Disentangling the X(3872) with T_{cc}

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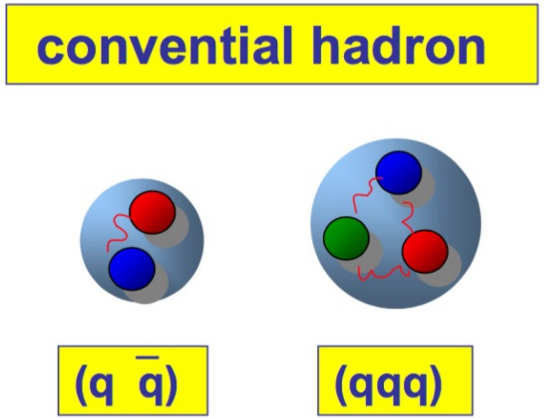
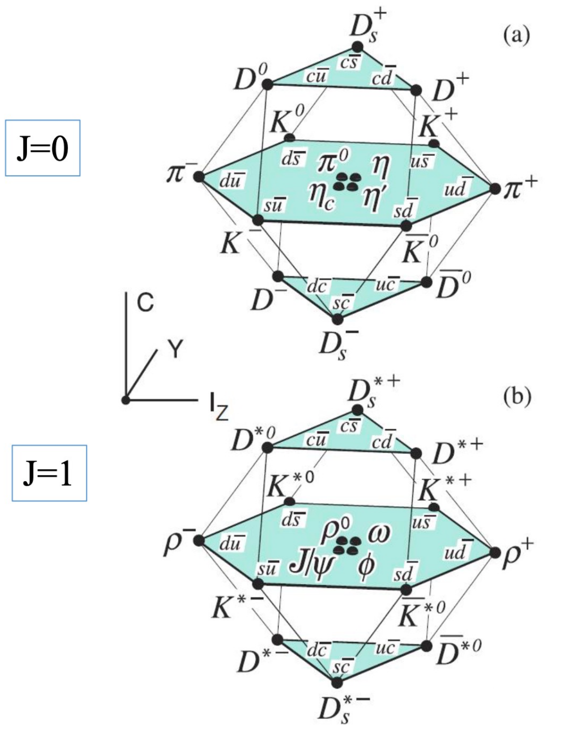
Outlines

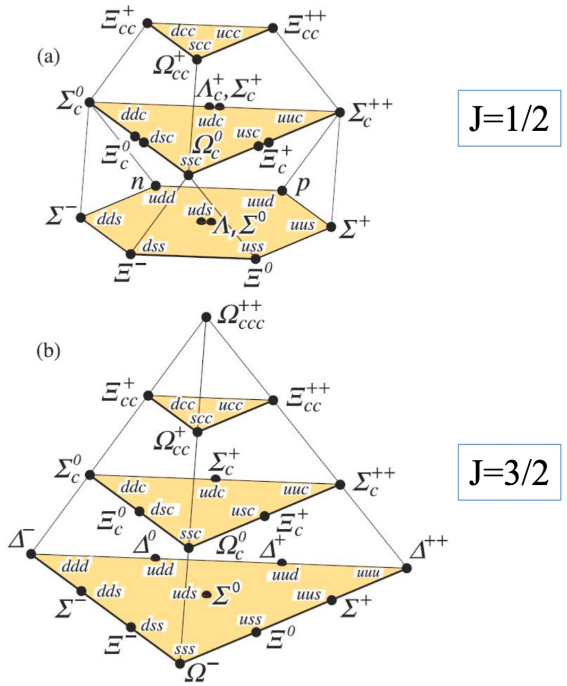
- Background
- Coupled-channel formalism: quark and hadron interactions
  - Production of T_{cc}
  - Properties of $X(3872)$
- Summary

Classical quark model

- Mesons ($\bar{q}q$) and Baryons (qqq) in a simple picture







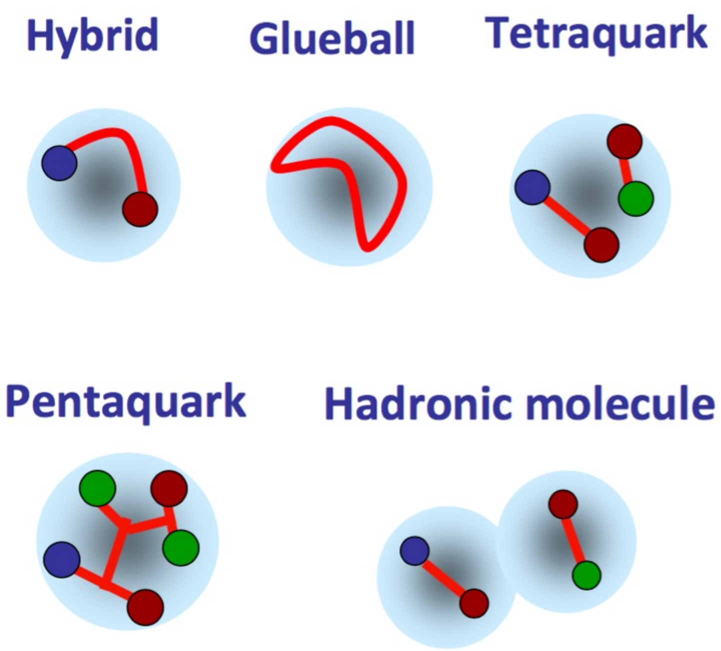
- Predictions for ground & excited hadrons.

- Successfully explained properties of the ground states.

- Failed badly in some excited mesons and baryons.

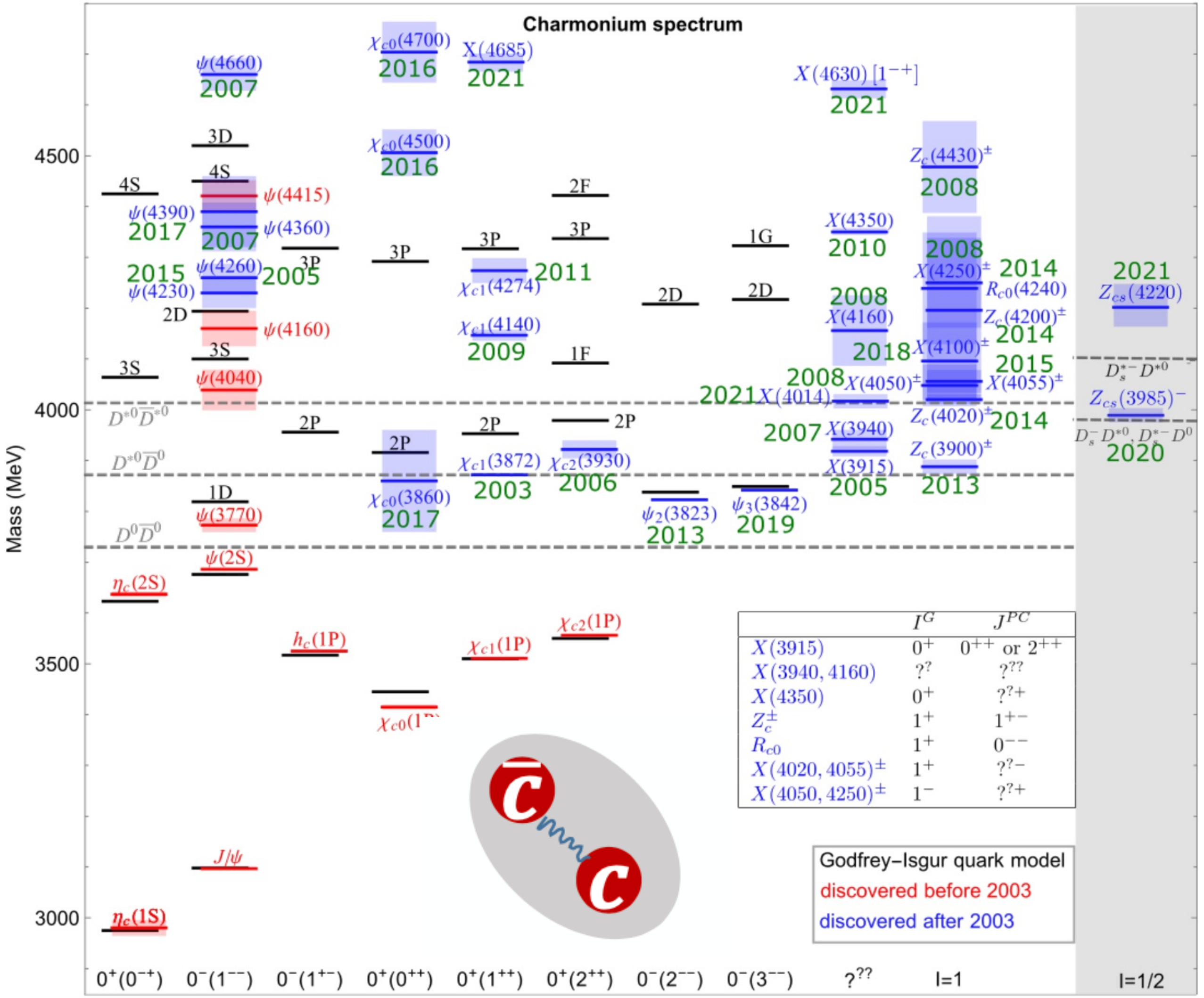
A short review of exotic hadrons

- The quantum chromodynamics (QCD):



More complicated hadron structures.

$D_{s0}^{*}(2317)$ &$X(3872)$@2003,…, P_c @2019, T_{cc}^{+}@2021



Popular star-$X(3872)$

Table 1: The resonance parameters of the $X(3872)$ and its observed productions and decay channels. Here the $X(3872)$ is abbreviated as X.

Experiment	Mass [MeV]	Width [MeV]	Productions and Decay Modes	J^{PC}
Belle [63]	$3872 \pm 0.6 \pm 0.5$	< 2.3	$B \to KX(\to \pi^+\pi^- J/\psi)$	
Belle [75]	–	–	$B \to KX(\to \gamma J/\psi,\ \omega J/\psi \to \pi^+\pi^-\pi^0 J/\psi)$	$C = +1$
Belle [76]	$3875.4 \pm 0.7^{+0.4}_{-1.7} \pm 0.9$	–	$B \to KX(\to D^0\bar{D}^0\pi^0)$	$1^{++}/2^{++}$
Belle [77]	$3871.46 \pm 0.37 \pm 0.07$	–	$B \to KX(\to \pi^+\pi^- J/\psi)$	
Belle [78]	$3872.9^{+0.6+0.4}_{-0.4-0.5}$	$3.9^{+2.8+0.2}_{-1.4-1.1}$	$B \to KX(\to D^{*0}\bar{D}^0)$	
Belle [79]	–	–	$B \to KX(\to \gamma J/\psi)$	
Belle [80]	$3871.84 \pm 0.27 \pm 0.19$	< 1.2	$B \to KX(\to \pi^+\pi^- J/\psi)$	
CDF [67]	$3871.3 \pm 0.7 \pm 0.4$	–	$p\bar{p} \to$ anything $+ X(\to \pi^+\pi^- J/\psi)$	
CDF [81]	–	–	$p\bar{p} \to$ anything $+ X(\to \pi^+\pi^- J/\psi)$	$C = +1$
CDF [82]	–	–	$p\bar{p} \to$ anything $+ X(\to \pi^+\pi^- J/\psi)$	$1^{++}/2^{-+}$
CDF [83]	$3871.61 \pm 0.16 \pm 0.19$	–	$p\bar{p} \to$ anything $+ X(\to \pi^+\pi^- J/\psi)$	
DØ [68]	$3871.8 \pm 3.1 \pm 3.0$	–	$p\bar{p} \to$ anything $+ X(\to \pi^+\pi^- J/\psi)$	
BaBar [84]	3873.4 ± 1.4	–	$B^- \to K^- X(\to \pi^+\pi^- J/\psi)$	
BaBar [85]	$3871.3 \pm 0.6 \pm 0.1$	< 4.1	$B^- \to K^- X(\to \pi^+\pi^- J/\psi)$	
	$3868.6 \pm 1.2 \pm 0.2$	–	$B^0 \to K^0 X(\to \pi^+\pi^- J/\psi)$	
BaBar [86]	–	–	$B \to KX(\to \gamma J/\psi)$	$C = +1$
BaBar [87]	$3875.1^{+0.7}_{-0.5} \pm 0.5$	$3.0^{+1.9}_{-1.4} \pm 0.9$	$B \to KX(\to \bar{D}^{*0}D^0)$	
BaBar [88]	$3871.4 \pm 0.6 \pm 0.1$	< 3.3	$B^+ \to K^+ X(\to \pi^+\pi^- J/\psi)$	
	$3868.7 \pm 1.5 \pm 0.4$	–	$B^0 \to K^0 X(\to \pi^+\pi^- J/\psi)$	
BaBar [89]	–	–	$B \to KX(\to \gamma J/\psi,\ \to \gamma\psi(3686))$	
BaBar [90]	$3873.0^{+1.8}_{-1.6} \pm 1.3$	–	$B \to KX(\to \omega J/\psi \to \pi^+\pi^-\pi^0 J/\psi)$	2^-
LHCb [91]	$3871.95 \pm 0.48 \pm 0.12$	–	$pp \to$ anything $+ X(\to \pi^+\pi^- J/\psi)$	
LHCb [70]	–	–	$pp \to$ anything $+ X(\to \pi^+\pi^- J/\psi)$	1^{++}
LHCb [92]	–	–	$pp \to$ anything $+ X(\to \gamma J/\psi,\ \to \gamma\psi(3686))$	
CMS [73]	–	–	$pp \to$ anything $+ X(\to \pi^+\pi^- J/\psi)$	
BESIII [93]	$3871.9 \pm 0.7 \pm 0.2$	< 2.4	$e^+e^-[\to Y(4260)] \to \gamma X(\to \pi^+\pi^- J/\psi)$	

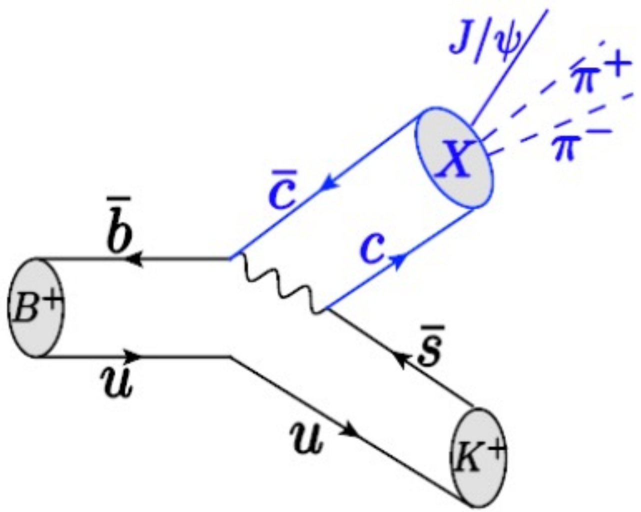
H.X. Chen, et al., Phys. Rept. 639 (2016) 1-121

Observation of a narrow charmonium-like state in exclusive $B^\pm \to K^\pm\pi^+\pi^- J/\psi$ decays

Belle Collaboration
Sep, 2003

10 pages
Published in: *Phys.Rev.Lett.* 91 (2003) 262001
e-Print: hep-ex/0309032 [hep-ex]
DOI: 10.1103/PhysRevLett.91.262001
PDG: chi_c1(3872) --> pi+ pi- J/psi(1S) Show All(5)
Experiments: KEK-BF-BELLE
View in: ADS Abstract Service

pdf links cite claim reference search 2,346 citations



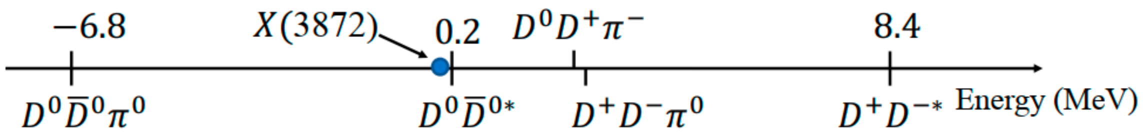
Properties of $X(3872)$

- Aka $\chi_{c1}(2P)$ in PDG. $J^{PC} = 1^{++}$.

- Extremely close to $\bar{D}^{*0}D^0\ /\bar{D}^0D^{*0}$ thresholds

$$\delta m = m_{\overline{D^{*0}}D^0} - m_{X(3872)} = 0.00 \pm 0.18\ \text{MeV}$$

PDG 22



- Large isospin violating decay patterns

$$\frac{\mathcal{B}[X \to J/\psi\pi^+\pi^-\pi^0]}{\mathcal{B}[X \to J/\psi\pi^+\pi^-]} = 1.0 \pm 0.4 \pm 0.3 \quad \text{Belle;} \qquad \frac{\mathcal{B}[X \to J/\psi\omega]}{\mathcal{B}[X \to J/\psi\pi^+\pi^-]} = \begin{cases} 1.6^{+0.4}_{-0.3} \pm 0.2 & \text{BESIII,} \\ 0.7 \pm 0.3 & B^+ \text{ events, BaBar,} \\ 1.7 \pm 1.3 & B^0 \text{ events, BaBar,} \end{cases}$$

L. Meng, et al. Phys. Rept. 1019 (2023) 1-149

Theoretical interpretations of $X(3872)$

- Conventional $\bar{c}c$: $\chi_{c1}(2P)$.

Eichten ,Lane, Quigg, Suzuki, Barnes, Godfrey,...

- Compact tetraquark state.

Close, Maiani, Piccinini, Polosa, Riquer,...

- The $\bar{D}^*D/\bar{D}D^*$ molecular state.

Swanson, Wong, Guo, liu,....

- The mixing of the $\bar{c}c$ core with $\bar{D}^*D\ /\bar{D}D^*$ component.

Chao, H. Q. Zheng, S.Takeuchi, Yu. S. Kalashnikova, P. G. Ortega...

Theoretical interpretations of $X(3872)$

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Mass coincidence with the threshold & large isospin violation?

- The $\bar{D}^*D/\bar{D}D^*$ molecular state.

Swanson, Wong, Guo, liu,....

- The mixing of the $\bar{c}c$ core with $\bar{D}^*D$ /$\bar{D}D^*$ component.

Chao, H. Q. Zheng, S.Takeuchi, Yu. S. Kalashnikova, P. G. Ortega...

✓*Complicated coupled-channel effect:* $\bar{c}c$ & $\bar{D}^{0*}D^0$ /D^+D^{-*}

Proximity to $\bar{D}^{*0}D^0 + c.c$

Isospin breaking: $D^{*-}D^+$-$\bar{D}^{*0}D^0$~ 8MeV+ phase space of $J/\psi\rho$& $J/\psi\omega$

Dominant decay mode: $\Gamma(X \to D^0\bar{D}^0\pi^0)/\Gamma_{\text{total}} = (49^{+18}_{-20})\%$, $\Gamma(X \to \bar{D}^{*0}D^0)/\Gamma_{\text{total}} = (37 \pm 9)\%$, PDG 22

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Coupled-channel Framework

- The Hamiltonian reads

$$H = H_0 + H_I,$$

- Non-interacting Hamiltonian

$$H_0 = \sum_B \underline{|B\rangle} m_B \langle B| + \sum_\alpha \int d^3\vec{k} \underline{|\alpha(\vec{k})\rangle} E_\alpha(\vec{k}) \langle \alpha(\vec{k})|.$$

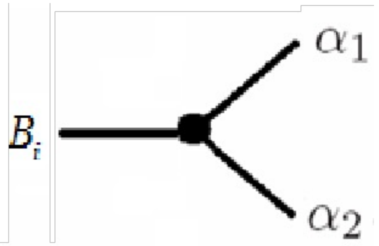
Bare $\bar{c}c$ meson

two-meson state $\bar{D}^* D$ / $\bar{D} D^*$

- Interacting Hamiltonian

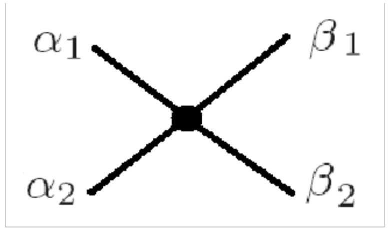
$$H_I = g + v$$

bare state core -> channel：



$$g = \sum_{\alpha,B} \int d^3\vec{k} \left\{ |\alpha(\vec{k})\rangle g_{\alpha B}(|\vec{k}|) \langle B| + h.c. \right\}$$

channel -> channel：

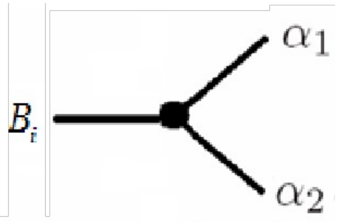


$$v = \sum_{\alpha,\beta} \int d^3\vec{k} d^3\vec{k}' |\alpha(\vec{k})\rangle V^L_{\alpha,\beta}(|\vec{k}|, |\vec{k}'|) \langle \beta(\vec{k}')|$$

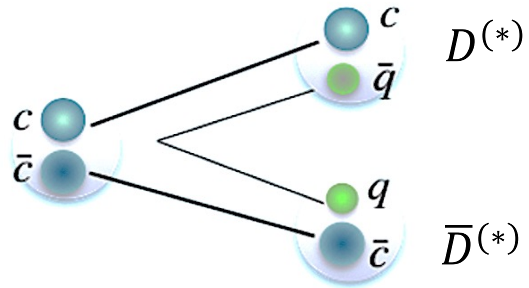
Coupled-channel Framework

- Interacting Hamiltonian $H_I = g + v$

bare state core -> channel：



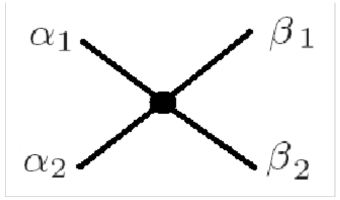
$$g = \sum_{\alpha,B} \int d^3\vec{k} \left\{ |\alpha(\vec{k})\rangle g_{\alpha B}(|\vec{k}|)\langle B| + h.c. \right\}$$



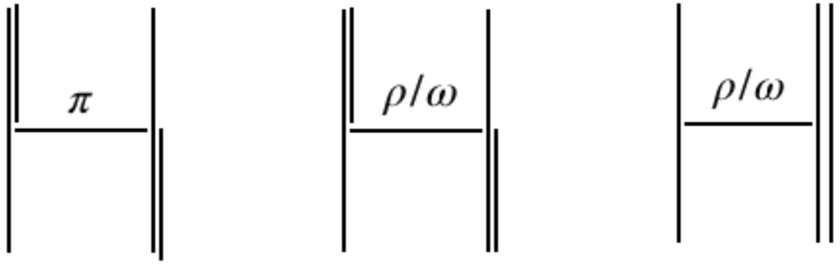
$$g_{D\bar{D}^*,c\bar{c}}(|\vec{k}_{D\bar{D}^*}|) = \gamma I_{D\bar{D}^*,c\bar{c}}(|\vec{k}_{D\bar{D}^*}|)$$

$\gamma = 4.69 - \psi(3770)(\bar{c}c\ {}^3D_1)$

channel -> channel：



$$v = \sum_{\alpha,\beta} \int d^3\vec{k} d^3\vec{k}' |\alpha(\vec{k})\rangle V^L_{\alpha,\beta}(|\vec{k}|,|\vec{k}'|)\langle\beta(\vec{k}')|$$

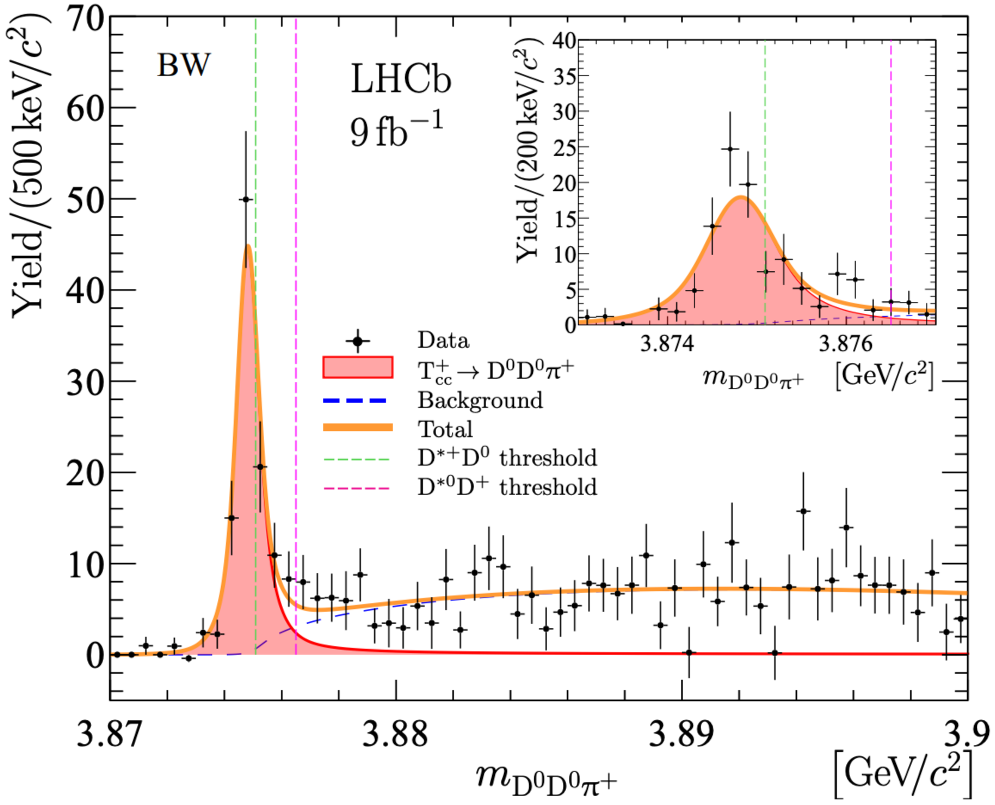


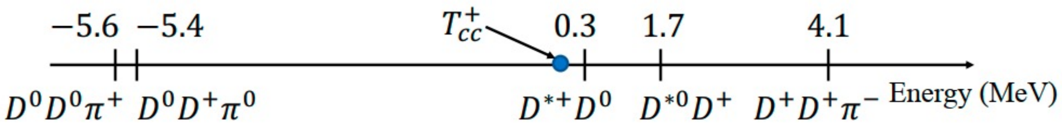
Various theoretical models contain undetermined parameters.

One-Boson-exchange model: determined by DD^*

C-parity → ***$\bar{D}^*D$ / $\bar{D}D^*$ interaction***

Observation of T_{cc}





L. Meng, et al. Phys. Rept. 1019 (2023) 1-149

- Close to $D^{*+}D^0$ thresholds:

Conventional Breit-Wigner: assumed $J^P = 1^+$.

$$\delta m_{BW} = m_{T_{cc}} - m_{D^{*+}D^0} = -273 \pm 61 \text{ keV}$$
$$\Gamma_{BW} = 410 \pm 165 \text{keV}$$

EPS-HEP conference, Ivan Polyakov's talk,29/07/2021; Nature Physics,22'

Unitarized Breit-Wigner:

$$\delta m_U = m_{T_{cc}} - m_{D^{*+}D^0} = -361 \pm 40 \text{ keV}$$
$$\Gamma_U = 47.8 \pm 1.9 \text{ keV}$$

LHCb, Nature Commun. 13 (2022) 1, 3351

- ***Only the D^*D coupled channel effect: $D^{*+}D^0$&$D^{*0}D^+$***

C-parity

→ *$\bar{D}^*D$ / $\bar{D}D^*$ interaction*

One-boson-exchange model

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

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

$$\bar{H}_a^{(Q)} \equiv \gamma_0 H^{(Q)\dagger}\gamma_0 = \left[P_a^{*\dagger\mu}\gamma_\mu + P_a^\dagger\gamma_5\right]\frac{1+ \not{v}}{2}$$

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

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

$$\mathcal{L}_{VH^{(Q)}H^{(Q)}} = i\beta\,\mathrm{Tr}\left[H_b^{(Q)} v_\mu \left(V_{ba}^\mu - \rho_{ba}^\mu\right)\bar{H}_a^{(Q)}\right] + i\lambda\,\mathrm{Tr}\left[H_b^{(Q)}\sigma_{\mu\nu}F^{\mu\nu}(\rho)_{ba}\bar{H}_a^{(Q)}\right]$$

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

$$H_a^{(\bar{Q})} \equiv C\left(\mathcal{C}H_a^{(Q)}\mathcal{C}^{-1}\right)^T C^{-1} = \left[P_{a\mu}^{(\bar{Q})*}\gamma^\mu - P_a^{(\bar{Q})}\gamma_5\right]\frac{1- \not{v}}{2}$$

$$\bar{H}_a^{(\bar{Q})} \equiv \gamma_0 H_a^{(\bar{Q})\dagger}\gamma_0 = \frac{1- \not{v}}{2}\left[P_{a\mu}^{(\bar{Q})*\dagger}\gamma^\mu + P_a^{(\bar{Q})\dagger}\gamma_5\right]$$

$$\tilde{P} = \left(\bar{D}^0, D^-, D_s^-\right) \& \tilde{P}^* = \left(\bar{D}^{*0}, D^{*-}, D_s^{*-}\right)$$

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

$$\mathcal{L}_{VH^{(\bar{Q})}H^{(\bar{Q})}} = -i\beta\,\mathrm{Tr}\left[\bar{H}_a^{(\bar{Q})} v_\mu \left(V_{ab}^\mu - \rho_{ab}^\mu\right) H_b^{(\bar{Q})}\right] + i\lambda\,\mathrm{Tr}\left[\bar{H}_a^{(\bar{Q})}\sigma_{\mu\nu}F_{ab}^{\prime\mu\nu}(\rho) H_b^{(\bar{Q})}\right]$$

$$\mathcal{V}(l, l'S, j) = \frac{1}{(2\pi)^3}\sqrt{\frac{1}{2E_D^i 2E_D^f 2E_K^i 2E_K^f}}\,2\pi\int d\cos\theta\, V^v(\vec{p}_f, \vec{p}_i)\left(\frac{\Lambda^2}{\Lambda^2 + p_f^2}\right)^2\left(\frac{\Lambda^2}{\Lambda^2 + p_i^2}\right)^2$$

- $g = 0.57$ is determined by the strong decays $D^* \to D\pi$.
- undetermined $\lambda \& \beta$.

T_{cc} & $X(3872)$ & Z_c& h_c

- In isospin limit: $[D\bar{D}^*]=\frac{1}{\sqrt{2}}(D\bar{D}^*-D^*\bar{D})$ $\{D\bar{D}^*\}=\frac{1}{\sqrt{2}}(D\bar{D}^*+D^*\bar{D})$

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

- The π interactions for $D^*D(I=0,T_{cc})$ are the same with those of $\bar{D}^*D(I=0,C=+)(X(3872))$

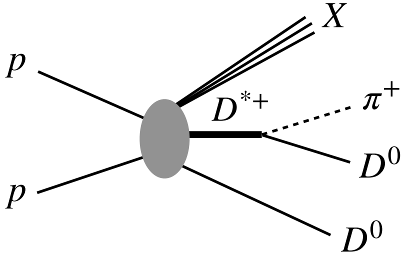
- The long-range light meson exchanging : $T_{cc}, X(3872),$ & Zc & h_c are related to each other.

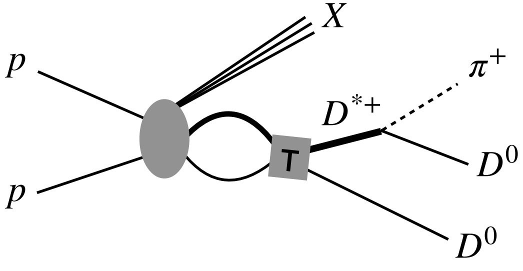
Crucial to understanding the inner structures

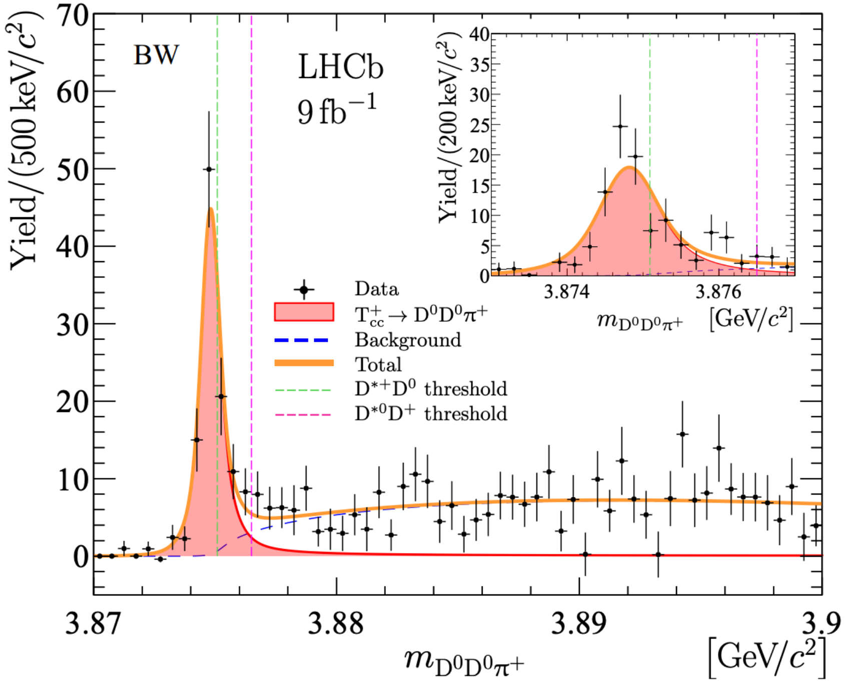
- Note there is additional short-range interactions for $X(3872)$ (by exchanging $c\bar{c}$)

Fitting

- $pp \to D(p_{D_1})D(p_{D_2})\pi(p_\pi)$



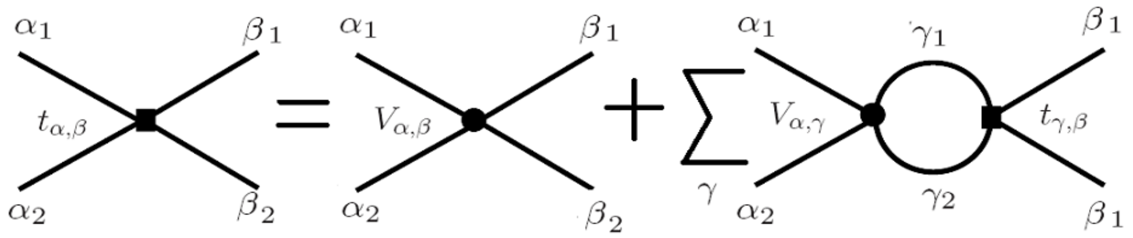




$$|\mathcal{M}|^2 = |a_{pp\to DD^*X}|^2 \sum_{\lambda_X} \epsilon_\mu(p_X,\lambda_X)\epsilon^\dagger_{\mu'}(p_X,\lambda_X) \sum_j \mathcal{B}_{j\mu}\mathcal{B}_j^{\dagger\mu'}$$

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

Fitting



$$T(\vec{k}_{D^*},\vec{k}'_{D^*};E)=\mathcal{V}(\vec{k}_{D^*},\vec{k}'_{D^*};E)+\int d\,\vec{q}\,\frac{\mathcal{V}(\vec{k}_{D^*},\vec{q};E)T(\vec{q},\vec{k}'_{D^*};E)}{E-\sqrt{m_D^2+q^2}-\sqrt{m_{D^*}^2+q^2}+i\epsilon}$$

- T_{cc}^+: $\mathcal{V}$ and T – 2×2 matrix

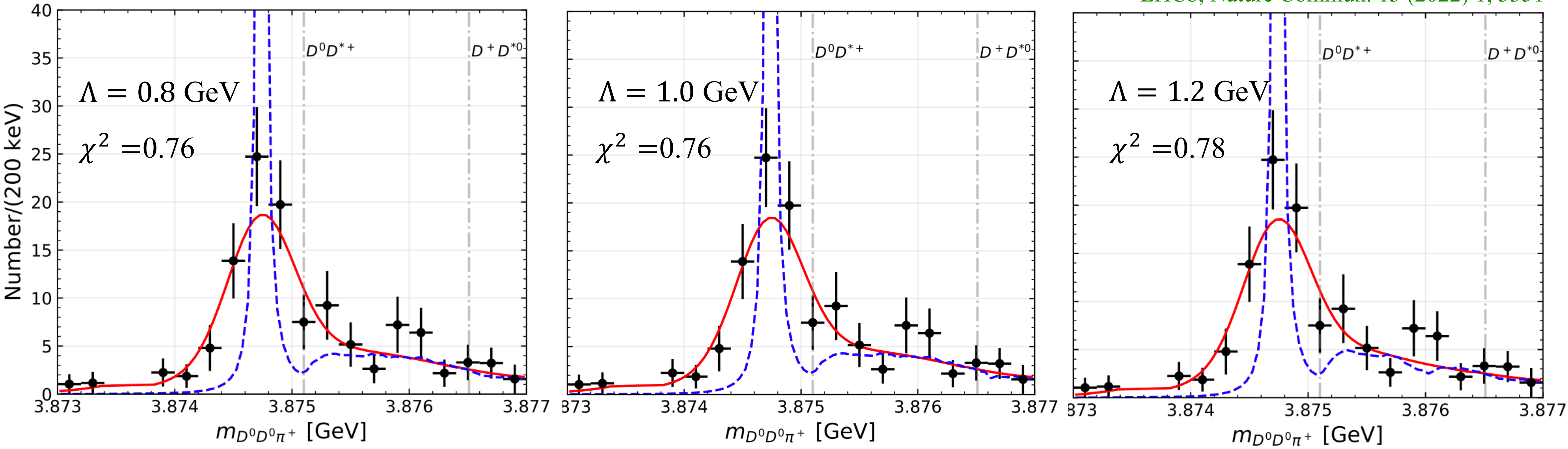
$$\begin{pmatrix} D^0 D^{*+} & \text{Coupled-channel effect} \\ \cdots & D^{*0}\,D^+ \end{pmatrix}$$

- $X(3872)$: $\mathcal{V}$ and T – 3×3 matrix

$$\begin{pmatrix} [D^0\bar{D}^{*0}] & & \\ & [D^+D^{-*}] & \\ \cdots & & c\bar{c} \end{pmatrix}$$

Fitting result

LHCb, Nature Commun. 13 (2022) 1, 3351



Λ(fixed)	λ	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 ± 0.027	0.550 ± 0.027
1.17 GeV [1]	0.56	0.9

Λ (GeV)	BE (keV)	Γ (keV)
0.8	-387.7	67.3
1.0	-393.0	70.4
1.2	-391.6	72.7

Cheng, et al. Phys. Rev. D 106,016012 (2022).

Complex scaling method (CSM)

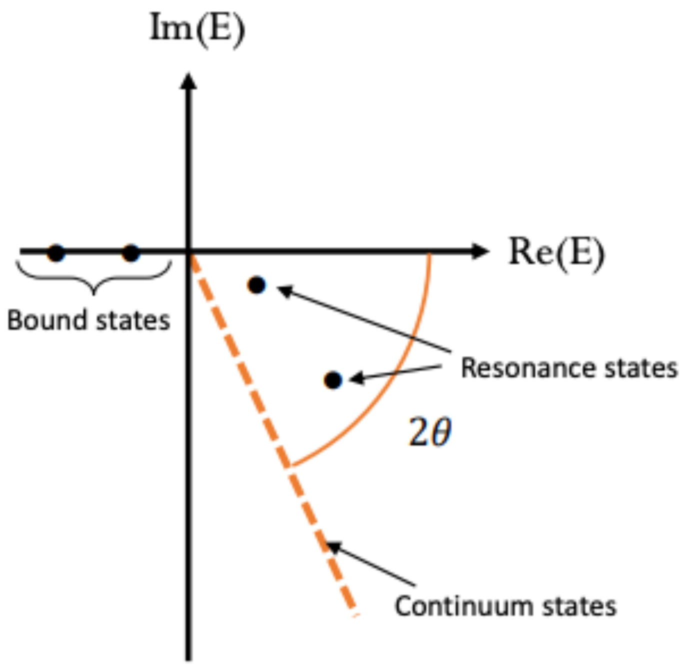
- Complex scaling method

$$\boldsymbol{r} \to \boldsymbol{r}e^{i\theta}, \quad \boldsymbol{q} \to \boldsymbol{q}e^{-i\theta}$$

$$H_\theta = H(\mathbf{r}_\theta, \mathbf{q}_\theta) = \frac{q^2}{2u}e^{-2i\theta} + V(\mathbf{r}e^{i\theta}, \mathbf{q}e^{-i\theta})$$

- Bound states & resonances: independent of θ

- Scattering state: along continuum line and rotate with 2θ



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

Results with $\Lambda = 1.0$ GeV

- Results in CSM are consistent with the T-matrix pole analysis
- Only one pole appears—bound states

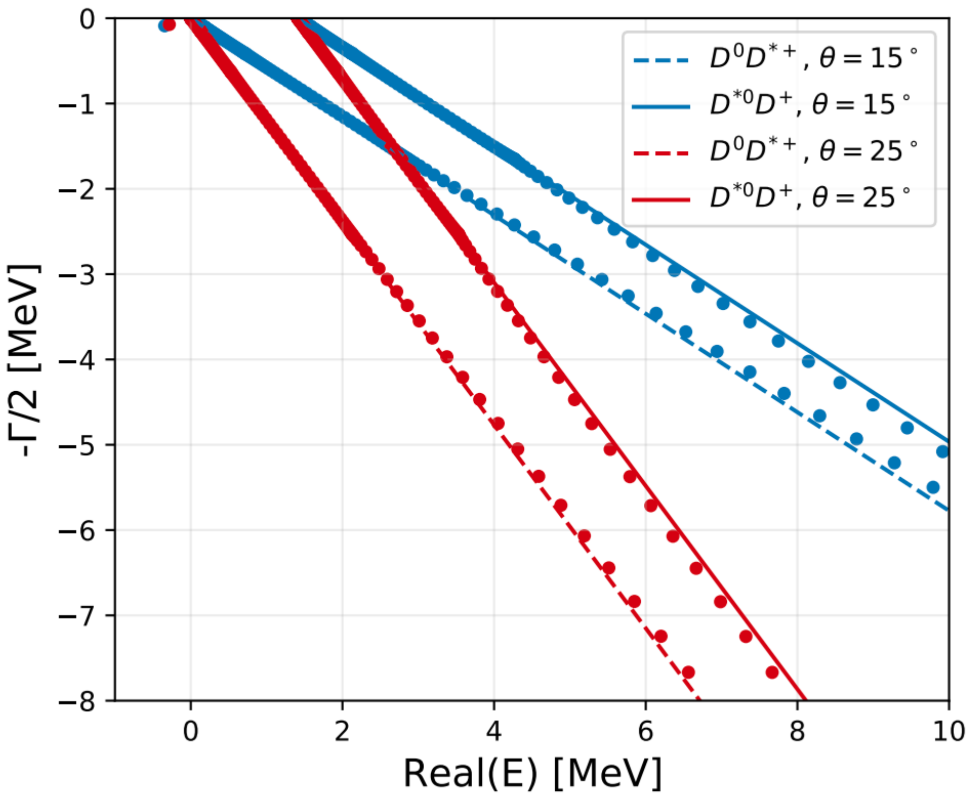
$\Delta E = -393.0\text{keV}\ \ \Gamma_{T_{cc}} = 70.4$ keV. $\left(\Delta E_{\text{exp}} = -360(40)\text{keV}, \Gamma_{\text{exp}}{=}47.8 \pm 1.9 \text{ keV}\right)$ LHCb, Nature Commun. 13 (2022) 1, 3351

- $\sqrt{\langle r^2 \rangle} = 4.7$ fm
- 70.0 % $D^{*+}D^0$, 30.0 % D^+D^{*0} ⟺ 95.8%, $DD^*(I=0)$ 4.2% $DD^*(I=1)$

- Isospin breaking: Mass differences considered in the T matrix
- Residue ratio:

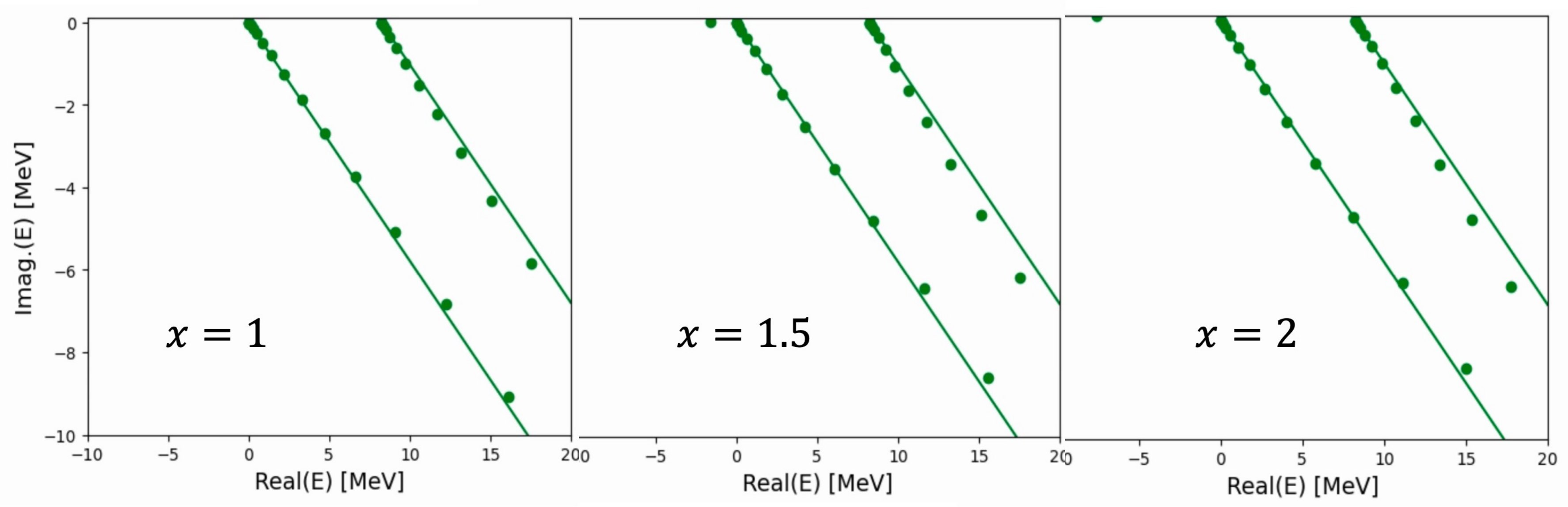
$$\left|\frac{Res(D^0D^{*+})}{Res(D^+D^{*0})}\right| = 1.055$$

Iso-breaking effect is not important



Direct application to $D\bar{D}^*$ with $\Lambda = 1.0$ GeV

- $V'_{\bar{D}^*D} = x * V_{\bar{D}^*D}$



- Virtual state at $x = 1$? --- 3870.0 + 0.26 i MeV.

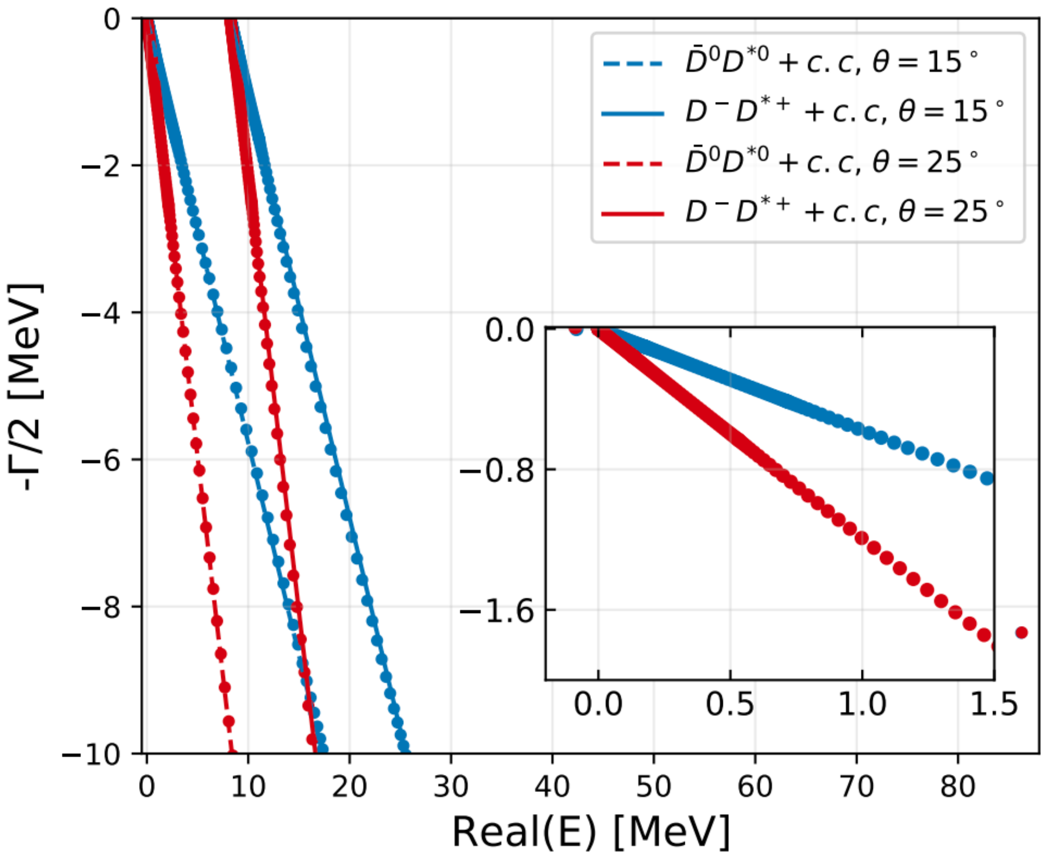
$\bar{D}^*D$ interaction is attractive but not strong enough to form a bound state

Inclusion of $c\bar{c}$ core

$X(3872)$

Inclusion of $c\bar{c}$ core

- A bound state + a resonant state
- Bound state -- $X(3872)$
  $\Delta E = -80.4$ keV
  $\Gamma_X = 32.5$ keV
- $\sqrt{\langle r^2 \rangle} = 11.2$ fm
- 94.0 % $D^{*0}\bar{D}^0$, 4.8 % D^+D^{*-}, 1.2% $c\bar{c}$ ⟺ 71.9%, $I = 0$; 28.1%, $I = 1$
- Important isospin breaking.



$X(3872)$: Isospin breaking patterns

- X(3872) is the large isospin violating decay patterns

$$\frac{\mathcal{B}[X \to J/\psi\pi^+\pi^-\pi^0]}{\mathcal{B}[X \to J/\psi\pi^+\pi^-]} = 1.0 \pm 0.4 \pm 0.3 \quad \text{Belle;} \qquad \frac{\mathcal{B}[X \to J/\psi\omega]}{\mathcal{B}[X \to J/\psi\pi^+\pi^-]} = \begin{cases} 1.6^{+0.4}_{-0.3} \pm 0.2 & \text{BESIII,} \\ 0.7 \pm 0.3 & B^+ \text{ events, BaBar,} \\ 1.7 \pm 1.3 & B^0 \text{ events, BaBar,} \end{cases}$$

$$R = \frac{\mathscr{B}[X \to J/\psi\pi^+\pi^-\pi^0]}{\mathscr{B}[X \to J/\psi\pi^+\pi^-]} = R_{\omega/\rho} \times R_2$$

$$R_{\omega/\rho} = \frac{\mathscr{B}[X \to J/\psi\omega]}{\mathscr{B}[X \to J/\psi\rho]} \sim \left| \int d\vec{p}\, \psi^{I=1/0}_{X(3872)}(\vec{p})\psi^*_{J/\psi}(\vec{p}) \right|^2 = 21.4$$

$$R_X = \sqrt{R_{\rho/\omega}} = \left| \frac{\mathscr{M}_{X(3872)\to J/\psi\rho^0}}{\mathscr{M}_{X(3872)\to J/\psi\omega}} \right| = 0.22 \qquad R_X^{LHCb} = 0.29 \pm 0.04$$

LHCb, Phys. Rev. D 108, L011103 (2023)

$X(3872)$: Isospin breaking patterns

- X(3872) is the large isospin violating decay patterns

$$\frac{\mathcal{B}[X \to J/\psi\pi^+\pi^-\pi^0]}{\mathcal{B}[X \to J/\psi\pi^+\pi^-]} = 1.0 \pm 0.4 \pm 0.3 \quad \text{Belle;} \qquad \frac{\mathcal{B}[X \to J/\psi\omega]}{\mathcal{B}[X \to J/\psi\pi^+\pi^-]} = \begin{cases} 1.6^{+0.4}_{-0.3} \pm 0.2 & \text{BESIII,} \\ 0.7 \pm 0.3 & B^+ \text{ events, BaBar,} \\ 1.7 \pm 1.3 & B^0 \text{ events, BaBar,} \end{cases}$$

$$R = \frac{\mathscr{B}[X \to J/\psi\pi^+\pi^-\pi^0]}{\mathscr{B}[X \to J/\psi\pi^+\pi^-]} = R_{\omega/\rho} \times R_2$$

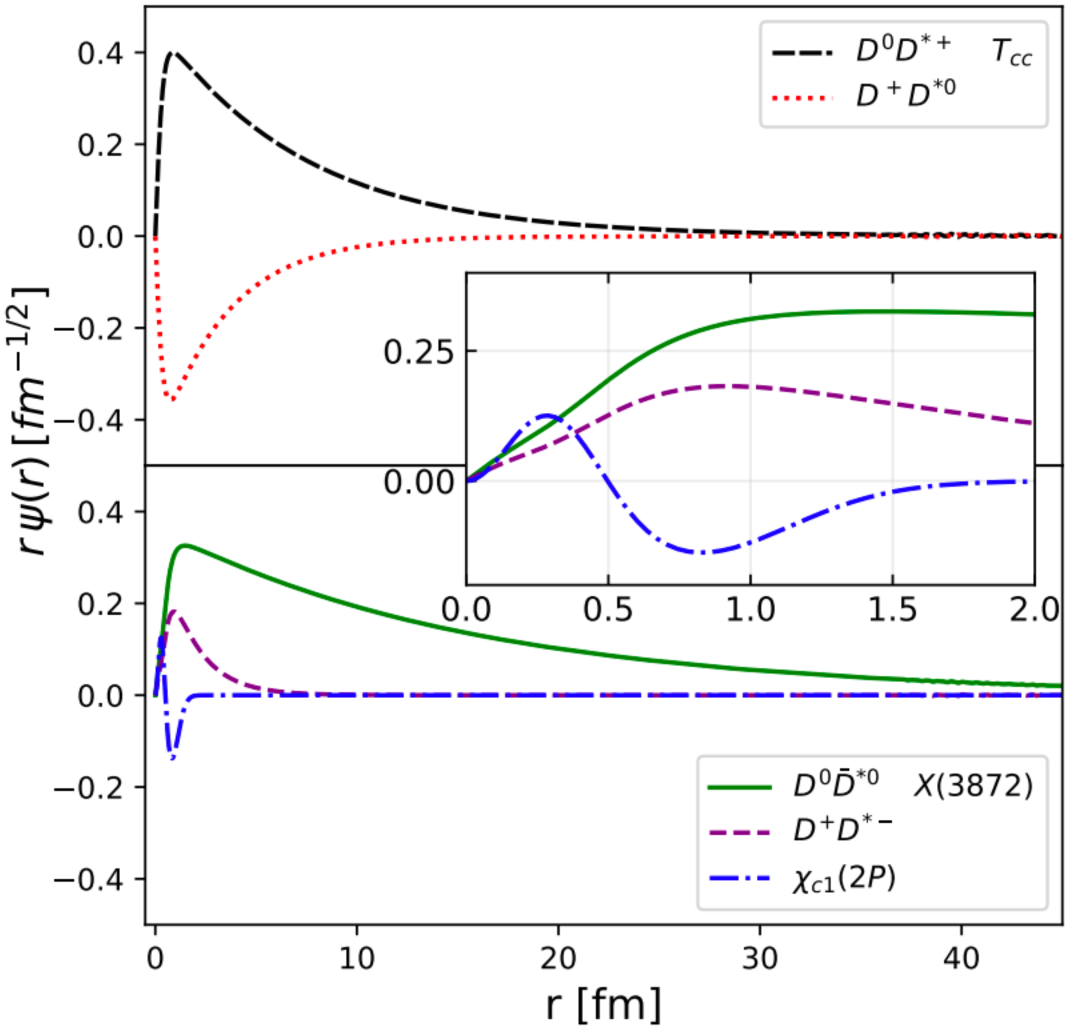
$$R_{\omega/\rho} = \frac{\mathscr{B}[X \to J/\psi\omega]}{\mathscr{B}[X \to J/\psi\rho]} \sim \left|\int d\vec{p}\,\psi^{I=1/0}_{X(3872)}(\vec{p})\psi^*_{J/\psi}(\vec{p})\right|^2 = 21.4$$

$$R_2 = \frac{\int_{(3m_\pi)^2}^{(m_X - m_{J/\psi})^2} \mathcal{S}\left(p_V^2, m_\omega, \Gamma_\omega\right) q\left(m_X, p_V, m_{J/\psi}\right) dp_V^2}{\int_{(2m_\pi)^2}^{(m_X - m_{J/\psi})^2} \mathcal{S}\left(p_V^2, m_\rho, \Gamma_\rho\right) q\left(m_X, p_V, m_{J/\psi}\right) dp_V^2} \times \frac{\mathscr{B}\left(\omega \to \pi^+\pi^-\pi^0\right)}{\mathscr{B}\left(\rho^0 \to \pi^+\pi^-\right)}$$

$R_2 \sim 0.087/0.147$ ➡ $R = 1.86/3.14$

E. Braaten et al, Phys. Rev. D 72, 054022 D. Gamermann et al, Phys. Rev. D 81, 014029

Wave function



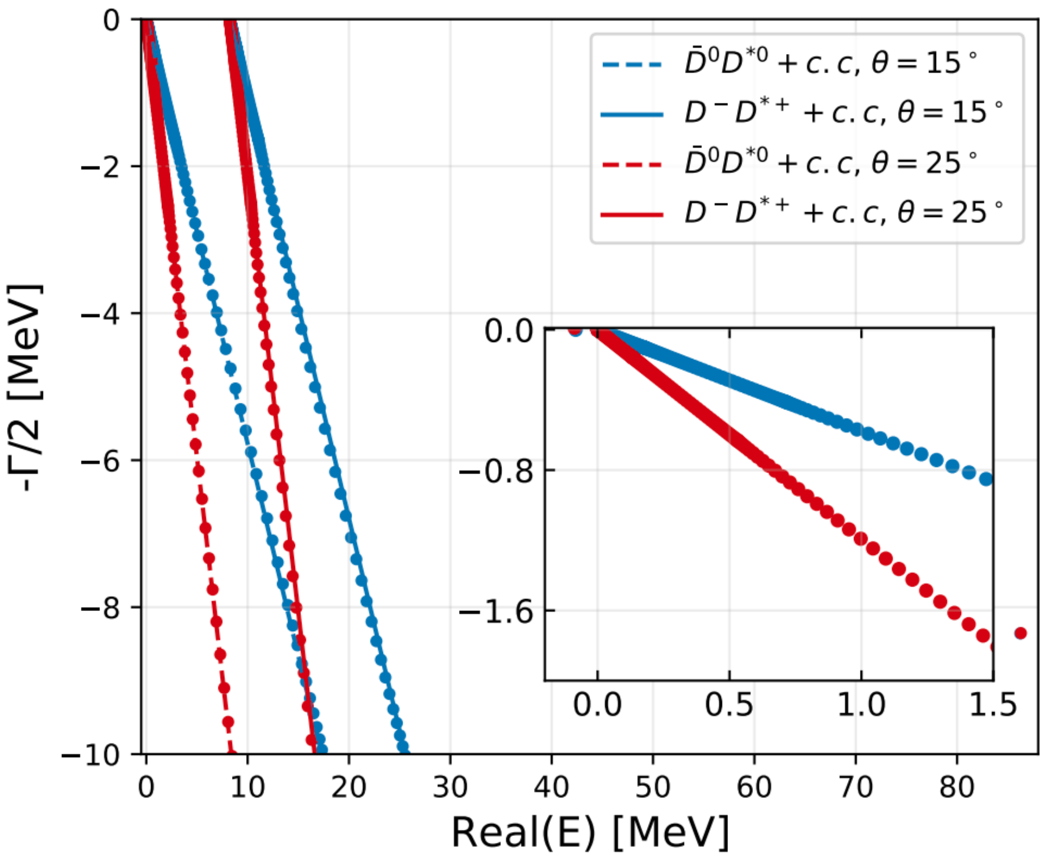
- Long tails for the radius distribution.
- $X(3872)$ has a even longer tail than T_{cc}
- $X(3872)$: $\sqrt{\langle r^2 \rangle} = 11.2$ fm

✓ $r < 2$ fm, $c\bar{c} + \bar{D}D^*$ are important.

✓ $r < 0.5$ fm, $c\bar{c}$ core dominates.

✓ $\bar{D}D^*$ plays the dominant role in the long-distance region, which contributes to $\sqrt{\langle r^2 \rangle}$.

Candidate for X(3940)?



$X(3940)$ MASS	3942 ± 9 MeV
$X(3940)$ WIDTH	37^{+27}_{-17} MeV

$X(3940)$ Decay Modes

PDG 22

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D\bar{D}^*$ + c.c.	seen

- Resonance (MeV): $J^{PC} = 1^{++}$, $M = 3957.9$ MeV, $\Gamma = 16.7$ MeV

- The decay width: $D\bar{D}^*$, $\chi_{c1}(2P)$ is important.

- Other explanations:
$\eta(3S)$: 0^{-+} − P-wave decay into $D\bar{D}^*$ channel

B.-Q. Li, et al, Phys. Rev. D, 79 (2009), 094004 **3991 GeV**
T. Barnes et al, Phys. Rev. D, 72 (2005), 054026 **4043(NR) 4064(GI)**

$D\bar{D}^*$ with $\mathrm{J}^{PC} = 1^{+-}$

- $\mathrm{I}(J^{PC}) = 0(1^{+-})$ sector: $D\bar{D}^*$ and $c\bar{c}$ ($h_c(2P)$) both contribute.

✓A ***virtual*** state $M = 3870.2$ MeV related to $\tilde{X}(3872)$ with $M = 3860.0 \pm 10.4$ MeV in COMPASS.

M. Aghasyan et al. (COMPASS), Phys. Lett. B 783, 334 (2018)

✓ The t-channel vector meson exchange potentials dominate, $\tilde{X}(3872)$ is related to X(3872).

✓ A ***resonant*** state $\boldsymbol{h'_c}$: $M = 3961.3$ MeV and $\Gamma = 1.1$ MeV.

Z.-G. Wang, Int. J. Mod. Phys. A 36, 2150107 (2021).
X.-K. Dong et al., Progr. Phys. 41, 65 (2021).
P.G.Ortega,et al., Phys.Lett. B 829, 137083.

- $\mathrm{I}(J^{PC}) = 1(1^{+-})$ sector: only $D\bar{D}^*$ contributes

✓ No pole is observed corresponding to Z_c

✓ Coupled-channel effects with the J/ψπ and η_cρ : significant in Lattice QCD calculations.

S. Prelovsek, et al., Phys. Rev. D 91, 014504 (2015).
S.-h. Lee et al. (Fermilab Lattice, MILC), arXiv:1411.1389 [hep-lat].
Y. Chen et al., Phys. Rev. D 89, 094506 (2014).
Y. Ikeda, et al. (HAL QCD), Phys. Rev. Lett. 117, 242001 (2016).
Y. Ikeda (HAL QCD), J. Phys. G 45, 024002 (2018).
C. Liu, et al., Phys. Rev. D 101, 054502 (2020).
T. Chen, et al. (CLQCD), Chin. Phys. C 43, 103103 (2019).

Summary

- The T_{cc} can be explained as the bound molecule.

  ✓ Only one pole appears.

  ✓The pole masses and decay widths coincided with unitarized analysis.

- T_{cc} and $X(3872)$: long-range dynamics related by OBE.

- X(3872) :

  ✓ Virtual state: $D^0\bar{D}^{*0}$

  ✓ is dominated by $D^0\bar{D}^{*0}$ molecular component & $c\bar{c}$ core is crucial to form the bound state.

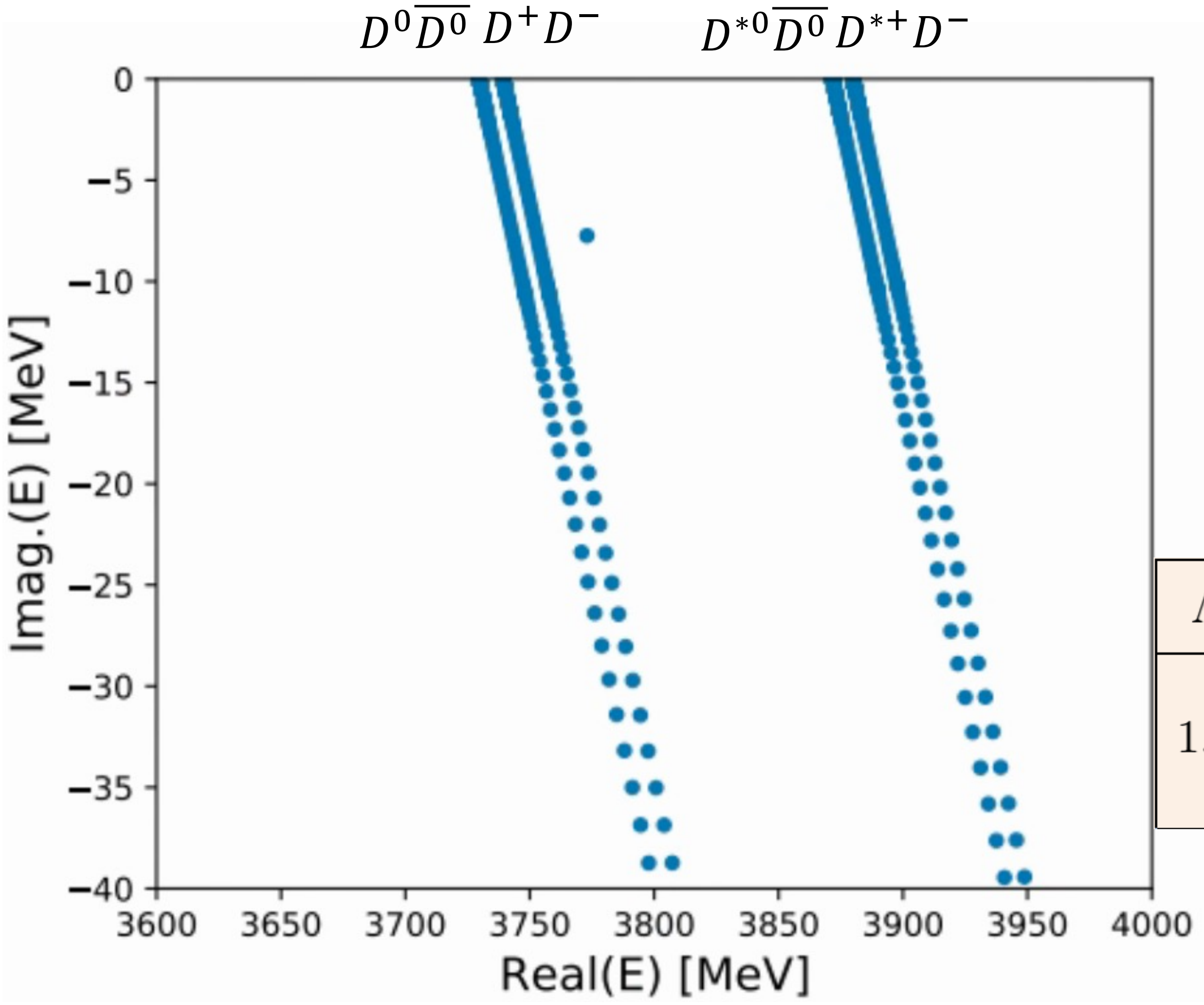
  ✓ Short-range interactions and structures of $X(3872)$ - $c\bar{c}$ core is important.

- Virtual VS bound states: decay pattern, LQCD energy levels, …

Thank you for your attention!

Backup slides

$\psi(3770)$



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

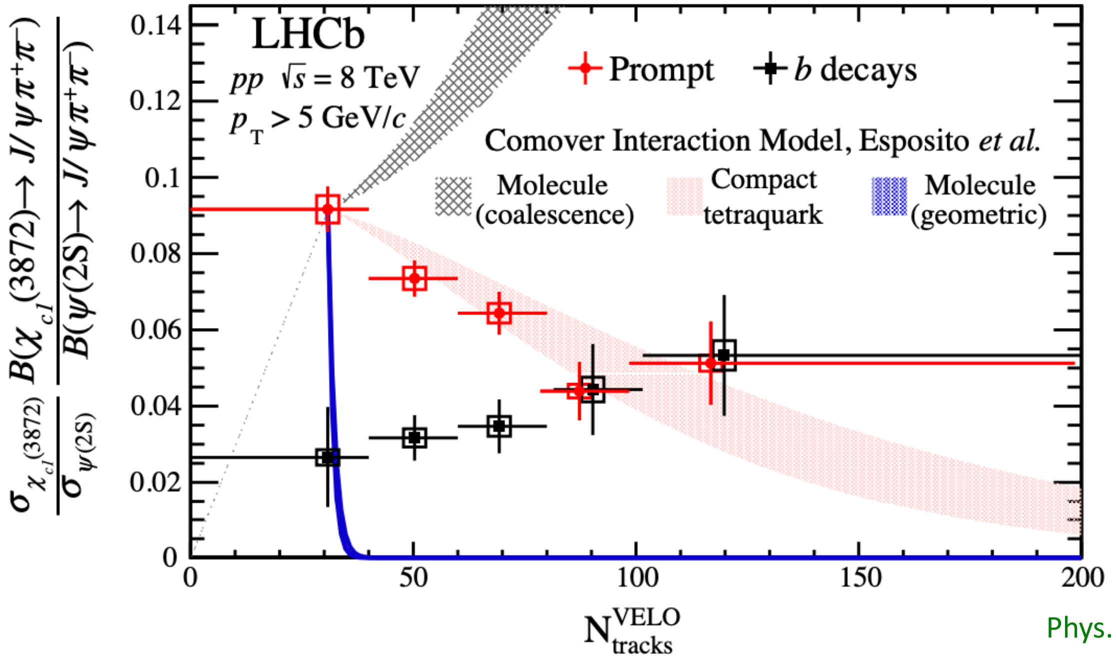
$$V^u_{\rho/\omega} = -2\lambda^2 g_V^2\frac{(\epsilon^\dagger_{\lambda'}\cdot q)(\epsilon_\lambda\cdot q)-q^2\left(\epsilon_\lambda\cdot\epsilon^\dagger_{\lambda'}\right)}{q^2-m^2_{\rho/\omega}},$$

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

$$m_{bare}(\ {}^3D1) = 3.81576$$

Λ	γ	$\psi(3770)\,1^{--}\to D\bar{D}/D\bar{D}^*$	$\psi(3770)$-experiment
1.0	$0.27\sqrt{96\pi}$	3772.8	3773.7 ± 0.4
		15.2	27.2 ± 1.0

Production



Phys. Rev. Lett. 126, no.9, 092001 (2021)

FIG. 4. The ratio of the $\chi_{c1}(3872)$ and $\psi(2S)$ cross sections measured in the $J/\psi\pi^+\pi^-$ channel as a function of the number of tracks reconstructed in the VELO. The point-to-point uncorrelated (correlated) uncertainties are shown as vertical error bars (boxes), and the bin widths are shown as horizontal error bars. See text for details on calculations from Ref. [43].

The production of the T_{cc}

The differential cross section for the $pp \to D(p_{D_1})D(p_{D_2})\pi(p_\pi)$ channel reads

$$d\sigma_{pp\to XDD\pi} = \frac{(2\pi)^4}{4\sqrt{(p_{p_1}\cdot p_{p_2} - m_p^2 m_p^2)}} |\mathcal{M}|^2 d\Phi_{XDD\pi}$$

$$\frac{d\sigma_{pp\to XDD\pi}}{dm_{DD\pi}} \approx 2m_{DD\pi}\int d\sigma_{pp\to X+DD\pi} B_2 d\Phi_{DD\pi}$$

$$\approx 2m_{DD\pi}\int dm_{12} dm_{23} B_2(E; m_{12}, m_{23})$$

B_2 is obtained with the $\mathcal{M}$,

$$|\mathcal{M}|^2 = |a_{pp\to DD^*X}|^2 B_2,$$

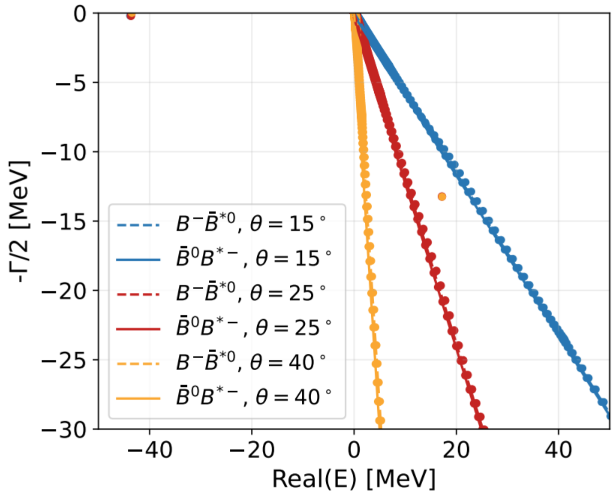
$$B_2 = \sum_{\lambda_X} \epsilon_\mu(p_X,\lambda_X)\epsilon^\dagger_{\mu'}(p_X,\lambda_X)\mathcal{B}\mu\mathcal{B}^{\dagger\mu'}.$$

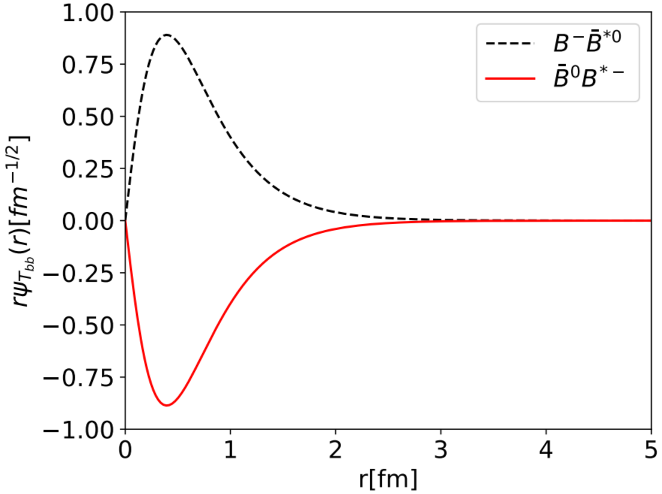
We have approximated $\mathcal{A}^\mu_{pp\to DD^*X} = a_{pp\to DD^*X}\,\epsilon^\mu(p_X,\lambda_X)$.

T_{bb}

- Heavy quark flavor symmetry: all the parameters in OBE are the same as those in the charmed sector.

- A ***bound*** state & a ***resonance***





Λ (GeV)	T-matrix	CMS				
	mass (MeV)	mass (MeV)	$\sqrt{\langle r^2 \rangle}$	$P(B^-\bar{B}^{*0})$	$P(\bar{B}^0 B^{*-})$	$\left\lvert\frac{\text{Res}(\bar{B}^0 B^{*-})}{\text{Res}(B^-\bar{B}^{*0})}\right\rvert$
1.0	10560.1	10560.1	0.6 fm	50.2%	49.8%	0.997

$\sim$ 44 MeV below the $\bar{B}\bar{B}^*$

$E(\Gamma)$

T-matrix	CMS
10621.2(26.4)	10621.2(26.4)

arXiv: 2310.09836

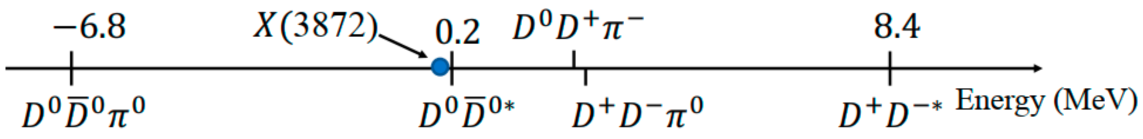
Observation of $X(3872)$

- Aka $\chi_{c1}(2P)$ in PDG. $J^{PC} = 1^{++}$.

- Extremely close to $\bar{D}^{*0}D^0 / \bar{D}^0 D^{*0}$ thresholds

$$\delta m = m_{\overline{D^{*0}}D^0} - m_{X(3872)} = 0.00 \pm 0.18 \text{ MeV}$$

PDG 22



✓Close to charmonium $\chi_{c1}(2P)$ $[\bar{c}c, 2^3P_1]$

$$\delta m = m_{\chi_{c1}(2P)} - m_{X(3872)} = 81.35 \text{ MeV}$$

S. Godfrey, et al. Phys. Rev. D 32, 189 (1985)

✓*Complicated coupled-channel effect:* $\bar{c}c$ *&* $\bar{D}^{0*}D^0 / D^+D^{-*}$

- Large isospin violating decay patterns

$$\frac{\mathcal{B}[X \to J/\psi\pi^+\pi^-\pi^0]}{\mathcal{B}[X \to J/\psi\pi^+\pi^-]} = 1.0 \pm 0.4 \pm 0.3 \quad \text{Belle;} \qquad \frac{\mathcal{B}[X \to J/\psi\omega]}{\mathcal{B}[X \to J/\psi\pi^+\pi^-]} = \begin{cases} 1.6^{+0.4}_{-0.3} \pm 0.2 & \text{BESIII,} \\ 0.7 \pm 0.3 & B^+ \text{ events, BaBar,} \\ 1.7 \pm 1.3 & B^0 \text{ events, BaBar,} \end{cases}$$

L. Meng, et al. Phys. Rept. 1019 (2023) 1-149