Study of T_{cc} and X(3872)

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Collaborator: G.-J. Wang(KEK), Zhi Yang(UESTC), Makoto Oka(RIKEN), Shi-lin Zhu(PKU)

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QCHSC2024 2024.08.22 Cairns, Queensland, Australia

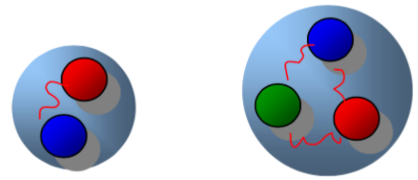
Outline

- Background
- Introduction of HEFT and OBE
- The generation of T_{cc}
- The nature of X(3872)
- Summary and Outlook

Background

Tranditional Qurk model

convential hadron

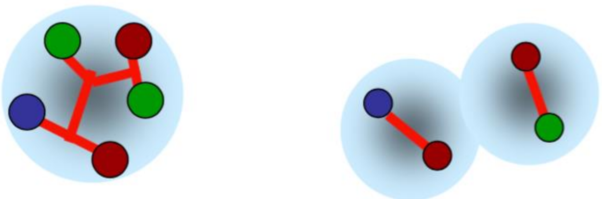


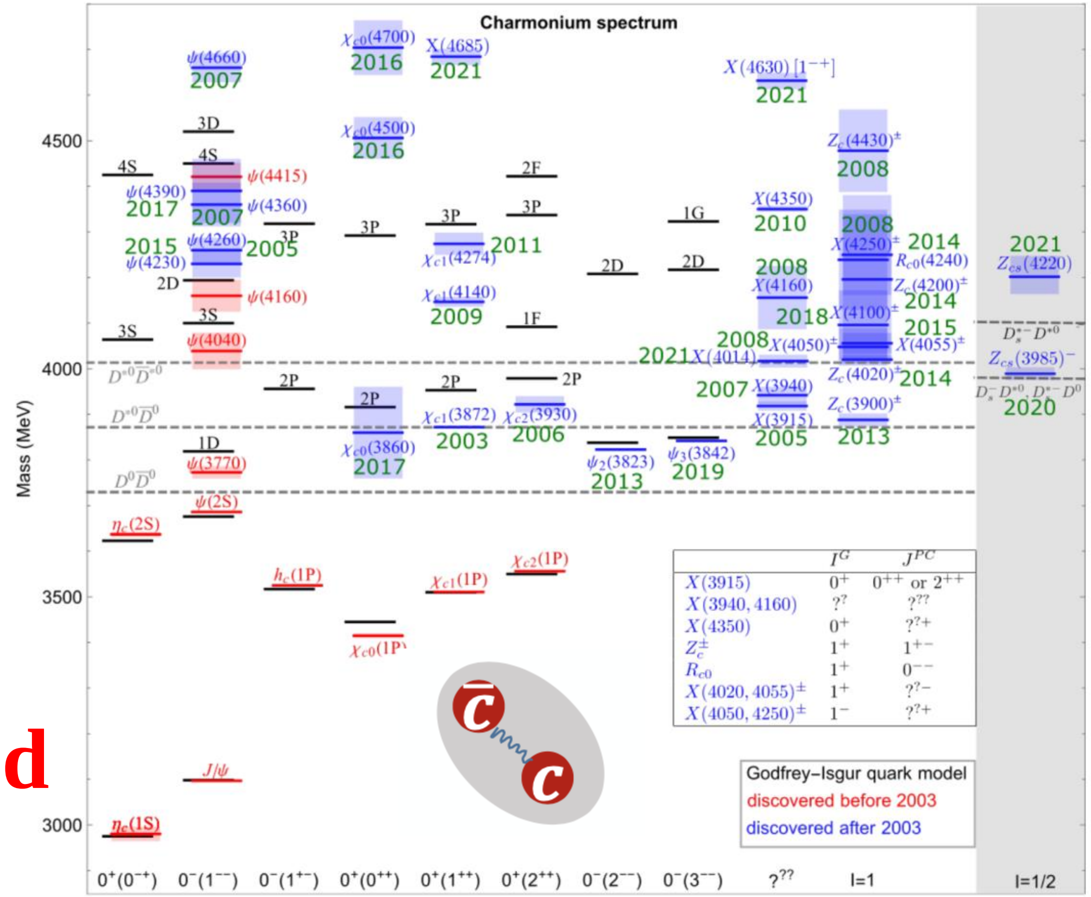
(q $\bar{q}$)　　(qqq)

Excotic

Hybrid　Glueball　Tetraquark

Pentaquark　Hadronic molecule





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strong interaction

- Colorful → quark level
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A more comprehensive framework for systematically describing hadrons

Include quark level and hadron level.

Not only one, at least a set of hadron

Introduction of HEFT

Section B Tue. 16:00 Curtis Abell Δ(1600)
Section C Wed. 18:10 Guang-Juan Wang Ds, Bs
Section C Thu. 14:00 Lu Meng Tcc

$$H = H_0 + H_I$$

$$H_0 = \sum_{i=1,n} |B_i\rangle m_i \langle B_i| + \sum_{\alpha} |\alpha(k_\alpha)\rangle \left[\sqrt{m_{\alpha 1}^2 + k_\alpha^2} + \sqrt{m_{\alpha 2}^2 + k_\alpha^2}\right] \langle \alpha(k_\alpha)|$$

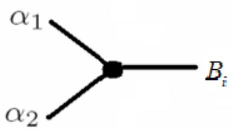
$|B_i\rangle$ bare state， bare mass m_i ⟷ Quark level

$|\alpha(k_\alpha)\rangle$ non-interaction channels ⟷ Hadron level

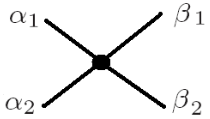
$$H_I = \hat{g} + \hat{v}$$

$$\hat{g} = \sum_{\alpha} \sum_{i=1,n} \left[|\alpha(k_\alpha)\rangle g_{i,\alpha}^{+} \langle B_i| + |B_i\rangle g_{i,\alpha} \langle \alpha(k_\alpha)| \right]$$

$$\hat{v} = \sum_{\alpha,\beta} |\alpha(k_\alpha)\rangle v_{\alpha,\beta} \langle \beta(k_\beta)|$$



From 3P0 model, and the wavefunction of quark model



One boson exchange (OBE)

Resonance
(Mass, width, pole position, coupling)

HEFT

T matrix
(phase shift, Inelascity)

Lattice spectrum

Introduction of HEFT

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$$\hat{g} = \sum_{\alpha} \sum_{i=1,n} \left[\left| \alpha(k_\alpha) \right\rangle g^{+}_{i,\alpha} \left\langle B_i \right| + \left| B_i \right\rangle g_{i,\alpha} \left\langle \alpha(k_\alpha) \right| \right]$$

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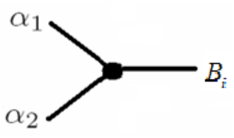

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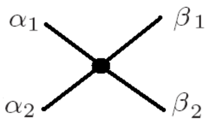
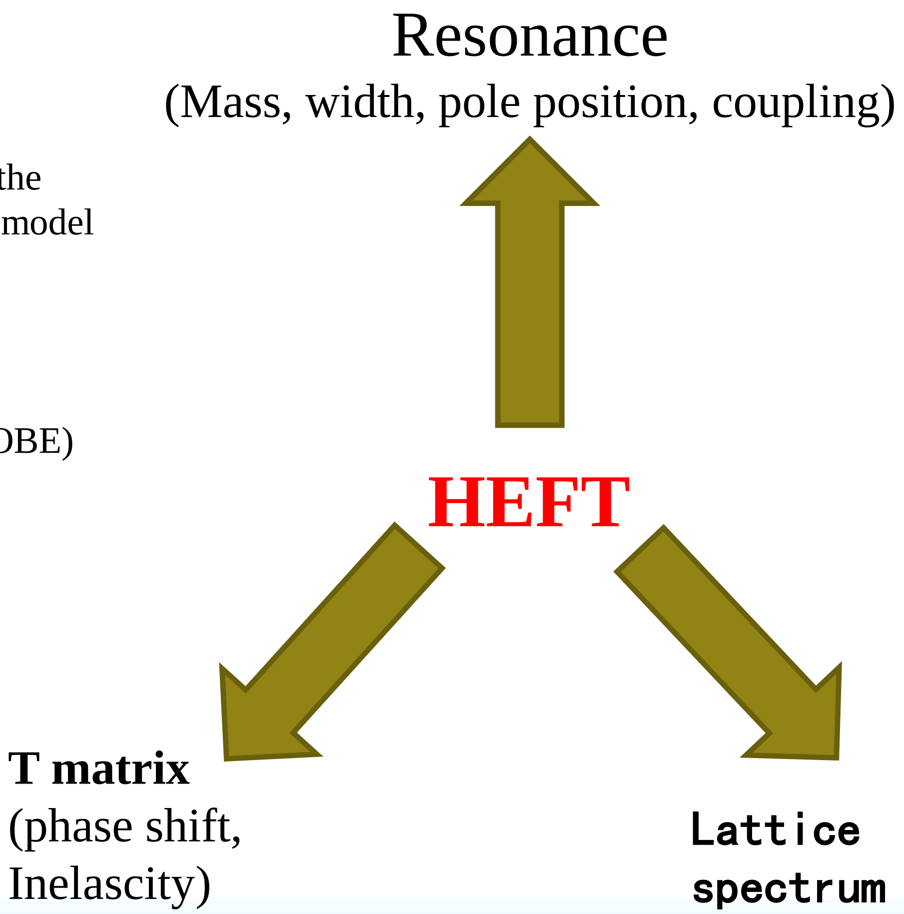


One boson exchange (OBE)

Question： Two interactions ?

Too many solutions of a+b=5



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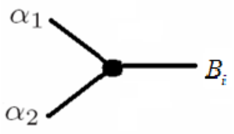

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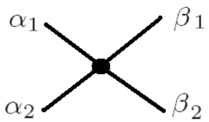

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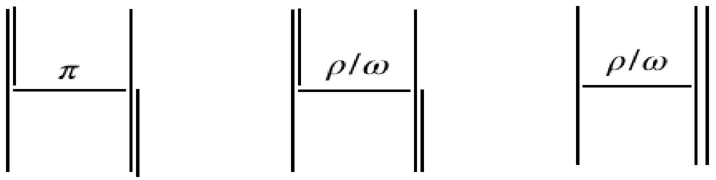
Model dependence!

Study X(3872) from T_{cc}

Introduction of OBE and DD^* vs $D\bar{D}^*$

The interaction between D and D* OBE



$$V_\pi = \frac{g^2}{f_\pi^2}\frac{(q\cdot\epsilon_\lambda)\left(q\cdot\epsilon^\dagger_{\lambda'}\right)}{q^2-m_\pi^2},$$

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$$V^t_{\rho/\omega} = \frac{\beta^2 g_V^2}{2}\frac{\left(\epsilon_\lambda\cdot\epsilon^\dagger_{\lambda'}\right)}{q^2-m^2_{\rho/\omega}}.$$

PWA Just S-wave

$$\mathcal{V}(l,l'S,j) = \frac{1}{(2\pi)^3}\sqrt{\frac{1}{2E^i_D 2E^f_D 2E^i_K 2E^f_K}}$$

$$2\pi\int d\cos\theta V^v(\vec{p}_f,\vec{p}_i)\left(\frac{\Lambda^2}{\Lambda^2+p_f^2}\right)^2\left(\frac{\Lambda^2}{\Lambda^2+p_i^2}\right)^2$$

Heavy Quark Symmetry

$D^{(*)}D^{(*)}$

$$H_a^{(Q)} = \frac{1+\not{v}}{2}\left[P_a^{*\mu}\gamma_\mu - P_a\gamma_5\right]$$

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$$P = (D^0, D^+, D_s^+)\ \&P^* = (D^{*0}, D^{*+}, D_s^{*+})$$

$$\mathcal{L}_{MH^{(Q)}H^{(Q)}} = ig\,\mathrm{Tr}\left[H_b^{(Q)}\gamma_\mu\gamma_5 A^\mu_{ba}\bar{H}_a^{(Q)}\right]$$

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- $g = 0.57$ from the decay width of $D^* \to D\pi$, while undetermined parameters $\lambda \& \beta$.

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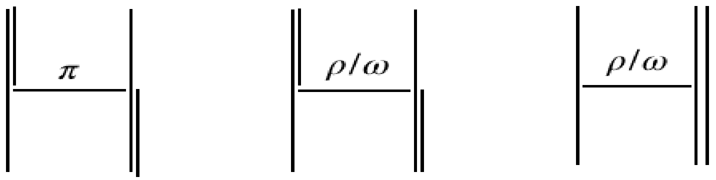

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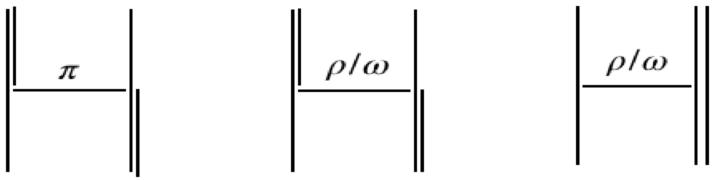

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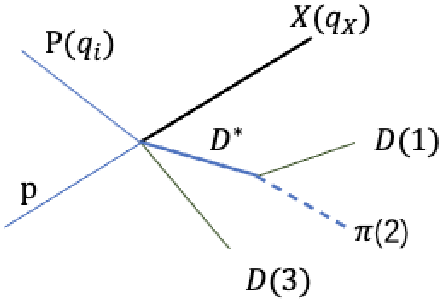
	wave function	$I(J^{PC})$	$u-$ channel : π	$u-$ channel : ρ/ω	$t-$ channel : ρ/ω
DD^*	$\frac{1}{\sqrt{2}}(D^+D^{*0}-D^0D^{*+})$	$0(1^+)$ $[T^+_{cc}]$	$\frac{3}{2}V_\pi$	$\frac{3}{2}V^u_\rho-\frac{1}{2}V^u_\omega$	$-\frac{3}{2}V^t_\rho+\frac{1}{2}V^t_\omega$
	$\frac{1}{\sqrt{2}}(D^+D^{*0}+D^0D^{*+})$	$1(1^+)$	$\frac{1}{2}V_\pi$	$\frac{1}{2}V^u_\rho+\frac{1}{2}V^u_\omega$	$\frac{1}{2}V^t_\rho+\frac{1}{2}V^t_\omega$
$D\bar{D}^*$	$\frac{1}{\sqrt{2}}([D^+D^{*-}]+[D^0\bar{D}^{*0}])$	$0(1^{++})[X(3872)]$	$\frac{3}{2}V_\pi$	$-\frac{3}{2}V^u_\rho-\frac{1}{2}V^u_\omega$	$-\frac{3}{2}V^t_\rho-\frac{1}{2}V^t_\omega$
	$\frac{1}{\sqrt{2}}([D^+D^{*-}]-[D^0\bar{D}^{*0}])$	$1(1^{++})$	$-\frac{1}{2}V_\pi$	$\frac{1}{2}V^u_\rho-\frac{1}{2}V^u_\omega$	$\frac{1}{2}V^t_\rho-\frac{1}{2}V^t_\omega$
	$\frac{1}{\sqrt{2}}(\{D^+D^{*-}\}+\{D^0\bar{D}^{*0}\})$	$0(1^{+-})[h_c]$	$-\frac{3}{2}V_\pi$	$\frac{3}{2}V^u_\rho+\frac{1}{2}V^u_\omega$	$-\frac{3}{2}V^t_\rho-\frac{1}{2}V^t_\omega$
	$\frac{1}{\sqrt{2}}(\{D^+D^{*-}\}-\{D^0\bar{D}^{*0}\})$	$1(1^{+-})$ $[Z_c(3900)]$	$\frac{1}{2}V_\pi$	$-\frac{1}{2}V^u_\rho+\frac{1}{2}V^u_\omega$	$\frac{1}{2}V^t_\rho-\frac{1}{2}V^t_\omega$

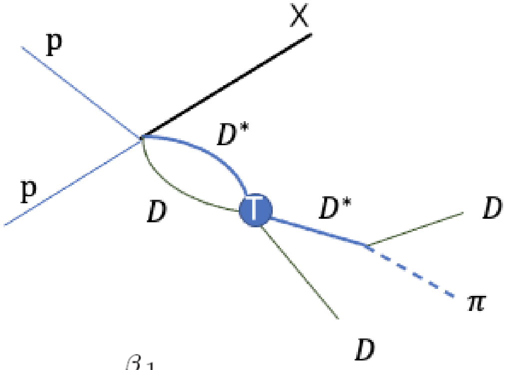
The mass differences leads to isospin breaking, our calculations are based on the physical states of the particles.

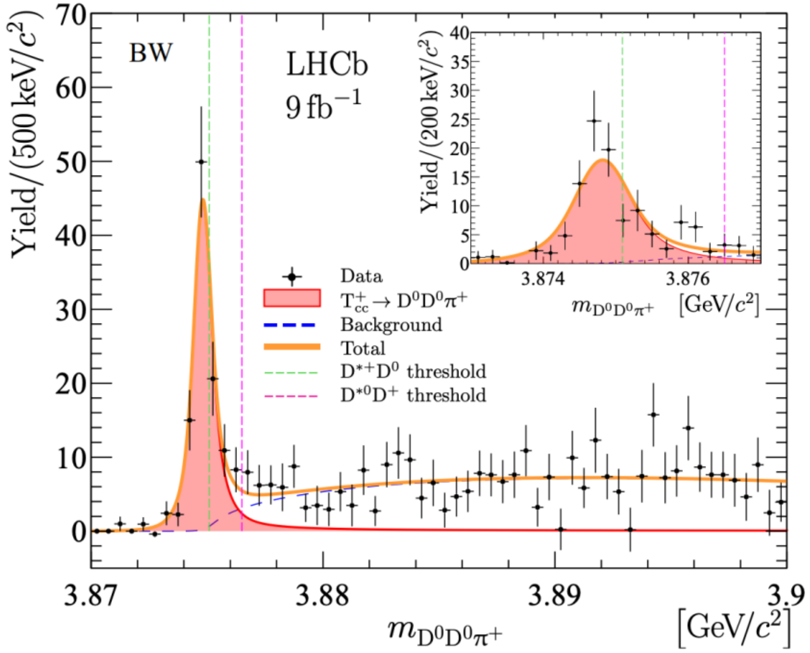
The generation of T_{cc}

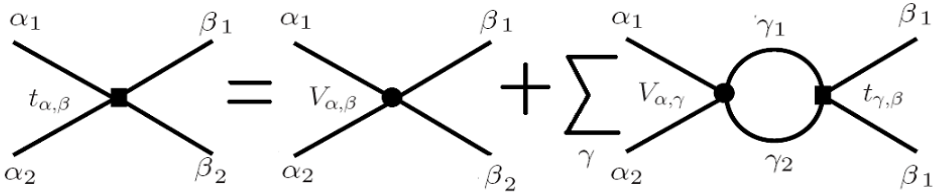
$pp \to X\, D^0 D^0 \pi^+$

p^t









$$t_{\alpha,\beta}(k_\alpha,k_\beta,E)=V_{\alpha,\beta}(k_\alpha,k_\beta)+\sum_\gamma\int k_\gamma{}^2 dk_\gamma \frac{V_{\alpha,\gamma}(k_\alpha,k_\gamma)t_{\gamma,\beta}(k_\gamma,k_\beta,E)}{E-\sqrt{m_{\gamma1}^2+k_\gamma^2}-\sqrt{m_{\gamma2}^2+k_\gamma^2}+i\varepsilon}$$

$$|\mathcal{M}|^2=|a_{pp\to DD^*X}|^2\sum_{\lambda_X}\epsilon_\mu(p_X,\lambda_X)\epsilon^\dagger_{\mu'}(p_X,\lambda_X)\sum_j\mathcal{B}_{j\mu}\mathcal{B}_j^{\dagger\mu'}$$

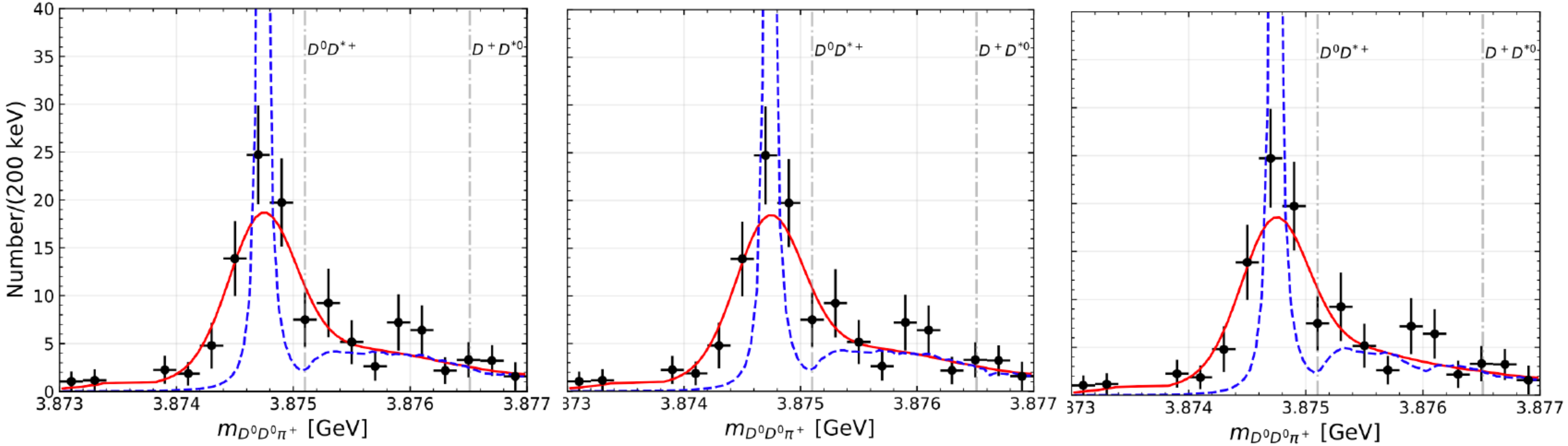
$$\mathcal{B}_j^\mu(p_{12},p_{23})=g\left\{\frac{-i(p_\pi^\mu-\frac{p_{12}^\mu p_{12}\cdot p_\pi}{m_{D^*}^2})}{p_{12}^2-m_{D^*}^2+im_{D^*}\Gamma_{D^*}}\right\}_j+\sum_{i=1,2}ig\left\{\int dq_{D^*}q_{D^*}^2\frac{d\Omega_{q_{D^*}}}{4\pi}\frac{\sqrt{2w_{D_2}}}{\sqrt{2w_{D^*}}}\frac{\sqrt{2w_{D^*_{12}}}}{\sqrt{2w_D}}\frac{T_{ij}^{J00}(M,|q_{D^*}|,|p_{12}|)}{(M-w^i_{D^*})-w^i_D+i\epsilon}\frac{\epsilon_a^{*\mu}(w_{D^*},q_{D^*})\epsilon_a(p_{12})\cdot p_\pi}{p_{12}^2-m_{D^*}^2+im_{D^*}\Gamma_{D^*}}\right\}_j+(p_{D_1}\to p_{D_2})$$

The generation of T_{cc}

$pp \to X\ D^0 D^0 \pi^+$

Λ(fixed)	λ (/GeV)	β
0.8 GeV	0.890 ± 0.20	0.810 ± 0.11
1 GeV	0.683 ± 0.025	0.687 ± 0.017
1.2 GeV	0.587 ± 0.21	0.550 ± 0.12
1.17 GeV	0. 56	0. 9

Cheng, et al. PRD 106,016012



Λ (GeV)	BE (keV)	Γ (keV)	$\sqrt{\langle r^2\rangle}$	$I=0$	$I=1$	$P(D^0D^{*+})$	$P(D^+D^{*0})$	$\frac{\text{Res}(D^0D^{*+})}{\text{Res}(D^+D^{*0})}$
0.8	-387.7	67.3	4.8 fm	95.8%	4.2%	70.0%	30.0%	$-1.063+0.001I$
1.0	-393.0	70.4	4.7 fm	95.8%	4.2%	70.0%	30.0%	$-1.055+0.001I$
1.2	-391.6	72.7	4.7 fm	95.7%	4.3%	70.3%	29.7%	$-1.052+0.001I$

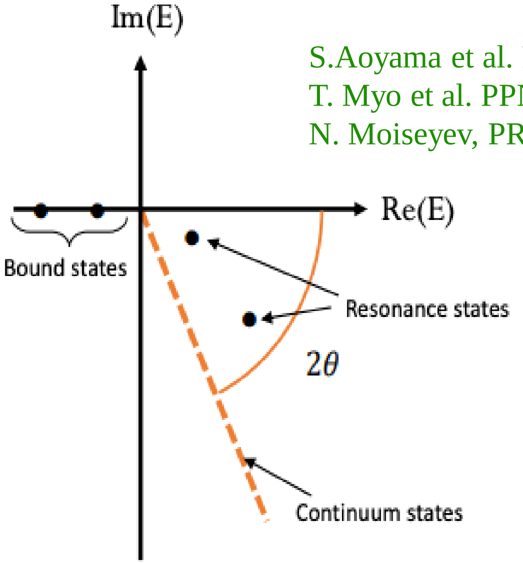
The nature of T_{cc}

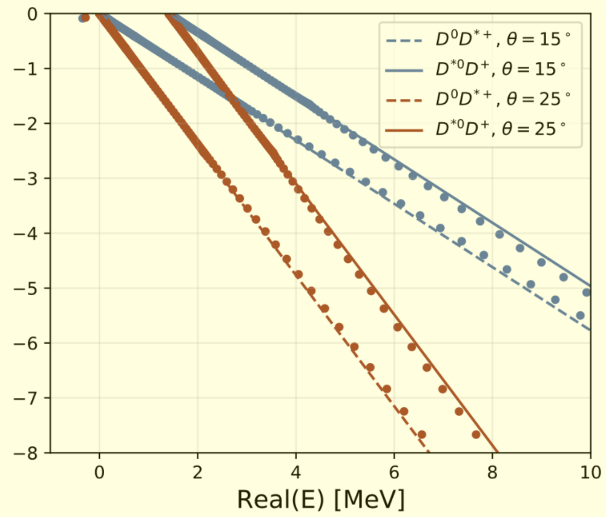
Complex scaling method

$$\boldsymbol{r} \rightarrow \boldsymbol{r}e^{i\theta}, \quad \boldsymbol{q} \rightarrow \boldsymbol{q}e^{-i\theta} \qquad H_\theta \Phi_\theta = E_\theta \Phi_\theta,$$

$$\begin{pmatrix} \overline{D^{*0}}D^0 \,/\, \overline{D^0}D^{*0} & \text{Coupled-channel effect} \\ \cdots & D^{*-}\,D^+/D^{*+}\,D^- \end{pmatrix}$$

S.Aoyama et al. PTP. 116, 1 (2006).
T. Myo et al. PPNP. 79, 1 (2014)
N. Moiseyev, PR 302, 212 (1998)





- **Bound state: T_{cc}**

$m_{T_{cc}}$=3874.7 MeV,
$\Delta E = -393$ keV
$\Gamma_{T_{cc}} = 70.4$ keV

- $\sqrt{\langle r^2 \rangle} = 4.7\, fm$

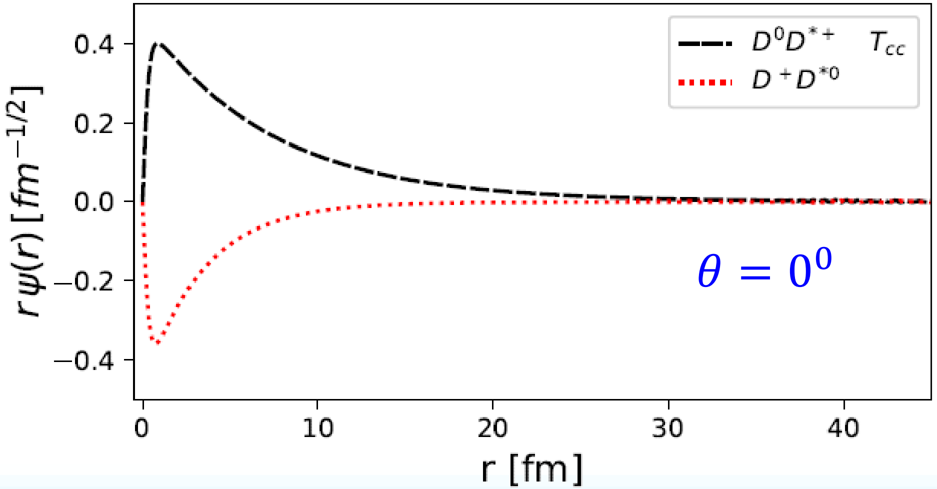
- 70.0% $D^{*+}D^0$, 30.0% D^+D^{*0}

95.8%, $DD^*(I=0)$
4.2% $DD^*(I=1)$

Because of mass difference

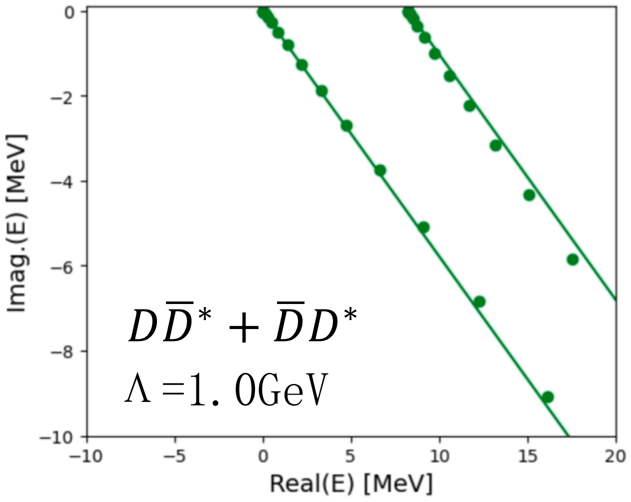
$$[I=0] = \frac{1}{\sqrt{2}}(D^{*+}D^0 - D^{*0}D^+)$$

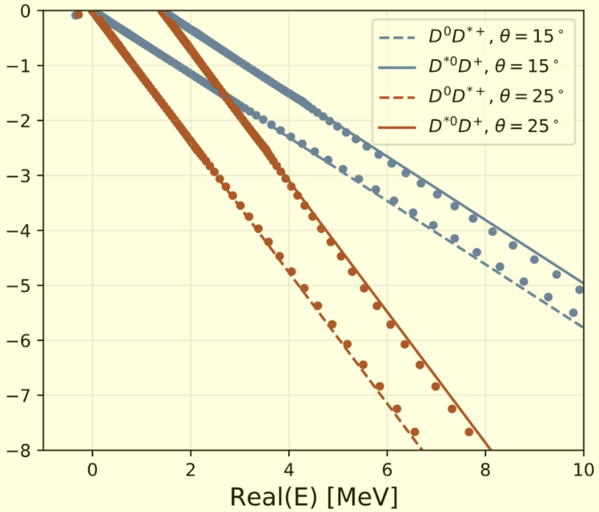
$$[I=1] = \frac{1}{\sqrt{2}}(D^{*+}D^0 + D^{*0}D^+)$$



Produce X(3872) with pure $D\bar{D}^* + \bar{D}D^*$

From the interaction of DD^* to obtain the interaction of $D\bar{D}^* + \bar{D}D^*$, check X(3872) exists or not by pure $D\bar{D}^* + \bar{D}D^*$ interaction, without $c\bar{c}$ state.





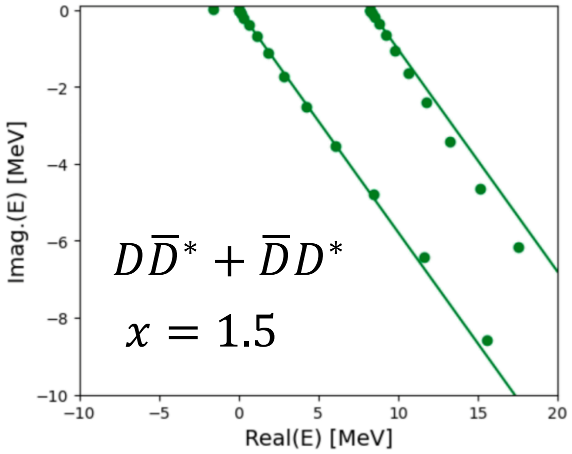
- **Bound state: T_{cc}**

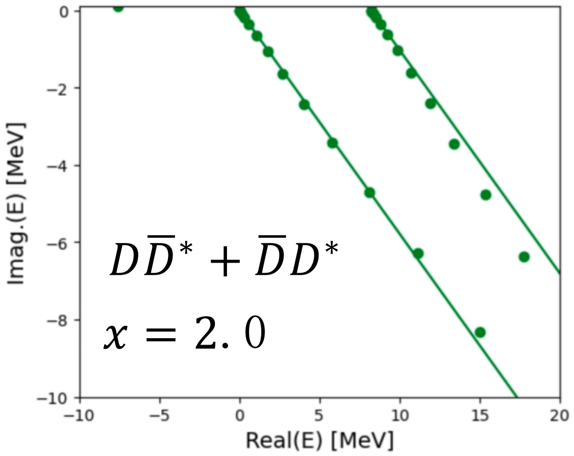
$m_{T_{cc}}$=3874.7 MeV,
$\Delta E = -393$ keV
$\Gamma_{T_{cc}} = 70.4$ keV

- $\sqrt{\langle r^2 \rangle} = 4.7\ fm$

- 70.0% $D^{*+}D^0$, 30.0% D^+D^{*0}

$$\mathbf{V'_{\overline{D^*D}} = x * V_{\overline{D^*D}}}$$



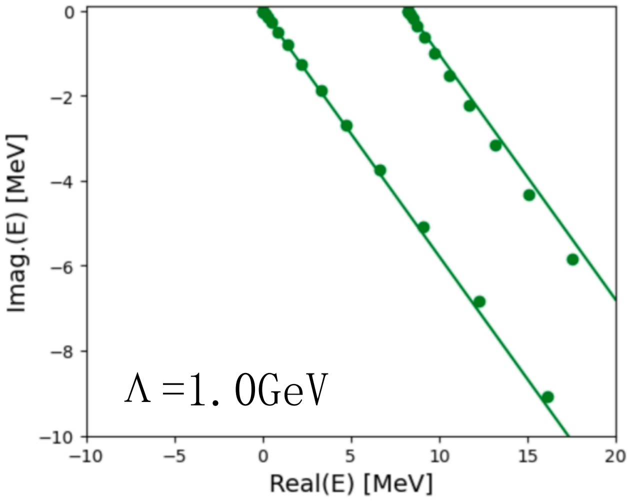


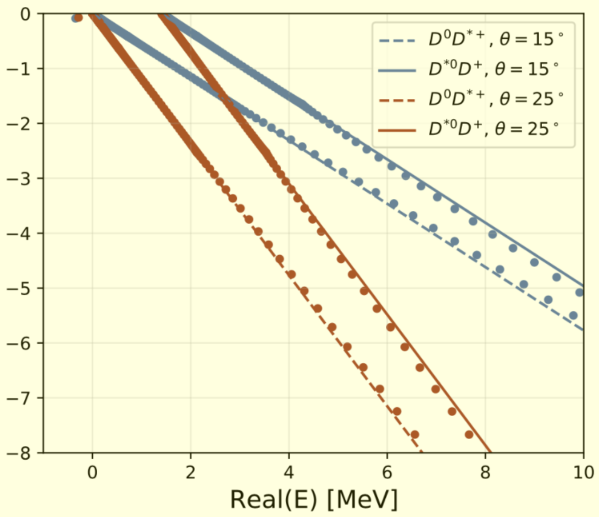
First of all， it is attractive interaction while it is not enough to form a bound state, while just a virtual state

3870.0 + 0.26 i MeV

Produce X(3872) with $D\bar{D}^* + \bar{D}D^*$ and $c\bar{c}$

From the interaction of DD^* to obtain the intraction of $D\bar{D}^* + \bar{D}D^*$, check X(3872) exists or not by pure $D\bar{D}^* + \bar{D}D^*$ interaction, without $c\bar{c}$ state.





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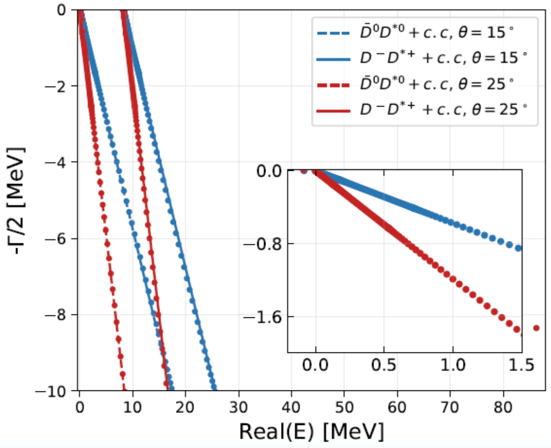
- 70.0% $D^{*+}D^0$, 30.0% D^+D^{*0}

Attractive interaction BUT not enough to form a bound state

- **A bare state shows the $c\bar{c}$ bare state component. χc1(2P, 3940) and its wave function, determined by the quark model.**
- **The interaction parameter γ = 4.69 for the 3P0 model is determined through ψ(3770) to $D\bar{D}$.**
- **Therefore the analysis of X(3872) does not introduce any additional parameters.**



(b)

- **Bound state for X(3872)**

$\Delta E = -80.4$ keV
$\Gamma_{T_{cc}} = 32.5$ keV

- $\sqrt{\langle r^2 \rangle} = 11.2\ fm$

- 94.0% $\bar{D}^{*0}D^0$, 4.8% $D^{*-}D^+$, 1.2% $c\bar{c}$

The nature of T_{cc} and X(3872)

- **T_{cc} bound state of $D^{*+}D^0$**

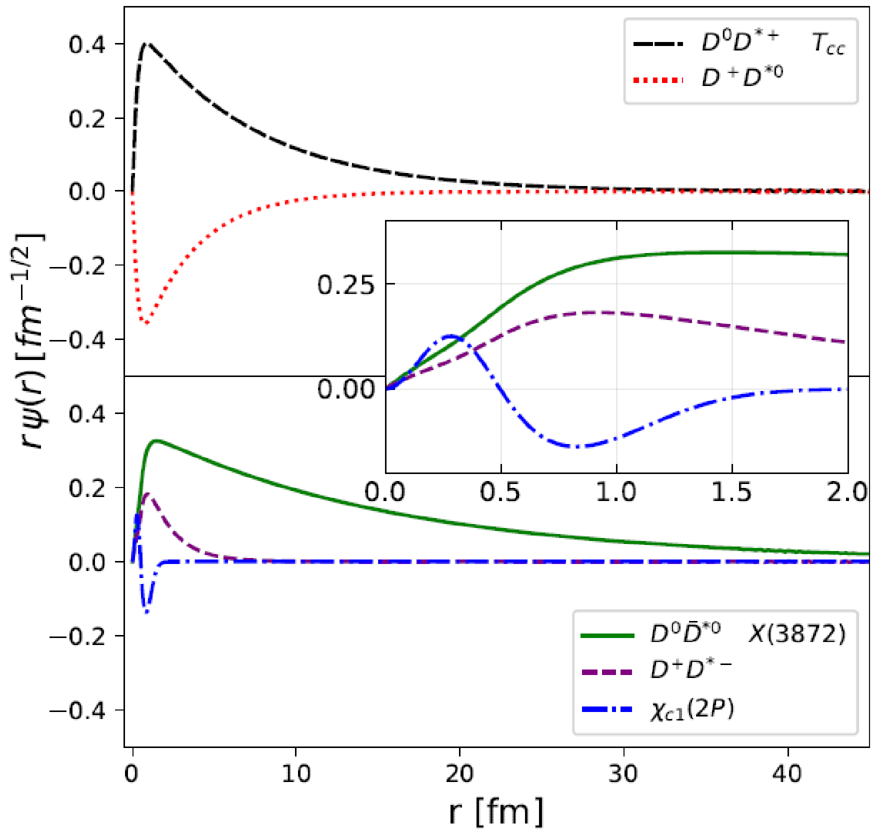
$\Delta E = -393$ keV $\Gamma_{T_{cc}} = 70.4$ keV

- $\sqrt{\langle r^2 \rangle} = 4.7\ fm$
- $70.0\% D^{*+}D^0$, $30.0\% D^+D^{*0}$

- **X(3872) bound state of $\bar{D}^{*0}D^0$**

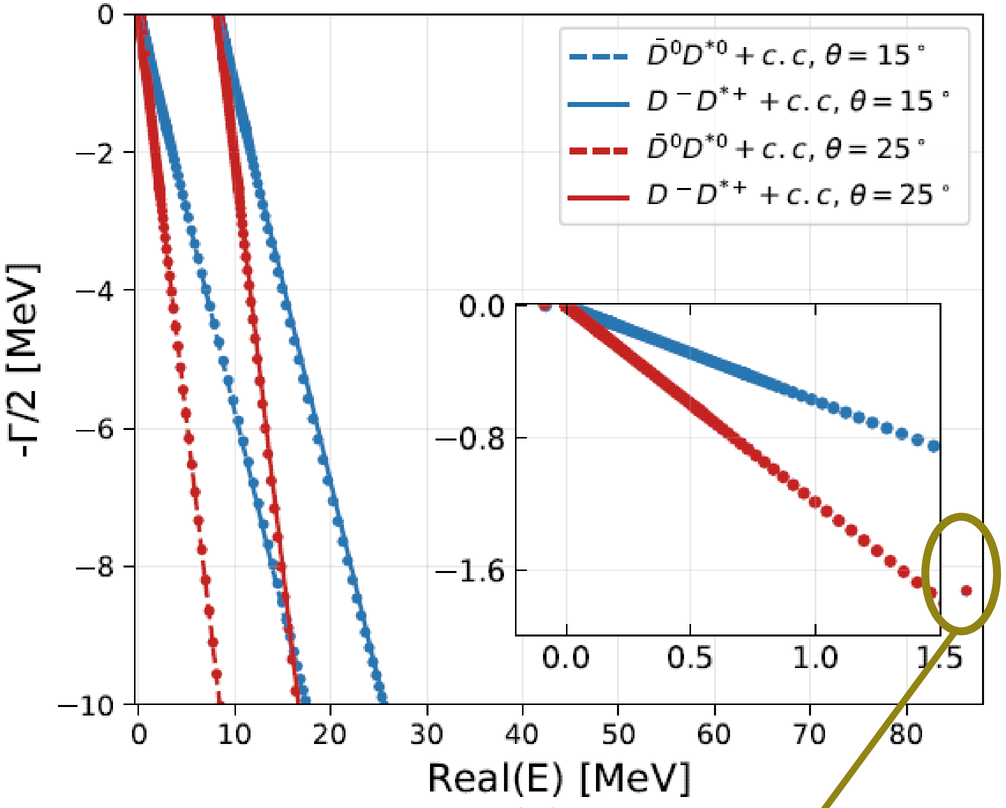
$\Delta E = -80.4$ keV $\Gamma_{T_{cc}} = 32.5$ keV

- $\sqrt{\langle r^2 \rangle} = 11.2\ fm$
- $94.0\% \bar{D}^{*0}D^0$, $4.8\% D^{*-}D^+$, $1.2\%\ c\bar{c}$



ΔE of **X(3872)** is extremely small, a significant $\boldsymbol{D^{*0}\bar{D}^0}$ wave function, dominates in long-range
the $\boldsymbol{c\bar{c}}$ component predominant in short-range, it is important to form this bound state

Prediction



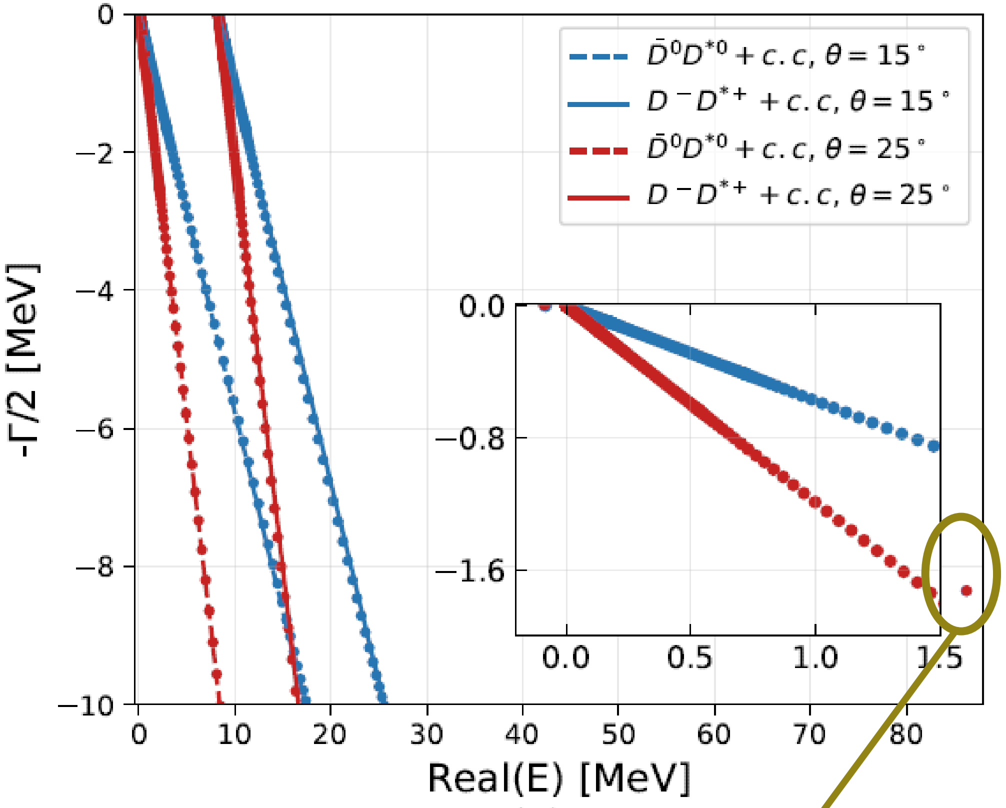
(b)

- χ_{c1}**(2p)**

  M = 3957.9 MeV $\Gamma_{\chi_{c1(2P)}} = 16.7$ MeV

- Main decay channel： $\bar{D}^* D$

Prediction



(b)

- χ_{c1}(2p)

M = 3957.9 MeV $\Gamma_{\chi_{c1(2P)}}$ = 16.7 MeV

- Main decay channel： $\bar{D}^* D$

J^{pc}	$Lq\bar{q}$	$Sq\bar{q}$		
0^{-+}	0	0	$\eta_c(2980)$	$\eta_c(2S)$
1^{--}	0	1	$J/\psi(3096)$	$\psi(2S)$, ····
	2	1	$\psi(3770)$	
1^{+-}	1	0	$h_c(3525)$	z_c
0^{++}	1	1	$\chi_{c0}(3414)$	$\chi_{c0}(3860)$
1^{++}	1	1	$\chi_{c1}(3510)$	?
2^{++}	1	1	$\chi_{c2}(3556)$	$\chi_{c2}(3930)$
2^{--}	2	1	$\psi_2(3823)$	
3^{--}	2	1	$\psi_3(3842)$	
2^{-+}	2	0	?	

Prediction

J^{pc}	$Lq\bar{q}$	$Sq\bar{q}$		
0^{-+}	0	0	$\eta_c(2980)$	$\eta_c(2S)$
1^{--}	0	1	$J/\psi(3096)$	$\psi(2S)$, ····
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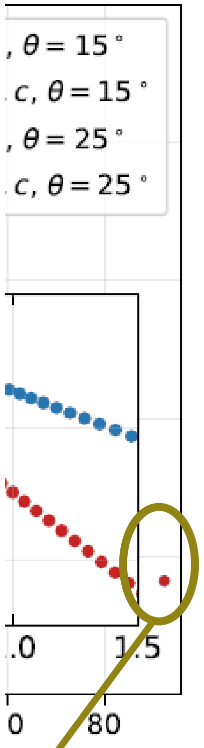
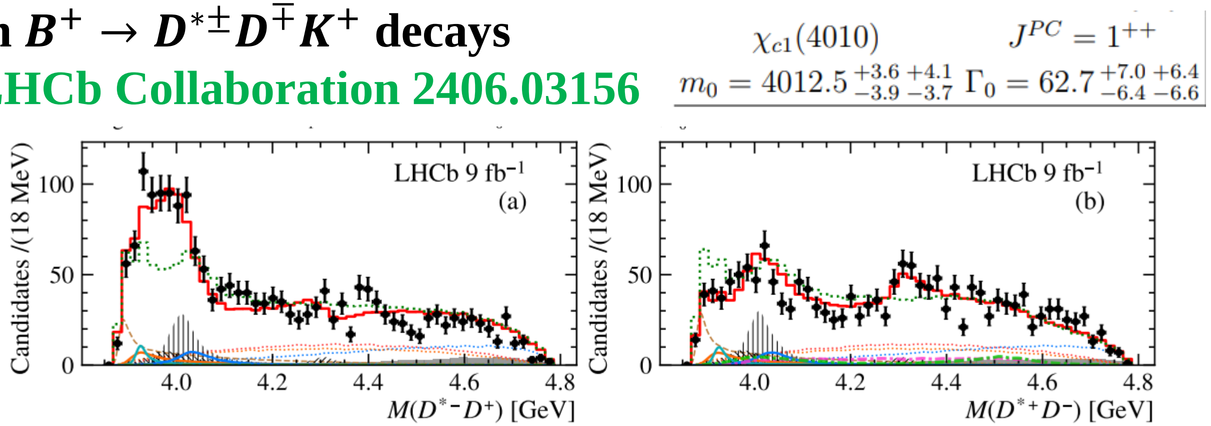
2^{-+}	2	0	?	



Observation of new charmonium(-like) states in $B^+ \to D^{*\pm}D^{\mp}K^+$ decays

LHCb Collaboration 2406.03156



- χ_{c1}(2p)

  M = 3957.9 MeV $\Gamma_{\chi_{c1(2P)}}$ = 16.7 MeV

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Prediction

J^{PC}	$Lq\bar{q}$	$Sq\bar{q}$		
0^{-+}	0	0	$\eta_c(2980)$	$\eta_c(2S)$
1^{--}	0	1	$J/\psi(3096)$	$\psi(2S)$, ….
	2	1	$\psi(3770)$	
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0^{++}	1	1	$\chi_{c0}(3414)$	$\chi_{c0}(3860)$
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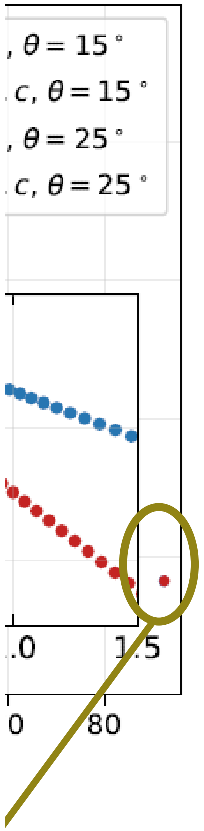
2^{--}	2	1	$\psi_2(3823)$	
3^{--}	2	1	$\psi_3(3842)$	
2^{-+}	2	0	?	



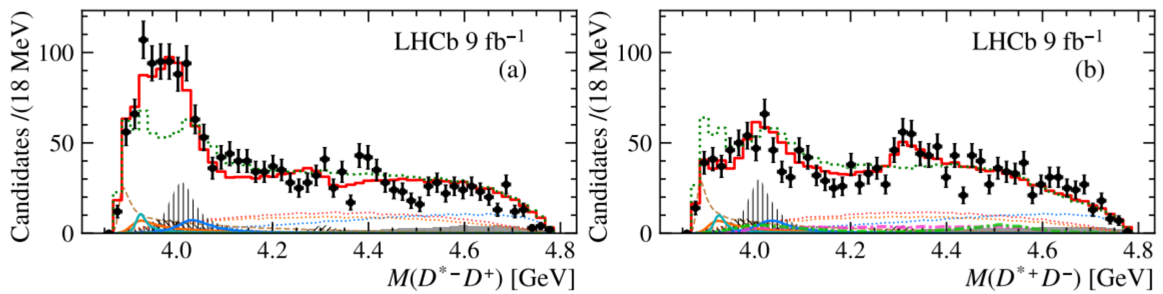
- **$\chi_{c1}(2p)$**
  M = 3957.9 MeV $\Gamma_{\chi_{c1(2P)}}$ = 16.7 MeV
- Main decay channel： $\bar{D}^*D$

Observation of new charmonium(-like) states in $B^+ \to D^{*\pm}D^{\mp}K^+$ decays

LHCb Collaboration 2406.03156

$\chi_{c1}(4010)$ $J^{PC} = 1^{++}$

$m_0 = 4012.5\,^{+3.6}_{-3.9}\,^{+4.1}_{-3.7}$ $\Gamma_0 = 62.7\,^{+7.0}_{-6.4}\,^{+6.4}_{-6.6}$



X(3872) Relevant $D\bar{D}^*$ Scattering in $N_f = 2$ Lattice QCD

H. Li, C. Shi, Y. Chen, M. Gong, J. Liang et al

CLQCD 2402.14541

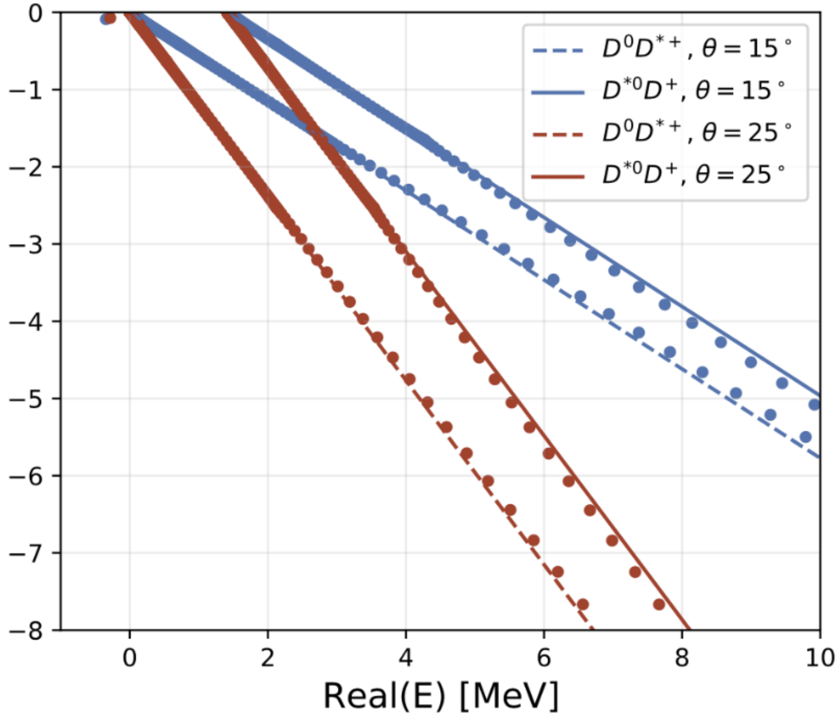
$$t(s) = \frac{K(s)}{1 - K(s)i\rho(s)}$$

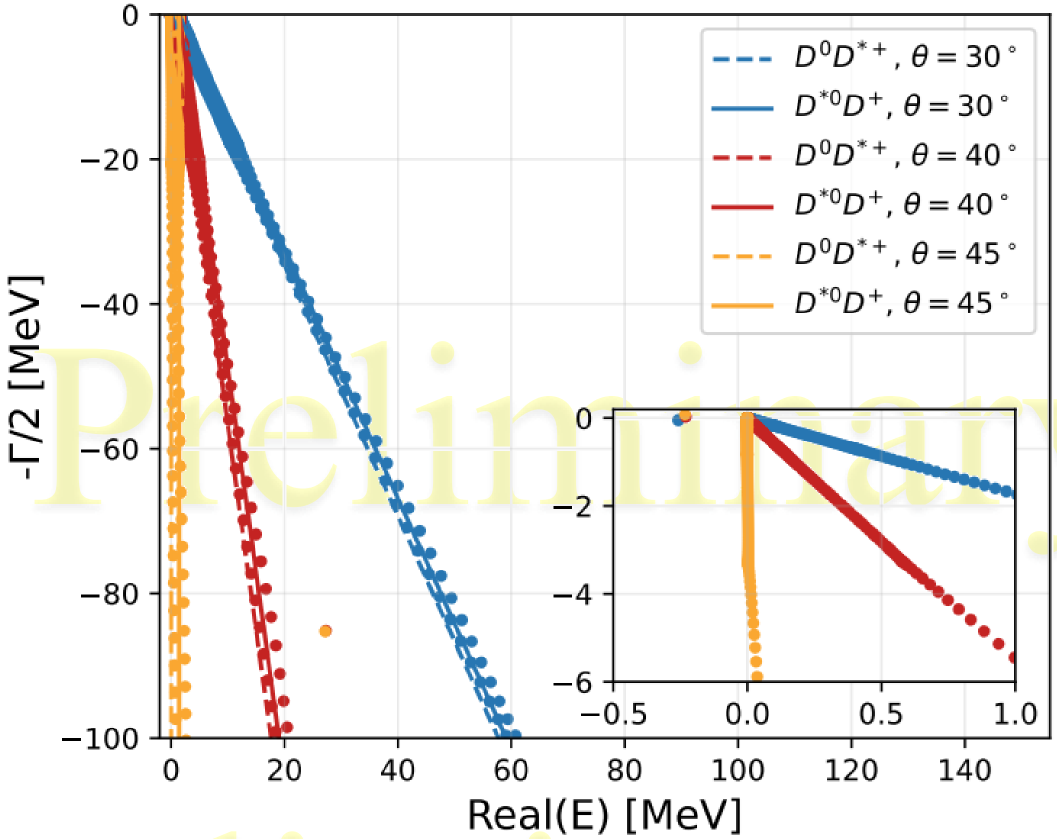
$$K(s) = \frac{g}{M^2 - s} + \gamma$$

m_π(MeV)	250(3)	307(2)	362(1)	417(1)
Bound state from $E_{2,3}$				
E_B(MeV)	$-9.7^{+2.1}_{-2.2}$	$-9.7^{+1.9}_{-2.0}$	$-1.3^{+0.6}_{-0.8}$	$\mathbf{-1.3^{+0.8}_{-1.0}}$
BW fit from $E_{3,4}$				
m_R(MeV)	3924(5)	3926(6)	3969(4)	3995(4)
Γ_R(MeV)	63(23)	57(18)	37(13)	57(10)
Bound state pole and residual from $E_{2,3,4}$				
E_B(MeV)	−11(1)	−10(2)	−1.6(7)	−1.7(7)
Resonance pole and residue				
m_R(MeV)	4008(4)	4029(4)	4050(3)	4071(3)
Γ_R(MeV)	60(6)	38(9)	43(8)	50(7)
$\mathrm{Br}_{D\bar{D}^*}$(%)	∼ 100	∼ 100	∼ 100	∼ 100

中国科学院大学
University of Chinese Academy of Sciences

Prediction





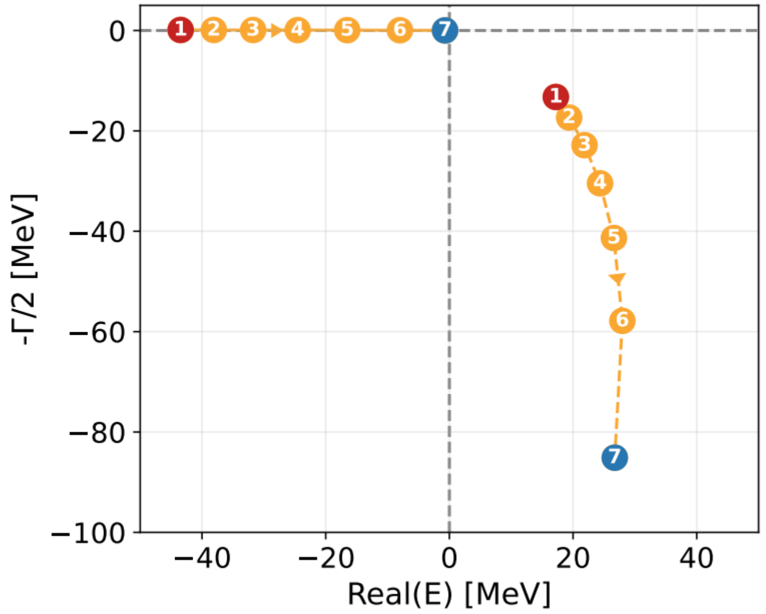
A new T_{cc} resonance M=3902.4 MeV , Γ=170.3 MeV， I ~ 1

Summary

- Through Tcc to determine the DD^* interaction
- Through fixed DD^* interaction, and the nature of bare state to study X(3872)
- We find that the $\bar{D}D^*$ component dominates in X(3872), but it is mainly distributed in the long-range part, i.e., >1 fm, while the bare state still dominates in the short-range part.
- We predict X(3957) which may corresponding to X(4010) from LHCb

A more comprehensive framework for systematically describing hadrons

Outlook



T_{bb}

$c \to b$

arXiv 2310.09836

Yu-Shan Ren, Guang-Juan Wang, Zhi Yang, Jia-Jun Wu

T_{cc} → DD^*, $D\bar{D}^*$ interaction

$J/\psi\pi$, $\eta_c\rho$ → Study $Z_c(3900)$, soon …

$c\bar{c}$ state

X(3872)

Study the decay of X(3872), soon…

Study the decay of X(4010)

Lattice spectrum soon…

Thanks for attention

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FB23

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- Few-body aspects of atomic and molecular physics
- Hadrons and related high-energy physics
- Neutrinos and their interactions with matter
- Strange and exotic matter, including hypernuclear physics
- Few-nucleon systems, including QCD inspired approaches
- Few-body aspects of nuclear physics and nuclear astrophysics
- Interdisciplinary aspects of few-body physics and techniques

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