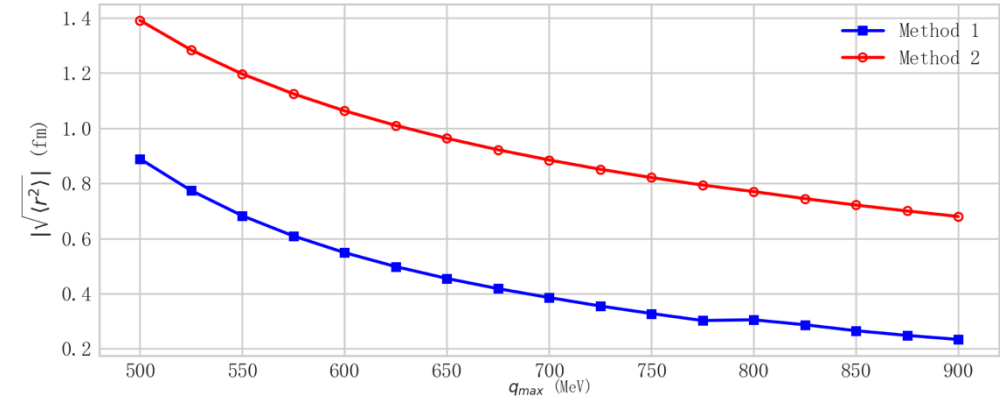
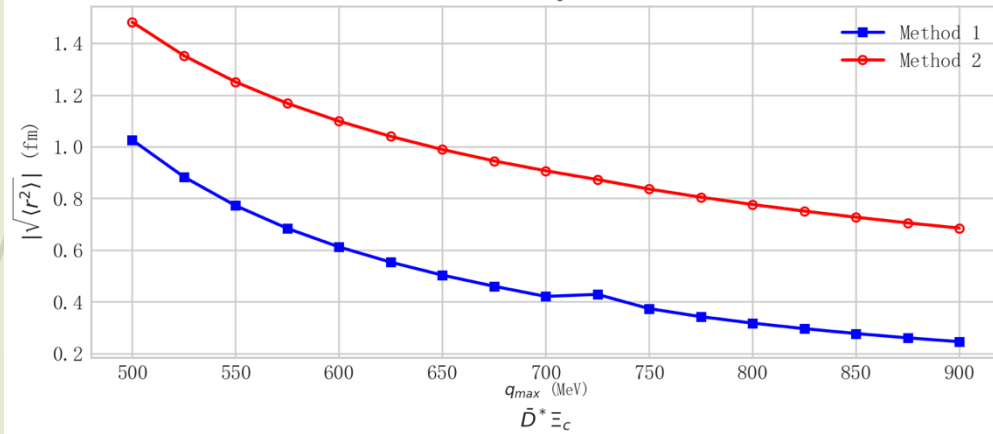
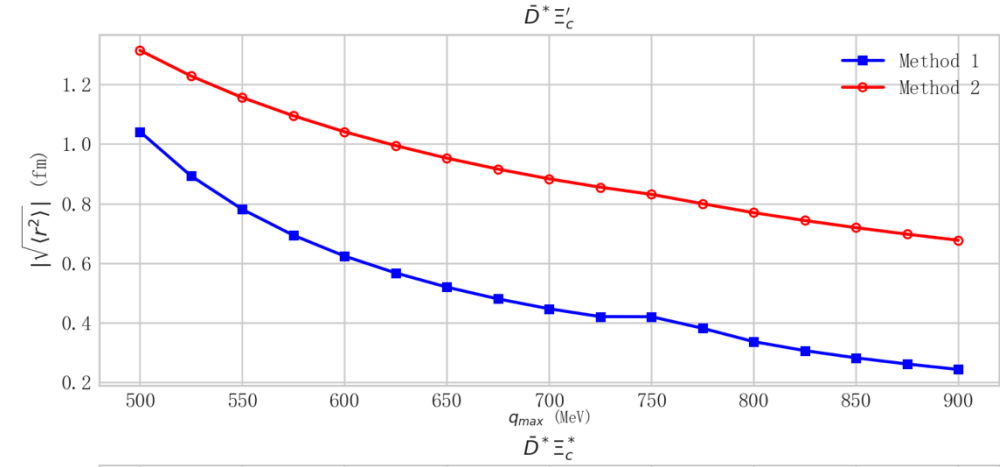
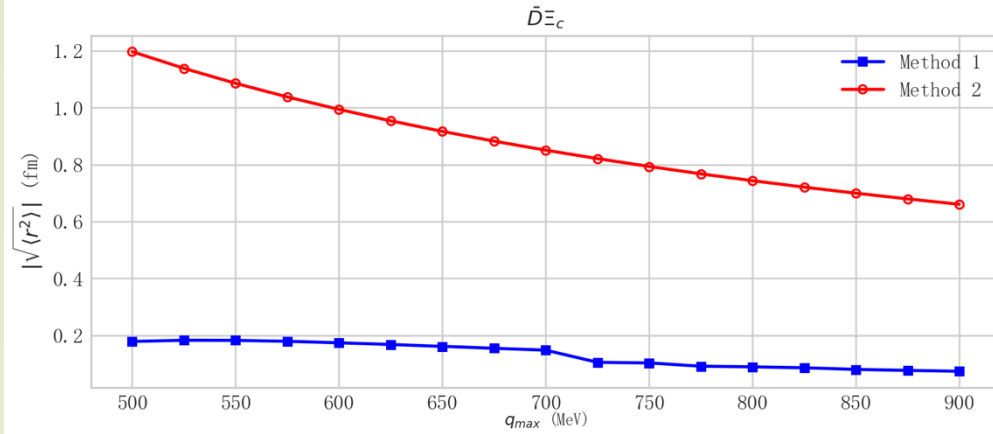




# (3) Pcs radii: full coupled channels

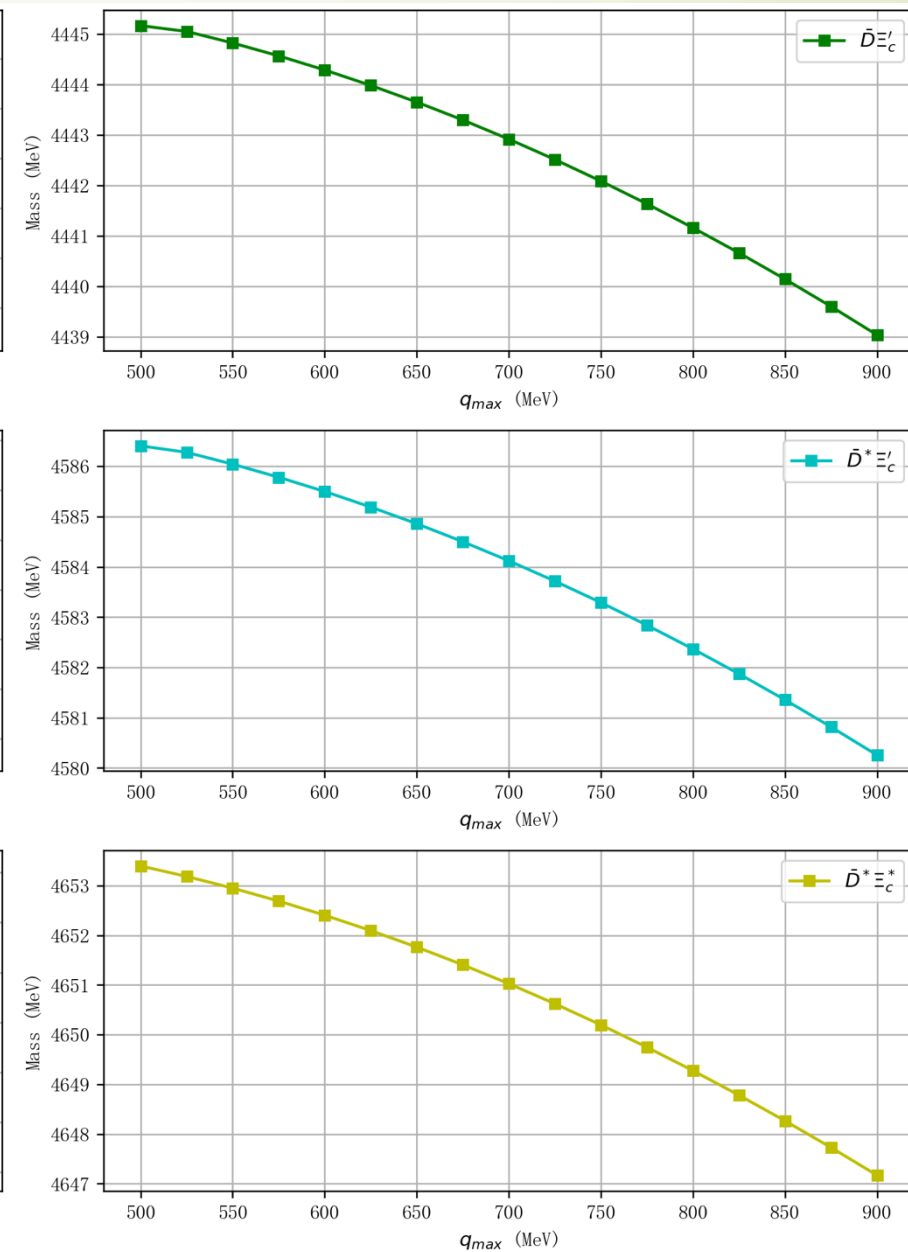
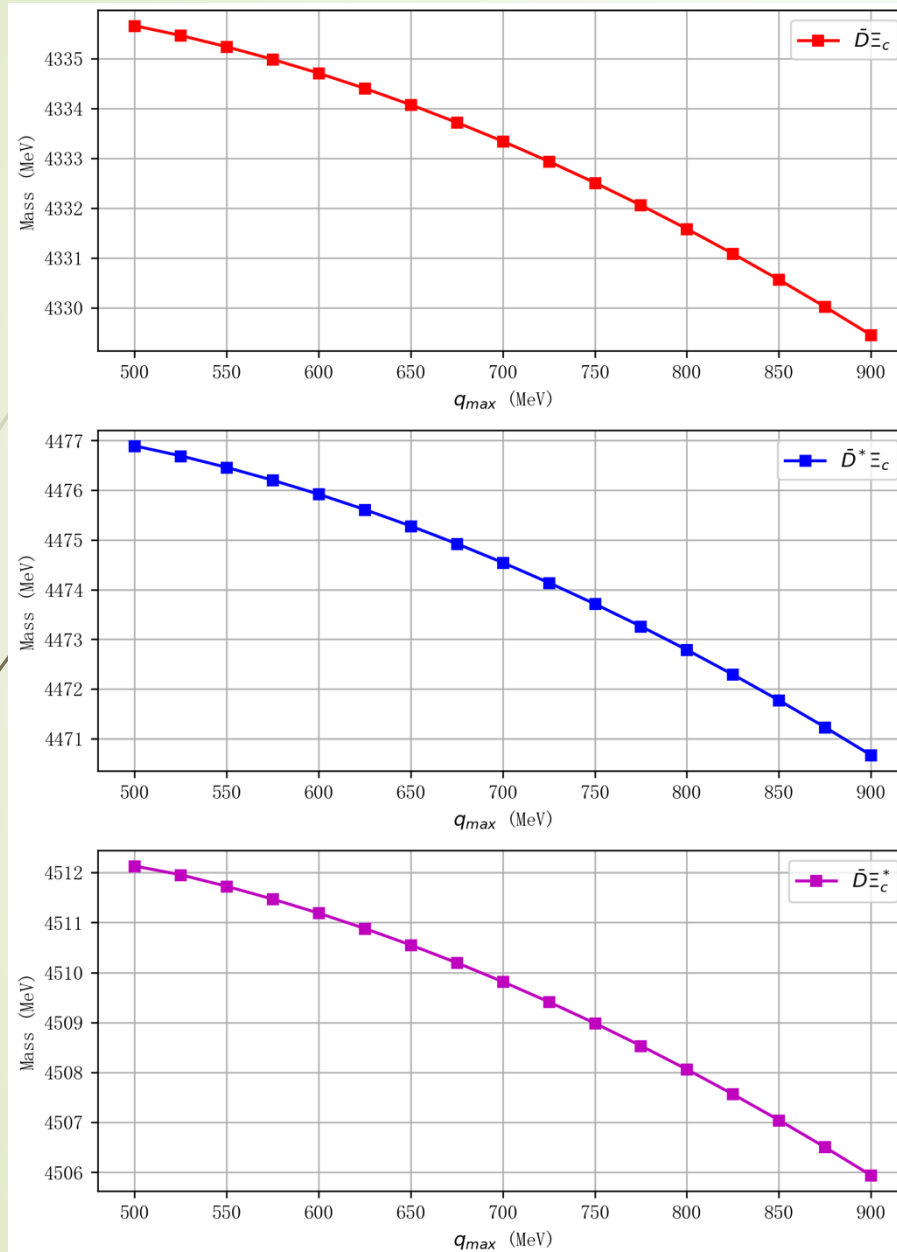


# (3) Pcs radii: PB and VB sectors

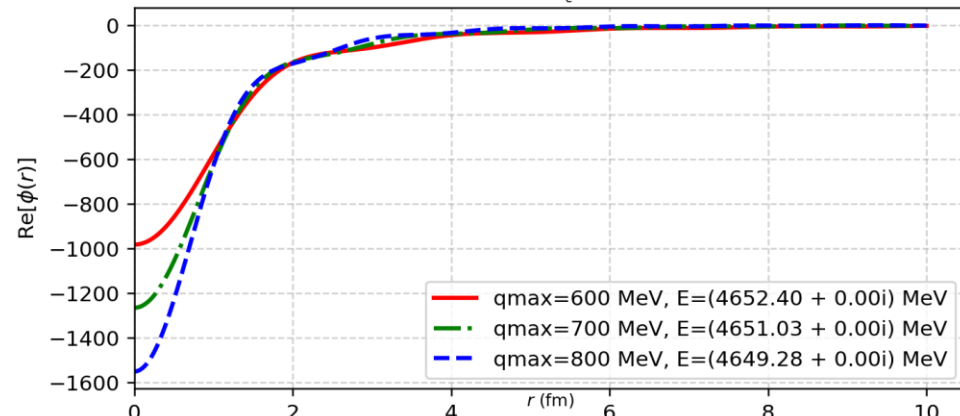
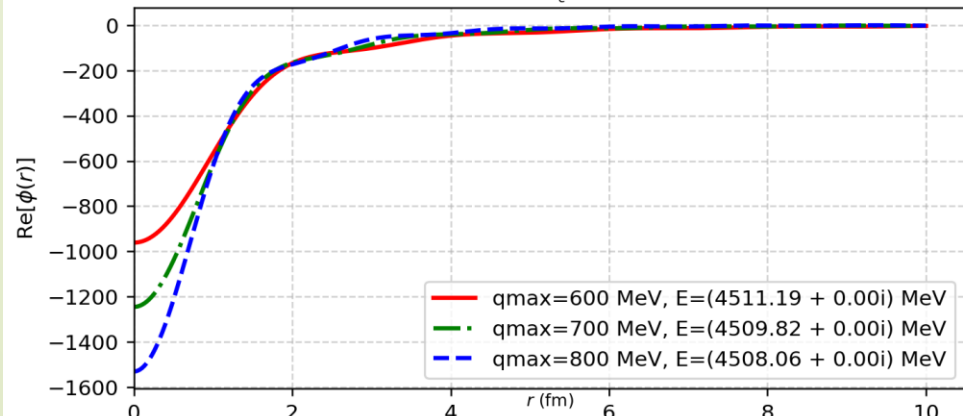
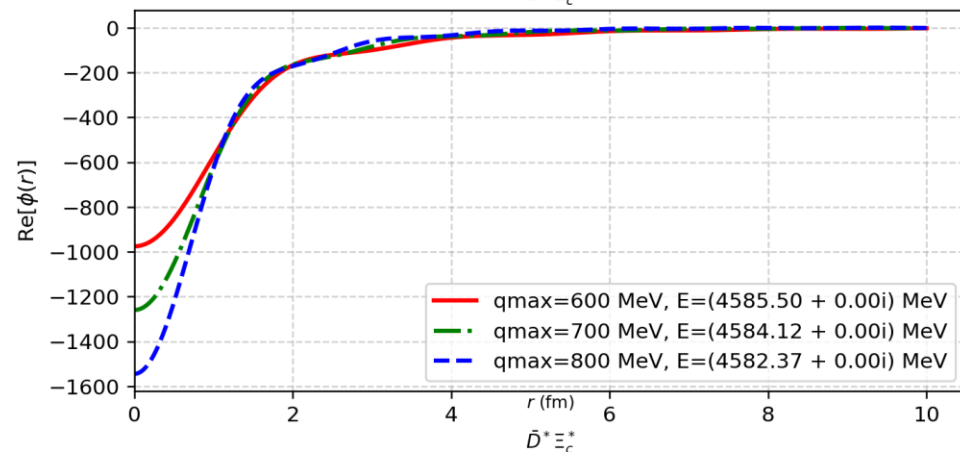
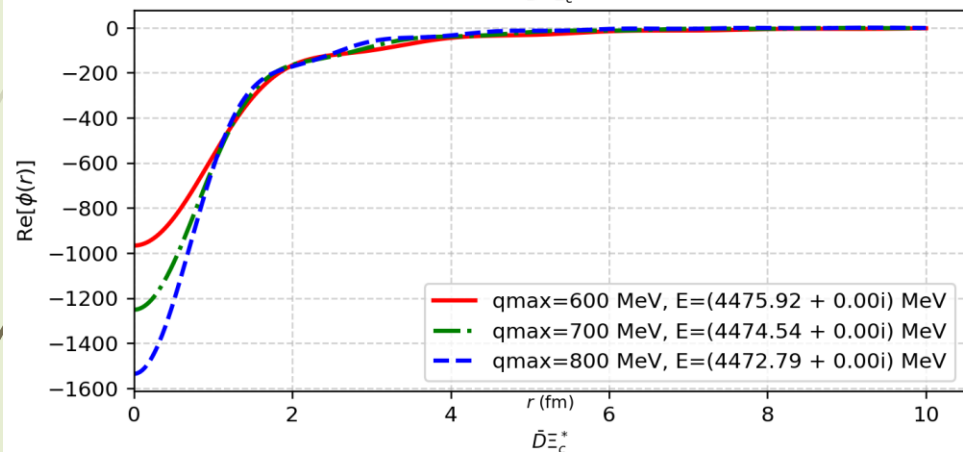
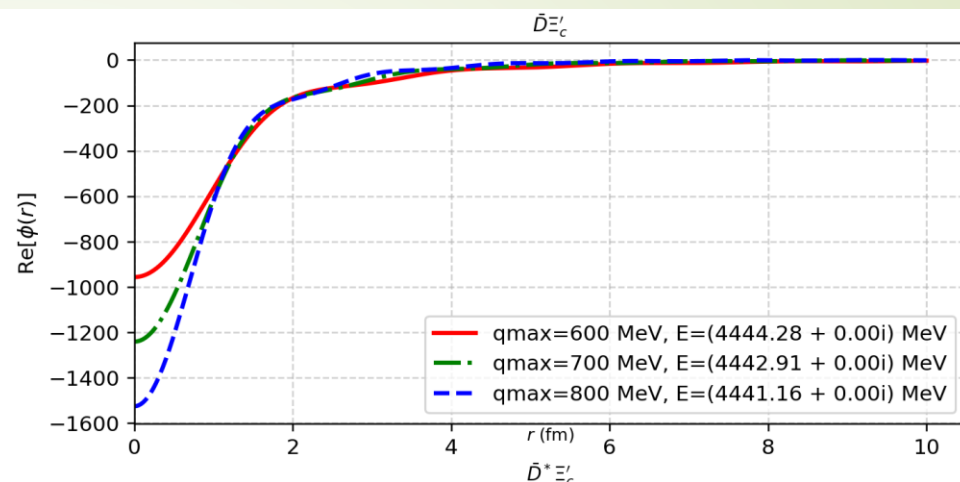
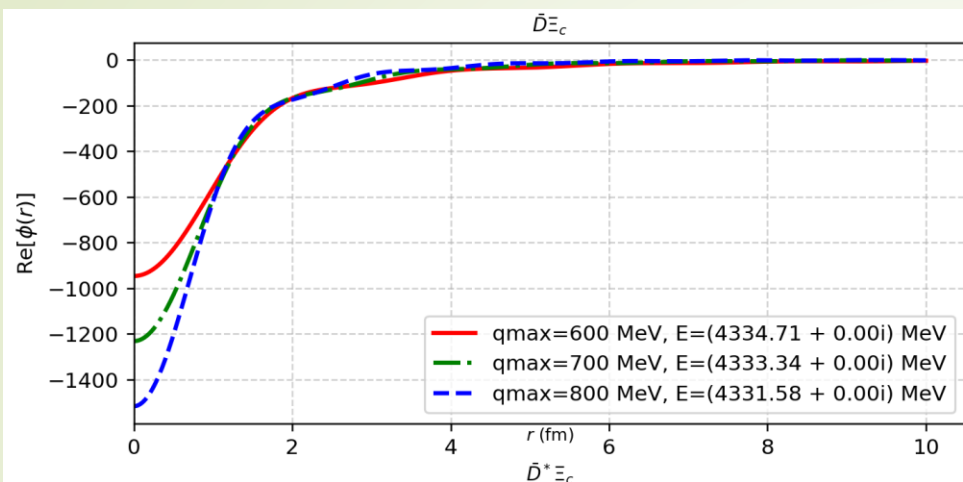


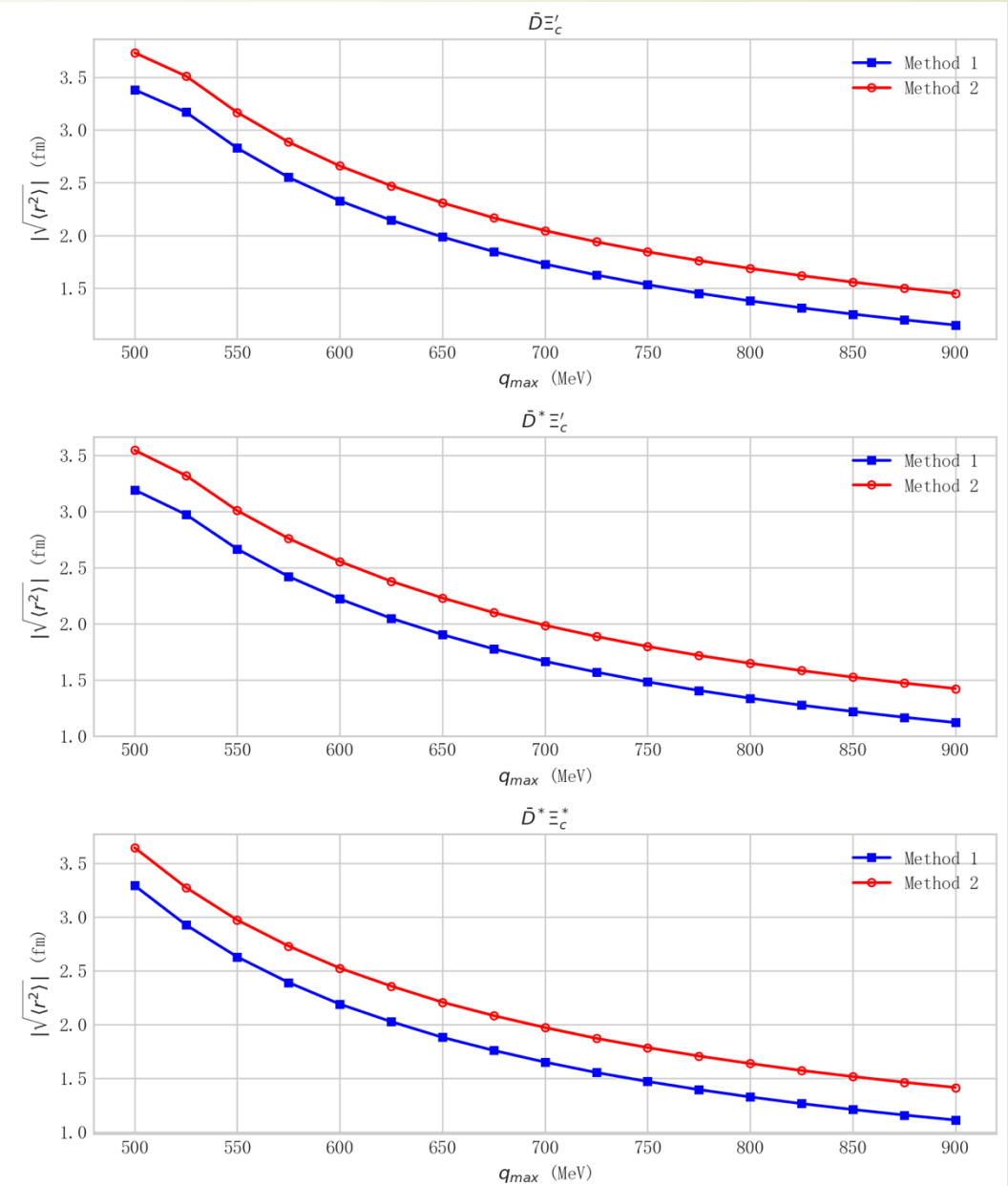
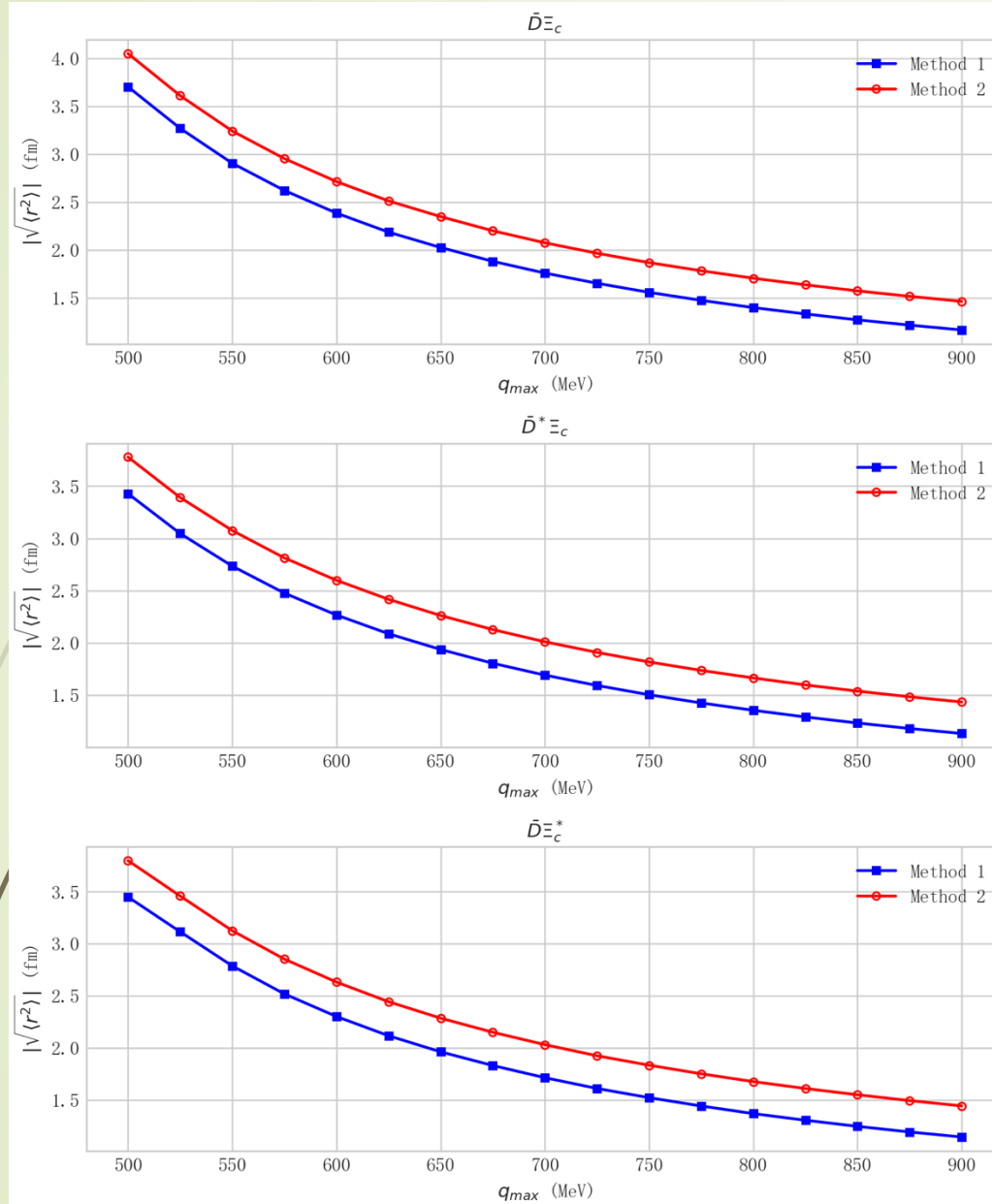
# (4) Single channel interaction poles:

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



# Wave functions:







## §4. Summary

- To generate the  $P_c$  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  $P_{cs}$  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.



*Thanks for your attention!*

感谢大家的聆听！