# Production mechanism of Hidden-Charm Exotic Mesons

2025년 한국고에너지물리학회

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# Outline

- *Introduction*
- *Coupled-channel formalism*
- *Effective Lagrangian*
- *Numerical Results*
- *Summary*

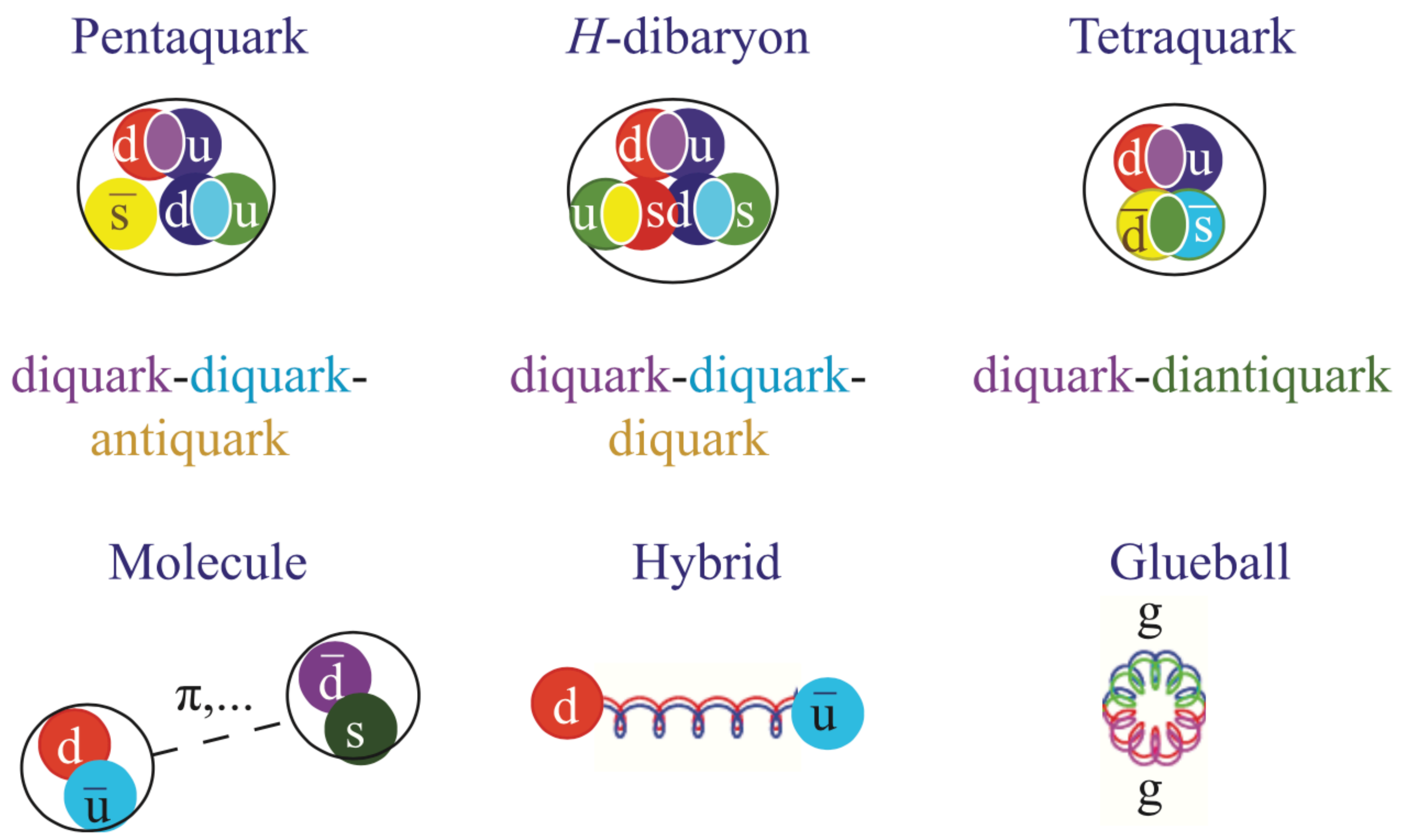
# Introduction

# Exotic States Beyond the Quark Model

QCD allows for many different types of color-neutral objects

Meson : $q\bar{q}$ $qq\bar{q}\bar{q}$ (tetraquark), $q\bar{q}g$ (hybrids), glueballs, …

Baryon : $qqq$ $qqqq\bar{q}$ (pentaquark), $qqqqqq$…




S.L.Olsen Front.Phys.(Beijing) 10 (2015) 2, 121-154

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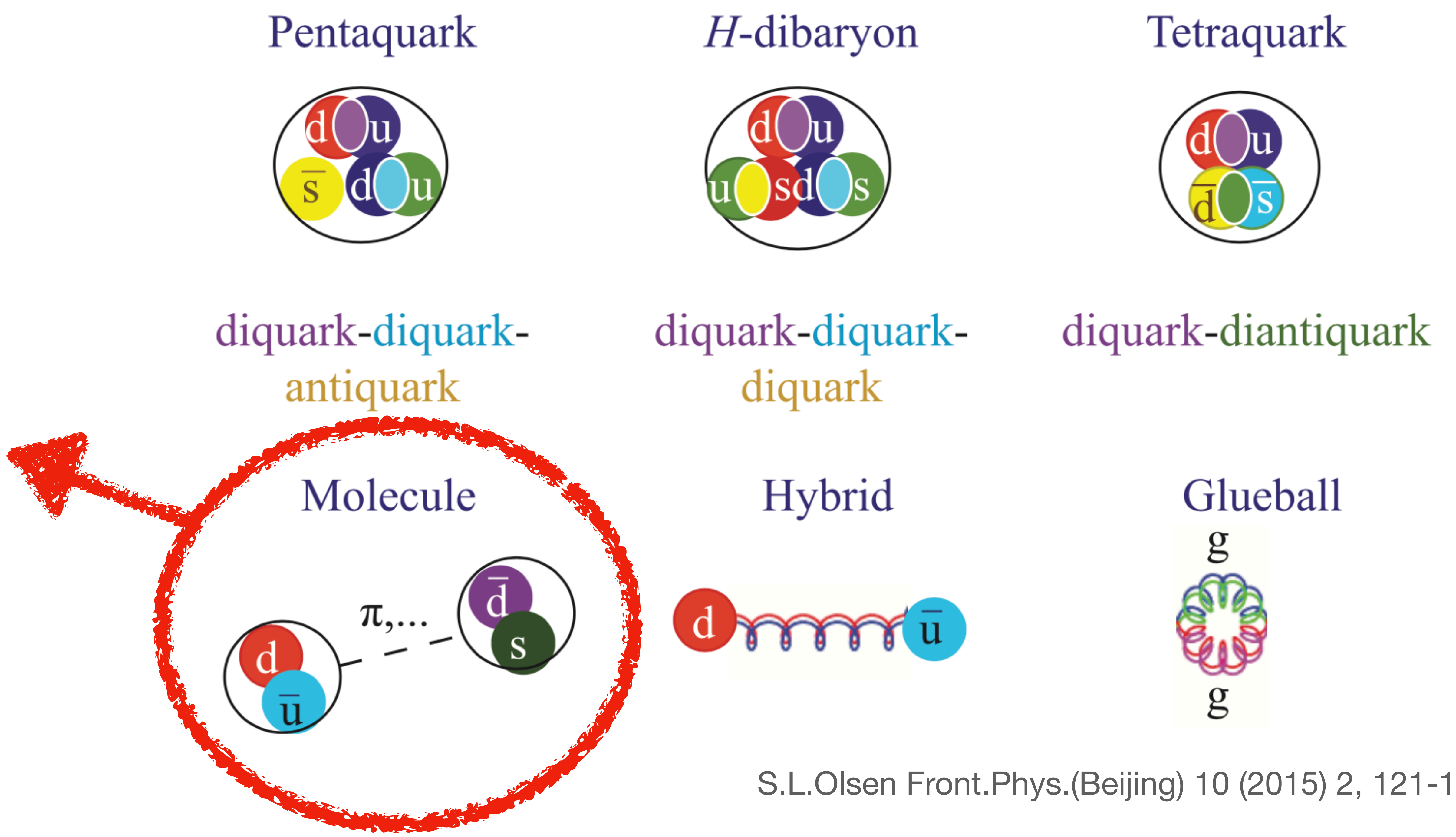
Baryon : $qqq$ $\quad$ $qqqq\bar{q}$ (pentaquark), $qqqqqq$…

## Hadronic molecule

- Bound states of color-neutral states mediated by meson-exchanges
- Typically appear near two-particle thresholds
- Dominantly decay into their consistituent two-particle channels

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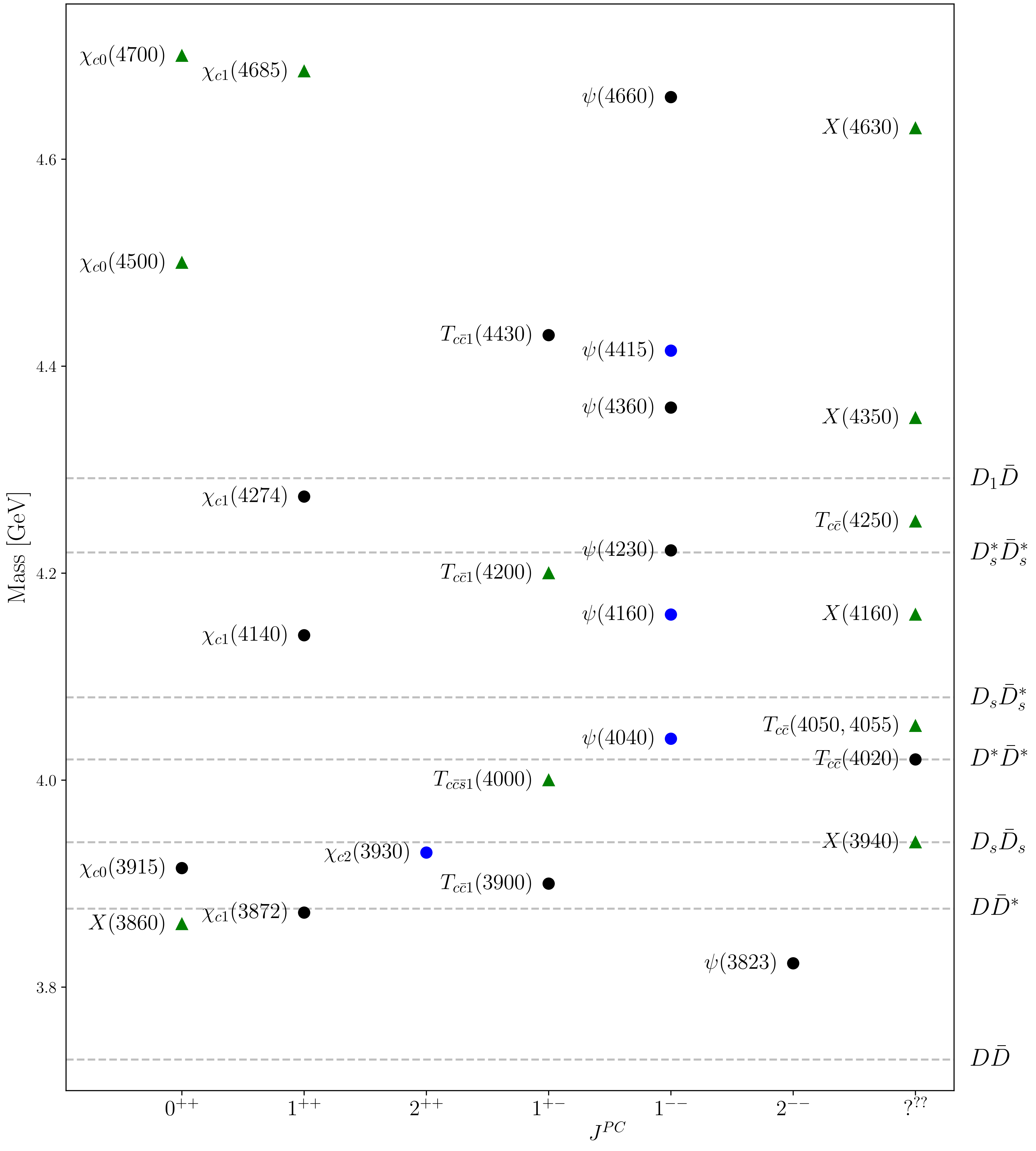
# Hadronic Molecules

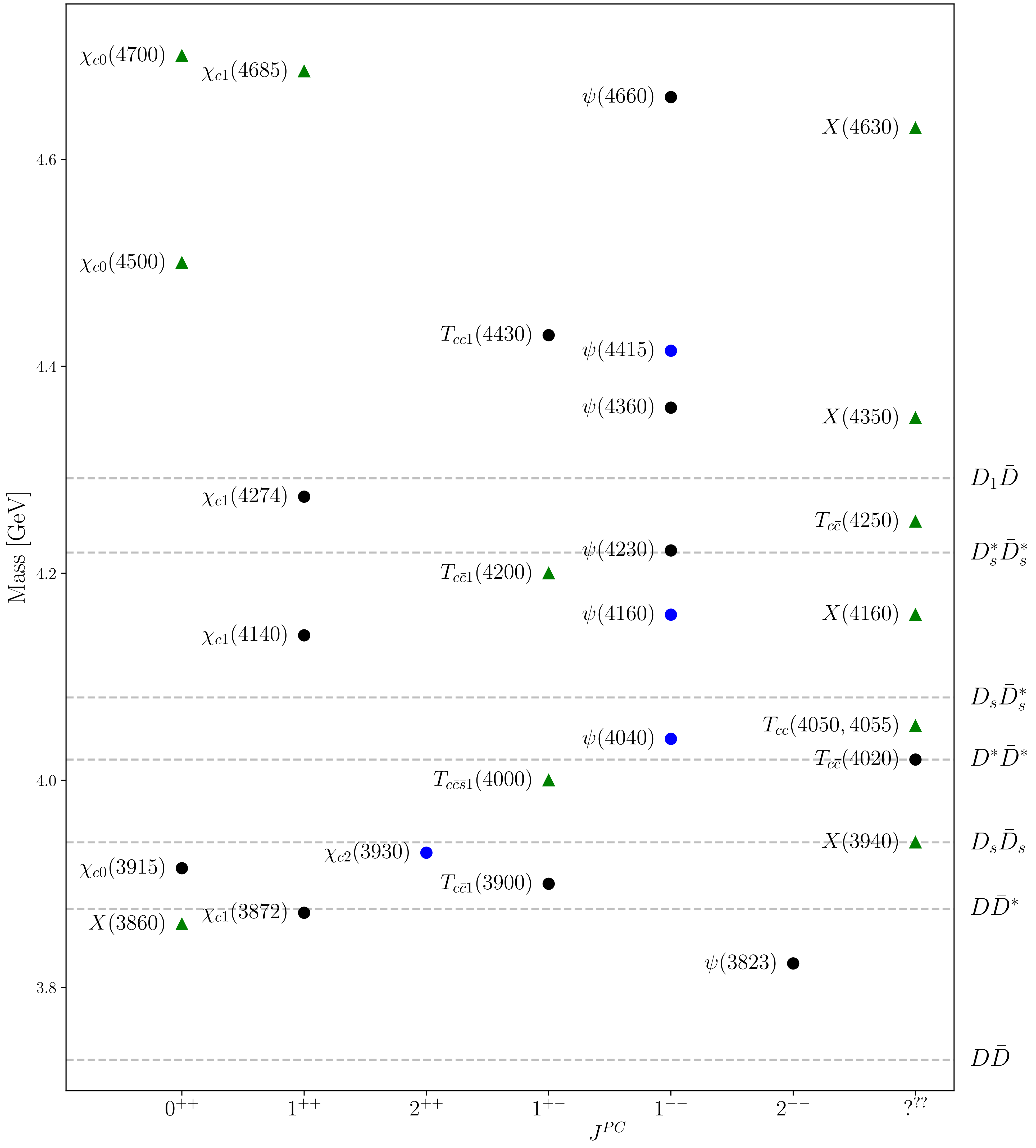



The representative candidate for a hadron molecule is $\chi_{c1}(3872)$

$I^G(J^{PC}) = 0^+(1^{++})$ QM candidates: $M(2^3P_1\ c\bar{c}) \approx 3950\,\mathrm{MeV}$

$M_{\chi_{c1}} = 3871.84\,\mathrm{MeV}$

# Hadronic Molecules

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$$M_{\chi_{c1}} = 3871.84\,\mathrm{MeV}$$

Its mass is very close to the $D^0\bar{D}^{*0}$ threshold:

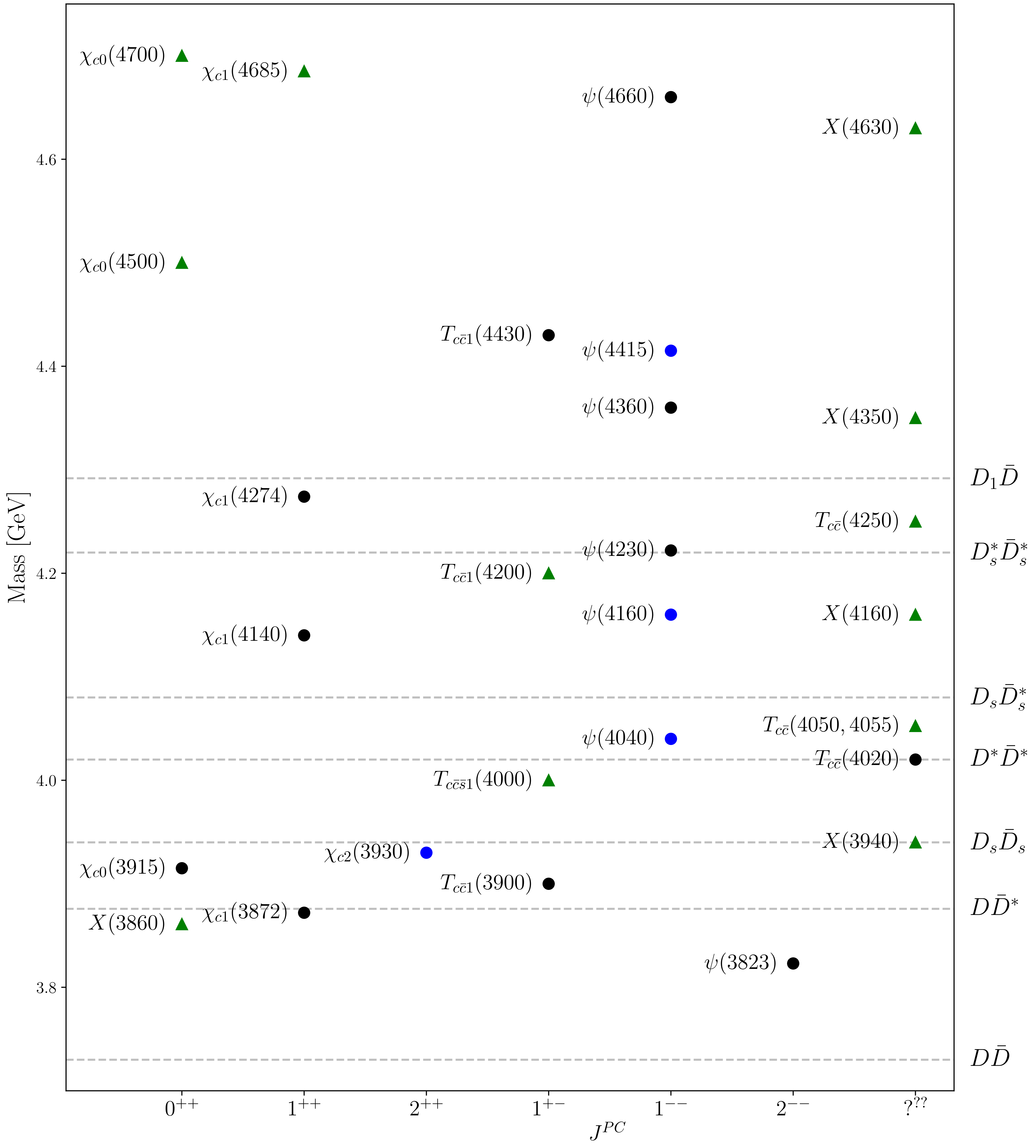
$$M_{\chi_{c1}} - (m_{D^0} + m_{\bar{D}^{*0}}) = -0.09 \pm 0.28\,\mathrm{MeV}$$

It dominantly decays into this channel:

$$\mathscr{B}(\chi_{c1}(3872) \to D^0\bar{D}^{0*}) > 34\,\%$$

***Consistent with the characteristics of hadronic molecules***

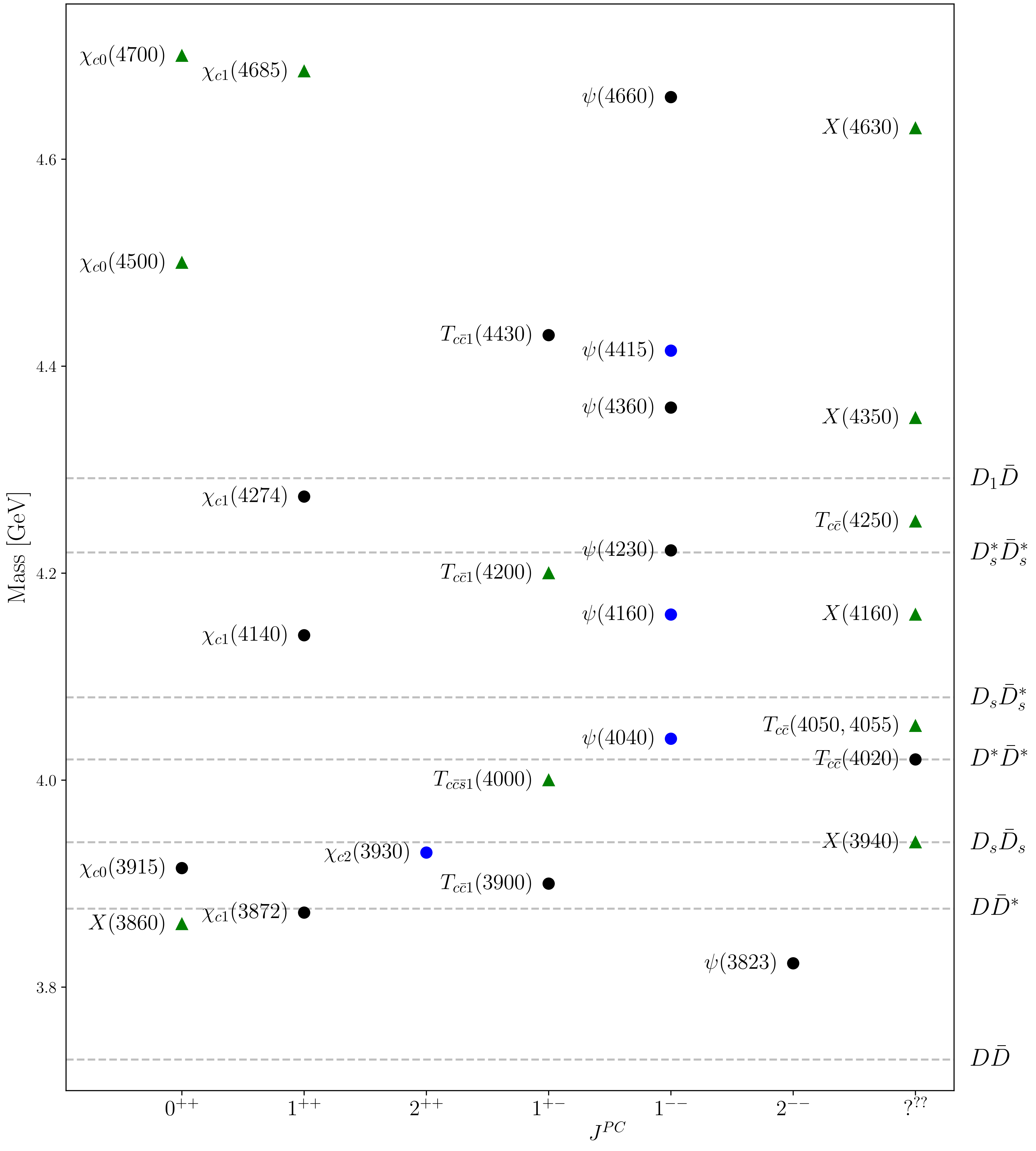
# Multi-quark candidates




***Observed multiquark candidates listed in PDG:***

- Low-lying scalar mesons : $a_0/f_0(980), f_0(500), a_1(1260), b_1(1235)\ldots$
- Exotic states with an heavy flavor : $D_{s0}^*(2317), D^*(2400), \ldots$
- Exotic $c\bar{c}$ or $b\bar{b}$ states : $\chi_{c1}(3872), T_{c\bar{c}1}(3900), T_{b\bar{b}1}(10610), \ldots$
- Open heavy-flavored states : $T_{cc}^+$
- Fully heavy tetraquarks : $T_{cc\bar{c}\bar{c}}(6900)$

# Multi-quark candidates

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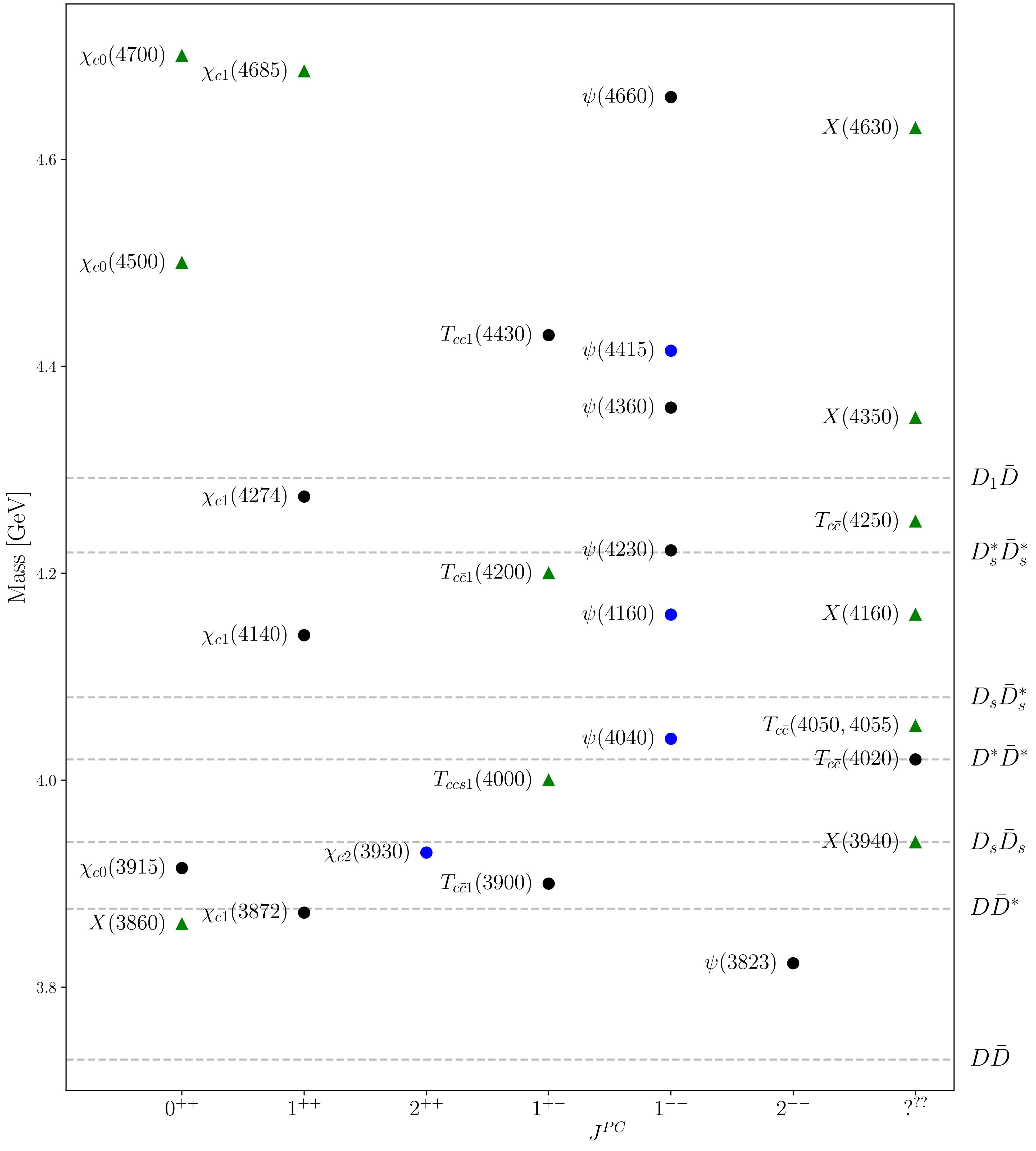


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***Charmonium-like exotics***

- $\chi_{c0}(2P)$ : $\chi_{c0}(3860)$? or $\chi_{c0}(3915)$?
- $\chi_{cJ}$ states below open-charm ($D\bar{D}$) threshold
- Do $D^*\bar{D}^*$ molecular states exist?
- $\psi(J^{--})$ molecular states?
- Excited $h_c$ and $\eta_c$-like states?

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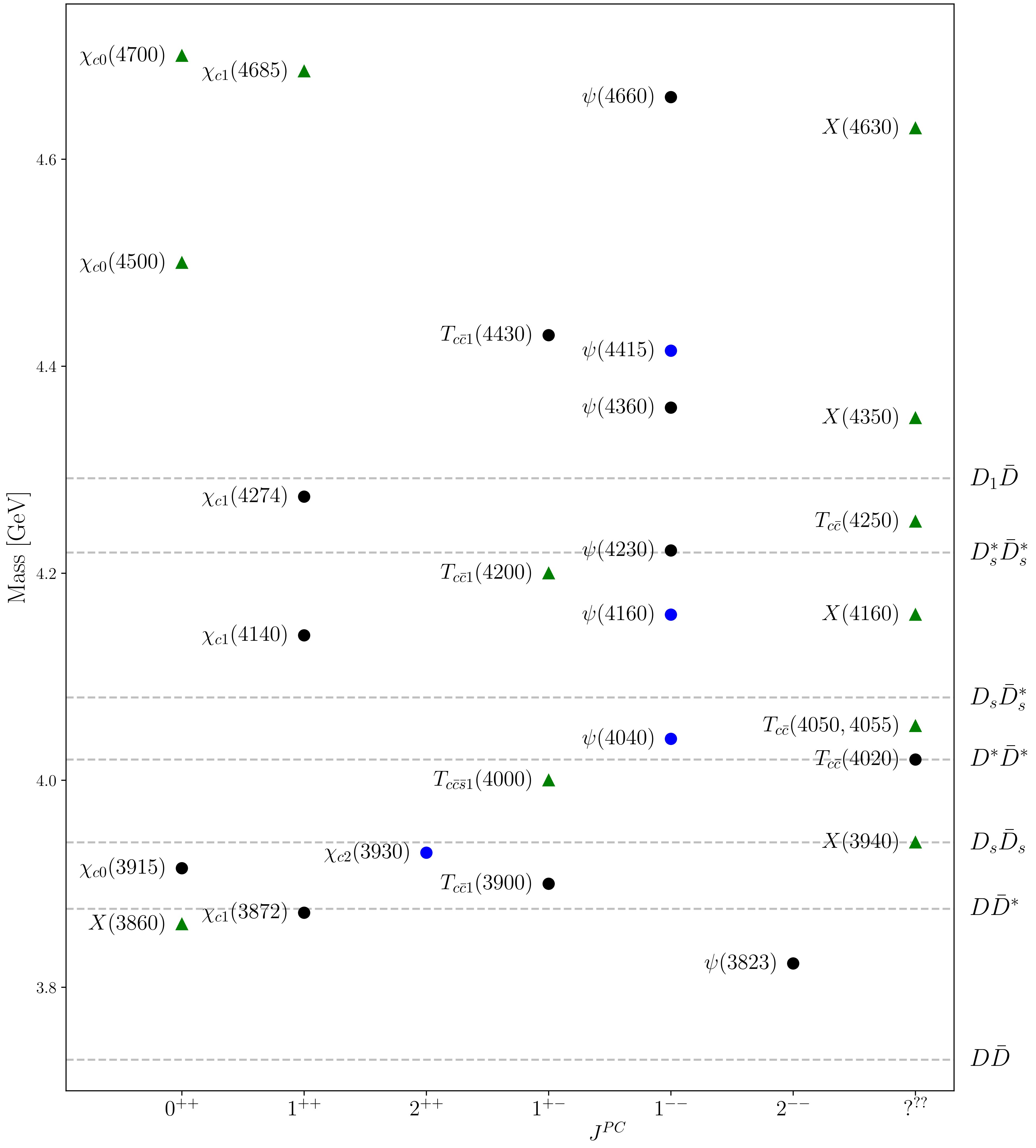


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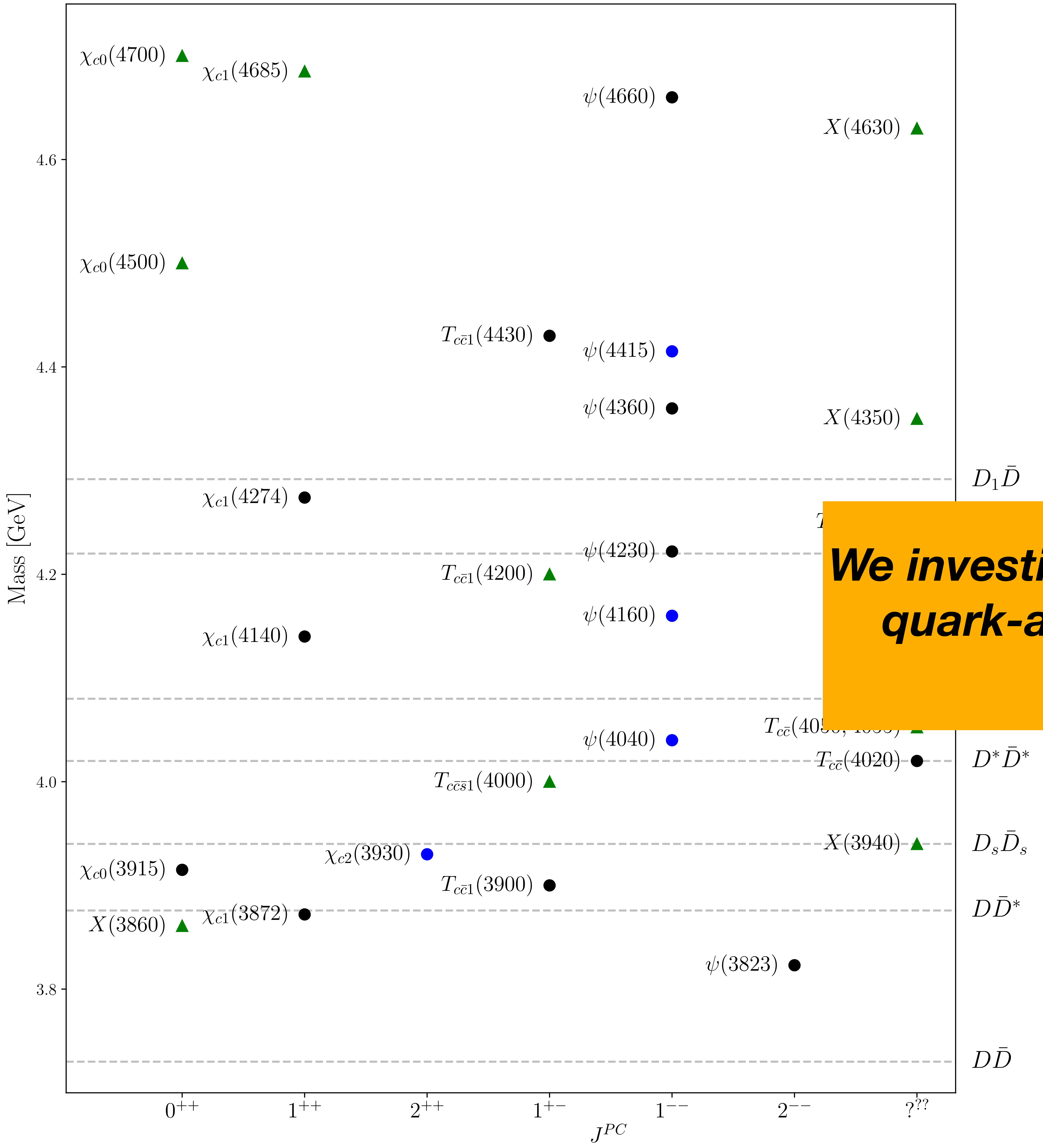


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***We investigate the production mechanism of the exotic states containing heavy quark-anti heavy quark pair using the fully off-mass-shell coupled-channel formalism within the meson-exchange framework.***

- Do $D^*\bar{D}^*$ molecular states exist?
- $\psi(J^{--})$ molecular states?
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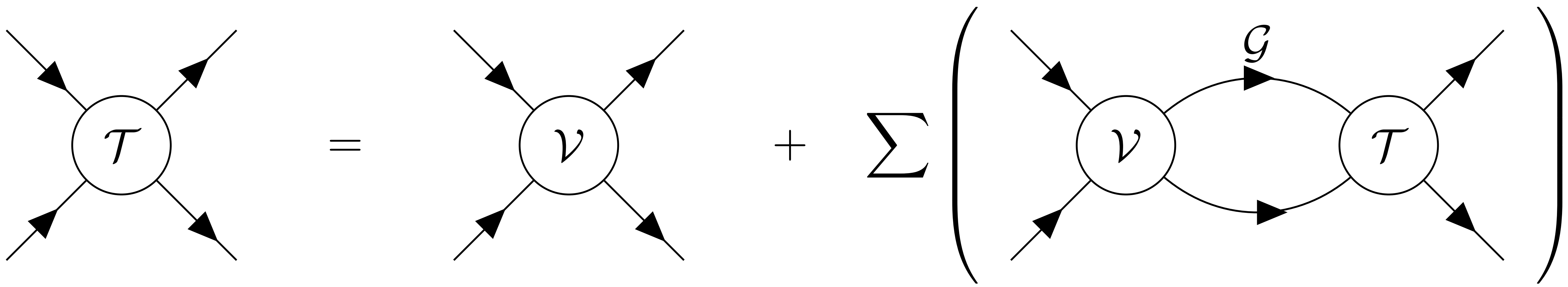
# Coupled-channel formalism

# Two-Body Scattering Equations

- **Blankenbecler-Sugar equation**




$$T = V + VGT$$

- The two-body T-matrix is obtained by solving the *Bethe-Salpeter* equation:

$$T_{fi} = V_{fi} + \sum_n \int \frac{d^4k_1}{(2\pi)^4} \frac{d^4k_2}{(2\pi)^4} \frac{V_{fn}T_{ni}}{(k_1^2 - m_1^2 + i\epsilon)(k_2^2 - m_2^2 + i\epsilon)}$$

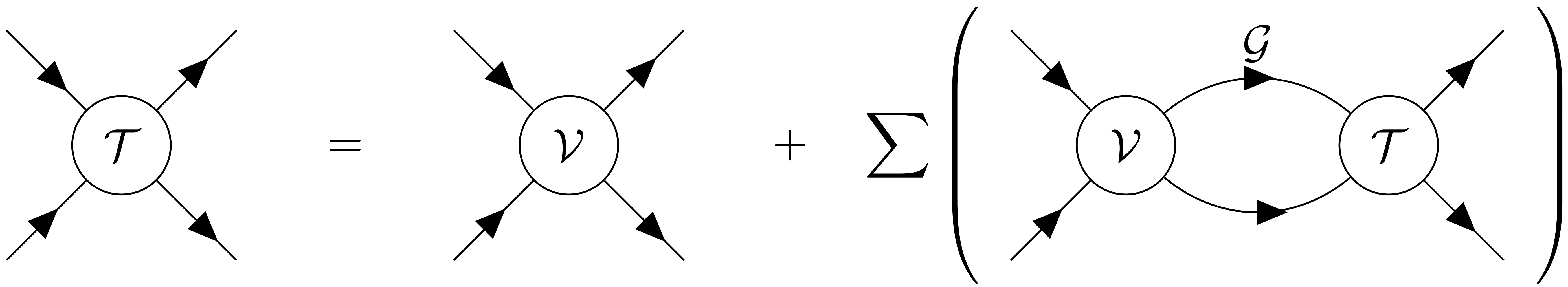
- The three-dimensional reduction within the ***Blankenbecler-Sugar*** scheme preserves both unitarity and off-shell behavior:

$$G_k(q) = \frac{\pi}{\omega_1^k \omega_2^k} \delta\left(q^0 - \frac{\omega_1^k - \omega_2^k}{2}\right) \frac{\omega_1^k + \omega_2^k}{s - (\omega_1^k + \omega_2^k)^2 + i\epsilon}$$

$$T_{fi}(\boldsymbol{p}, \boldsymbol{p}') = V_{fi}(\boldsymbol{p}, \boldsymbol{p}') + \sum_n \int \frac{d^3q}{(2\pi)^3} \frac{\omega_1^n + \omega_2^n}{s - (\omega_1^n + \omega_2^n)^2 - i\varepsilon} V_{ni}(\boldsymbol{p}, \boldsymbol{q}) T_{fn}(\boldsymbol{q}, \boldsymbol{p}')$$

# Two-Body Scattering Equations

- **Blankenbecler-Sugar equation**



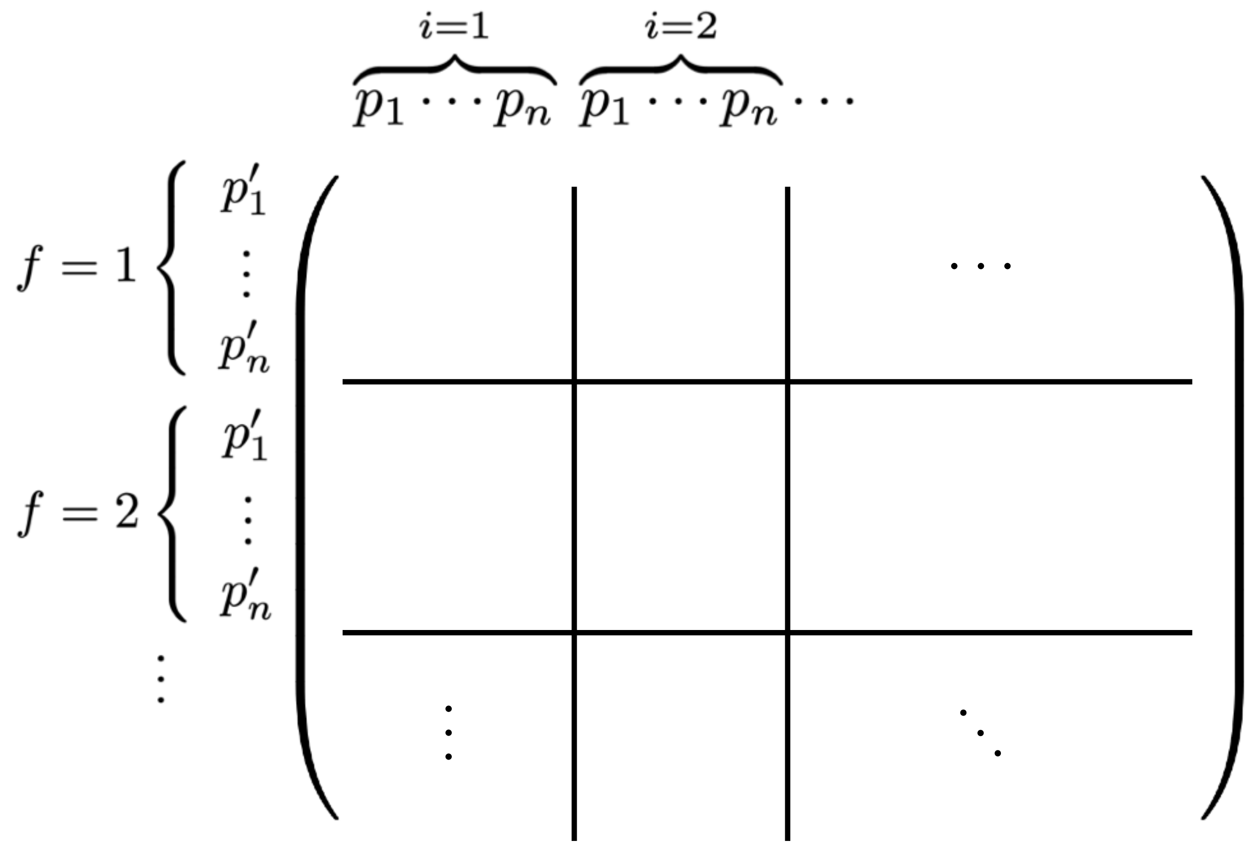

$$T = V + VGT$$

- Projection onto total angular momentum

$$T_{fi}^J(p,p') = V_{fi}^J(p,p') + \frac{1}{(2\pi)^3}\int_0^\infty dq\, \frac{\omega_1+\omega_2}{2\omega_1\omega_2}\frac{q^2 V_{fk}^J(p,q)T_{ki}^J(q,p')}{s-(\omega_1+\omega_2)^2-i\varepsilon}$$

*Matrix inversion method:* $T^J = V^J + V^J G T^J \implies T^J = (1-V^JG)^{-1}V^J$

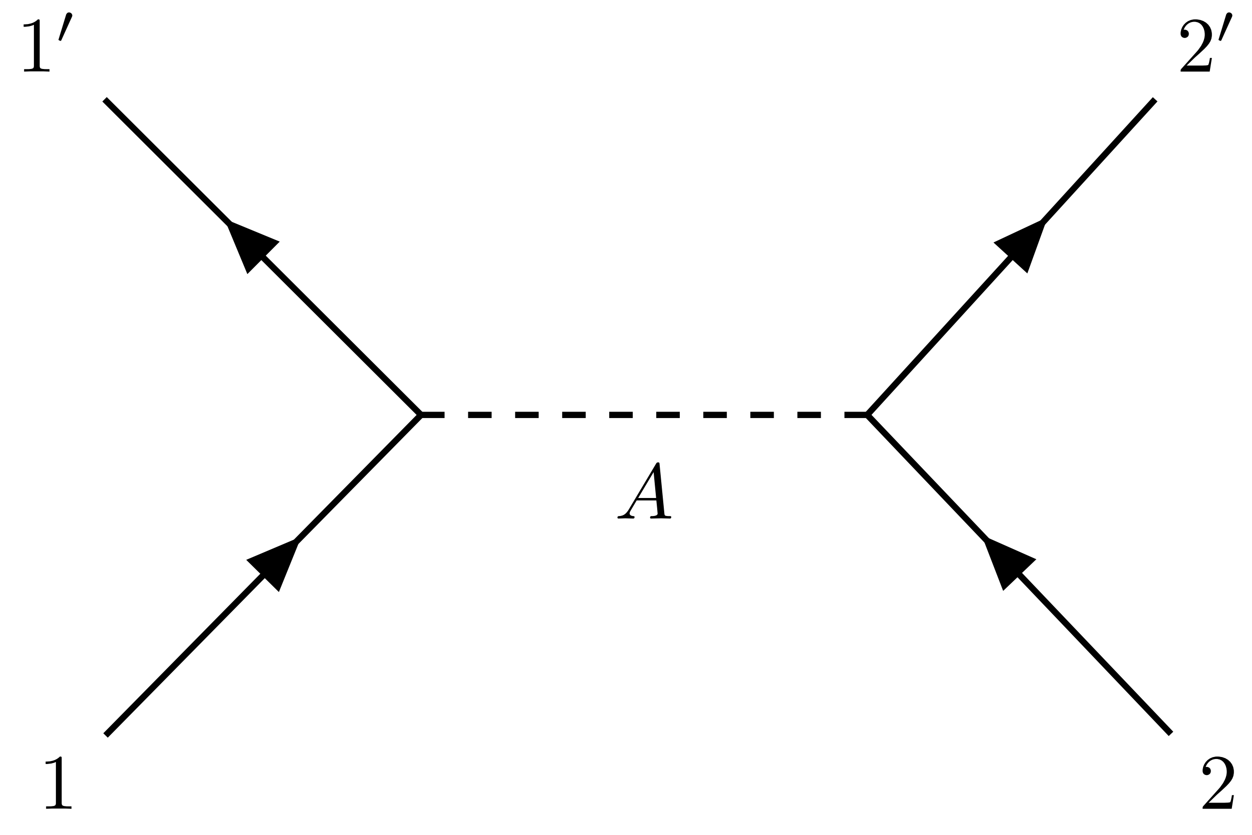
The *off-mass-shell* $T$ matrix in the full-channel momentum space



# Kernel amplitudes

- **Scattering amplitudes**

$$\mathcal{V}_{12\to 1'2'} = \sum_A \mathcal{M}^A_{12\to 1'2'}$$




$$\mathcal{M}^A_{12\to 1'2'} = \mathrm{IS} F^2(q^2)\Gamma^A_{11'}\mathcal{P}^A\Gamma^A_{22'}$$

- Since the hadron has a finite size, form factor is need to be considered at each vertex: $F(q^2) = \left(\frac{n\Lambda^2 - m_{\mathrm{ex}}^2}{n\Lambda^2 - q^2}\right)^n$
- Reduced cutoff mass: $\Lambda_0 = \Lambda - m_{\mathrm{ex}} = 600\,\mathrm{MeV}$
- $IS$: product of the isospin symmetric factor from the isospin projection (for definite isospin channels) and SU(3) factor

# Effective Lagrangian

# Effective Lagrangian

- **Heavy chiral Lagrangian**

The coupling constants between heavy and light mesons are determined by the interaction Lagrangian based on the *Heavy Quark Effective Field Theory*(HQEFT).

$$\mathcal{L}_{\text{heavy}} = ig\text{Tr}[H_b \gamma_\mu \gamma_5 \mathcal{A}^\mu_{ba} \bar{H}_a] + i\beta \text{Tr}[H_b v^\mu (\mathcal{V}_\mu - \rho_\mu)_{ba} \bar{H}_a] + i\lambda \text{Tr}[H_b \sigma_{\mu\nu} F^{\mu\nu}_{ba}(\rho) \bar{H}_a] + g_\sigma \bar{H}_a H_a \sigma$$

A heavy-light meson is made up by a heavy quark $Q$ and a light antiquark $\bar{q}$.

→ Heavy Quark Spin Symmetry(HQSS), Heavy Quark Flavor Symmetry(HQFS) + Chiral symmetry

- *Heavy superfield:* HQSS, HQFS, Lorentz invariance, Parity invariance

$$H^a = \frac{1+\not{v}}{2}(P^{*a}_\mu \gamma^\mu - P^a \gamma_5), \quad \bar{H} = \gamma_0 H^\dagger \gamma_0 = (P^{*\dagger a}_\mu \gamma^\mu + P^{\dagger a} \gamma_5)\frac{1+\not{v}}{2}$$

Pseudoscalar heavy field: $P^a = \{D^+, D^0, D^+_s\}$ or $\{B^-, \bar{B}^0, \bar{B}^0_s\}$

Vector heavy field: $P^{*a}_\mu = \{D^{*+}_\mu, D^{*0}_\mu, D^{*+}_{s\mu}\}$ or $\{B^{*-}_\mu, \bar{B}^{*0}_\mu, \bar{B}^{*0}_{s\mu}\}$

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- *Light pseudoscalar mesons:* chiral symmetry spontaneous break down

$$\mathcal{A}^\mu = \frac{i}{f_\pi}\partial^\mu\mathcal{M} + \cdots \qquad \mathcal{M} = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}$$

- *Light vector mesons:* dynamical gauge boson of the hidden local symmetry

$$\rho^\mu = i\frac{g_V}{\sqrt{2}}V^\mu, \quad V^\mu = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{6}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{6}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & -\sqrt{\frac{2}{3}}\omega \end{pmatrix}^\mu$$

# Numerical Results

# Feynman amplitudes

- **Kernel matrices**

$$\mathcal{V}^{J=0(2),I=0} = \begin{pmatrix} \mathcal{V}_{D\bar{D}\to D\bar{D}} & \mathcal{V}_{D\bar{D}\to J/\psi\omega} & \mathcal{V}_{D\bar{D}\to D_s\bar{D}_s} & \mathcal{V}_{D\bar{D}\to D^*\bar{D}^*} & \mathcal{V}_{D\bar{D}\to J/\psi\phi} & \mathcal{V}_{D\bar{D}\to D_s^*\bar{D}_s^*} \\ \mathcal{V}_{J/\psi\omega\to D\bar{D}} & \mathcal{V}_{J/\psi\omega\to J/\psi\omega} & \mathcal{V}_{J/\psi\omega\to D_s\bar{D}_s} & \mathcal{V}_{J/\psi\omega\to D^*\bar{D}^*} & \mathcal{V}_{J/\psi\omega\to J/\psi\phi} & \mathcal{V}_{J/\psi\omega\to D_s^*\bar{D}_s^*} \\ \mathcal{V}_{D_s\bar{D}_s\to D\bar{D}} & \mathcal{V}_{D_s\bar{D}_s\to J/\psi\omega} & \mathcal{V}_{D_s\bar{D}_s\to D_s\bar{D}_s} & \mathcal{V}_{D_s\bar{D}_s\to D^*\bar{D}^*} & \mathcal{V}_{D_s\bar{D}_s\to J/\psi\phi} & \mathcal{V}_{D_s\bar{D}_s\to D_s^*\bar{D}_s^*} \\ \mathcal{V}_{D^*\bar{D}^*\to D\bar{D}} & \mathcal{V}_{D^*\bar{D}^*\to J/\psi\omega} & \mathcal{V}_{D^*\bar{D}^*\to D_s\bar{D}_s} & \mathcal{V}_{D^*\bar{D}^*\to D^*\bar{D}^*} & \mathcal{V}_{D^*\bar{D}^*\to J/\psi\phi} & \mathcal{V}_{D^*\bar{D}^*\to D_s^*\bar{D}_s^*} \\ \mathcal{V}_{J/\psi\phi\to D\bar{D}} & \mathcal{V}_{J/\psi\phi\to J/\psi\omega} & \mathcal{V}_{J/\psi\phi\to D_s\bar{D}_s} & \mathcal{V}_{J/\psi\phi\to D^*\bar{D}^*} & \mathcal{V}_{J/\psi\phi\to J/\psi\phi} & \mathcal{V}_{J/\psi\phi\to D_s^*\bar{D}_s^*} \\ \mathcal{V}_{D_s^*\bar{D}_s^*\to D\bar{D}} & \mathcal{V}_{D_s^*\bar{D}_s^*\to J/\psi\omega} & \mathcal{V}_{D_s^*\bar{D}_s^*\to D_s\bar{D}_s} & \mathcal{V}_{D_s^*\bar{D}_s^*\to D^*\bar{D}^*} & \mathcal{V}_{D_s^*\bar{D}_s^*\to J/\psi\phi} & \mathcal{V}_{D_s^*\bar{D}_s^*\to D_s^*\bar{D}_s^*} \end{pmatrix}$$

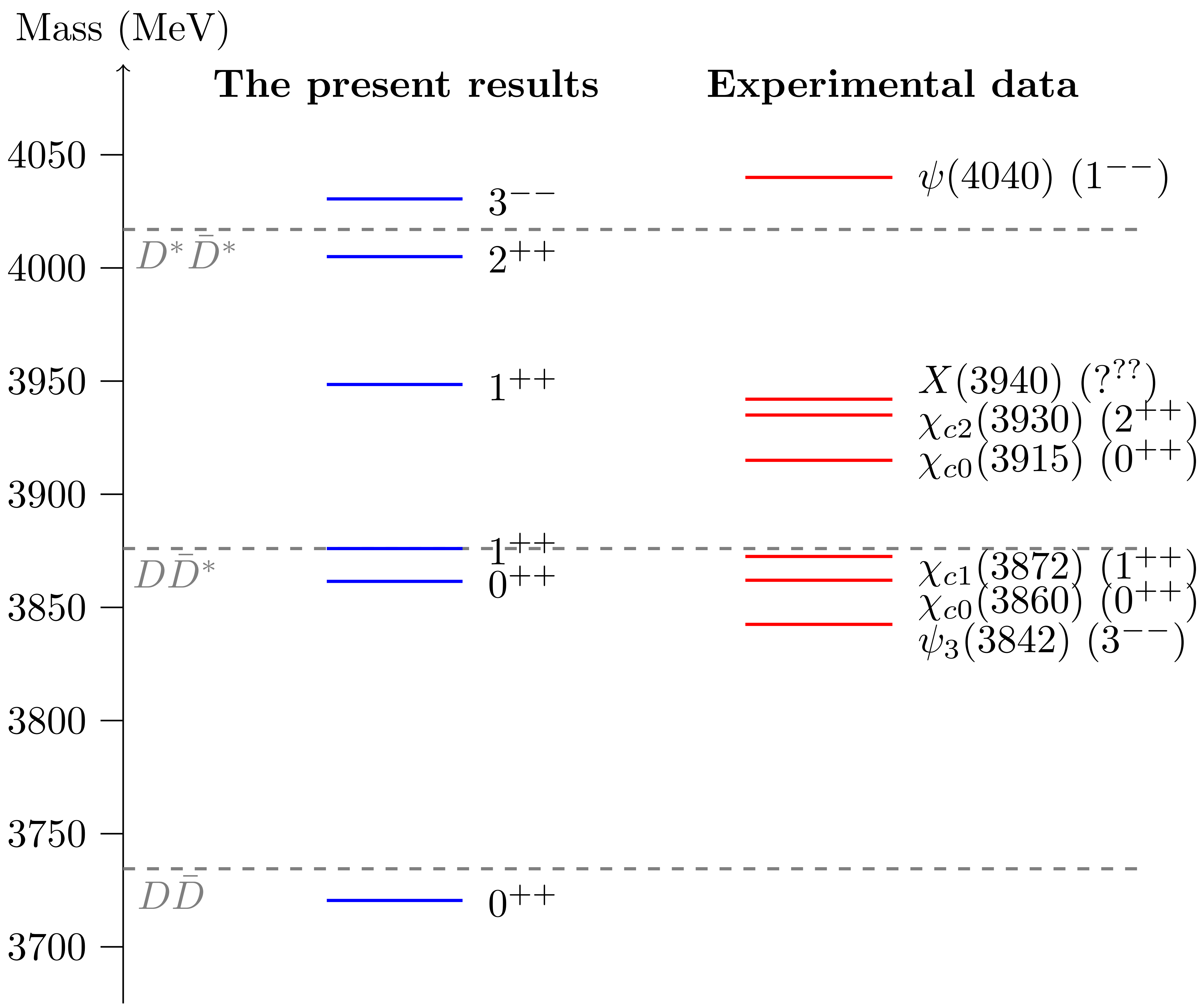
$$\mathcal{V}^{J=1,I=0} = \begin{pmatrix} \mathcal{V}_{\eta_c\omega\to\eta_c\omega} & \mathcal{V}_{\eta_c\omega\to D\bar{D}^*} & \mathcal{V}_{\eta_c\omega\to\eta_c\phi} & \mathcal{V}_{\eta_c\omega\to D\bar{D}^*} & \mathcal{V}_{\eta_c\omega\to D_s\bar{D}_s^*} & \mathcal{V}_{\eta_c\omega\to D_s^*\bar{D}_s^*} \\ \mathcal{V}_{D\bar{D}^*\to\eta_c\omega} & \mathcal{V}_{D\bar{D}^*\to D\bar{D}^*} & \mathcal{V}_{D\bar{D}^*\to\eta_c\phi} & \mathcal{V}_{D\bar{D}^*\to D\bar{D}^*} & \mathcal{V}_{D\bar{D}^*\to D_s\bar{D}_s^*} & \mathcal{V}_{D\bar{D}^*\to D_s^*\bar{D}_s^*} \\ \mathcal{V}_{\eta_c\phi\to\eta_c\omega} & \mathcal{V}_{\eta_c\phi\to D\bar{D}^*} & \mathcal{V}_{\eta_c\phi\to\eta_c\phi} & \mathcal{V}_{\eta_c\phi\to D\bar{D}^*} & \mathcal{V}_{\eta_c\phi\to D_s\bar{D}_s^*} & \mathcal{V}_{\eta_c\phi\to D_s^*\bar{D}_s^*} \\ \mathcal{V}_{D\bar{D}^*\to\eta_c\omega} & \mathcal{V}_{D\bar{D}^*\to D\bar{D}^*} & \mathcal{V}_{D\bar{D}^*\to\eta_c\phi} & \mathcal{V}_{D\bar{D}^*\to D\bar{D}^*} & \mathcal{V}_{D\bar{D}^*\to D_s\bar{D}_s^*} & \mathcal{V}_{D\bar{D}^*\to D_s^*\bar{D}_s^*} \\ \mathcal{V}_{D_s\bar{D}_s^*\to\eta_c\omega} & \mathcal{V}_{D_s\bar{D}_s^*\to D\bar{D}^*} & \mathcal{V}_{D_s\bar{D}_s^*\to\eta_c\phi} & \mathcal{V}_{D_s\bar{D}_s^*\to D\bar{D}^*} & \mathcal{V}_{D_s\bar{D}_s^*\to D_s\bar{D}_s^*} & \mathcal{V}_{D_s\bar{D}_s^*\to D_s^*\bar{D}_s^*} \\ \mathcal{V}_{D_s^*\bar{D}_s^*\to\eta_c\omega} & \mathcal{V}_{D_s^*\bar{D}_s^*\to D\bar{D}^*} & \mathcal{V}_{D_s^*\bar{D}_s^*\to\eta_c\phi} & \mathcal{V}_{D_s^*\bar{D}_s^*\to D\bar{D}^*} & \mathcal{V}_{D_s^*\bar{D}_s^*\to D_s\bar{D}_s^*} & \mathcal{V}_{D_s^*\bar{D}_s^*\to D_s^*\bar{D}_s^*} \end{pmatrix}$$

Each kernel matrix element represents the sum of all allowed Feynman amplitudes

All elements are expressed in momentum space

We thus construct the *off-mass-shell* kernel matrix in the full coupled-channel momentum space

## Mass spectrum in hidden-charm channel



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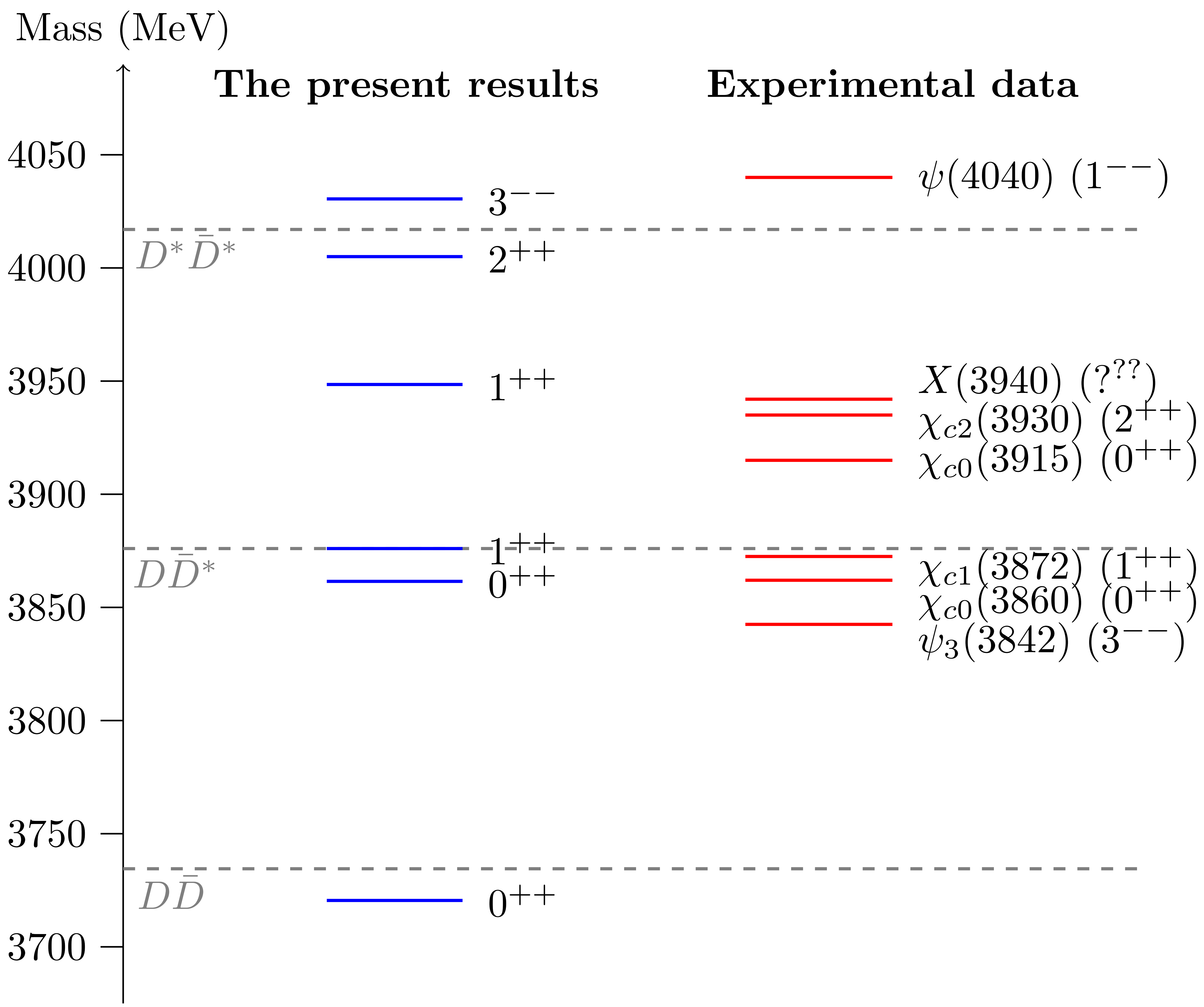


*Our model predicts several $\chi_{cJ}$ and $\psi_J$ states in the energy region between 3.7 and 4.1 GeV.*

- Two $\chi_{c0}$ states around 3720 MeV and 3860 MeV
- Two $\chi_{c1}$ states near 3875 MeV and 3950 MeV
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- A $\psi_3$ state above the $D^*\bar{D}^*$ threshold

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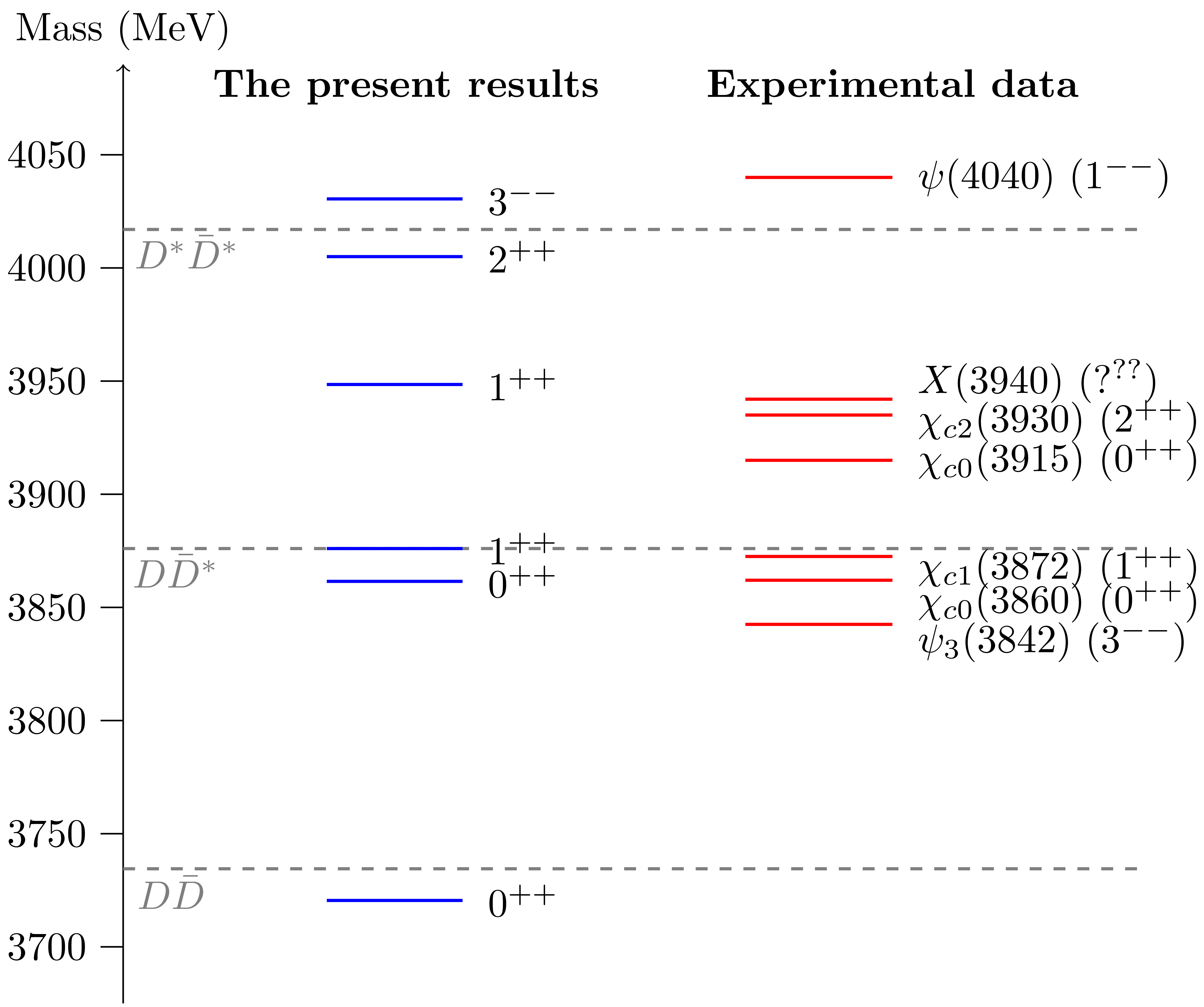


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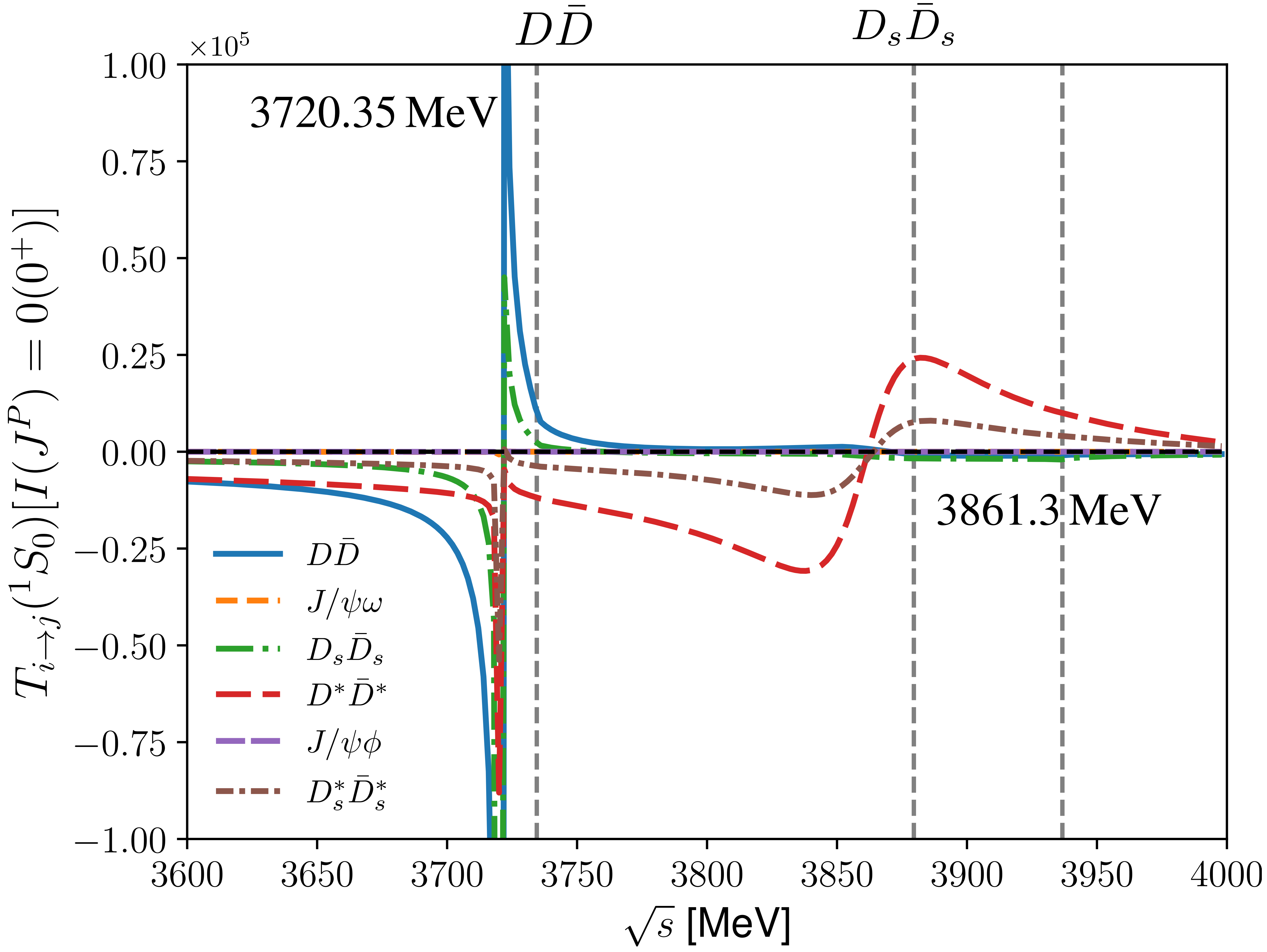
*Experimental candidates:*

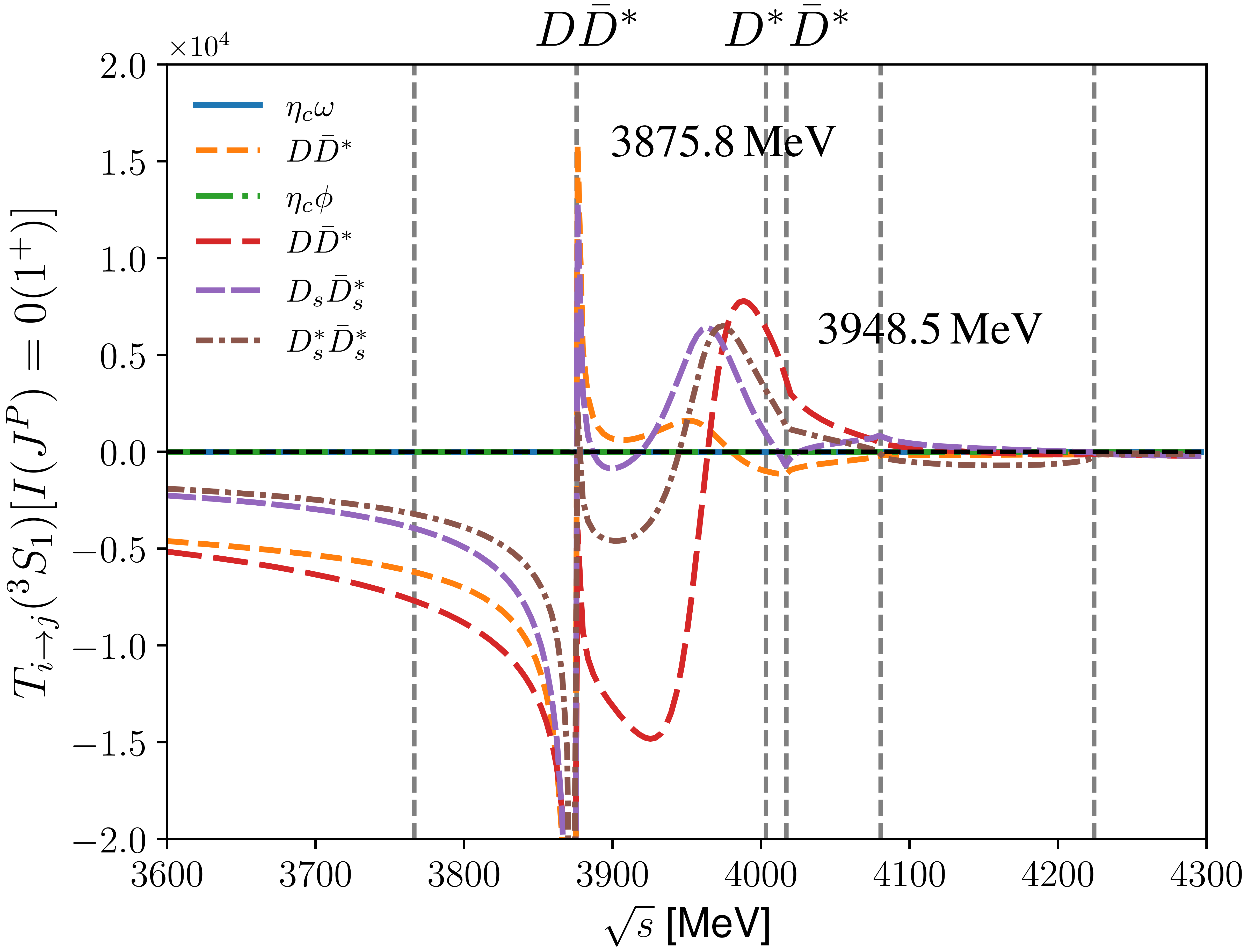
- $\chi_{c0}(3860)$, $\chi_{c0}(3915)$
- $\chi_{c1}(3872)$, $X(3940)$
- $\chi_{c2}(3930)$
- $\psi_3(3842)$, $\psi(4040)$

# Fully-coupled T-matrices

3720.5 MeV

- $\chi_{c0}$ and $\chi_{c1}$ states



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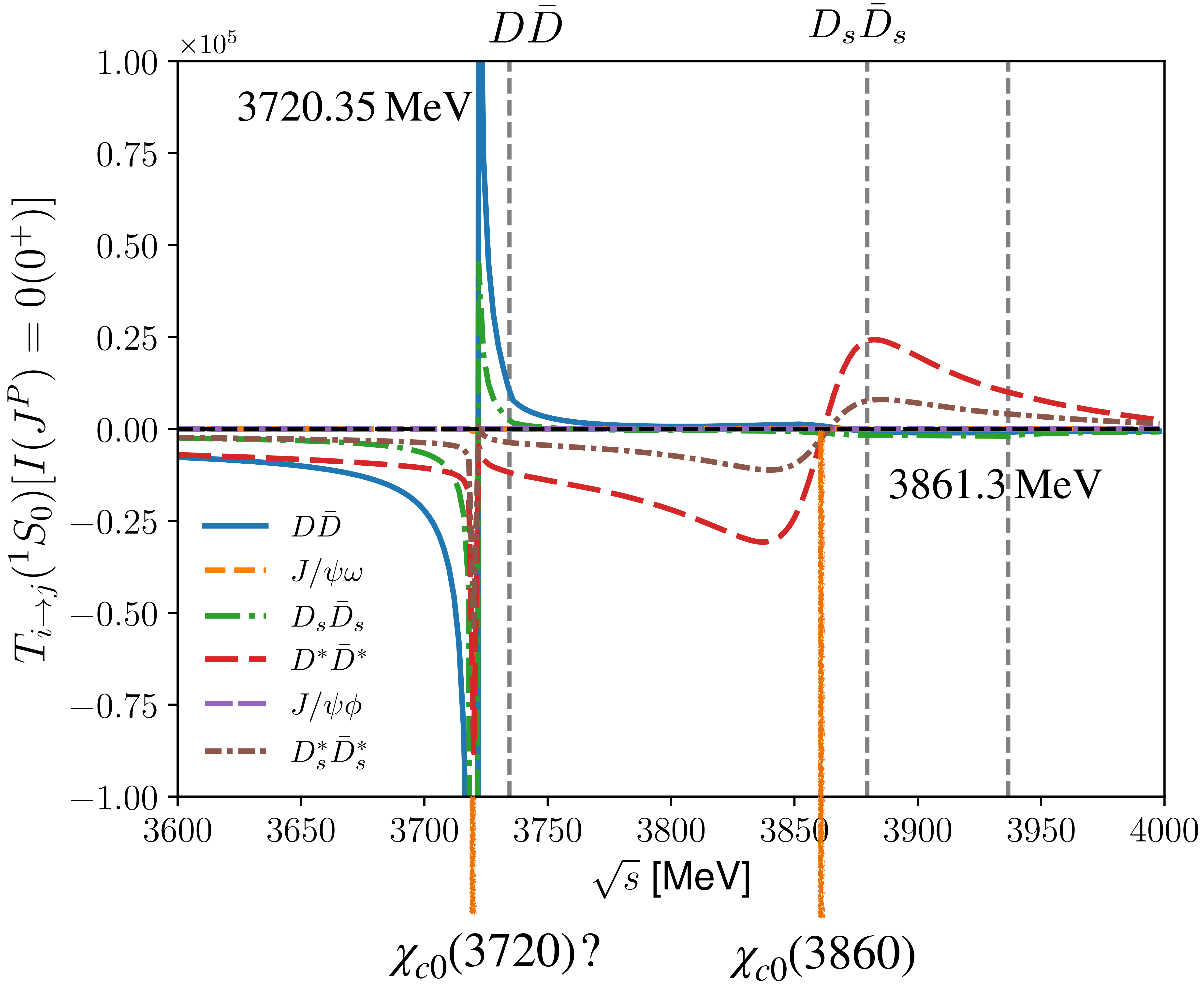
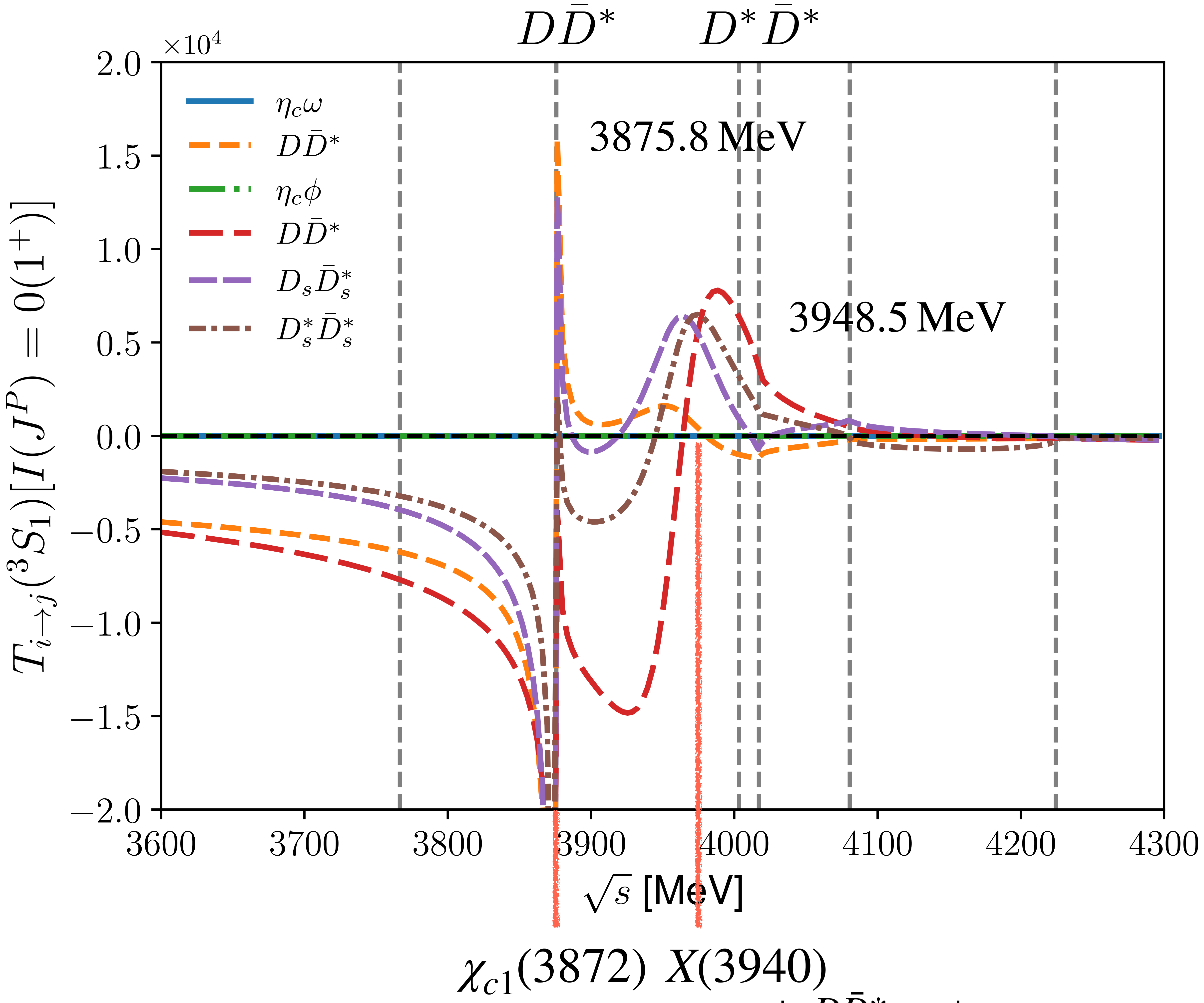



seen in $D\bar{D}$ modes

Belle PRD95, 112003

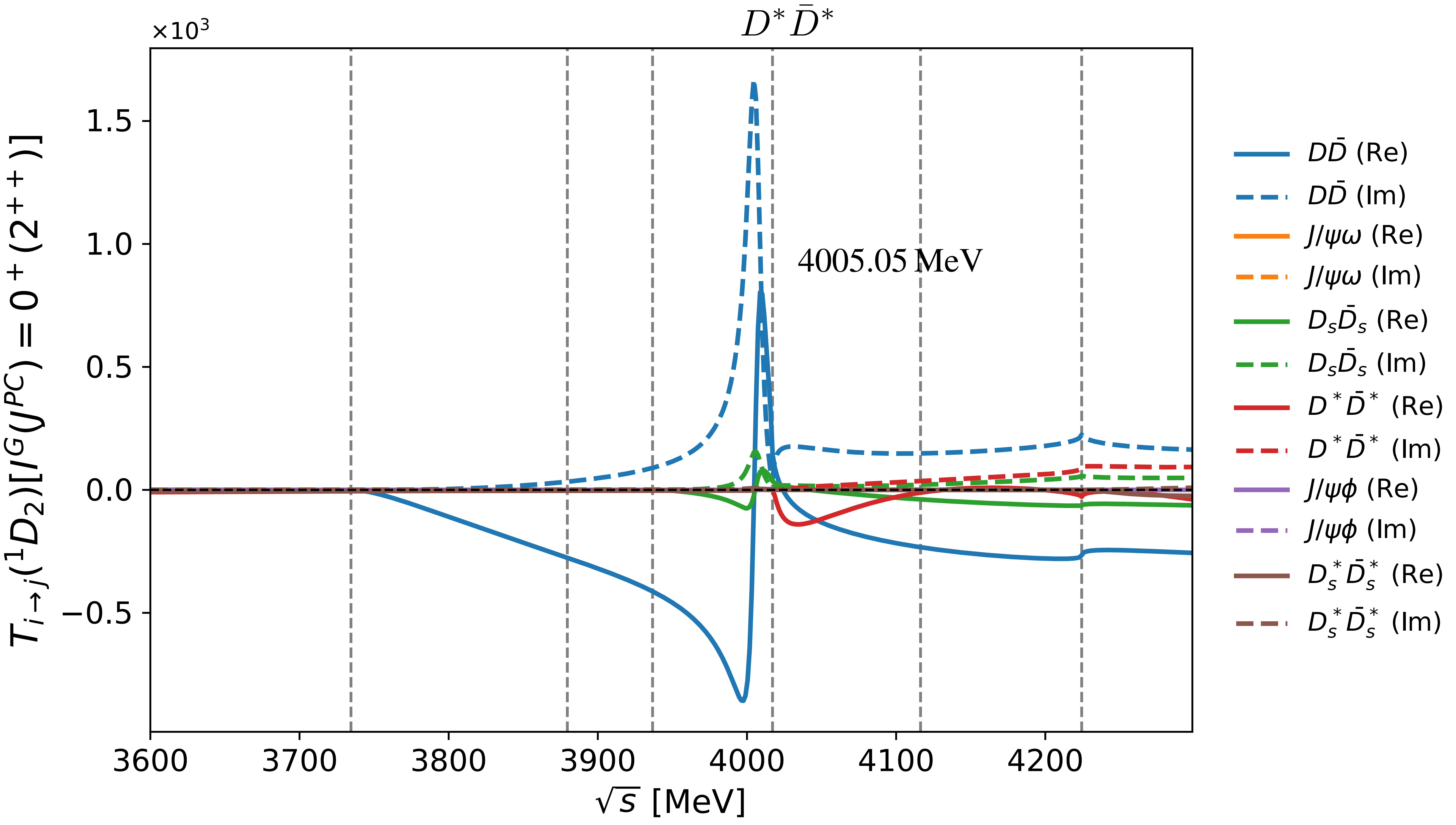



seen in $D\bar{D}^*$ mode

Belle PRL98, 082001

# Fully-coupled T-matrices

- $\chi_{c2}$ **state**

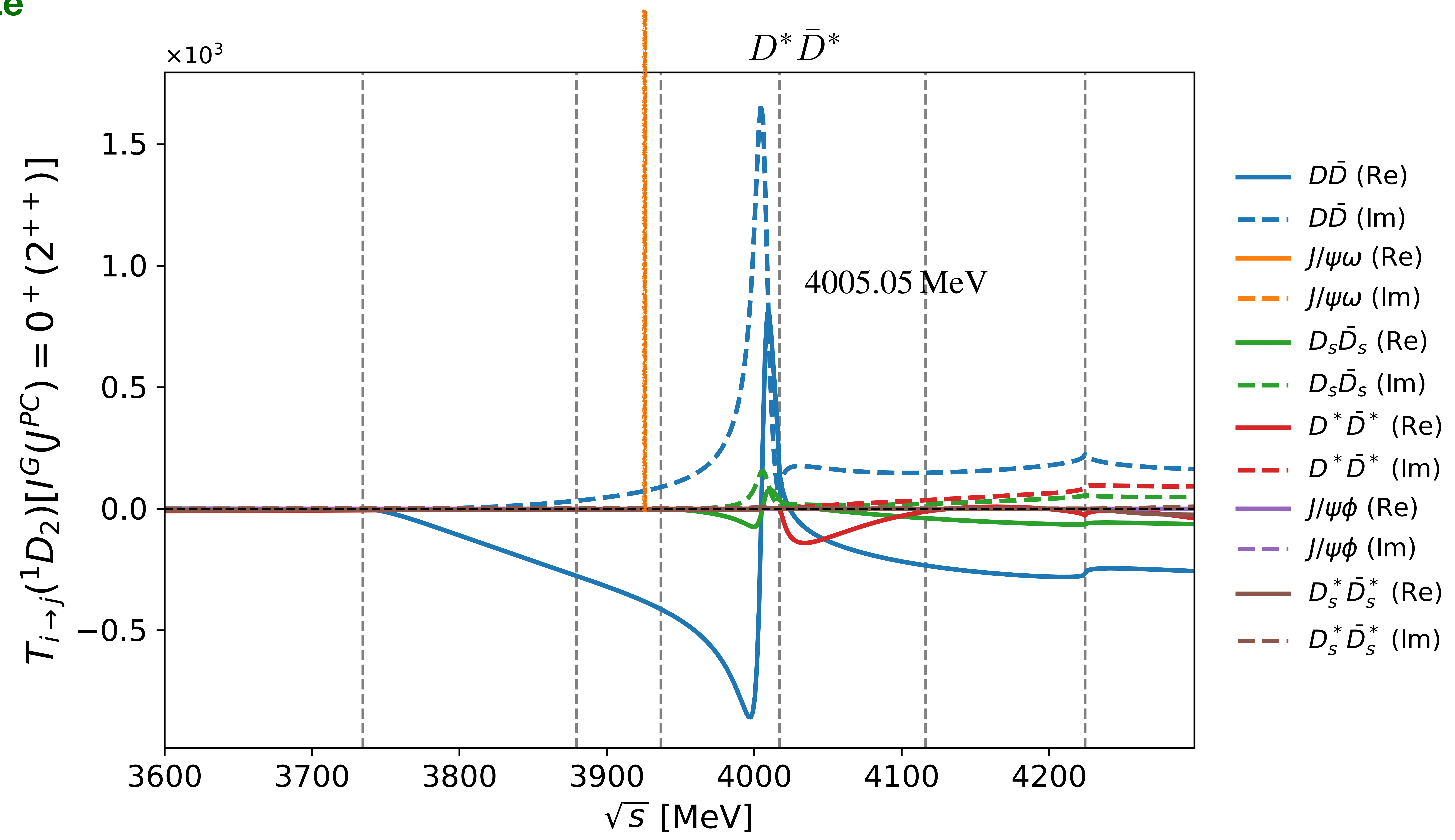


# Fully-coupled T-matrices

- $\chi_{c2}$ **state**

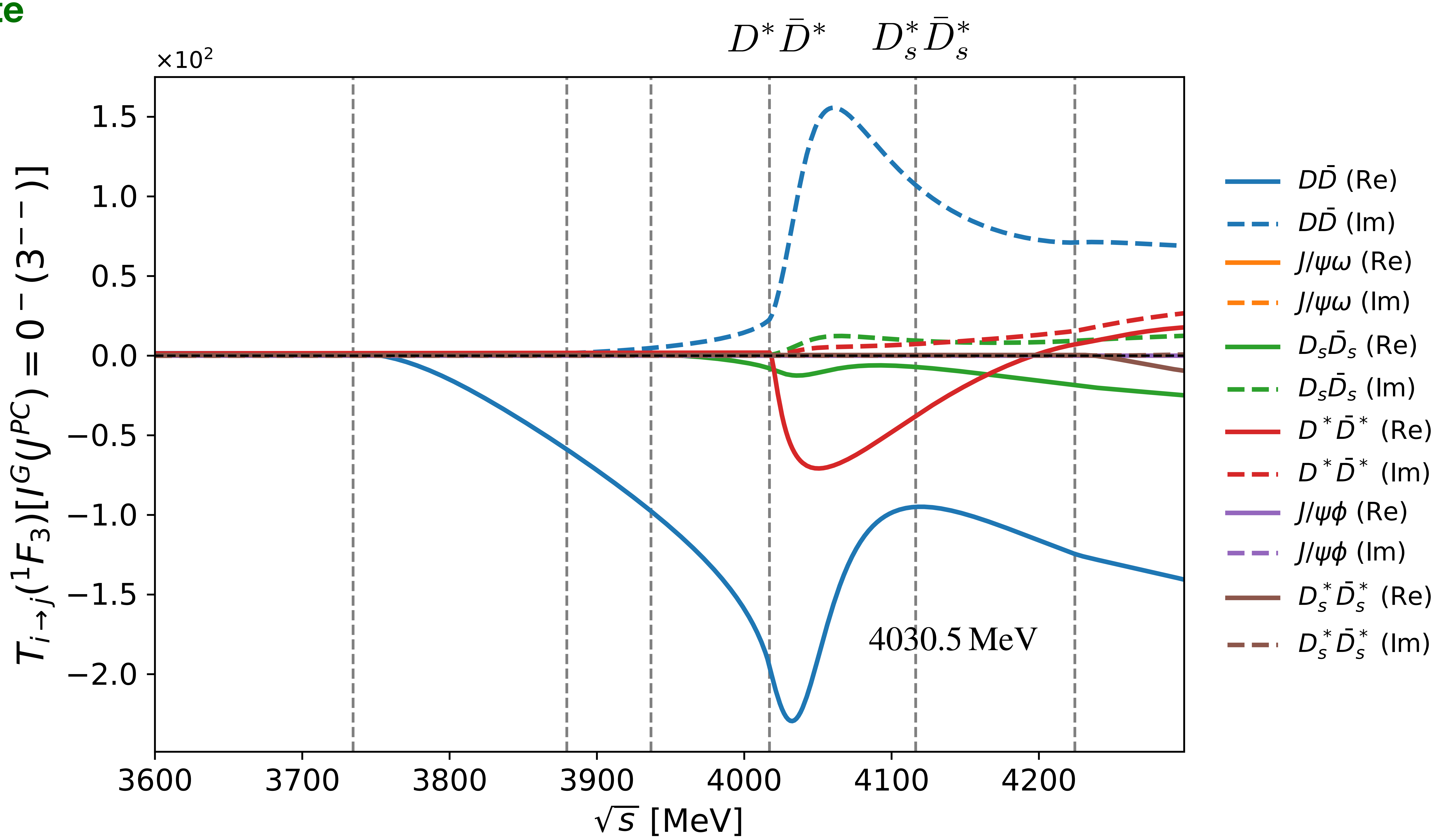
$\chi_{c2}(3930)$ seen in $D\bar{D}$ modes

Belle PRL 96 082003, BABAR PRD 81 92003



## Fully-coupled T-matrices

- $\psi_3$ **state**



# Channel Coupling Strengths

- $\chi_{c0}$ **states**

| $\sqrt{s_R}$[MeV] | 3720.35 | $3861.31 - i\,22.5$ |
|---|---|---|
| $g_{D\bar{D}(^1S_0)}$ | 14.132 | $5.547 + i\,5.774$ |
| $g_{J/\psi\,\omega(^1S_0)}$ | 0.190 | $0.561 - i\,0.099$ |
| $g_{D_s\bar{D}_s(^1S_0)}$ | 7.484 | $2.272 + i\,4.924$ |
| $g_{D^*\bar{D}^*(^1S_0)}$ | 2.680 | $36.412 - i\,16.022$ |
| $g_{J/\psi\,\phi(^1S_0)}$ | 0.178 | $0.482 - i\,0.074$ |
| $g_{D_s^*\bar{D}_s^*(^1S_0)}$ | 2.228 | $20.894 - i\,10.769$ |

- $\chi_{c1}$ **states**

| $\sqrt{s_R}$[MeV] | 3875.80 | $3948.5 - i\,32.25$ |
|---|---|---|
| $g_{\eta_c\,\omega(^3S_1)}$ | 0.016 | $0.162 + i\,0.249$ |
| $g_{\eta_c\,\omega(^3D_1)}$ | – | $0.104 - i\,0.021$ |
| $g_{D\bar{D}^*(^3S_1)}$ | 0.732 | $4.018 + i\,6.604$ |
| $g_{D\bar{D}^*(^3D_1)}$ | – | $0.130 - i\,1.056$ |
| $g_{\eta_c\,\phi(^3S_1)}$ | 0.016 | $0.369 + i\,0.188$ |
| $g_{\eta_c\,\phi(^3D_1)}$ | – | $0.002 + i\,0.005$ |
| $g_{D^*\bar{D}^*(^3S_1)}$ | 0.526 | $21.904 + i\,0.316$ |
| $g_{D^*\bar{D}^*(^3D_1)}$ | 0.009 | $0.144 + i\,0.087$ |
| $g_{D_s\bar{D}_s^*(^3S_1)}$ | 0.729 | $11.095 + i\,8.403$ |
| $g_{D_s\bar{D}_s^*(^3D_1)}$ | 0.017 | $0.117 + i\,0.154$ |
| $g_{D_s^*\bar{D}_s^*(^3S_1)}$ | 0.501 | $14.539 + i\,5.397$ |
| $g_{D_s^*\bar{D}_s^*(^3D_1)}$ | 0.021 | $0.424 + i\,0.222$ |

# Channel Coupling Strengths

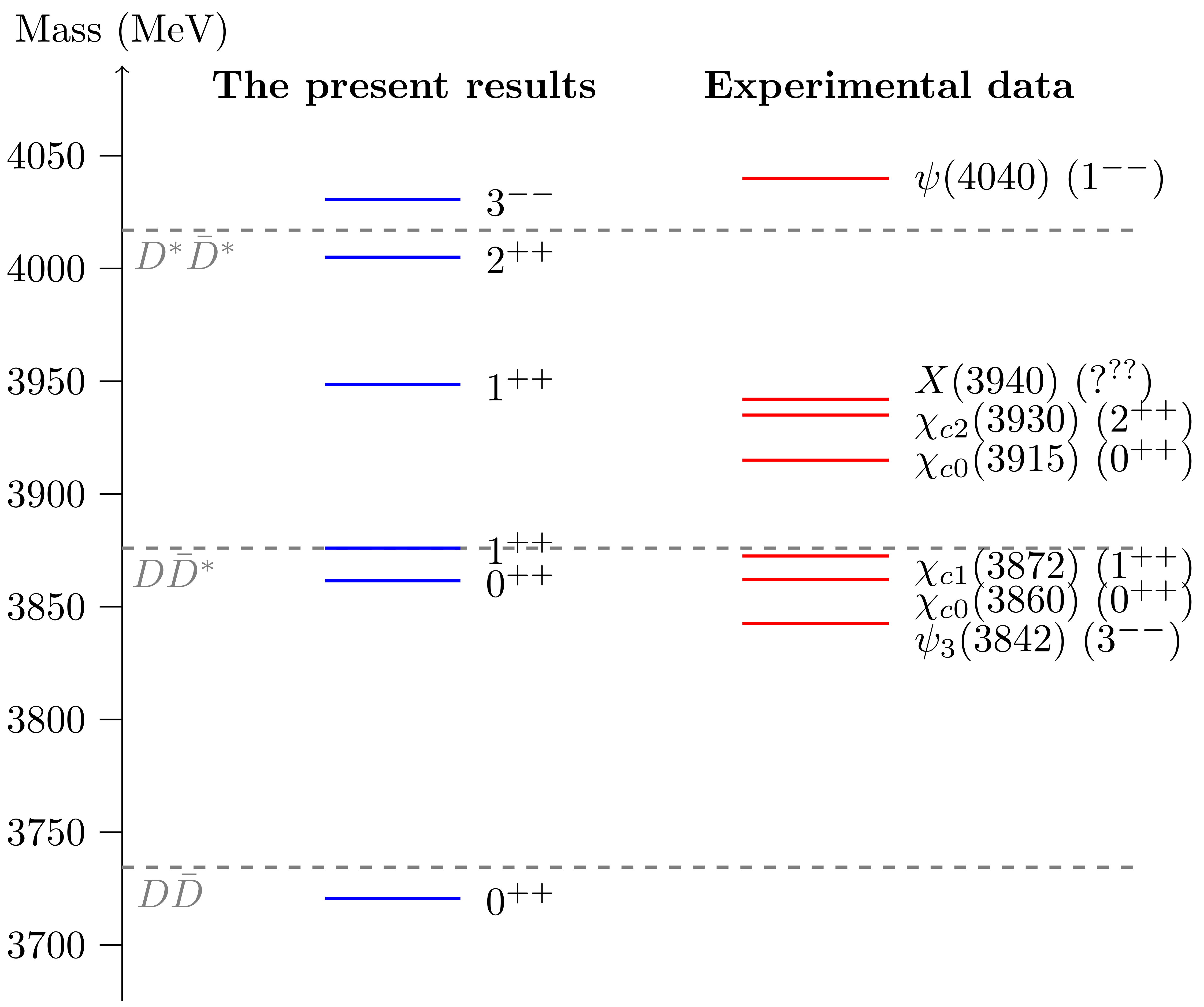
- $\chi_{c2}$ and $\psi_3$ states

TABLE III. Comparison of coupling strengths $g_i$ for $\chi_{c2}(^1D_2)$ and $\psi_3(^1F_3)$.

| $\sqrt{s_R}$[MeV] | $4005.300 - i\,5.950$ | | $4030.380 - i\,33.330$ | |
|---|---|---|---|---|
| Channel | $g_i(\chi_{c2})$ | $\lvert g_i\rvert_{\chi_{c2}}$ | $g_i(\psi_3)$ | $\lvert g_i\rvert_{\psi_3}$ |
| $g_{D\bar{D}}$ | $2.415 + i\,0.619$ | 2.494 | $0.977 - i\,1.061$ | 1.441 |
| $g_{J/\psi\,\omega}$ | $6.722 \times 10^{-4} - i\,2.492 \times 10^{-3}$ | 0.003 | $9.233 \times 10^{-4} - i\,3.240 \times 10^{-3}$ | 0.003 |
| $g_{D_s\bar{D}_s}$ | $0.766 + i\,7.944 \times 10^{-2}$ | 0.770 | $0.261 - i\,0.330$ | 0.421 |
| $g_{D^*\bar{D}^*}$ | $1.561 \times 10^{-2} + i\,1.180 \times 10^{-2}$ | 0.020 | $0.209 - i\,0.147$ | 0.255 |
| $g_{J/\psi\,\phi}$ | $2.879 \times 10^{-4} + i\,3.495 \times 10^{-5}$ | 0.000 | $8.131 \times 10^{-6} - i\,1.194 \times 10^{-5}$ | 0.000 |
| $g_{D_s^*\bar{D}_s^*}$ | $0.165 + i\,4.324 \times 10^{-2}$ | 0.170 | $1.707 \times 10^{-4} - i\,1.040 \times 10^{-3}$ | 0.001 |

# Summary

# Summary




- Using the fully off-mass-shell coupled-channel formalism, we have investigated the spectrum and production mechanisms of hidden-charm exotic mesons.
- Our results predict several bound and resonance states near the relevant open-charm thresholds, as summarized in the figure on the left.
- For $\chi_{cJ}$ states, we predict a $D\bar{D}$ bound state at $3720$ MeV and a higher $\chi_{c2}$ state at $4005$ MeV.
- Our $\chi_{c1}$ at 3948 MeV exhibits properties quite similar to those of the $X(3940)$ state.
- A $\psi_3$-like state is found above the $D^*\bar{D}^*$ threshold with significant coupling to the $D\bar{D}$ channel.

# Thank you