Dynamical generation of Exotic Heavy Mesons in the heavy meson scattering

2025 CENuM Workshop
Seogwipo KAL Hotel, Jeju Island
January, 16-19 2025

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Outline

- *Introduction*
- *Coupled-channel formalism*
- *Effective Lagrangian*
- *Heavy meson scattering in doubly charmed-channels*
- *Heavy meson scattering in hidden-charm channels*
- *Summary*

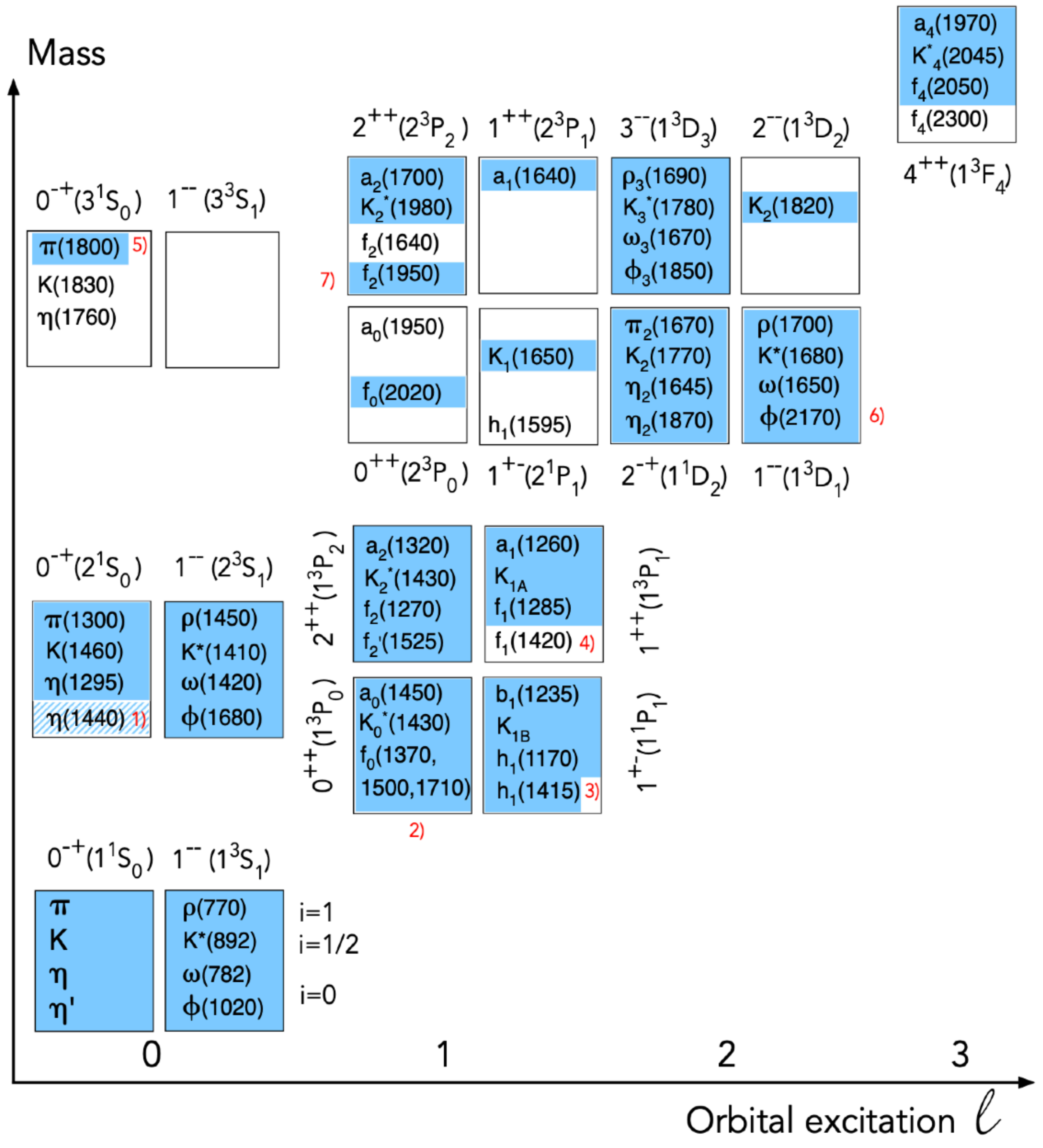
Introduction

Hadron spectroscopy

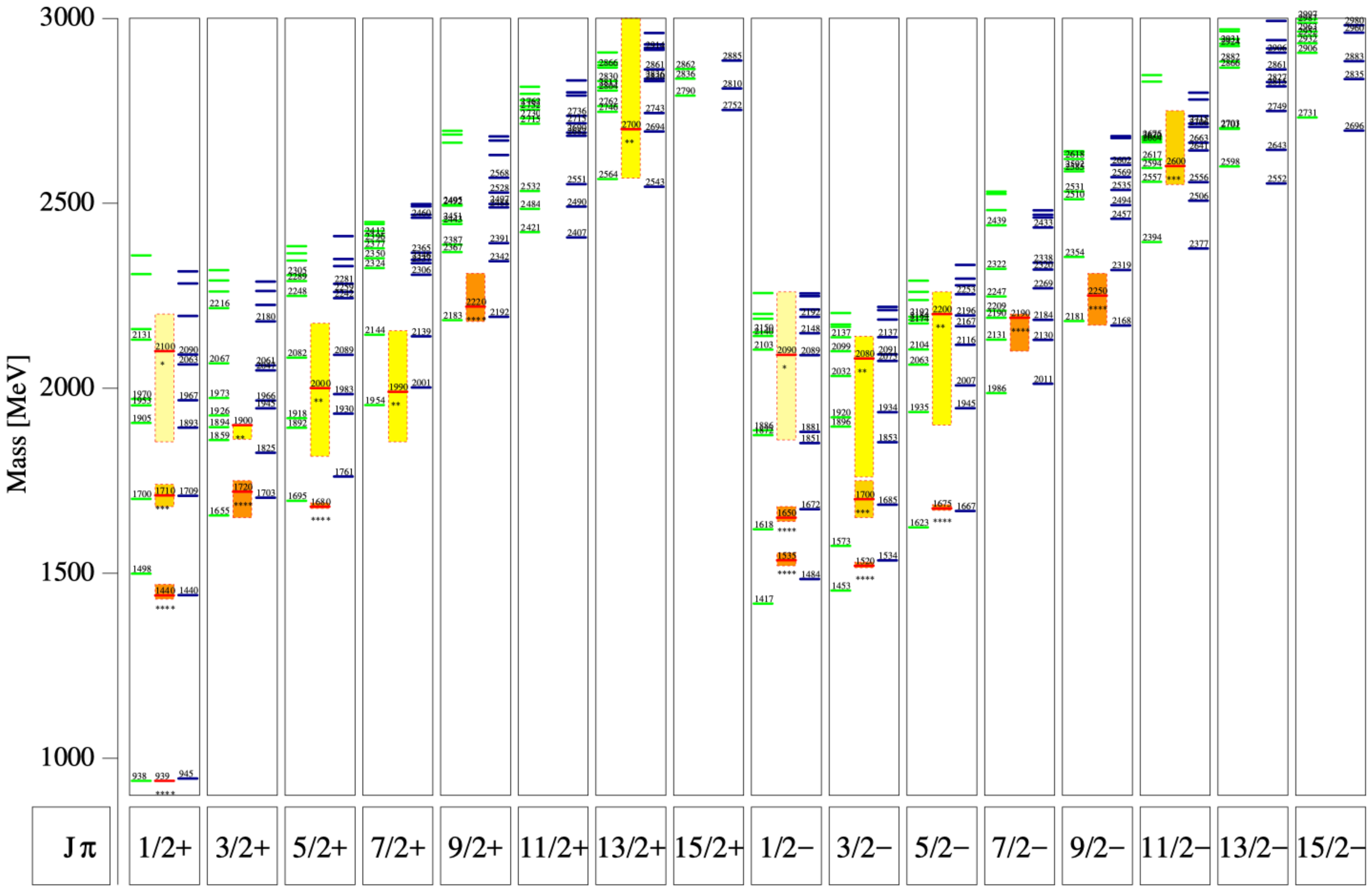
Conventional Quark Model

- The spectrum of strongly interacting particles consists of a tower of many states.

Conventional hadrons : Mesons($q\bar{q}$) and Baryons(qqq)



R.L. Workman *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01.



A. Thiel *et al*. Prog, Part. Nucl. Phys.125 2022, 103949

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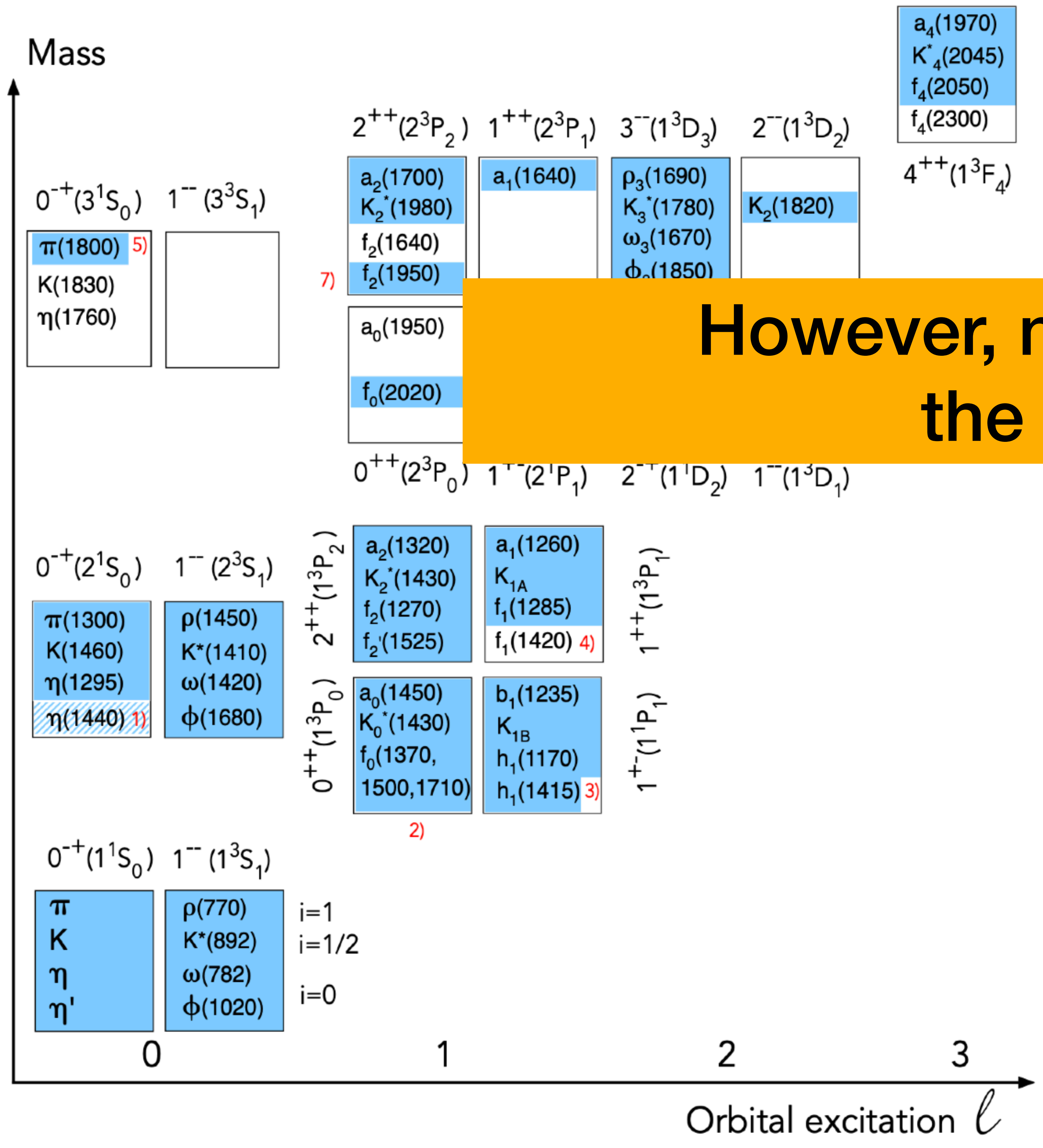

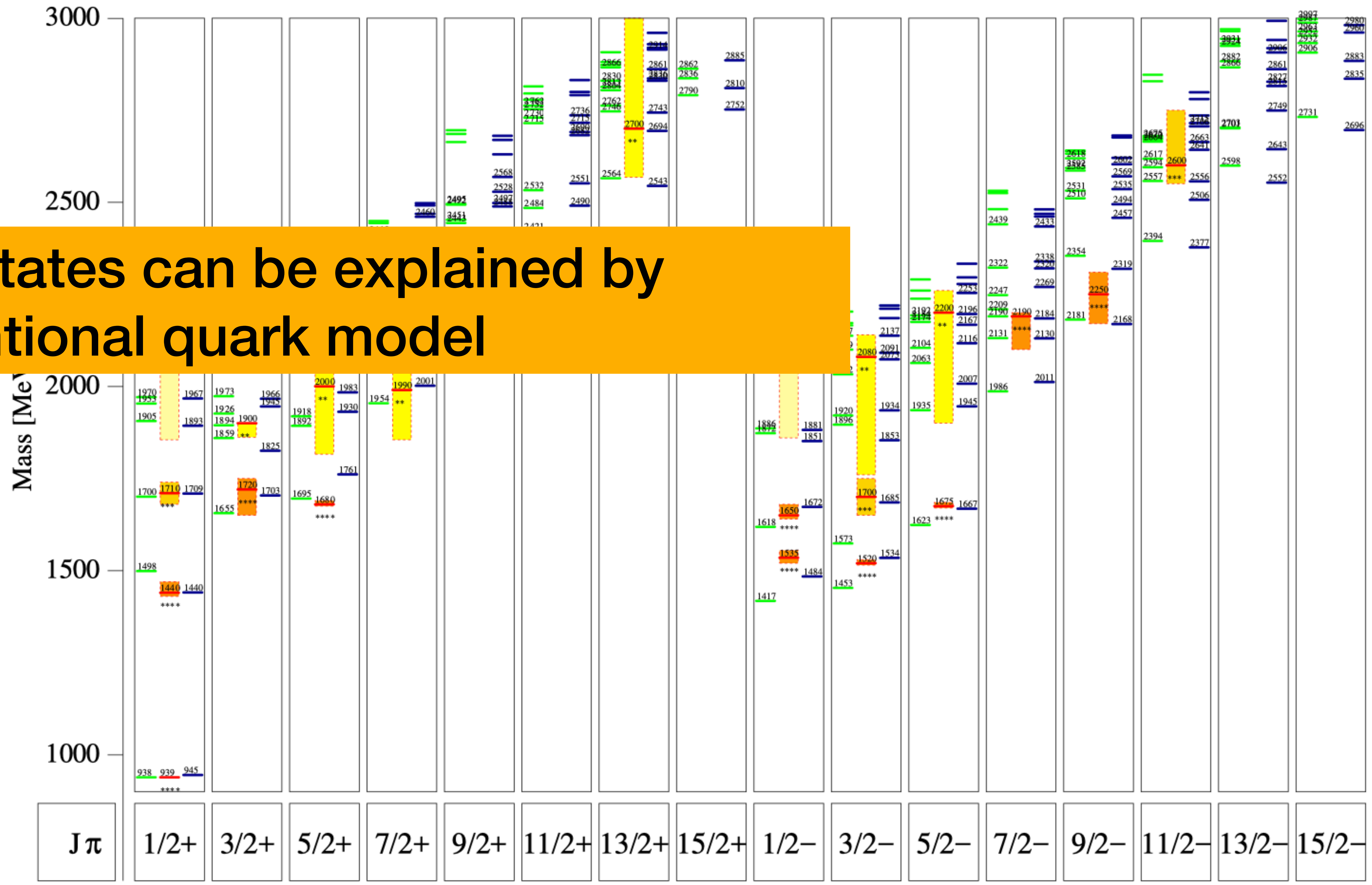

However, not all states can be explained by the conventional quark model

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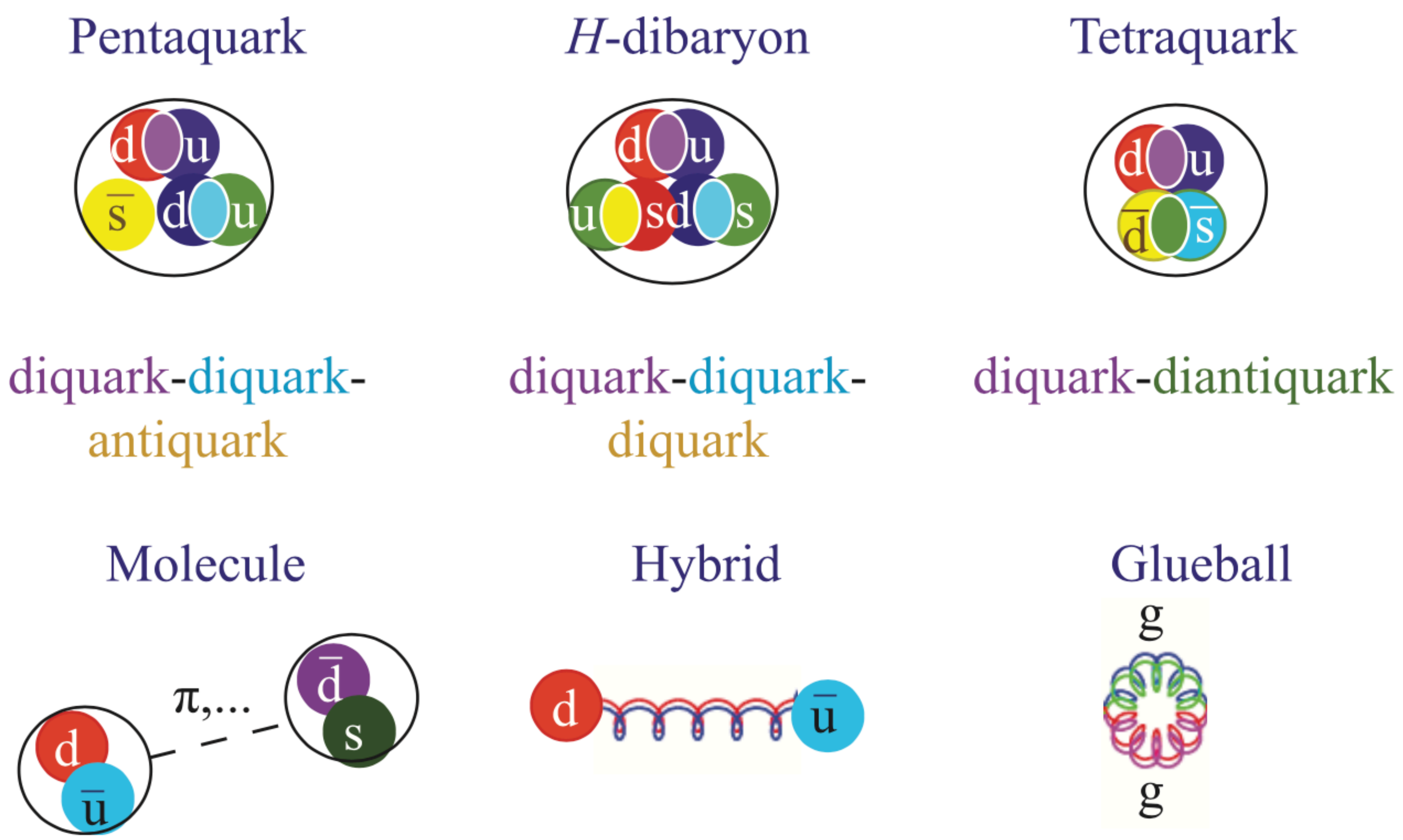
Beyond Quark Model

QCD allows 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), $qqqqqq\ldots$



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

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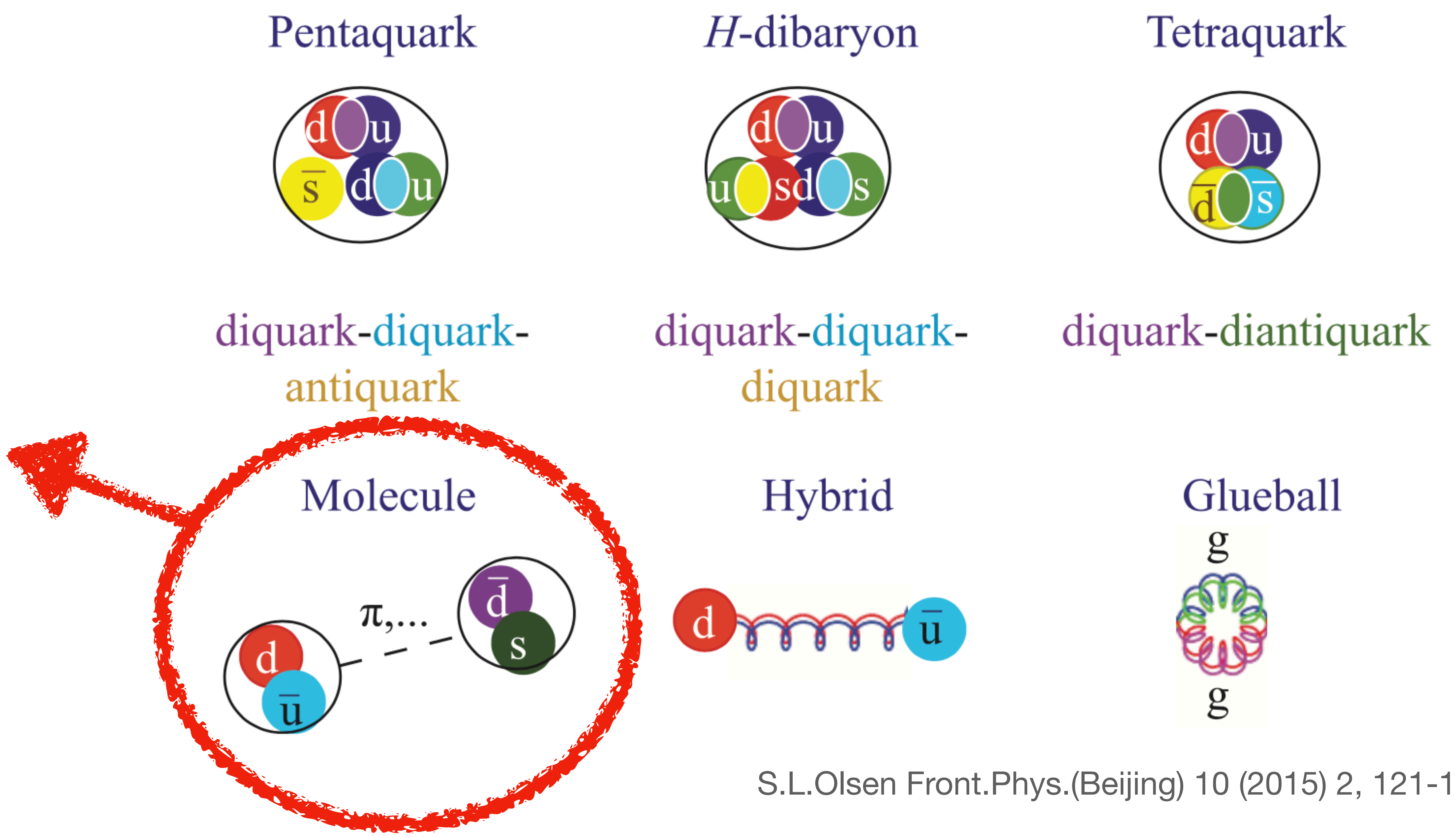
Baryon : qqq $\quad$ $qqqq\bar{q}$(pentaquark), $qqqqqq$…

Hadronic molecule

- Bound states of color-neutral states via meson-exchanges
- Near certain two-particle thresholds
- Dominantly decay into the two-particle channels



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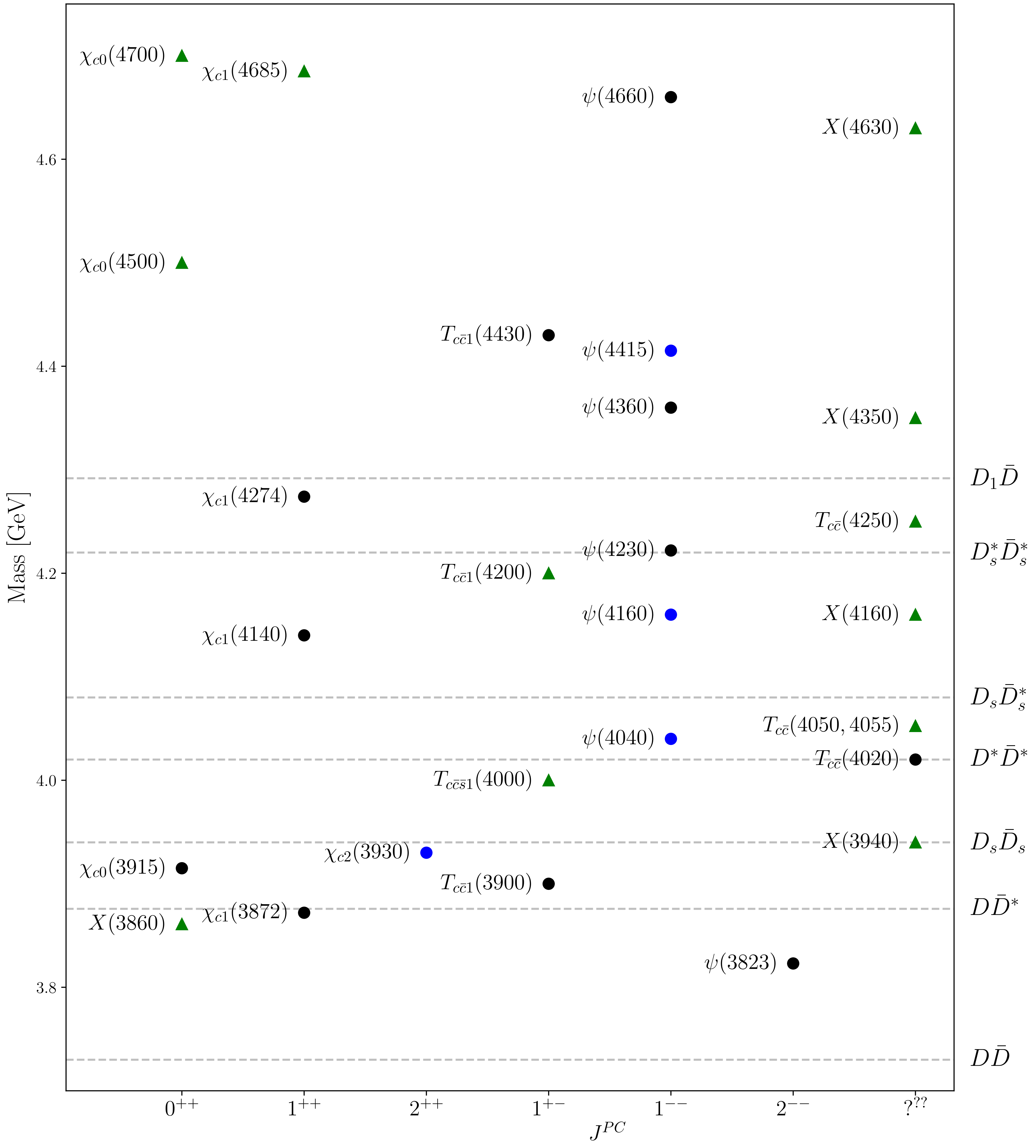
Exotic states

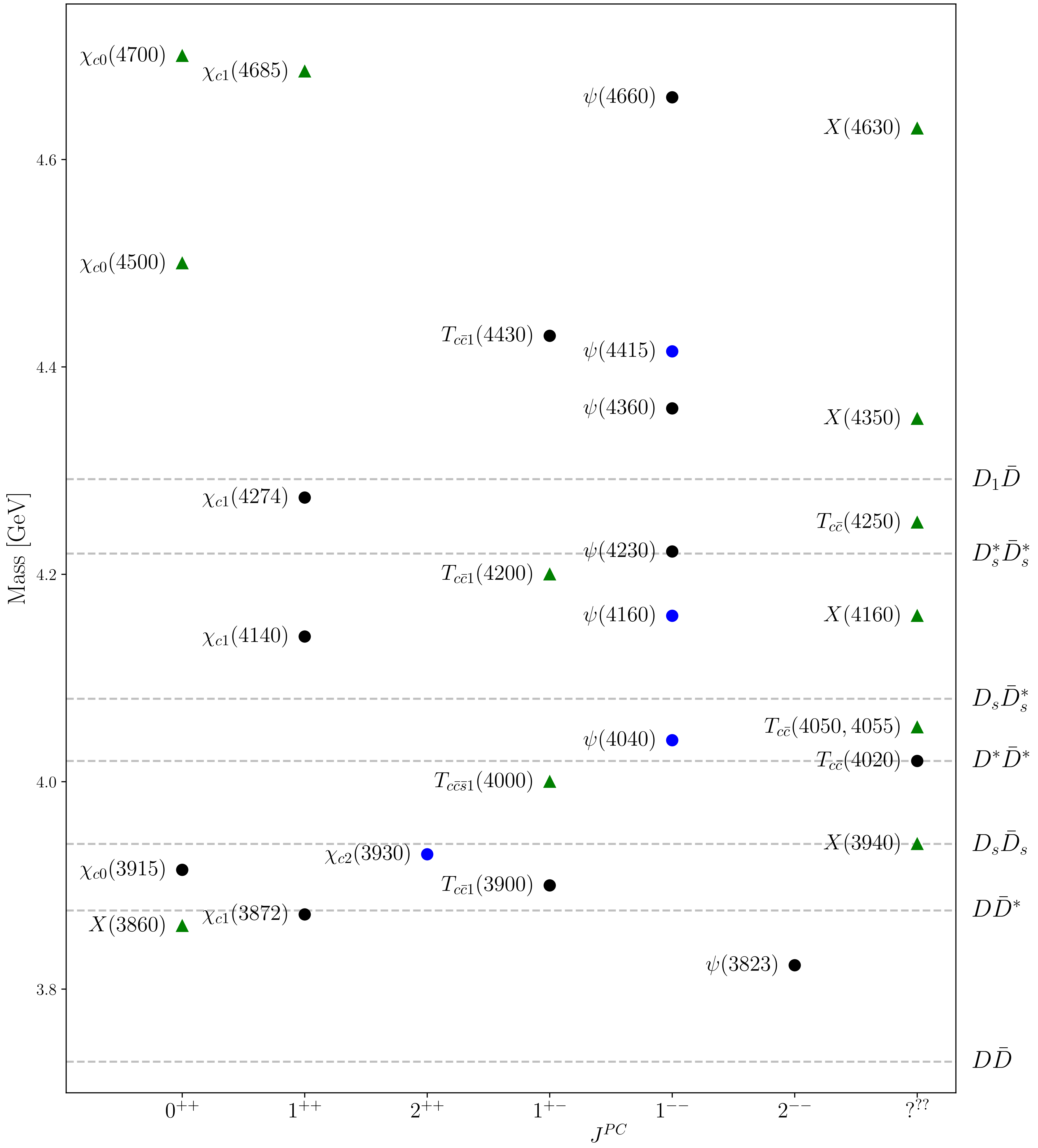


The representative hadronic-molecule candidate is $\chi_{c1}(3872)$

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

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

Exotic states



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

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

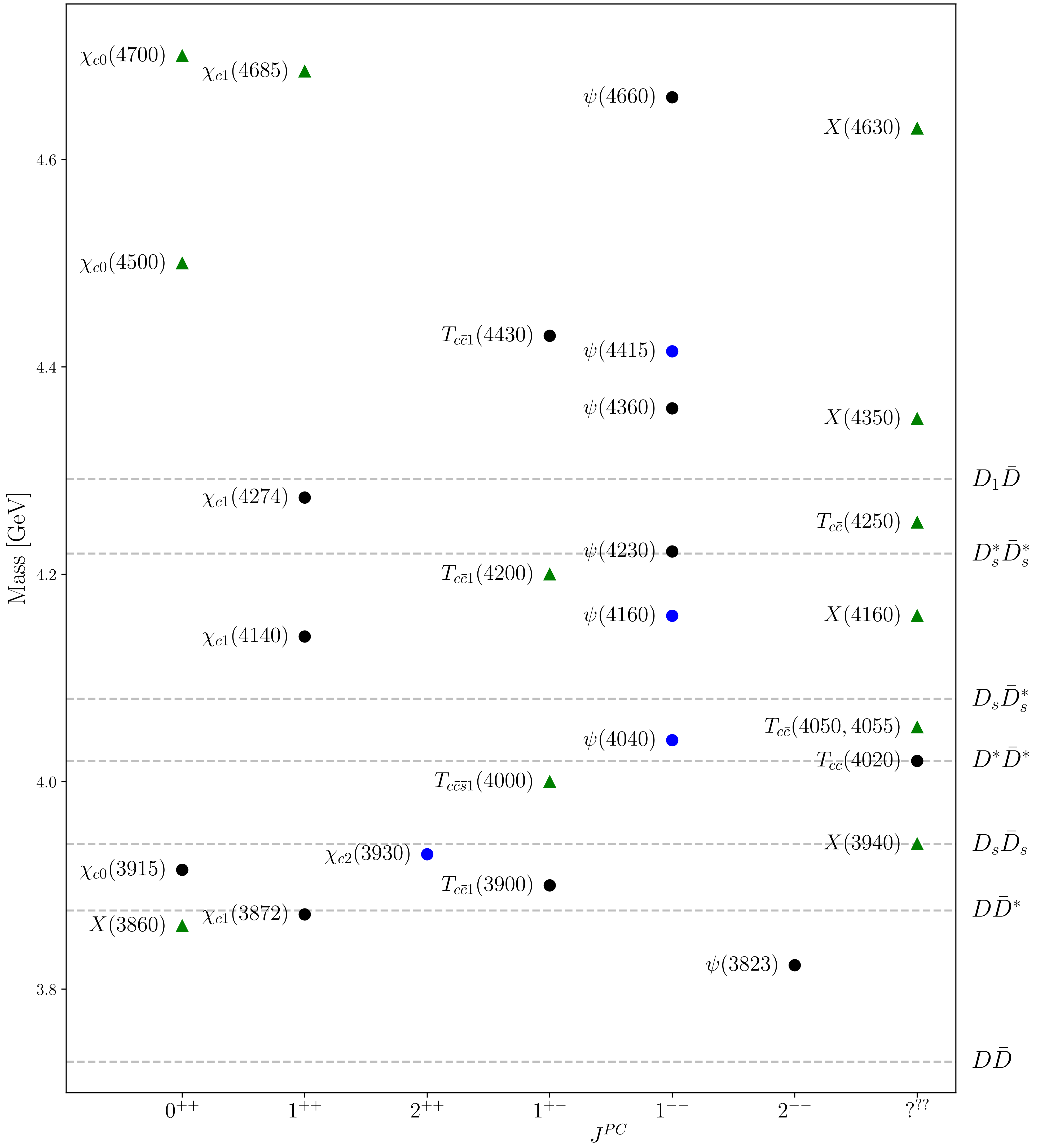
$$M_{\chi_{c1}} - (m_{D^0} + m_{\bar{D}^{*0}}) = -0.09 \pm 0.28\,\text{MeV}$$

Dominantly decay into this channel:

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

Consistent with the characteristics of hadronic molecules

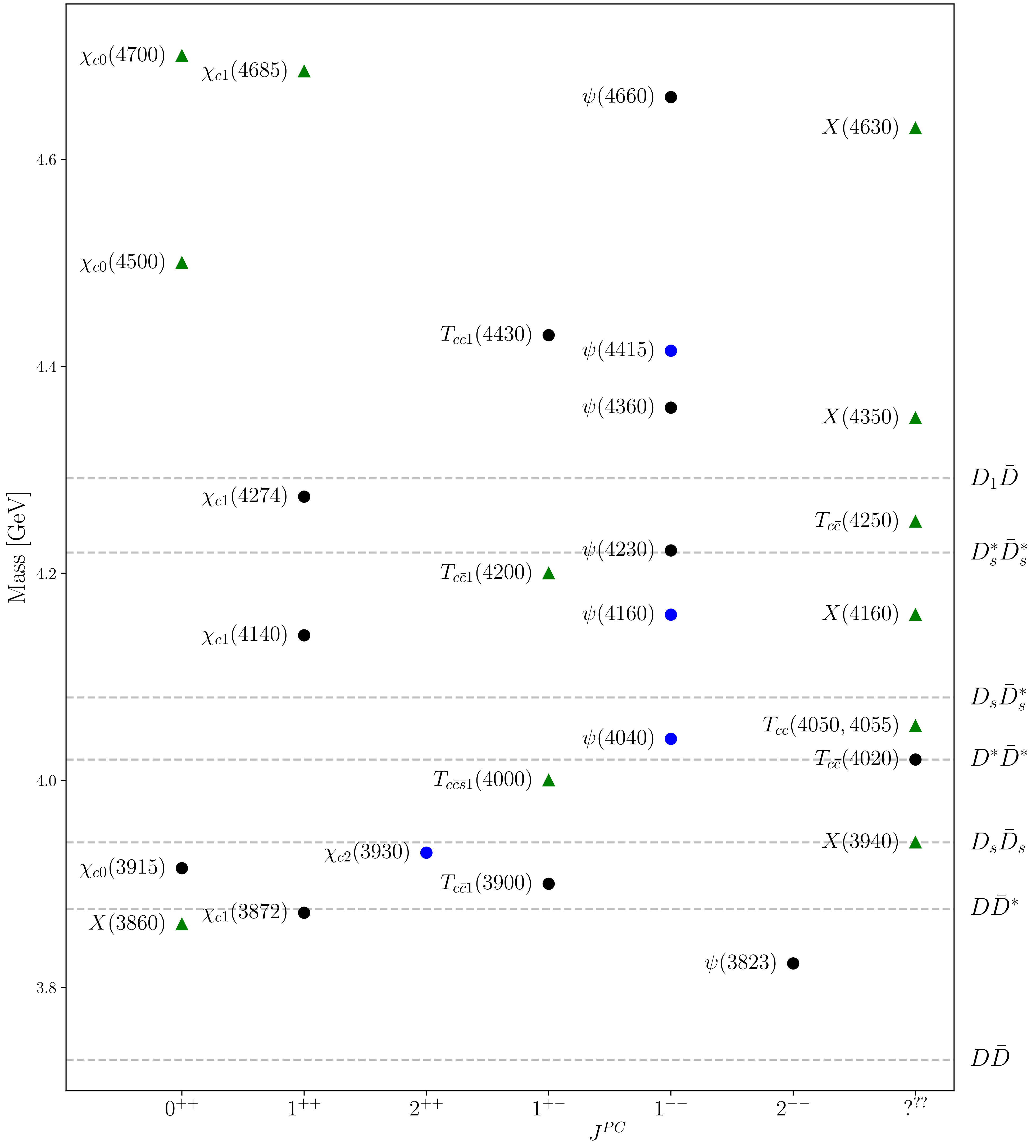
Exotic heavy mesons



Observed multiquark candidates listed in PDG:

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

Exotic heavy mesons



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D. Lohse, Nucl. Phys. A516, 513

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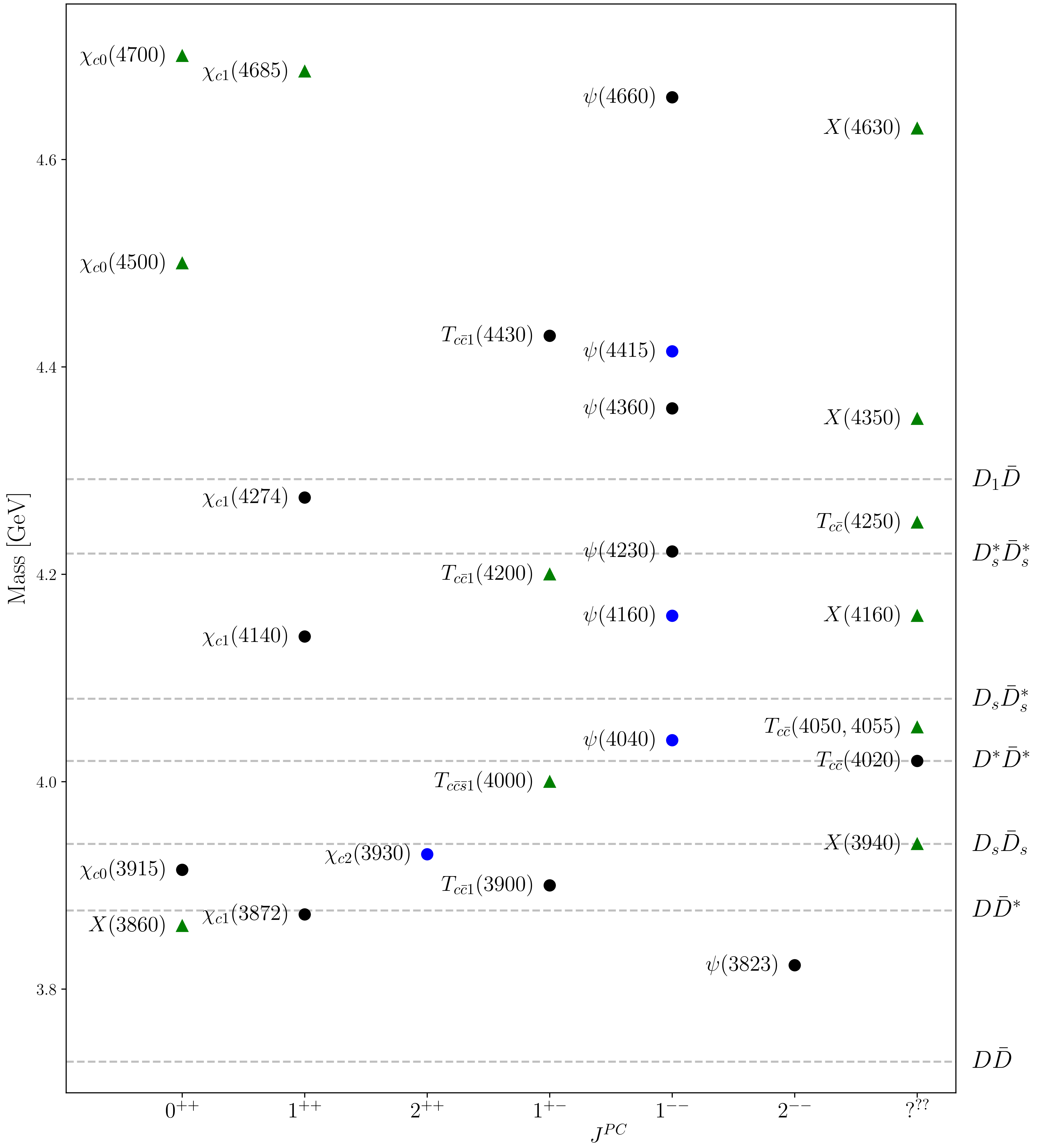

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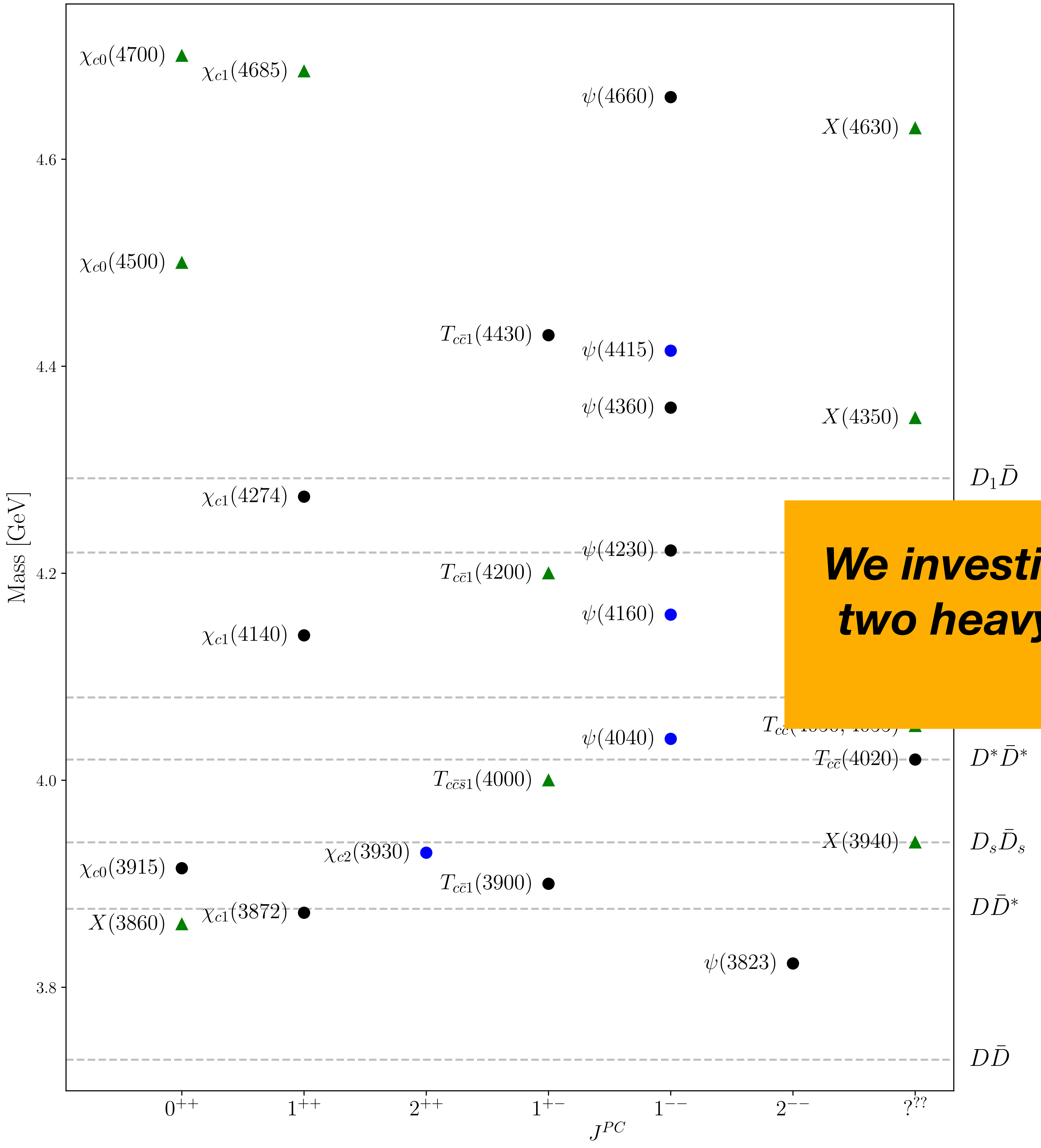

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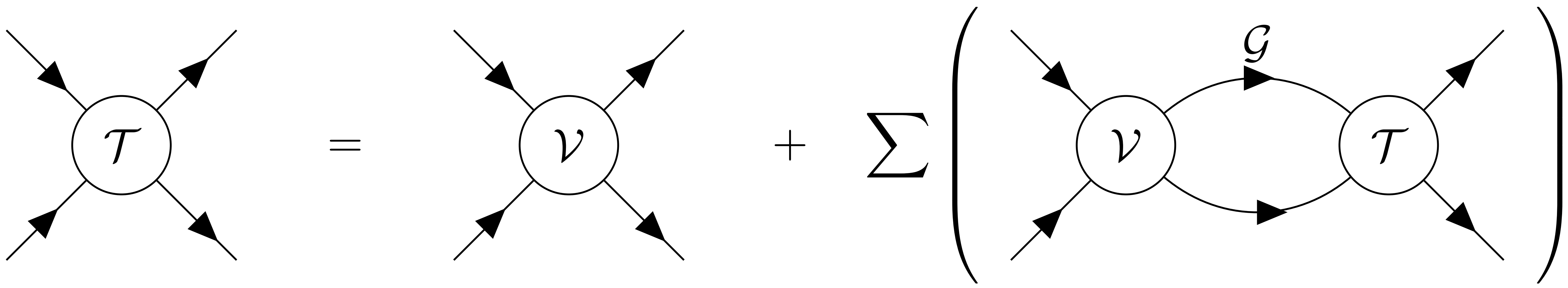
We investigate the hadron molecular features of the exotic states containing two heavy quarks using the fully off-mass-shell coupled-channel formalism within the meson-exchange framework.

Coupled-channel formalism

Two-body scattering equation

- **Blankenbecler-Sugar equation**



$$T = V + VGT$$

- The two-body T-matrix are 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 via the Blankenbecler-Sugar scheme preserves unitarity and off-shellness:

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

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

Two-body scattering equation

- **Blankenbecler-Sugar equation**
  - Total angular momentum projection

$$T^J_{fi}(p,p') = V^J_{fi}(p,p') + \frac{1}{(2\pi)^3}\int_0^\infty dq\, \frac{\omega_1+\omega_2}{2\omega_1\omega_2}\frac{q^2 V^J_{fk}(p,q)T^J_{ki}(q,p')}{s-(\omega_1+\omega_2)^2 - i\varepsilon}$$

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

Two-body scattering equation

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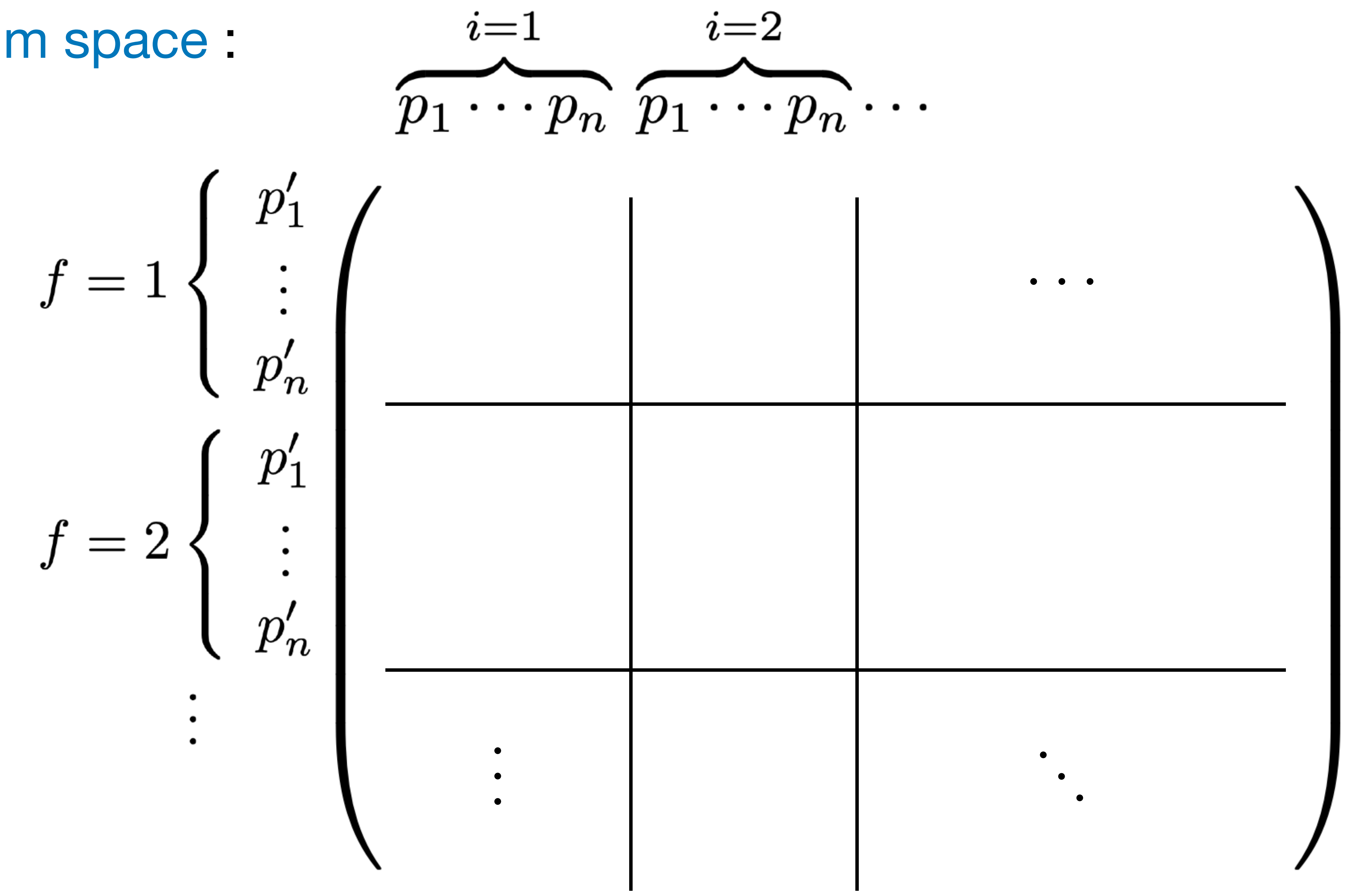
Matrix inversion method: $T^J = V^J + V^J G T^J \implies T^J = (1-V^J G)^{-1} V^J$

We obtain the *off-mass-shell* T matrix in the full-channel momentum space :



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Regularization of the two-body propagator:

- The two-body propagator is singular at the on-mass-shell momentum point, $\omega^2(\tilde{q}) = s,\ \tilde{q} = \dfrac{\lambda^{\frac{1}{2}}(s, m_1^2, m_2^2)}{2\sqrt{s}}$
- Change of the variable

$$\omega = \omega_1 + \omega_2, \quad d\omega = \frac{\omega_1+\omega_2}{\omega_1\omega_2} q\, dq \quad \Longrightarrow \quad \int_{m_1+m_2}^\infty d\omega \frac{f(q)}{\omega^2 - s}, \quad \text{where } f(q) = \frac{1}{2} q V(q) T(q)$$

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- Decompose into regular part and singular part.

$$\int_{m_1+m_2}^\infty d\omega \frac{f(q)-f(\tilde{q})}{\omega^2 - s} + \int_{m_1+m_2}^\infty d\omega \frac{f(\tilde{q})}{\omega^2 - s}$$

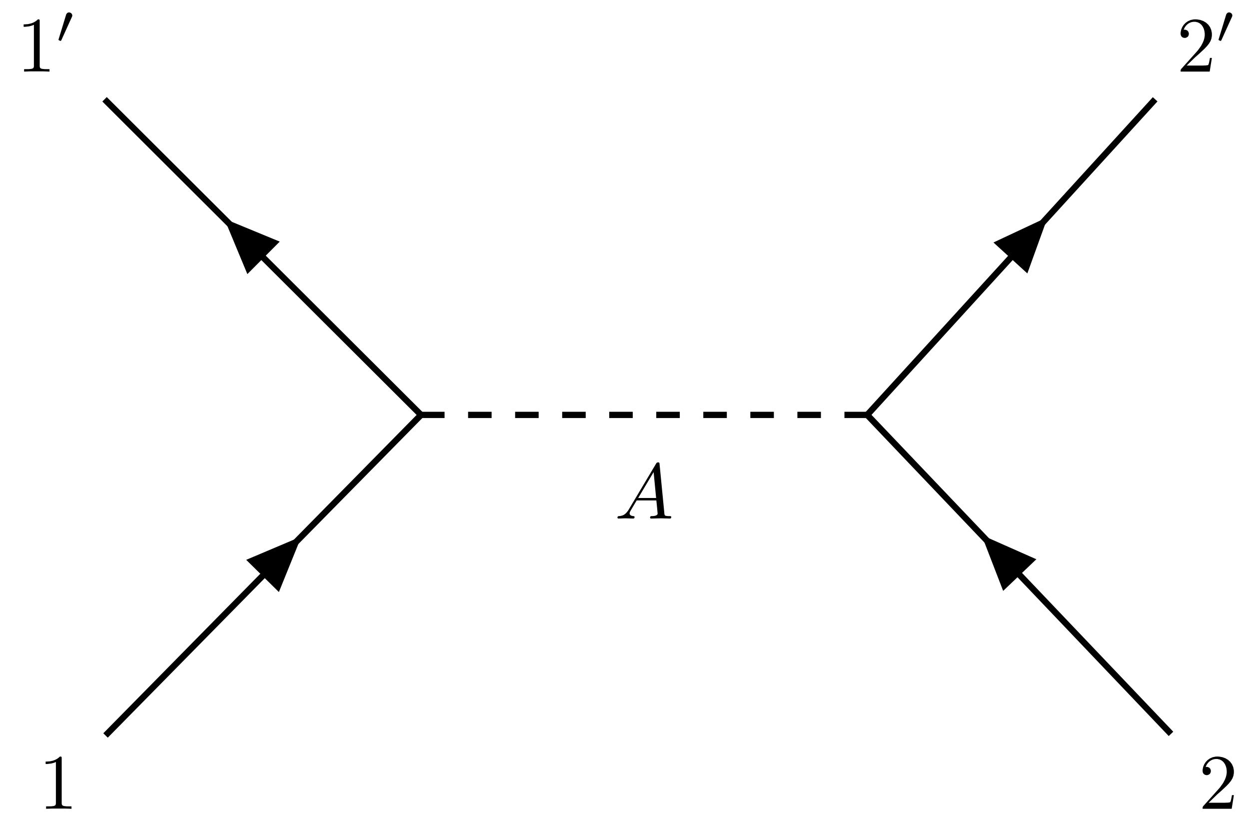
- One can regularize the singular part:

$$\int_{m_1+m_2}^\infty d\omega \frac{f(\tilde{q})}{\omega^2 - s} = P\int_{m_1+m_2}^\infty d\omega \frac{f(\tilde{q})}{\omega^2 - s} + \int_C d\omega \frac{f(\tilde{q})}{\omega^2 - s} = \frac{f(\tilde{q})}{2\sqrt{s}}\left(i\pi - \log\left|\frac{\sqrt{s}-m_1-m_2}{\sqrt{s}+m_1+m_2}\right|\right)$$

Kernel amplitudes

- **Scattering amplitudes**

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



$$\mathcal{M}^A_{12\to 1'2'} = \mathrm{IS} F_A^2 \Gamma^A_{12} P^A \Gamma^A_{1'2'}$$

Since the hadron has a finite size, form factor is need to be considered at each vertex: $F(q^2) = \left(\frac{n\Lambda^2 - m_{\rm ex}^2}{n\Lambda^2 - q^2}\right)^n$

For minimal uncertainty from the cutoff parameters, we strictly fixed the values about $\Lambda = m_{\rm ex} + 600$ MeV.

IS is the isospin symmetric factor from the isospin projection (for definite isospin channels)

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

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

Effective Lagrangian

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- **Effective Lagrangian for charmonium interactions**

$$\mathcal{L}_J = g_\psi \text{Tr}[J \bar{H}^{\bar{Q}}_a \gamma_\mu \partial^\mu \bar{H}^Q_a]$$

Charminum superfield: $J = \dfrac{1+\not{v}}{2} [\psi^\mu \gamma_\mu - \eta_c \gamma_5] \dfrac{1-\not{v}}{2}$

$\eta_c(J^P = 0^-), \psi^\mu(J^P = 1^-)$

SU(2) heavy quark spin symmetry : $J \to S_c J S_{\bar{c}}^\dagger$

$$\bar{H}^Q \to \bar{H}^Q S_c^\dagger$$

$$\bar{H}^{\bar{Q}} \to S_{\bar{c}} \bar{H}^{\bar{Q}}$$

Heavy meson scattering in the doubly charm channel

Kernel matrix in Doubly-charm sector

- **Hadron channels in doubly-charm sector**

Possible two-hadron states with $cc\bar{q}\bar{q}'$:

- DD, DD^*, D^*D^* $(I = 0, 1)$

Four sets of coupled channels: mesons can be classified by quantum numbers, $I^G(J^{PC})$

- $0^{\pm}(0^{+\pm}, 2^{+\pm})$: $DD,\ D^*D^*$
- $0^{\pm}(1^{+\pm})$: $DD^*,\ D^*D^*$
- $1^{\pm}(0^{+\mp})$: $DD,\ D^*D^*$
- $1^{\pm}(1^{+\mp})$: $DD^*,\ D^*D^*$

Kernel matrix element:

$$\mathcal{V} = \begin{pmatrix} \mathcal{V}_{DD\to DD} & \mathcal{V}_{DD\to DD^*} & \mathcal{V}_{DD\to D^*D^*} \\ \mathcal{V}_{DD^*\to DD} & \mathcal{V}_{DD^*\to DD^*} & \mathcal{V}_{D^*D^*\to D^*D^*} \\ \mathcal{V}_{D^*D^*\to DD} & \mathcal{V}_{D^*D^*\to DD^*} & \mathcal{V}_{D^*D^*\to D^*D^*} \end{pmatrix}$$

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Kernel matrix element:

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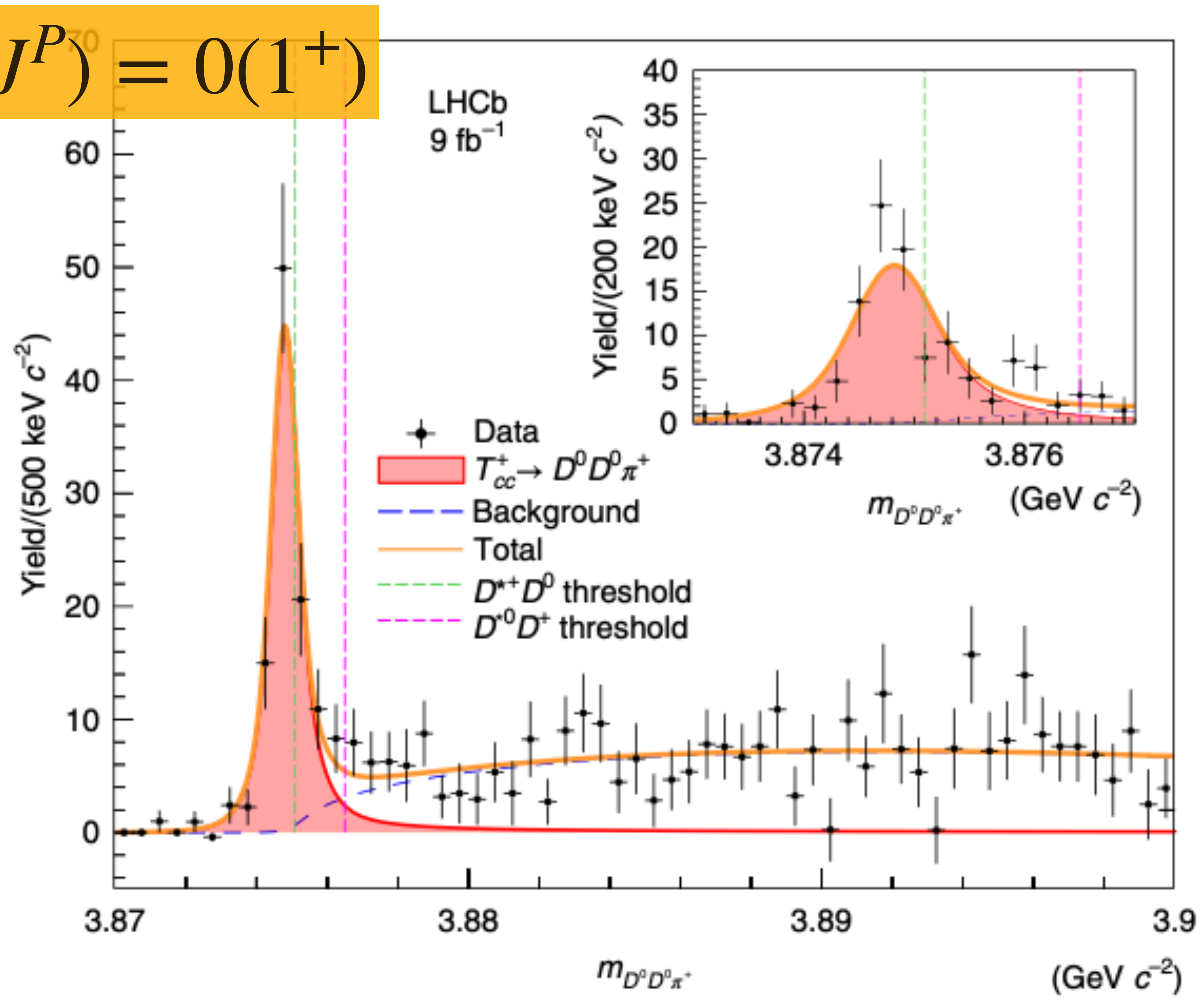
$I(J^P)=0(1^+)$

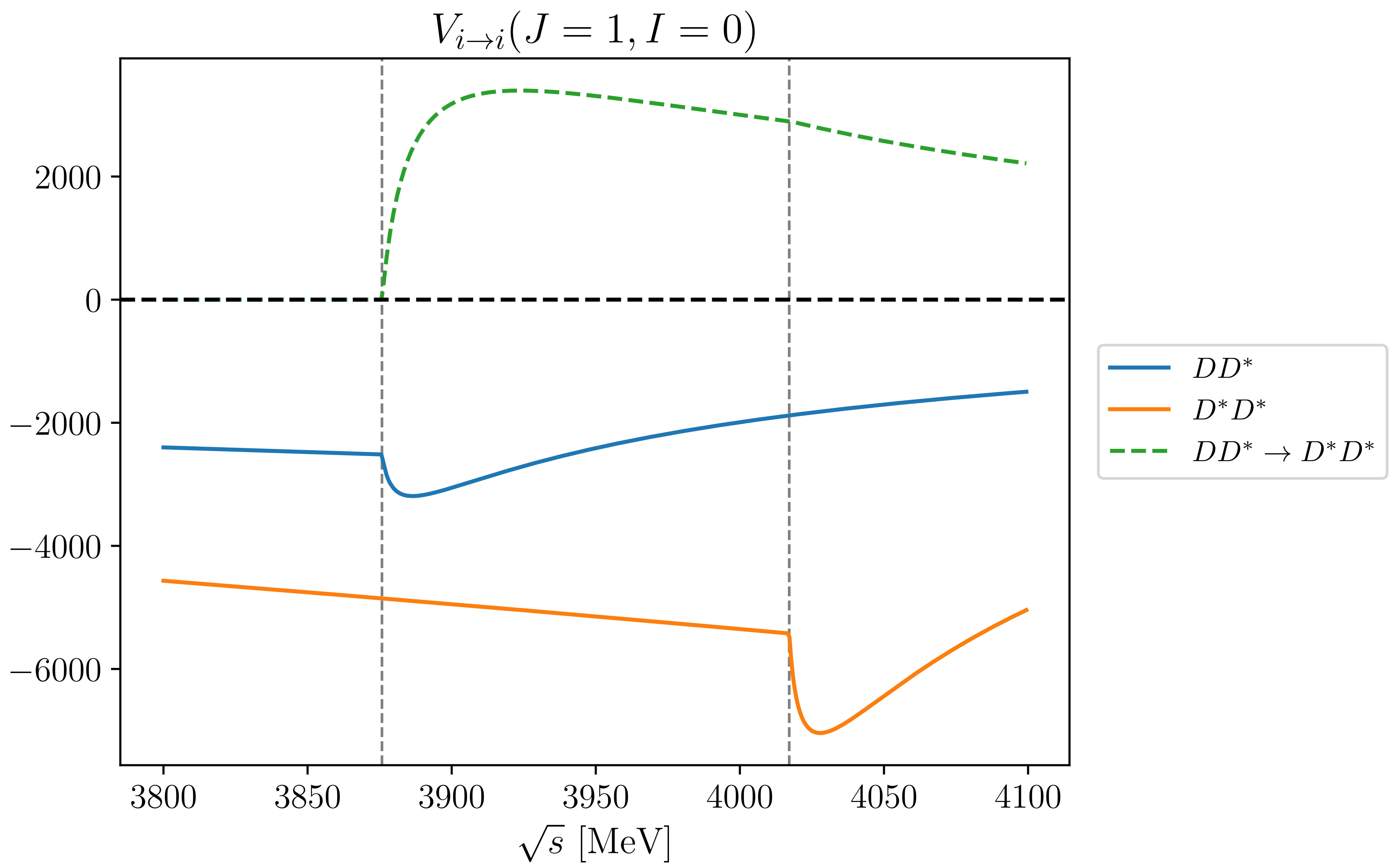


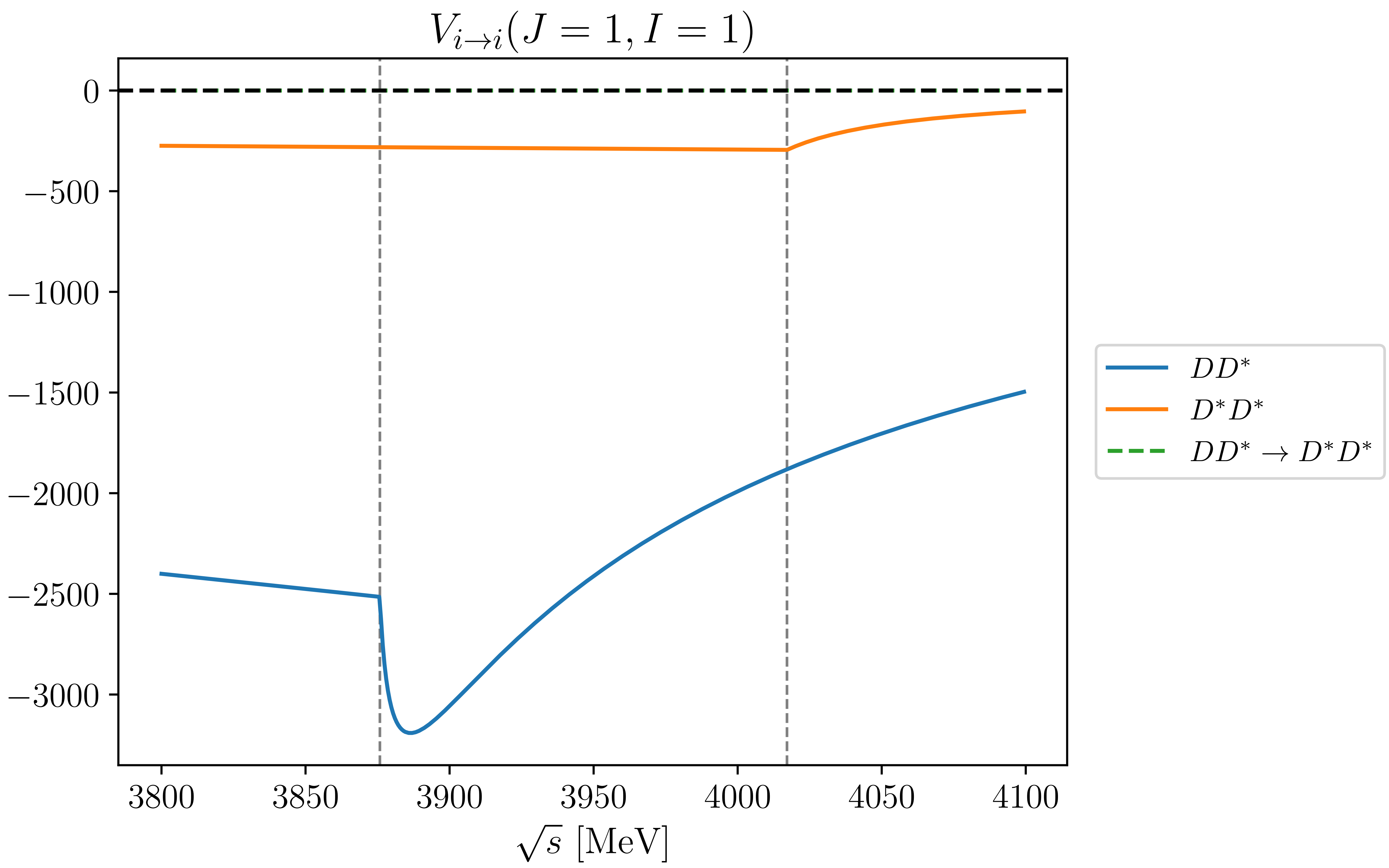
R. Aaij et.al.(LHCb Collabration) Nature Physics. 18 (2022) 7, 751-754

Dynamical generation of the poles

Kernel amplitudes

Vector channels (J=1)





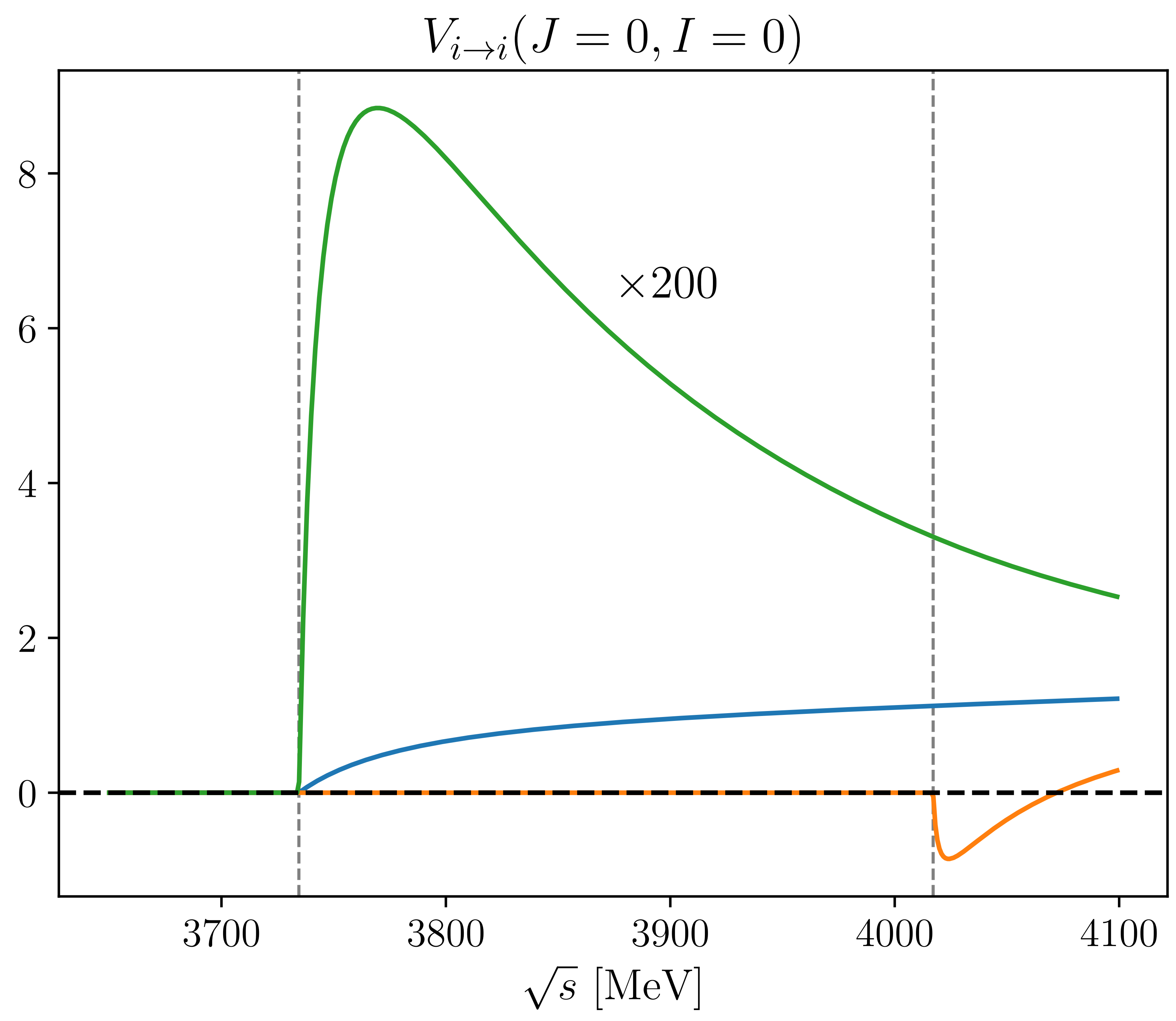
Strong attractions for both diagonal elements
→ Pole is expected to generate in the coupled-channel solution

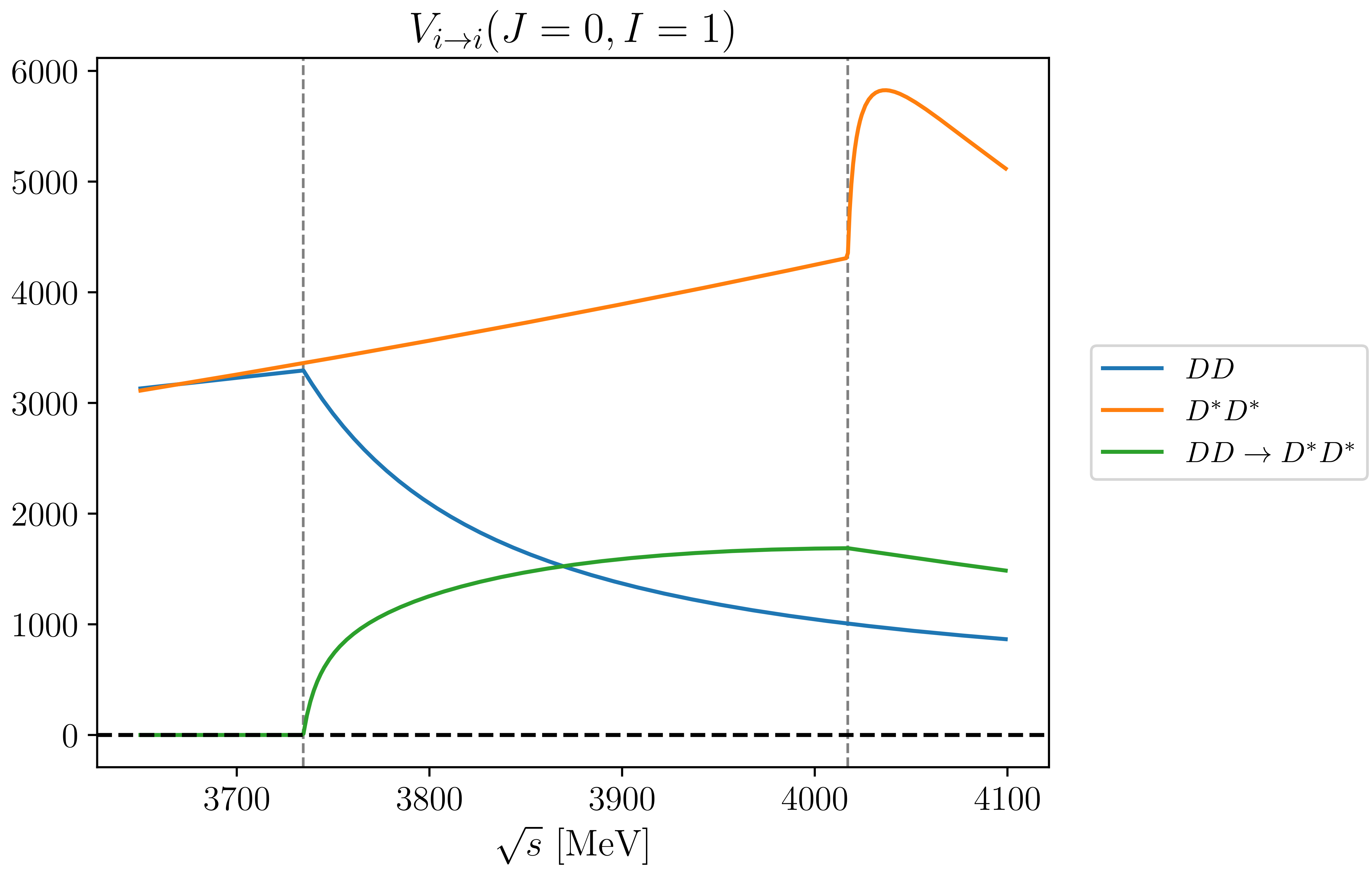
Strong attraction for $DD^* \to DD^*$
No transition appears in the $DD^* \to D^*D^*$ process.

Dynamical generation of the poles

Kernel amplitudes

Scalar channels (J=0)





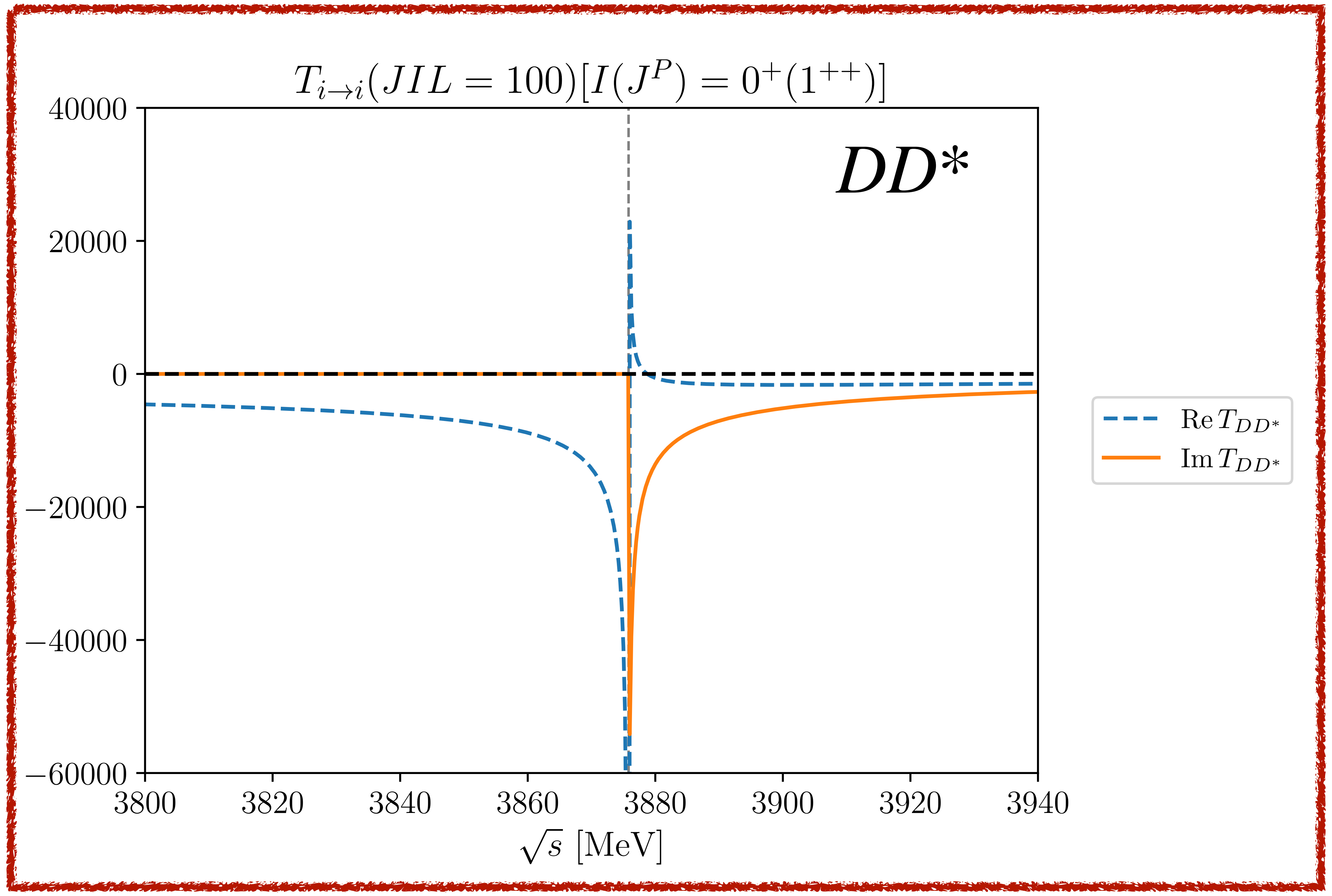
destructive interference between kernel amplitudes in the diagonal elements due to the IS factors.

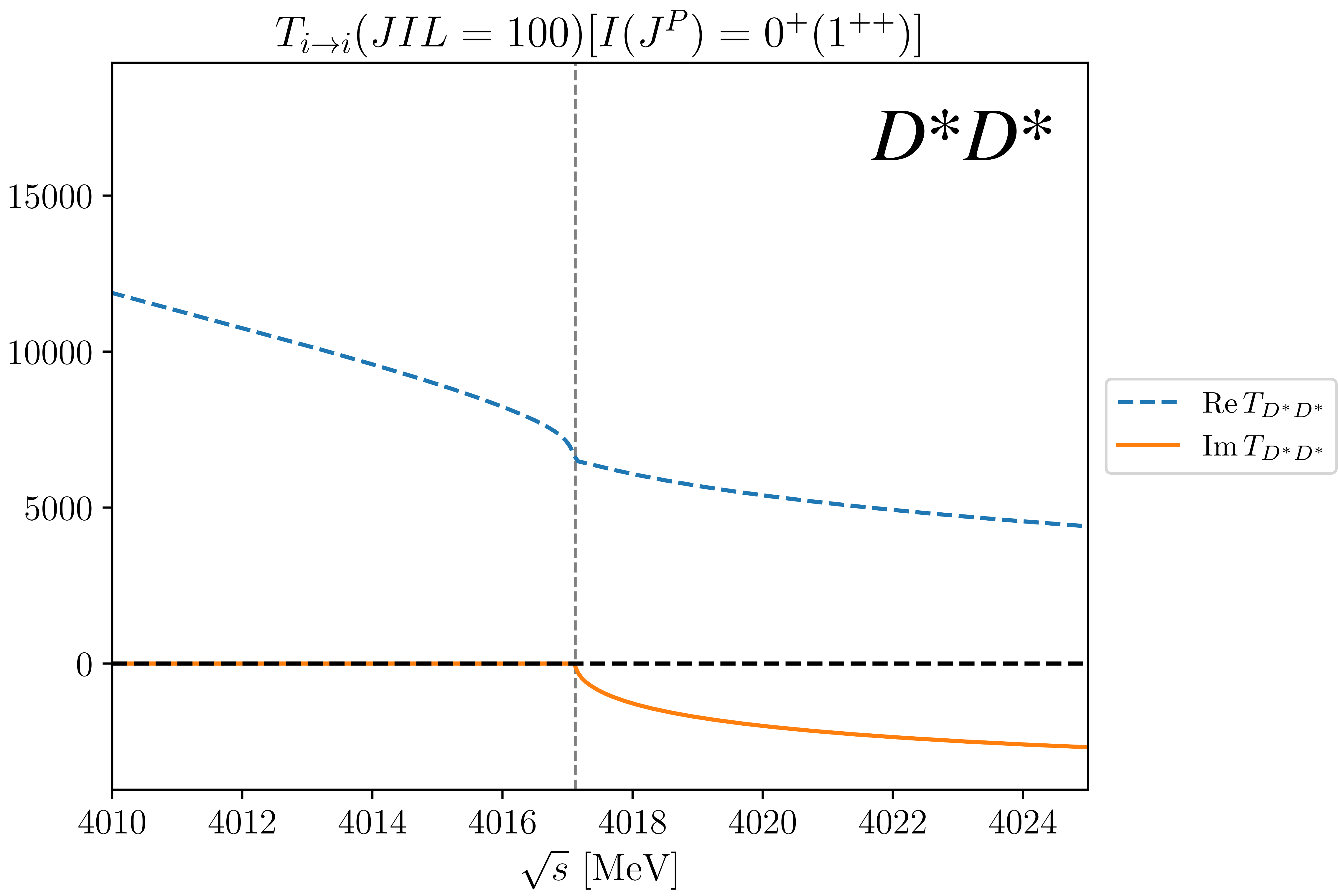
all interactions are strongly **repulsive**.

Dynamical generation of the poles

Single channel T matrix elements

Vector-isoscalar channel (J=1, I=0)



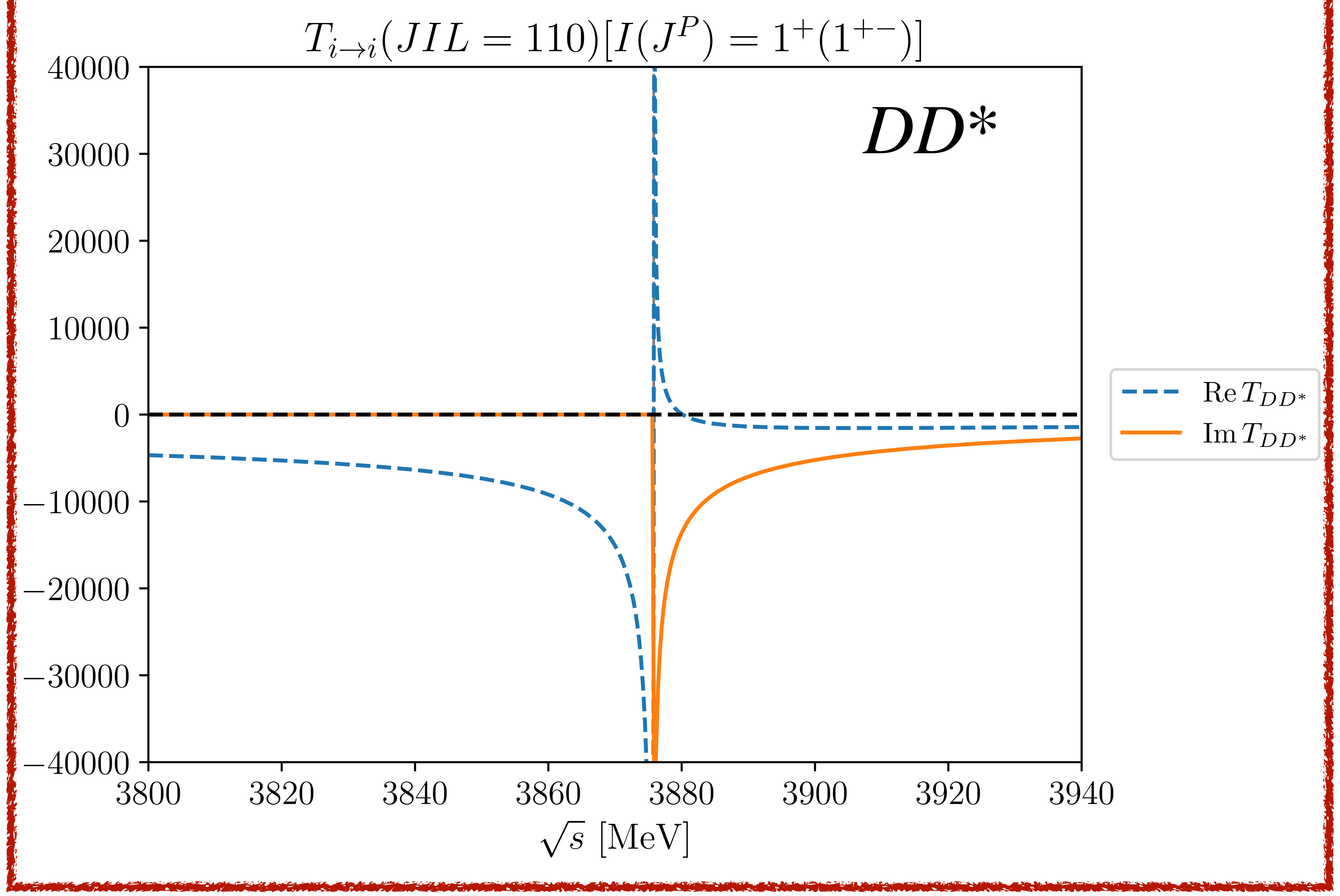


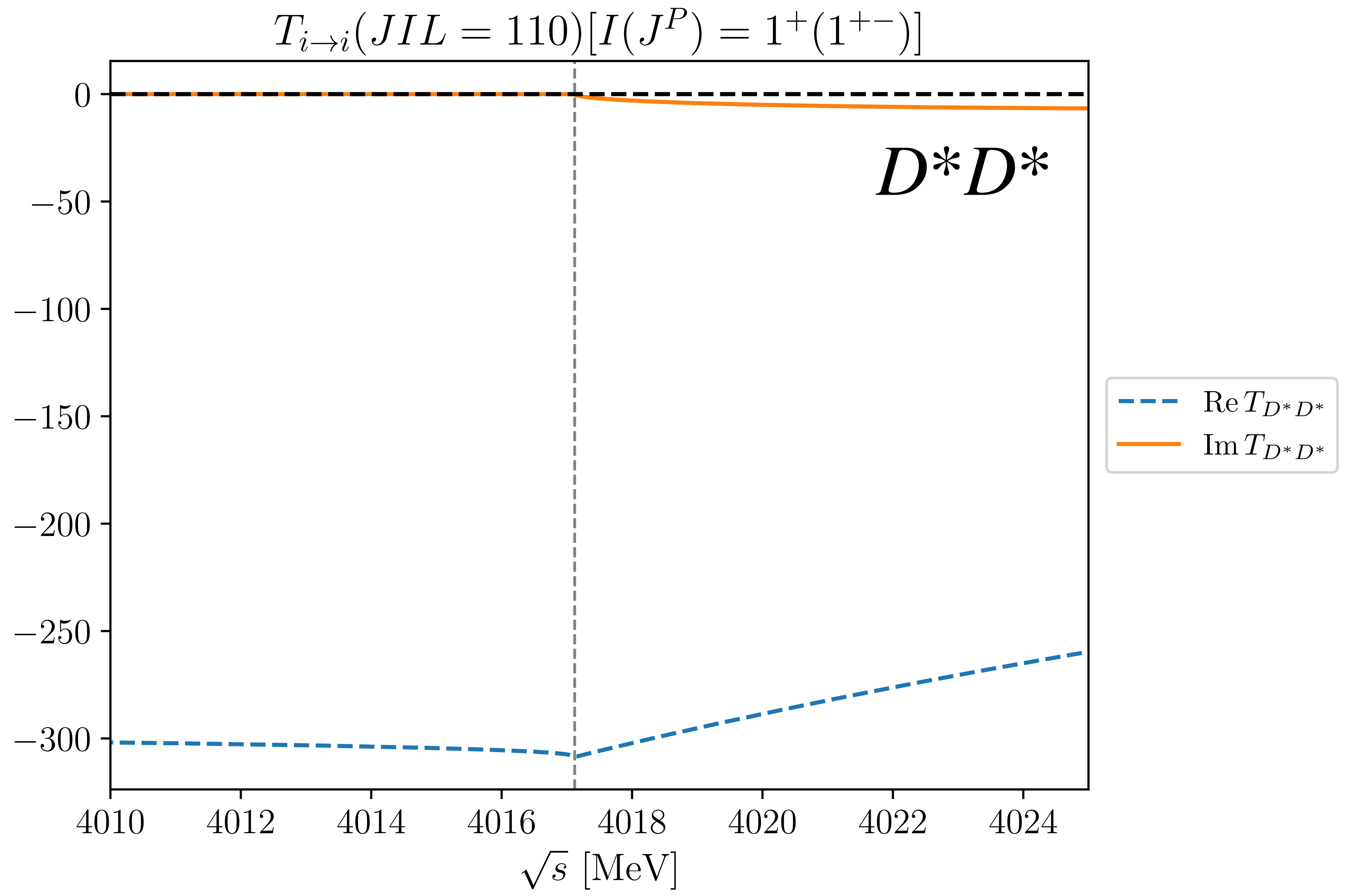
The attraction in DD^* kernel is nearly sufficient to generate a pole at the threshold.

Dynamical generation of the poles

Single channel T matrix elements

Vector-isovector channel (J=1, I=1)



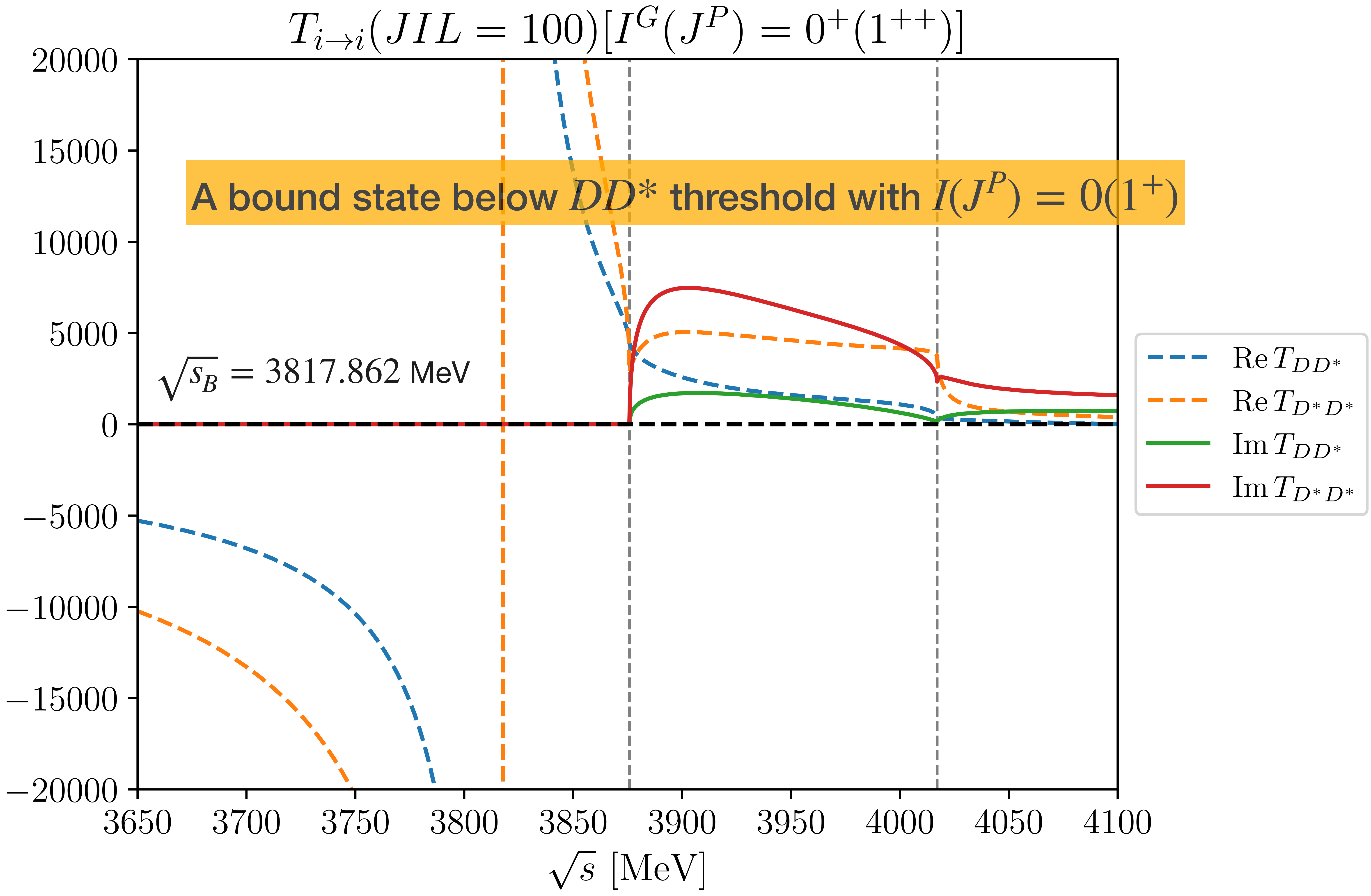


The pole is about to emerge at DD^* mass threshold.

Dynamical generation of the poles

Fully-coupled T-matrices

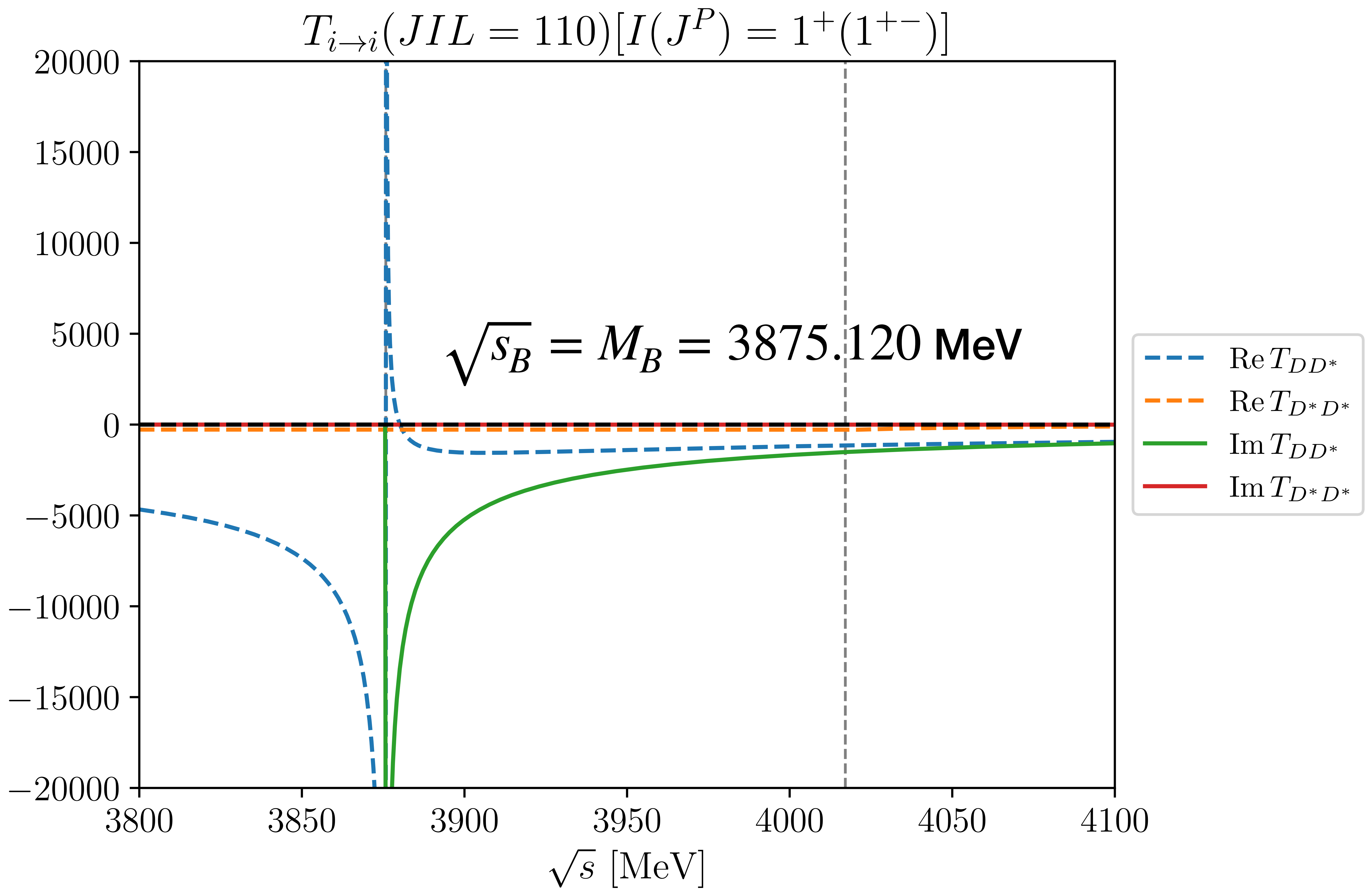
Vector-isoscalar channel (I=0,J=1)



Dynamical generation of the poles

Fully-coupled T-matrices

Vector-isovector channel (I=1,J=1)



Heavy meson scattering in the hidden charm channel

Feynman amplitudes

- **Hadron channels in hidden-charm sector**

Possible two-hadron states with $c\bar{c}q\bar{q}'$:

- $D\bar{D},\ D\bar{D}^*,\ D^*\bar{D}^*\ (I=0,1)$
- $D_s\bar{D}_s,\ D_s\bar{D}_s^*,\ D_s^*\bar{D}_s^*,\ \eta_c\omega,\ J/\psi\omega,\ \eta_c\phi,\ J/\psi\phi\ (I=0)$
- $\eta_c\pi,\ J/\psi\pi,\ \eta_c\rho,\ J/\psi\rho\ (I=1).$

Four sets of coupled channels: mesons can be classified by quantum numbers, $I^G(J^{PC})$

- $0^\pm(0^{+\pm},2^{+\pm})$: $D\bar{D},\ J/\psi\omega,\ D_s\bar{D}_s,\ D^*\bar{D}^*,\ J/\psi\phi,\ D_s^*\bar{D}_s^*$
- $0^\pm(1^{+\pm})$: $\eta_c\omega,\ D\bar{D}^*,\ \eta_c\phi,\ D^*\bar{D}^*,\ D_s\bar{D}_s^*,\ D_s^*\bar{D}_s^*$
- $1^\pm(0^{+\mp})$: $D\bar{D},\ J/\psi\rho,\ D^*\bar{D}^*$
- $1^\pm(1^{+\mp})$: $\eta_c\rho,\ D\bar{D}^*,\ D^*\bar{D}^*$

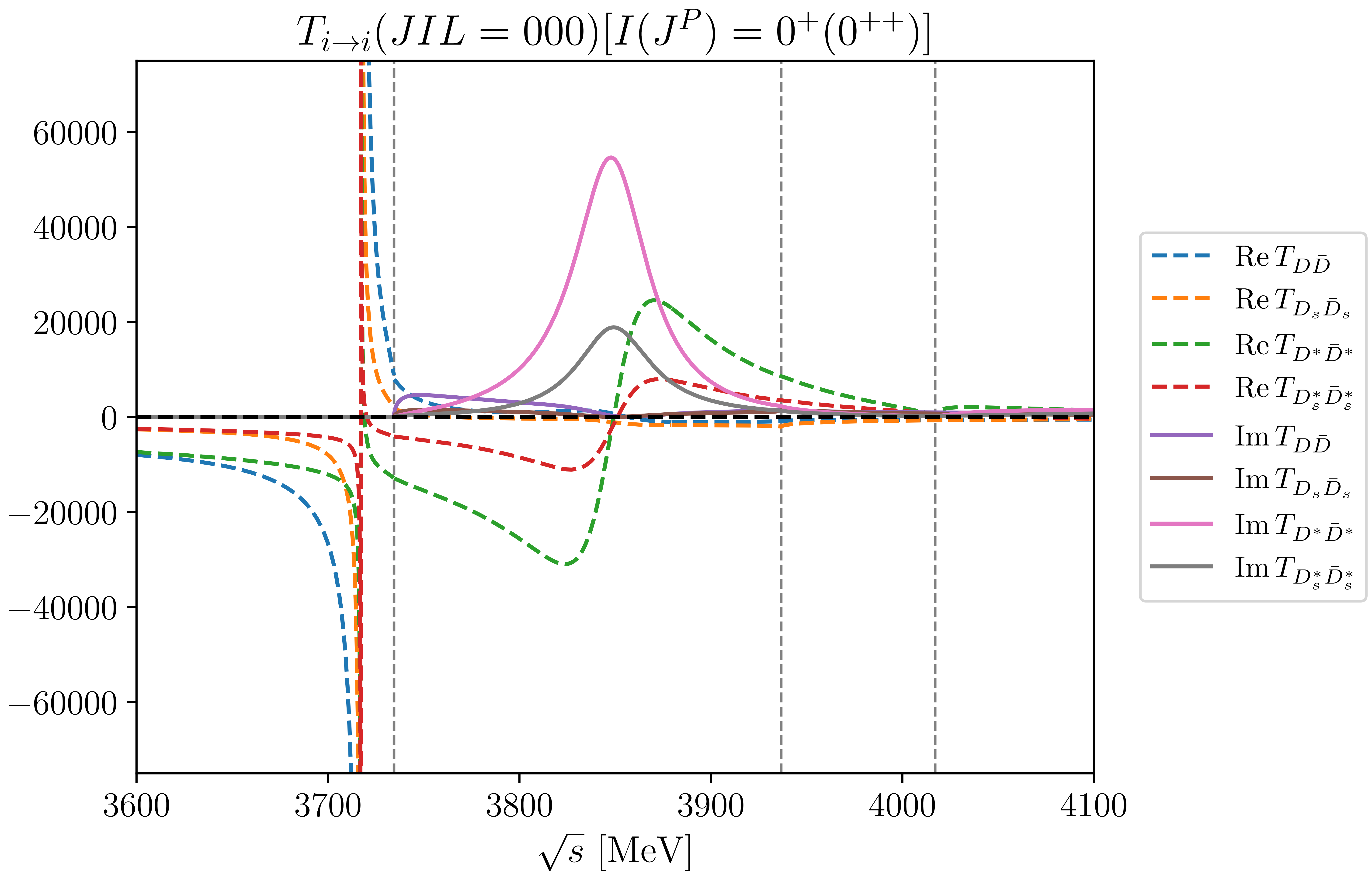
- $0^+(0^{++})$: $\chi_{c0}(3860),\ \chi_{c0}(3915)$
- $0^+(1^{++})$: $\chi_{c1}(3872),\ \chi_{c1}(4140),\ \chi_{c1}(4274)$
- $0^+(2^{++})$: $\chi_{c2}(3930)$
- $1^+(1^{+-})$: $T_{c\bar{c}1}(3900),\ T_{c\bar{c}1}(4200),\ T_{c\bar{c}1}(4430)$

Isoscalar channels ($I = 0$)

Dynamical generation of the poles

Fully-coupled T-matrices

Scalar-isoscalar(J=0, I=0) channel



- A bound state below $D\bar{D}$ threshold

  $\sqrt{s_B} = 3720$ MeV

  lower charmonium channels($\eta_c\eta, J/\psi\eta, \ldots$) are additionally coupled, leading to resonance

- A resonance between $D\bar{D}$ and $D_s\bar{D}_s$

  $\sqrt{s_R} = 3861.34 - i22.76$ MeV

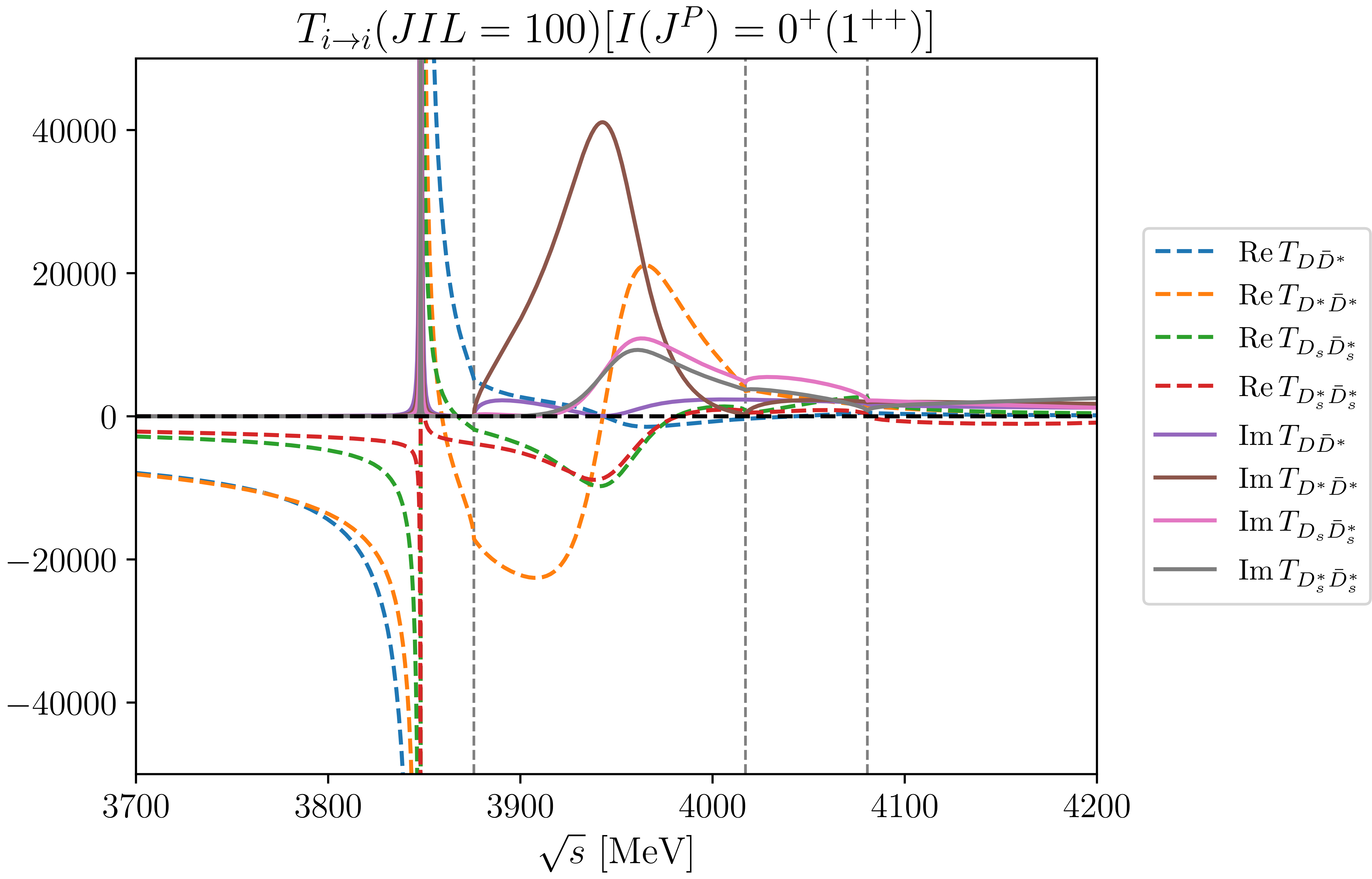
  very close to the mass of X(3860).
  ($M_{X(3860)} = 3862^{+50}_{35}$ MeV)

  but much narrower width than X(3860).
  ($\Gamma_{X(3860)} \simeq 200^{+180}_{-110}$ MeV)

Dynamical generation of the poles

Fully-coupled T-matrices

Vector-isoscalar(J=1, I=0) channel



- Nearly bound state below $D\bar{D}^*$ threshold

  $\sqrt{s_B} = 3848.11$ MeV

  Within our cutoff scheme,
  larger binding energy than $\chi_{c1}(3872)$

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

- A resonance between $D\bar{D}^*$ and $D^*\bar{D}^*$

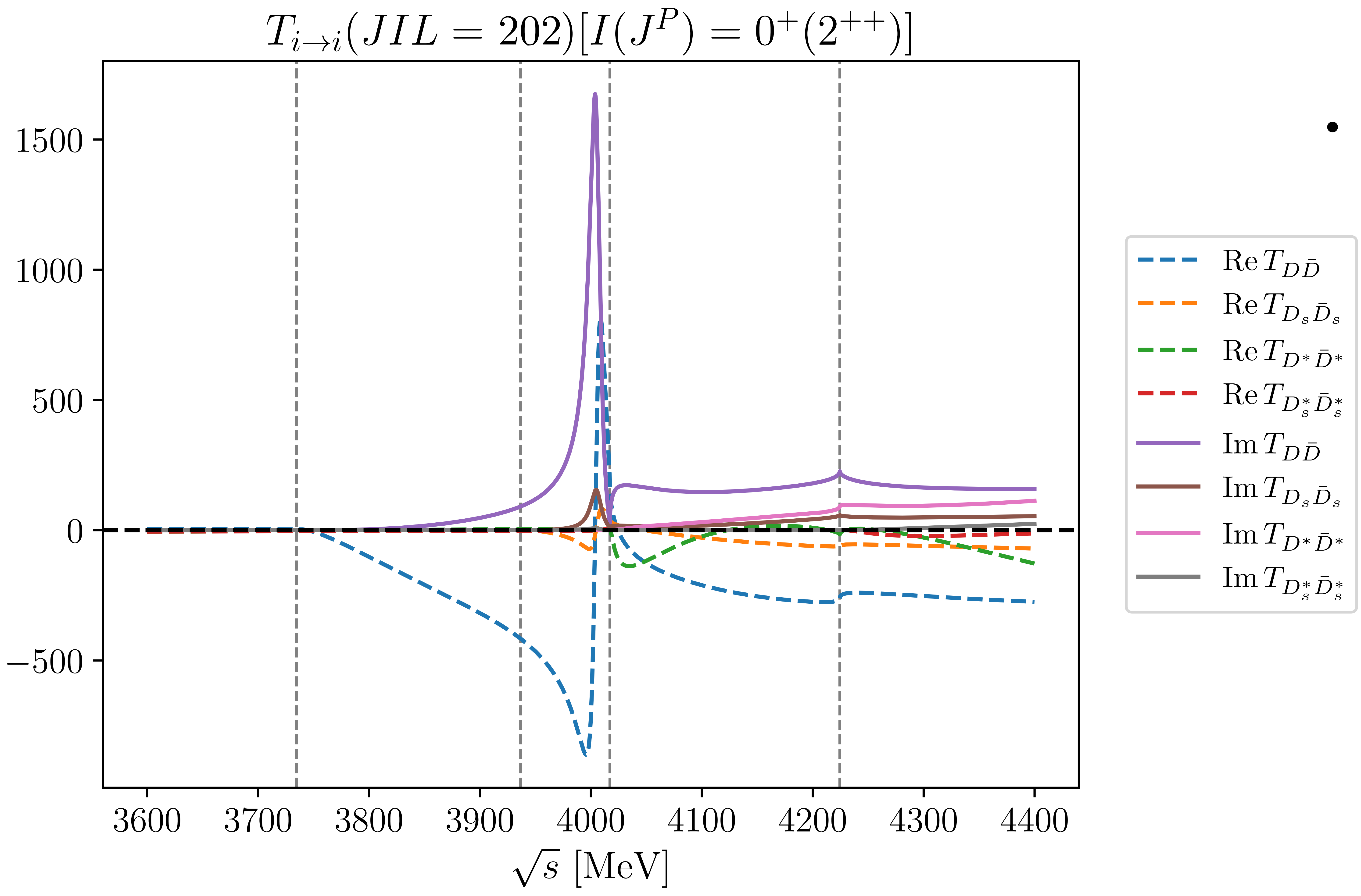
  $\sqrt{s_R} = 3948.622 - i26.98$ MeV

  nice candidate for $X(3940)$:
  $m_{X(3940)} = 3942 \pm 9$ MeV
  $\Gamma_{X(3940)} = 37^{+27}_{-17}$ MeV

Dynamical generation of the poles

Fully-coupled T-matrices

Tensor-isoscalar(J=2, I=0) channel



- A very narrow resonance near $D^*\bar{D}^*$ threshold

$$\sqrt{s_R} = 4005.26 - i5.95 \text{ MeV}$$

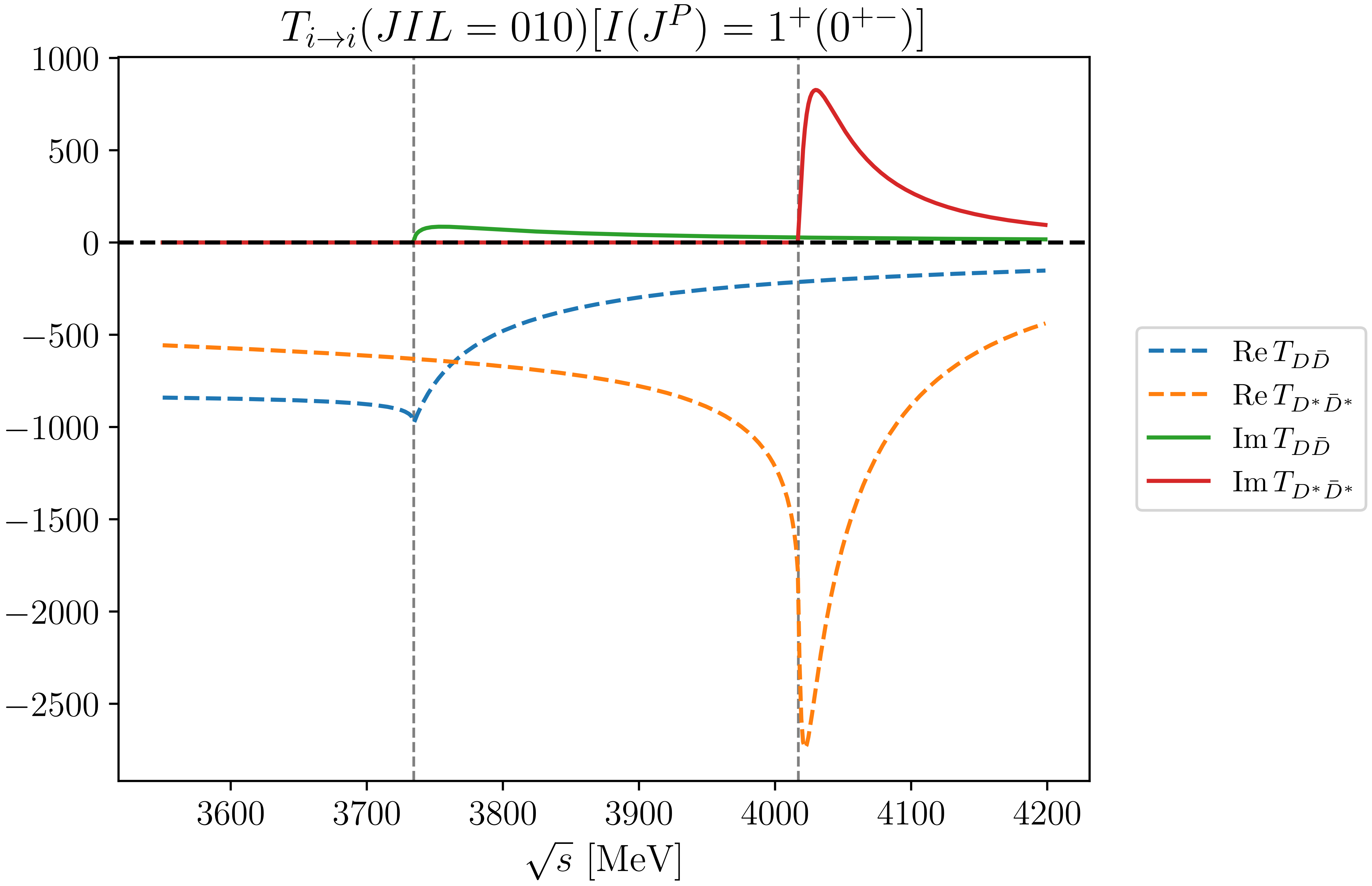
positioned near $D^*\bar{D}^*$ threshold but dominantly coupled to the $D\bar{D}$ like $\chi_{c2}(3930)$.

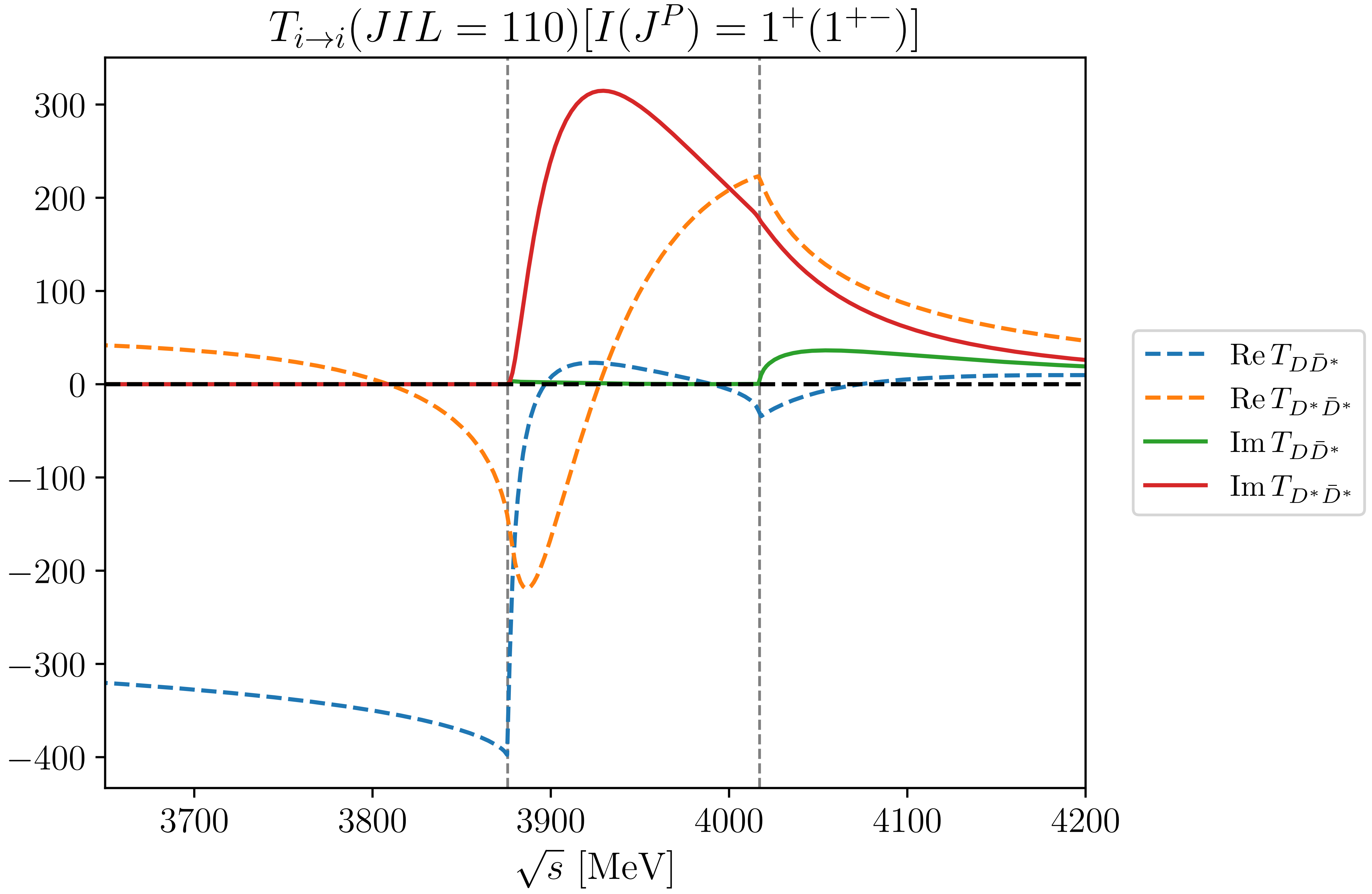
about 80 MeV heavier than $\chi_{c2}(3930)$...

Isovector channels ($I = 1$)

Dynamical generation of the poles

Fully-coupled T-matrices





- No resonant shape in scalar channels
- A pronounce cusp at the $D\bar{D}^*$ mass threshold

- A peak appears between two mass thresholds
- This structure is found to be a virtual state

Summary

Summary

- We investigated the production of exotic mesons containing two heavy quarks via coupled-channel dynamics within meson-exchange framework.
- The tree-level interactions between heavy mesons and light-unflavored mesons are described through the effective Lagrangian approach based on HQEFT.
- In the doubly charm sector, we searched two vector bound states. The isoscalar state may be nice candidate for observed doubly charmed meson by LHCb: $T_{cc}^{+}(3875)$, $T_{cc}^{I=1}$.
- Our investigation in the hidden-charm sector revealed three states: a new scalar bound state below the $D\bar{D}$ threshold, along with scalar, vector and tensor resonances as $D^*\bar{D}^*$, $D\bar{D}^*$ and $D\bar{D}$ molecular states, respectively: $X(3860)$, $\chi_{c1}(3872)$, $X(3940)$, $\chi_{c2}(3930)$.
- A virtual state with quantum numbers $I(J^P) = 1(1^+)$ between $D\bar{D}^*$ and $D^*\bar{D}^*$: $T_{c\bar{c}1}(3900)$
- This study enhances the understanding of production mechanism of exotic mesons as hadron molecule.

Thank you