$X(3872)$, T_{cc}, and heavy meson interactions

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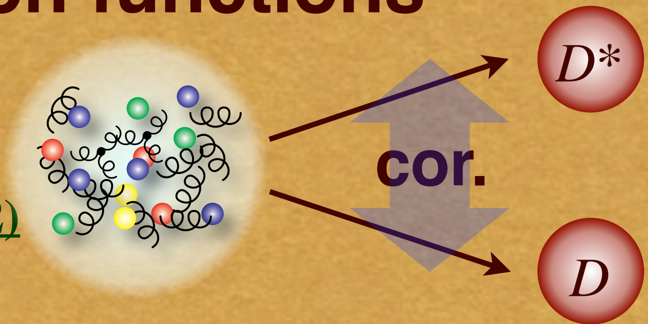
Y. Kamiya, T. Hyodo, A. Ohnishi, EPJA58, 131 (2022)



- **Mixture of compact quark states**
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I. Terashima, T. Hyodo, in preparation

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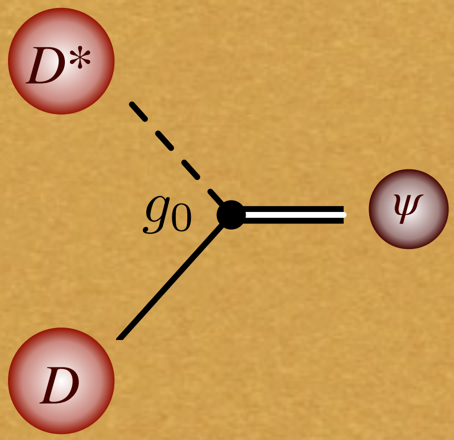
T. Kinugawa, T. Hyodo, in preparation



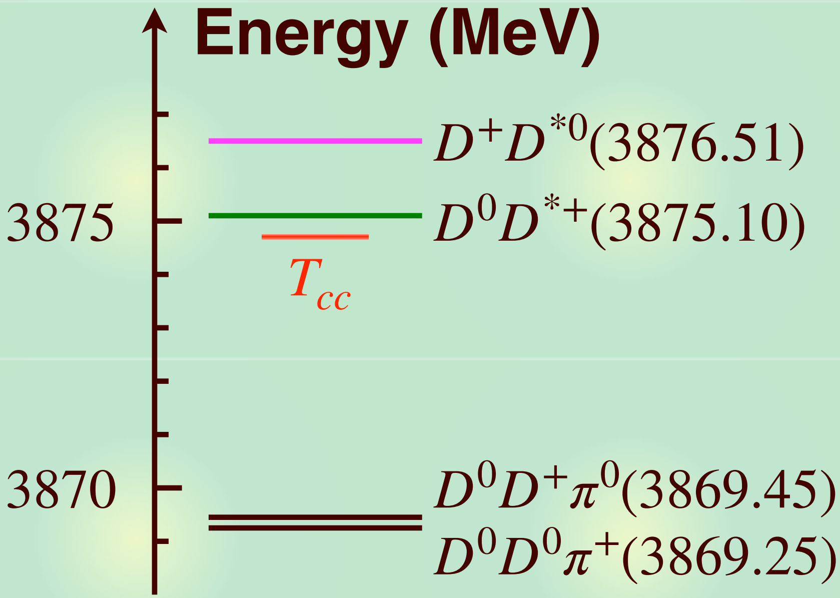
- **Summary**

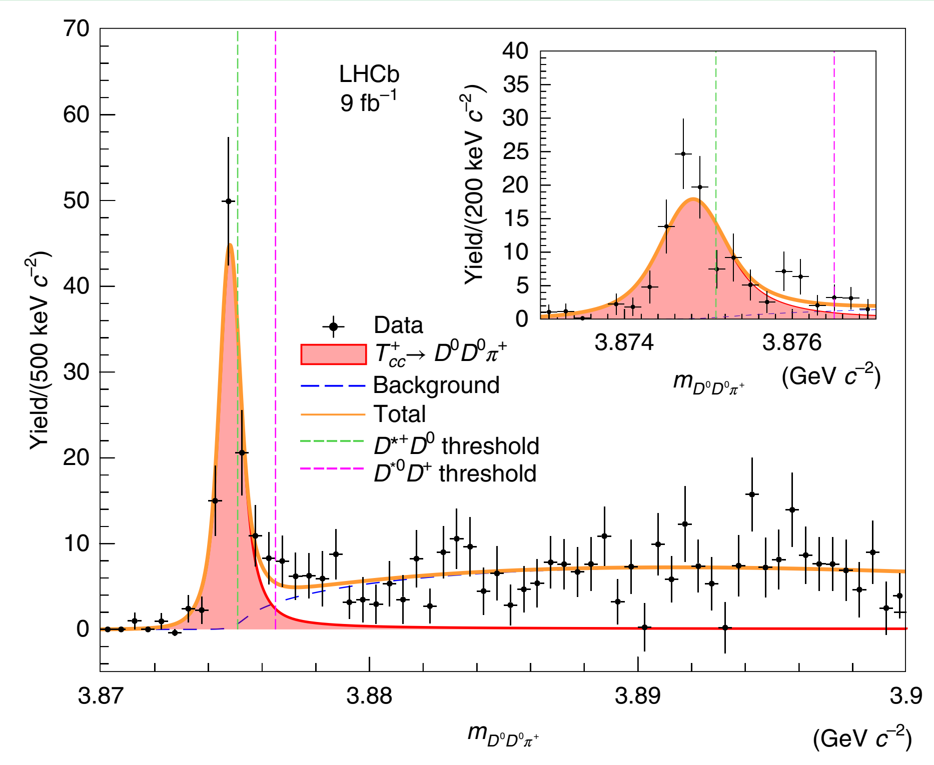
Observation of T_{cc}

T_{cc} observed in $D^0D^0\pi^+$ spectrum

LHCb collaboration, Nature Phys., 18, 751 (2022); Nature Comm., 13, 3351 (2022)

- Signal near DD^* threshold
- Charm $C = +2 : \sim cc\bar{u}\bar{d}$
- Level structure

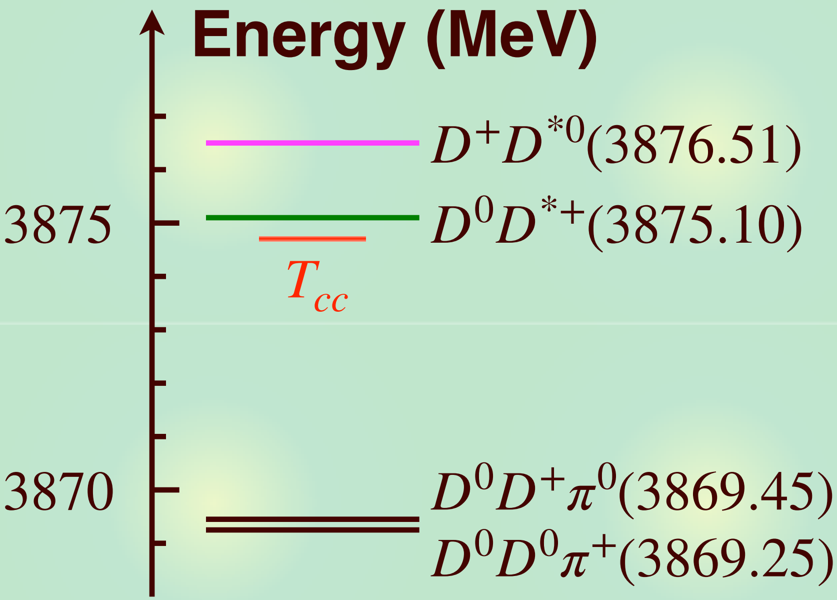


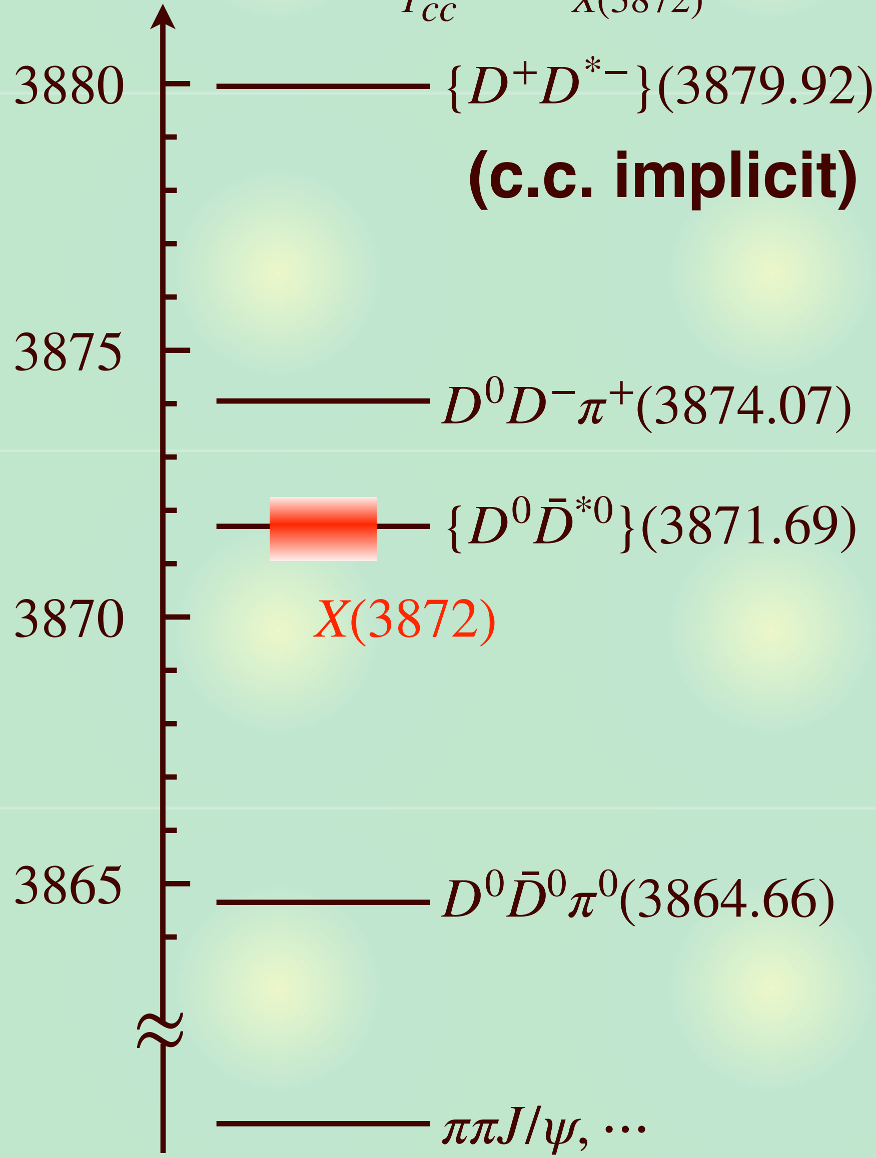


- Very small (few MeV ~ keV) energy scale involved

T_{cc} and $X(3872)$

$X(3872)$: another near-threshold state with $M_{T_{cc}} \sim M_{X(3872)}$

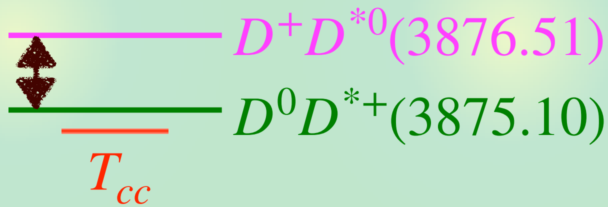




- T_{cc}, $X(3872)$ **near** DD^*, $D\bar{D}^*$
- **Various thresholds**
- $X(3872)$ **has decay channels**

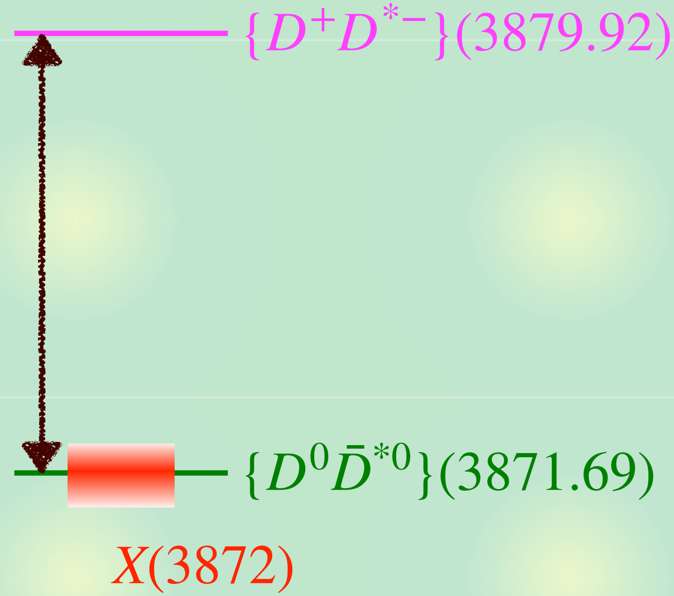
Simplified picture

In this talk, we consider two-body channels



$$E_h = -0.36 - i\frac{0.048}{2}\ \mathrm{MeV}$$

(pole mass by LHCb)



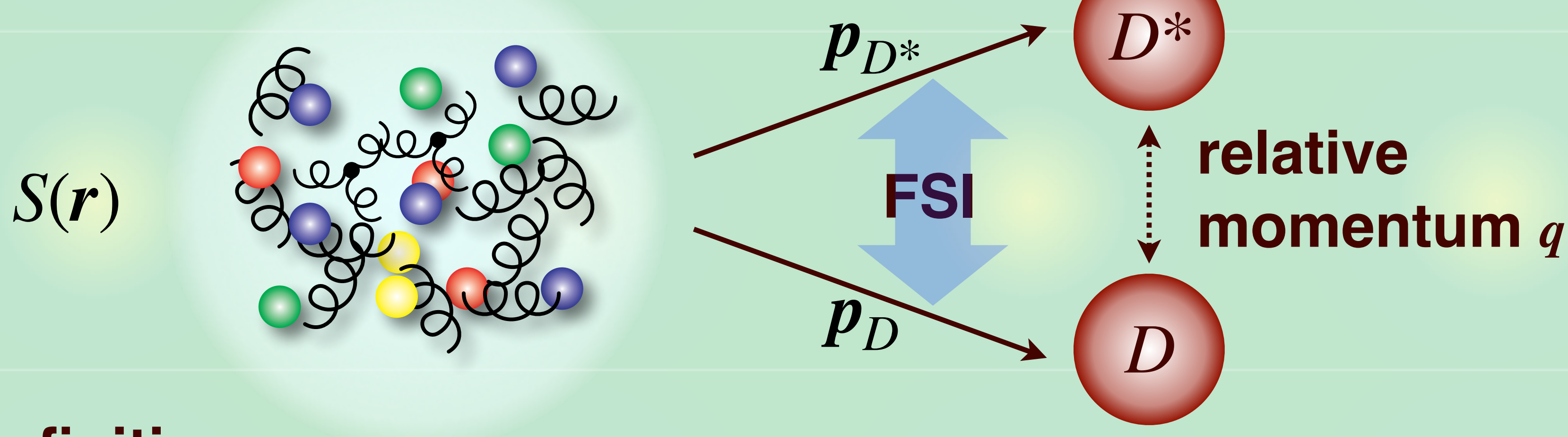
$$E_h = -0.04 - i\frac{1.19}{2}\ \mathrm{MeV}$$

(mass and width by PDG)

- **Binding energy** : $T_{cc} > X(3872)$
- **Decay width** : $T_{cc} < X(3872)$
- **Isospin breaking** : $T_{cc} \sim 1.41\ \mathrm{MeV}$, $X(3872) \sim 8.23\ \mathrm{MeV}$

Correlation function and hadron interaction

High-energy collision: chaotic source $S(\boldsymbol{r})$ of hadron emission



- Definition

$$C(\boldsymbol{q}) = \frac{N_{DD^*}(\boldsymbol{p}_D, \boldsymbol{p}_{D^*})}{N_D(\boldsymbol{p}_D) N_{D^*}(\boldsymbol{p}_{D^*})}$$ **(= 1 in the absence of FSI)**

- Theory (Koonin-Pratt formula)

$$C(\boldsymbol{q}) \simeq \int d^3\boldsymbol{r}\, S(\boldsymbol{r})\, |\Psi_{\boldsymbol{q}}^{(-)}(\boldsymbol{r})|^2$$

Source function <—> two-body wave function (FSI)

ALICE collaboration, Nature 588, 232 (2020); …

$DD^*, D\bar{D}^*$ potentials

Coupled-channel potentials

$$V_{DD^*/D\bar{D}^*} = \frac{1}{2}\begin{pmatrix} V_{I=1}+V_{I=0} & V_{I=1}-V_{I=0} \\ V_{I=1}-V_{I=0} & V_{I=1}+V_{I=0}+V_c \end{pmatrix} \begin{array}{l} D^0D^{*+}/\{D^0\bar{D}^{*0}\} \\ D^+D^{*0}/\{D^+D^{*-}\} \end{array}$$

↑ **Coulomb for** $\{D^+D^{*-}\}$

- $I=0$ **: one-range gaussian potentials,** $I=1$ **neglected**

$$V_{I=0} = V_0 \exp\{-m_\pi^2 r^2\}, \quad V_{I=1} = 0$$

↑ **range by** π **exchange**

$V_0 \in \mathbb{C}$ **<— scattering lengths (molecule picture)**

- T_{cc} **:** $a_0^{D^0D^{*+}} = -7.16 + i1.85$ fm **(LHCb analysis)**

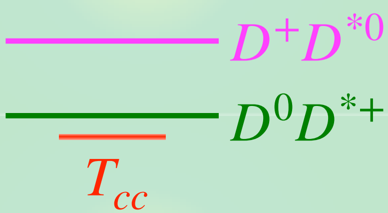
LHCb collaboration, Nature Comm., 13, 3351 (2022)

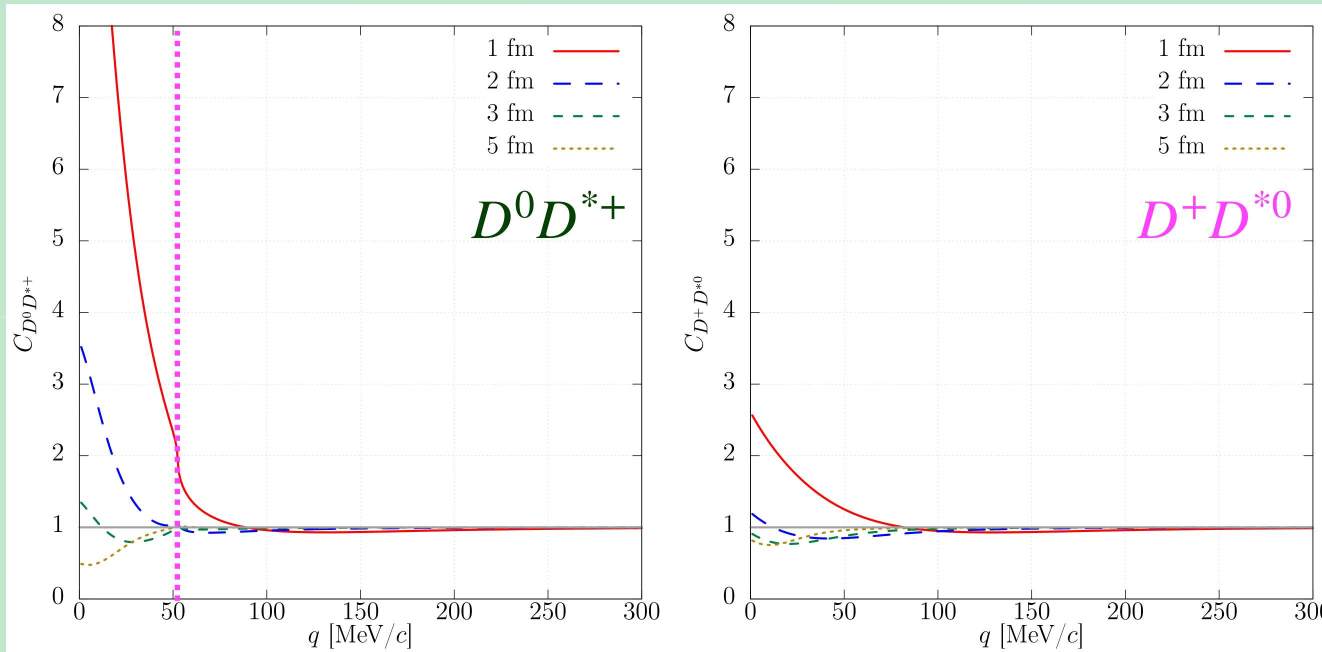
- $X(3872)$ **:** $a_0^{D^0\bar{D}^{*0}} = -4.23 + i3.95$ fm **(**$a_0 = -i/\sqrt{2\mu E_h}$ **with PDG** E_h**)**

$DD^* \sim T_{cc}$ sector

D^0D^{*+} and D^+D^{*0} correlation functions ($cc\bar{u}\bar{d}$, exotic)

Y. Kamiya, T. Hyodo, A. Ohnishi, EPJA58, 131 (2022)



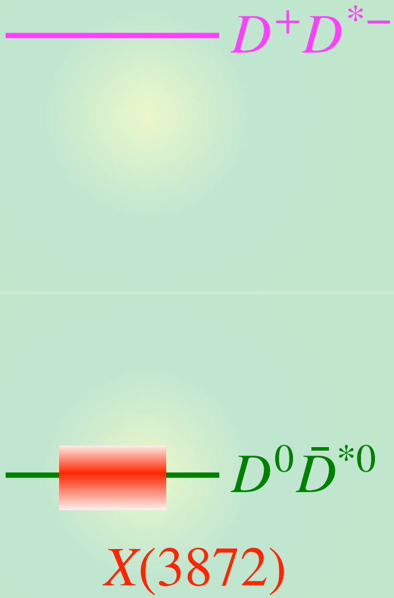


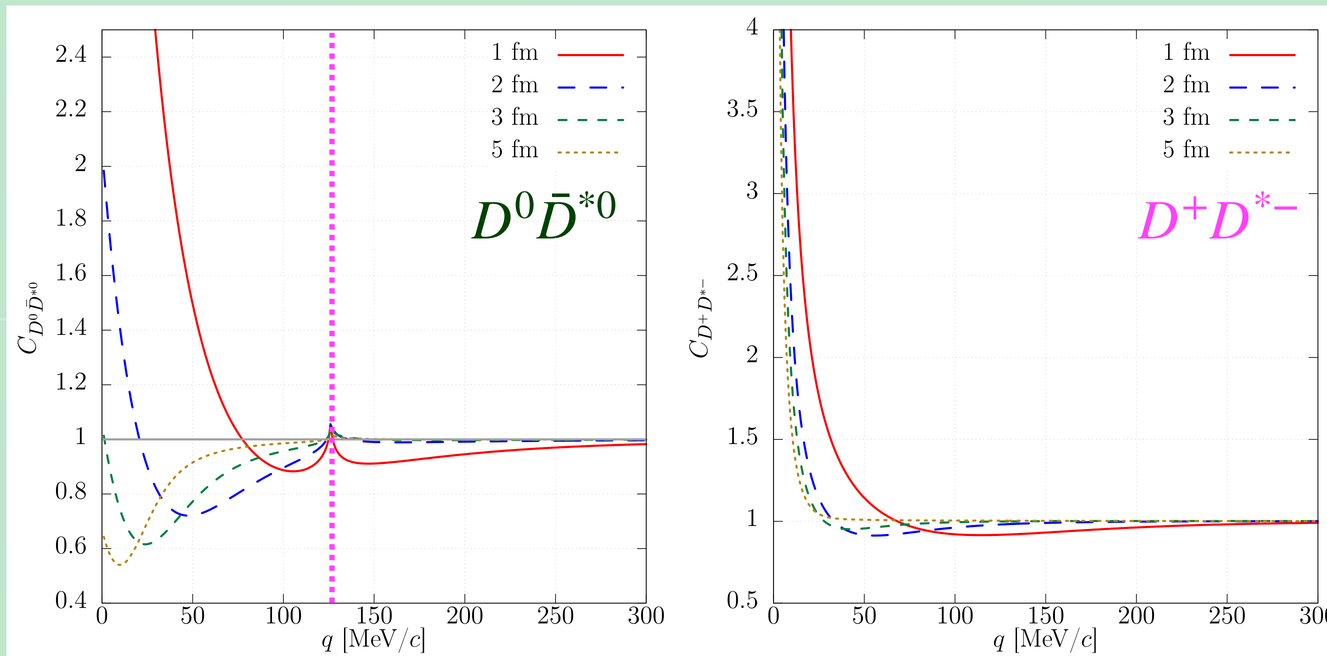
- Bound state feature (source size dep.) in both channels
- Strong signal in D^0D^{*+}, weaker one in D^+D^{*0}
- D^+D^{*0} cusp in D^0D^{*+} ($q \sim 52$ MeV) is not very prominent

$D\bar{D}^* \sim X(3872)$ sector

$D^0\bar{D}^{*0}$ and D^+D^{*-} correlation functions ($c\bar{c}q\bar{q}$)

Y. Kamiya, T. Hyodo, A. Ohnishi, EPJA58, 131 (2022)



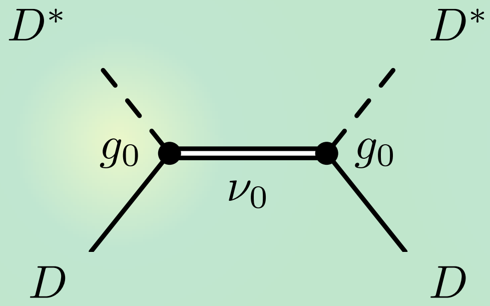


- Bound state feature in $D^0\bar{D}^{*0}$ correlation
- Sizable D^+D^{*-} cusp in $D^0\bar{D}^{*0}$ ($q \sim 126$ MeV)
- D^+D^{*-} correlation : Coulomb attraction dominance

Effect of compact quark states

Coupling to compact quark states —> $DD^*, D\bar{D}^*$ potentials?

- s-channel exchange of bare state $\psi \sim cc\bar{u}\bar{d}, c\bar{c}$



Feshbach method : effective DD^* potential with ψ effect

H. Feshbach, Ann. Phys. 5, 357 (1958); ibid, 19, 287 (1962)

$$\langle \boldsymbol{r}'_{DD^*} | V_{\text{eff}}^{DD^*}(E) | \boldsymbol{r}_{DD^*} \rangle = V^{DD^*}(\boldsymbol{r})\delta(\boldsymbol{r}' - \boldsymbol{r}) + \underline{\frac{\langle \boldsymbol{r}'_{DD^*} | V^t | \psi \rangle \langle \psi | V^t | \boldsymbol{r}_{DD^*} \rangle}{E - \nu_0}}$$

$$= V(\boldsymbol{r}'_{DD^*}, \boldsymbol{r}_{DD^*}; E)$$

- Effective potential is non-local and energy-dependent

I. Terashima, T. Hyodo, arXiv:2208.14075 [nucl-th]

local approximation

Non-local potential with Yukawa FF $\langle \boldsymbol{r}_{DD^*} | V^t | \psi \rangle = g_0 e^{-\Lambda r}/r$

S. Aoki and K. Yazaki, PTEP2022, 033B04 (2022)

- Wave function $\psi_k(r)$ is analytically solvable ($k = \sqrt{2\mu E}$)

Local approximations : $\{D^0 \bar{D}^{*0}\}$ potentials for $X(3872)$ at $E = 0$

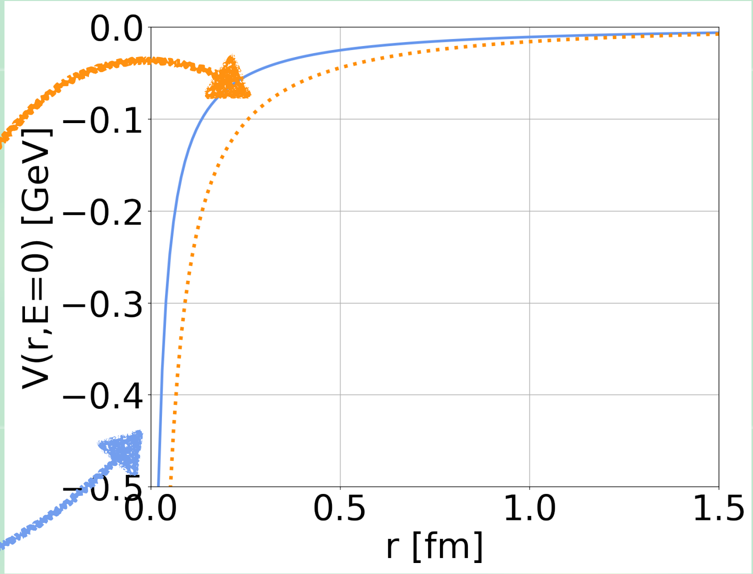
I. Terashima, T. Hyodo, in preparation

- Formal derivative expansion

$$V^{\mathrm{formal}}(r, E) = \frac{4\pi g_0^2}{\Lambda^2 (E - \nu_0)} \frac{e^{-\Lambda r}}{r} + \mathcal{O}(\nabla)$$

- HALQCD (reproduces $\delta(E)$)

$$V^{\mathrm{HAL}}(r, E) = \frac{1}{2\mu r \psi_k(r)} \frac{d^2}{dr^2} [r \psi_k(r)] + \mathcal{O}(\nabla^2)$$



- $V(\boldsymbol{r}'_{DD^*}, \boldsymbol{r}_{DD^*}; E)$ can be approximated by $V^{\mathrm{HAL}}(r{,}0)$ around $E \sim 0$

Compositeness theorem

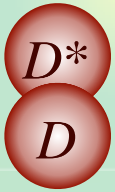
Near-threshold s-wave states are **all molecules!**

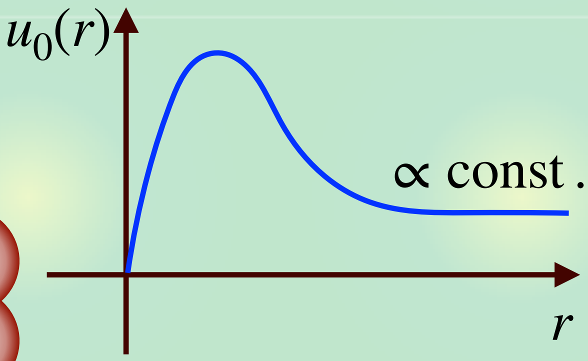
- Compositeness theorem

T. Hyodo, PRC90, 055208 (2014)

$$1 = \underbrace{|\langle T_{cc}|\psi\rangle|^2}_{Z} + \underbrace{\int d\boldsymbol{r}\,|\langle T_{cc}|\boldsymbol{r}_{DD^*}\rangle|^2}_{\text{compositeness } X}$$

Z compositeness X





—> Fully molecule state $X = 1$ in $B \to 0$ limit

- Low-energy universality

E. Braaten, H.-W. Hammer, Phys. Rept. 428, 259 (2006);
P. Naidon, S. Endo, Rept. Prog. Phys. 80, 056001 (2017)

- Threshold rule of cluster nuclei

H. Horiuchi, K. Ikeda, Y. Suzuki, PTPS 55, 89 (1972)

- Peculiar pole trajectories

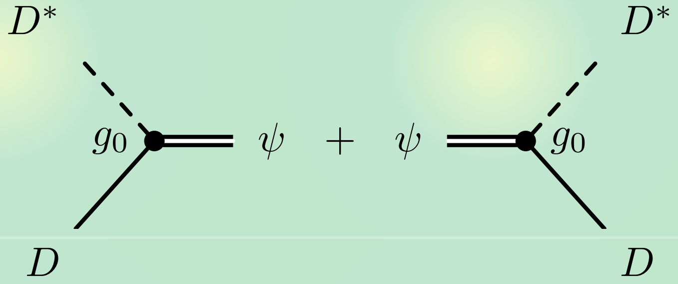
C. Hanhart, A. Nefediev, arXiv:2209.10165 [hep-ph]

Model setup

EFT model for T_{cc} (single channel)

T. Kinugawa, T. Hyodo, in preparation

- DD^* coupled with a bare state ψ (no direct DD^* int.)



Parameters : coupling g_0 and bare energy ν_0 (cutoff $\Lambda = m_\pi$)

- Bound state condition with B —> $g_0(\nu_0; \Lambda, B)$
- ν_0 free parameter (c.f. quark model ~ 7 MeV)

M. Karlinar, J.L. Rosner, PRL 119, 202001 (2018)

Compositeness $X(\nu_0; \Lambda, B)$: fraction of DD^* molecule

Y. Kamiya, T. Hyodo, PRC93, 035203 (2016); PTEP2017, 023D02 (2017);
T. Kinugawa, T. Hyodo, PRC 106, 015205 (2022)

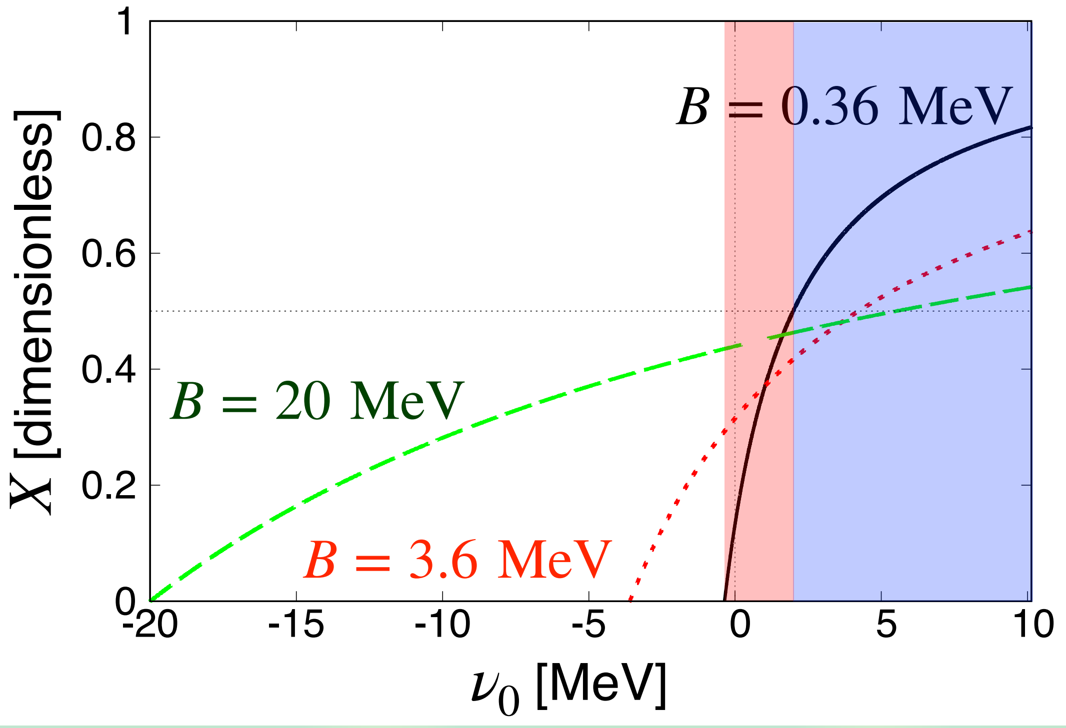
Structure of bound state

Natural binding energy <— scale of strong interaction : 1 fm

T. Kinugawa, T. Hyodo, in preparation

$$B \sim \frac{1}{2\mu_{DD^*}(1\ \mathrm{fm})^2} \sim 20\ \mathrm{MeV}$$

cutoff energy scale ↓



Natural : $B = 20$ MeV

- $X > 0.5$ **for 15% of** ν_0
- **Elementary dominance**

<— Bare state origin

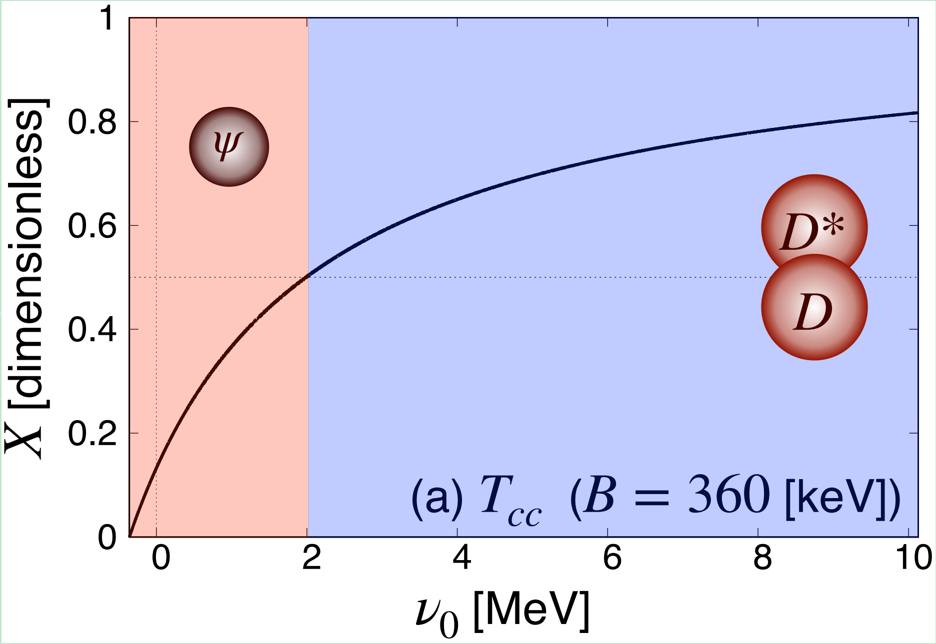
Shallow : $B = 0.36$ MeV

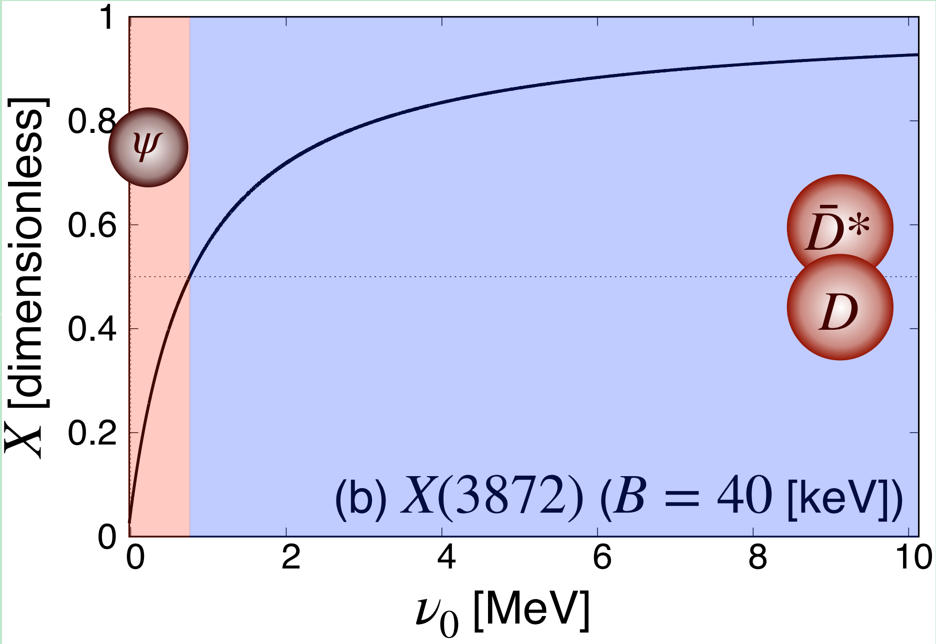
- $X > 0.5$ **for 78% of** ν_0
- **Composite dominance even without** DD^* **direct interaction**
- **To have** $X < 0.5$, **fine tuning of** ν_0 **is necessary**

Application to T_{cc} and $X(3872)$

T_{cc} and $X(3872)$: single-channel case

T. Kinugawa, T. Hyodo, in preparation



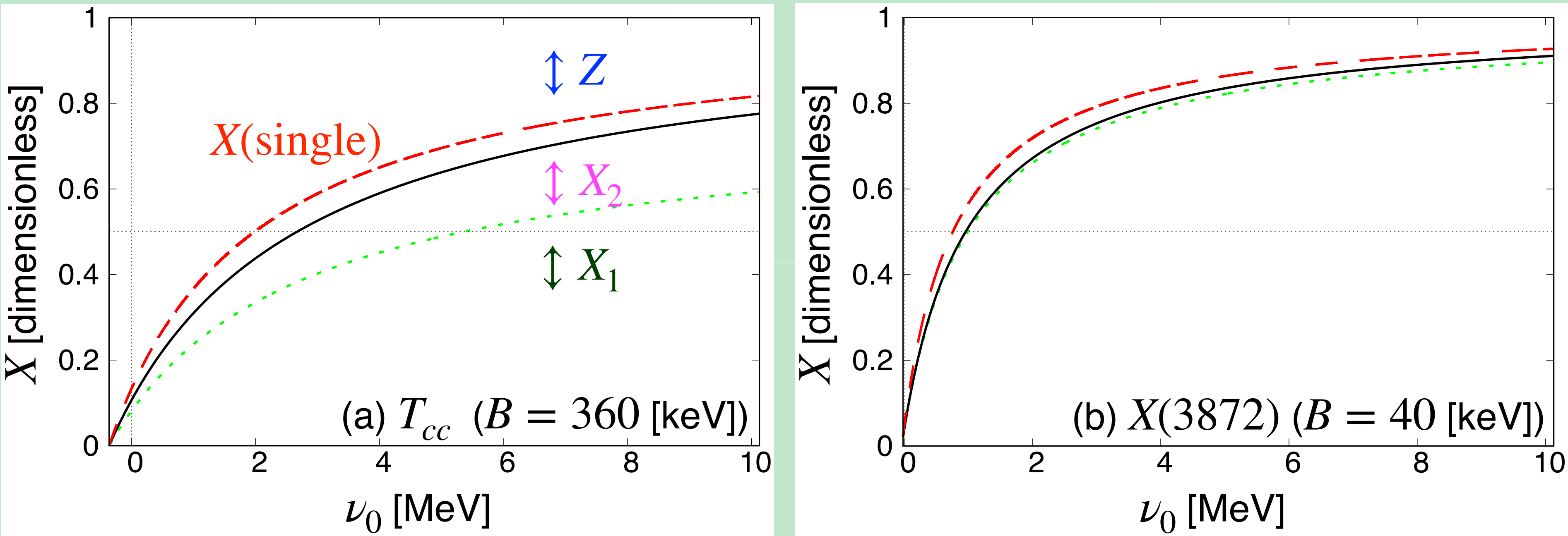


- $X > 0.5$ **for 78% of ν_0 for T_{cc}**, $X > 0.5$ **for 92% of ν_0 for $X(3872)$**
- $X(3872)$ **is more composite <— smaller B**
- **To have $X < 0.5$, extreme fine tuning of ν_0 is necessary**

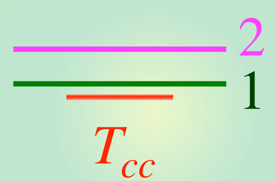
More realistic T_{cc} and $X(3872)$

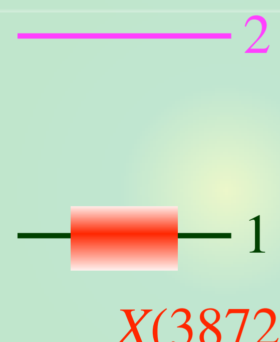
T_{cc} and $X(3872)$: coupled-channel case

T. Kinugawa, T. Hyodo, in preparation



- X(single) $\sim X_1 + X_2$: Z is stable
- DD^* effect is shared by 1 and 2
- $X_{2,T_{cc}} > X_{2,X(3872)}$ <— closer D^+D^{*0}

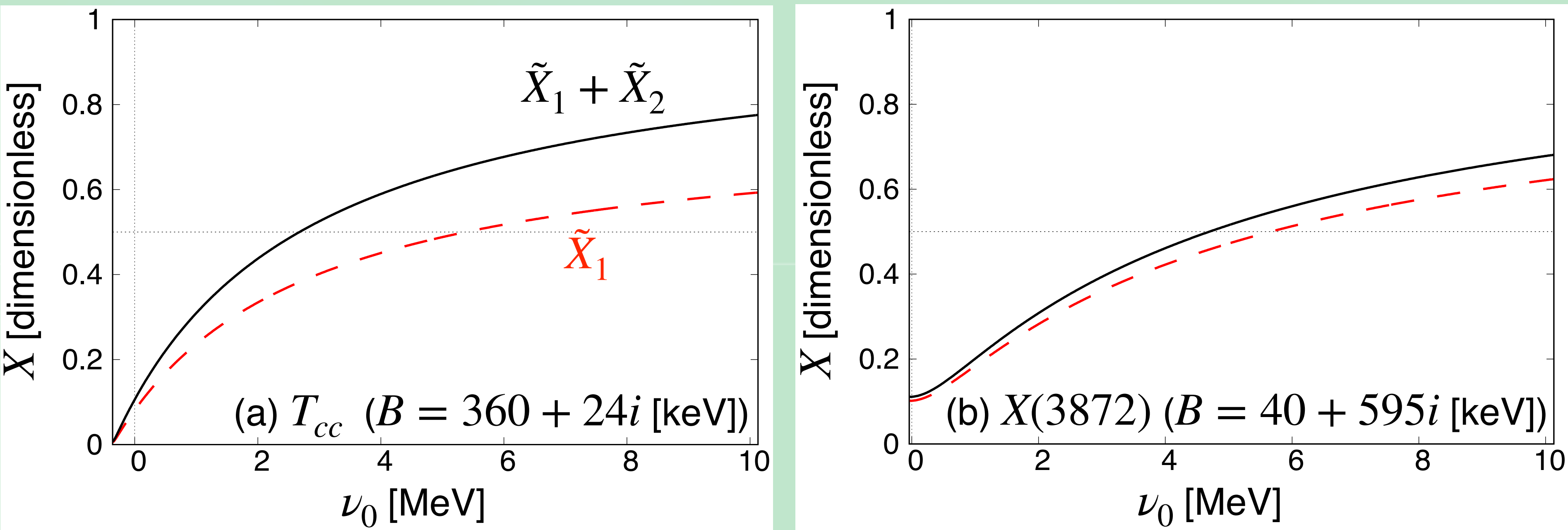




Further realistic T_{cc} and $X(3872)$

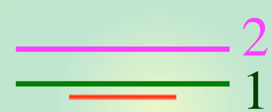
T_{cc} and $X(3872)$: coupled-channel case with decay width

T. Kinugawa, T. Hyodo, in preparation

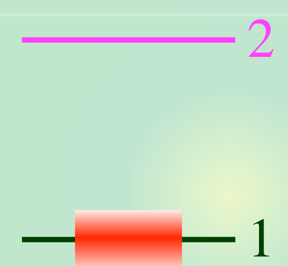


- $\tilde{X}_i = \dfrac{|X_i|}{\sum_i |X_i| + |Z|}$

T. Sekihara, *et al.*, PRC 93, 035204 (2016)



T_{cc}



$X(3872)$

- **Important in $X(3872)$ <— large width**

Summary

- $D^0 D^{*+}$ and $D^0 \bar{D}^{*0}$ correlations
  - (quasi-)bound nature of T_{cc} and $X(3872)$

Y. Kamiya, T. Hyodo, A. Ohnishi, EPJA58, 131 (2022)

- Coupling to compact quark states
  - Potential becomes non-local and E-dep., but effective local potential can be constructed.

I. Terashima, T. Hyodo, in preparation

- Compositeness theorem
  - Near-threshold s-wave states are molecules, no matter how you construct them.

T. Hyodo, PRC 90, 055208 (2014); T. Kinugawa, T. Hyodo, in preparation