D-wave dimeson resonance interpretation to the $Z_c/Z_{cs}/Z_b$ states

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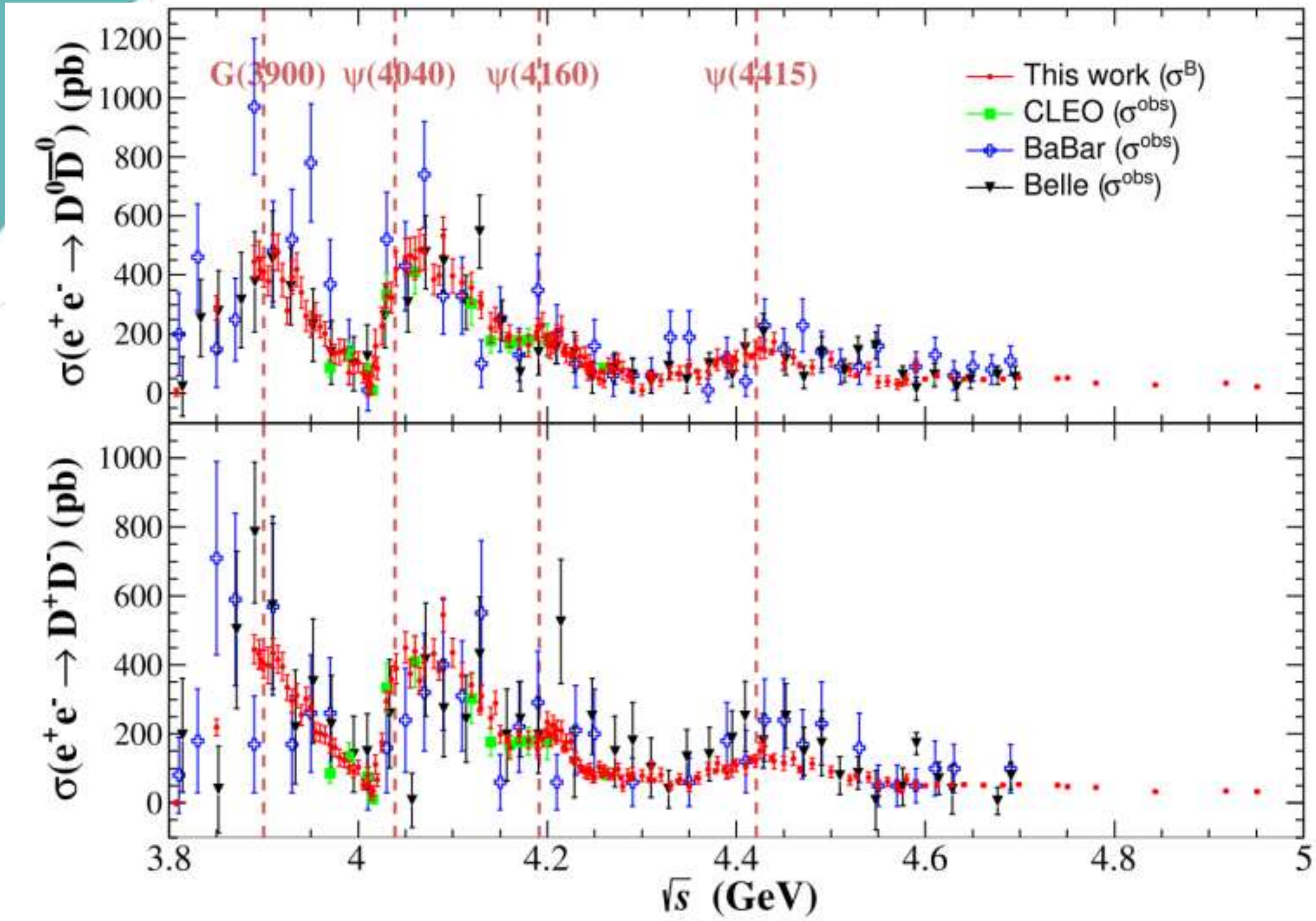
Outline

- Motivation
- Theoretical framework
- Numerical results and discussions

Motivation



Observation of $G(3900)$ [1]
Consistent with previous measurements[2-4]

[1]. LHCb, PHYSICAL REVIEW LETTERS 133, 081901(2024)
[2]. BABAR, Phys. Rev. D 76, 111105 (2007)
[3]. BABAR, arXiv:0710.1371
[4]. BELLE, Phys. Rev. D 77, 011103 (2008)

Possible interpretations:
Threshold effect [5]
Interference effects [6-8]
Final state interaction [9]
P-wave resonance [10,11,...]

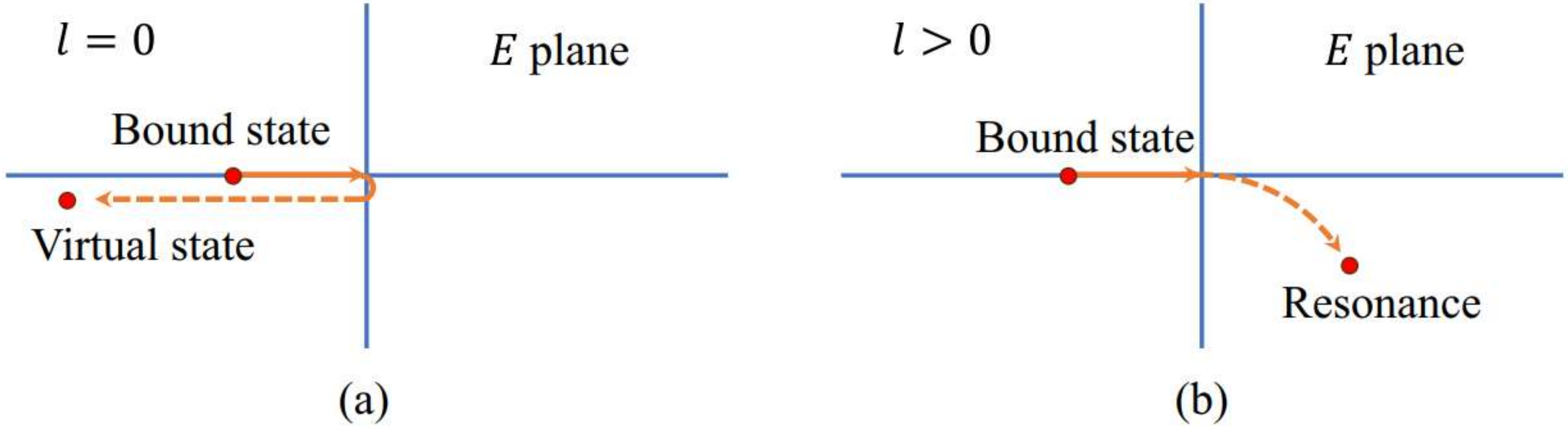
[5].Y, Huang, X. R. Chen, arXiv: 2509.06353
[6]. E. Eichten, K. Gottfried, T. Kinoshita, K. D. Lane and T. M. Yan, Phys. Rev. D 21, 203 (1980).
[7]. N. Hüsken, R. F. Lebed, R. E. Mitchell, E. S. Swanson, Y. Q. Wang and C. Z. Yuan, Phys. Rev. D 109, no.11, 114010 (2024).
[8]. Y. J. Zhang and Q. Zhao, Phys. Rev. D 81, 034011 (2010).
[9]. S. G. Salnikov and A. I. Milstein, Phys. Rev. D 109, no.11, 114015 (2024).
[10]. Z. Y. Lin, J. Z. Wang, J. B. Cheng, L. Meng and S. L. Zhu, Phys. Rev. Lett. 133, no.24, 241903 (2024).
[11]. M. L. Du, U. G. Meißner and Q. Wang, Phys. Rev. D 94, no.9, 096006 (2016)…

$G(3900)$: Possible P-wave resonance?

Mass: $3872.2 \pm 14.2 \pm 3.0$ MeV

Width: $179.7 \pm 14.1 \pm 7.0$ MeV

Very close to the $D\bar{D}^*$ threshold



[1]. Z. Y. Lin, J. Z. Wang, J. B. Cheng, L. Meng, S. L. Zhu, PHYSICAL REVIEW LETTERS 133, 241903 (2024)
[2]. J. R. Taylor, Scattering Theory: The Quantum Theory of Nonrelativistic Collisions

State	$I^G(J^{PC})$	Mass	Width	Threshold
$Z_c(3900)^{\pm}$[1]	$1^+(1^{+-})$	3887 ± 3	28 ± 3	$D\bar{D}^*(3876)$
$Z_c(4020)^{\pm}$[1]	$1^+(?^{?-})$	4024 ± 2	13 ± 5	$D^*\bar{D}^*(4017)$
$Z_b(10610)^0$[1]	$1^+(1^{+-})$	10607 ± 2	18 ± 2	$B\bar{B}^*(10604)$
$Z_b(10650)^0$[1]	$1^+(1^{+-})$	10652 ± 2	12 ± 2	$B^*\bar{B}^*(10650)$
State	$I(J^P)$	Mass	Width	Threshold
$Z_{cs}(4000)^+$[2]	$\frac{1}{2}(1^+)$	4003^{+7}_{-15}	131 ± 30	$D_s\bar{D}^* + D_s^*\bar{D}(3977)$
$Z_{cs}(4220)^+$[2]	$\frac{1}{2}(1^+)$	4216^{+49}_{-38}	233^{+110}_{-90}	$D_s^*\bar{D}^*(4121)$

[1] Prog. Theor. Exp. Phys. 2022, 083C01 (2022).
[2] Phys. Rev. Lett. 127, 082001 (2021).

Possible interpretations: Molecular state, virtual state, tetraquark, kinematical effects (cusp effect, rescattering effect).

$$J^{PC} = 1^{+-} \quad {}^3S_1 \quad {}^3D_1 \; ?$$

Framework

$$V_{\text{Cont}} = V\left(\boldsymbol{F}_1, \boldsymbol{F}_2, \boldsymbol{\sigma}_1, \boldsymbol{\sigma}_2, \boldsymbol{p}, \boldsymbol{p}'\right) \qquad V_{\text{Cont}} = \left(\boldsymbol{F}_1 \cdot \boldsymbol{F}_2\right) \tilde{V}\left(\boldsymbol{\sigma}_1, \boldsymbol{\sigma}_2, \boldsymbol{p}, \boldsymbol{p}'\right)$$

Effective potential

$$\begin{aligned}
V_{\text{Cont}} &= \left(\boldsymbol{F}_1 \cdot \boldsymbol{F}_2\right) \tilde{V}\left(\boldsymbol{\sigma}_1, \boldsymbol{\sigma}_2, \boldsymbol{p}, \boldsymbol{p}'\right) \\
&= \left(\boldsymbol{F}_1 \cdot \boldsymbol{F}_2\right)\left(V_{\text{Cont}}^{(0)} + V_{\text{Cont}}^{(2)} + V_{\text{Cont}}^{(4)}\right), \\
V_{\text{Cont}}^{(0)} &= C_S + C_T \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2, \\
V_{\text{Cont}}^{(2)} &= C_1 \boldsymbol{q}^2 + C_2 \boldsymbol{k}^2 + \sum_{i=3}^{7} C_i \mathcal{O}_i, \\
V_{\text{Cont}}^{(4)} &= D_1 \boldsymbol{q}^4 + D_2 \boldsymbol{k}^4 + D_3 \boldsymbol{q}^2 \boldsymbol{k}^2 + D_4 \left(\boldsymbol{q} \times \boldsymbol{k}\right)^2 \\
&\quad + \sum_{j=5}^{15} D_j \mathcal{O}'_j,
\end{aligned}$$

E. Epelbaum, W. Glockle and U. G. Meissner, Nucl. Phys. A 747, 362-424 (2005).

$$\left|{}^{s}_{I}[D^{(*)}\bar{D}^{*}]^{L}_{J}, c\right\rangle$$

L: angular momentum
s: total spin
J: total angular momentum
I: total isospin
c: C-parity

Effective potential

$$\begin{aligned}
V_{|{}^{s}_{I}[D^{(*)}\bar{D}^{*}]^{S}_{J},c\rangle} &= \left\langle {}^{s}_{I}[D^{(*)}\bar{D}^{*}]^{S}_{J}, c\right| V_{\mathrm{Cont}} \left|{}^{s}_{I}[D^{(*)}\bar{D}^{*}]^{S}_{J}, c\right\rangle \\
&= \underline{\tilde{C}_{|{}^{s}_{I}[D^{(*)}\bar{D}^{*}]^{S}_{J},c\rangle}} + C_{|{}^{s}_{I}[D^{(*)}\bar{D}^{*}]^{S}_{J},c\rangle}\left(p^2+p'^2\right) \\
&\quad + D^{1}_{|{}^{s}_{I}[D^{(*)}\bar{D}^{*}]^{S}_{J},c\rangle} p^2 p'^2 + D^{2}_{|{}^{s}_{I}[D^{(*)}\bar{D}^{*}]^{S}_{J},c\rangle}\left(p^4+p'^4\right), \\
V_{|{}^{s}_{I}[D^{(*)}\bar{D}^{*}]^{P}_{J},c\rangle} &= \left\langle {}^{s}_{I}[D^{(*)}\bar{D}^{*}]^{P}_{J}, c\right| V_{\mathrm{Cont}} \left|{}^{s}_{I}[D^{(*)}\bar{D}^{*}]^{P}_{J}, c\right\rangle \\
&= \underline{C_{|{}^{s}_{I}[D^{(*)}\bar{D}^{*}]^{P}_{J},c\rangle} pp'} + D_{|{}^{s}_{I}[D^{(*)}\bar{D}^{*}]^{P}_{J},c\rangle} pp'\left(p^2+p'^2\right), \\
V_{|{}^{s}_{I}[D^{(*)}\bar{D}^{*}]^{D}_{J},c\rangle} &= \left\langle {}^{s}_{I}[D^{(*)}\bar{D}^{*}]^{D}_{J}, c\right| V_{\mathrm{Cont}} \left|{}^{s}_{I}[D^{(*)}\bar{D}^{*}]^{D}_{J}, c\right\rangle \\
&= \underline{D_{|{}^{s}_{I}[D^{(*)}\bar{D}^{*}]^{D}_{J},c\rangle} p^2 p'^2},
\end{aligned}$$

Only include Lowest order contribution

Effective potential

$$V_{|{}^1_1[D\bar{D}^*]^S_1,-\rangle} = g_0^{D\bar{D}^*},$$
$$V_{|{}^1_1[D\bar{D}^*]^D_1,-\rangle} = g_2^{D\bar{D}^*} p^2 p'^2,$$
$$V_{|{}^1_0[D\bar{D}^*]^P_1,-\rangle} = g_1^{D\bar{D}^*} p p'.$$

$$g_0^{D\bar{D}^*} = 4\pi (C_S - C_T),$$
$$g_2^{D\bar{D}^*} = \frac{\pi}{90}(192D_1 + 12D_2 - 48D_3 - 48D_4 - 192D_5 - 12D_6 + 48D_7 + 48D_8 - 72D_9 + 18D_{10} - 176D_{11} + 44D_{12} + 44D_{13} - 11D_{14} - 40D_{15}),$$
$$g_1^{D\bar{D}^*} = \frac{\pi}{3}(-8C_1 + 2C_2 + 8C_3 - 2C_4 + 2C_5 - 4C_6 + C_7).$$

Heavy quark symmetry

$$V_{|D\bar{D}^*,{}^3S_1,+\rangle} \leftrightarrow V_{|D^*\bar{D}^*,{}^5S_2,+\rangle},$$
$$V_{|D\bar{D}^*,{}^3S_1,-\rangle} \leftrightarrow V_{|D^*\bar{D}^*,{}^3S_1,-\rangle},$$

$$V_{|D\bar{D}^*,{}^3D_1,-\rangle} \leftrightarrow V_{|D^*\bar{D}^*,{}^3D_1,-\rangle},$$

$$V_{|D\bar{D}^*,{}^3D_2,+\rangle} \leftrightarrow V_{|D^*\bar{D}^*,{}^3D_2,+\rangle},$$
$$V_{|D\bar{D}^*,{}^3D_3,-\rangle} \leftrightarrow V_{|D^*\bar{D}^*,{}^3D_3,-\rangle},$$

$$V_{|D\bar{D}^*,{}^3P_0,+\rangle} \leftrightarrow V_{|D^*\bar{D}^*,{}^3P_0,+\rangle},$$
$$V_{|D\bar{D}^*,{}^3P_1,-\rangle} \leftrightarrow V_{|D^*\bar{D}^*,{}^3P_1,-\rangle},$$

$$V_{|D\bar{D}^*,{}^3P_2,+\rangle} \leftrightarrow V_{|D^*\bar{D}^*,{}^3P_2,+\rangle},$$

Lippmann-Schwinger equation (LSE)

$$T(\boldsymbol{p},\boldsymbol{p}') = V(\boldsymbol{p},\boldsymbol{p}') + \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} \frac{V(\boldsymbol{p},\boldsymbol{q})\, T(\boldsymbol{q},\boldsymbol{p}')}{E - \frac{\boldsymbol{q}^2}{2\mu} + i\epsilon}$$

Two types of FF

$$F_\Lambda(p) = \exp\left(-\frac{p^2}{\Lambda^2}\right)$$

$$F_\Lambda(p) = \theta(\Lambda - p)\left(1 - \frac{p^2}{\Lambda^2}\right)$$

$\Lambda = 0.5$ GeV

Bound/virtual states:

$$1 - g_L^{D\bar{D}^*} \mu_{D\bar{D}^*} G_{2L}(k) = 0,$$

Resonance:

$$\mathrm{Re}\left(1 - g_L^{D\bar{D}^*} \mu_{D\bar{D}^*} G_{2L}(k)\right) = 0,$$

$$\mathrm{Im}\left(1 - g_L^{D\bar{D}^*} \mu_{D\bar{D}^*} G_{2L}(k)\right) = 0,$$

Relating $D^{(*)}\bar{D}^{(*)}$ to $B^{(*)}\bar{B}^{(*)}$

$$
\begin{aligned}
1 - g_L^{D\bar{D}^*}\mu_{D\bar{D}^*}G_{2L}(k) &= 0,\\
1 - g_L^{B\bar{B}^*}\mu_{B\bar{B}^*}G_{2L}(k) &= 0,
\end{aligned}
$$

$$
\begin{aligned}
\mu_{D\bar{D}^*}E^R_{D\bar{D}^*} &= \mu_{B\bar{B}^*}E^R_{B\bar{B}^*},\\
\mu_{D\bar{D}^*}\Gamma_{D\bar{D}^*} &= \mu_{B\bar{B}^*}\Gamma_{B\bar{B}^*}.
\end{aligned}
$$

$$
g_L^{D\bar{D}^*}\mu_{D\bar{D}^*} = g_L^{B\bar{B}^*}\mu_{B\bar{B}^*},
$$

$$
\frac{g_L^{D\bar{D}^*}}{g_L^{B\bar{B}^*}} = \frac{\mu_{B\bar{B}^*}}{\mu_{D\bar{D}^*}},
$$

State	Mass	Width	Threshold
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$Z_b(10610)^0$	10607 ± 2	18 ± 2	$B\bar{B}^*(10604)$
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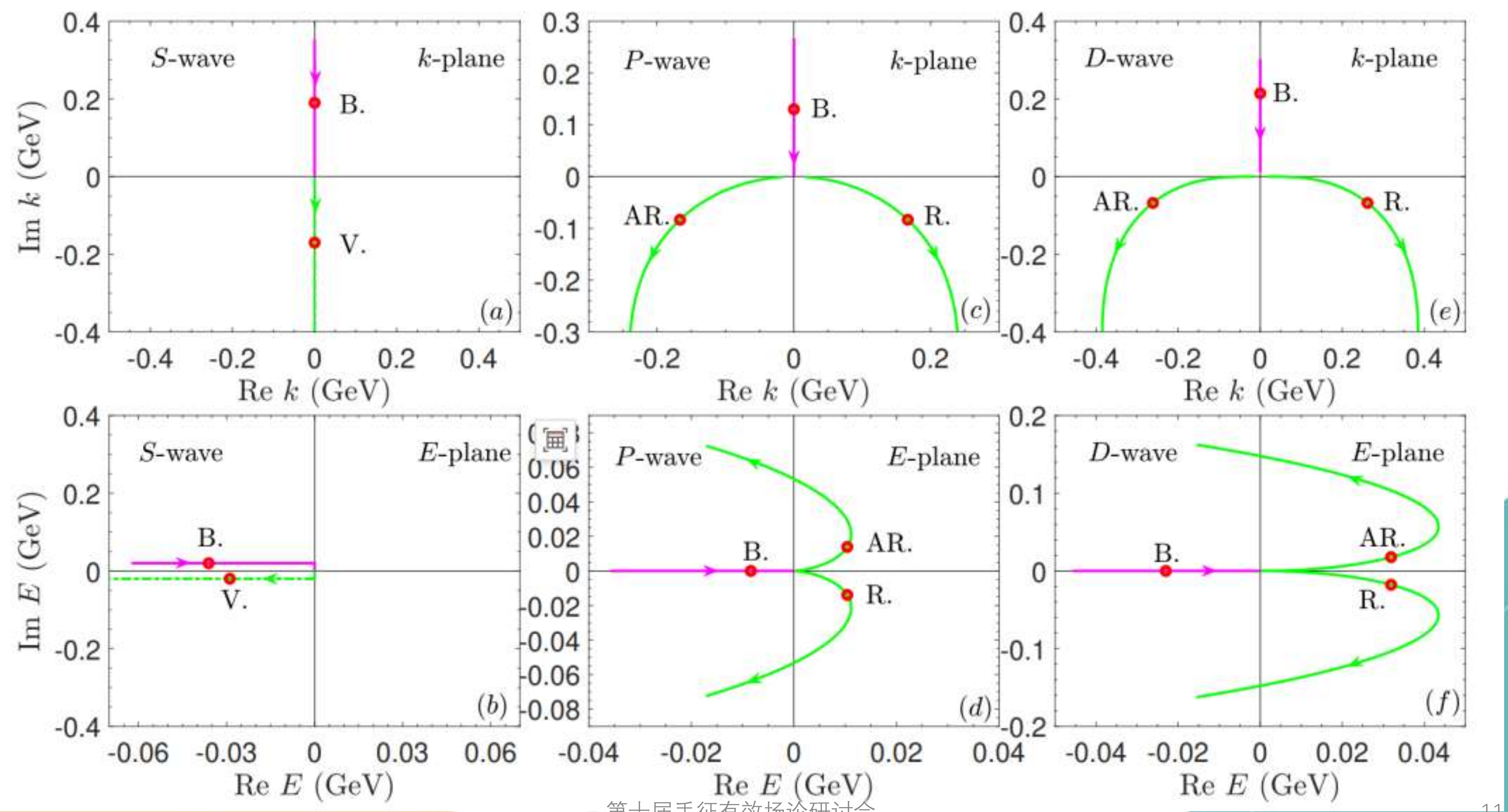
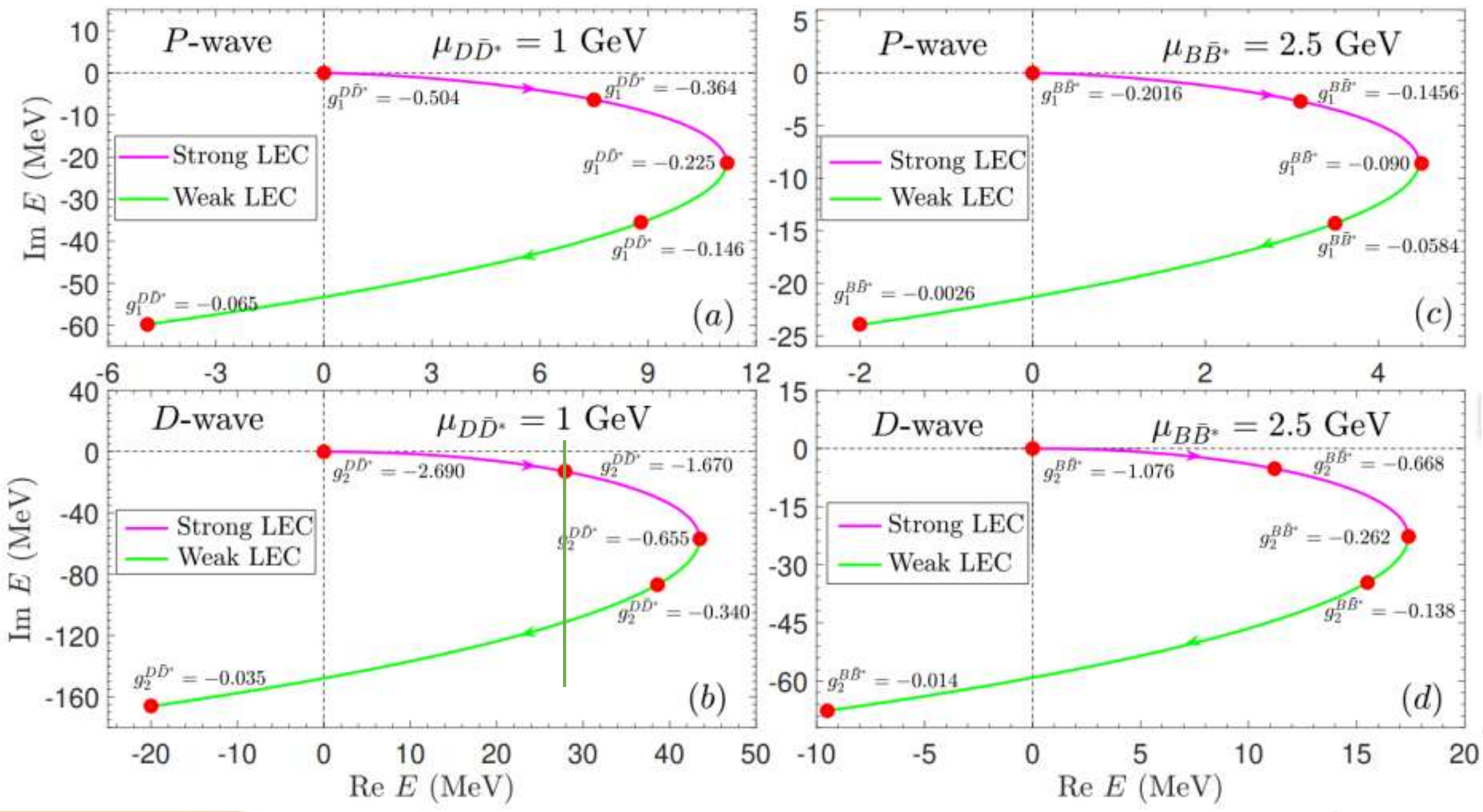
S/P/D-wave pole trajectories



Numerical results and discussion



Results for P-wave resonance

$G(3900)$ Exp:

Mass: $3872.2 \pm 14.2 \pm 3.0$ MeV

Width: $179.7 \pm 14.1 \pm 7.0$ MeV

	Model I ($g_1^{D\bar{D}^*} = -72.7^{+31.5}_{-131.5}$ GeV^{-4})		Model II ($g_1^{D\bar{D}^*} = -58.6^{+33.8}_{-270.4}$ GeV^{-4})	
State	Mass (MeV)	Width (MeV)	Mass (MeV)	Width (MeV)
$\vert{}^1_0[D\bar{D}^*]^P_1, -\rangle$	$^\dagger 3872.5 \pm 14.5$	$119.0^{+30.8}_{-65.9}$	$^\dagger 3872.5 \pm 14.5$	$125.4^{+51.6}_{-85.4}$
$\vert{}^1_0[D^*\bar{D}^*]^P_1, -\rangle$	4014.0 ± 14.0	$114.8^{+27.6}_{-63.7}$	$4014.0^{+12.2}_{-14.1}$	$120.8^{+50.7}_{-82.3}$
$\vert{}^1_0[B\bar{B}^*]^P_1, -\rangle$	10603.1 ± 5.3	$43.4^{+11.3}_{-24.0}$	$10603.1^{+4.6}_{-5.3}$	$45.8^{+19.2}_{-31.2}$
$\vert{}^1_0[B^*\bar{B}^*]^P_1, -\rangle$	10648.3 ± 5.3	$43.2^{+11.2}_{-23.9}$	$10648.3^{+4.6}_{-5.3}$	$45.6^{+19.0}_{-31.1}$

1. $D^*\bar{D}^*$ partner of $G(3900)$

$\psi(4040)$ [a]

$I^G(J^{PC}) = 0^-(1^{--})$

[a] J^{PC} known by production in e^+e^- via single photon annihilation. I^G is not known; interpretation of this state as a single resonance is unclear because of the expectation of substantial threshold effects in this energy region.

2. $B^{(*)}\bar{B}^*$ partner of $G(3900)$

Also predicted within the OBE [1,2]

1. J. Z. Wang, Z. Y. Lin, J. B. Cheng, L. Meng and S. L. Zhu, arXiv:2505.02742
2. Z. P. Wang, F. L. Wang, G. J. Wang and X. Liu, arXiv:2505.03647

Results for D-wave resonance

	Model I ($g_2^{D\bar{D}^*} = -2.274^{+0.600}_{-0.503}$ 10^3 GeV^{-6})		Model II ($g_2^{D\bar{D}^*} = 7.640^{+5.460}_{-5.210}$ 10^3 GeV^{-6})		Exp.	
	Mass (MeV)	Width (MeV)	Mass (MeV)	Width (MeV)	Mass (MeV)	Width (MeV)
$D\bar{D}^*$	$^\dagger 3890.8 \pm 15.0$	$6.4^{+22.7}_{-6.4}$	$^\dagger 3890.8 \pm 15.0$	$11.0^{+51.6}_{-11.0}$	3887.1 ± 2.6	28.4 ± 2.6
$D^*\bar{D}^*$	$4031.6^{+14.4}_{-14.5}$	$6.0^{+22.1}_{-6.0}$	$4031.6^{+14.4}_{-14.5}$	$10.5^{+49.9}_{-10.5}$	4024.1 ± 1.9	13 ± 5
$B\bar{B}^*$	10609.8 ± 5.5	$2.3^{+8.3}_{-2.3}$	10609.8 ± 5.5	$4.0^{+18.8}_{-4.0}$	10607.2 ± 2.0	18.4 ± 2.4
$B^*\bar{B}^*$	10655.0 ± 5.5	$2.2^{+8.4}_{-2.2}$	10655.0 ± 5.5	$4.0^{+18.8}_{-4.0}$	10652.2 ± 1.5	11.5 ± 2.2
	Model I ($g_2^{D\bar{D}_s^*} = -0.164^{+0.072}_{-0.065}$ 10^3GeV^{-6})		Model II ($g_2^{D\bar{D}_s^*} = -0.033^{+0.029}_{-0.225}$ 10^3GeV^{-6})		Exp.	
	Mass (MeV)	Width (MeV)	Mass (MeV)	Width (MeV)	Mass (MeV)	Width (MeV)
$D\bar{D}_s^*$	$^\dagger 4003.0^{+7.2}_{-15.2}$	$234.8^{+41.5}_{-26.0}$	$^\dagger 4003.0^{+7.2}_{-15.4}$	$294.2^{+196.6}_{-131.6}$	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$
$D^*\bar{D}_s^*$	$4144.7^{+6.9}_{-14.5}$	$226.5^{+39.9}_{-25.3}$	$4144.7^{+6.9}_{-14.6}$	$283.6^{+189.6}_{-126.8}$	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$
$B\bar{B}_s^*$	$10702.5^{+2.7}_{-5.6}$	$87.2^{+15.4}_{-9.7}$	$10702.5^{+2.7}_{-5.6}$	$109.3^{+73.0}_{-48.9}$		
$B^*\bar{B}_s^*$	$10749.4^{+2.7}_{-5.6}$	$86.8^{+15.4}_{-9.6}$	$10749.4^{+2.7}_{-5.6}$	$108.8^{+72.6}_{-48.7}$		

Thanks for your attention!