# Axial meson exchange and the molecular $Z_c(3900)$ and $Z_{cs}(3985)$ resonances


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# Outline

1. **Observations on $Z_c(3900)$ and $Z_{cs}(3985)$**
2. **Models of the molecular $Z_c(3900)$**
3. **Axial meson in the molecular $Z_c(3900)$**
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   - Saturated potential from light meson exchange
   - $X(3872)$ and $Z_c(3900)$ in $D^*\bar{D}$ scattering
   - $Z_{cs}(3985)$ generation
4. **More thinking on $\sigma$ exchange**
5. **Summary**

# Observations on $Z_c(3900)$ and $Z_{cs}(3985)$

## Observations on $Z_c(3900/4020)$

- $e^+e^- \to J/\psi\pi^+\pi$, $Z_c(3900) \to J/\psi\pi^\pm$,
  $M_R - i\Gamma = 3899.0 \pm 8.5 - i46 \pm 10.8\,\mathrm{MeV}$ PRL 110,252001(2013), BESIII
  $D^*\bar{D}$ threshold: $3875.80\ \mathrm{MeV}$
- $e^+e^- \to h_c\pi^+\pi$, $Z_c(4020) \to h_c\pi^\pm$ and $Z_c(3900) \to h_c\pi^\pm$ not seen
  $M_R - i\Gamma = 4022.9 \pm 3.5 - i7.9 \pm 5.3\,\mathrm{MeV}$ PRL 111,242001(2013), BESIII
  $D^*\bar{D}^*$ threshold: $4017.11\ \mathrm{MeV}$

## Observation on $Z_{cs}(3985)$

- $e^+e^- \to K^+Z_{cs}(3985) \to K^+\left(D_s^-D^{*0} + D_s^{*-}D^0\right)$
  $3982.5^{+1.8}_{-2.6} - i12.8^{+5.3}_{-4.4}\,\mathrm{MeV}$ PRL 126,102001(2021), PRL 129,112003 (2022), BESIII
  $D_s^-D^{*\,0} - D_s^{*\,-}D^0$ thresholds: $3975.19\text{-}3977.03\ \mathrm{MeV}$
- A broad $Z_{cs}(4000) \to J/\psi K$, PRL 127 8, 082001(2021), LHCb
- $Z'_{cs}(4123) \to D_s^{*-}D^{*0}$ (2.1 $\sigma$), CPC 47 (2023) 3, 033001, BESIII

# Models on the molecular $Z_c(3900)$

## $\pi$ exchange

- $\pi$ exchange generates $Z_c(3900)$ 2306.12406, G.J. Wang et al

## $\sigma$ and $\pi$ exchange

- $\pi$ and $\sigma$ exchange generate $Z_c(4020)$ , EPJC,61,(2009),Xiang Liu et al;PRD 99, (2019), M.Z. Liu et al

## Two pions exchange

- Two-pion exchange generates $Z_c(3900/4020)$, PRD 90, (2014), E. Oset et al

## Charmonium exchange

- Charmonium exchange generate $Z_c(3900/4020)$, PRD 90,(2014) J. He; Prog. Phys. 41. 65 (2021) X.K. Dong et al

## Coupled scattering

- Probing $Z_c(3900)$ in $J/\psi\pi - D^*\bar{D}$, 2307.12283, Lin-Wan Yan et al

# Linear sigma model, $\pi - a_1$ mixing

## The L$\sigma$M

- $\mathcal{L}_{\rm int}^{\rm N\sigma L} = g\,\bar{\psi}_N(\phi_0 + i\,\gamma_5\,\vec{\tau}\cdot\vec{\phi})\psi_N$ ,
  where $\psi_N$ is the relativistic nucleon field and $g$ a coupling constant.
- $(\langle\phi_0\rangle = f_\pi/\sqrt{2})$ which also provides the nucleons with mass.
- The $\sigma$ field is defined as a perturbation of the $\phi_0$ field around its vacuum expectation value $(\phi_0 = f_\pi/\sqrt{2} + \sigma)$.
- $g = g_{\sigma NN} = g_{\pi NN} = \sqrt{2}M_N/f_\pi = 10.2.$

## $\pi - a_1$ mixing

- $I^G(J^{PC}) = 1^-(1^{++})$ can mix with the pions, $\partial_\mu\pi \to \partial_\mu\pi + \lambda_1\,m_{a1}\,a_{1\mu}$ where $\pi^a$ and $a_{1\mu}$ are the pion and axial meson fields and $\lambda_1$ a proportionality constant, which we expect to be in the $\lambda_1 \sim (1.6 - 2.1)$ range.

# Saturated potential: scalar and axial meson

Scalar meson:

$$\mathcal{L}_S = g_{\sigma 1}\, q_L^\dagger \sigma q_L\,,$$

$$V_\sigma(\vec{q}) = -\frac{g_{\sigma 1}^2}{\vec{q}^2 + m_\sigma^2}\,,$$

Axial meson:

$$\mathcal{L} = \frac{g_1}{\sqrt{2} f_\pi} q_L^\dagger\, \vec{\sigma}_L \cdot \vec{a}\, q_L\,,$$

with $\vec{\sigma}_L$ the spin operators (Pauli matrices) as applied to the light-quark spin.

$$V_\pi(\vec{q}) = -\zeta\, \frac{g_1^2}{6 f_\pi^2}\, \vec{\tau}_1 \cdot \vec{\tau}_2\, \frac{\vec{\sigma}_{L1} \cdot \vec{\sigma}_{L2}\, \vec{q}^2}{\vec{q}^2 + m_\pi^2}$$

$$V_{a_1}(\vec{q}) = -\zeta\, \lambda_1^2 \frac{g_1^2 m_{a1}^2}{2 f_\pi^2}\, \vec{\tau}_1 \cdot \vec{\tau}_2\, \frac{\vec{\sigma}_{L1} \cdot \vec{\sigma}_{L2}}{\vec{q}^{\,2} + m_{a_1}^2} \left(1 + \frac{\vec{q}^{\,2}}{3 m_{a_1}^2}\right) + \ldots$$

# Saturated potential: vector meson exchange

Lagrangian (HHV) reads

$$\mathcal{L}_V = \mathcal{L}_{E0} + \mathcal{L}_{M1} = q_L^\dagger \left[ g_{V1} V^0 + \frac{f_{V1}}{2M} \epsilon_{ijk} \sigma_{Li} \partial_j V_k \right] q_L \,,$$

with $g_{V1}$ and $f_{V1} = g_{V1} \kappa_{V1}$ .

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with $g_{V1}$ and $f_{V1} = g_{V1} \kappa_{V1}$ .The potential reads

$$V_V(\vec{q}) = V_{E0}(\vec{q}) + V_{M1}(\vec{q}) \,,$$

which read

$$\begin{aligned} V_{E0}(\vec{q}) &= + \frac{g_{V1}^2}{\vec{q}^2 + m_V^2} \,, \\ V_{M1}(\vec{q}) &= - \frac{f_{V1}^2}{4M^2} \frac{(\vec{\sigma}_{L1} \times \vec{q}) \cdot (\vec{\sigma}_{L1} \times \vec{q})}{\vec{q}^2 + m_V^2} \\ &= - \frac{f_{V1}^2}{6M^2} \vec{\sigma}_{L1} \cdot \vec{\sigma}_{L1} \frac{\vec{q}^2}{\vec{q}^2 + m_V^2} + \dots \,, \end{aligned}$$

# $X(3872)$ and $Z_c(3900)$ generation in $D^*\bar{D}$ scattering

## Assuming $X(3872)$ and $Z_c(3900)$ are molecules

- $V_X$ and $V_Z$ are determined by light meson saturation
- Regularizing the potential in a form of

$$V_M(\vec{q}) \to f_M^2(\vec{q})\, V_M(\vec{q})\,.$$

with

$$f_M(q) = \left(\frac{\Lambda^2 - m^2}{\Lambda^2 - q^2}\right)^{n_P}\,,$$

and $n_P = 2$.

- After Fourier transformation and solving the *Schrödinger* equation, $\Lambda$ is a parameter to produce the binding energies.
- Generation on $X(3872)$ and $Z_c(3900)$ correspond to binding energies in $D^*\bar{D}$ scattering, $BE_X = 4\,\mathrm{MeV}$ and $BE_Z = 0\,\mathrm{MeV}$

### $m_\sigma = 550,\ 450 - 600\,\mathrm{MeV},\ \Lambda_X = 1.0\,\mathrm{GeV}$

- light meson saturation:

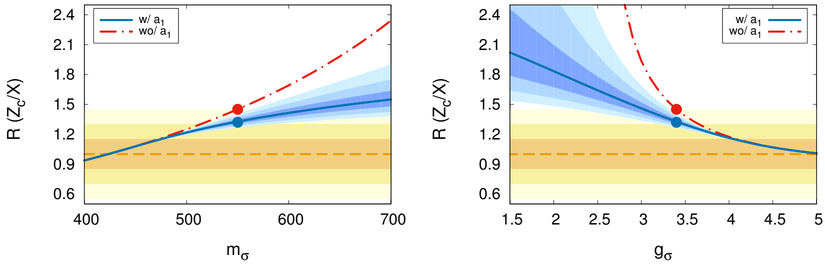
$$\frac{\Lambda(Z_c)}{\Lambda(X)} = 1.33\,(1.08 - 1.41)\,.$$

### Within HQSS uncertainty

$$\frac{\Lambda_Z}{\Lambda_X} = 1 \pm 0.15 = (0.85 - 1.15)\,,$$

| Polarity ($n_P$) | $R(Z_c/X)$ | $R^{\not a_1}(Z_c/X)$ |
|---|---|---|
| 2 | 1.33 (1.08-1.41) | 1.45 (1.08-1.69) |
| 3 | 1.33 (1.09-1.42) | 1.48 (1.10-1.72) |
| 4 | 1.39 (1.15-1.48) | 1.65 (1.18-1.98) |

# $X(3872)$ and $Z_c(3900)$ in $D^*\bar{D}$ scattering




- $a_1$ exchange provides additional attractive interaction in $Z_c$ spectrum in blue.
- w/o $a_1$ exchange, isovector $D\bar{D}$ generates a virtual pole.

# $Z_{cs}(3985)$ generation

For the $D^*\bar{D}_s$-$D\bar{D}_s^*$ molecules, even if we consider these two channels to be degenerate (which we do here), the structure of the potential is still better understood as a coupled channel problem, i.e.

$$V(Z_{cs}) = \begin{pmatrix} V_a^{(1)} & V_b^{(1)} \\ V_b^{(1)} & V_a^{(1)} \end{pmatrix} ,$$

where $V_a^{(1)}$ and $V_b^{(1)}$ are the central and spin-dependent parts of the potential.

$$\begin{aligned} V(\tilde{Z}_{cs}) &= V_a^{(1)} + V_b^{(1)} , \\ V(Z_{cs}) &= V_a^{(1)} - V_b^{(1)} , \end{aligned}$$

which would be the strange counterparts of the $1^{++}$ and $1^{+-}$ isovector configurations

# $Z_{cs}(3985)$ : $\sigma$ and $f_1$ exchange

While the $a_0$ and $K_0^*$ are pure octets, the $\sigma$ and $f_0(980)$ are a mixture of singlet and octet, i.e.

$$\begin{pmatrix} f_0(500) \\ f_0(980) \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} S_1 \\ S_8 \end{pmatrix},$$

with $\theta = 19 \pm 5^\circ$.

The second problem is the singlet and octet mixing: if we consider that the isoscalar partners of the $a_1$ are the $f_1(1285)$ and $f_1(1420)$, they will be a non-trivial mixture of a singlet and octet axial meson

$$\begin{pmatrix} f_1(1285) \\ f_1(1420) \end{pmatrix} = \begin{pmatrix} \cos\theta_1 & \sin\theta_1 \\ -\sin\theta_1 & \cos\theta_1 \end{pmatrix} \begin{pmatrix} f_1^1 \\ f_1^8 \end{pmatrix},$$

where $f_1^1$ and $f_1^8$ are the singlet and octet components of the two $f_1$'s.

# $Z_{cs}(3985)$ : $m_\sigma = 550,\ 450 - 600\,\text{MeV}$

$$\left.\frac{\Lambda^{\sigma(\mathrm{NS})}(Z_{cs})}{\Lambda^{\sigma(\mathrm{NS})}(Z_c)}\right|_{\theta_1^+} = 3.69\,(3.35 - 4.92)\,,$$

$$\left.\frac{\Lambda^{\sigma(\mathrm{NS})}(Z_{cs})}{\Lambda^{\sigma(\mathrm{NS})}(Z_c)}\right|_{\theta_1^-} = 3.57\,(3.24 - 4.74)\,,$$

$$\left.\frac{\Lambda^{\sigma(\mathrm{FS})}(Z_{cs})}{\Lambda^{\sigma(\mathrm{FS})}(Z_c)}\right|_{\theta_1^+} = 1.04\,(1.00 - 1.06)\,,$$

$$\left.\frac{\Lambda^{\sigma(\mathrm{FS})}(Z_{cs})}{\Lambda^{\sigma(\mathrm{FS})}(Z_c)}\right|_{\theta_1^-} = 1.06\,(1.00 - 1.09)\,,$$

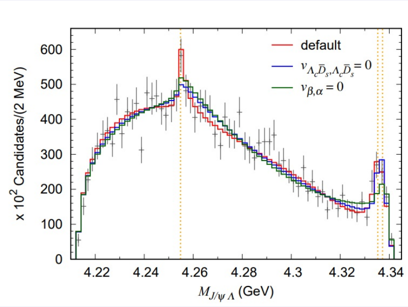
with $\theta_1^\pm = 35.3^\circ \pm (31^\circ \pm 2^\circ)$.
SU(3)-flavor symmetry,

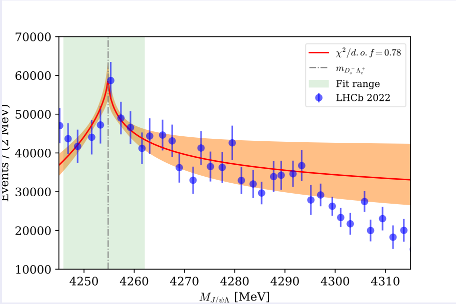
$$\frac{\Lambda(Z_{cs})}{\Lambda(Z_c)} \simeq 1.0\,.$$

# More thinking on $\sigma$ exchange

## $\sigma$ coupling

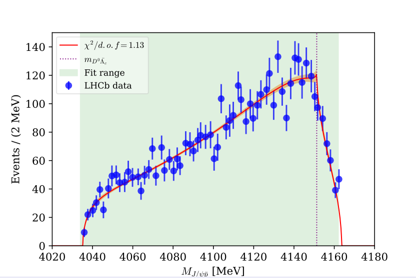
- $g_\sigma = 2.4$, a virtual pole ($Z_R = 3860\,\mathrm{MeV}$) corresponding to $\tilde{X}(3872)$.
- $D_s^-\Lambda_c$ binds as $P^\Lambda_{\psi s}(4255)$, which is suggested to be a virtual pole by the fit. 2211.08211, Z. Y. Yang et al; PRD 108 (2023) L011501, Satoshi et al
- $\mathcal{M} = V_p/(1/(a_1 + ia_2) - ik)$ in $J/\psi\Lambda - D_s^-\Lambda_c^+$ scattering with $a^{\mathrm{eff}} = (0.24 \pm 0.06) + i(0.35 \pm 0.04)\,\mathrm{fm}$.

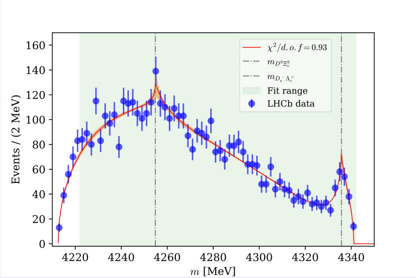


## $\sigma$ exchange in $P_\psi^N$ and $P_{\psi s}^\Lambda$

- $P_\psi^N$: $\mathcal{M} = P_1 t_{11} + P_2 t_{21}$, 5 pars
- $P_{\psi s}^\Lambda$: $\mathcal{M} = P_1 t_{11} + P_2 t_{21} + P_3 t_{31}$ with HQSS, 5 pars
- A virtual pole $(4211, 48)\,\mathrm{MeV}$ w.r.t $\bar{D}\Lambda_c$, 2305.01449, D. Winney et al.
- $\omega$-exchange providing repulsive interaction in $\bar{D}\Lambda_c$ scatttering.



# Summary

- L$\sigma$M and $\pi - a_1$ are introduced to the light meson exchange and explain $X(3872)$ and $Z_c(3900)$ in $D^*\bar{D}$ scattering, where $\sigma$ and $a_1$ contribute to attractive potentials, simultaneously.
- $Z_{cs}(3985)$ can be understood as a $D_s^- D^{*0} - D_s^{*-} D^0$ molecule.
- $\sigma$ may couple to strange quark with identical strength to u/d quark.
- Besides $\sigma$ exchange, $a_1$ exchange is non-negligible in $I = I_1 + I_2$ cases.
- $\sigma$ exchange potential plays a crucial role in $\bar{D}_s\Lambda_c$ and $\bar{D}\Lambda_c$ scattering.

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- Is there a duality of $\sigma$ and charmonium exchange? $s - t$ symmetry in scattering?

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**Thanks !**

# Backup: potential in coordinate space

If we particularize for the $\rho$ meson, we will have to include isospin factors

$$V_\rho(\vec{r}) \;=\; \vec{\tau}_1 \cdot \vec{\tau}_2 \left[ g_{\rho 1}^2 + f_{\rho 1}^2 \frac{m_\rho^2}{6M^2} \, \vec{\sigma}_{L1} \cdot \vec{\sigma}_{L1} \right] \frac{e^{-m_\rho r}}{4\pi r} + \dots .$$

For the $\omega$ no isospin factor is required, but there is a sign coming from the negative G-parity of this meson

$$V_\omega(\vec{r}) \;=\; \zeta \left[ g_{\omega 1}^2 + f_{\omega 1}^2 \frac{m_\omega^2}{6M^2} \, \vec{\sigma}_{L1} \cdot \vec{\sigma}_{L1} \right] \frac{e^{-m_\omega r}}{4\pi r} + \dots ,$$

where, as usual, $\zeta = +1$ $(-1)$ for the meson-meson (meson-antimeson) potential.

# Backup: inputs

| Coupling | Value | Relevant to meson(s) |
|---|---|---|
| $g_1$ | 0.60 | $\pi$, $a_1$ |
| $g_\sigma$ | 3.4 | $\sigma$ |
| $g_{V1}$ | 2.9 | $\rho$, $\omega$ |
| $\kappa_{V1}$ | 2.8 | $\rho$, $\omega$ |
| $\lambda_1$ | 1.8 | $a_1$ |

**Table 1:** Couplings of the light-mesons we are considering in this work ($\pi$, $\sigma$, $\rho$, $\omega$ and $a_1$) to the charmed mesons. For the masses of the light-mesons we will use $m_\pi = 138\,\mathrm{MeV}$, $m_\sigma = 550\,\mathrm{MeV}$, $m_\rho = 770\,\mathrm{MeV}$, $m_\omega = 780\,\mathrm{MeV}$ and $m_{a_1} = 1230\,\mathrm{MeV}$. For the vector mesons we use the scaling mass $M = 938\,\mathrm{MeV}$. For the charmed mesons we will consider their isospin-averaged masses, $m_D = 1867\,\mathrm{MeV}$ and $m_{D^*} = 2009\,\mathrm{MeV}$.

# Backup: delta force

The momentum dependent light meson exchange potential always contains contribution in short distance, which is not important in shallow bound state generation. To remove this ambiguity, a scheme in renormalization is introduced as

$$\frac{\vec{q}^2}{m^2+\vec{q}^2} \to 1 - \frac{m^2}{m^2+\vec{q}^2},$$

where 1 corresponds the $\delta$ force and will be dropped in the following calculations.

# Backup: finite width

The basic idea is to substitute the narrow meson propagator by a propagator averaged over the actual mass distribution of the meson

$$\frac{1}{m^2 + \vec{q}^{\,2}} \to \int_{m_{\rm th}}^{\infty} \frac{\rho(\mu^2)\, d(\mu^2)}{\mu^2 + \vec{q}^{\,2}}\,, \tag{1}$$

where $\rho(\mu^2)$ is the spectral distribution of the wide meson and $m_{\rm th}$ the threshold mass of the particles into which this meson can decay,which amounts to a two-pole approximation of the previous integral

$$\int_{m_{\rm th}}^{\infty} \frac{\rho(\mu^2)\, d(\mu^2)}{\mu^2 + \vec{q}^{\,2}} \approx \frac{\alpha_1}{m_1^2 + \vec{q}^{\,2}} + \frac{\alpha_2}{m_2^2 + \vec{q}^{\,2}}\,,$$

where $\alpha_1$ and $\alpha_2$ are positive numerical coefficients such that $\alpha_1 + \alpha_2 = 1$ and $m_1$, $m_2$ are the masses of the two poles, which obey the relation $m_1 < m$ and $m_2 > m$.

# Backup: finite width

The two most important of these contributions are the following: close to $mr \sim 1$, the original Yukawa potential is modified into a potential of the type

$$V_Y(r) \approx -\frac{g^2}{4\pi}\frac{e^{-mr}}{r}\left(1-\frac{\Gamma r}{\pi}-\frac{\Gamma}{\pi m}\right),$$

with $\Gamma$ the width of the meson.
At short distances the potential for a broad meson is weaker than for a narrow one;
A broad meson decaying into two lighter mesons of mass $2M$ generates an additional attractive longer-range contribution to the potential at distances $2Mr \sim 1$.

# Backup: uncertainty from $a_1$ exchange

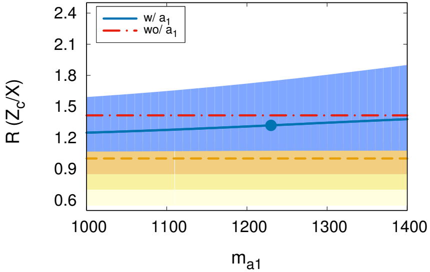


**Figure 1:** Cutoff ratios $R(Z_c/X)$ as a function of the mass (left panel) and coupling (right panel) of the axial meson for the OBE model. The mass and coupling of the scalar meson are taken to be $m_\sigma = 550\,\mathrm{MeV}$ and $g_\sigma = 3.4 \pm 1.0$, where in the case of the coupling we have added a $30\%$ relative uncertainty, which is shown as the error band around the solid line. The $m_{a_1} = 1230\,\mathrm{MeV}$ and $\lambda_1 = 1.8$ ratios for the axial-full theory are highlighted as a round dot. When we vary the axial mass (coupling), we set the axial coupling (mass) to its expected central value, i.e. $\lambda_1 = 1.8$ ($m_{a_1} = 1230\,\mathrm{MeV}$).

# Backup: more molecules with $g_\sigma = 3.4 \pm 1.0$

| (X-like) | $I^G$ | $J^{PC}$ | $B^{\not a_1}$ / $E_V^{\not a_1}$ | $M^{\not a_1}$ | $B^{a_1}$ / $E_V^{a_1}$ | $M^{a_1}$ |
|---|---|---|---|---|---|---|
| $D\bar{D}$ | $0^+$ | $0^{++}$ | $-0.0^{+0.1}_{-0.7}$ | $3734.4^{+0.0}_{-0.7}$ | $-0.0^{+0.1}_{-0.8}$ | $3734.4^{+0.0}_{-0.8}$ |
| $D^*\bar{D}$ | $0^+$ | $1^{++}$ | Input | Input | Input | Input |
| $D^*\bar{D}$ | $0^-$ | $1^{+-}$ | $-4.0^{+3.6}_{-10.3}$ | $3871.8^{+3.6}_{-10.3}$ | $-4.2^{+3.9}_{-11.2}$ | $3871.6^{+3.9}_{-11.2}$ |
| $D^*\bar{D}^*$ | $0^+$ | $0^{++}$ | $-^{-}_{-0.3}$ | $-$ | $-^{-}_{-0.3}$ | $-$ |
| $D^*\bar{D}^*$ | $1^-$ | $1^{+-}$ | $-1.0^{+1.0}_{-1.8}$ | $4016.2^{+1.0}_{-1.8}$ | $-1.0^{+1.0}_{-1.9}$ | $4016.2^{+1.0}_{-1.9}$ |
| $D^*\bar{D}^*$ | $0^+$ | $2^{++}$ | $+3.5^{+0.0}_{-0.1}$ | $4013.7^{+0.1}_{-0.0}$ | $+3.5^{+0.0}_{-0.1}$ | $4013.7^{+0.1}_{-0.0}$ |
| ($Z_c$-like) | $I^G$ | $J^{PC}$ | $B^{\not a_1}$ / $E_V^{\not a_1}$ | $M^{\not a_1}$ | $B^{a_1}$ / $E_V^{a_1}$ | $M^{a_1}$ |
| $D\bar{D}$ | $0^+$ | $0^{++}$ | $-0.1^{+0.0}_{-\infty}$ | $3734.3^{0.0}_{-\infty}$ | $-0.6^{+6.9}_{-13.4}$ | $3733.8^{+0.6}_{-13.4}$ |
| $D^*\bar{D}$ | $1^+$ | $1^{++}$ | $-0.0^{+0.0}_{-\infty}$ | $3875.8^{+0.0}_{-\infty}$ | $-1.3^{+6.0}_{-16.1}$ | $3874.5^{+1.3}_{-16.1}$ |
| $D^*\bar{D}$ | $1^-$ | $1^{+-}$ | Input | Input | Input | Input |
| $D^*\bar{D}^*$ | $1^-$ | $0^{++}$ | $+0.0^{+0.0}_{-\infty}$ | $4017.2^{+0.0}_{-\infty}$ | $+0.3^{+10.2}_{-0.3}$ | $4016.9^{+0.3}_{-10.2}$ |
| $D^*\bar{D}^*$ | $1^+$ | $1^{+-}$ | $+0.0^{+0.0}_{-\infty}$ | $4017.2^{+0.0}_{-\infty}$ | $+0.0^{+0.0}_{-0.0}$ | $4017.2^{+0.0}_{-\infty}$ |
| $D^*\bar{D}^*$ | $1^-$ | $2^{++}$ | $+0.2^{+0.0}_{-\infty}$ | $4017.0^{+0.2}_{-\infty}$ | $-0.5^{+0.7}_{-4.7}$ | $4016.7^{+0.5}_{-4.7}$ |