Finding new characteristic spectrum to identify charmoniumlike molecules

arXiv: 2103.04698

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Outline

- Background:

1. Pc states as meson-baryon molecular states
2. A comparison between the Pc states and XYZ states from B decay
3. A comparison of the experimental data and the DDbar mass thresholds

- New characteristic spectrum to identify charmoniumlike molecules

1. Mass spectrum for the isoscalar $D^*\bar{D}^*$ bound states
2. Hidden-charm decay behavior for the isoscalar $D^*\bar{D}^*$ bound states
3. Other possible DDbar charmoniumlike molecules around 4.3 GeV

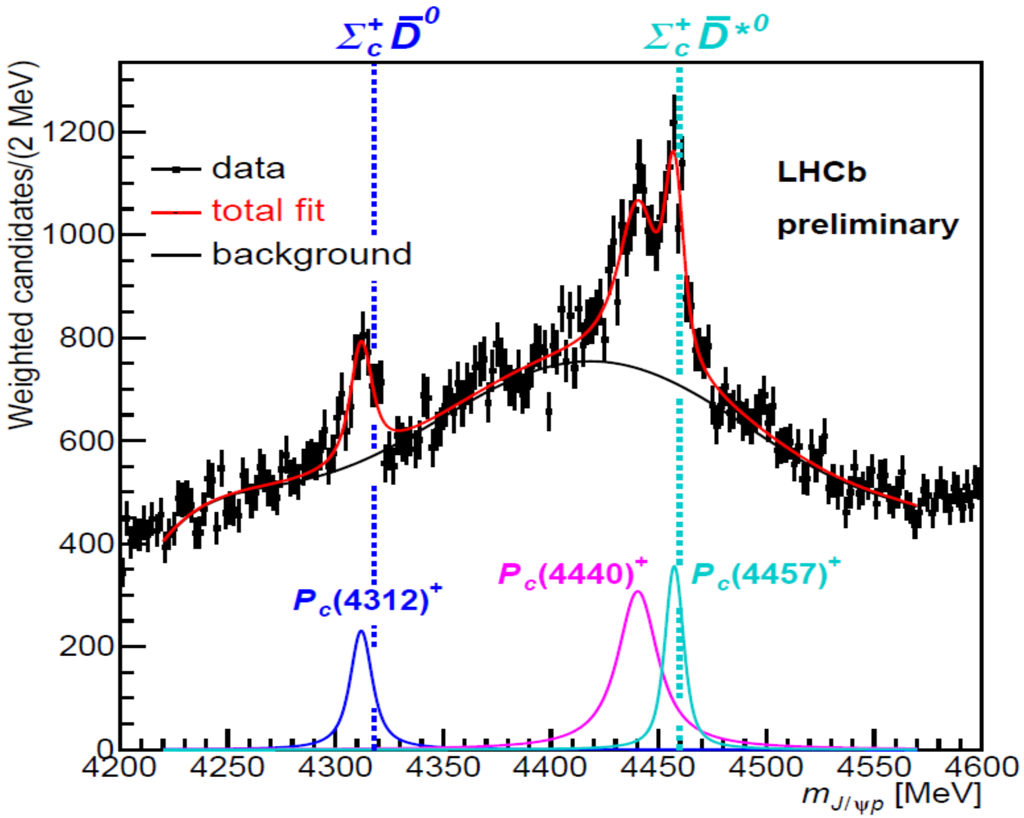
- Summary

I. Background

1. Pc states as meson-baryon molecular states
2. A comparison between the Pc states and XYZ states from B decay
3. A comparison of the experimental data and the DDbar mass thresholds

Pc states as hidden-charm molecular pentaquarks

PRL122, 222001 $\Lambda_b^0 \to J/\psi p K^-$



State	M [MeV]	Γ [MeV]	(95% CL)
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)

PRD110, 011502(R)

$I(J^P) = 1/2(1/2^-)$ reproduce Pc(4312) and Pc(4440)

- Pc(4312): $\boldsymbol{\Sigma_c \bar{D}}: \Sigma_c \overline{D^*}: \Sigma_c^* \overline{D^*}$ =**0.66**:0.18:0.16, root-mean-square radius: R=1.03 fm
- Pc(4440): $\boldsymbol{P[\Sigma_c \overline{D^*}] > 92\%}$, R=0.83 fm

$I(J^P) = 1/2(3/2^-)$ reproduce Pc(4457)

- Pc(4457): $\boldsymbol{\Sigma_c \overline{D^*}}: \Sigma_c^* \overline{D^*} = 3:1$, root-mean-square radius: R=1.61 fm, coupled-channel effect: **important**

- Pc(4380)

M=4379 MeV, **P[$\Sigma_c^* \bar{D}$]>87%,** R=1.40 fm,

Prediction of hidden-charm molecular pentaquarks

Jia-jun Wu, T. -S. H. Lee, B. S. Zou,
Phys. Rev. C85,044002(2012)

	PB System		VB System	
$J^P=\frac{1}{2}^-$ Λ	$M-i\Gamma/2$	ΔE	$M-i\Gamma/2$	ΔE
650	-			
800			$4462.178-0.002i$	0.002
1200	$4318.964-0.362i$	1.826	$4459.513-0.417i$	2.667
1500	$4314.531-1.448i$	6.259	$4454.088-1.662i$	8.092
2000	$4301.115-5.835i$	19.68	$4438.277-7.115i$	23.90
$J^P=\frac{3}{2}^-$				
650	-			
800	-	-	$4462.178-0.002i$	0.002
1200	-	-	$4459.507-0.420i$	2.673
1500	-	-	$4454.057-1.681i$	8.123
2000	-	-	$4438.039-7.268i$	23.14

$\Sigma_c\bar{D}^*$(I=1/2,JP=1/2-)

$\Sigma_c\bar{D}$(I=1/2,JP=1/2-)

$\Sigma_c\bar{D}^*$(I=1/2,JP=3/2-)

arXiv:1105.2901

CPC(HEP & NP), 2012, **36**(1): 6–13 Chinese Physics C Vol. 36, No. 1, Jan., 2012

Possible hidden-charm molecular baryons composed of an anti-charmed meson and a charmed baryon*

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Abstract: Using the one-boson-exchange model, we studied the possible existence of very loosely bound hidden-charm molecular baryons composed of an anti-charmed meson and a charmed baryon. Our numerical results indicate that the $\Sigma_c\bar{D}^*$ and $\Sigma_c\bar{D}$ states exist, but that the $\Lambda_c\bar{D}$ and $\Lambda_c\bar{D}^*$ molecular states do not.

- ✓ Different groups predicted the existence of hidden-charm molecular pentaquarks before experiment
- ✓ Observations perfect match theoretical predictions in meson-baryon molecular scenario

Loosely bound meson-baryon molecular explanations for these three Pc states after 2019

1. M. Z. Liu, et al, Phys. Rev. Lett. 122, 242001 (2019).
2. J. He, Eur. Phys. J. C 79, 393 (2019).
3. C. W. Xiao, J. Nieves, and E. Oset, Phys. Rev. D 100, 014021 (2019).
4. L. Meng, B. Wang, G. J. Wang, and S. L. Zhu, Phys. Rev. D 100, 014031 (2019).
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8. J. J. Wu, T.-S. H. Lee, and B. S. Zou, Phys. Rev. C 100, 035206 (2019).
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17. T. J. Burns and E. S. Swanson, Phys. Rev. D 100, 114033 (2019).
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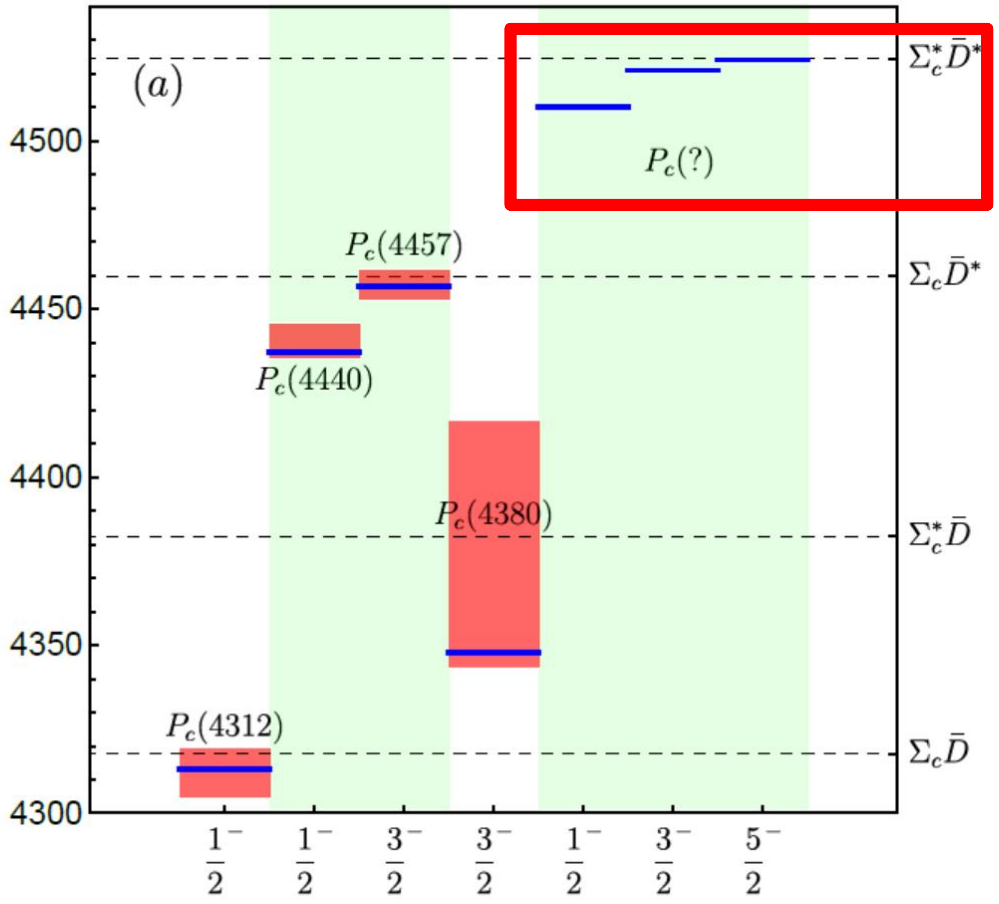
20. B. Wang, L. Meng, and S. L. Zhu, J. High Energy Phys. 11 (2019) 108

Other predictions

Bo Wang, Lu Meng, Shi-Lin Zhu JHEP11(2019), 108

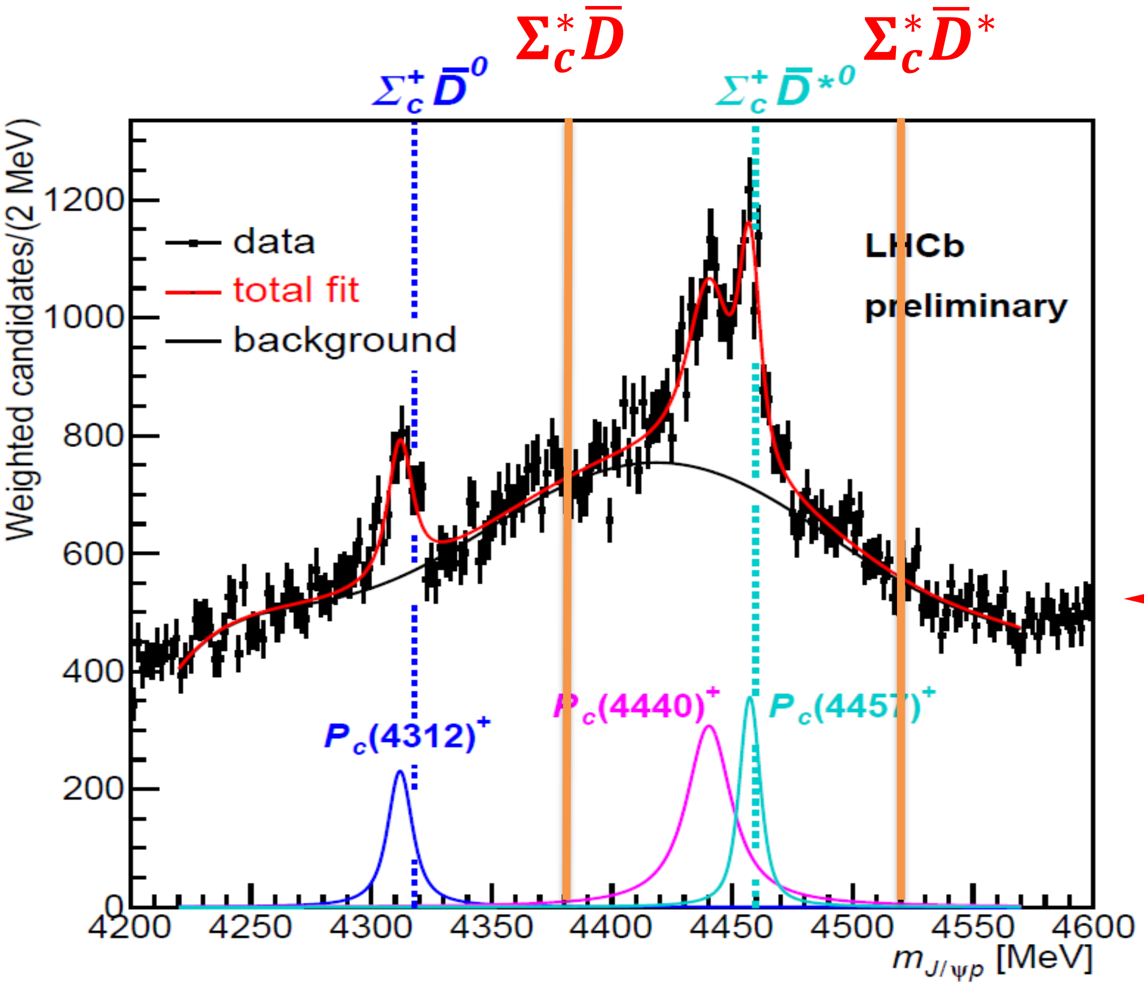


M. Z. Liu, et al PRL122, 242001 (2019)

Scenario	Molecule	J^P	B (MeV)	M (MeV)
A	$\bar{D}\Sigma_c$	$(1/2)^-$	7.8–9.0	4311.8–4313.0
A	$\bar{D}\Sigma_c^*$	$(3/2)^-$	8.3–9.2	4376.1–4377.0
A	$\bar{D}^*\Sigma_c$	$(1/2)^-$	Input	4440.3
A	$\bar{D}^*\Sigma_c$	$(3/2)^-$	Input	4457.3
A	$\bar{D}^*\Sigma_c^*$	$(1/2)^-$	25.7–26.5	4500.2–4501.0
A	$\bar{D}^*\Sigma_c^*$	$(3/2)^-$	15.9–16.1	4510.6–4510.8
A	$\bar{D}^*\Sigma_c^*$	$(5/2)^-$	3.2–3.5	4523.3–4523.6
B	$\bar{D}\Sigma_c$	$(1/2)^-$	13.1–14.5	4306.3–4307.7
B	$\bar{D}\Sigma_c^*$	$(3/2)^-$	13.6–14.8	4370.5–4371.7
B	$\bar{D}^*\Sigma_c$	$(1/2)^-$	Input	4457.3
B	$\bar{D}^*\Sigma_c$	$(3/2)^-$	Input	4440.3
B	$\bar{D}^*\Sigma_c^*$	$(1/2)^-$	3.1–3.5	4523.2–4523.6
B	$\bar{D}^*\Sigma_c^*$	$(3/2)^-$	10.1–10.2	4516.5–4516.6
B	$\bar{D}^*\Sigma_c^*$	$(5/2)^-$	25.7–26.5	4500.2–4501.0

- Identify Pc(4312), Pc(4440), and Pc(4457) in meson-baryon molecular pentaquarks
- Predicting other hidden-charm molecular pentaquarks partners

What can we learn from the Pc states?



PRL115, 072001

	$P_c(4380)^+$	$P_c(4450)^+$
Mass (MeV)	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width (MeV)	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$

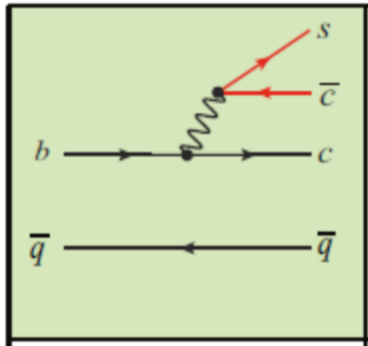
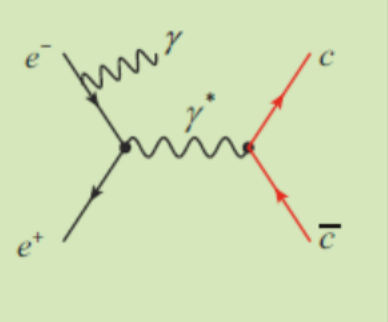
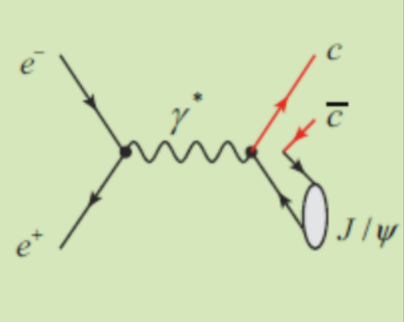
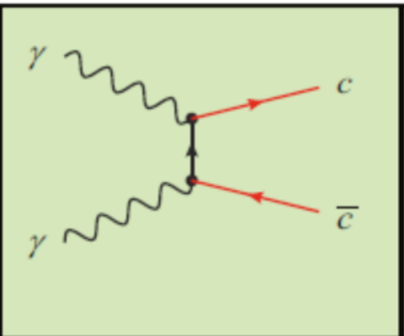
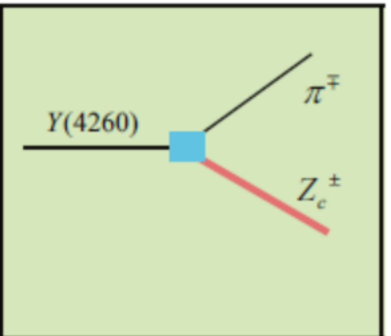
Pc(4380)/Pc(4450) spin-parities J^P
Best solution $(3/2^-, 5/2^+)$
Acceptable solutions $(3/2^+, 5/2^-)$ or $(5/2^+, 3/2^-)$
Challenge to the hadronic molecular assignment

PRL122, 222001

- Pc(4450) is composed of two substructures Pc(4440) and Pc(4457)
- The measurement of spin-parity quantum number of the observed $P_c(4450)$ can be ignored

- Higher precision to the study of hadron spectroscopy is very important.
- How to understand the wide structure?
- Can the $\Sigma_c^*\bar{D}$(3/2-) and $\Sigma_c^*\bar{D}^*$(1,3,5/2-) be the possible hidden-charm molecule?

Production mechanisms for the X/Y/Z states

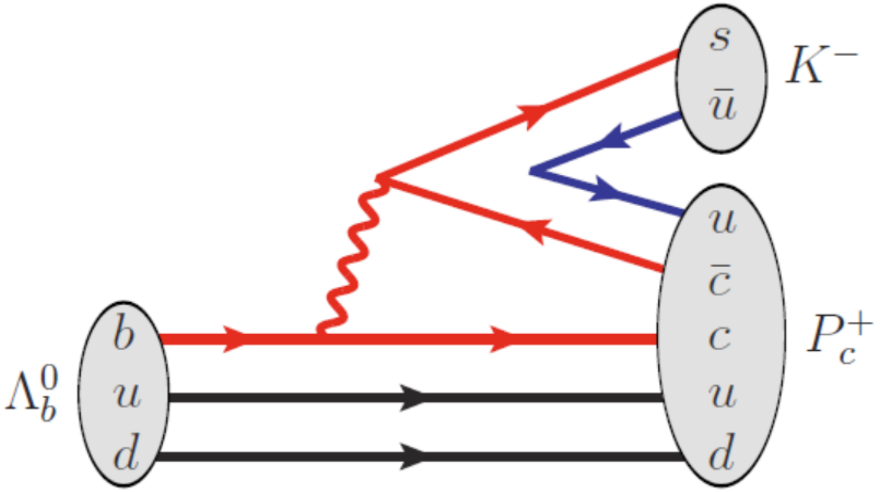
					
$D\bar{D}^*$ →	$X(3872)$	$Y(4260)$	$X(3940)$	$X(3915)$	$Z_c(3900)$
$D^*\bar{D}^*$	$Y(3940)$	$Y(4008)$	$X(4160)$	$X(4350)$	$Z_c(4025)$
$D^*\bar{D}_1/D^*\bar{D}_2^*$	$Z^+(4430)$	$Y(4360)$		$Z(3930)$	$Z_c(4020)$
$D^*\bar{D}^*$	$Z^+(4051)$	$Y(4630)$			$Z_c(3885)$
$D\bar{D}_1/\ D\bar{D}_2^*$	$Z^+(4248)$	$Y(4660)$			
	$Y(4140)$				
$D_s^*\bar{D}_s^*$	$Y(4274)$				
	$Z_c^+(4200)$				
	$Z^+(4240)$				
	$X(3823)$				

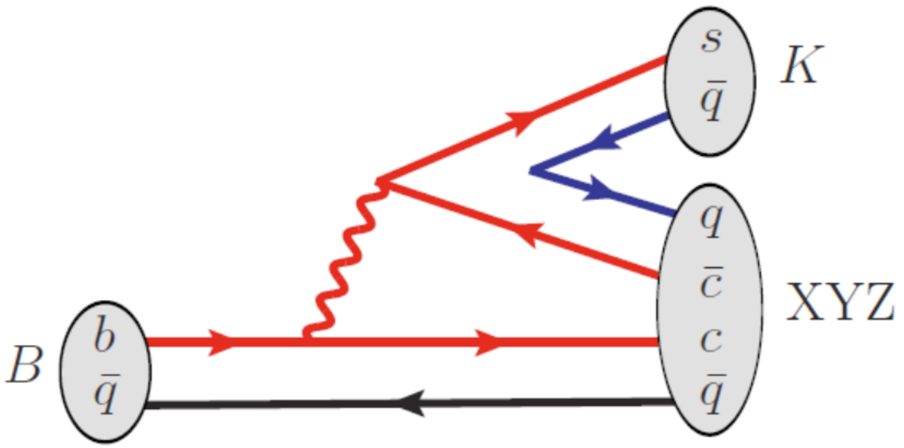
Many XYZ states lie very close to open-charm thresholds

H. X. Chen, W. Chen, X. Liu and S. L. Zhu
Phys. Rept. 639, 1 (2016)

Xiang Liu, Chin. Sci. Bull. 59, 3815 (2014)
F. K. Guo, et al, Rev. Mod. Phys. 90, 015004 (2018)
A. Hosaka, et al, PTEP 2016, 062C01 (2016)
Y. R. Liu, et al, Prog. Part. Nucl. Phys. 107, 237 (2019)
N. Brambilla, et al, Phys. Rept. 873, 1-154 (2020)

Questions: How to establish the charmoniumlike molecules?

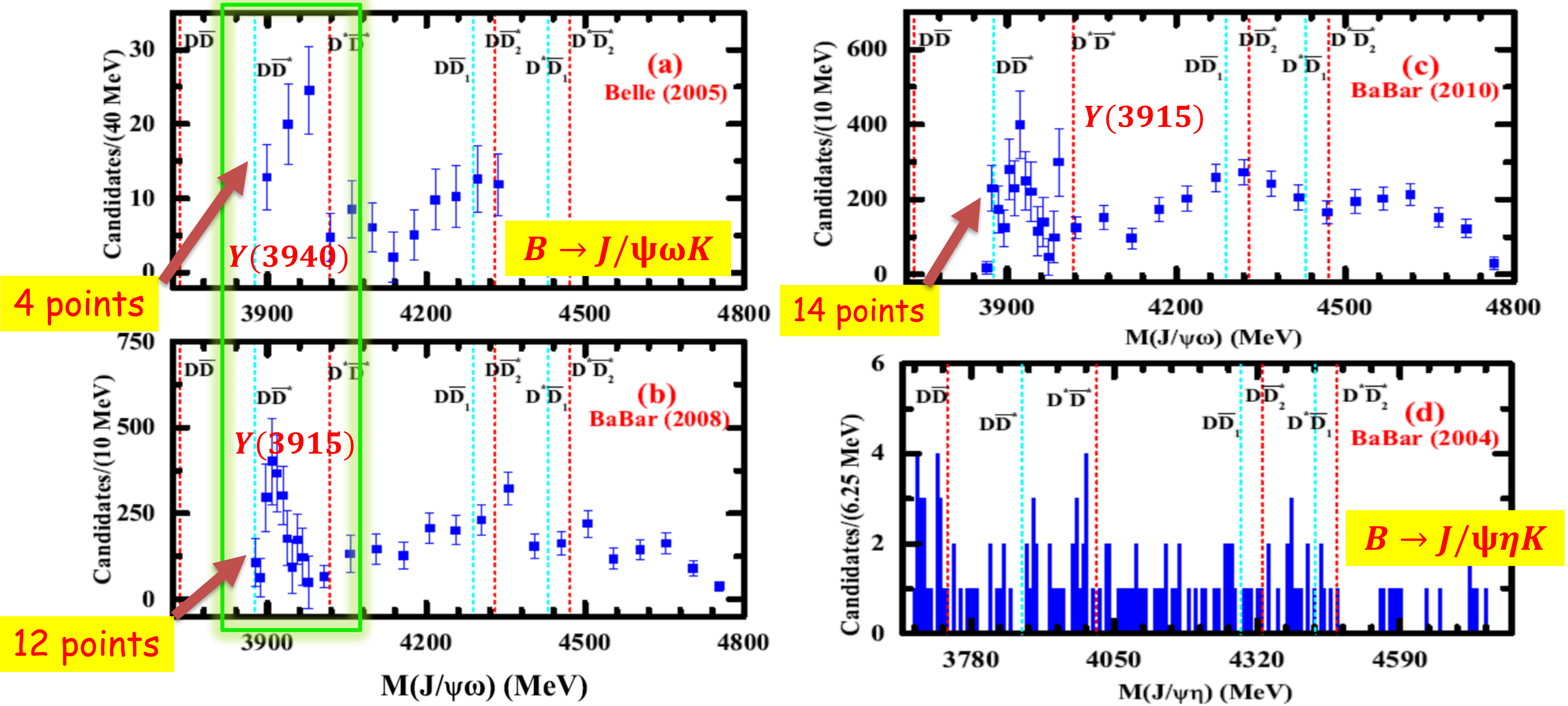




$\Lambda_b \rightarrow P_c + K$ $\quad$ $B \rightarrow X/Y/Z + K$

- Production mechanism: b quark weak decay, very similar
- Pc states as hidden-charm molecular pentaquarks
- B -> XYZ + K should be the ideal processes to produce the charmoniumlike molecules

Isoscalar XYZ data without hidden-strange quantum number



- Structures in $J/\psi\omega$ below $D^*\bar{D}^*$ thresholds: two substructures exist or not?
- Structures in $J/\psi\eta$ below $D^*\bar{D}^*$ thresholds: a single peak exist or not?
- How to understand the very broad structure around 4.3 GeV in $J/\psi\omega$?

(a) Phys. Rev. Lett. 94, 182002 (b) Phys. Rev. Lett.101, 082001 (c) Phys. Rev. D 82, 011101 (d) Phys. Rev. Lett. 93, 041801

II. New characteristic spectrum to identify charmoniumlike molecules

1. Mass spectrum for the isoscalar $D^*\bar{D}^*$ bound states
2. Hidden-charm decay behavior for the isoscalar $D^*\bar{D}^*$ molecular states
3. Other possible DDbar charmoniumlike molecules around 4.3 GeV

One-boson-exchange (OBE) model

Yukawa, Proc. Phys. Math. Soc. Japan 17, 48 (1935)

- 1935, Yukawa: pion-exchange and nucleon-nucleon interaction
- Nijimegen potential and Bonn potential: scalar meson σ **exchange~two** π exchange; vector meson-ρ/ω exchange~**multi-**π exchange

1
- OBE model
- Scattering amplitude

$$\langle f|S|i\rangle = \delta_{fi} + i\langle f|T|i\rangle = \delta_{fi} + i(2\pi)^4\delta^4(p_f - p_i)\mathcal{M}_{fi}$$
$$\langle f|S|i\rangle = \delta_{fi} - i(2\pi)\delta(E_f - E_i)V_{fi}(p)$$

2
- Breit approximation
- Effective potential in momentum space

$$V_{fi}(p) = -\frac{\mathcal{M}_{fi}}{\sqrt{\prod_f 2p_f^0 \prod_i 2p_i^0}} \approx -\frac{\mathcal{M}_{fi}}{\sqrt{\prod_f 2m_f^0 \prod_i 2m_i^0}}$$

3
- Fourier transformation
- Effective potential in coordinate space

$$V(r) = \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} e^{i\boldsymbol{q}\cdot\boldsymbol{r}} \mathcal{V}_{fi}(\boldsymbol{q})\mathcal{F}^2(q^2, m_E^2)$$

One free parameter

Form factor $\mathcal{F}(q^2, m^2) = \frac{\Lambda^2 - m^2}{\Lambda^2 - q^2}$ Λ, m and q are the cutoff, mass and four-momentum of the exchanged meson, respectively.

$\Lambda \sim 1.0$ GeV

N. A. Tornqvist, Z. Phys. C 61, 525 (1994)
N. A. Tornqvist, Nuovo Cim. A 107, 2471 (1994)

Mass spectrum for the isoscalar $D^*\bar{D}^*$ bound states

Charmed mesons: $H\,(D,\ D^*), \{\,0^-|\,1^-\}$, $S(D_0, D_1'), \{\,0^+|\,1^+\}$, $\mathrm{T}\,(D_1, D_2^*), \{\,1^+|\,2^+\}$

S-wave $D^*\bar{D}^*(J^{PC})$: 0^{++}, 1^{+-}, 2^{++}

OBE effective potentials:

$$V\sigma + V\pi + V\eta + V\rho + V\omega$$

$$V^{D^*\bar{D}^*}(r) = -g_s^2\mathcal{Y}_\sigma + \frac{g^2}{3f_\pi^2}\left(\frac{3}{2}\mathcal{Z}_\pi + \frac{1}{6}\mathcal{Z}_\eta\right) - \frac{1}{2}\beta^2 g_V^2\left(\frac{3}{2}\mathcal{Y}_\rho + \frac{1}{2}\mathcal{Y}_\omega\right) + \frac{4}{3}\lambda^2 g_V^2\left(\frac{3}{2}\mathcal{X}_\rho + \frac{1}{2}\mathcal{X}_\omega\right)$$

$0.8 < \Lambda < 2$ **GeV**, exist bound state solutions, isoscalar S-wave $D^*\bar{D}^*$ can be molecular states

Cutoff relation $\Lambda[0(0^{++})] < \Lambda[0(1^{+-})] < \Lambda[0(2^{++})]$

Mass spectrum $M[0(0^{++})] < M[0(1^{+-})] < M[0(2^{++})]$

Bound state solutions

$D^*\bar{D}^*$	GeV Λ	MeV E	fm r_{RMS}
0^{++}	0.86	−0.33	4.74
	0.94	−10.80	1.18
1^{+-}	0.98	−0.60	4.03
	1.07	−11.29	1.18
2^{++}	1.38	−0.32	5.08
	1.97	−12.33	1.31

Hidden-charm decay behavior

Strong decay channels for the isoscalar $D^*\bar{D}^*$ molecules: $D\bar{D}$, $D\bar{D}^*$, $\eta_c\eta^{(\prime)}$, $\eta_c\omega$, $J/\psi\eta$, $J/\psi\omega$

Heavy quark symmetry

$$|0^{++}\rangle = \frac{\sqrt{3}}{2}\left|0_{c\bar{c}}^{-+}, 0_{q\bar{q}}^{-+}, 0^{++}\right\rangle - \frac{1}{2}\left|1_{c\bar{c}}^{--}, 1_{q\bar{q}}^{--}, 0^{++}\right\rangle,$$

$$|1^{+-}\rangle = \frac{1}{\sqrt{2}}\left|0_{c\bar{c}}^{-+}, 1_{q\bar{q}}^{--}, 1^{+-}\right\rangle + \frac{1}{\sqrt{2}}\left|1_{c\bar{c}}^{--}, 0_{q\bar{q}}^{-+}, 1^{+-}\right\rangle,$$

$$|2^{++}\rangle = \left|1_{c\bar{c}}^{--}, 1_{q\bar{q}}^{--}, 2^{++}\right\rangle,$$

Spin parities for heavy quarks

$$|S_{c\bar{c}}^{P_Q,C_Q}, L_{q\bar{q}}^{P_q,C_q}, J^{PC}\rangle$$

Spin parities for light quarks

Numerical calculations: Proceeding
Decay width ~ several MeV

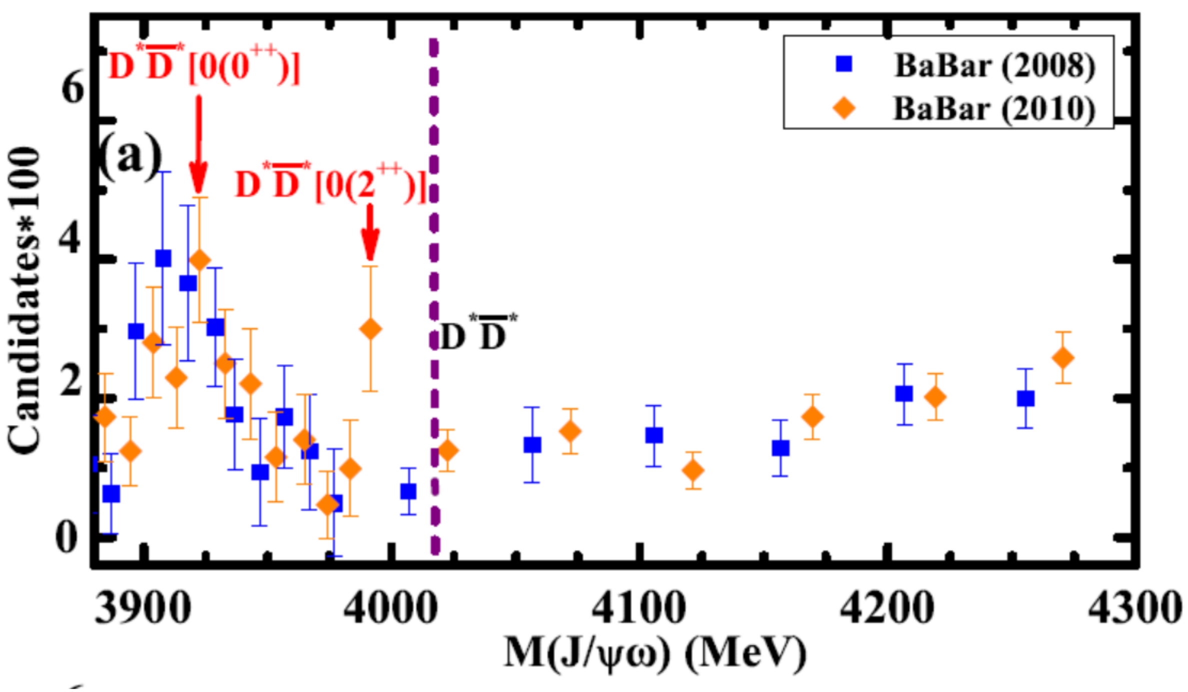
	$\eta_c\eta^{(\prime)}$	$\eta_c\omega$	$J/\psi\eta$	$J/\psi\omega$	Channel
0^{++}	3	×	×	1	$\eta_c\eta^{(\prime)} > J/\psi\omega$
1^{+-}	×	1	1	×	$J/\psi\eta > \eta_c\omega$
2^{++}	×	×	×	1	$J/\psi\omega$

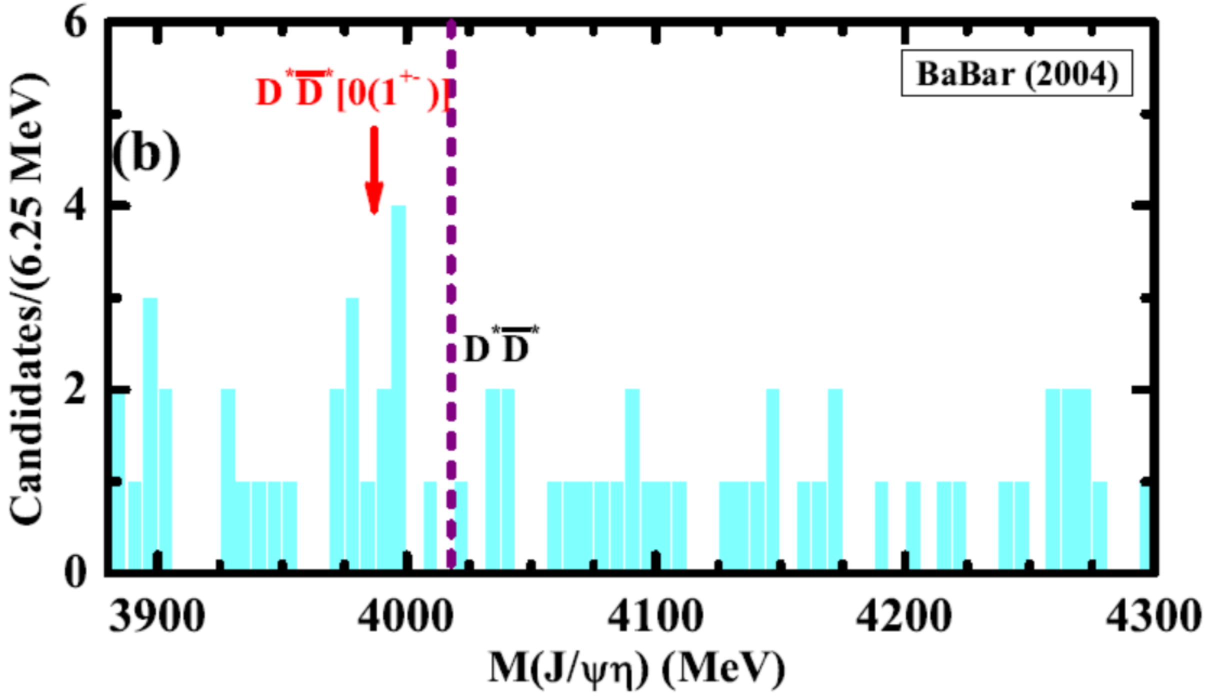
× Suppressed

If the $D^*\bar{D}^*$ can be bound together to form charmoniumlike molecules

- Exist three isoscalar $D^*\bar{D}^*$ molecular states with 0^{++}, 1^{+-}, 2^{++}
- 0^{++} and 2^{++} can appear in the $\mathbf{B} \to J/\psi\omega K$
- 1^{+-} can appear in the $\mathbf{B} \to J/\psi\eta K$

Similar to the Pc(4450) --> Pc(4440) + Pc(4457) with precise data





BaBar, Phys. Rev. Lett.101, 082001(2008) BaBar, Phys. Rev. D 82, 011101(2010) BaBar, Phys. Rev. Lett. 93, 041801 (2004)

Other possible charmoniumlike molecules around 4.3 GeV

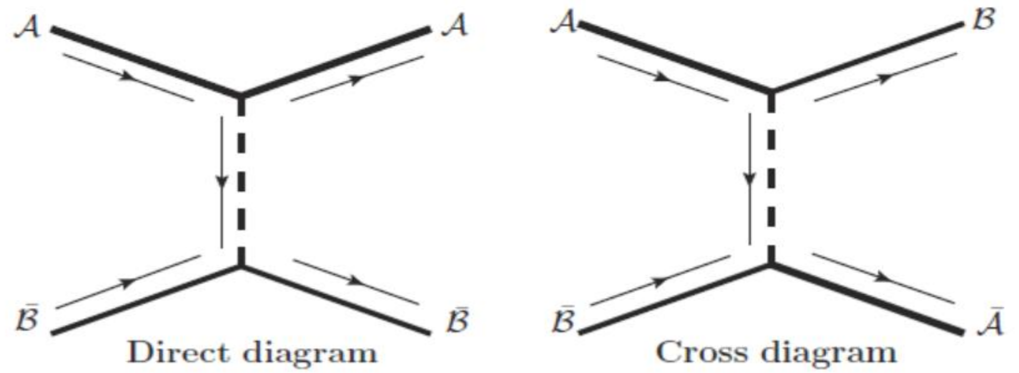


FIG. 6: The direct channel and cross channel Feynman diagrams fo the $\mathcal{A}\bar{\mathcal{B}}$ systems. Here, the notations $\mathcal{A}$ and $\mathcal{B}$ represent two differen charmed (charmed-strange) mesons.

$D\bar{D}_1$

$$\mathcal{V}_D = g_\sigma g_\sigma'' \mathcal{O}_1 Y_\sigma + \frac{1}{2}\beta\beta'' g_V^2 \mathcal{O}_2 \mathcal{G}(I) Y_V,$$

$$\mathcal{V}_C = \frac{2h_\sigma'^2}{9f_\pi^2}(\mathcal{O}_2\mathcal{Z} + \mathcal{O}_3\mathcal{T}) Y_{\sigma 1} + \frac{\zeta_1^2 g_V^2}{3}\mathcal{O}_2 \mathcal{G}(I) Y_{V1}.$$

$D\bar{D}_2^*$

$$\mathcal{V}_D = g_\sigma g_\sigma'' \mathcal{O}_7 Y_\sigma + \frac{1}{2}\beta\beta'' g_V^2 \mathcal{O}_7 \mathcal{G}(I) Y_V,$$

$$\mathcal{V}_C = \frac{h'^2}{f^2}[\mathcal{O}_8\mathcal{Z}\mathcal{Z} + \mathcal{O}_9\mathcal{T}\mathcal{T} + \mathcal{O}_{10}\{\mathcal{T},\mathcal{Z}\}]\mathcal{H}(I) Y_{P2}.$$

Bound states solutions

States$[J^{PC}]$	Λ (GeV)	E (MeV)	r_{RMS} (fm)	States$[J^{PC}]$	Λ	E	r_{RMS}
$D\bar{D}_1[1^{--}]$	1.38	−0.29	4.92	$D\bar{D}_2^*[2^{--}]$	1.46	−0.25	5.08
	1.63	−12.63	1.09		1.85	−12.22	1.11
$D\bar{D}_1[1^{-+}]$	1.39	−0.36	4.72	$D\bar{D}_2^*[2^{-+}]$	1.30	−0.36	4.69
	1.67	−12.13	1.14		1.47	−12.03	1.11

Numerical calculations: Proceeding
Decay width ~ several MeV

Large phase space	$J/\psi\eta$	$J/\psi\omega$
$D\bar{D}_1[1^{--}]$	P-wave	×
$D\bar{D}_1[1^{-+}]$	×	P-wave
$D\bar{D}_2^*[2^{--}]$	P-wave	×
$D\bar{D}_2^*[2^{-+}]$	×	P-wave

Other important decay modes: $\chi_{cJ}\eta$, $\chi_{cJ}\omega$ ~o(1 MeV)

Other possible charmoniumlike molecules around 4.3 GeV

$D^*\bar{D}_1$ (GeV, MeV, fm)

J^{PC}	Λ	E	r_{RMS}
0^{--}	0.96	−0.59	3.73
	1.03	−11.12	1.07
0^{-+}	0.92	−0.56	3.91
	0.99	−11.42	1.08
1^{--}	1.10	−0.48	4.11
	1.20	−12.57	1.03
1^{-+}	1.06	−0.45	4.25
	1.15	−11.80	1.07
2^{--}	2.56	−0.32	4.89
	2.58	−9.86	1.16
2^{-+}	1.73	−0.81	3.68
	2.14	−12.16	1.24

$D^*\bar{D}_2^*$

J^{PC}	Λ	E	r_{RMS}
1^{--}	0.97	−0.27	4.80
	1.05	−10.92	1.09
1^{-+}	0.94	−0.28	4.78
	1.02	−12.82	1.01
2^{--}	1.11	−0.31	4.77
	1.21	−11.55	1.08
2^{-+}	1.21	−0.67	3.68
	1.36	−12.76	1.04
3^{--}	1.97	−0.32	4.94
	2.74	−12.49	1.21
3^{-+}	1.90	−0.32	4.94
	2.87	−12.26	1.23

- ✓ With important pion-exchange interactions
- ✓ Systems with lower spin have stronger attractive interaction
- ✓ $D^*\bar{D}_1$ with $[0^{-\mp}, 1^{-\mp}]$ and $D^*\bar{D}_2^*$ with $[1^{-\mp}, 2^{-\mp}]$ can be promising charmoniumlike molecular candidates

Large phase space	$J/\psi\eta$	$J/\psi\omega$
$D^*\bar{D}_1[0^{--}]$	P-wave	×
$D^*\bar{D}_1[0^{-+}]$	×	P-wave
$D^*\bar{D}_1[1^{--}]$	P-wave	×
$D^*\bar{D}_1[1^{-+}]$	×	P-wave
$D^*\bar{D}_2^*[1^{--}]$	P-wave	×
$D^*\bar{D}_2^*[1^{-+}]$	×	P-wave
$D^*\bar{D}_2^*[2^{--}]$	P-wave	×
$D^*\bar{D}_2^*[2^{-+}]$	×	P-wave

Summary

- Restudy the S -wave interactions between a charmed meson and an anti-charmed meson in the framework of the OBE model.
- A peculiar characteristic mass spectrum of isoscalar $D^*\bar{D}^*$ molecular system to identify the charmoniumlike molecules.
- Find a serial of possible charmoniumlike molecules around 4.2 to 4.4 GeV
- We strongly encourage our experimental colleague to focus on the detail of the structures provided here with more precise data.

Thanks for your attention !