Scalar and tensor charmonium resonances from lattice QCD

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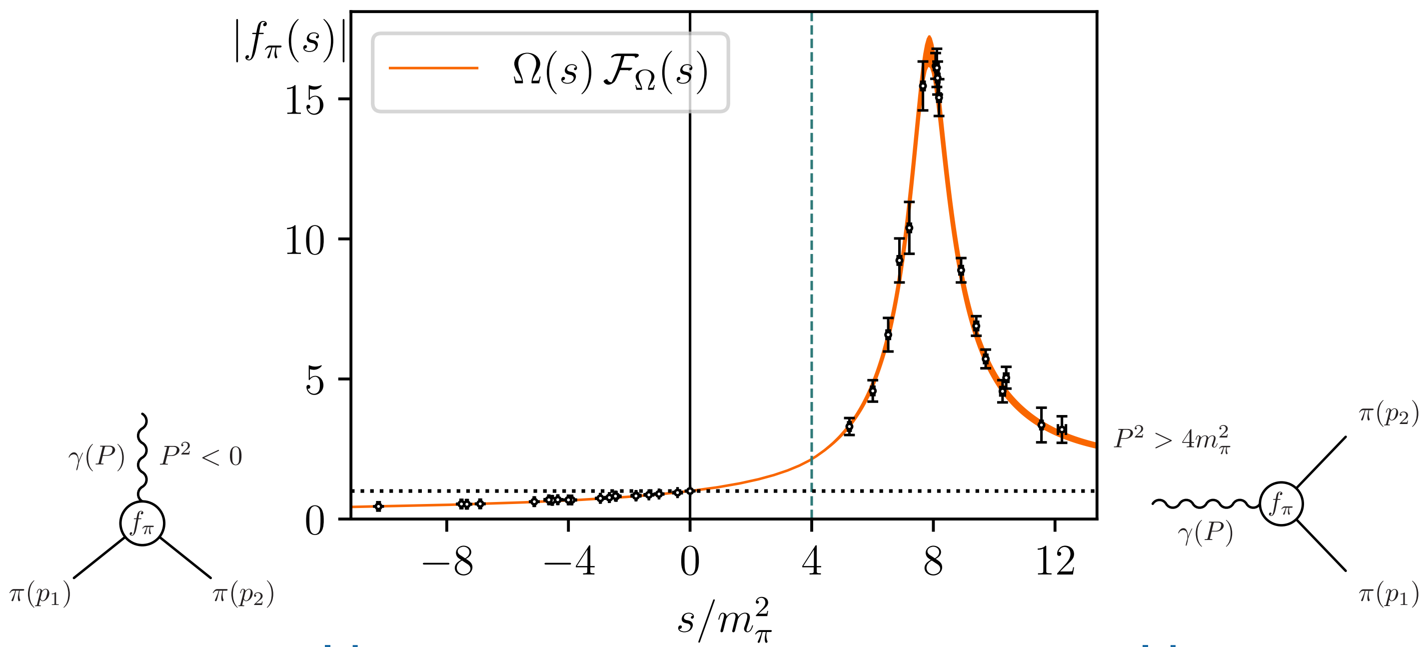
hadspec
hadspec.org

Chiral Dynamics, Bochum
26th August 2024

based on work:
PRL Editors' choice: arXiv: 2309.14070 (7 pages)
PRD Editors' choice: arXiv: 2309.14071 (55 pages)

UNIVERSITY OF CAMBRIDGE

THE ROYAL SOCIETY



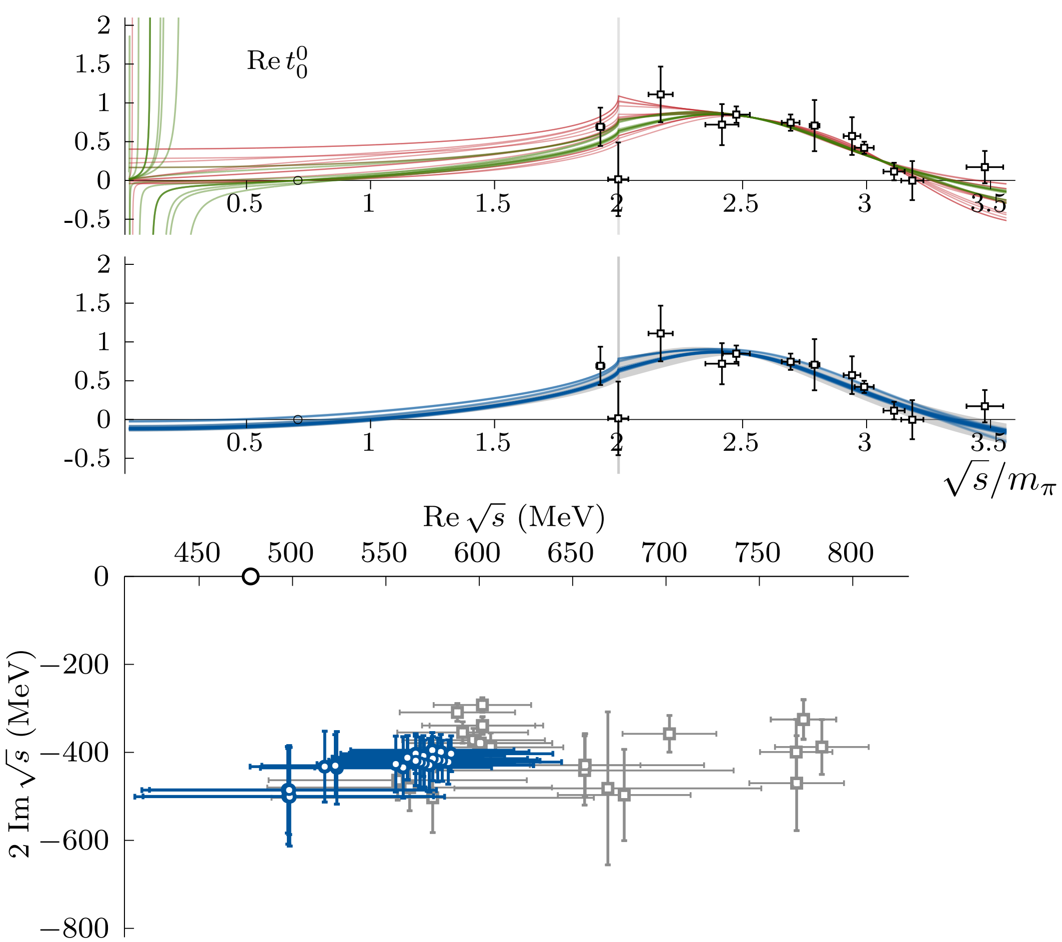
spacelike timelike

Timelike meson form-factors

Ortega-Gama, Dudek, Edwards

arXiv:2407.20617

- Lellouch-Lüscher analysis to extract infinite volume scattering amplitude
- Extended to coupled-channel region (KKbar)

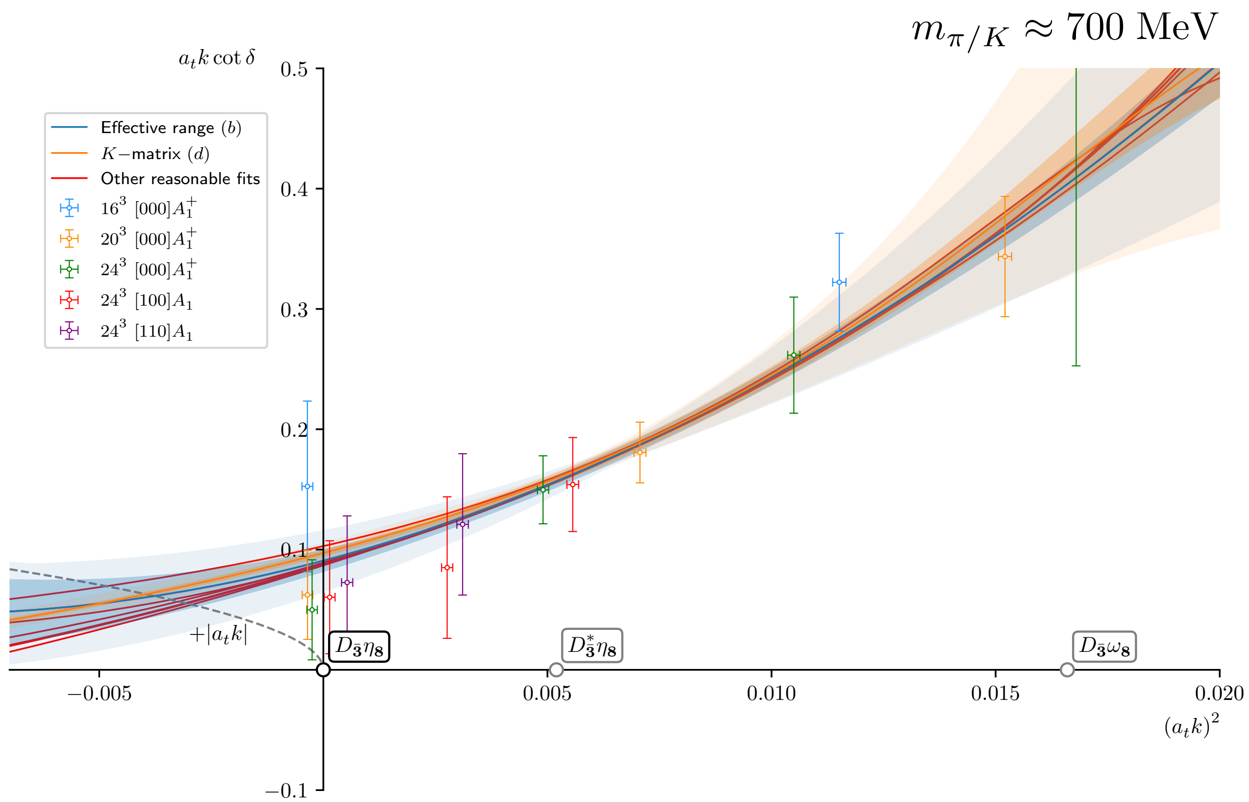


ππ dispersive + light quark mass-dependence

Rodas, Dudek, Edwards

arXiv:2303.10701 & arXiv:2304.03762

- pins down σ-pole position
- Adler zero arises naturally
- interesting interplay with bound-state σ and Adler zeros when considering the light-quark mass dependence

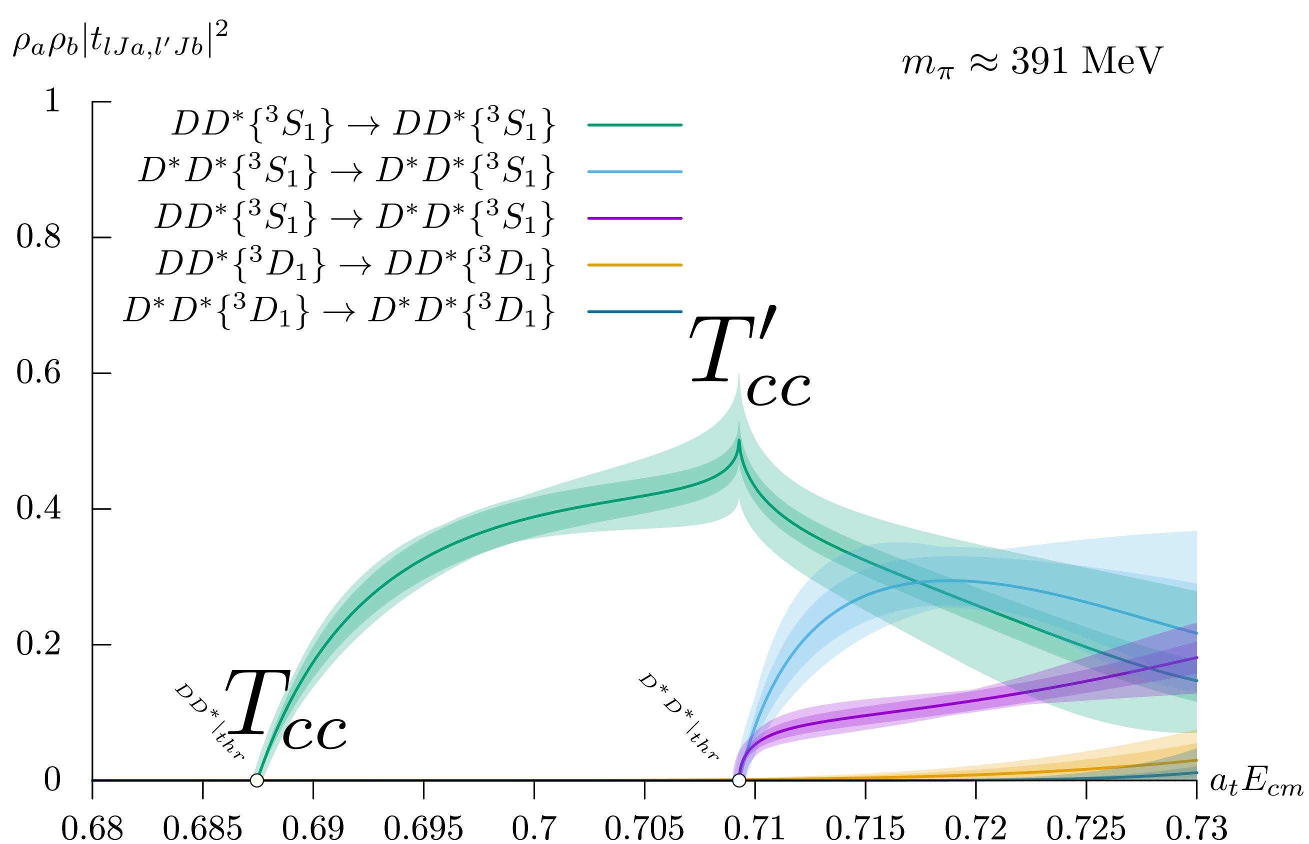


Dπ/DK scattering with SU(3) flavour symmetry

Yeo, Thomas, Wilson

arXiv:2403.10498

- S-wave interactions in flavour SU(3) 3bar, 6, 15bar
- Virtual bound state sextet pole
- Also deeply bound 3bar state, similar to Ds0(2317), much greater binding

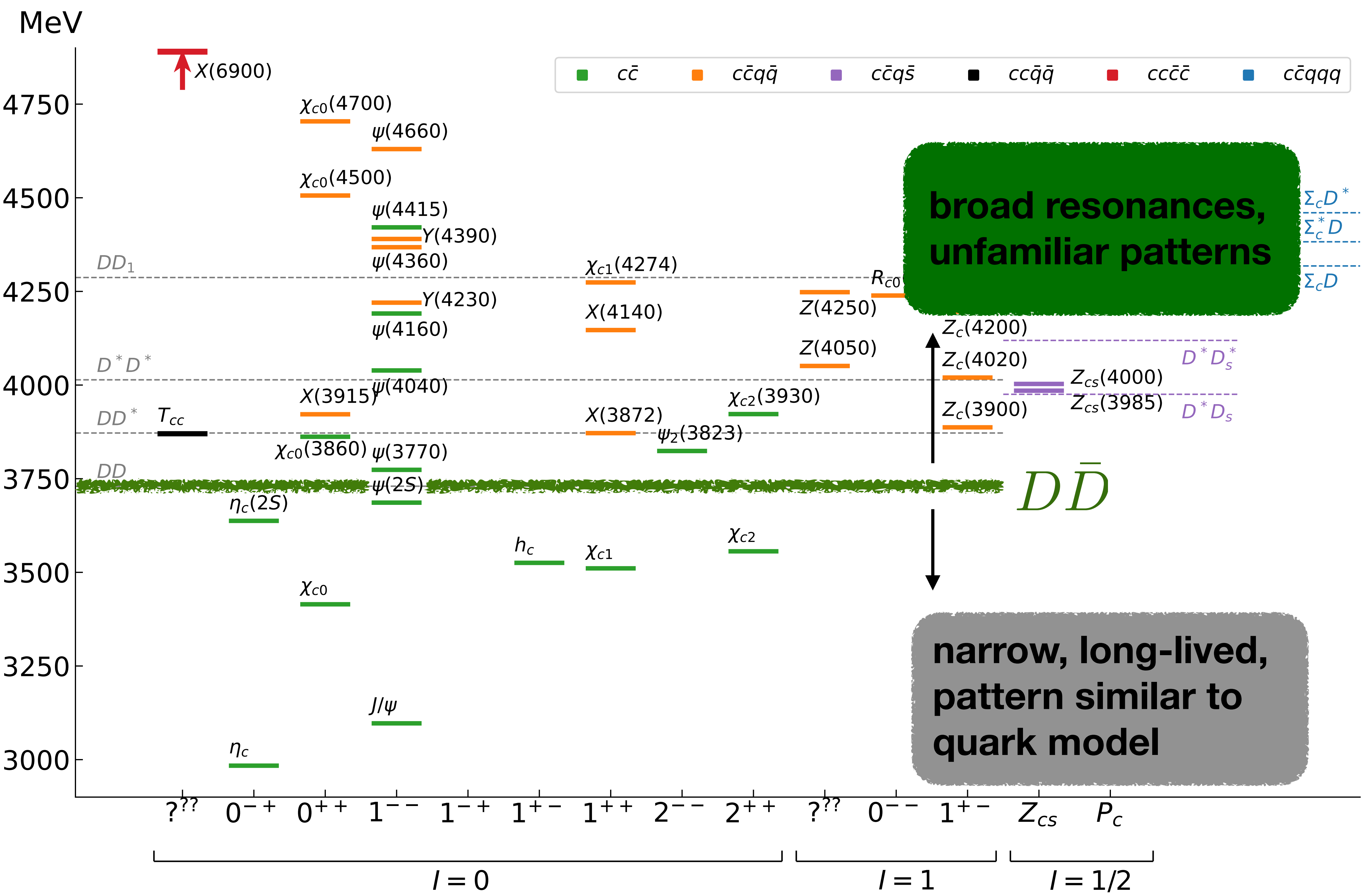


DD*-D*D* coupled channel

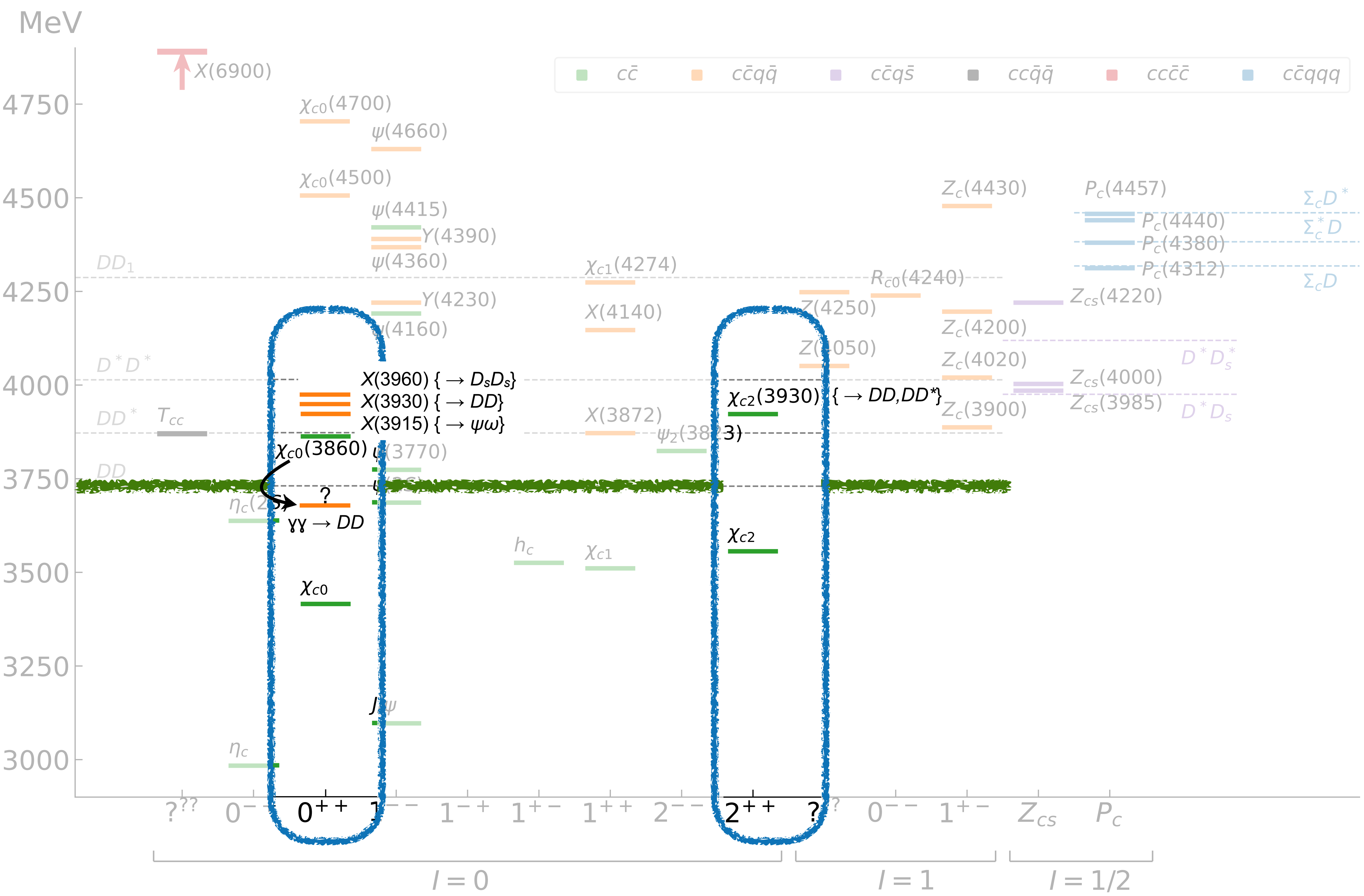
Whyte, Wilson, Thomas

arXiv:2405.15741

- *S* and *D*-wave in $J^P=1^+$
- virtual bound state below DD* and resonance below D*D*
- (neglecting left cuts)



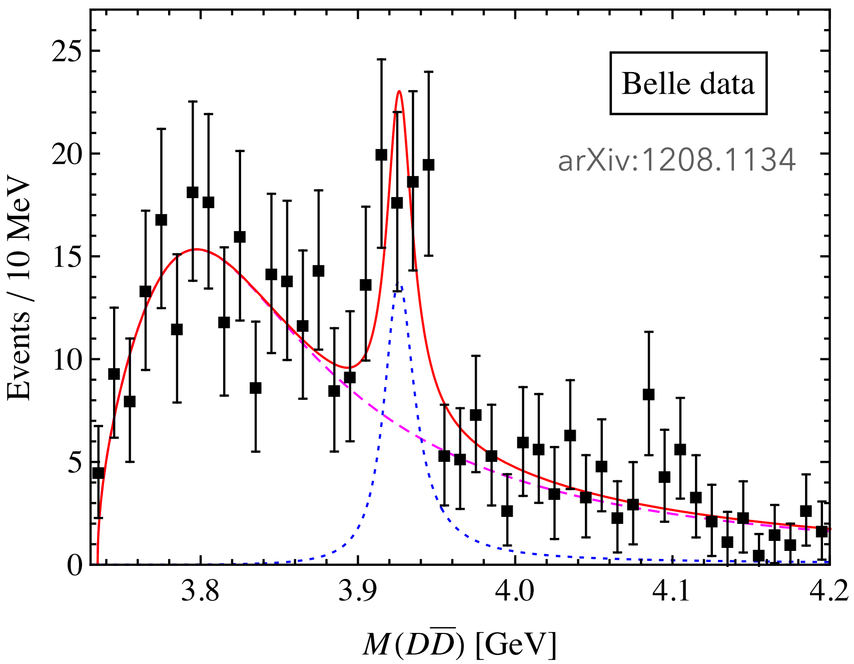
JPAC arXiv:2112.13436



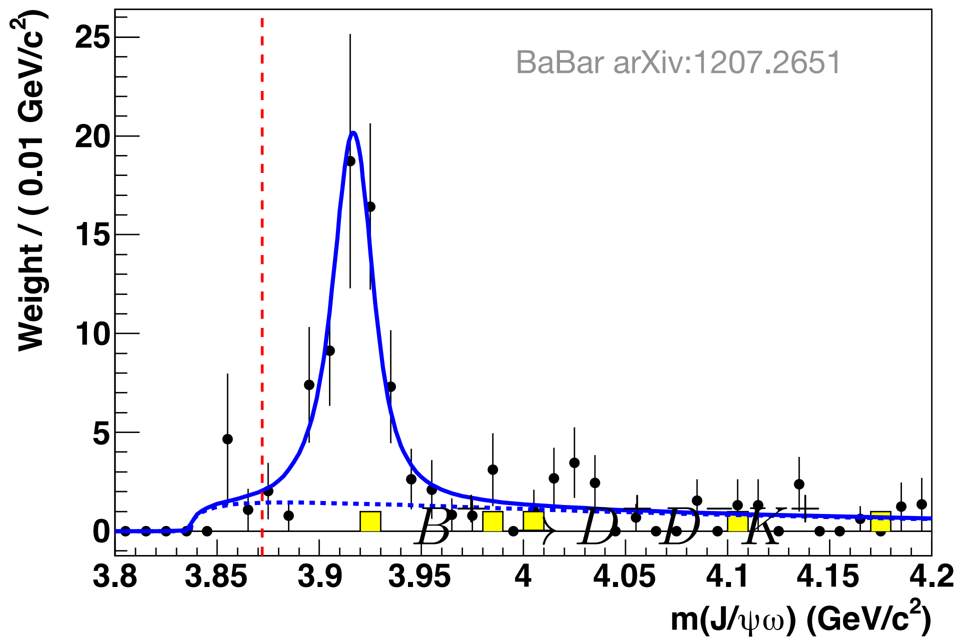
Level counting is completely unclear
- Near threshold behaviour?
- Multiple decoupled resonances?

Probably one resonance

$\gamma\gamma \to D\bar{D}$



$J/\psi\omega$



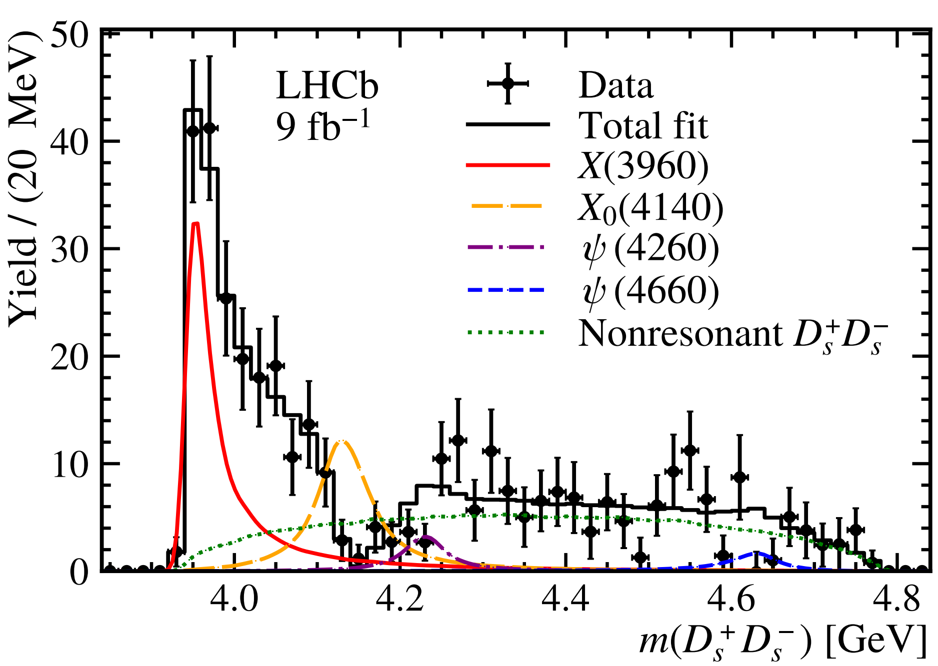
$m = (3919.4 \pm 2.2 \pm 1.6)$ MeV

$\Gamma = (13 \pm 6 \pm 3)$ MeV

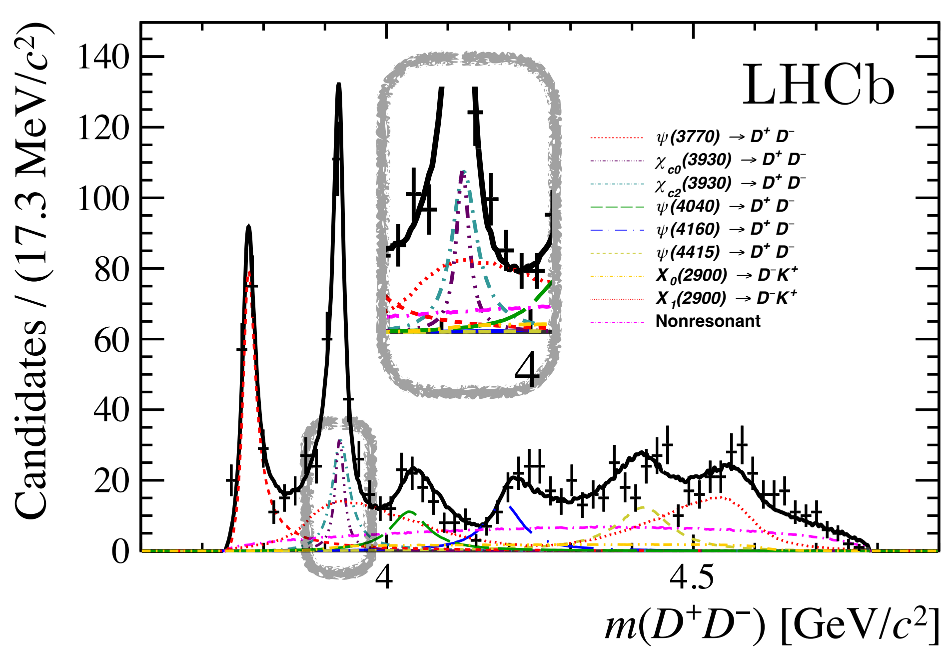
$J^P = 0^+$

Just a few examples
Many many more
(References in the longer paper)

$B^+ \to D_s^+ D_s^- K^+$ arXiv:2210.15153 LHCb



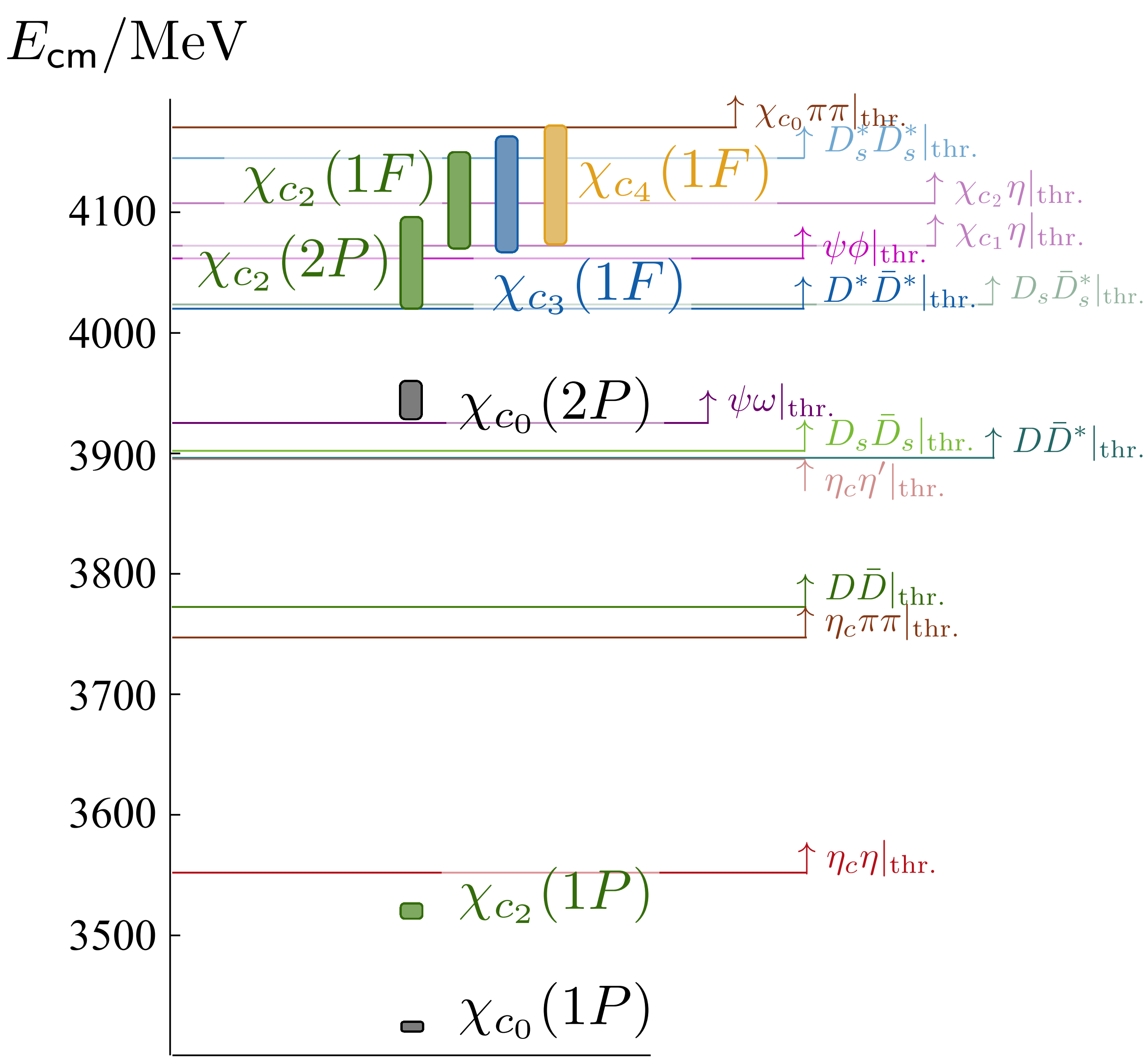
$B^+ \to D^+ D^- K^+$ arXiv:2009.00026



overlapping 0++ and 2++ resonances around 3925 MeV

no need for a low 0++ resonance

Previously:



spectra from qqbar operators only,
Liu et al JHEP 1207 (2012) 126

"HadSpec" lattices

anisotropic (3.5 finer spacing in time)
Wilson-Clover

L/a_s=16, 20, 24
m_π = 391 MeV

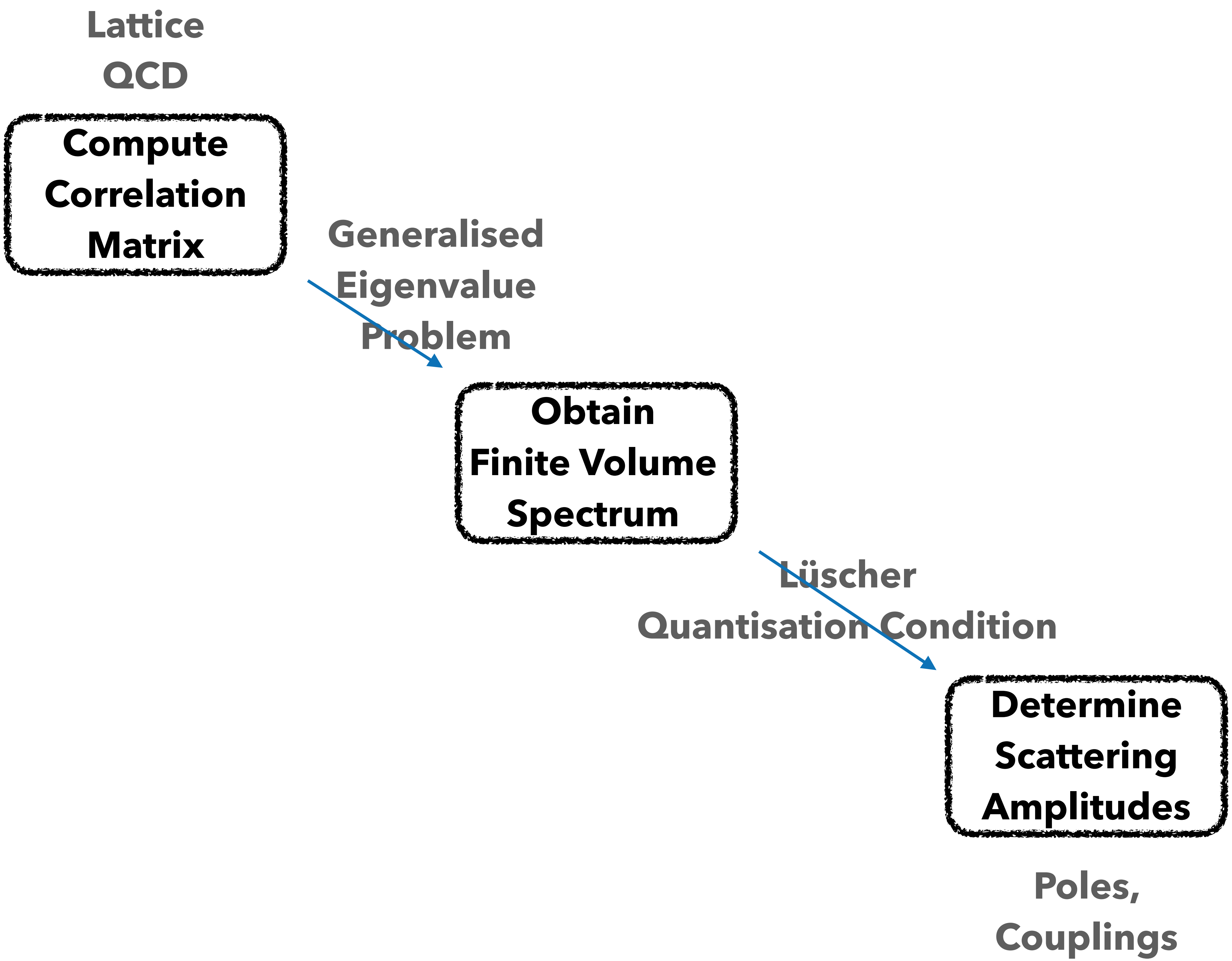
rest and moving frames

N_f = 2+1 flavours
all light+strange annihilations included
no charm annihilation

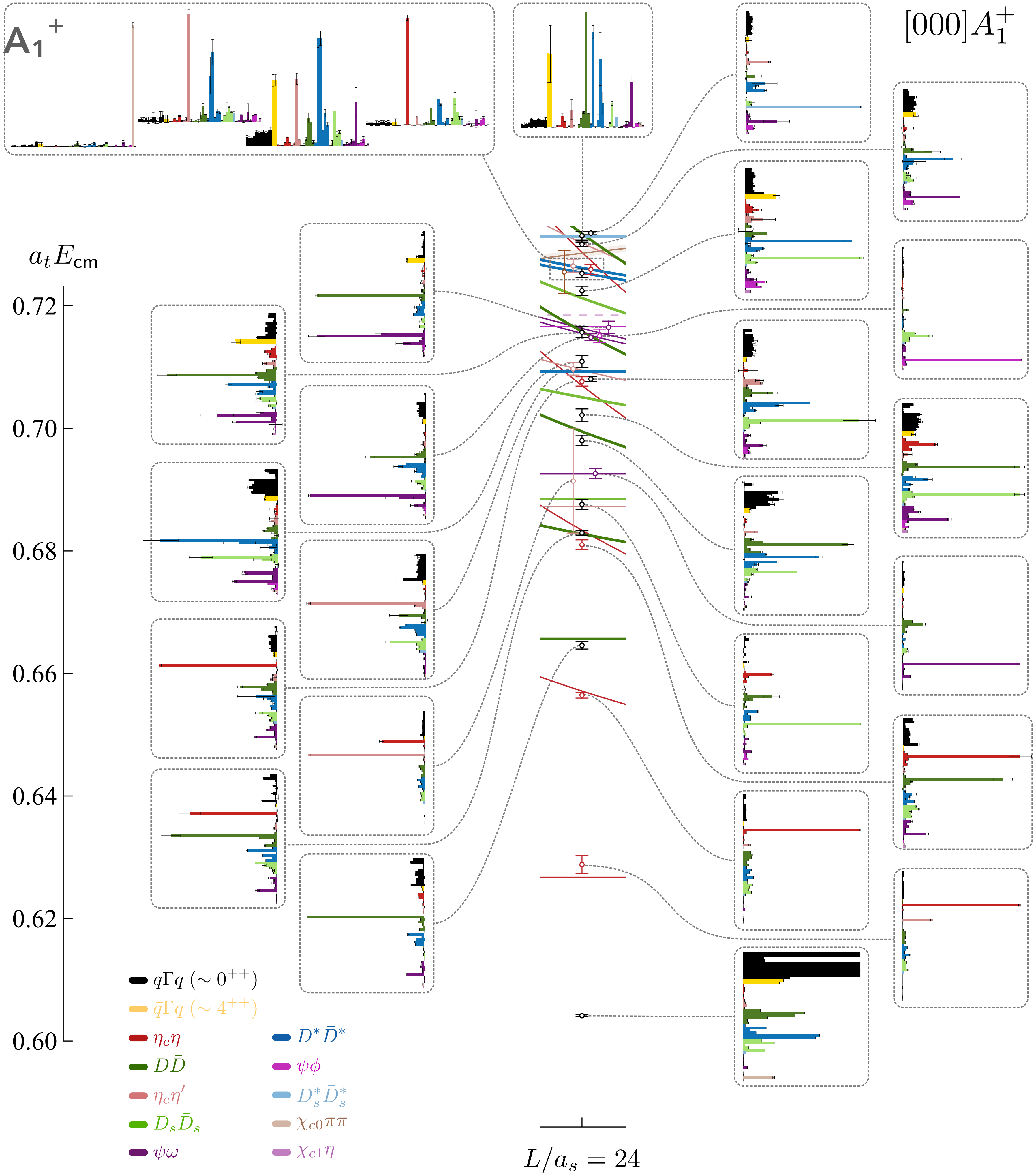
using *distillation* (Peardon *et al* 2009)
many channels, many wick contractions

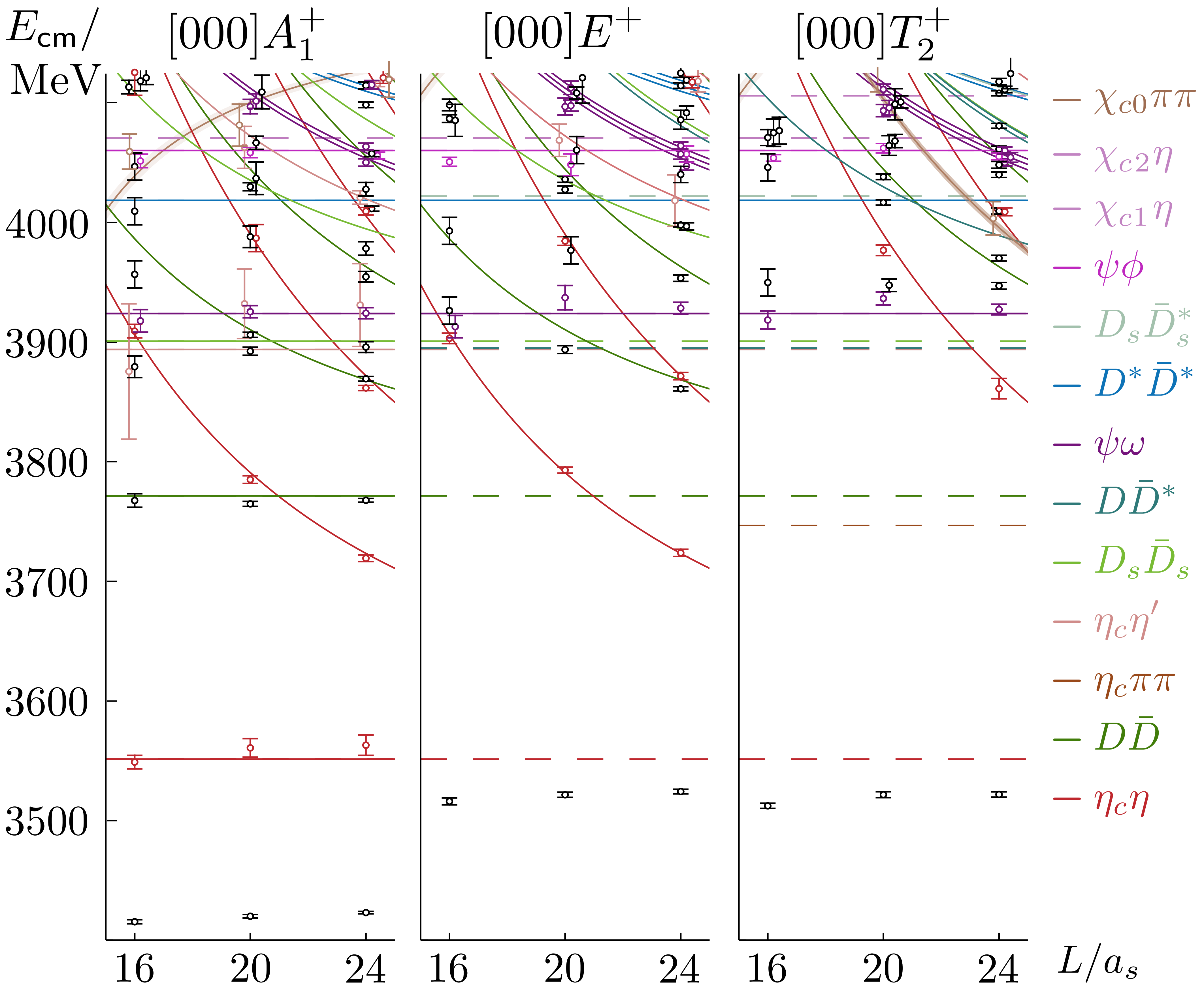
This study: Meson-meson + qqbar ops

- compute a large correlation matrix
- solve generalised eigenvalue problem to extract energies



Review: Briceño, Dudek, Young,
https://doi.org/10.1103/RevModPhys.90.025001


$[000]A_1^+$
$a_t E_{\mathrm{cm}}$
0.72
0.70
0.68
0.66
0.64
0.62
0.60
$\bar{q}\Gamma q$ ($\sim 0^{++}$)
$\bar{q}\Gamma q$ ($\sim 4^{++}$)
$\eta_c\eta$
$D\bar{D}$
$\eta_c\eta'$
$D_s\bar{D}_s$
$\psi\omega$
$D^*\bar{D}^*$
$\psi\phi$
$D_s^*\bar{D}_s^*$
$\chi_{c0}\pi\pi$
$\chi_{c1}\eta$
$L/a_s = 24$



$E_{\mathrm{cm}}/$ MeV
$[000]\,A_1^+$
$[000]\,E^+$
$[000]\,T_2^+$
4000
3900
3800
3700
3600
3500
16
20
24
L/a_s
$\chi_{c0}\pi\pi$
$\chi_{c2}\eta$
$\chi_{c1}\eta$
$\psi\phi$
$D_s\bar{D}_s^*$
$D^*\bar{D}^*$
$\psi\omega$
$D\bar{D}^*$
$D_s\bar{D}_s$
$\eta_c\eta'$
$\eta_c\pi\pi$
$D\bar{D}$
$\eta_c\eta$

"0++" "2++" "2++ & 3++"

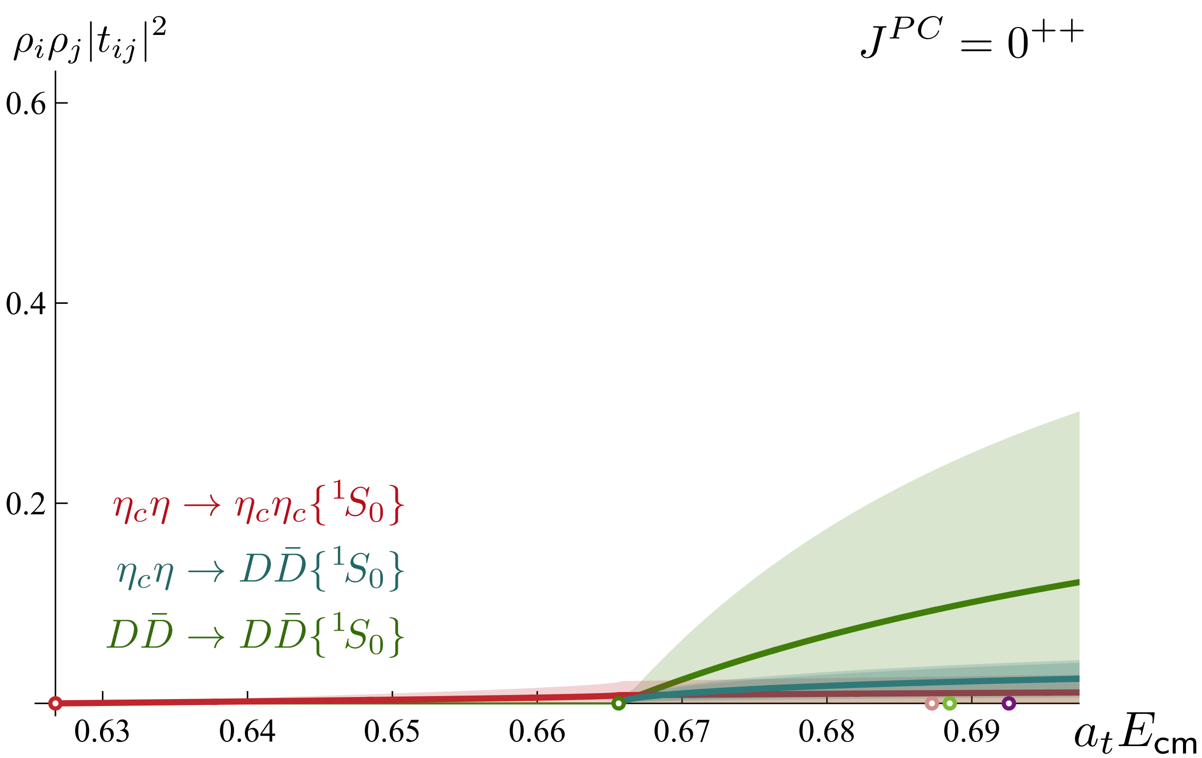
$$\boldsymbol{S} = \mathbf{1} + 2i\boldsymbol{\rho}^{\frac{1}{2}} \cdot \boldsymbol{t} \cdot \boldsymbol{\rho}^{\frac{1}{2}}$$

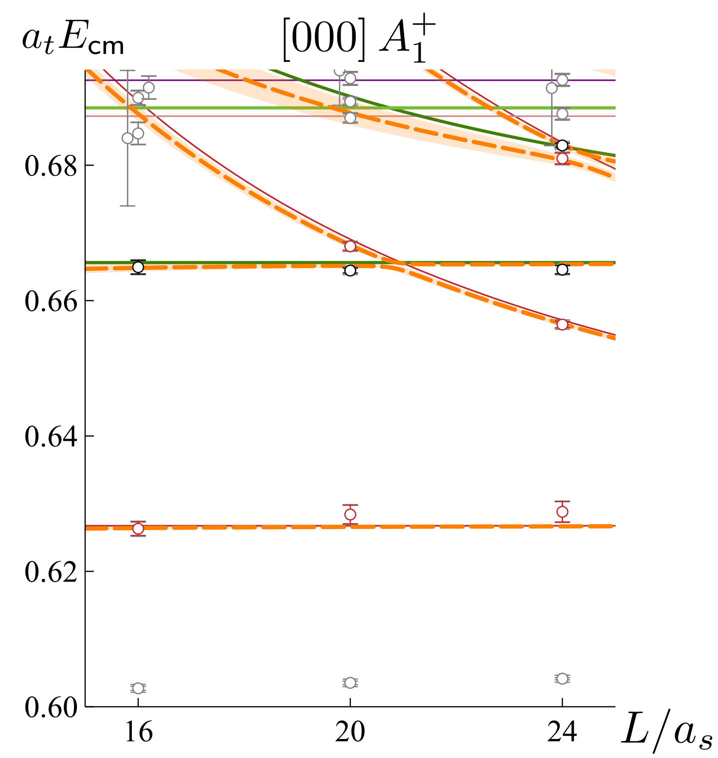
$$\boldsymbol{t}^{-1} = \boldsymbol{K}^{-1} + \boldsymbol{I}$$

$$\mathrm{Im} I_{ij} = -\rho_i = 2k_i/\sqrt{s}$$

$$\det[\mathbf{1} + i\boldsymbol{\rho} \cdot \boldsymbol{t}\,(\mathbf{1} + i\boldsymbol{\mathcal{M}}(L))] = 0$$

$$\boldsymbol{K} = \begin{bmatrix} \gamma_{\eta_c\eta\to\eta_c\eta} & \gamma_{\eta_c\eta\to D\bar{D}} \\ \gamma_{\eta_c\eta\to D\bar{D}} & \gamma_{D\bar{D}\to D\bar{D}} \end{bmatrix}$$



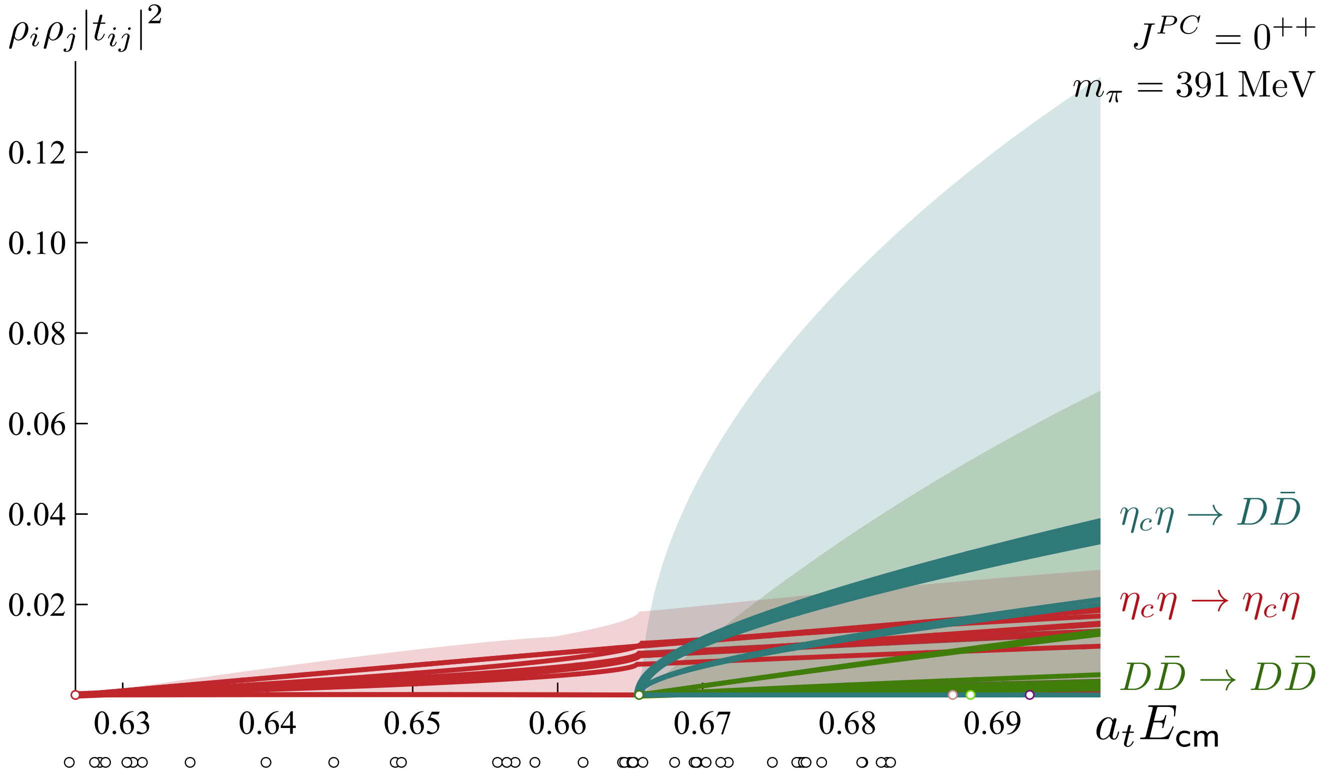


using rest-frame only

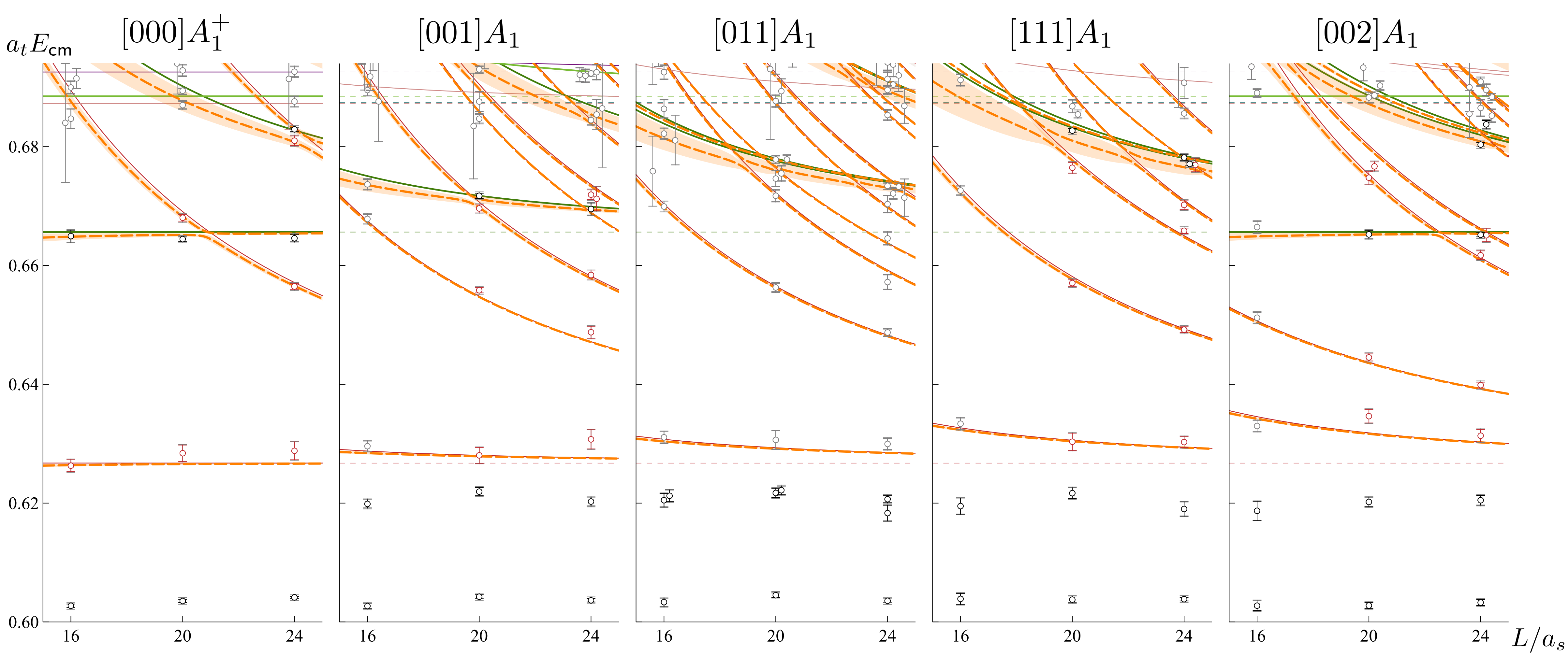
$$\begin{aligned} \gamma_{\eta_c\eta\to\eta_c\eta} &= (0.34 \pm 0.23 \pm 0.09) \\ \gamma_{\eta_c\eta\to D\bar{D}} &= (0.58 \pm 0.29 \pm 0.05) \\ \gamma_{D\bar{D}\to D\bar{D}} &= (1.39 \pm 1.19 \pm 0.24) \end{aligned} \qquad \begin{bmatrix} 1.00 & 0.77 & -0.24 \\ & 1.00 & -0.22 \\ & & 1.00 \end{bmatrix}$$

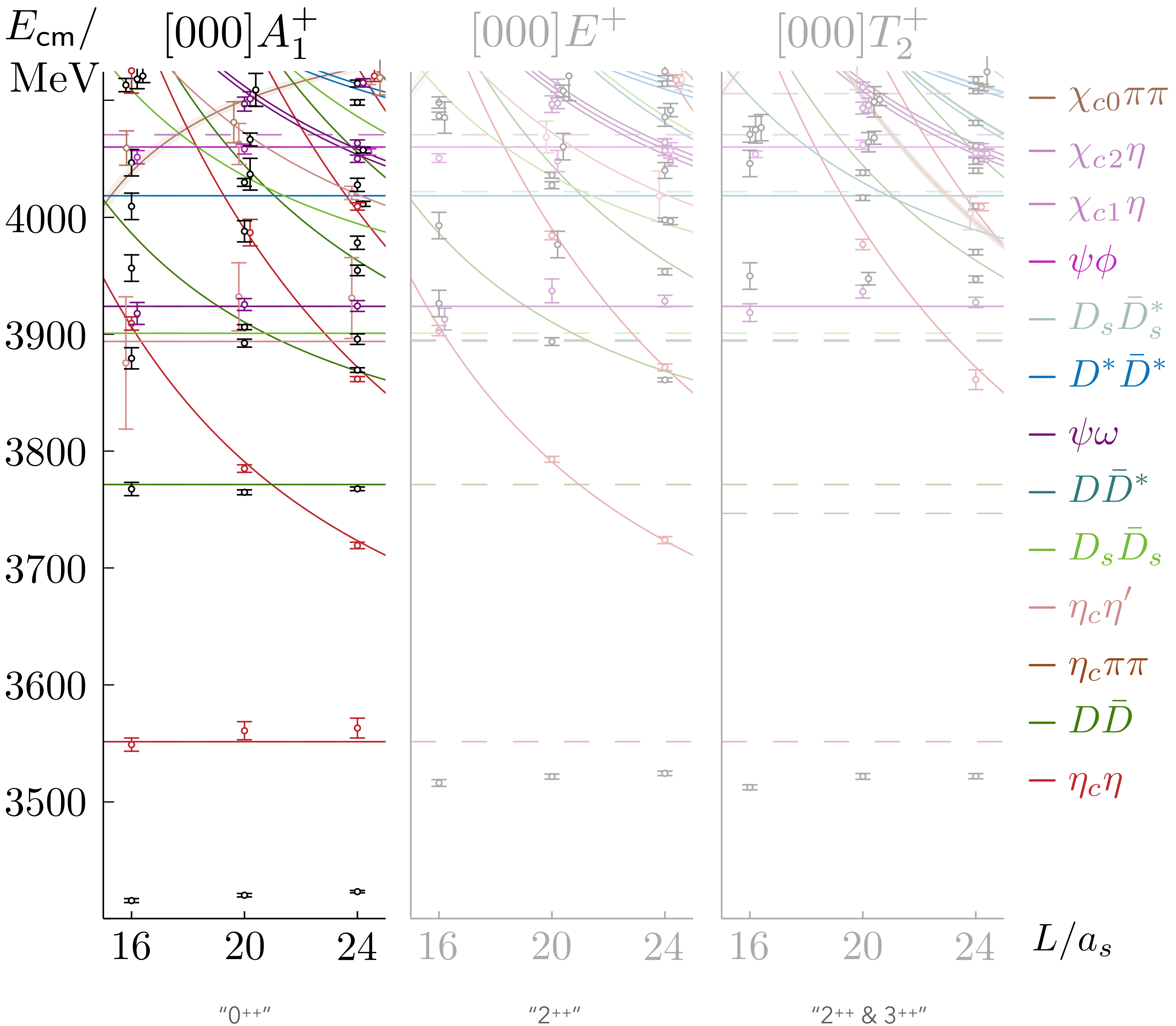
$$\chi^2/N_{\mathrm{dof}} = \frac{5.65}{10-3} = 0.81$$

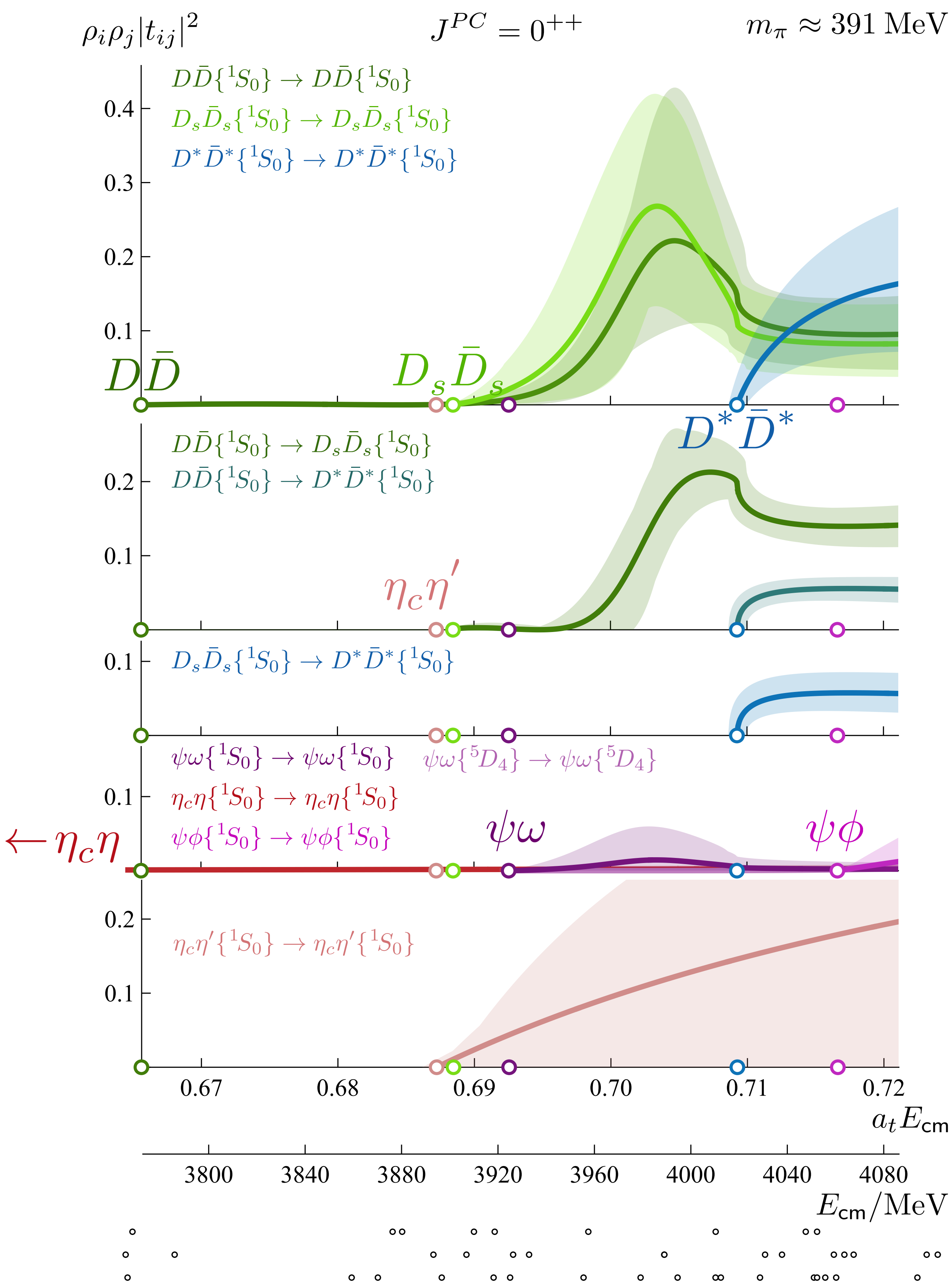
(smaller range)



using zero and non-zero total momentum




$E_{\mathsf{cm}}/$ MeV
$[000]A_1^+$
$[000]E^+$
$[000]T_2^+$
3500
3600
3700
3800
3900
4000
16
20
24
L/a_s
$\chi_{c0}\pi\pi$
$\chi_{c2}\eta$
$\chi_{c1}\eta$
$\psi\phi$
$D_s\bar{D}_s^*$
$D^*\bar{D}^*$
$\psi\omega$
$D\bar{D}^*$
$D_s\bar{D}_s$
$\eta_c\eta'$
$\eta_c\pi\pi$
$D\bar{D}$
$\eta_c\eta$
"0++"
"2++"
"2++ & 3++"



three channels open close together: $\eta_c\eta'$, $D_s\bar{D}_s$, $\psi\omega$

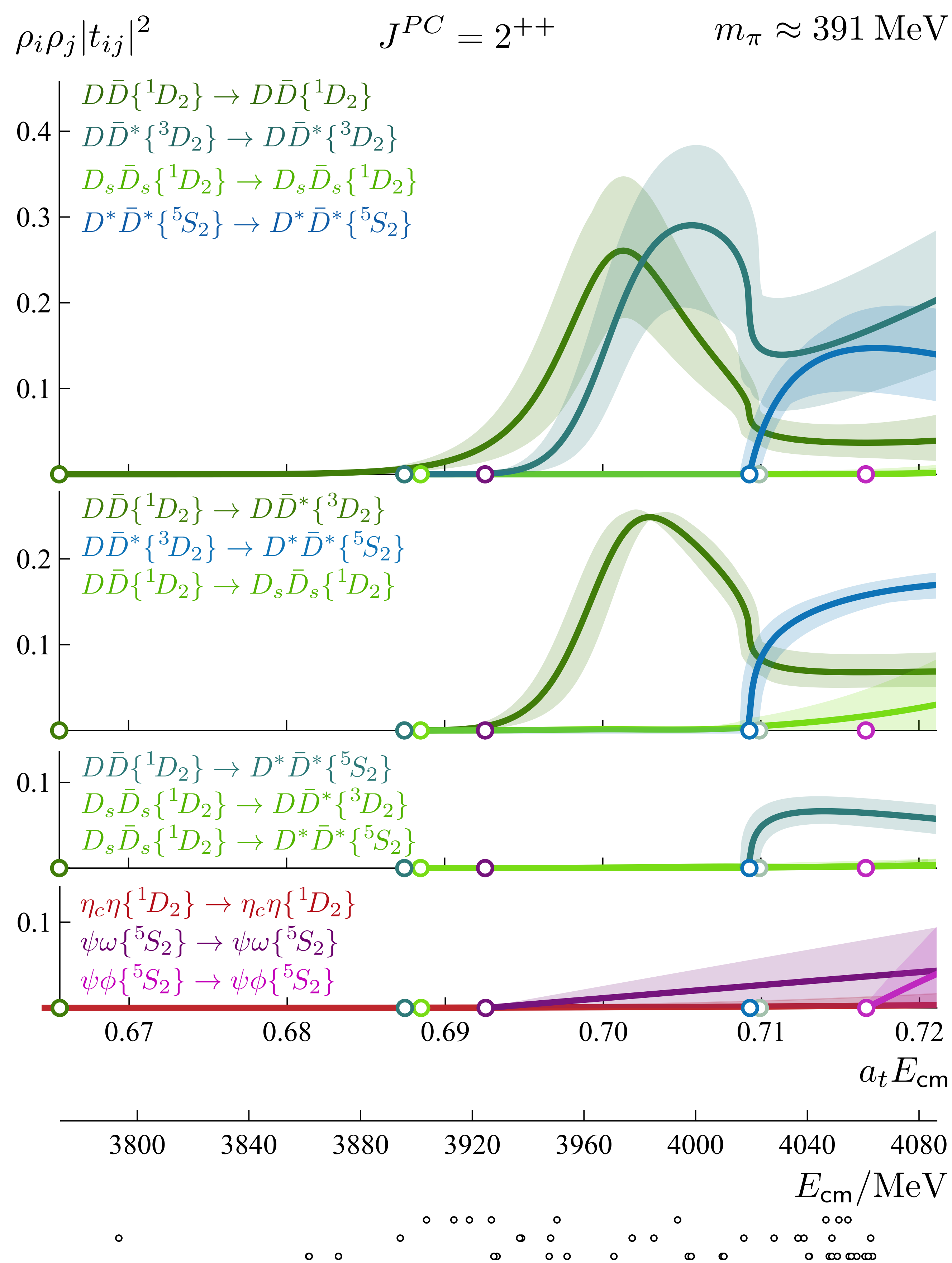
operator overlaps suggest $D^*\bar{D}^*$ is important

$\psi\phi$ has been seen to be important in some places

consider 7-channel system

$$K_{ij} = \frac{g_i g_j}{m^2 - s} + \gamma_{ij}$$

K-matrix pole terms become necessary to obtain a good quality of fit



7-channels, mixture of *S* and *D*

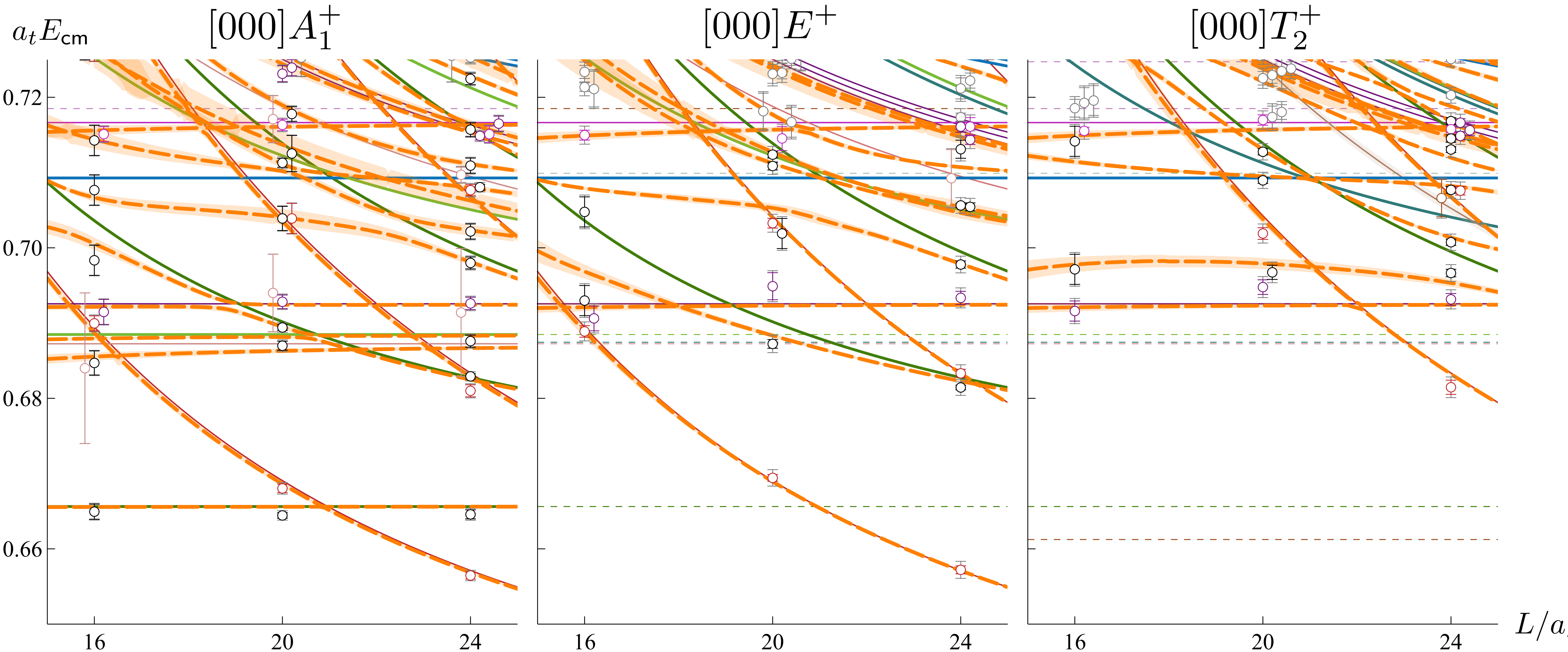
$D\bar{D}, D_s\bar{D}_s\{^1D_2\}$ $D\bar{D}^*\{^3D_2\}$ $D^*\bar{D}^*\{^5S_2\}$

$\eta_c\eta\{^1D_2\}$ $\psi\omega, \psi\phi\{^5S_2\}$

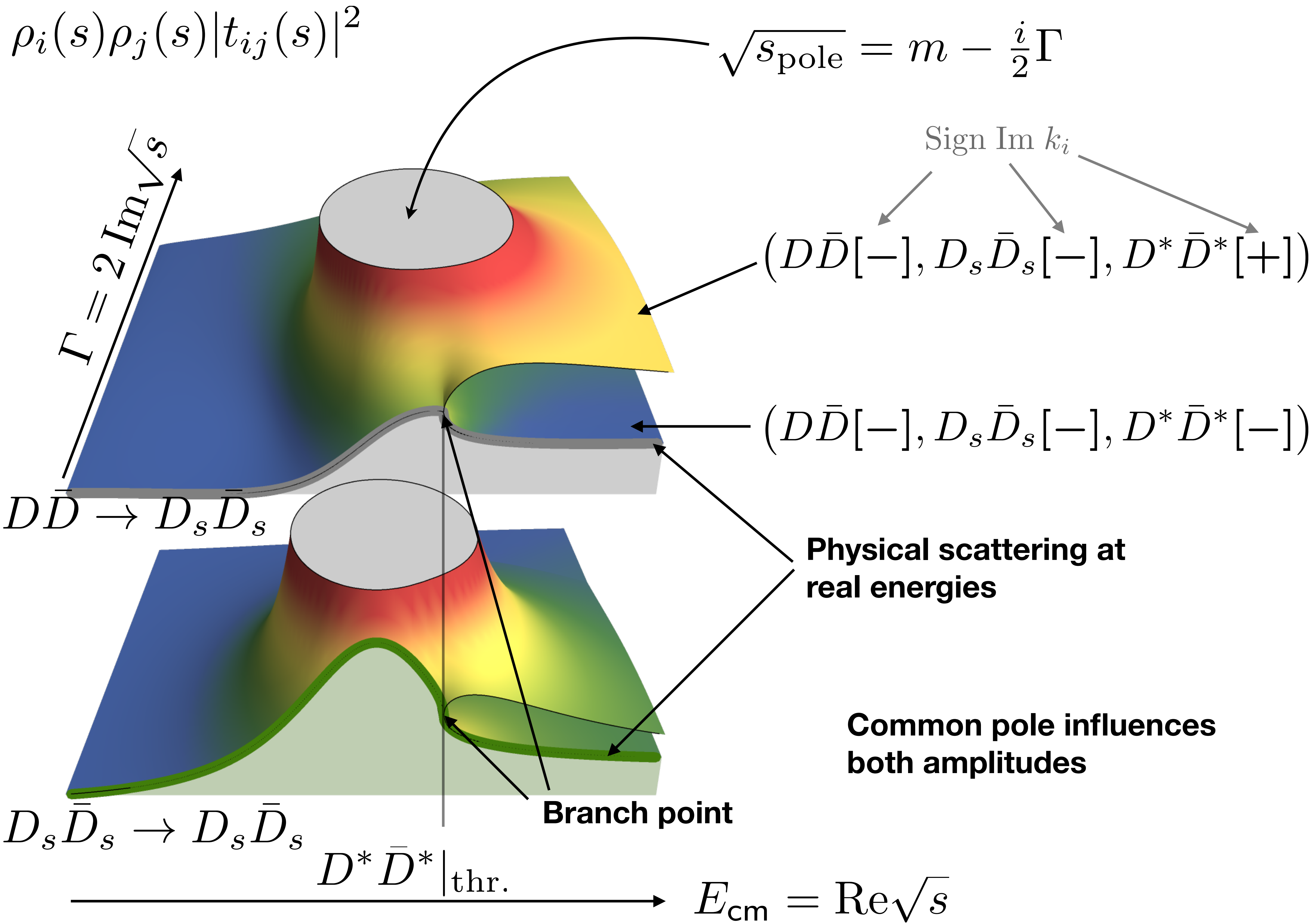
peaks at a similar energy

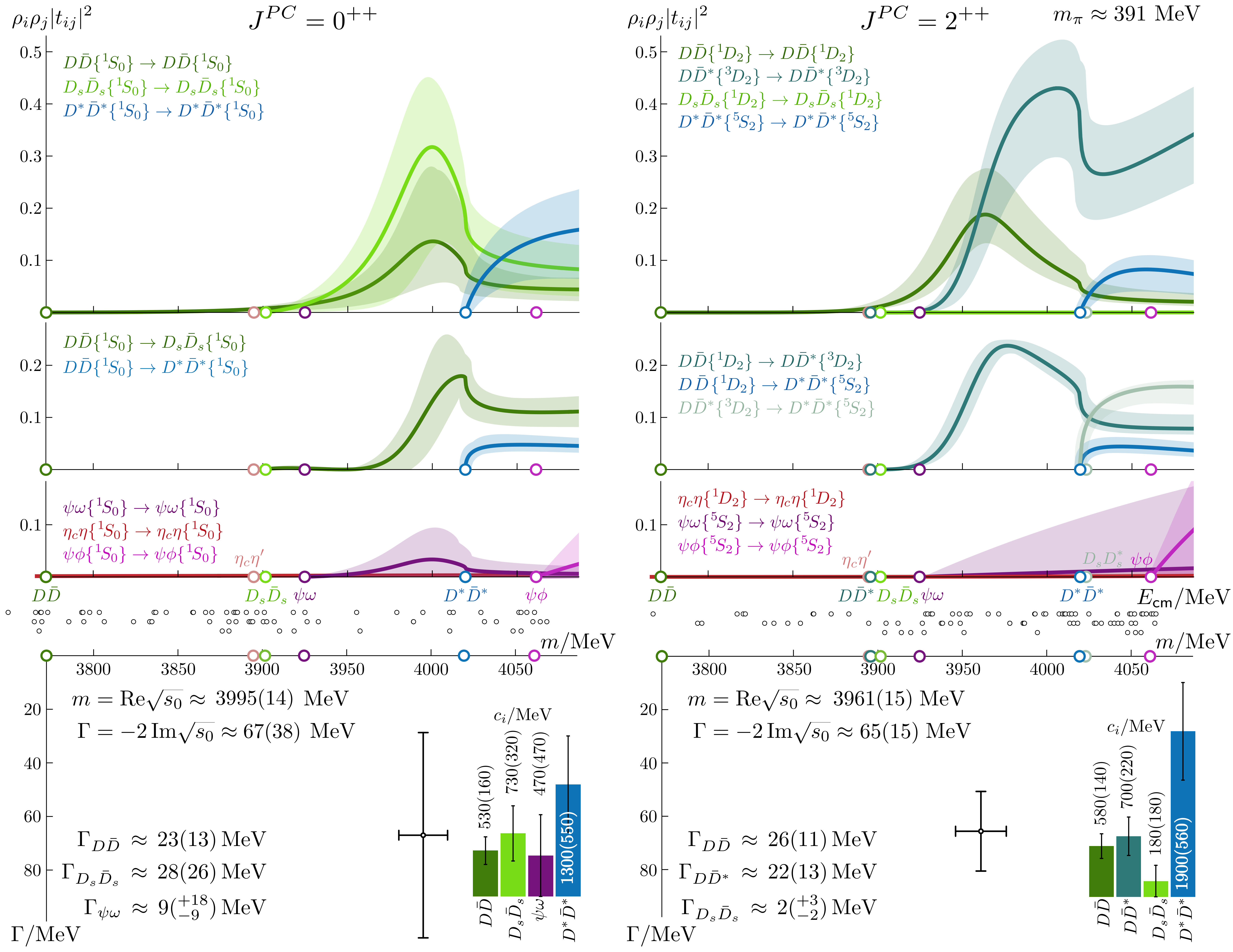
very small DsDs amplitudes -
some phase space suppression

DD* is large -
similar phase space to DsDs



$$\det[\mathbf{1} + i\boldsymbol{\rho}\cdot\boldsymbol{t}\,(\mathbf{1} + i\boldsymbol{\mathcal{M}}(L))] = 0$$


$\rho_i(s)\rho_j(s)|t_{ij}(s)|^2$
$\sqrt{s_{\mathrm{pole}}} = m - \frac{i}{2}\Gamma$
Sign Im k_i
$(D\bar{D}[-], D_s\bar{D}_s[-], D^*\bar{D}^*[+])$
$(D\bar{D}[-], D_s\bar{D}_s[-], D^*\bar{D}^*[-])$
$\Gamma = 2\,\mathrm{Im}\sqrt{s}$
$D\bar{D} \to D_s\bar{D}_s$
Physical scattering at real energies
Common pole influences both amplitudes
Branch point
$D_s\bar{D}_s \to D_s\bar{D}_s$
$D^*\bar{D}^*|_{\mathrm{thr.}}$
$E_{\mathrm{cm}} = \mathrm{Re}\sqrt{s}$



$\rho_i\rho_j|t_{ij}|^2$
$J^{PC}=0^{++}$
$D\bar{D}\{^1S_0\}\to D\bar{D}\{^1S_0\}$
$D_s\bar{D}_s\{^1S_0\}\to D_s\bar{D}_s\{^1S_0\}$
$D^*\bar{D}^*\{^1S_0\}\to D^*\bar{D}^*\{^1S_0\}$
$D\bar{D}\{^1S_0\}\to D_s\bar{D}_s\{^1S_0\}$
$D\bar{D}\{^1S_0\}\to D^*\bar{D}^*\{^1S_0\}$
$\psi\omega\{^1S_0\}\to\psi\omega\{^1S_0\}$
$\eta_c\eta\{^1S_0\}\to\eta_c\eta\{^1S_0\}$
$\psi\phi\{^1S_0\}\to\psi\phi\{^1S_0\}$
$\eta_c\eta'$
$D\bar{D}$ $D_s\bar{D}_s$ $\psi\omega$ $D^*\bar{D}^*$ $\psi\phi$
m/MeV
$m=\mathrm{Re}\sqrt{s_0}\approx 3995(14)$ MeV
$\Gamma=-2\,\mathrm{Im}\sqrt{s_0}\approx 67(38)$ MeV
$\Gamma_{D\bar{D}}\approx 23(13)$ MeV
$\Gamma_{D_s\bar{D}_s}\approx 28(26)$ MeV
$\Gamma_{\psi\omega}\approx 9(^{+18}_{-9})$ MeV
c_i/MeV
530(160) 730(320) 470(470) 1300(550)
$D\bar{D}$ $D_s\bar{D}_s$ $\psi\omega$ $D^*\bar{D}^*$
Γ/MeV
$\rho_i\rho_j|t_{ij}|^2$
$J^{PC}=2^{++}$
$m_\pi\approx 391$ MeV
$D\bar{D}\{^1D_2\}\to D\bar{D}\{^1D_2\}$
$D\bar{D}^*\{^3D_2\}\to D\bar{D}^*\{^3D_2\}$
$D_s\bar{D}_s\{^1D_2\}\to D_s\bar{D}_s\{^1D_2\}$
$D^*\bar{D}^*\{^5S_2\}\to D^*\bar{D}^*\{^5S_2\}$
$D\bar{D}\{^1D_2\}\to D\bar{D}^*\{^3D_2\}$
$D\bar{D}\{^1D_2\}\to D^*\bar{D}^*\{^5S_2\}$
$D\bar{D}^*\{^3D_2\}\to D^*\bar{D}^*\{^5S_2\}$
$\eta_c\eta\{^1D_2\}\to\eta_c\eta\{^1D_2\}$
$\psi\omega\{^5S_2\}\to\psi\omega\{^5S_2\}$
$\psi\phi\{^5S_2\}\to\psi\phi\{^5S_2\}$
$\eta_c\eta'$ $D_sD_s^*$ $\psi\phi$
$D\bar{D}$ $D\bar{D}^*$ $D_s\bar{D}_s$ $\psi\omega$ $D^*\bar{D}^*$
E_{cm}/MeV
m/MeV
$m=\mathrm{Re}\sqrt{s_0}\approx 3961(15)$ MeV
$\Gamma=-2\,\mathrm{Im}\sqrt{s_0}\approx 65(15)$ MeV
$\Gamma_{D\bar{D}}\approx 26(11)$ MeV
$\Gamma_{D\bar{D}^*}\approx 22(13)$ MeV
$\Gamma_{D_s\bar{D}_s}\approx 2(^{+3}_{-2})$ MeV
c_i/MeV
580(140) 700(220) 180(180) 1900(560)
$D\bar{D}$ $D\bar{D}^*$ $D_s\bar{D}_s$ $D^*\bar{D}^*$
Γ/MeV

Scalar and tensor charmonium

- at m_π=391 MeV, one scalar and one tensor pole is found.
- The **level counting** is not obviously different from the **quark model**

- large **coupled-channel** effects in OZI **connected D-meson channels**
- OZI **disconnected** channels look **small everywhere**

- we have extracted a **complete** unitary **S-matrix** and this naturally **connects** features seen in **different channels** and simplifies the overall picture
- some amplitudes are **very different** to the simple **Breit-Wigners** often used in experimental analyses

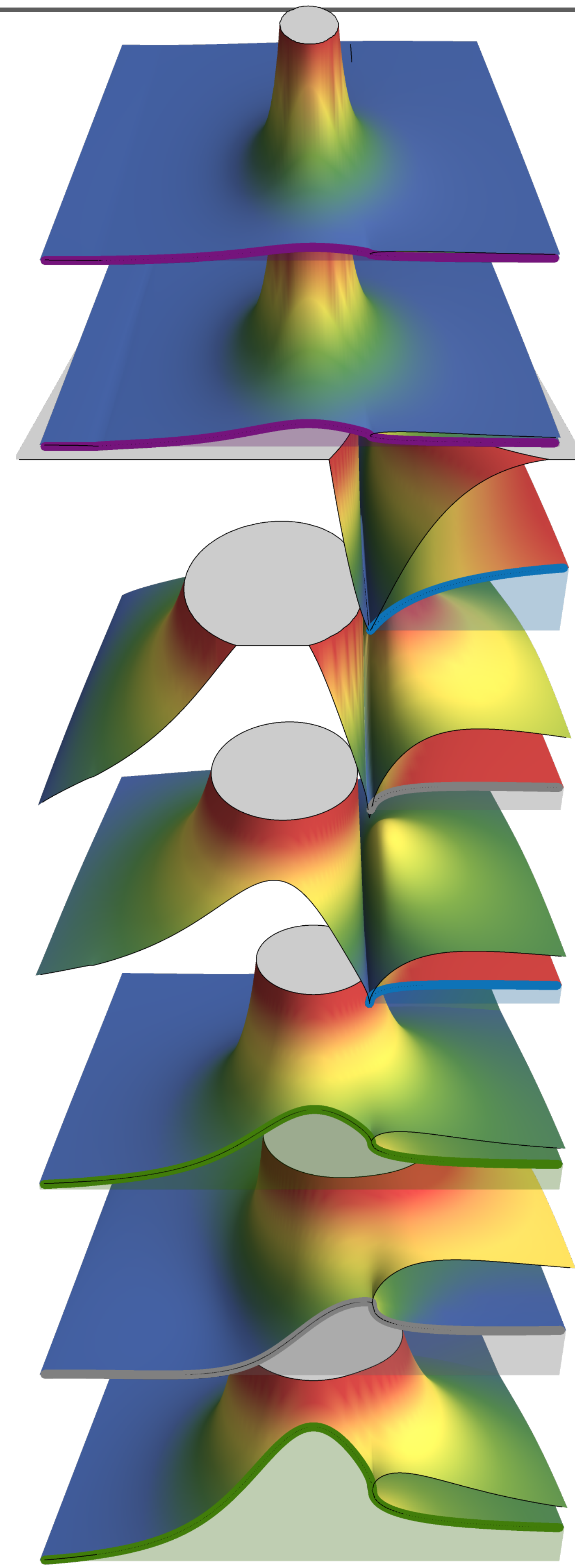
- a clear, as yet unobserved, 3++ resonance is present in DDbar* & a bound state in 2-+
- we **do not find** a **near-threshold DDbar** state (between 3700 and 3860 MeV)

- these methods can also be applied to the X(3872) 1++ channel

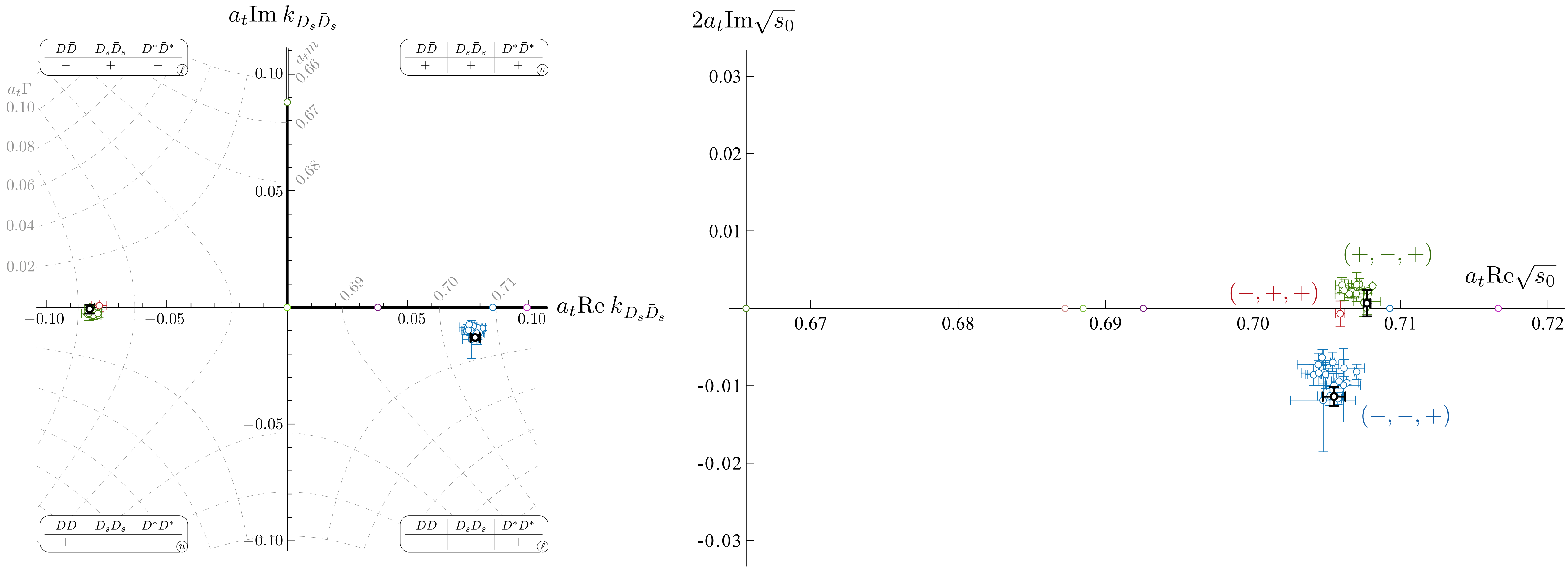
Full details and references:
arXiv: 2309.14070 (7 pages)
arXiv: 2309.14071 (55 pages)

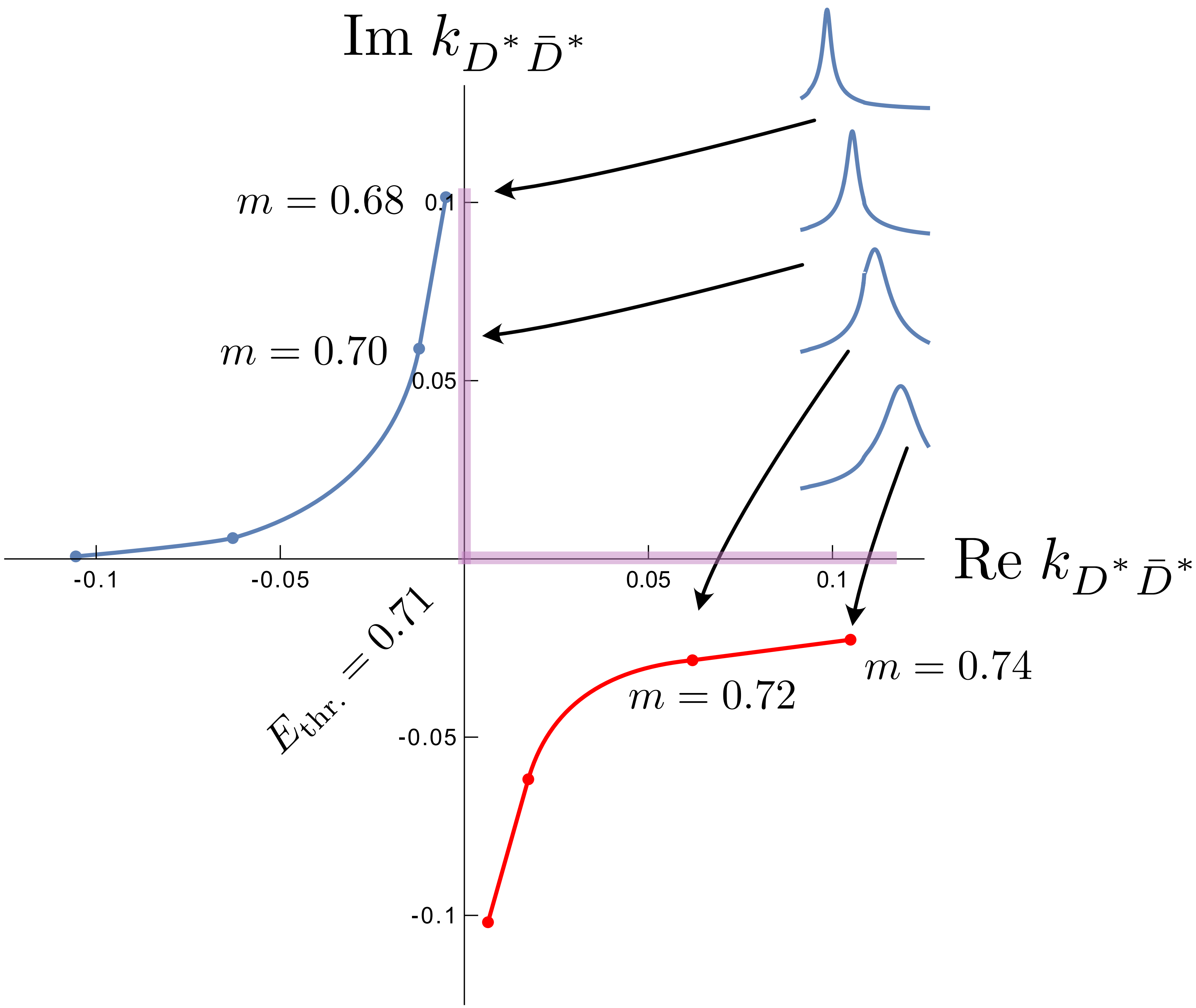
$\rho_i(s)\rho_j(s)|t_{ij}(s)|^2$

one resonance pole
— many different amplitudes

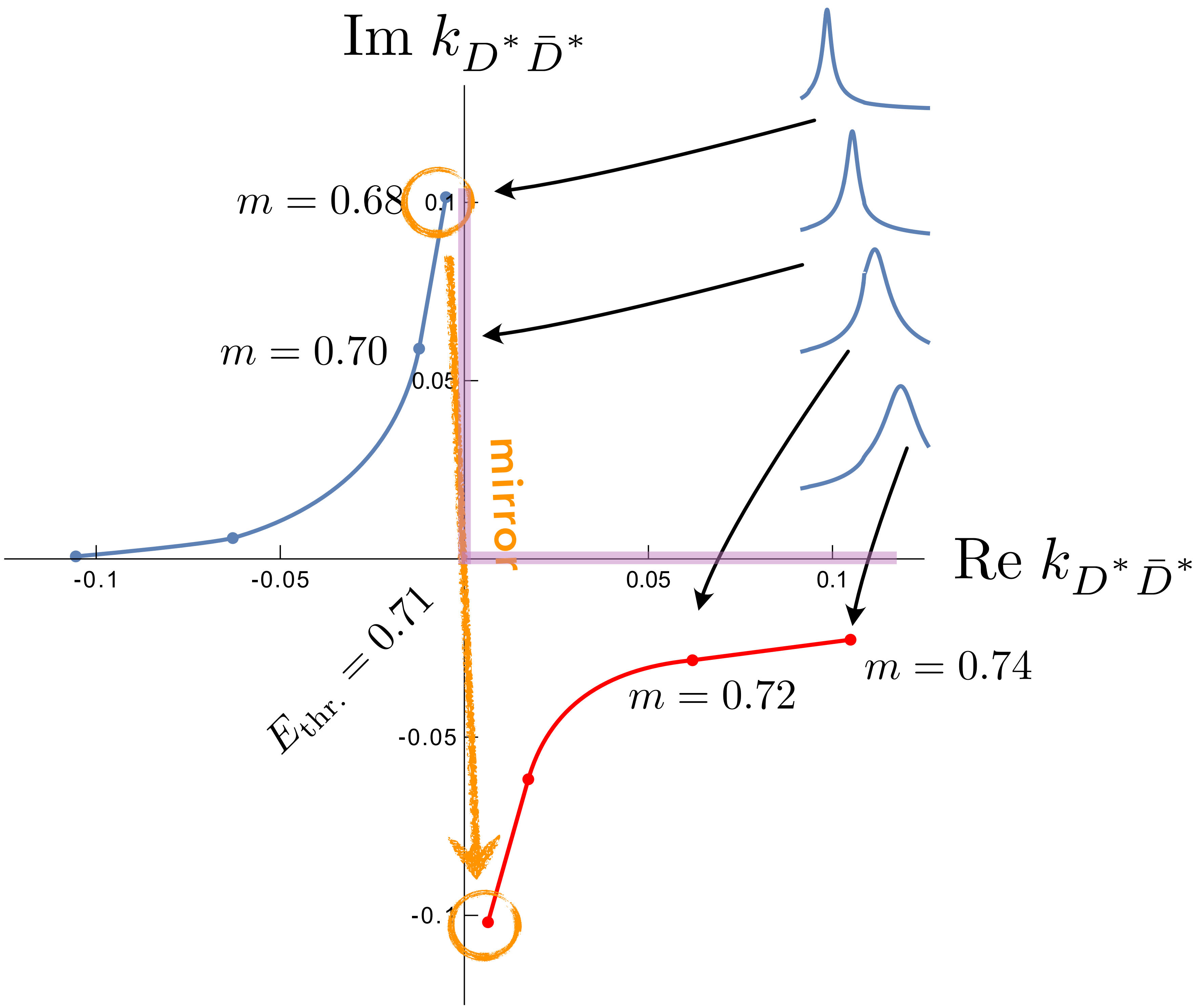


poles - scalar

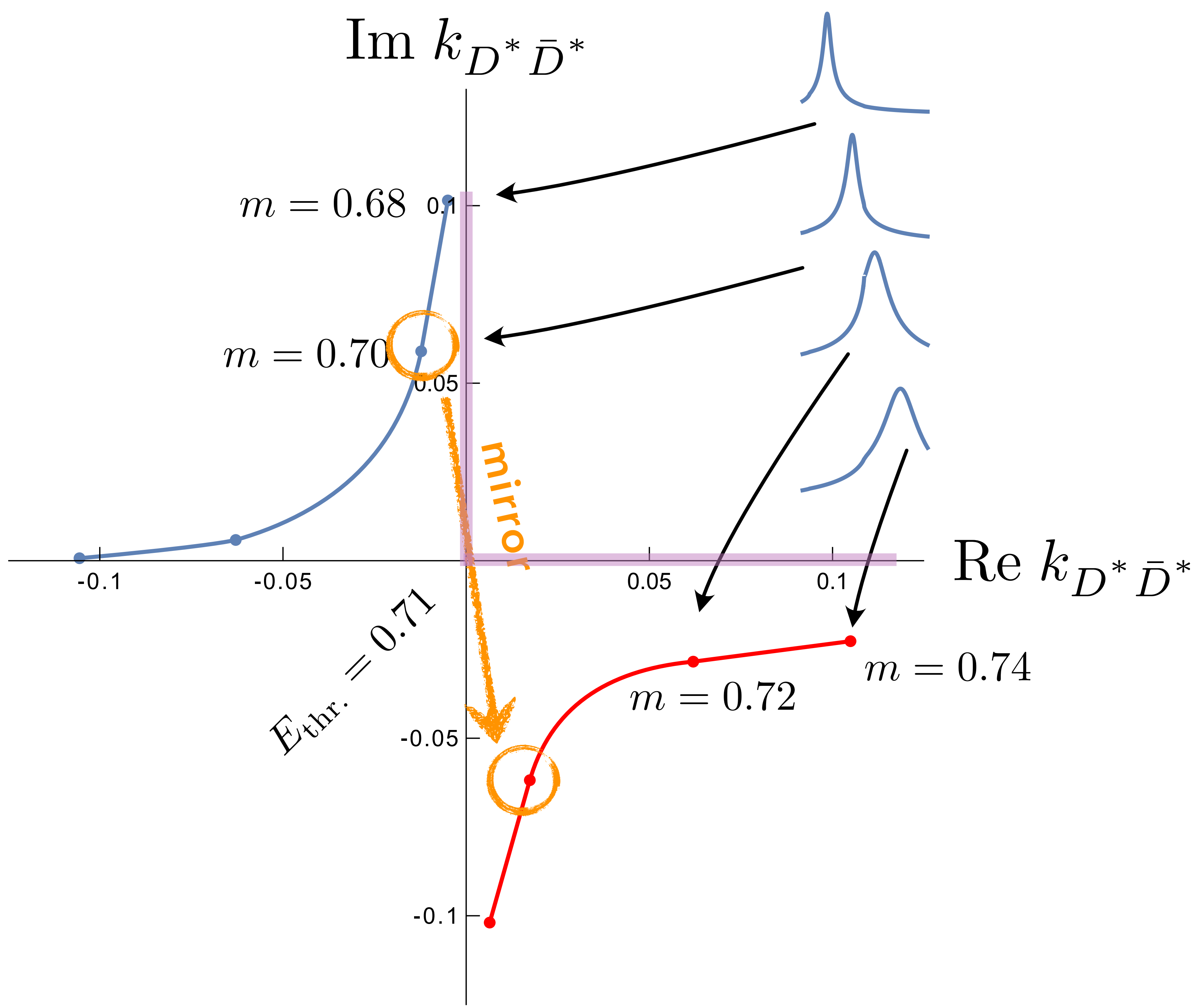




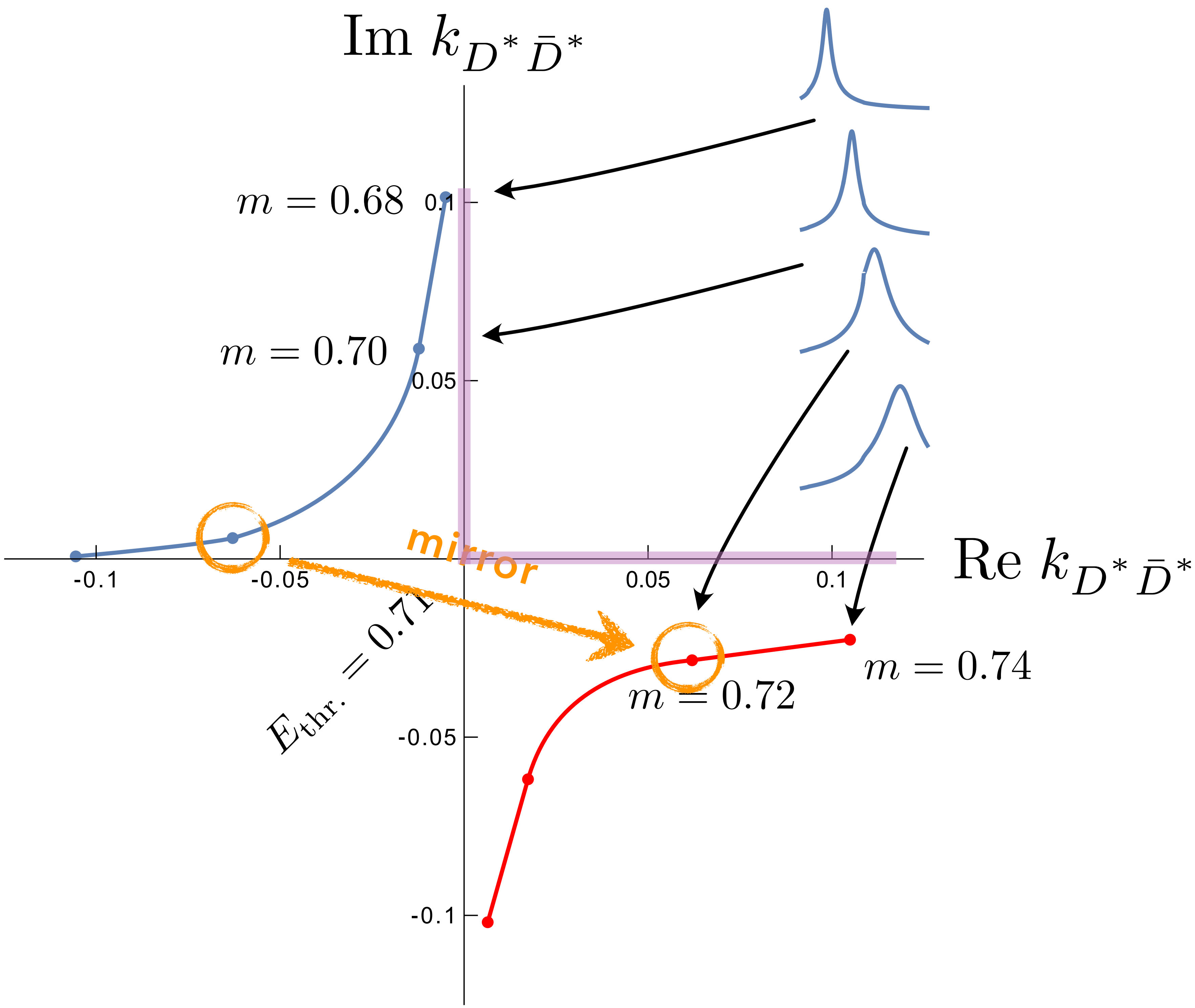
$$t_{ij} = \frac{g_i g_j}{m_0^2 - s - i g_{D\bar{D}}^2 \rho_{D\bar{D}} - i g_{D^*\bar{D}^*}^2 \rho_{D^*\bar{D}^*}}$$



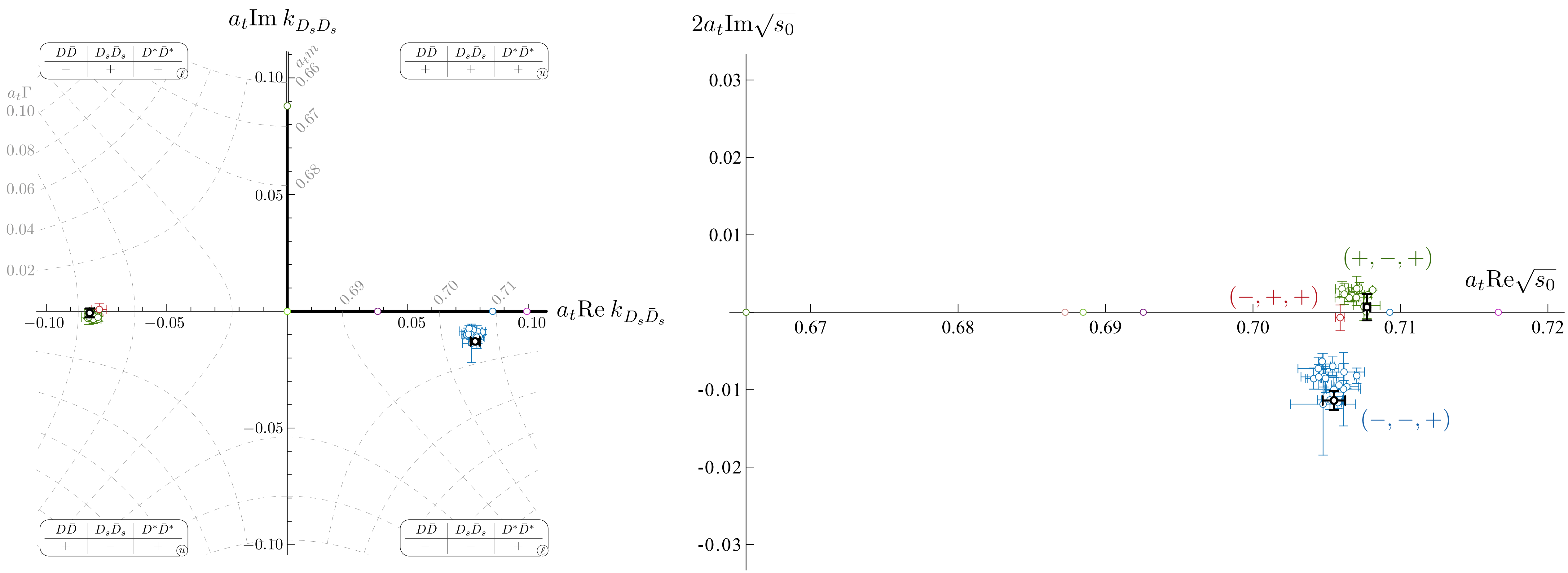
$$t_{ij} = \frac{g_i g_j}{m_0^2 - s - i g^2_{D\bar{D}} \rho_{D\bar{D}} - i g^2_{D^*\bar{D}^*} \rho_{D^*\bar{D}^*}}$$



$$t_{ij} = \frac{g_i g_j}{m_0^2 - s - i g^2_{D\bar{D}}\rho_{D\bar{D}} - i g^2_{D^*\bar{D}^*}\rho_{D^*\bar{D}^*}}$$

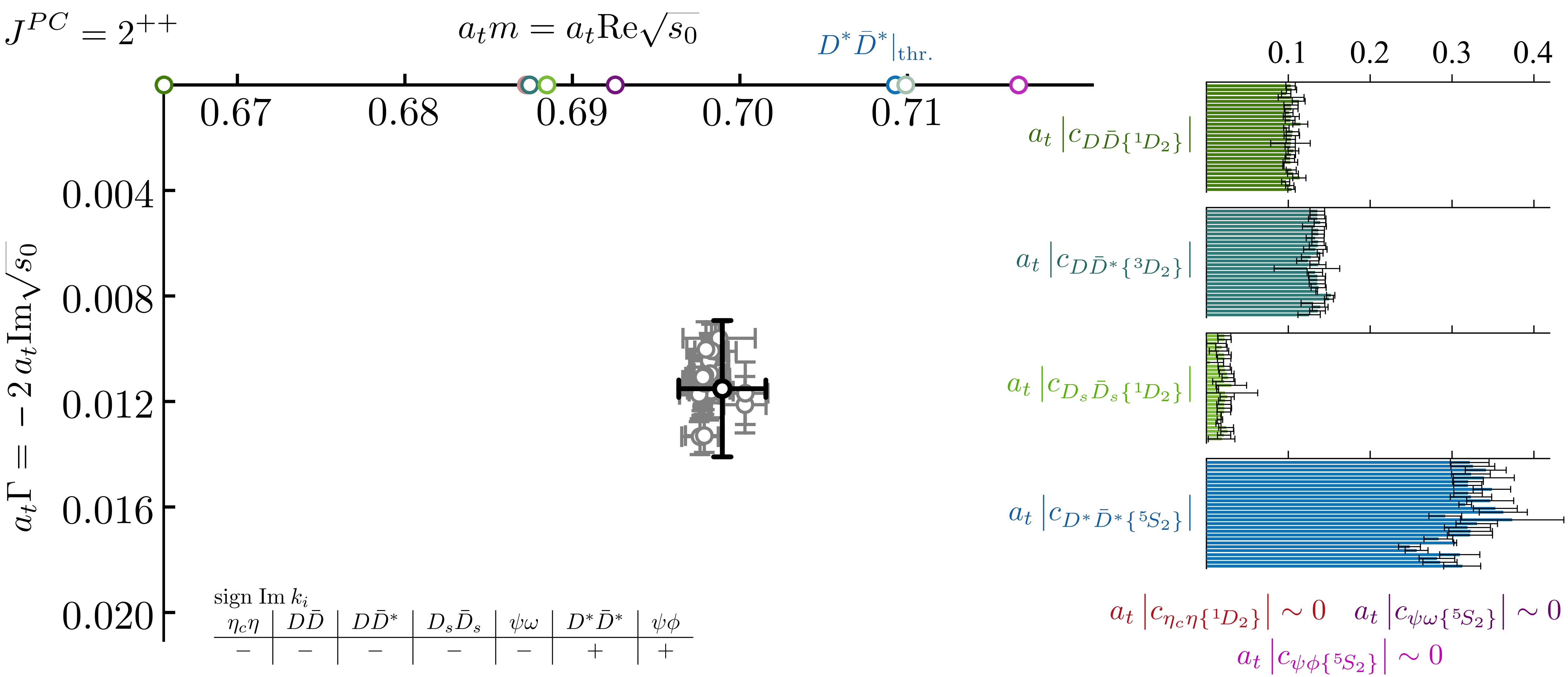


$$t_{ij} = \frac{g_i g_j}{m_0^2 - s - i g_{D\bar{D}}^2 \rho_{D\bar{D}} - i g_{D^*\bar{D}^*}^2 \rho_{D^*\bar{D}^*}}$$



the “green” cluster of poles are just mirror poles

- amplitude is **dominated by a single resonance pole** in this energy region

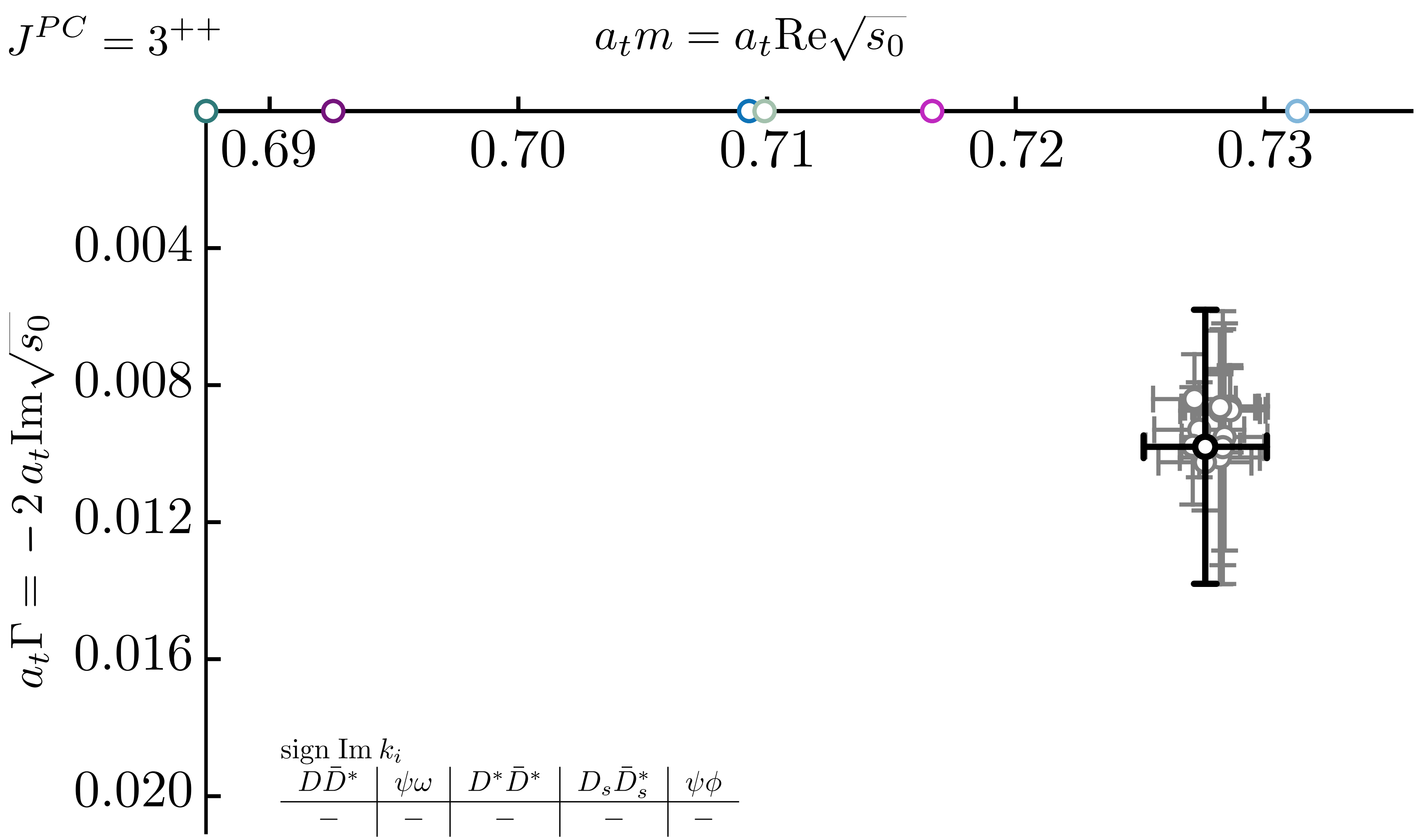


additional poles were found

- don't appear to be important

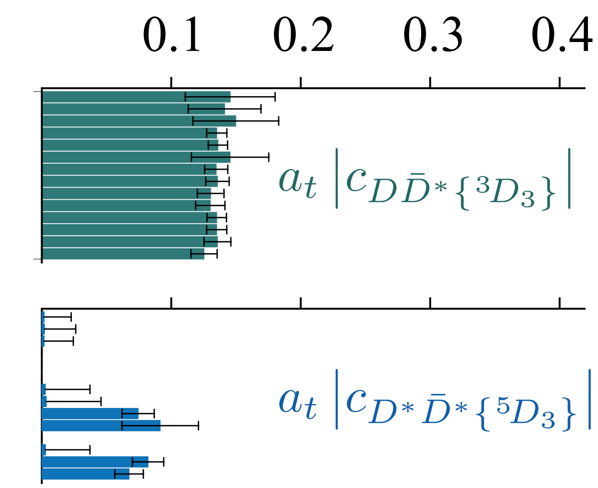
"coupling-ratio" phenomena seen in K-matrix pole parameters

- possible to rescale K-matrix g_i factors and obtain similar amplitudes
- t-matrix couplings are found to be well-determined



sign Im k_i

$D\bar{D}^*$	$\psi\omega$	$D^*\bar{D}^*$	$D_s\bar{D}_s^*$	$\psi\phi$
−	−	−	−	−

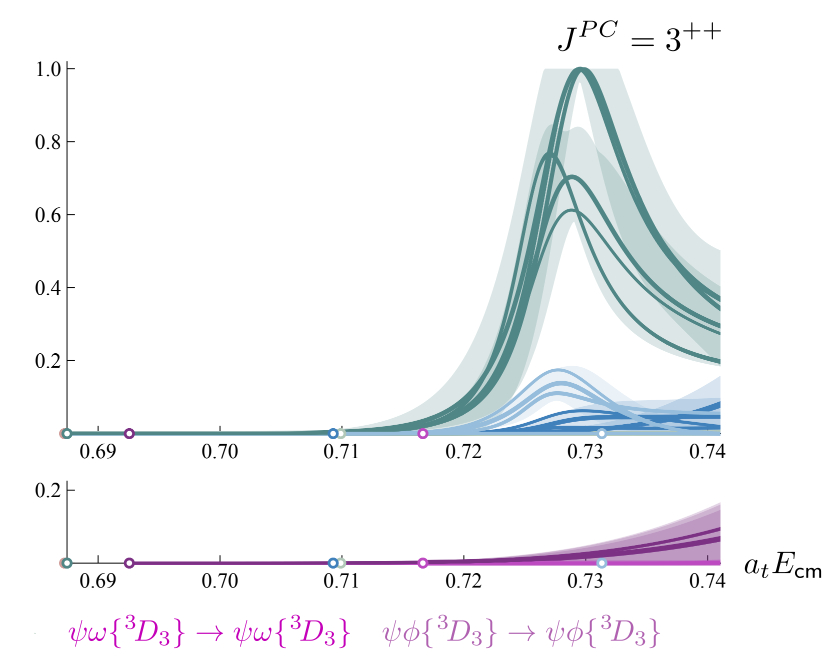


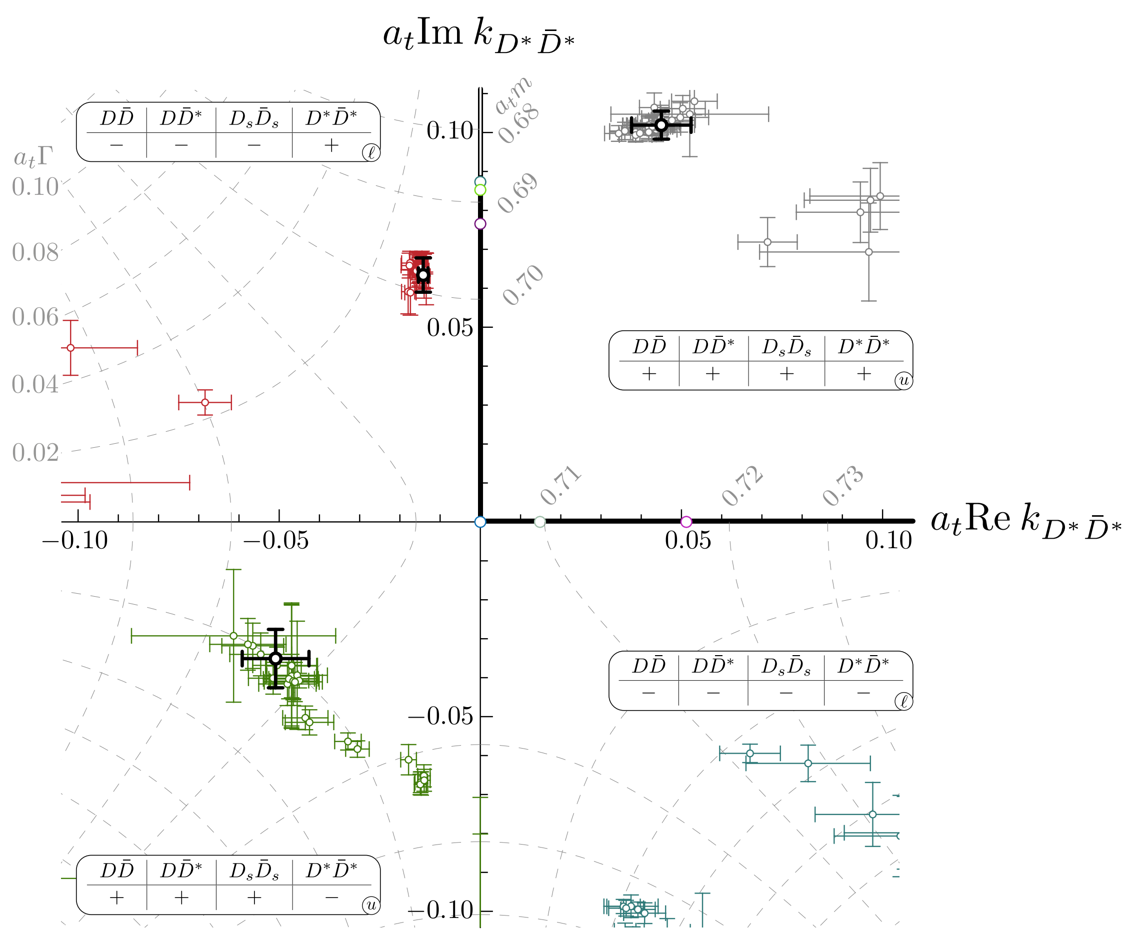
$a_t \left|c_{D_s\bar{D}_s^*\{^3D_3\}}\right| \sim 0$

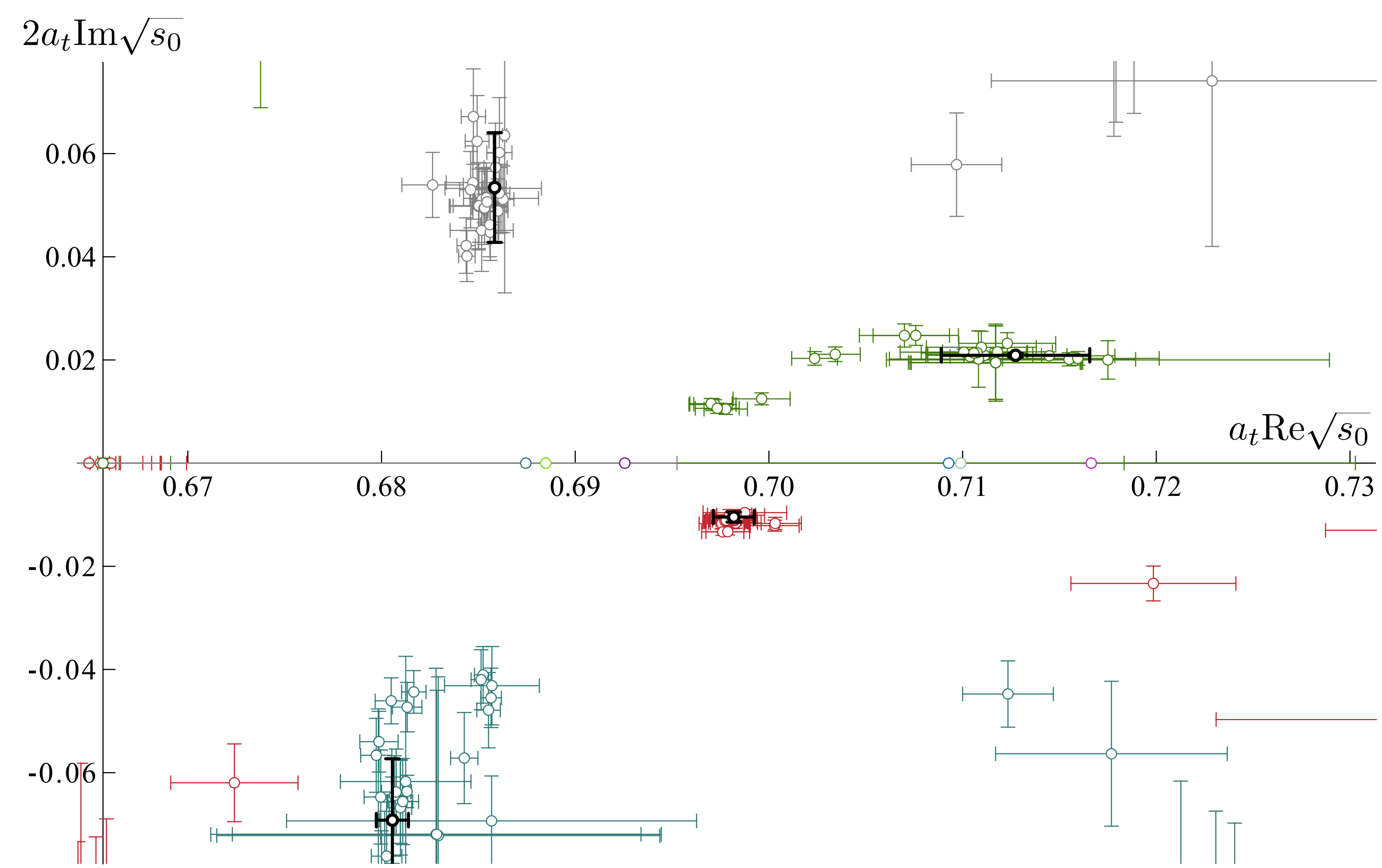
$a_t \left|c_{\psi\omega\{^3D_3\}}\right| \sim 0$

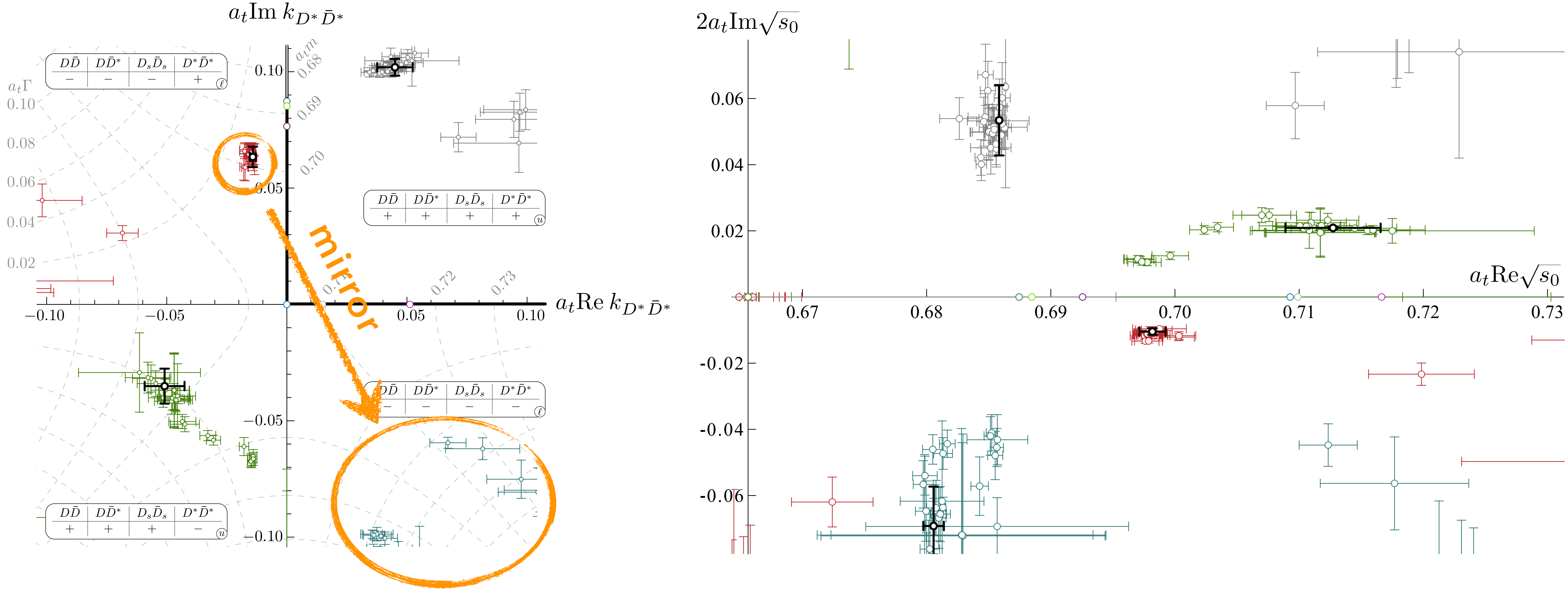
$a_t \left|c_{\psi\omega\{^5D_3\}}\right| \sim 0$

$a_t \left|c_{\psi\phi\{^3D_3\}}\right| \sim 0$

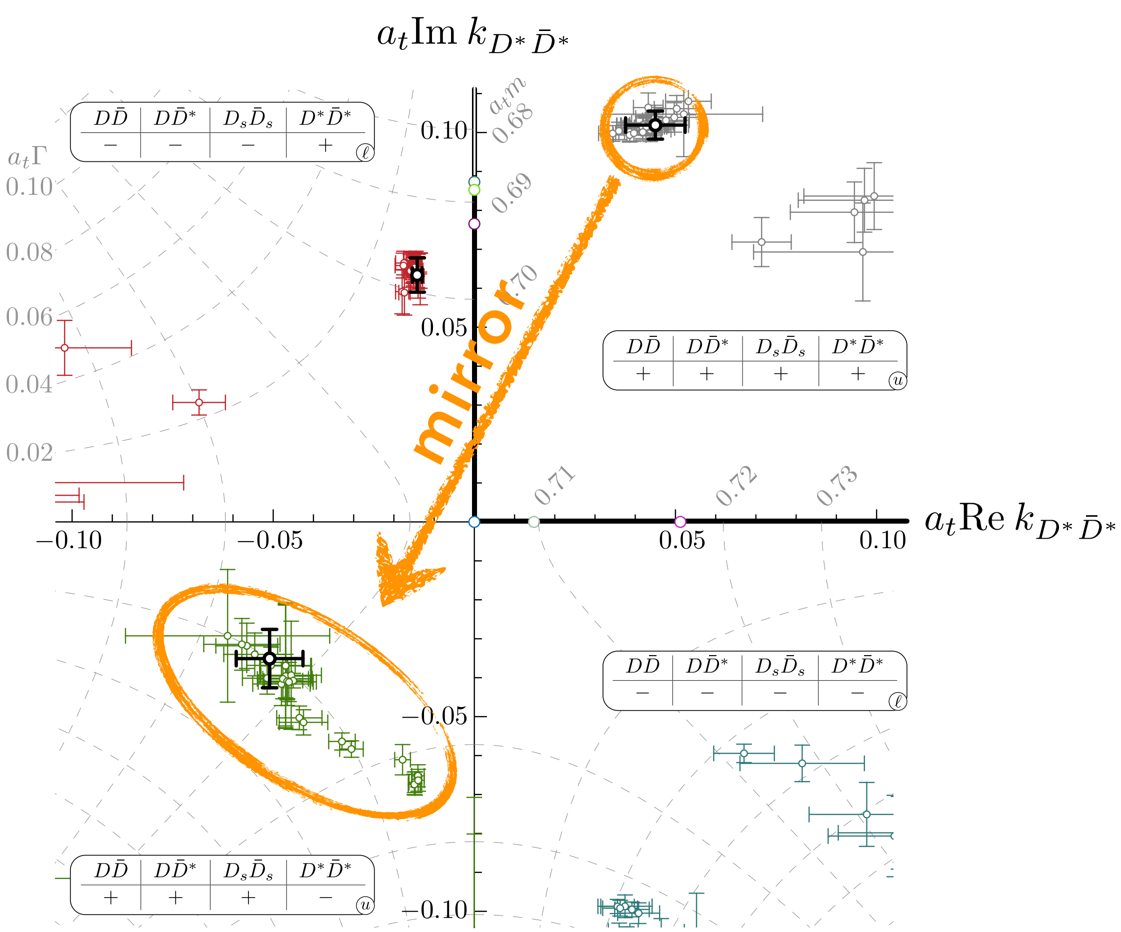


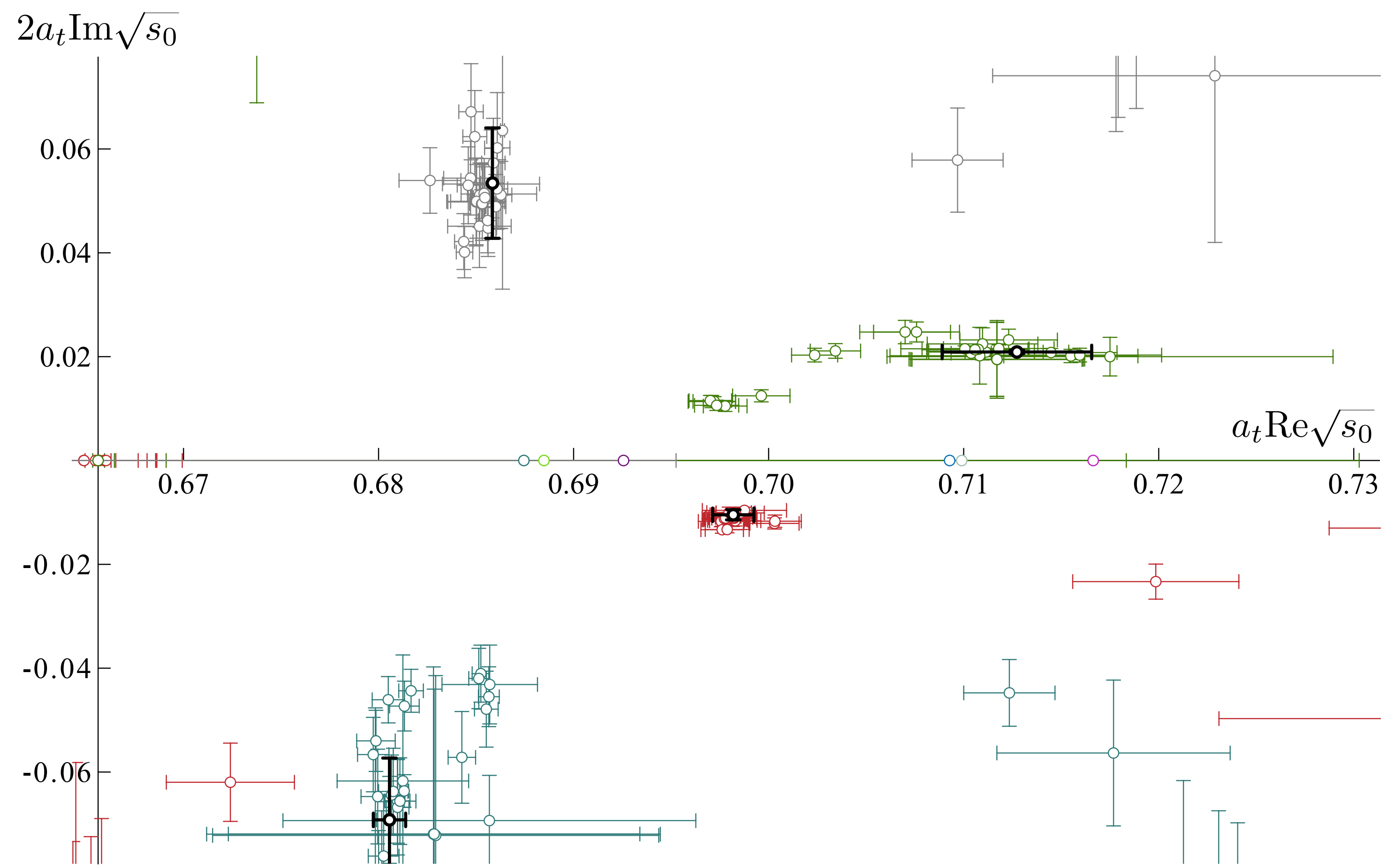

$a_t \mathrm{Im}\, k_{D^*\bar{D}^*}$
$a_t \mathrm{Re}\, k_{D^*\bar{D}^*}$
$a_t m$
$a_t \Gamma$
0.10
0.08
0.06
0.04
0.02
0.68
0.69
0.70
0.71
0.72
0.73
−0.10
−0.05
0.05
0.10
$D\bar{D}$ | $D\bar{D}^*$ | $D_s\bar{D}_s$ | $D^*\bar{D}^*$
− − − + ℓ
+ + + + u
− − − − ℓ
+ + + − u


$2a_t \mathrm{Im}\sqrt{s_0}$
$a_t \mathrm{Re}\sqrt{s_0}$
0.06
0.04
0.02
-0.02
-0.04
-0.06
0.67
0.68
0.69
0.70
0.71
0.72
0.73



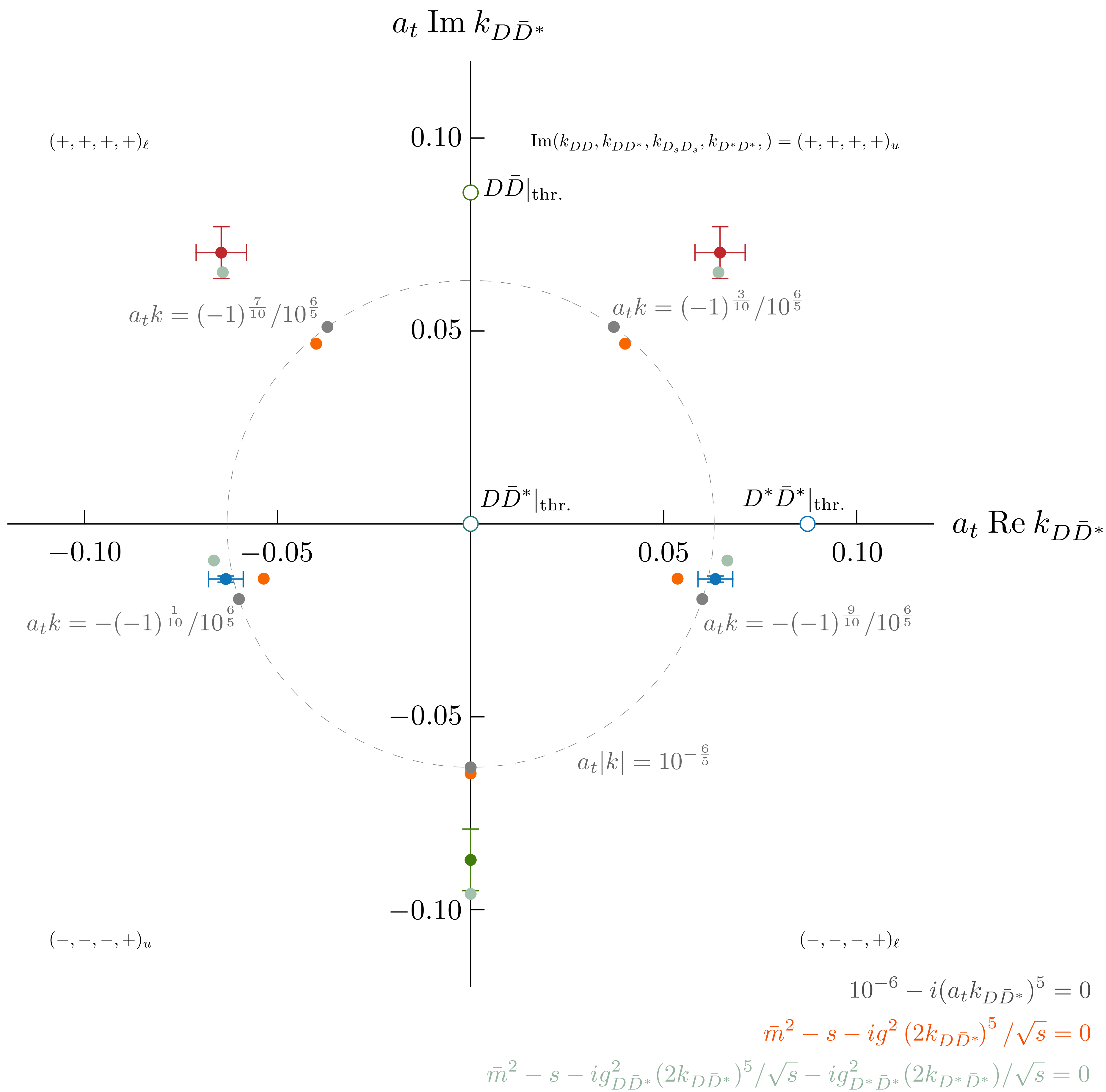
mirror pole - similar to a Flatté



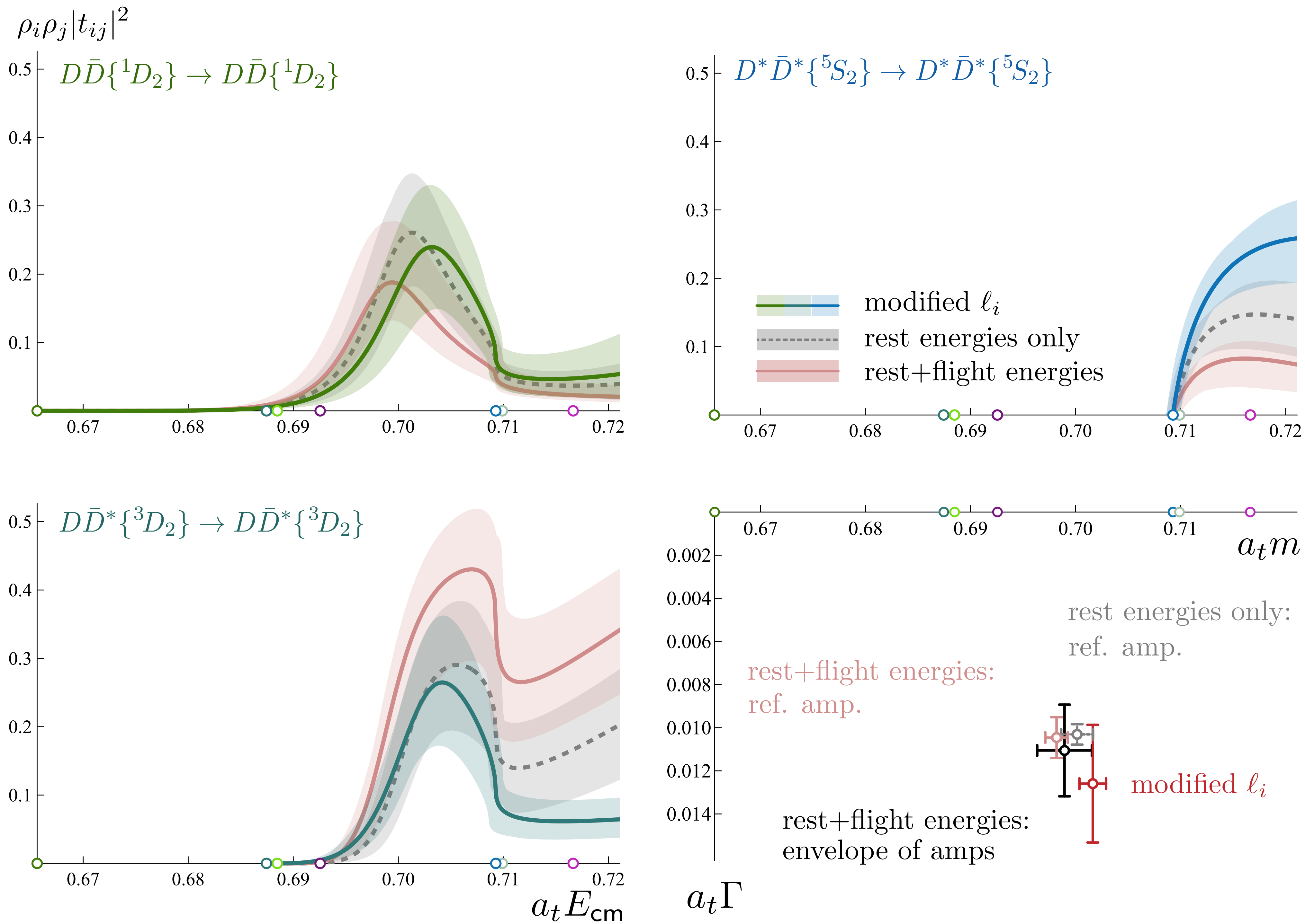


"green" pole is a mirror of the physical sheet pole

physical sheet pole arises because of the large g_{DD^*}



$a_t \, \mathrm{Im}\, k_{D\bar{D}^*}$
$a_t \, \mathrm{Re}\, k_{D\bar{D}^*}$
0.10
0.05
−0.05
−0.10
−0.10
−0.05
0.05
0.10
$(+,+,+,+)_\ell$
$\mathrm{Im}(k_{D\bar{D}}, k_{D\bar{D}^*}, k_{D_s\bar{D}_s}, k_{D^*\bar{D}^*},) = (+,+,+,+)_u$
$D\bar{D}|_{\mathrm{thr.}}$
$D\bar{D}^*|_{\mathrm{thr.}}$
$D^*\bar{D}^*|_{\mathrm{thr.}}$
$a_t k = (-1)^{\frac{7}{10}}/10^{\frac{6}{5}}$
$a_t k = (-1)^{\frac{3}{10}}/10^{\frac{6}{5}}$
$a_t k = -(-1)^{\frac{1}{10}}/10^{\frac{6}{5}}$
$a_t k = -(-1)^{\frac{9}{10}}/10^{\frac{6}{5}}$
$a_t |k| = 10^{-\frac{6}{5}}$
$(-,-,-,+)_u$
$(-,-,-,+)_\ell$
$10^{-6} - i(a_t k_{D\bar{D}^*})^5 = 0$
$\bar{m}^2 - s - ig^2 \left(2k_{D\bar{D}^*}\right)^5 / \sqrt{s} = 0$
$\bar{m}^2 - s - ig^2_{D\bar{D}^*}(2k_{D\bar{D}^*})^5/\sqrt{s} - ig^2_{D^*\bar{D}^*}(2k_{D^*\bar{D}^*})/\sqrt{s} = 0$

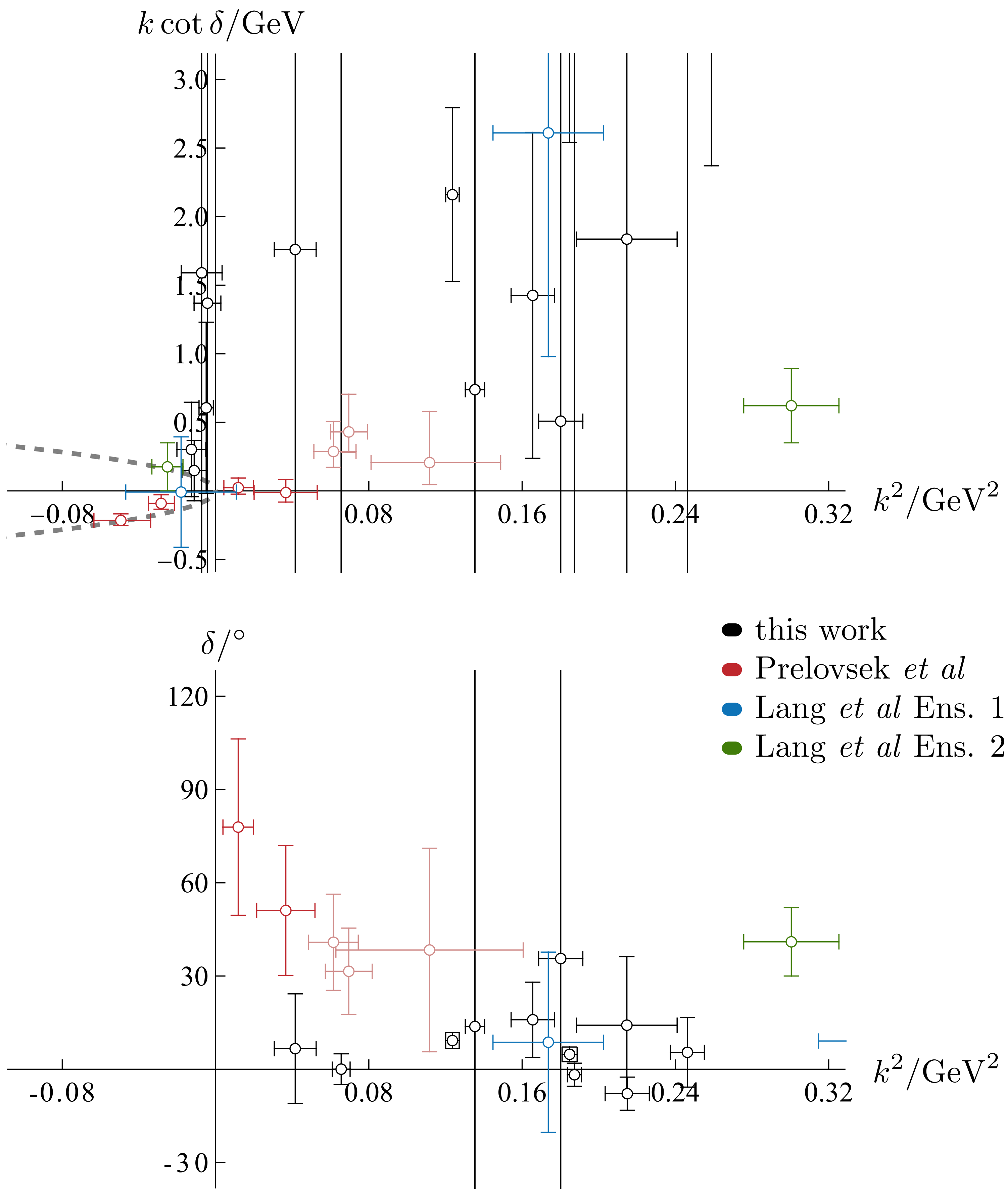


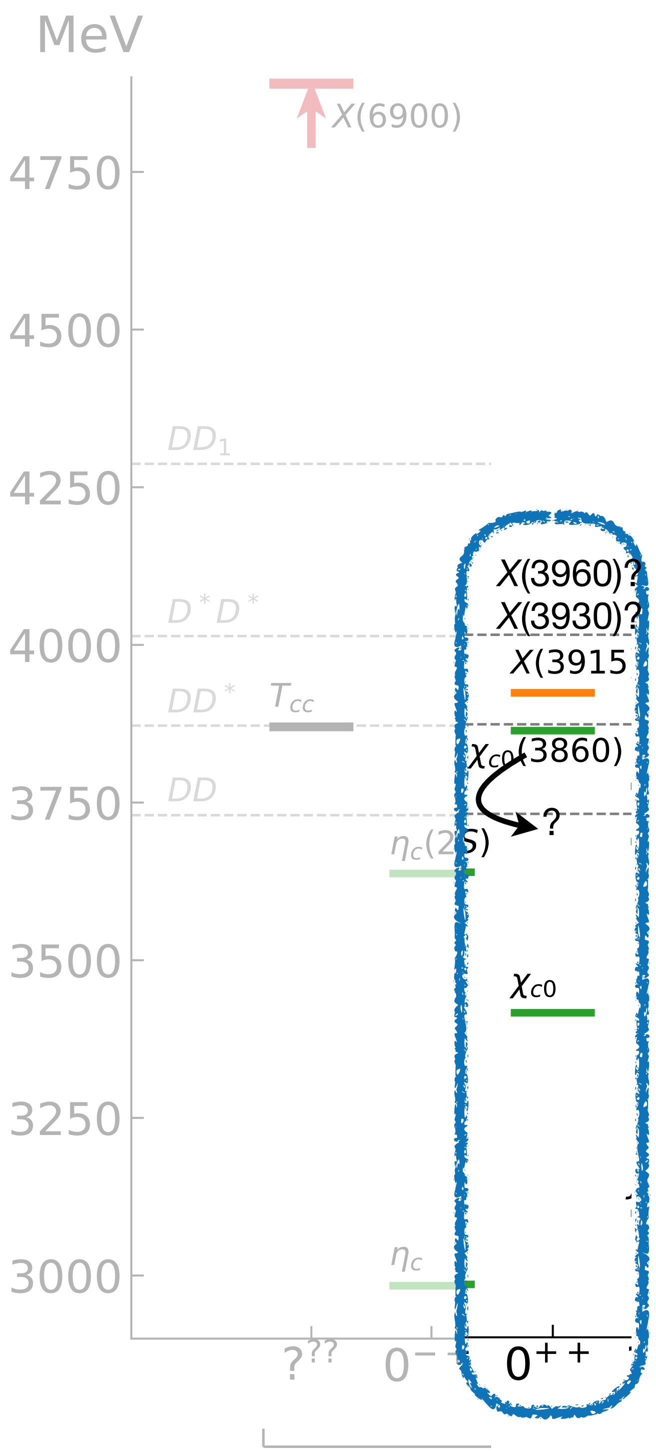
- different physical sheet pole
- no obvious nearby (+,+,+,-) sheet pole (there are some with a_t E >0.74)

Results from Prelovsek, Padmanath et al, suggest effects at DDbar and DsDsbar thresholds

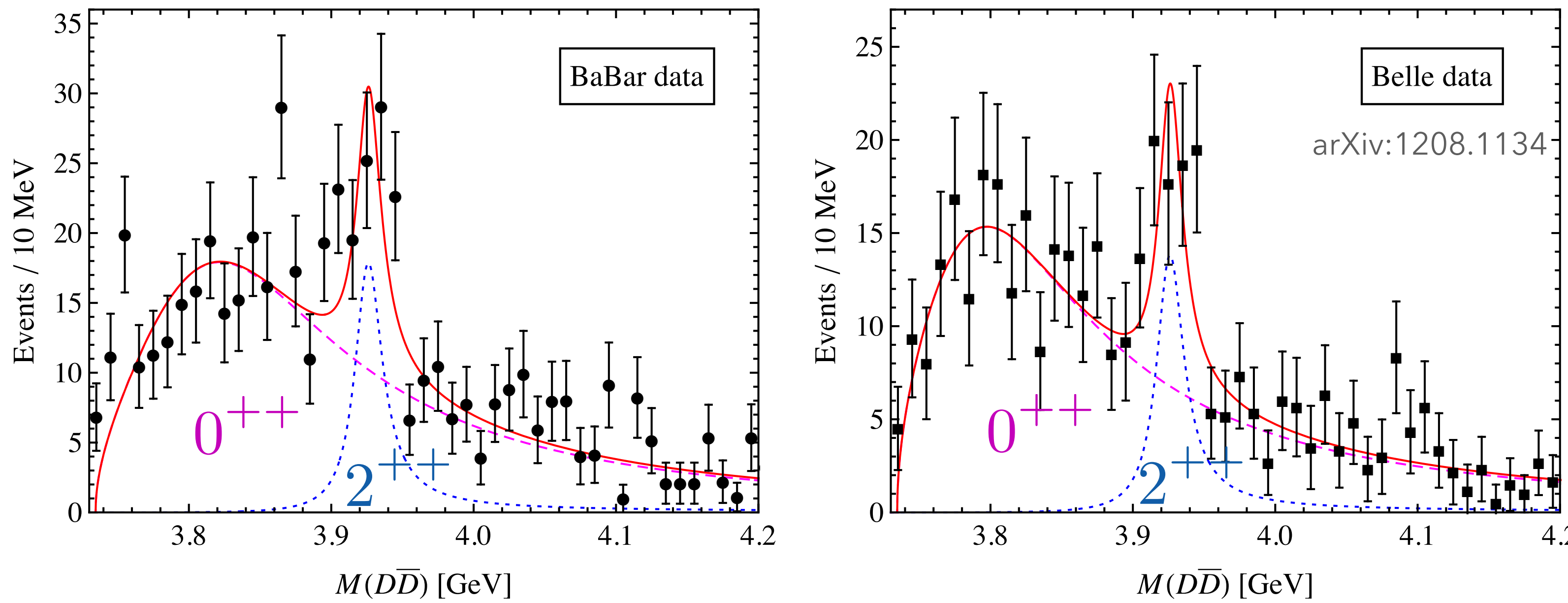
- pion mass ~ 280 MeV
- light quark heavier than physical, strange quark lighter than physical

hard to justify such a large change due to the light quark mass (no one-pion-exchange term)



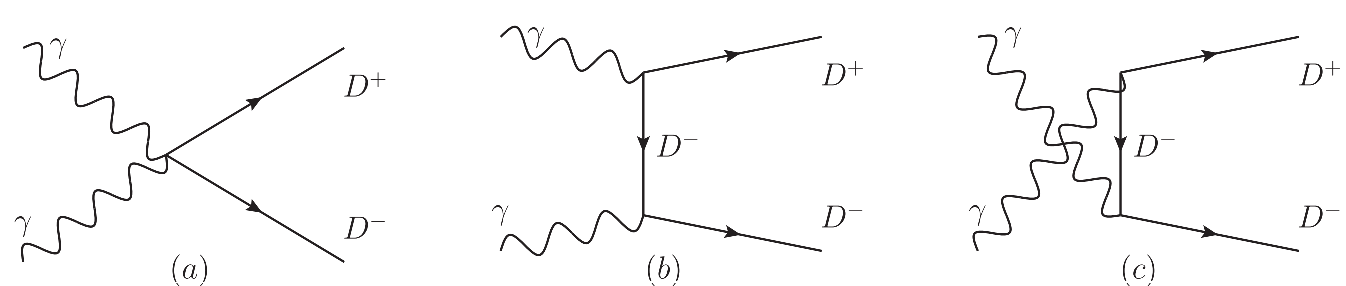


- BaBar, Belle - resonance around 3860 MeV $\gamma\gamma \to D\bar{D}$



- Guo & Meissner (2012)
m = 3840 MeV, Γ = 220 MeV

- Wang et al (2021), Daneika et al (2022):
Complications from Born exchanges lead to a lower state around 3700 MeV



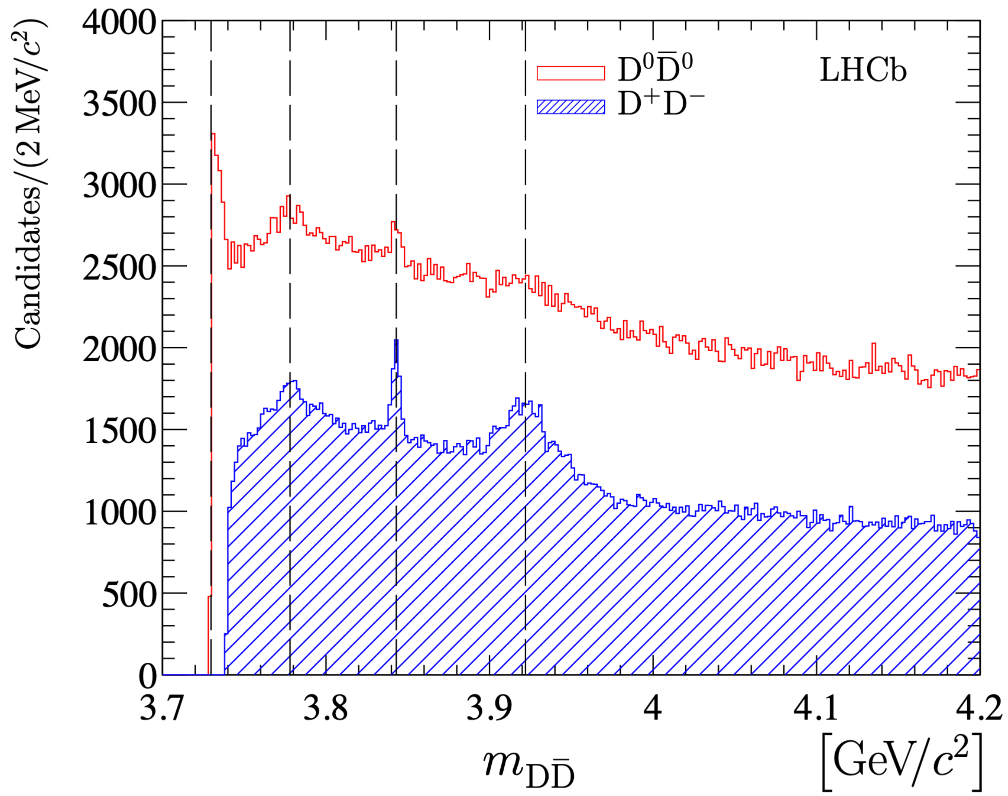
arXiv:2010.15431

no state around 3840-3860 MeV (?)

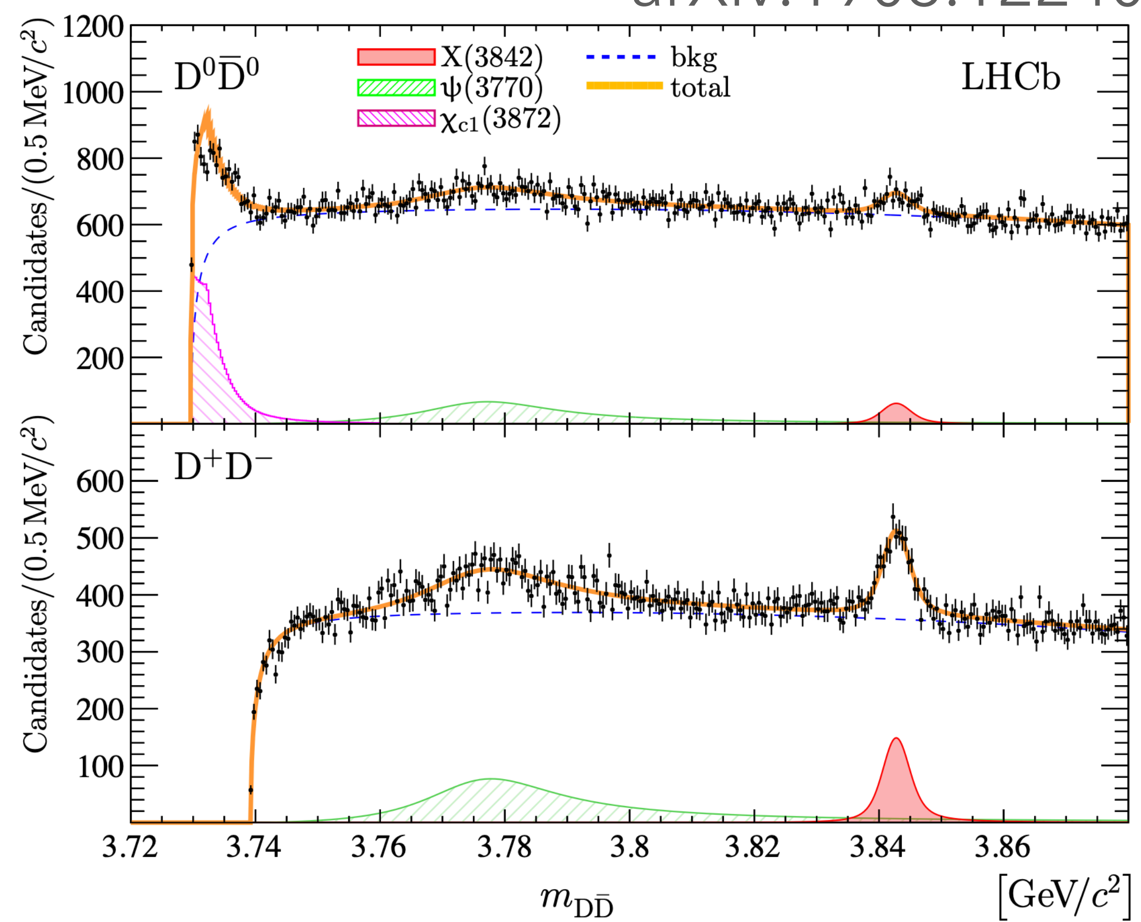
Many models with meson-meson components find strong effects in S-wave DDbar

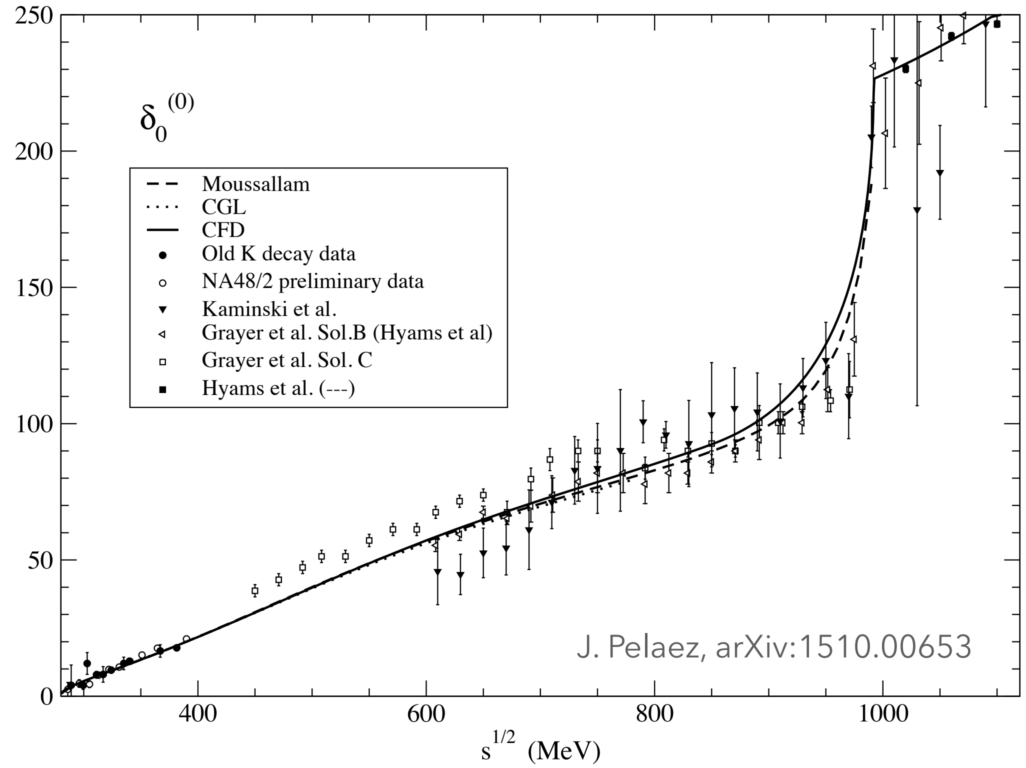
Several suggestions of a near-threshold state in DDbar scattering
- $\gamma\gamma$ to DDbar (BaBar, Belle)
- near threshold structure partly due to Born/t-channel photon exchange
- see e.g. Guo & Meißner 2012, Wang et al 2021, Deineka et al 2022

Recent LHCb analyses find a peak at DDbar threshold but attribute this to "feed-down" from X(3872) decays

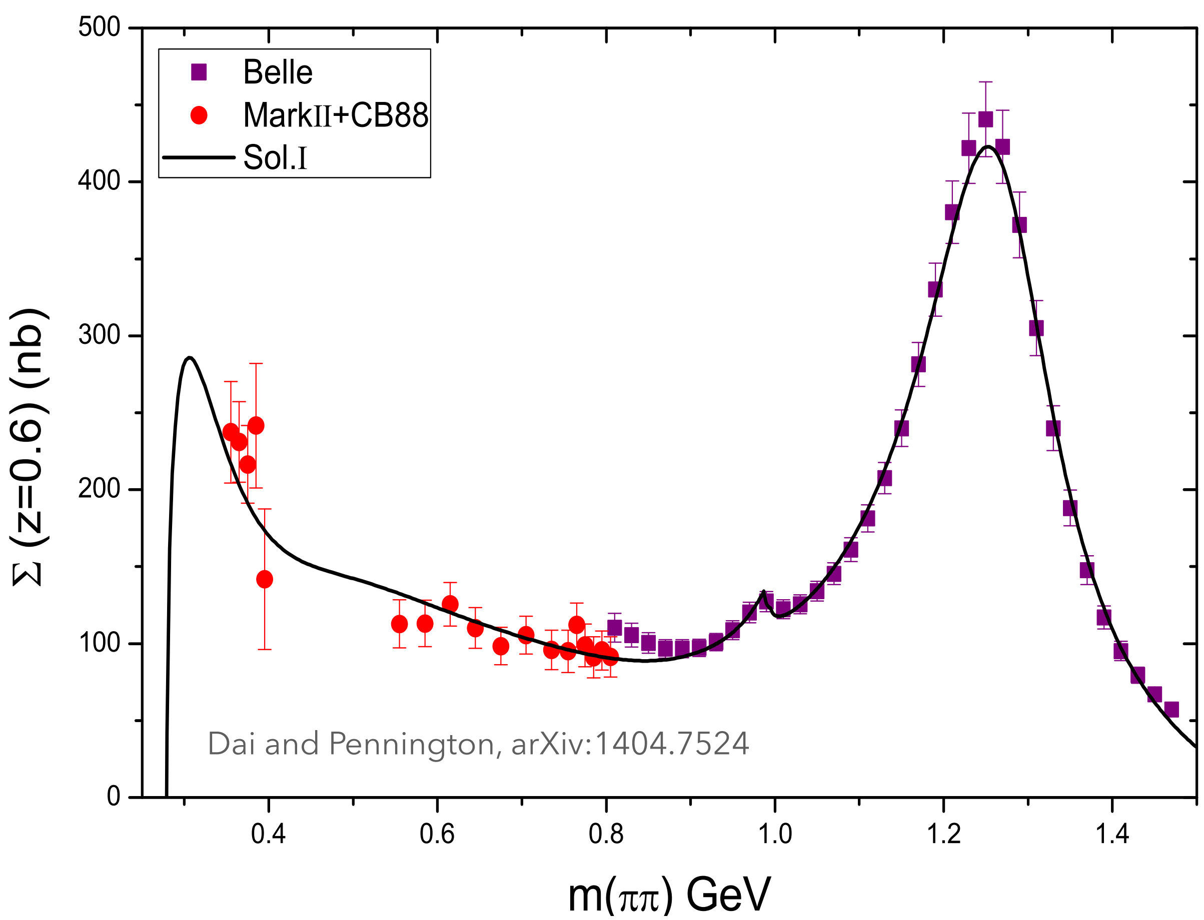


arXiv:1903.12240

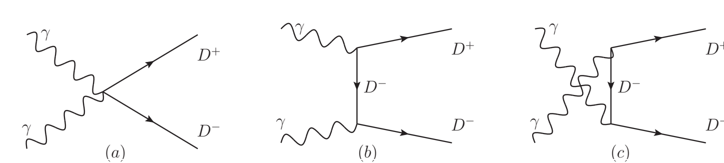




$$\pi\pi \to \pi\pi \quad (S-\text{wave})$$



$$\gamma\gamma \to \pi\pi$$



extra structure at threshold, not linked to a resonance or bound state