The identification of the new state Y(3872) as the P-wave $D\bar{D}^*/\bar{D}D^*$ resonance

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Based on arXiv: 2403.01727

Together with Zi-Yang Lin, Jian-Bo Cheng, Lu Meng
and **Prof. Shi-Lin Zhu** (PKU)

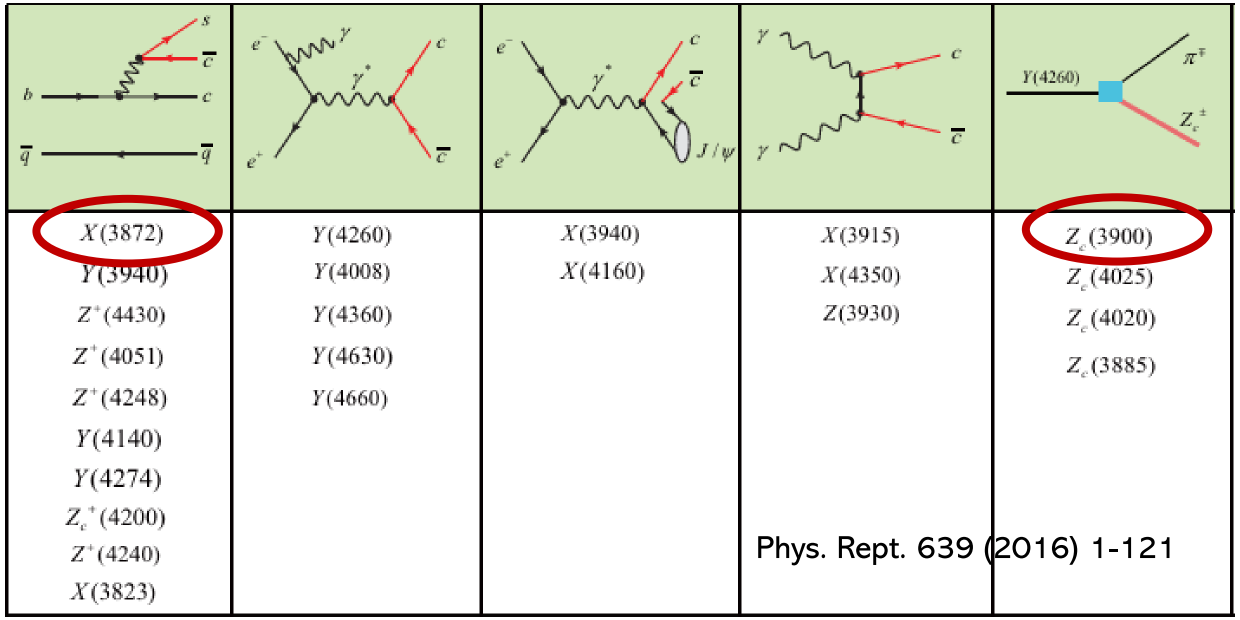
2024.04.26 电子科技大学@成都

Outline

- The background of the vector charmoniumlike state around 3.9 GeV

- The unified description of doubly charmed molecules X(3872), T_{cc}^{+}, $Z_c(3900)$ and Y(3872)

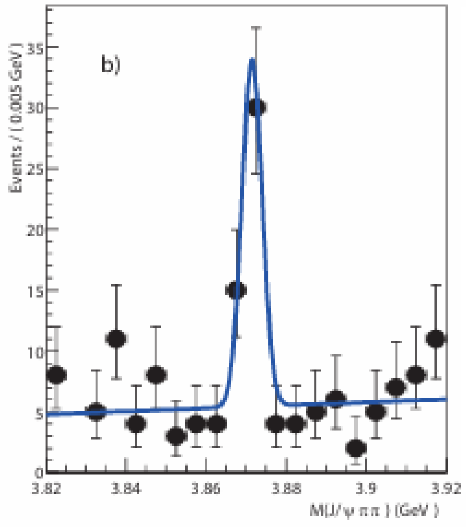
- Predictions for more P-wave $D\bar{D}^*$ resonances

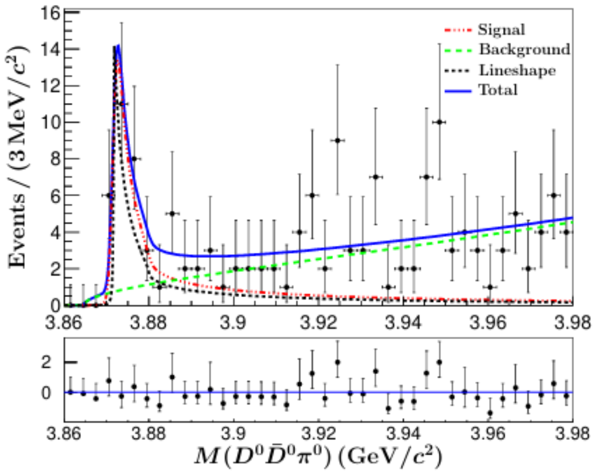


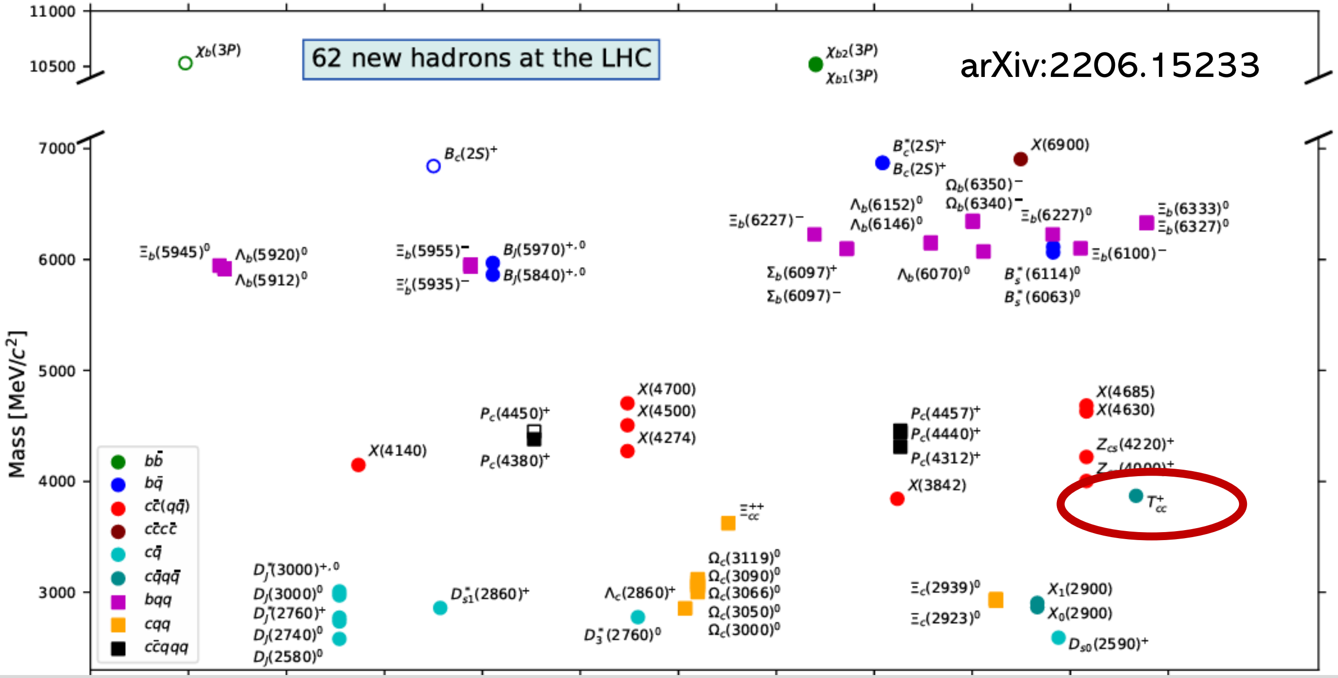
Phys. Rept. 639 (2016) 1-121

X(3872)

Phys. Rev. Lett. 91 (2003) 262001
Phys. Rev. Lett. 132 (2024) 15, 151903

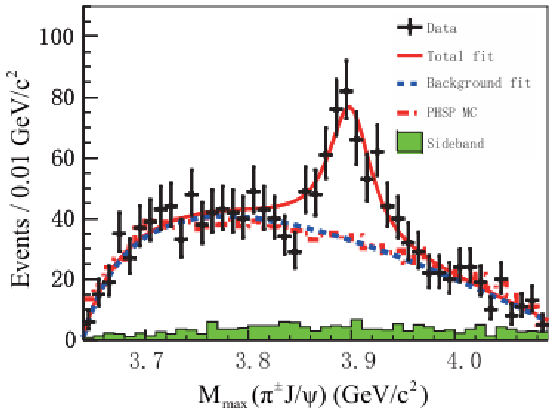






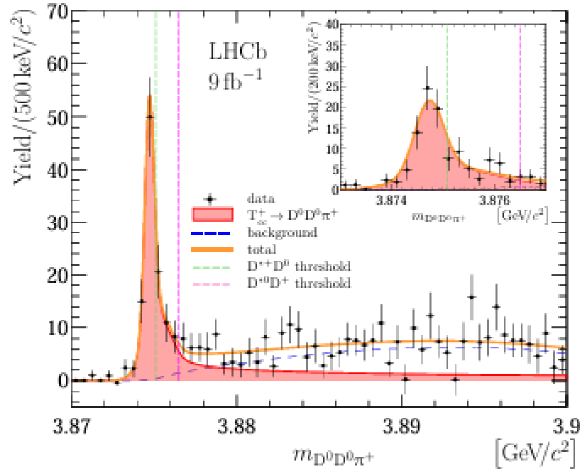
arXiv:2206.15233

Zc(3900)



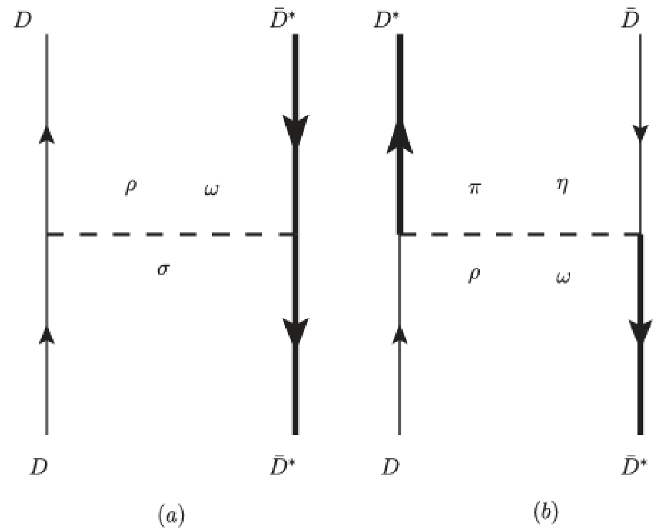
Phys. Rev. Lett. 110 (2013) 252001

Tcc

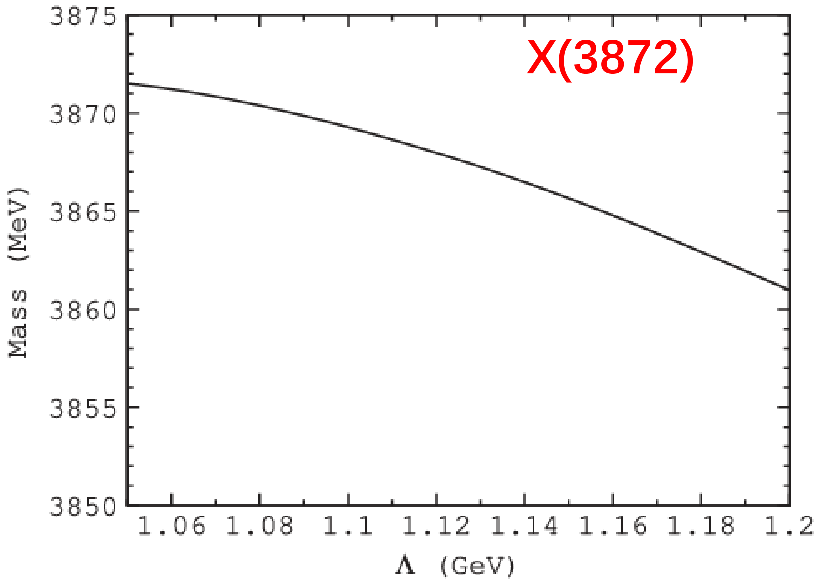


Nature Commun. 13 (2022) 3351

The one-boson exchange model



N. Li and S.-L. Zhu Phys. Rev. D 86, 074022 (2012)



The prediction for the existence of T_{cc}^{+}

N. Li, Z.-F. Sun, X. Liu, and S.-L. Zhu Phys. Rev. D 88,114008 (2013)

TABLE IV. The numerical results for the $D^{(*)}D^{(*)}$ system. "∗ ∗ ∗" means the corresponding state does not exist due to symmetry while "· · ·" means there does not exist binding energy with the cutoff parameter less than 3.0 GeV. The binding energies for the states $D^{(*)}D^{(*)}[I(J^P) = 0(1^+)]$ and $D^{(*)}D^{(*)}[I(J^P) = 1(1^+)]$ are relative to the threshold of DD^* while that of the state $D^{(*)}D^{(*)}[I(J^P) = 1(0^+)]$ is relative to the DD threshold.

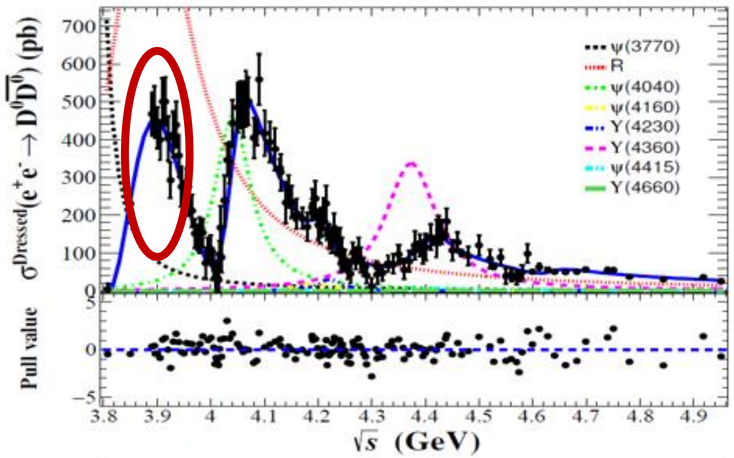
			$D^{(*)}D^{(*)}$							
I	J^P		OPE				OBE			
	0^+		∗ ∗ ∗				∗ ∗ ∗			
		Λ (GeV)	1.05	1.10	1.15	1.20	0.95	1.00	1.05	1.10
		B.E. (MeV)	1.24	4.63	11.02	20.98	0.47	5.44	18.72	42.82
		M (MeV)	3874.61	3871.22	3864.83	3854.87	3875.38	3870.41	3857.13	3833.03
		$r_{\rm rms}$ (fm)	3.11	1.68	1.12	0.84	4.46	1.58	0.91	0.64
0	1^+	P_1 (%)	96.39	92.71	88.22	83.34	97.97	92.94	85.64	77.88
		P_2 (%)	0.73	0.72	0.57	0.42	0.58	0.55	0.32	0.15
		P_3 (%)	2.79	6.45	11.07	16.11	1.41	6.42	13.97	21.91
		P_4 (%)	0.08	0.13	0.14	0.13	0.04	0.09	0.08	0.05

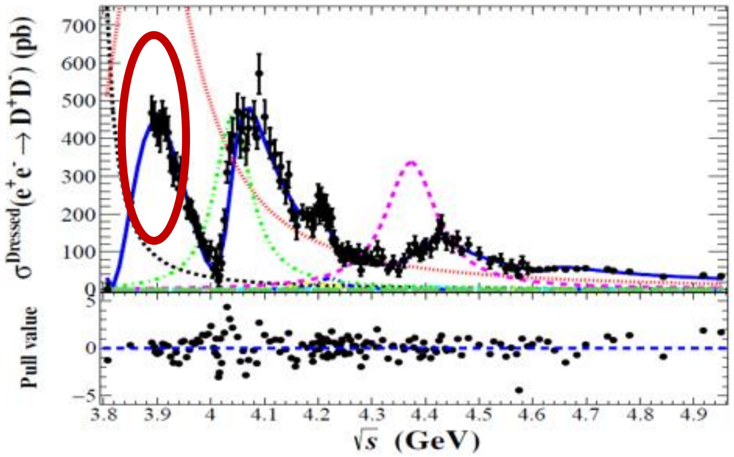
Precise Measurement of Born Cross Sections for $e^+e^- \to D\bar{D}$ and Observation of One Structure between $\sqrt{s} = 3.80 - 4.95$ GeV

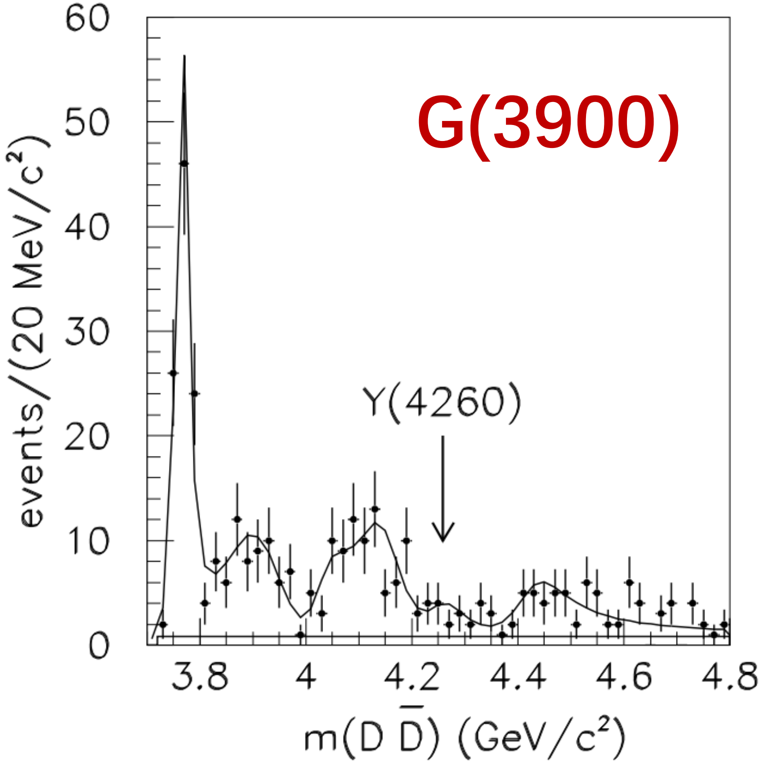
(BESIII Collaboration)

arXiv: 2402.03829

The charmoniumlike state with $J^{PC} = 1^{--}$







(BaBar Collaboration),
Phys. Rev. D **76**, 111105 (2007),

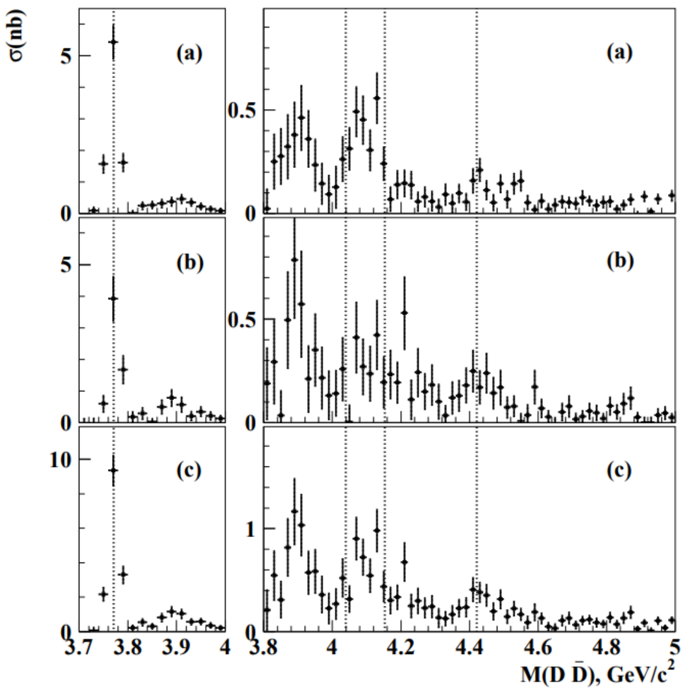


FIG. 3: The exclusive cross sections for: (a) $e^+e^- \to D^0\bar{D}^0$; (b) $e^+e^- \to D^+D^-$; (c) $e^+e^- \to D\bar{D}$. The dotted lines correspond to the $\psi(3770)$, $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$ masses [20].

(Belle Collaboration),
Phys. Rev. D 77, 011103 (2008)

Mass: $3872.5 \pm 14.2 \pm 3.0$ MeV

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

$S(\sigma) > 20$

A P-wave $D\bar{D}^*$ molecule?

PHYSICAL REVIEW D VOLUME 21, NUMBER 1 1 JANUARY 1980

Charmonium: Comparison with experiment

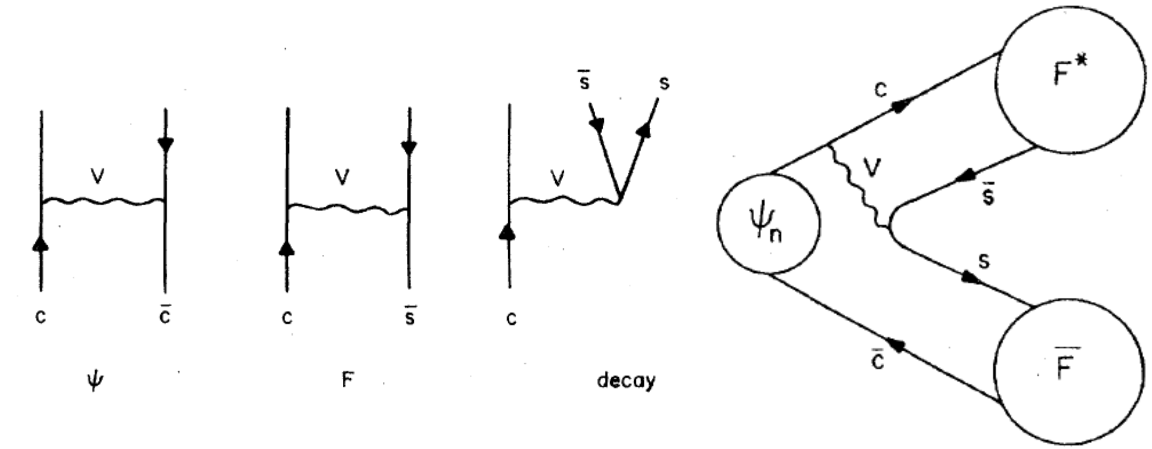
E. Eichten,* K. Gottfried, T. Kinoshita, K. D. Lane,* and T. M. Yan
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853

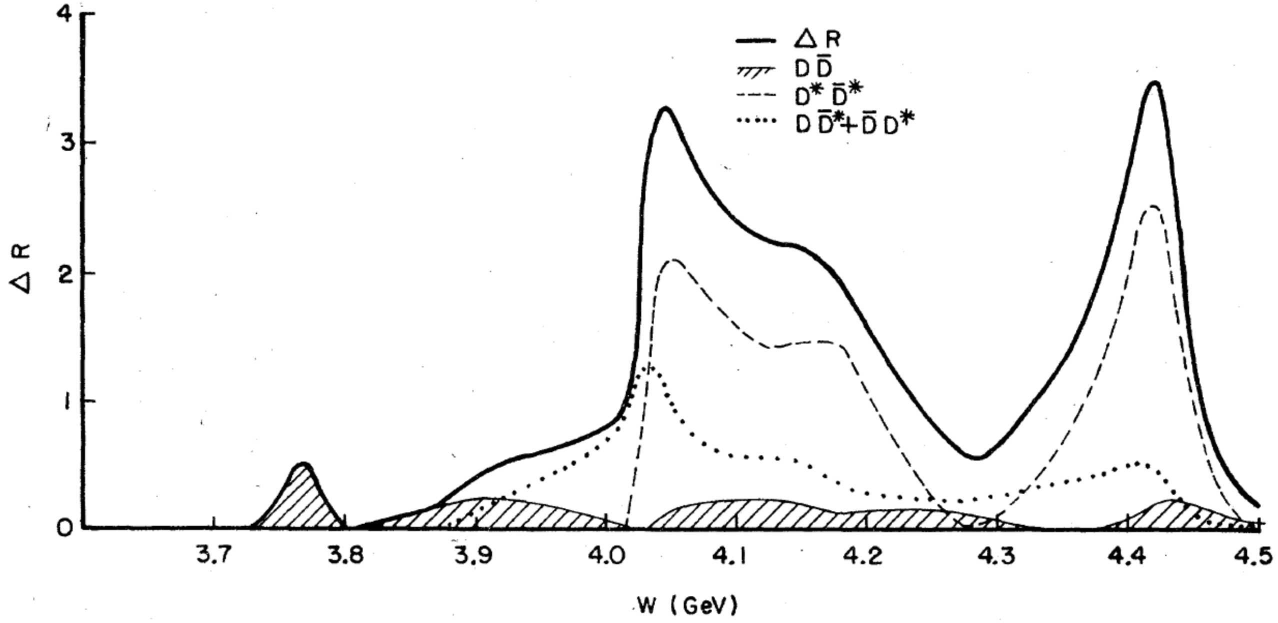
(Received 25 June 1979)

The charmonium model, formulated in detail in an earlier publication, is compared in a comprehensive fashion with the data on the ψ family. The parameters of the "naive" model, in which the system is described as a $c\bar{c}$ pair, are determined from the observed positions of ψ, ψ', and the P states. The model then yields a successful description of the spectrum of spin-triplet states above the charm threshold. It also accounts for the ratio of the leptonic widths of ψ' and ψ. When the $c\bar{c}$ potential is applied to the Υ family, it accounts, without any readjustment of parameters, for the positions of the $2S$ and $3S$ levels and for the leptonic widths of Υ and Υ' relative to that of ψ. The model does not give acceptable values of the absolute leptonic widths, a shortcoming which is ascribed to large quantum-chromodynamic corrections to the van Royen–Weisskopf formula. The calculated $E1$ rates are about twice the values observed in the ψ family. This naive model is also extended with considerable success to mesons composed of one heavy and one light quark. A significant extension of the model is achieved by incorporating coupling to charmed-meson decay channels. This gives a satisfactory understanding of $\psi(3772)$ as the 1^3D_1 $c\bar{c}$ state, mixed via open and closed decay channels to 2^3S. The model has decay amplitudes that are oscillatory functions of the decay momentum; these oscillations are a direct consequence of the radial nodes in the $c\bar{c}$ parent states. These amplitudes provide a qualitative understanding of the observed peculiar branching ratios into various charmed-meson channels near the resonance at 4.03 GeV, which is assigned to 3^3S. The coupling of the $c\bar{c}$ states below the charm threshold to closed decay channels modifies the bound states and leads to reduction of about 20% in $E1$ rates in comparison to those of the naive model.

$$V(r) = -\frac{\kappa}{r} + \frac{r}{a^2}\,,$$

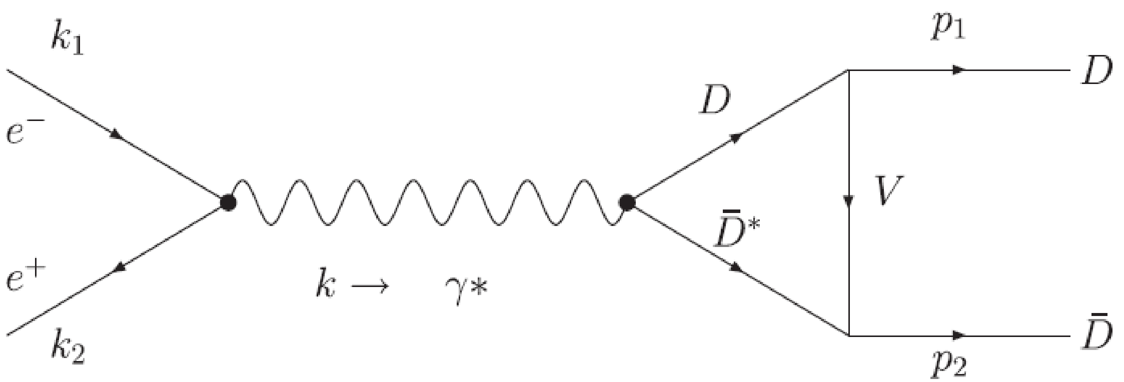
$$H_I = \frac{3}{8}\sum_{a=1}^{8}\int :\rho_a(\vec{r})V(\vec{r}-\vec{r}\,')\rho_a(\vec{r}\,'):d^3r\,d^3r'\,, \tag{3.1}$$

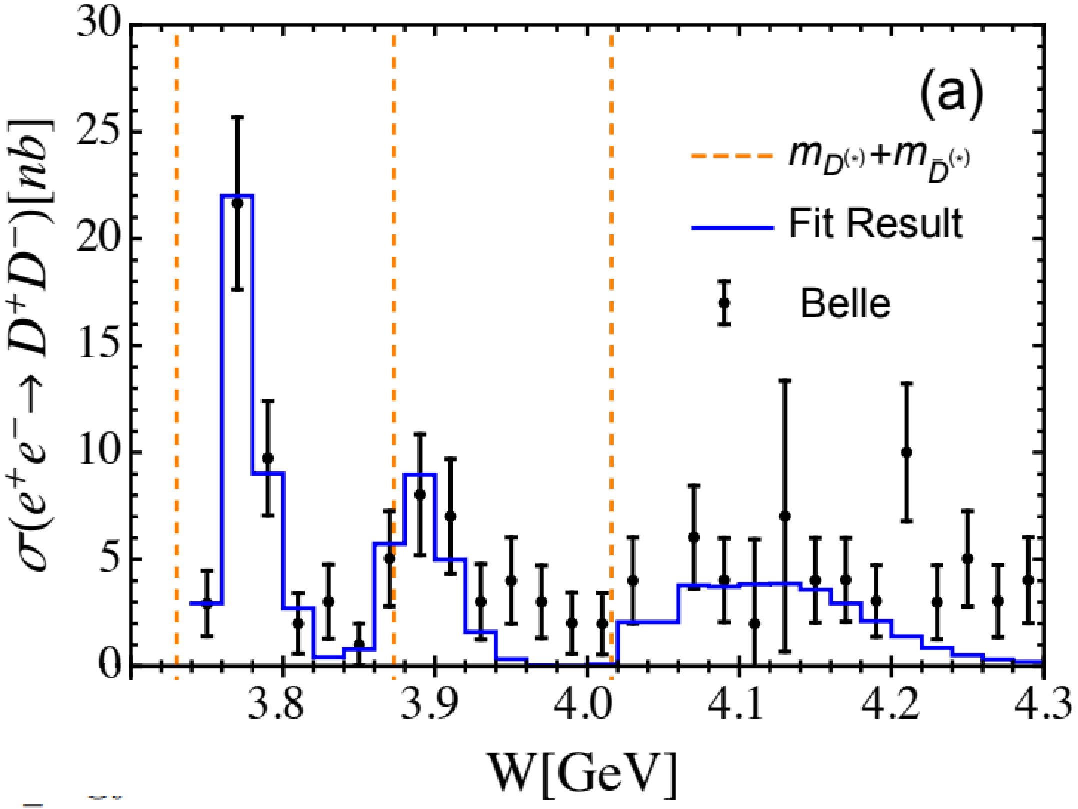




The $D\bar{D}^*$ threshold effect

Y.J. Zhang and Q. Zhao, Phys. Rev. D 81, 034011 (2010)





The pole from the coupled channel effect

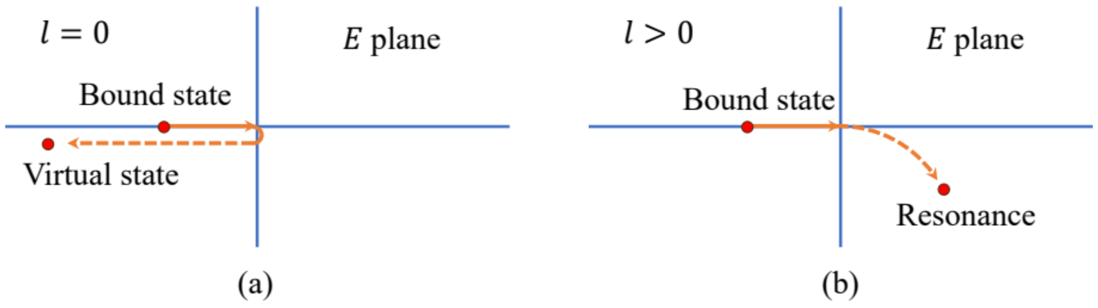
$$\psi(2S),\ \psi(3S),\ \psi(1D),\ \psi(2D) \bigotimes D\bar{D},\ D\bar{D}^* + c.c.,\ D^*\bar{D}^*_{s=0}$$

M.L. Du, U. G. Meissner and Q. Wang Phys. Rev. D 94 (2016) 9, 096006

Sheet	Poles (GeV)	$\lvert g_{D\bar{D}}\rvert$	$\lvert g_{D\bar{D}^*}\rvert$	$\lvert g_{D^*\bar{D}^*_{s=0}}\rvert$	$\lvert g_{D^*\bar{D}^*_{s=2}}\rvert$
II	$3.764 \pm i0.006$	13.53	9.48	5.88	16.78
III	$3.879 \pm i0.035$	4.40	10.96	7.63	18.15
IV	$4.034 \pm i0.014$	2.90	2.23	12.52	12.85

The dynamical calculation of the P-wave $D\bar{D}^*$ interaction

By applying the OBE model, the $D\bar{D}^*$ interaction can be restricted by the S-wave $X(3872)$ or T_{cc}, so the prediction on the corresponding P-wave molecular states should be reliable.



J. R. Taylor, Scattering Theory: The Quantum Theory of Nonrelativistic Collision

Heavy meson Lagrangians

$$
\begin{aligned}
\mathcal{L} =\; & g_s \mathrm{Tr}\left[\mathcal{H}\sigma\bar{\mathcal{H}}\right] + i g_a \mathrm{Tr}\left[\mathcal{H}\gamma_\mu\gamma_5\mathcal{A}^\mu\bar{\mathcal{H}}\right] \\
& + i\beta \mathrm{Tr}\left[\mathcal{H}v_\mu(\mathcal{V}^\mu-\rho^\mu)\bar{\mathcal{H}}\right] + i\lambda \mathrm{Tr}\left[\mathcal{H}\sigma_{\mu\nu}F^{\mu\nu}\bar{\mathcal{H}}\right] \\
& + g_s \mathrm{Tr}\left[\bar{\tilde{\mathcal{H}}}\sigma\tilde{\mathcal{H}}\right] + i g_a \mathrm{Tr}\left[\bar{\tilde{\mathcal{H}}}\gamma_\mu\gamma_5\mathcal{A}^\mu\tilde{\mathcal{H}}\right] \\
& - i\beta \mathrm{Tr}\left[\bar{\tilde{\mathcal{H}}}v_\mu(\mathcal{V}^\mu-\rho^\mu)\tilde{\mathcal{H}}\right] + i\lambda \mathrm{Tr}\left[\bar{\tilde{\mathcal{H}}}\sigma_{\mu\nu}F^{\mu\nu}\tilde{\mathcal{H}}\right]
\end{aligned}
$$

OBE model $(\pi, \eta, \sigma, \rho, \omega)$

$$
\rho^\mu = \frac{i g_V}{\sqrt{2}} \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} \end{pmatrix}^\mu, \qquad \mathbb{P} = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} \end{pmatrix}.
$$

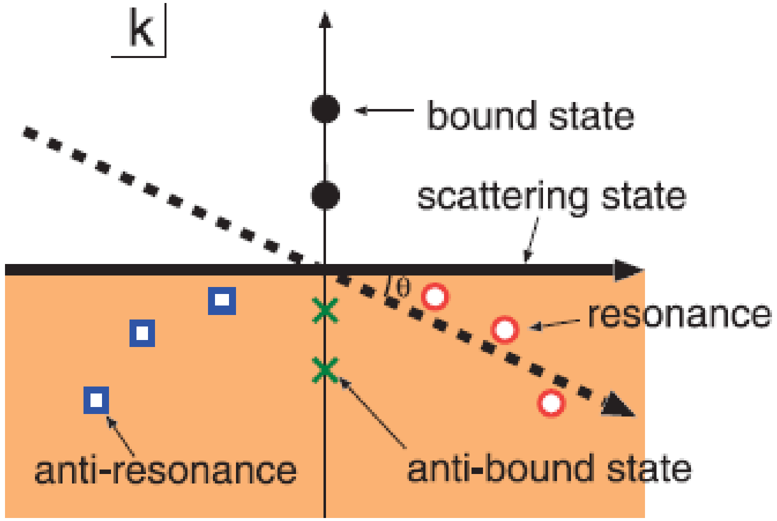
$$
\mathcal{V}^\mu = \frac{1}{2}[\xi^\dagger, \partial_\mu \xi], \quad \mathcal{A}^\mu = \frac{1}{2}\{\xi^\dagger, \partial_\mu \xi\} \qquad F^{\mu\nu} = \partial^\mu\rho^\nu - \partial^\nu\rho^\mu - [\rho^\mu, \rho^\nu]
$$

$$
\xi = \exp(i\mathbb{P}/f_\pi).
$$

Complex scaling method (CSM)

Operation: $U(\theta)r = re^{i\theta}, U(\theta)k = ke^{-i\theta}$

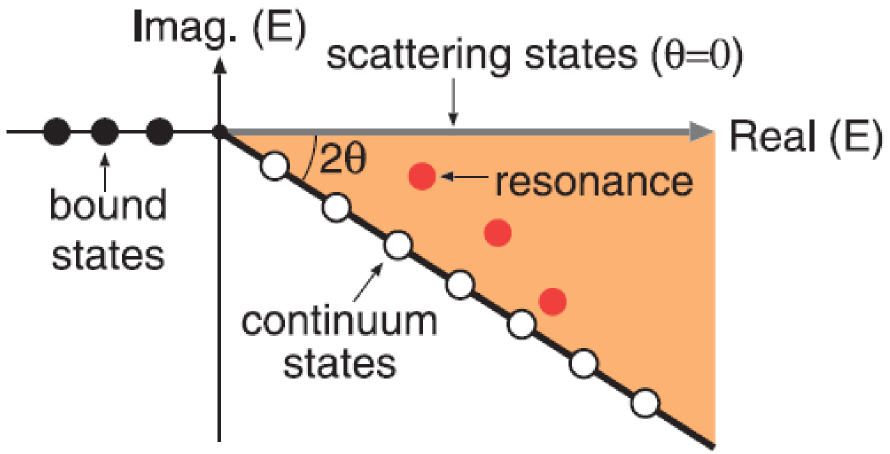
$$\left\{ \frac{\hbar^2}{2\mu}\left[-\frac{d^2}{dr^2}+\frac{l(l+1)}{r^2}\right]e^{-2i\theta}+V(re^{i\theta})\right\}\psi_l^\theta(k,r)=E(\theta)\psi_l^\theta(k,r)$$



$$\psi(r) \xrightarrow{r\to\infty} f_l^+(k)e^{-ikr}+f_l^-(k)e^{ikr},$$
$$\xrightarrow{r\to r\exp(i\theta)} f_l^+(k)e^{-ikre^{i\theta}}+f_l^-(k)e^{ikre^{i\theta}},$$

$f_l^\pm(k)$ are Jost functions.

$\mathrm{Arg}\, k_{\mathrm{res}} > -\theta$



Aguilar, Balslev and Combes (ABC theorem)
Commun. Math. Phys. 22, 269 (1971); Commun. Math. Phys. 22, 280 (1971);

Complex scaling method (CSM)

Schrödinger equation

$$\frac{\boldsymbol{k}^2}{2m}\phi(\boldsymbol{k}) + \int \frac{d^3\boldsymbol{p}}{(2\pi)^3} V(\boldsymbol{k},\boldsymbol{p})\phi(\boldsymbol{p}) = E\phi(\boldsymbol{k})$$

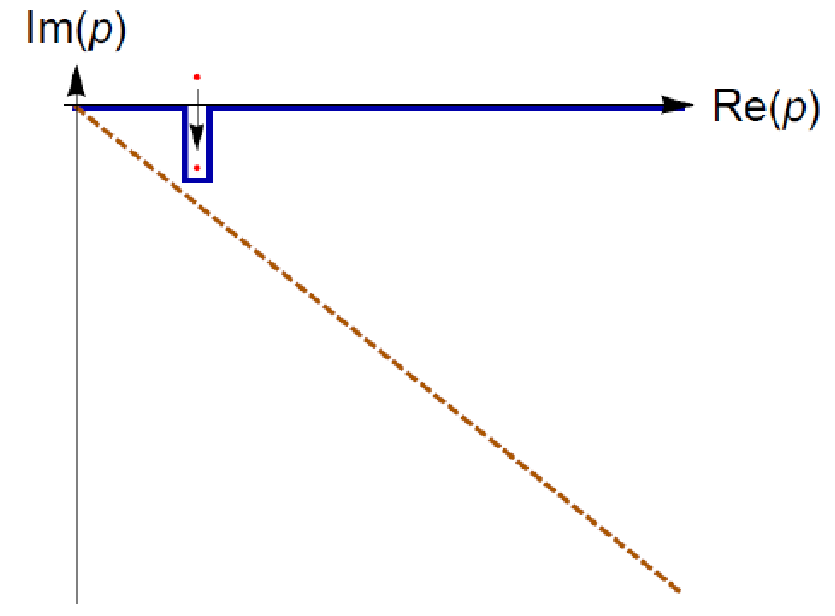
- Analytical extension of the wave function

$$\phi(\boldsymbol{k}) = \frac{1}{E_R - \frac{\boldsymbol{k}^2}{2m}} \int \frac{d^3\boldsymbol{p}}{(2\pi)^3} V(\boldsymbol{k},\boldsymbol{p})\phi(\boldsymbol{p})$$

k can be anywhere on the complex plane

p is on the integral path

- $\phi(\boldsymbol{k})$ has two poles $\quad k = \pm\sqrt{2mE_R}$



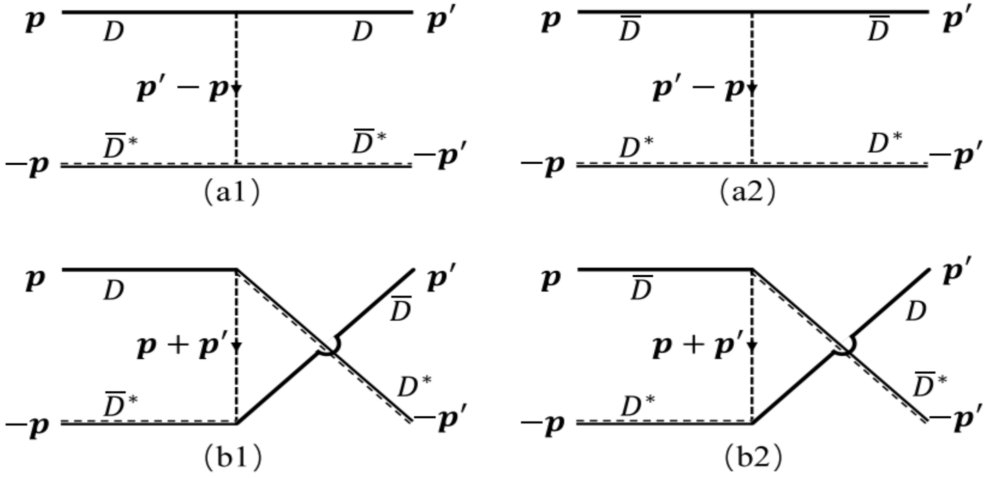
The development of CSM by our group

1. The solution to the virtual state pole

Y.K. Chen, L. Meng, Z. Y. Lin and S. L. Zhu Phys. Rev. D 109 (2024) 3, 034006

2. Complex scaled Lippmann-Schwinger equation

J.Z. Wang, Z. Y. Lin and S. L. Zhu, Phys. Rev. D 109 (2024) 7, L071505



$$V_\sigma^D(\boldsymbol{p}',\boldsymbol{p}) = -\frac{g_s^2}{\boldsymbol{q}^2+m_\sigma^2},$$

$$V_\pi^C(\boldsymbol{p}',\boldsymbol{p}) = -\frac{g^2}{2f_\pi^2}\frac{(\boldsymbol{\epsilon}\cdot\boldsymbol{k})(\boldsymbol{\epsilon}'\cdot\boldsymbol{k})}{\boldsymbol{k}^2-k_0^2+m_\pi^2}\tau\cdot\tau,$$

$$V_\eta^C(\boldsymbol{p}',\boldsymbol{p}) = -\frac{g^2}{6f_\pi^2}\frac{(\boldsymbol{\epsilon}\cdot\boldsymbol{k})(\boldsymbol{\epsilon}'\cdot\boldsymbol{k})}{\boldsymbol{k}^2-k_0^2+m_\eta^2}\mathbb{1}\cdot\mathbb{1},$$

$$V_{\rho/\omega}^D(\boldsymbol{p}',\boldsymbol{p}) = \frac{\frac{1}{4}\beta^2 g_V^2(\boldsymbol{\epsilon}\cdot\boldsymbol{\epsilon}')}{\boldsymbol{q}^2+m_{\rho/\omega}^2}\times\begin{cases}\tau\cdot\tau, & \text{for } \rho,\\ \mathbb{1}\cdot\mathbb{1}, & \text{for } \omega,\end{cases}$$

$$V_{\rho/\omega}^C(\boldsymbol{p}',\boldsymbol{p}) = \frac{\lambda^2 g_V^2}{\boldsymbol{k}^2-k_0^2+m_{\rho/\omega}^2}\{(\boldsymbol{k}\cdot\boldsymbol{\epsilon})(\boldsymbol{k}\cdot\boldsymbol{\epsilon}') -\boldsymbol{k}^2(\boldsymbol{\epsilon}\cdot\boldsymbol{\epsilon}')\}\times\begin{cases}\tau\cdot\tau, & \text{for } \rho,\\ \mathbb{1}\cdot\mathbb{1}, & \text{for } \omega,\end{cases}$$

$$|C=\pm\rangle = \frac{1}{\sqrt{2}}(|D(\boldsymbol{p})\bar{D}^*(-\boldsymbol{p})\rangle \mp |\bar{D}(\boldsymbol{p})D^*(-\boldsymbol{p})\rangle).$$

Nonlocal Regulator:

$$V(\boldsymbol{p}',\boldsymbol{p}) \to V(\boldsymbol{p}',\boldsymbol{p})\frac{\Lambda^2}{p'^2+\Lambda^2}\frac{\Lambda^2}{p^2+\Lambda^2}.$$

Partial wave decomposition of $(\boldsymbol{\epsilon}\cdot\boldsymbol{k})(\boldsymbol{\epsilon}'\cdot\boldsymbol{k})D(p',p,z)$

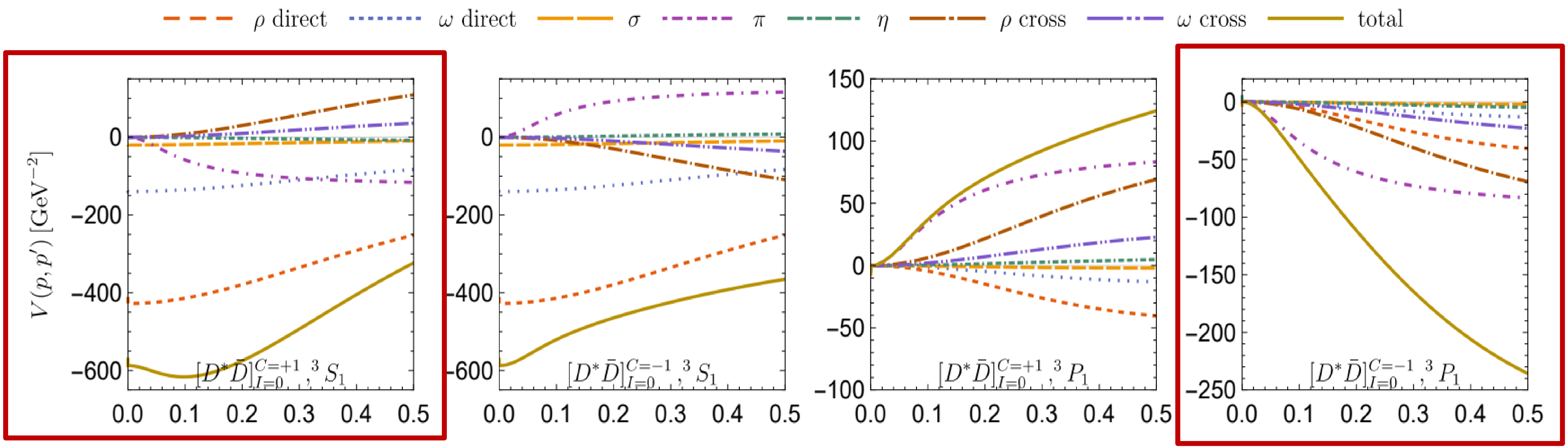
$$V_S^{J=0} = \frac{2\pi}{3}\int_{-1}^{1} D(p',p,z)(p^2+p'^2+2pp'z)dz,$$

$$V_P^{J=0} = 2\pi\int_{-1}^{1} D(p',p,z)\{(p^2+p'^2)z+pp'(1+z^2)\}dz,$$

$$V_P^{J=1} = 2\pi\int_{-1}^{1} D(p',p,z)\frac{1}{2}(z^2-1)pp'dz,$$

$$V_P^{J=2} = \frac{2\pi}{5}\int_{-1}^{1} D(p',p,z)\{2(p^2+p'^2)z + \frac{1}{2}pp'(1+7z^2)\}dz. \quad \text{(B3)}$$

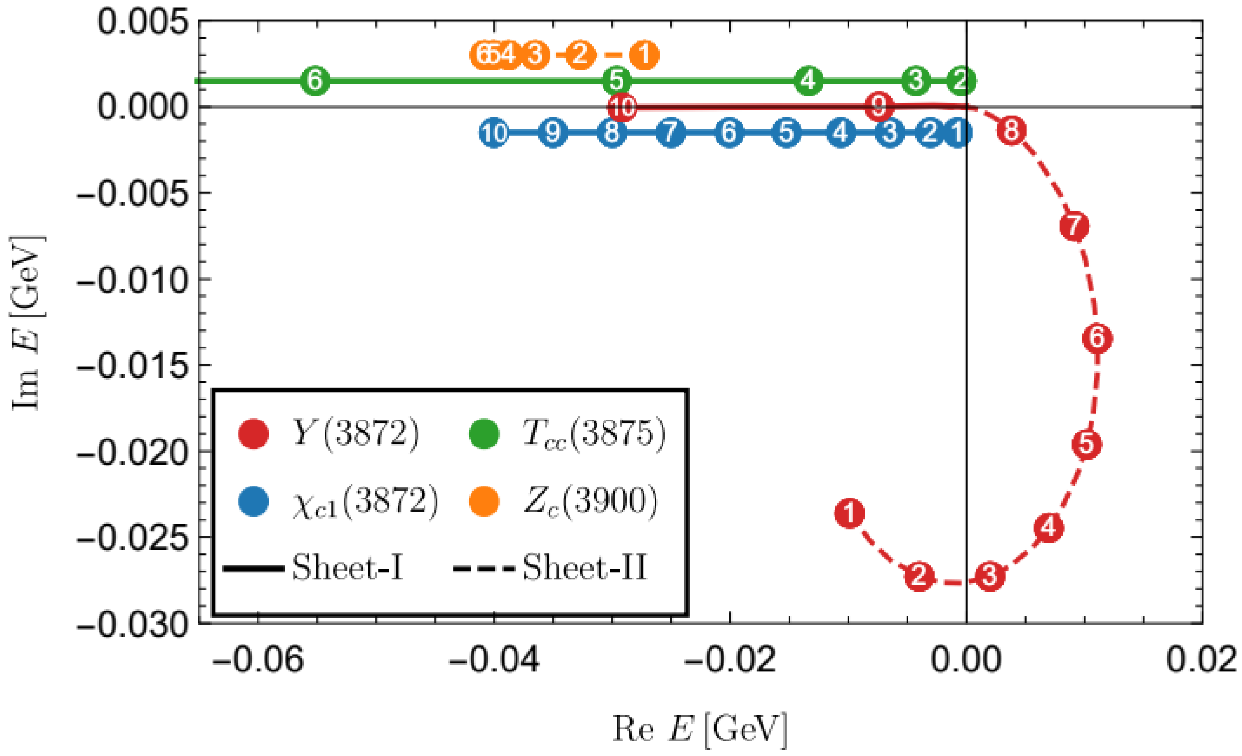
The partial-wave $D\bar{D}^*$ interaction(I=0)



$X(3872)$ (Attractive) 1^{+-} (Attractive) 1^{-+} (Repulsive) 1^{--} (Attractive)

The P-wave interaction is dominated by the long-distance pion-exchange.

The pole trajectories



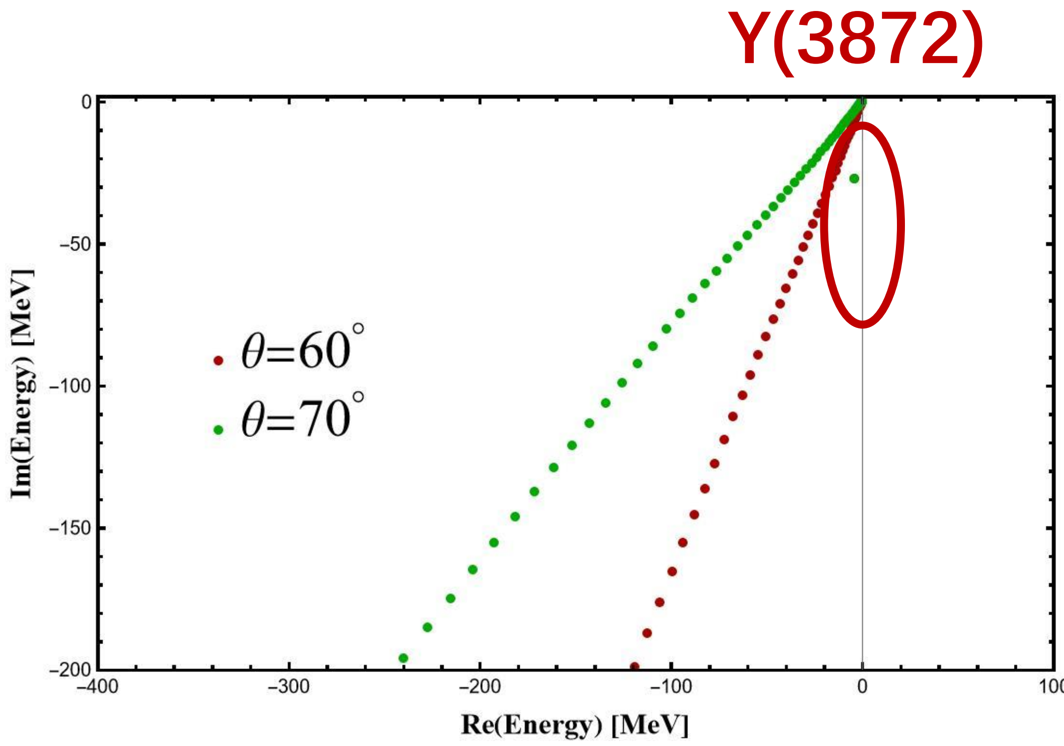


FIG. 4. The pole trajectories with the cutoff parameters correspond to $\chi_{c1}(3872)$, $T_{cc}(3875)$, $Z_c(3900)$ and the newly observed $Y(3872)$ states. The circled number 1-10 represent the increasing cutoff 0.4-1.3 GeV in order. The solid (dashed)

More P-wave $D\bar{D}^*$ molecular resonances

TABLE I. The poles in all channels of $D\bar{D}^*$ and DD^*, up to the orbital angular momentum $L = 1$. The B and V superscripts denote the bound state and the virtual state, respectively. Otherwise the pole refers to a resonance.

		$D\bar{D}^*, C=+$		$D\bar{D}^*, C=-$		DD^*	
		$I=0$	$I=1$	$I=0$	$I=1$	$I=0$	$I=1$
$\Lambda = 0.5\mathrm{GeV}$	$1^+(^3S_1)$	-3.1^B, $\chi_{c1}(3872)$	-	-1.60^B	-35.6^V, $Z_c(3900)$	-0.41^B, $T_{cc}(3875)$	-
	$0^-(^3P_0)$	$-1.5-14.5i$	-	-	-	$-9.6-9.7i$	-
	$1^-(^3P_1)$	-	-	$-4.0-27.3i$, $Y(3872)$	-	$-31.7-70.6i$	-
	$2^-(^3P_2)$	$-42.6-39.4i$	-	$-21.3-50.7i$	-	$-37.8-40.9i$	-
$\Lambda = 0.6\mathrm{GeV}$	$1^+(^3S_1)$	-6.5^B, $\chi_{c1}(3872)$	-	-5.8^B	-34.6^V, $Z_c(3900)$	-4.3^B, $T_{cc}(3875)$	-
	$0^-(^3P_0)$	$3.2-13.7i$	-	-	-	$-10.2-12.1i$	-
	$1^-(^3P_1)$	-	-	$2.0-27.3i$, $Y(3872)$	-	$-33.7-84.8i$	-
	$2^-(^3P_2)$	$-44.2-49.0i$	-	$-19.3-58.8i$	-	$-37.8-49.3i$	-

Local Regulator: $V^D(\boldsymbol{q}) \to V^D(\boldsymbol{q})\left(\frac{\Lambda^2 - m^2}{\Lambda^2 + \boldsymbol{q}^2}\right)^2, \quad V^C(\boldsymbol{k}) \to V^C(\boldsymbol{k})\left(\frac{\Lambda^2 - m^2}{\Lambda^2 + \boldsymbol{k}^2}\right)^2$

TABLE II. The poles in all channels of $D\bar{D}^*$ and DD^*, up to the orbital angular momentum $L = 1$ with the regularization in Eq. (C2). The B and V superscripts denote the bound state and the virtual state, respectively. Otherwise the pole refers to a resonance.

		$D\bar{D}^*, C = +$		$D\bar{D}^*, C = -$		DD^*	
		$I = 0$	$I = 1$	$I = 0$	$I = 1$	$I = 0$	$I = 1$
$\Lambda = 1.25$ GeV	$1^+(^3S_1)$	-0.40^B, $\chi_{c1}(3872)$	-	-25.0^V	-39.6^V, $Z_c(3900)$	-0.79^B, $T_{cc}(3875)$	-
	$0^-(^3P_0)$	$3.3 - 17.2i$	-	-	-	$-11.2 - 16.7i$	-
	$1^-(^3P_1)$	-	-	$4.4 - 39.9i$, $Y(3872)$	-	$-96.6 - 87.3i$	-
	$2^-(^3P_2)$	$-71.2 - 63.5i$	-	$-31.0 - 96.5i$	-	$-61.3 - 53.6i$	-
$\Lambda = 1.35$ GeV	$1^+(^3S_1)$	-2.8^B, $\chi_{c1}(3872)$	-	-2.2^V	-38.5^V, $Z_c(3900)$	-8.8^B, $T_{cc}(3875)$	-
	$0^-(^3P_0)$	$6.6 - 11.6i$	-	-	-	$-10.2 - 18.0i$	-
	$1^-(^3P_1)$	-	-	$10.2 - 33.7i$, $Y(3872)$	-	$-92.9 - 97.7i$	-
	$2^-(^3P_2)$	$-68.0 - 75.4i$	-	$-23.3 - 97.2i$	-	$-58.4 - 59.6i$	-

Regulator independence !

Summary

- The existence of the P-wave $D\bar{D}^*$ resonance with $J^{PC} = 1^{--}$ can be firmly established based on the scaling of the S-wave $D\bar{D}^*$ dynamics.
- The P-wave resonance is less sensitive to the potential shape compared with the S-wave resonance, so its theoretical prediction will be more reliable.
- This behavior contributes to the dense population of P-wave resonances in both the $D\bar{D}^*$ / $\bar{D}D^*$ and DD^* systems, which can be tested in the future experiments.

Thanks for your attention!