New heavy quarkoniumlike state: Y(10650)

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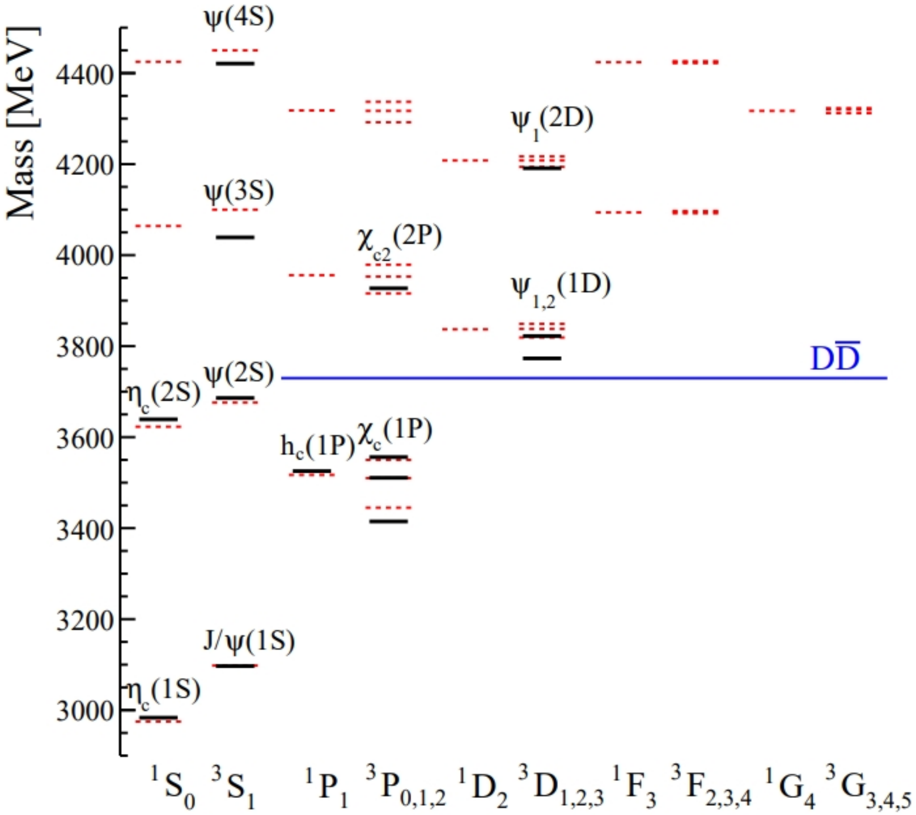
2026.04.26 重庆大学@重庆

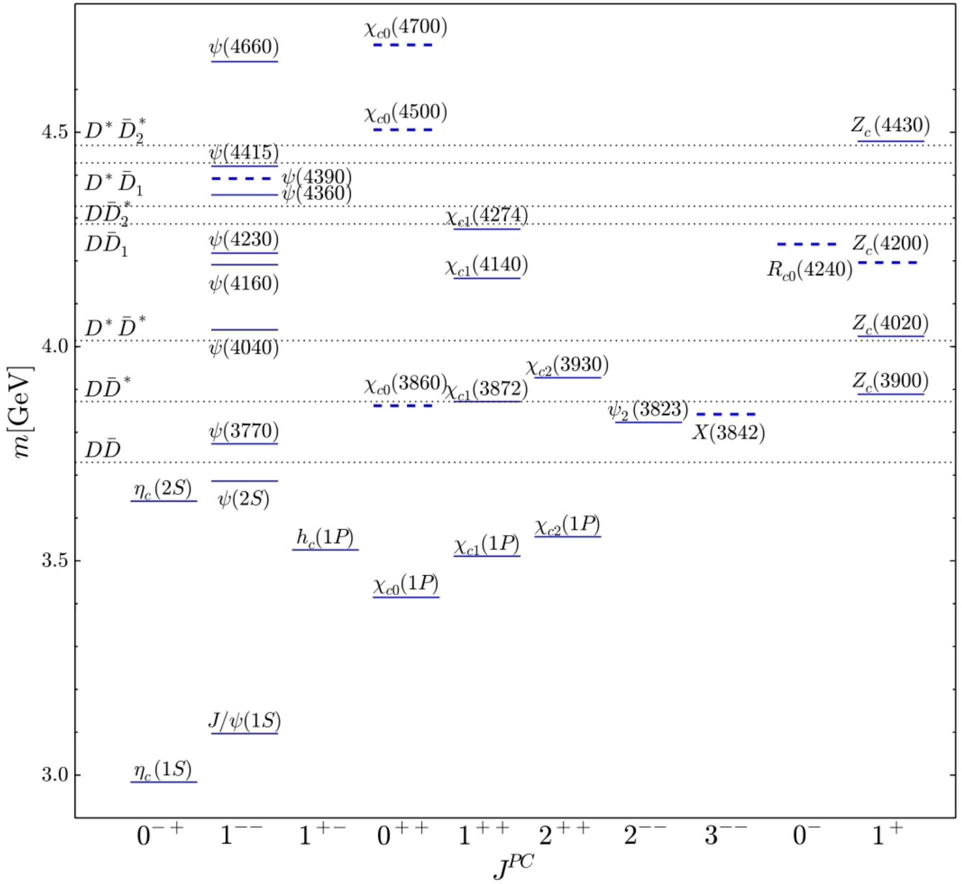
Outline

- Bottomonium and bottomoniumlike spectrum
- $G(3900)$: P-wave $D\bar{D}^*$ resonance
- Prediction of new bottomoniumlike state: Y(10650)
- Summary

Charmonium and charmoniumlike spectrum

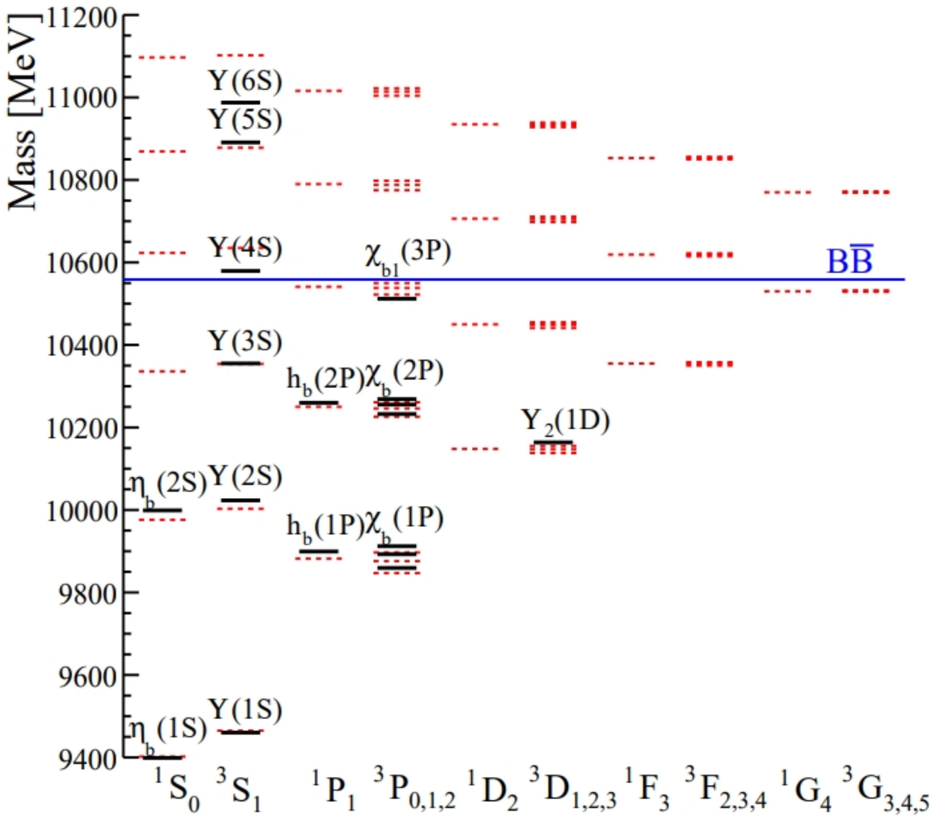


Rev. Mod. Phys. 90, 015003 (2018)

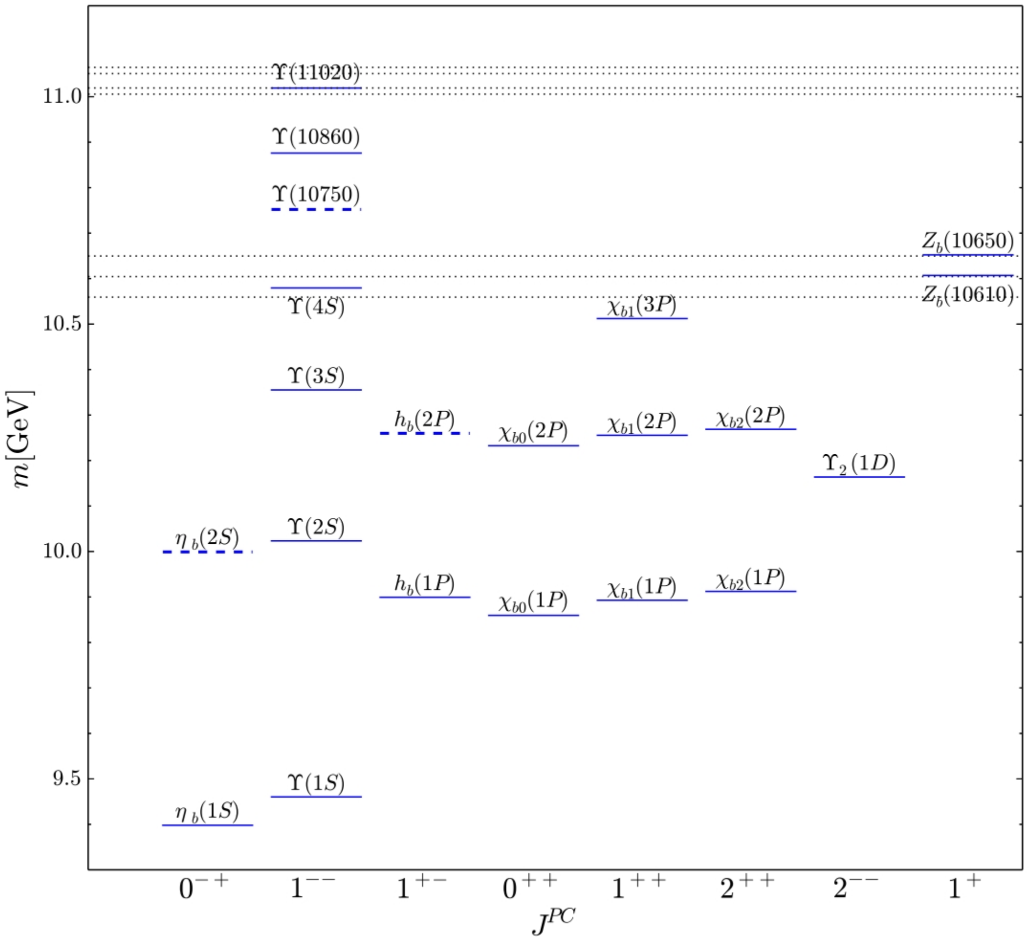


Phys. Rept. 873, 1 (2020)

Bottomonium and bottomoniumlike spectrum



Rev. Mod. Phys. 90, 015003 (2018)



Phys. Rept. 873, 1 (2020)

$Z_b(10600)$ & $Z_b(10650)$

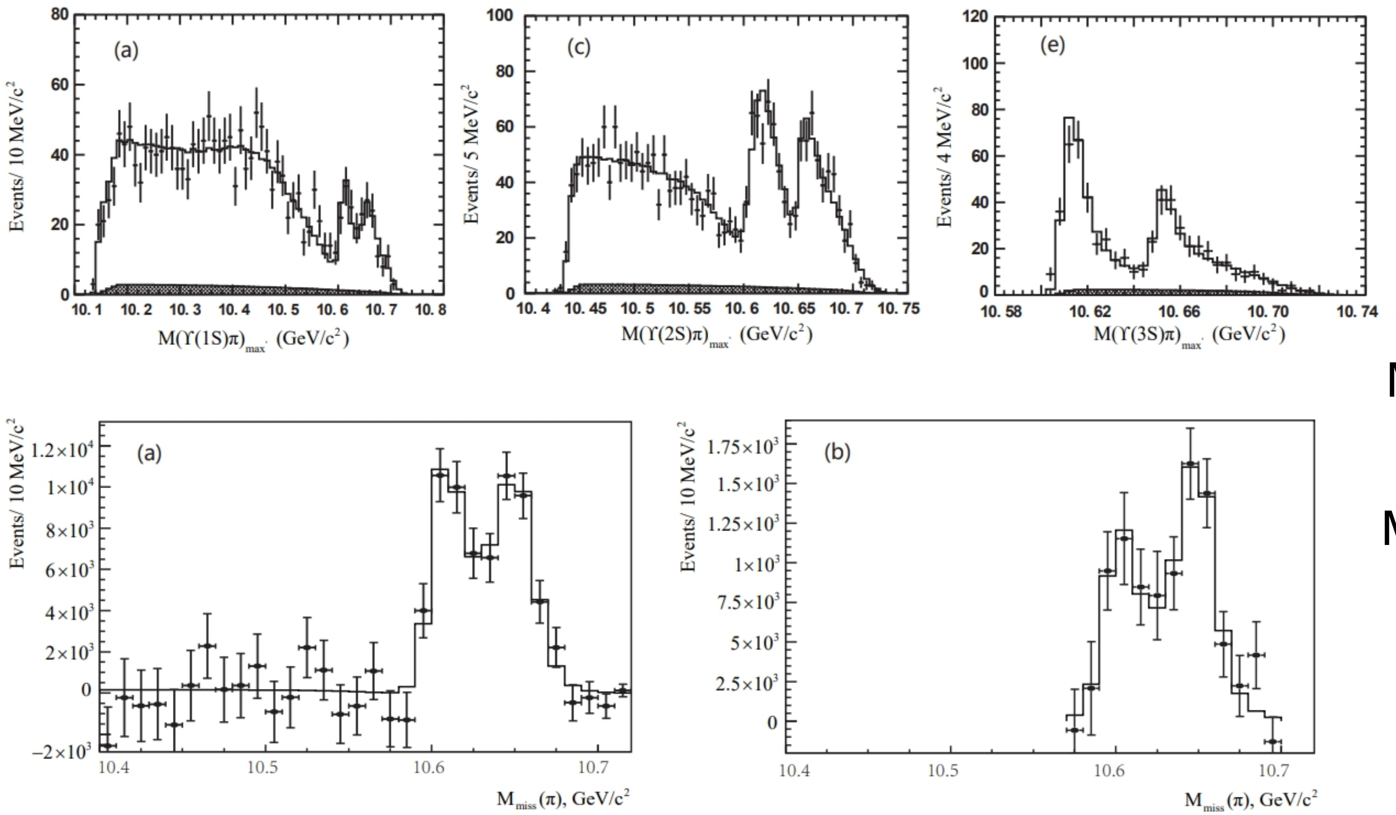


Figure 35: Signals for the $Z_b(10610)$ and $Z_b(10650)$ structures in $\Upsilon(1S)\pi$, $\Upsilon(2S)\pi$, $\Upsilon(3S)\pi$, $h_b(1P)\pi$ and (e) $h_b(2P)\pi$ from Belle [172].

	OBE			OPE		
State	Λ	E (MeV)	$r_{\rm RMS}$ (fm)	Λ	E (MeV)	$r_{\rm RMS}$ (fm)
$Z_b(10610)$	2.1	-0.22	3.05	2.2	-8.69	0.62
	2.3	-1.64	1.31	2.4	-20.29	0.47
	2.5	-4.74	0.84	2.6	-38.54	0.36
$Z_b(10650)$	2.2	-0.81	1.38	2	-2.17	1.15
	2.4	-3.31	0.95	2.2	-8.01	0.68
	2.6	-7.80	0.68	2.4	-19.00	0.48
	2.8	-14.94	0.52	2.6	-36.36	0.38

Molecular isovector bound state (positive results)

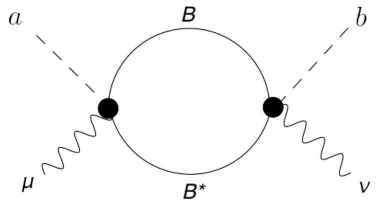
Phys. Rev. D84 (2011) 054002

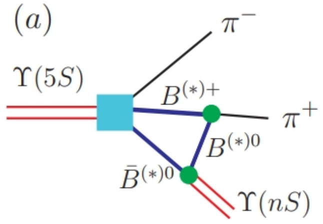
Molecular isovector bound state (negative results)

Phys. Rev. D88 (2013) 034018

Phys. Rev. D91 (7) (2015) 076001

Kinematical explanation

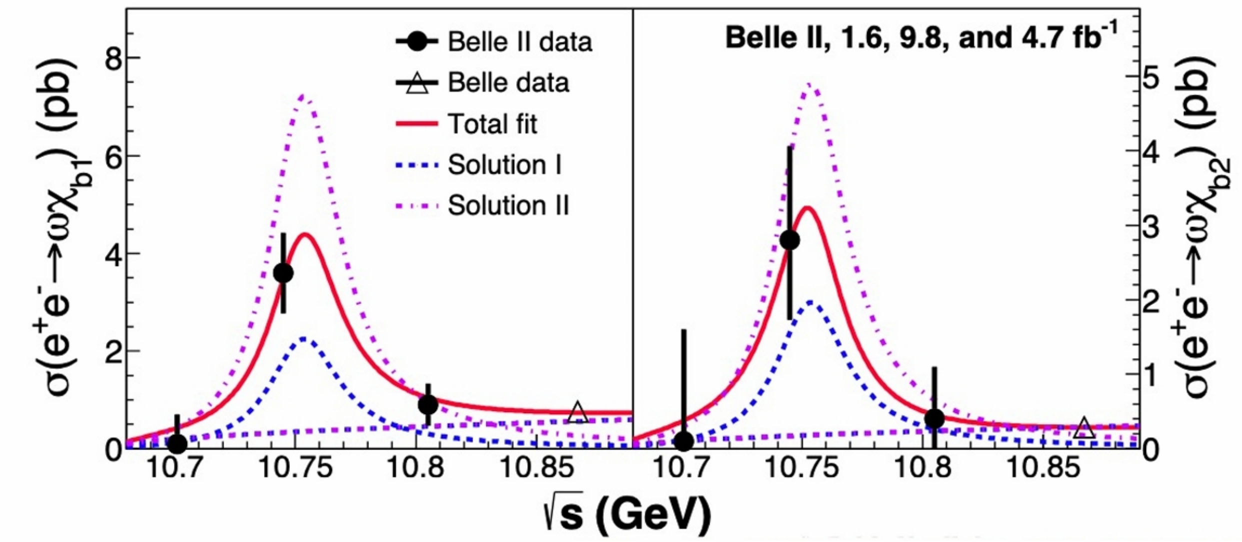




Phys. Rev. D91 (3) (2015) 034009   Phys. Rev. D84 (2011) 094003

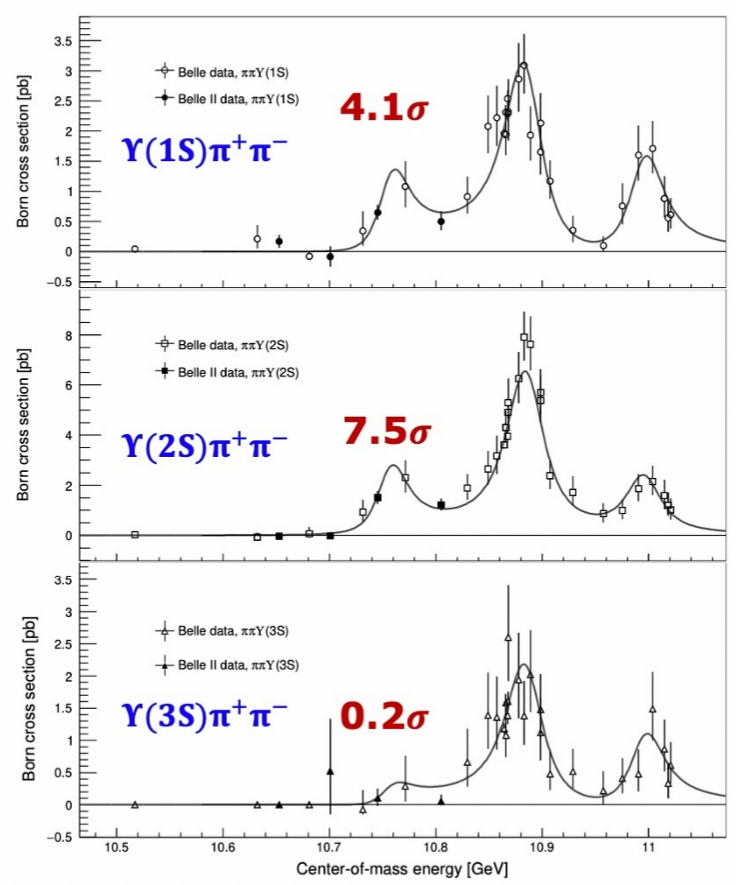
$\Upsilon(10750)$

$\Upsilon(10753) \to \omega\chi_{bJ}$



PRL 130, 091902 (2023)

$\Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS)$



JHEP 07 (2024) 116

The theoretical interpretations:

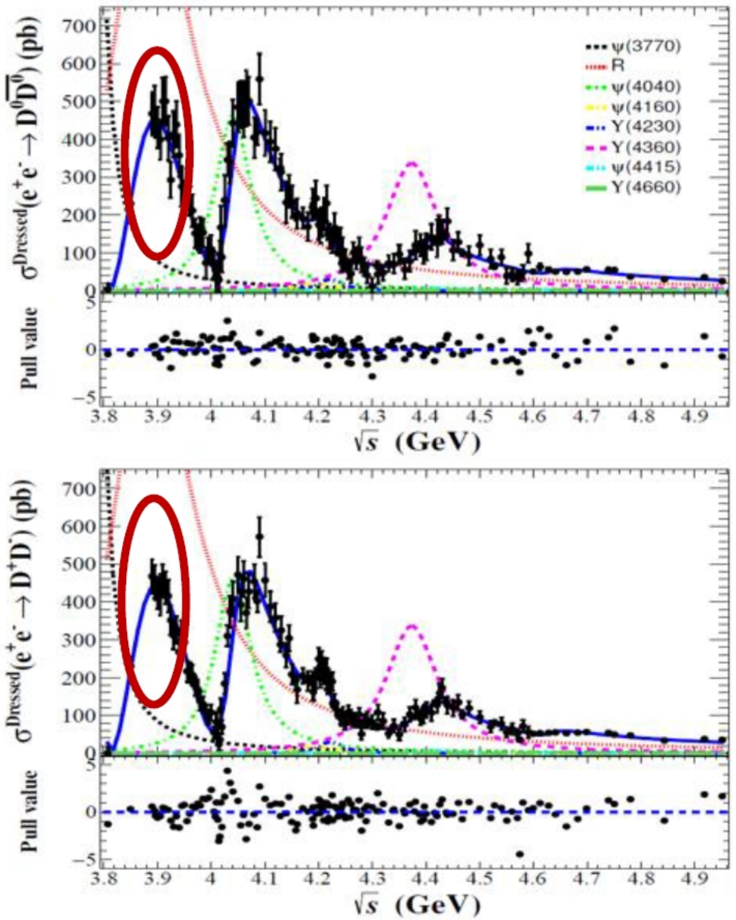
1. 4S-3D bottomonium state	PRD 105, 074007 (2022)
2. tetraquark state	PLB 802, 135217 (2020)
3. hybrid state	PRD 104, 034019 (2021)

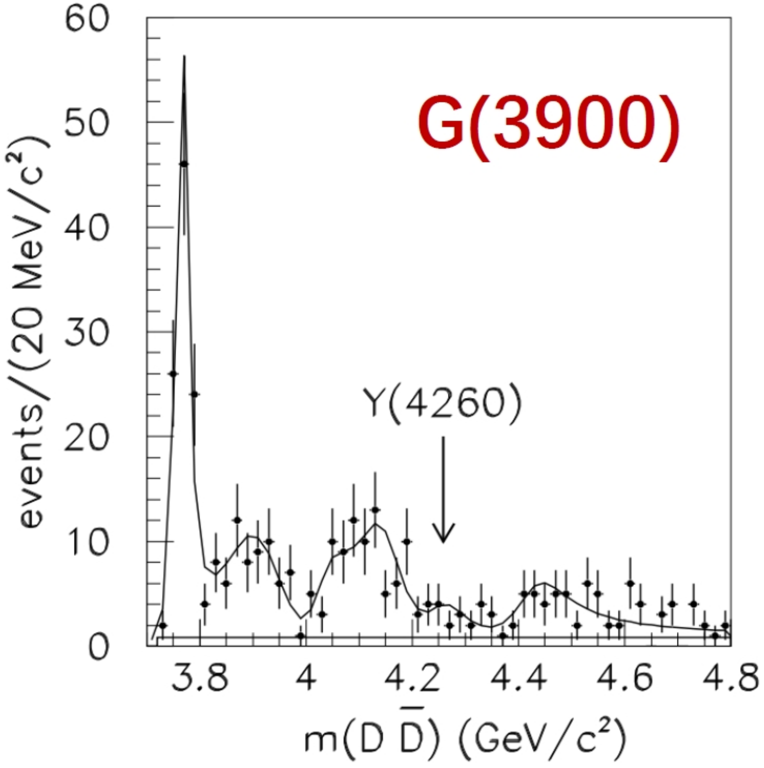
Precise Measurement of Born Cross Sections for $e^+e^- \to D\bar{D}$ and Observation of One Structure between $\sqrt{s} = 3.80 - 4.95$ GeV

(BESIII Collaboration)

arXiv: 2402.03829

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





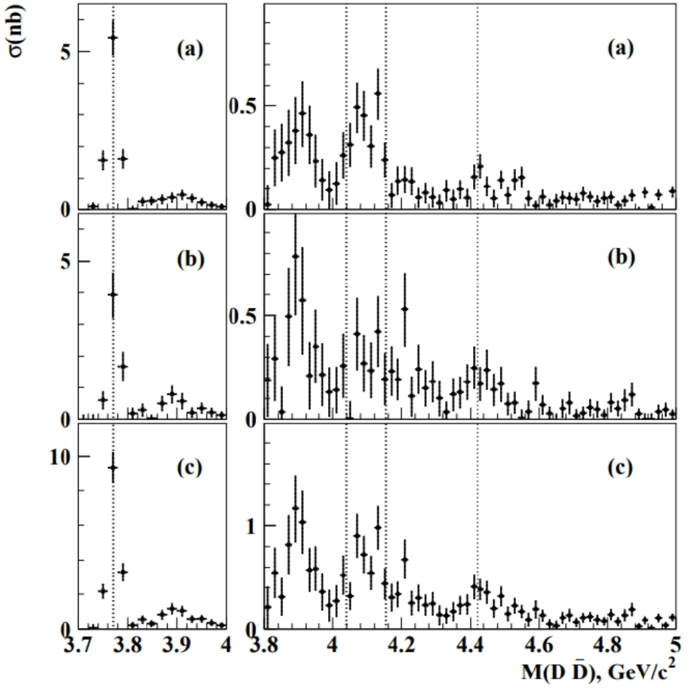


FIG. 3: The exclusive cross sections for: (a) $e^+e^- \to D^0\bar{D}^0$; (b)$e^+e^- \to D^+D^-$; (c) $e^+e^- \to D\bar{D}$. The dotted lines correspond to the $\psi(3770)$, $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$ masses [20].

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

(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?

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

- The hadron-hadron interactions are fullfilled with pseudoscalar and vector meson exchange

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

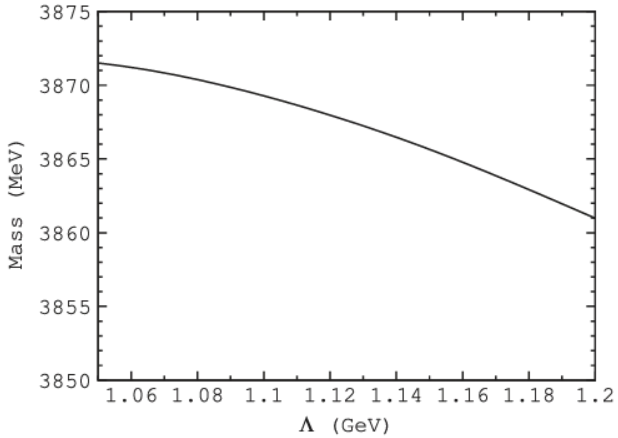
OBE model
$(\pi, \eta, \sigma, \rho, \omega)$

$$
\rho^\mu = \frac{ig_V}{\sqrt{2}}\begin{pmatrix} \frac{\rho_0}{\sqrt{2}}+\frac{\omega}{\sqrt{2}} & \rho^+ \\ \rho^- & -\frac{\rho_0}{\sqrt{2}}+\frac{\omega}{\sqrt{2}} \end{pmatrix}^\mu, \quad \mathbb{P} = \begin{pmatrix} \frac{\pi_0}{\sqrt{2}}+\frac{\eta}{\sqrt{6}} & \pi^+ \\ \pi^- & -\frac{\pi_0}{\sqrt{2}}+\frac{\eta}{\sqrt{6}} \end{pmatrix}.
$$

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

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

succeed in decribing the $X(3872)$ & predicting the T_{cc}^+



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

TABLE IV. The numerical results for the $D^{(*)}D^{(*)}$ system. "$***$" means the corresponding state does not exist due to symmetry while "$\cdots$" 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.

I	J^P		$D^{(*)}D^{(*)}$ OPE				$D^{(*)}D^{(*)}$ 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_{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

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

Complex scaling method (CSM)

Schrödinger equation

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

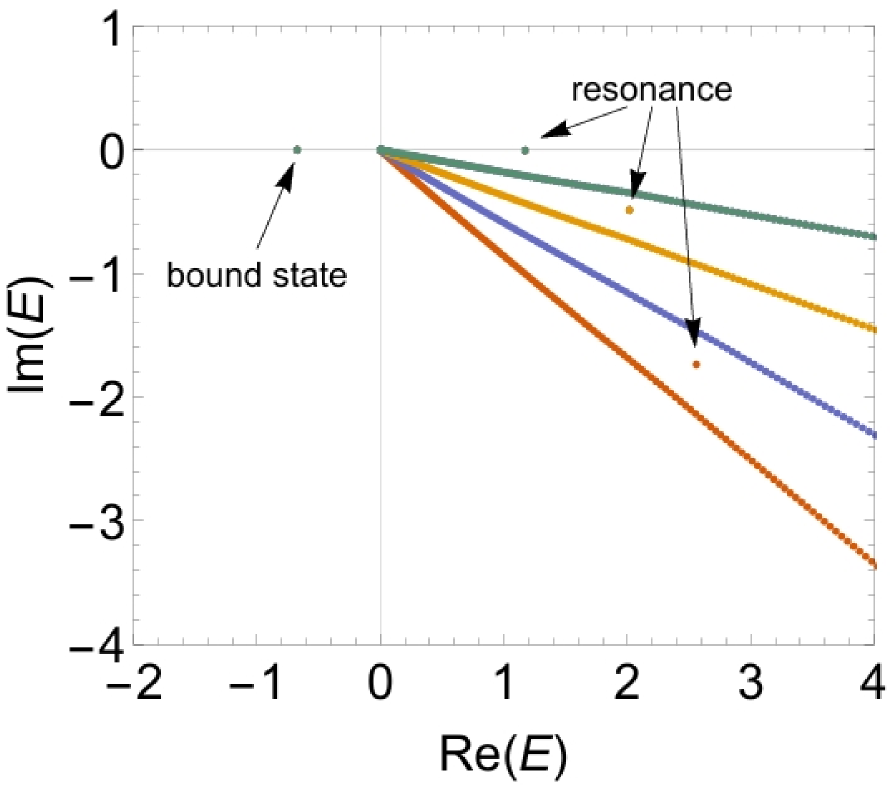
- Analytical extension of the wave function

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

k can be anywhere on the complex plane

p is on the integral path

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



The development of CSM by our group

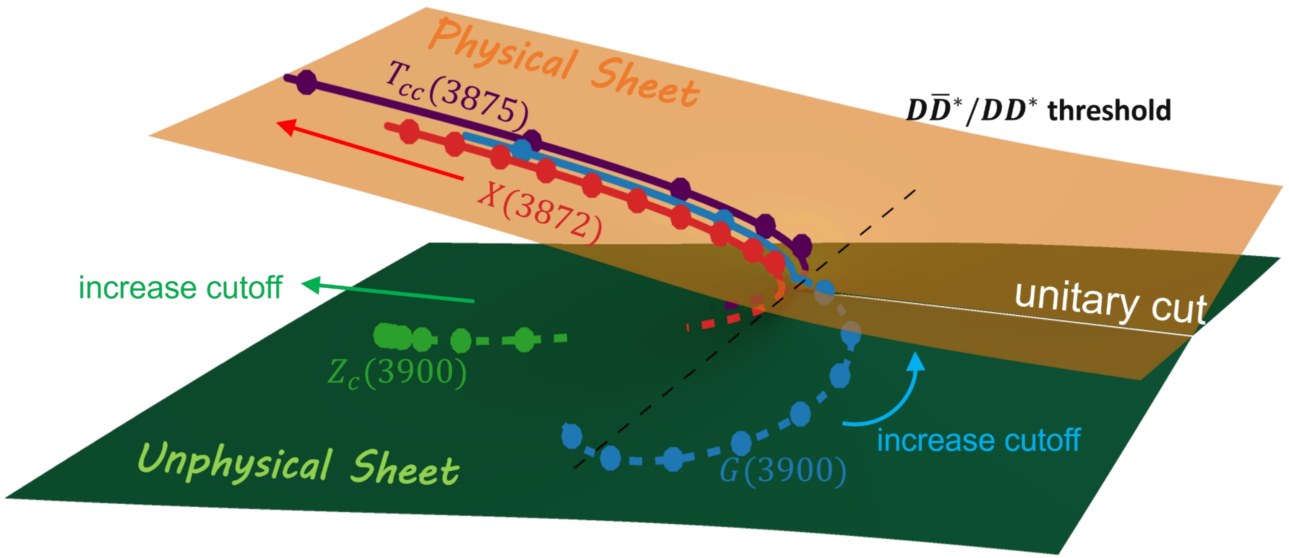
1. The solution to the virtual state pole

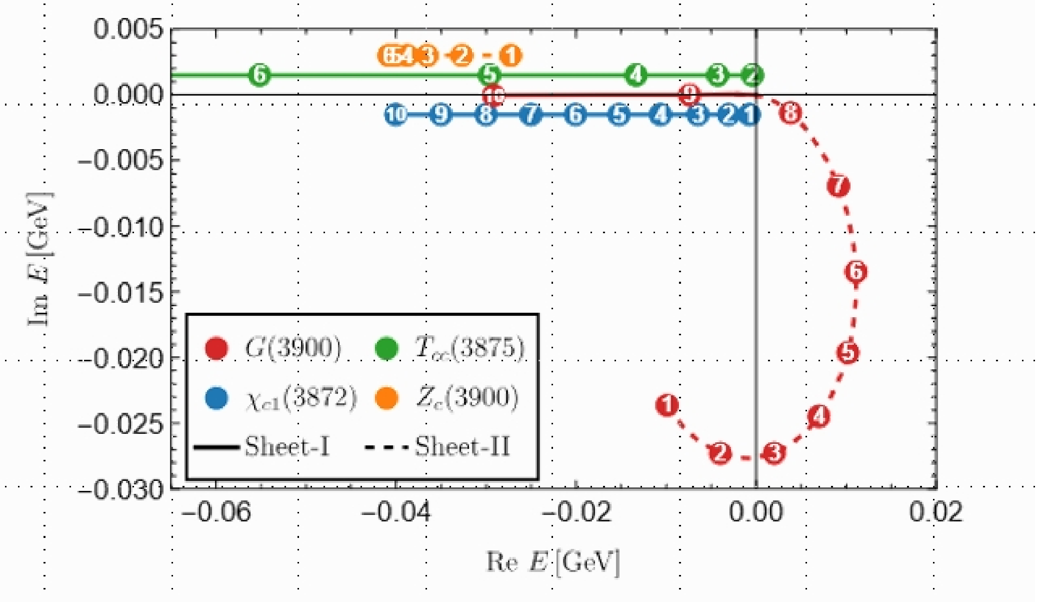
Y.K. Chen, L. Meng, Z. Y. Lin and S. L. Zhu Phys. Rev. D 109 (2024) 3, 034006

2. Complex scaled Lippmann-Schwinger equation

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

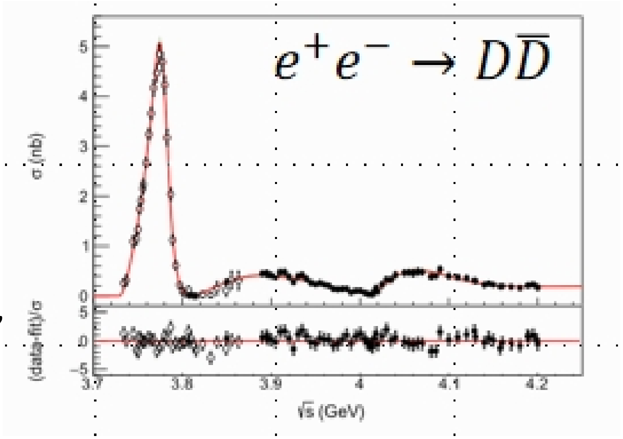
Dynamical explanation of G(3900)





Non-resonance explanation:Coupled-channel effect with $D\bar{D}^*, \psi(3770)$ and $\psi(4040)$

Phys. Rev. Lett. 133, 241903 (2024).



N. Hüsken et al,
Phys. Rev. D 109, 114010 (2024)

E. Eichten, K. Gottfried, T. Kinoshita, K. Lane, and T.-M. Yan, Phys. Rev. D 17, 3090 (1978)

R.Q.Qian and X.Liu,
Phys. Rev. D 112, L091502 (2025)

Support the explanation of resonance pole

S.X.Nakamura, X.H.Li, H.P.Peng, Z.T.Sun and X.R.Zhou, Phys. Rev. D 112, 054027 (2025)

Q.Ye, Z.Zhang, M.L.Du, U.G.Mei{\ss}ner, P.Y.Niu and Q.Wang,Phys. Rev. D 112, 016015 (2025)

Coupled-channel framework of P-wave $B^{(*)}\bar{B}^{(*)}$ scattering

Effective potentials (4 channels)

$$\mathcal{V}_{\sigma}^{B\bar{B}\to B\bar{B}} = -g_s^2 \frac{1}{\vec{q}^{\,2}+m_\sigma^2} C_\sigma, \quad (9)$$

$$\mathcal{V}_{\rho/\omega}^{B\bar{B}\to B\bar{B}} = -\frac{\beta^2 g_V^2}{2} \frac{1}{\vec{q}^{\,2}+m_{\rho/\omega}^2} C_{\rho/\omega}, \quad (10)$$

$$\mathcal{V}_{\pi/\eta}^{B\bar{B}\to B^*\bar{B}^*} = \frac{g^2}{f_\pi^2} \frac{(\vec{\epsilon}_3^{\,\dagger}\cdot\vec{q})(\vec{\epsilon}_4^{\,\dagger}\cdot\vec{q})}{\vec{q}^{\,2}+m_{\pi/\eta}^2} C_{\pi/\eta}, \quad (11)$$

$$\mathcal{V}_{\rho/\omega}^{B\bar{B}\to B^*\bar{B}^*} = 2\lambda^2 g_V^2 \frac{(\vec{\epsilon}_3^{\,\dagger}\times\vec{q})\cdot(\vec{\epsilon}_4^{\,\dagger}\times\vec{q})}{\vec{q}^{\,2}+m_{\rho/\omega}^2} C_{\rho/\omega}. \quad (12)$$

$$V_{\sigma}^{D} = -\frac{g_s^2}{\vec{q}^{\,2}+m_\sigma^2} C_\sigma^D, \quad (13)$$

$$V_{\pi/\eta}^{C} = -\frac{g^2}{f_\pi^2} \frac{(\vec{\epsilon}_2\cdot\vec{k})(\vec{\epsilon}_4^{\,\dagger}\cdot\vec{k})}{\vec{k}^{\,2}-k_0^2+m_{\pi/\eta}^2} C_{\pi/\eta}^C, \quad (14)$$

$$V_{\rho/\omega}^{D} = \frac{1}{2}\beta^2 g_V^2 \frac{(\vec{\epsilon}_2\cdot\vec{\epsilon}_4^{\,\dagger})}{\vec{q}^{\,2}+m_{\rho/\omega}^2} C_{\rho/\omega}^D, \quad (15)$$

$$V_{\rho/\omega}^{C} = \lambda^2 g_V^2 \frac{((\vec{\epsilon}_2\cdot\vec{k})(\vec{\epsilon}_4^{\,\dagger}\cdot\vec{k}) - \vec{k}^{\,2}(\vec{\epsilon}_2\cdot\vec{\epsilon}_4^{\,\dagger}))}{\vec{k}^{\,2}-k_0^2+m_{\rho/\omega}^2} C_{\rho/\omega}^C \quad (16)$$

$$\mathcal{V}_{\pi/\eta}^{[B^*\bar{B}]\to B^*\bar{B}^*} = \frac{ig^2}{f_\pi^2} \frac{(\vec{\epsilon}_3^{\,\dagger}\cdot\vec{q})(\vec{\epsilon}_4^{\,\dagger}\times\vec{q})\cdot\vec{\epsilon}_2}{\vec{q}^{\,2}+m_{\pi/\eta}^2} C'_{\pi/\eta}, \quad (17)$$

$$\mathcal{V}_{\rho/\omega}^{[B^*\bar{B}]\to B^*\bar{B}^*} = 2i\lambda^2 g_V^2 \frac{(\vec{\epsilon}_3^{\,\dagger}\times\vec{q})\cdot\vec{\epsilon}_4^{\,\dagger}(\vec{\epsilon}_2\cdot\vec{q})}{\vec{q}^{\,2}+m_{\rho/\omega}^2} C'_{\rho/\omega}, \quad (18)$$

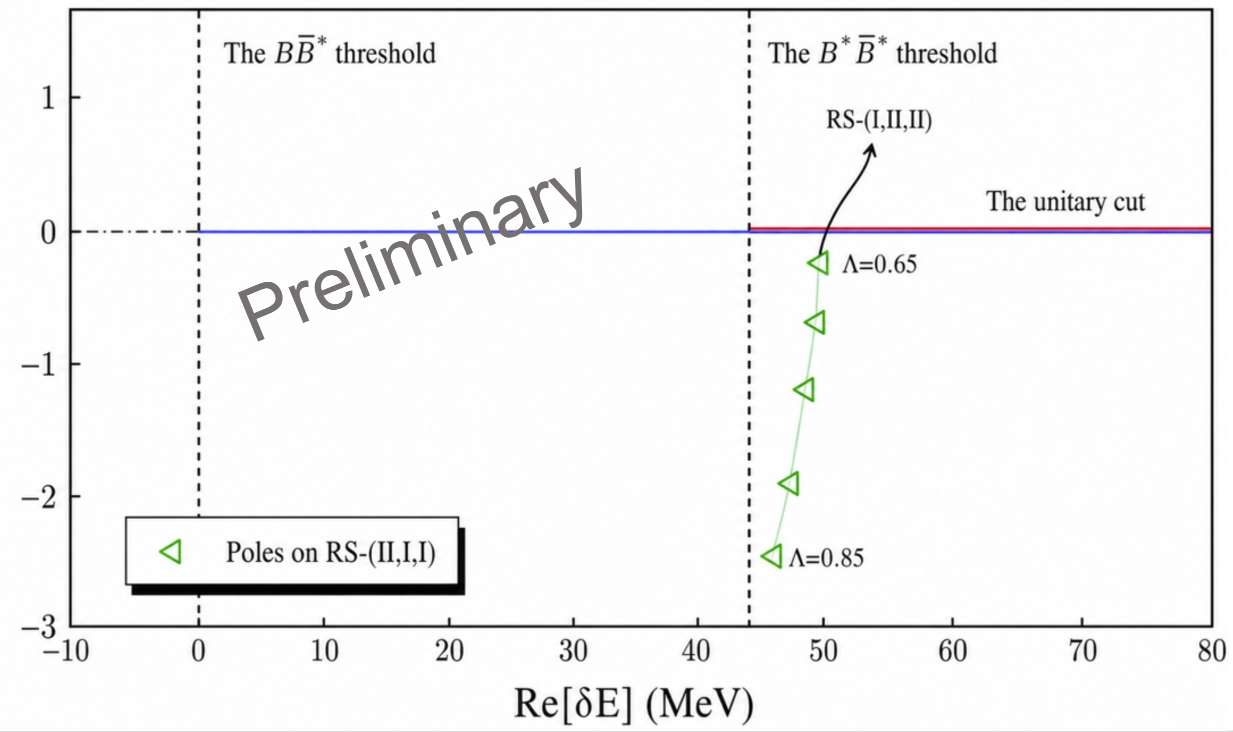
pion-exchange coupling

$g_B/g_D = 0.78 \pm 0.38$

(Dyson-Schwinger equation)
Phys.Rev.D 112 (2025) 1, 014046

vector mseon exchange coupling

$\lambda = 0.16, 0.36, 0.56\ \mathrm{GeV}^{-1}$



The c-product of wave function: $$(\phi|\phi) = \sum_i \int \frac{d\boldsymbol{p}^3}{(2\pi)^3} e^{-3i\theta} \phi_i(\tilde{\boldsymbol{p}})^2 = 1,$$

Wave function of the resonance pole: $$\phi(\boldsymbol{k}) = \frac{1}{E_R - \frac{\boldsymbol{k}^2}{2m}} \int \frac{d^3\boldsymbol{p}}{(2\pi)^3} e^{-3i\theta} V(\boldsymbol{k}, \boldsymbol{p}e^{-i\theta}) \tilde{\phi}(\boldsymbol{p}),$$

$$\begin{aligned} \psi_l(r) &= \int_0^\infty \frac{4\pi p^2}{(2\pi)^3} \phi_l(p) i^l j_l(pr) dp + 2\pi i \mathrm{Res}\{\frac{4\pi p^2}{(2\pi)^3} \phi_l(p) i^l j_l(pr)\}\Big|_{p=k_R} \\ &= \int_0^\infty \frac{4\pi p^2}{(2\pi)^3} \phi_l(p) i^l j_l(pr) dp + i^{l+1} \frac{k_R^2}{\pi} j_l(k_R r) \lim_{p\to k_R} (p - k_R) \phi_l(p), \end{aligned}$$

Asymptotic behavior of wave function:

$$\psi_{l,j}(r) \to \frac{i^l k_{R,j}}{2\pi} \lim_{p\to k_{R,j}} (p - k_{R,j}) \phi_{l,j}(p) \frac{e^{i(k_{R,j} r - \pi l/2)}}{r}.$$

$$\frac{\Gamma_1}{\Gamma_2} = \left|\frac{k_{R,1}/\mu_1}{k_{R,2}/\mu_2}\right| \left|\frac{k_{R,1} \lim_{p\to k_{R,1}} (p - k_{R,1}) \phi_1(p)}{k_{R,2} \lim_{p\to k_{R,2}} (p - k_{R,2}) \phi_2(p)}\right|^2.$$

→

$$\mathrm{Res}\ |S_{jj}(E)|\Big|_{E=E_R} = \left|\frac{\mu_j k_{R,j}}{4\pi^2} \langle k_{R,j}|\hat{V}|\phi\rangle^2\right|,$$

$$\langle k_{R,j}|\hat{V}|\phi\rangle = \int \frac{p^2 dp}{(2\pi)^3} e^{-3i\theta} V_{jm}(k_{R,j}, pe^{-i\theta}) \tilde{\phi}_m(p),$$

Phys.Rev.D 108 (2023) 11, 114014

Preliminary

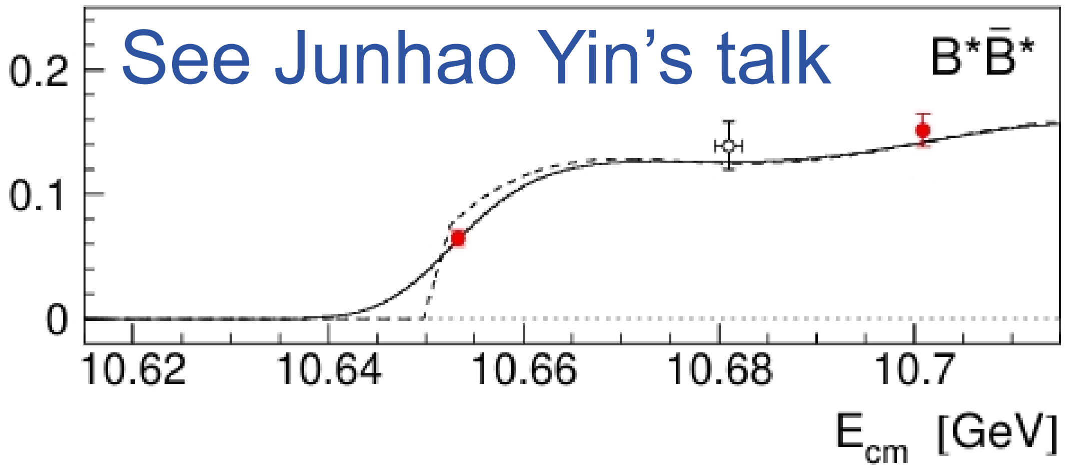
TABLE II. The pole properties of the $Y(10650)$. $\delta E = E_{\rm pole} - m^0_{th}$ with $m^0_{th} = m_B + m_{B^*}$, and $\mathcal{P}_i = (\phi_i|\phi_i)$ roughly reflects the ratio of the i-th channel, and "Res" represents the pole residue coupled to different channels.

States /Λ (GeV)	0.85	0.80	0.75	0.70	0.65
Pole position (MeV)	10651.0-2.6i	10652.0-2.0i	10652.9-1.3i	10653.4-0.7i	10653.5-0.2i
δE (MeV)	1.0-2.6i	2.0-2.0i	2.9-1.3i	3.4-0.7i	3.5-0.2i
Riemann Sheet	(II,I,I)	(II,I,I)	(II,I,I)	(II,I,I)	(II,I,I)
$\mathcal{P}(\bar{B}^*B + c.c.)$	(3.5+7.7i) %	(3.0+8.5i) %	(3.2+9.4i) %	(3.0 + 9.7i) %	(0.5+7.7i) %
$\mathcal{P}(\bar{B}^*B^*(^1P_1))$	(78.2-7.0i) %	(77.1-9.4i) %	(75.1-13.0i) %	(70.8 -16.3i) %	(63.3-16.2i) %
$\mathcal{P}(\bar{B}^*B^*(^5P_1))$	(18.3-0.7i) %	(19.9+0.9i) %	(21.7+3.6i) %	(26.2 +6.6i) %	(36.2+8.5i) %
Res$(\bar{B}^*B + c.c.)$	0.208	0.212	0.226	0.223	0.168
Res$(\bar{B}^*B^*(^1P_1))$	0.555	0.511	0.520	0.488	0.338
Res$(\bar{B}^*B^*(^5P_1))$	0.269	0.260	0.287	0.310	0.264

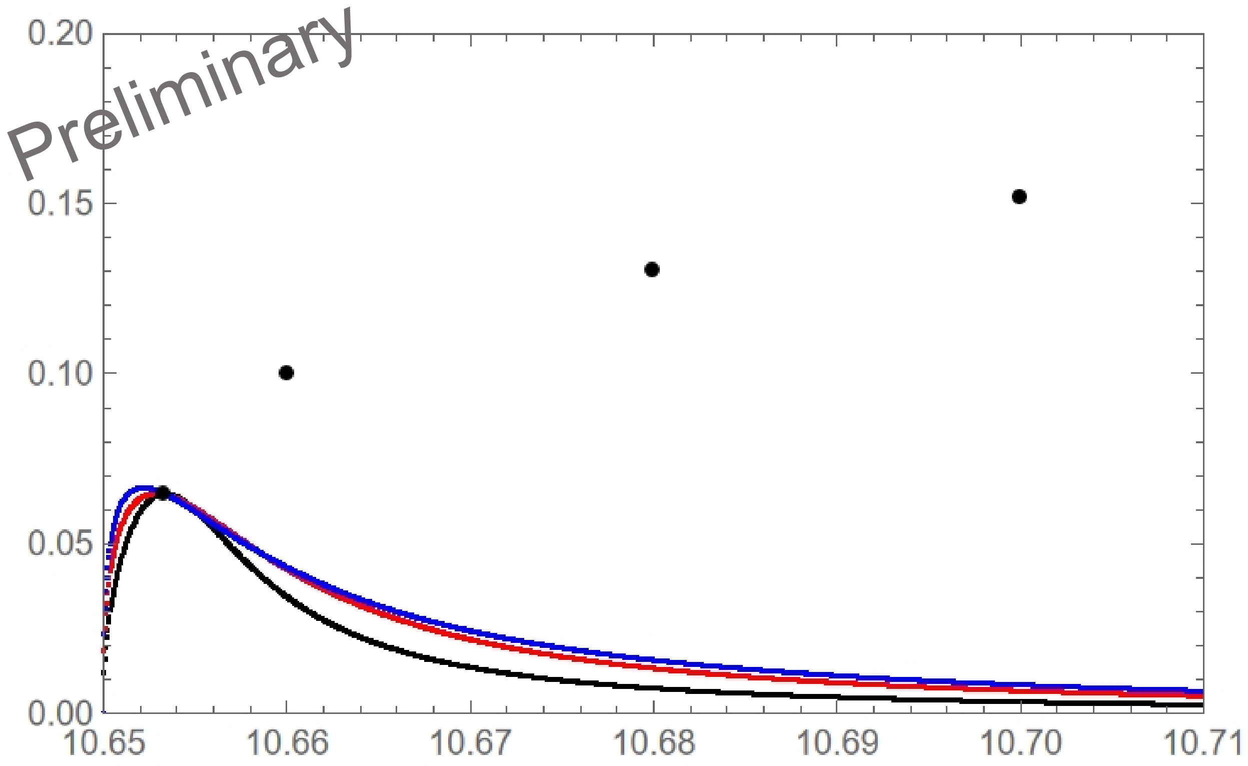
The cross section of $e^+e^- \to Y \to (B^{(*)}\bar{B}^{(*)})_j$

$$\frac{d\sigma_j}{dE} = \mathcal{B}(\Lambda)\frac{\mu_j g_j(\Lambda) k^j(E)/(4\pi^2)}{(E - E_Y - \sum_i \frac{\mu_i}{8\pi^2} g_i(\Lambda)\sqrt{-2\mu_i(E - m^i_{\rm th})})^2}$$

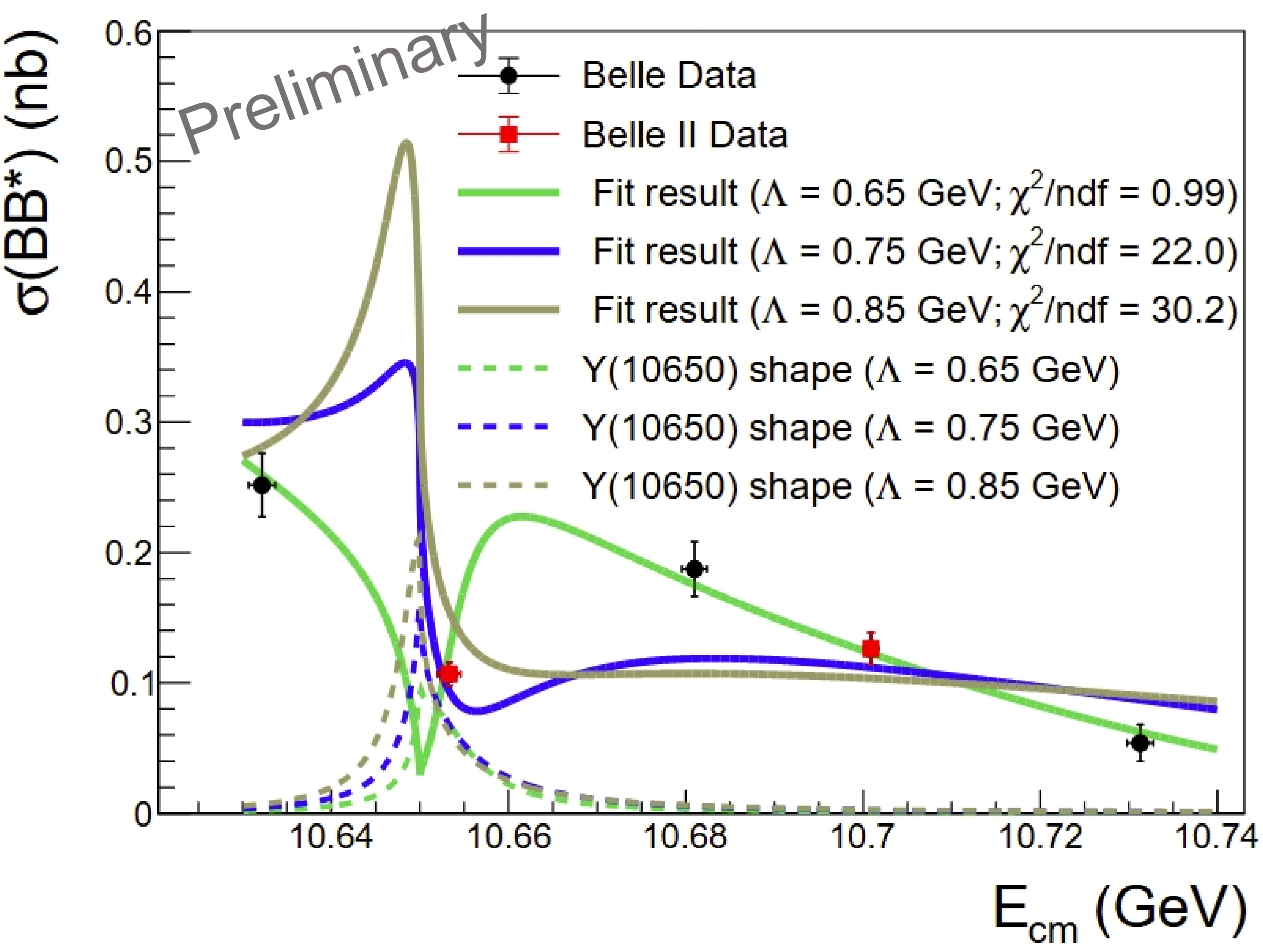
$$\begin{aligned} g_i &= Res(i) = \lim_{E\to E_R}(E - E_R)T_{ii}(E) \\ &= |\langle k_{R,j}|\hat{V}|\phi\rangle|^2, \end{aligned}$$



(Belle-II) JHEP 10, 114 (2024)

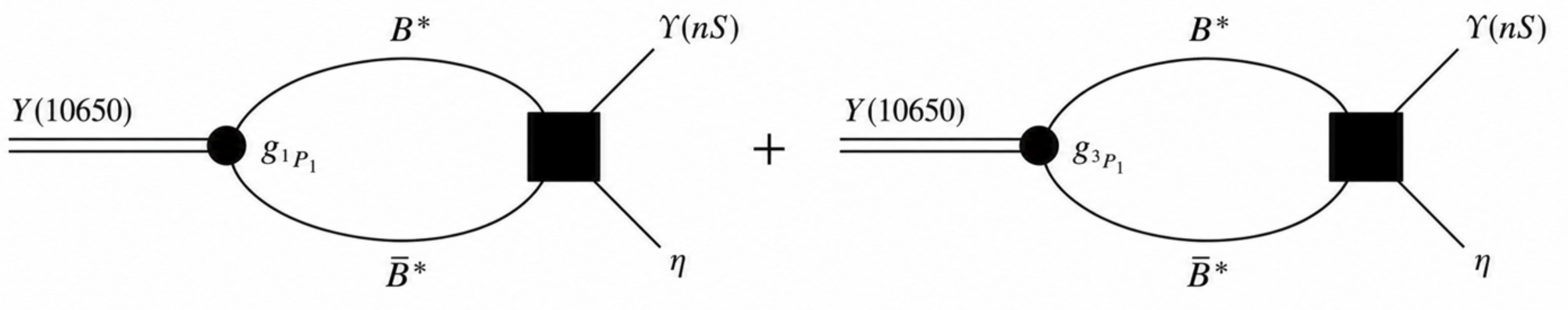


Analysis of open-bottom processes



Prediction for hidden-bottom decays of Y(10650)

Based on NR treatment



$$\mathcal{A}_t = \int \frac{d^3l}{(2\pi)^3} \frac{1}{E_X - l^2/m_{B^*} + i0} \epsilon_3^{*\,i} X^{\nu\rho}(l) K_{t\,i}{}^{(\nu\rho)}(l, p_4).$$

$$X^{\nu\rho}(l) = i g_X^{(1)} \delta^{\nu\rho}(\epsilon_X \cdot l) + i g_X^{(5)} \left[\epsilon_X^\nu l^\rho + \epsilon_X^\rho l^\nu - \frac{2}{3}\delta^{\nu\rho}(\epsilon_X \cdot l)\right]$$

$$\int \frac{d^3l}{(2\pi)^3} \frac{l^r l^m}{E_X - l^2/m_{B^*} + i0} = \frac{\delta^{rm}}{3} I_2(E_X, \Lambda)$$

$$i\mathcal{M}_{4pt} = i\,\epsilon_3^{*\,i}\epsilon_1^\nu \epsilon_2^\rho K_i{}^{\nu\rho}(l, p_4)$$

$$\begin{aligned}
\mathcal{O}_1 &= (\epsilon_3 \cdot \epsilon_1)\, \vec{l} \cdot (\epsilon_2 \times p_4), \\
\mathcal{O}_2 &= (\epsilon_3 \cdot \epsilon_2)\, \vec{l} \cdot (\epsilon_1 \times p_4), \\
\mathcal{O}_3 &= (\epsilon_3 \cdot l)\,(\epsilon_1 \times \epsilon_2) \cdot p_4, \\
\mathcal{O}_4 &= (\epsilon_1 \cdot l)\,(\epsilon_3 \times \epsilon_2) \cdot p_4, \\
\mathcal{O}_5 &= (\epsilon_2 \cdot l)\,(\epsilon_3 \times \epsilon_1) \cdot p_4, \\
\mathcal{O}_6 &= (\epsilon_1 \cdot p_4)\,(\epsilon_3 \times \epsilon_2) \cdot l, \\
\mathcal{O}_7 &= (\epsilon_2 \cdot p_4)\,(\epsilon_3 \times \epsilon_1) \cdot l.
\end{aligned}$$

Bstar-exchange matching

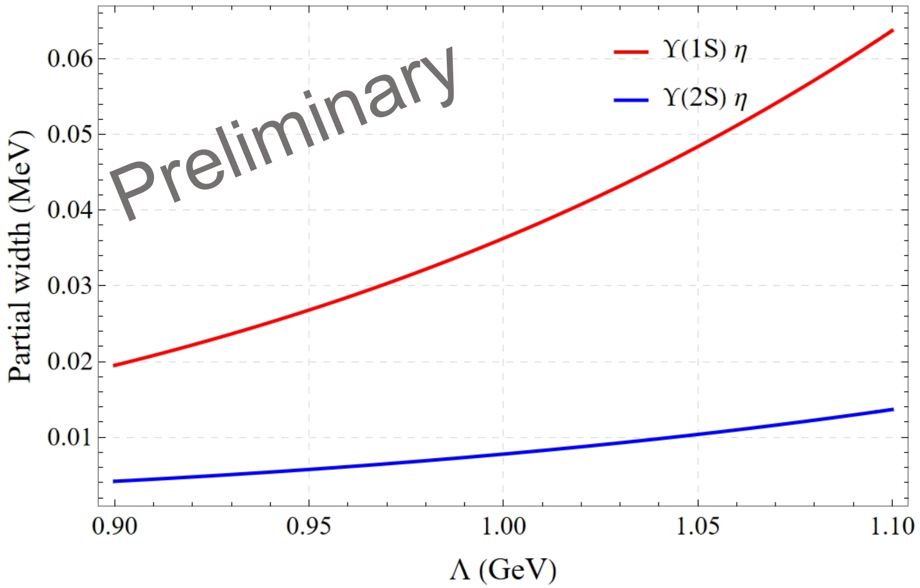
$$K_{t\,i}{}^{\nu\rho} = \mathcal{C}_n\left[l^\nu \epsilon_{\rho i m} p_4^m - \delta_i^\nu A^\rho\right], \qquad A^\rho \equiv \epsilon^{\rho m n} l_m p_{4n}.$$

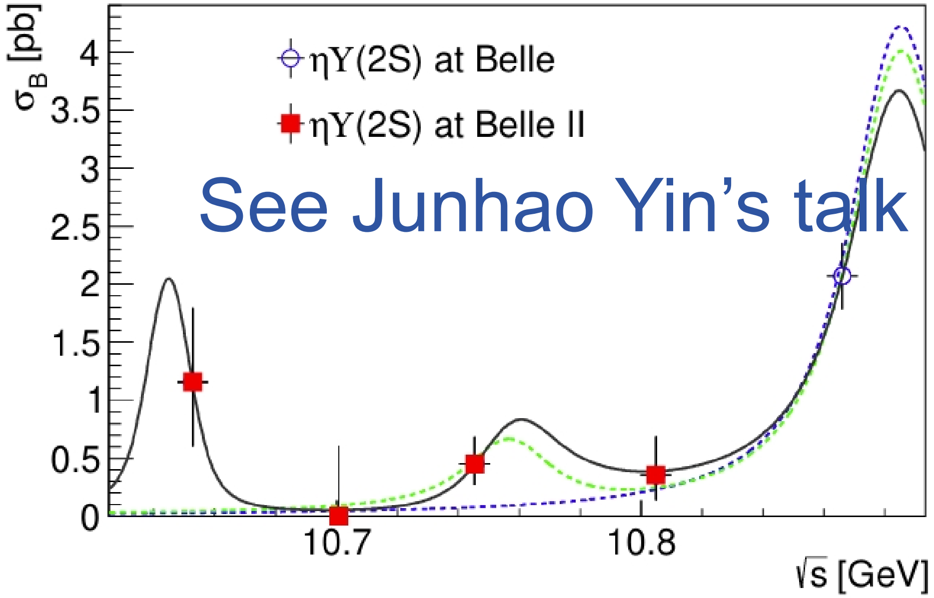
$$K_{t\,i}{}^{(\nu\rho)} = \mathcal{C}_n\left[\frac{1}{2}\left(l^\nu \epsilon_{\rho i m} p_4^m + l^\rho \epsilon_{\nu i m} p_4^m\right) - \frac{1}{2}\left(\delta_i^\nu A^\rho + \delta_i^\rho A^\nu\right)\right],$$

$$K_{t\,i}{}^{[\nu\rho]} = \mathcal{C}_n\left[\frac{1}{2}\left(l^\nu \epsilon_{\rho i m} p_4^m - l^\rho \epsilon_{\nu i m} p_4^m\right) - \frac{1}{2}\left(\delta_i^\nu A^\rho - \delta_i^\rho A^\nu\right)\right].$$

$$\Downarrow$$

$$\mathcal{A}_n^{\text{full}} = i\,\mathcal{C}_n\, I_2(E_X, \Lambda)\left[\frac{4}{3} g_X^{(1)} + \frac{10}{9} g_X^{(5)}\right](\epsilon_X \times \epsilon_\Upsilon^*) \cdot p_4.$$





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(Belle-II) arXiv:2509.01917.

Summary

1. We predict the existence of a new bottomonium-like state, $Y(10650)$, and identify it as a near-threshold P-wave pole dominantly associated with the $B^*\bar{B}^*$ channel.

2. We point out that the existing Belle open-bottom data already provide strong evidence for the signal of this new state.

3. If confirmed by future Belle measurements, $Y(10650)$ would be a strong candidate for the first isoscalar manifestly exotic state in the bottomonium sector, owing to its distinctive mass location.

Thanks for your attention!