Compositeness of T_{cc} and $X(3872)$ with decay and coupled-channel effects

arXiv:2303.07038 [hep-ph]

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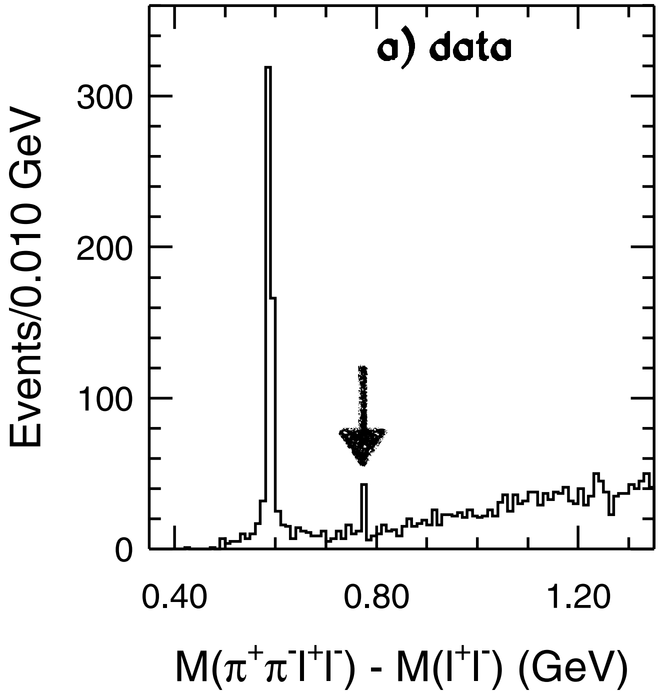
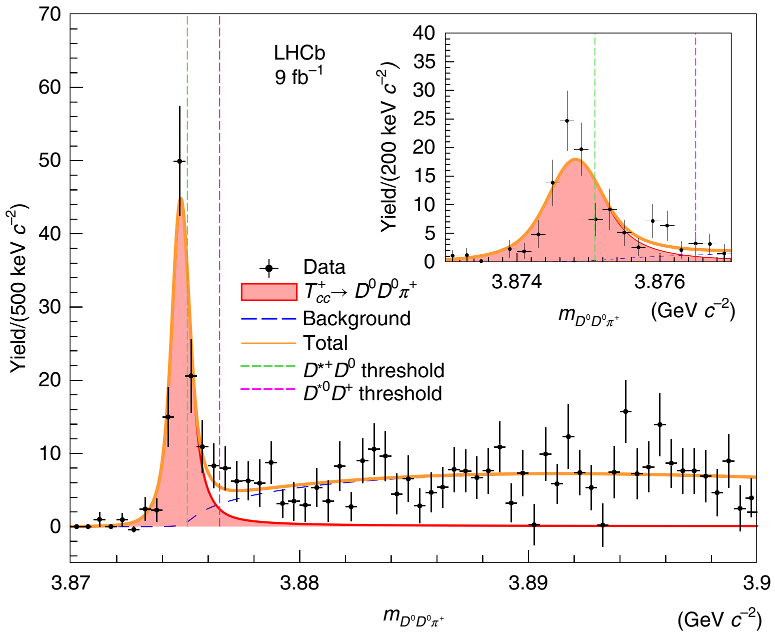
Near-threshold exotic hadrons

$X(3872) \to \pi^+\pi^- J/\psi$



S. K. Choi *et al.* (Belle), Phys. Rev. Lett. **91**, 262001 (2003).

$T_{cc} \to D^0 D^0 \pi^+ \ (cc\bar{u}\bar{d})$



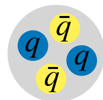
LHCb Collaboration, Nature Phys. **18** (2022) no.7, 751-754;

LHCb Collaboration, Nat. Commun. **13** 3351 (2022).

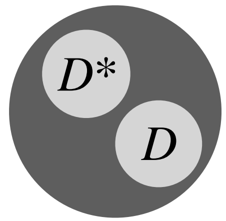
internal structure?

exotic hadron

$\neq$ qqq or $q\bar{q}$ → multiquarks, hadronic molecules



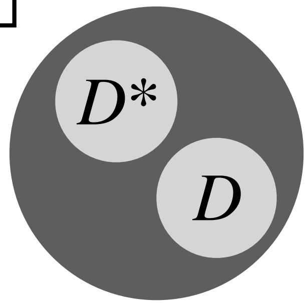
multiquarks

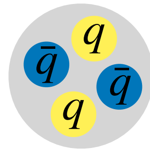


hadronic molecules

Compositeness

T. Hyodo, D. Jido, and A. Hosaka, Phys. Rev. C **85**, 015201 (2012);
F. Aceti and E. Oset, Phys. Rev. D **86**, 014012 (2012).





◉ definition

hadron wavefunction

$$|\Psi\rangle = \sqrt{X}\,|\text{hadronic molecule}\rangle + \sqrt{1-X}\,|\text{others}\rangle$$

compositeness **elementarity**

T. Hyodo, Int. J. Mod. Phys. A 28, 1330045 (2013).

※ $0 \leq X \leq 1$ ⟶ $X > 0.5 \Leftrightarrow$ **composite dominant**

$X < 0.5 \Leftrightarrow$ **elementary dominant**

- **quantitative** analysis of internal structure

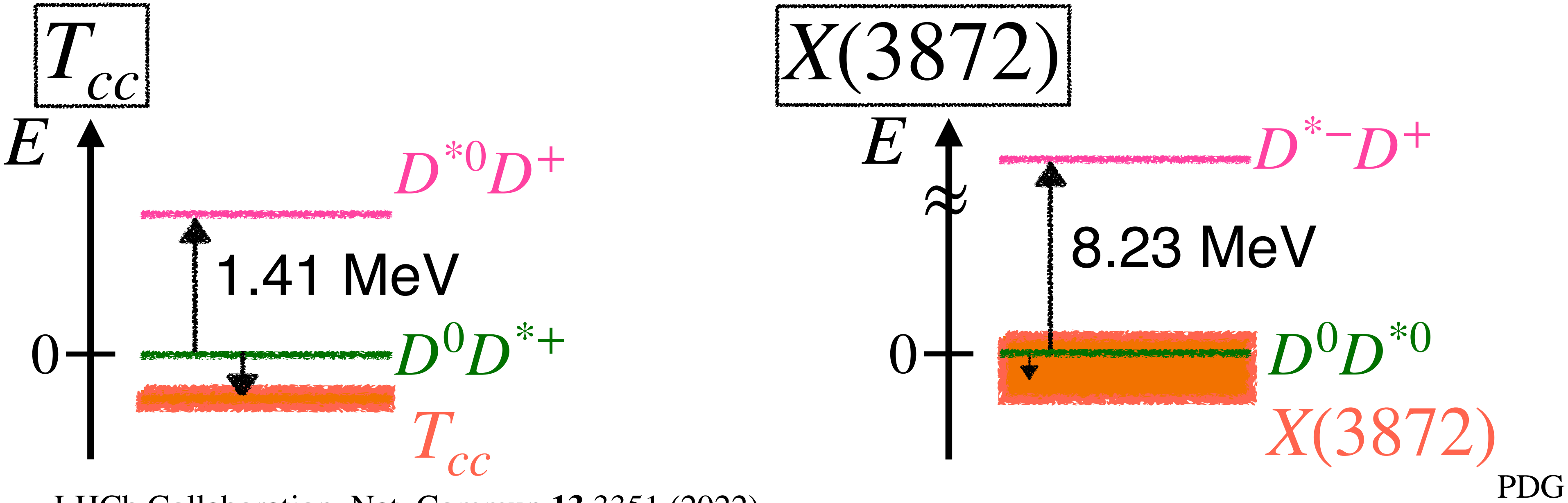
deuteron is not an elementary particle Weinberg, S. Phys. Rev. 137, 672–678 (1965).

$f_0(980)$, $a_0(980)$ Y. Kamiya and T. Hyodo, PTEP 2017, Phys. Rev. C 93, 035203 (2016); T. Sekihara, S. Kumano, Phys. Rev. D 92, 034010 (2015) etc.

$\Lambda(1405)$ T. Sekihara, T. Hyodo, Phys. Rev. C 87, 045202 (2013) ; Z.H. Guo, J.A. Oller, Phys. Rev. D 93, 096001 (2016) etc.

nuclei & atomic systems T. Kinugawa, T. Hyodo, Phys. Rev. C 106, 015205 (2022) etc.

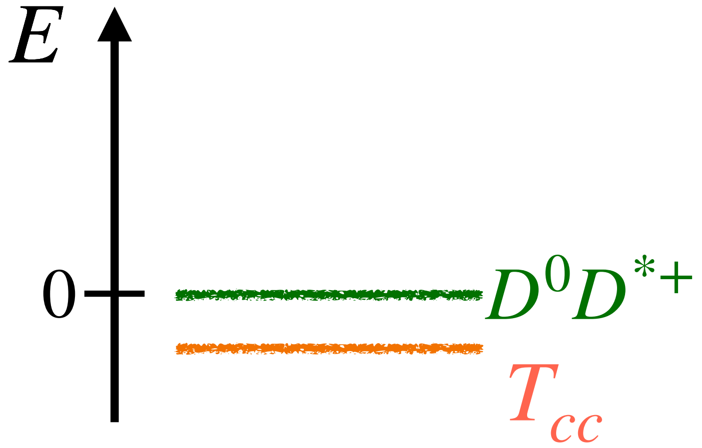
Near-threshold states



LHCb Collaboration, Nat. Commun **13** 3351 (2022).

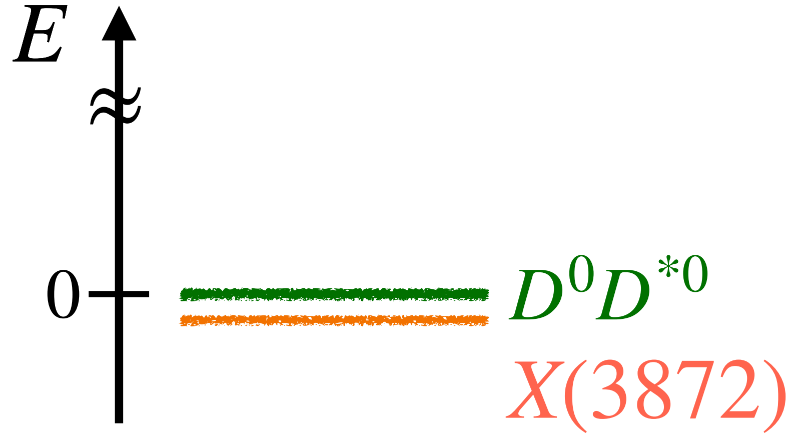
Near-threshold states

T_{cc}



LHCb Collaboration, Nat. Commun **13** 3351 (2022).

$X(3872)$



PDG

- compositeness $X = 1$ in $B \to 0$ limit (universality)

T. Hyodo, Phys. Rev. C **90**, 055208 (2014) .

Near threshold states ($B \neq 0$) is composite dominant ?

- However, elementary dominant states is realized with fine tuning

T. Hyodo, Phys. Rev. C **90**, 055208 (2014) ;
C. Hanhart, J. R. Pelaez, and G. Rios, Phys. Lett. B **739**, 375 (2014).

⟶ How finely tuning parameter?

Model

E. Braaten, M. Kusunoki, and D. Zhang, Annals Phys. 323, 1770 (2008).

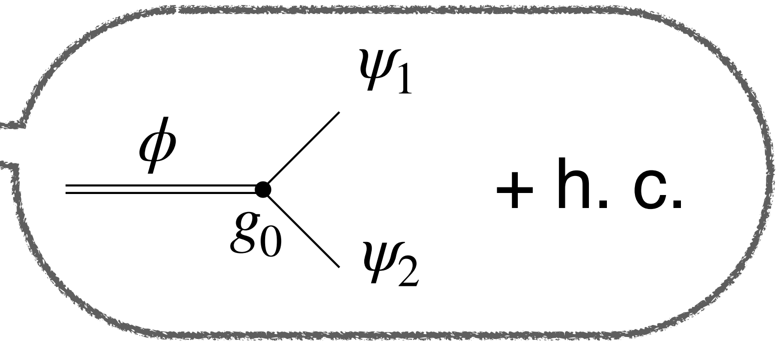
◉ single-channel resonance model

$$\mathcal{H}_{\text{free}} = \frac{1}{2m_1}\nabla\psi_1^\dagger\cdot\nabla\psi_1 + \frac{1}{2m_2}\nabla\psi_2^\dagger\cdot\nabla\psi_2 + \frac{1}{2m_\phi}\nabla\phi^\dagger\cdot\nabla\phi + \nu_0\phi^\dagger\phi,$$

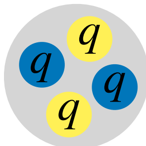
1.

$$\mathcal{H}_{\text{int}} = g_0(\phi^\dagger\psi_1\psi_2 + \psi_1^\dagger\psi_2^\dagger\phi)\,.$$

2.



1. single-channel scattering
2. coupling to bare state ϕ



◉ scattering amplitude

$$V = \frac{g_0^2}{E-\nu_0}, \quad G = -\frac{\mu}{\pi^2}\left[\Lambda + ik\arctan\left(\frac{\Lambda}{-ik}\right)\right]. \quad \Lambda : \text{cutoff}$$

$$\xrightarrow{T = \frac{1}{V^{-1}-G}} \quad f(k) = -\frac{\mu}{2\pi}\left[\frac{\frac{k^2}{2\mu}-\nu_0}{g_0^2} + \frac{\mu}{\pi^2}\left[\Lambda + ik\arctan\left(\frac{\Lambda}{-ik}\right)\right]\right]^{-1}.$$

Model scales and parameters

- typical energy scale : $E_{\rm typ} = \Lambda^2/(2\mu)$

- three model parameters g_0, ν_0, Λ

1. calculation with given B

coupling const. g_0 : $g_0^2(B, \nu_0, \Lambda) = \frac{\pi^2}{\mu}(B + \nu_0)\left[\Lambda - \kappa \arctan(\Lambda/\kappa)\right]^{-1}$

∵ bound state condition $f^{-1} = 0$ $\kappa = \sqrt{2\mu B}$.

2. use dimensionless quantities with Λ

⟶ results do not depend on cutoff Λ

3. energy of bare quark state ν_0

varied in the region : $-B/E_{\rm typ} \le \nu_0/E_{\rm typ} \le 1$

∵ to have $g_0^2 \ge 0$ & applicable limit of model

Calculation

◉ <u>compositeness X</u>

scattering amplitude : $T = \dfrac{1}{V^{-1} - G}$ Y. Kamiya and T. Hyodo, PTEP 2017, 023D02 (2017).

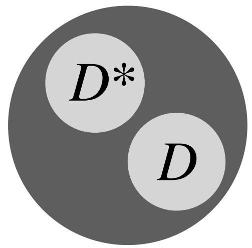
$$\longrightarrow X = \frac{G'(-B)}{G'(-B) - [V^{-1}(-B)]'}, \quad \alpha'(E) = d\alpha/dE$$

$$= \left[1 + \frac{\pi^2\kappa}{g_0^2\mu^2}\left(\arctan(\Lambda/\kappa) - \frac{\Lambda/\kappa}{1+(\Lambda/\kappa)^2}\right)^{-1}\right]^{-1}.$$

- ν_0 region : $-B/E_{\mathrm{typ}} \leq \nu_0/E_{\mathrm{typ}} \leq 1$

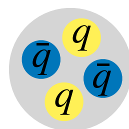
ν_0 dependence ⟷ model dependence

$X > 0.5$



or

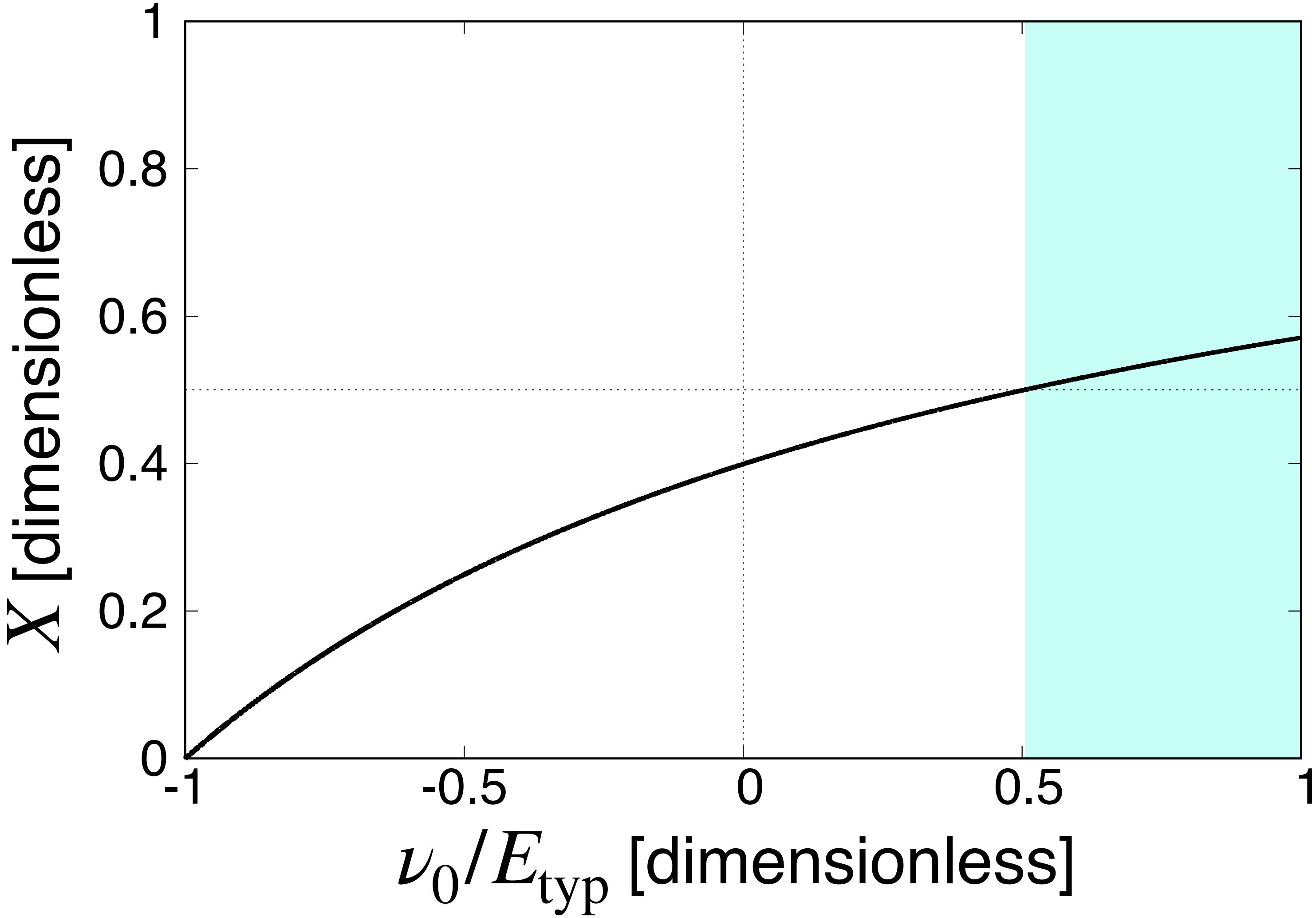
$X < 0.5$

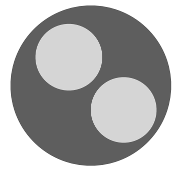


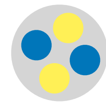
compositeness X as a function of ν_0

⟶ internal structure of bound state?

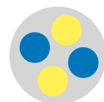
◉ X as a function of $\nu_0/E_{\rm typ}$ of bound state $B = E_{\rm typ}$



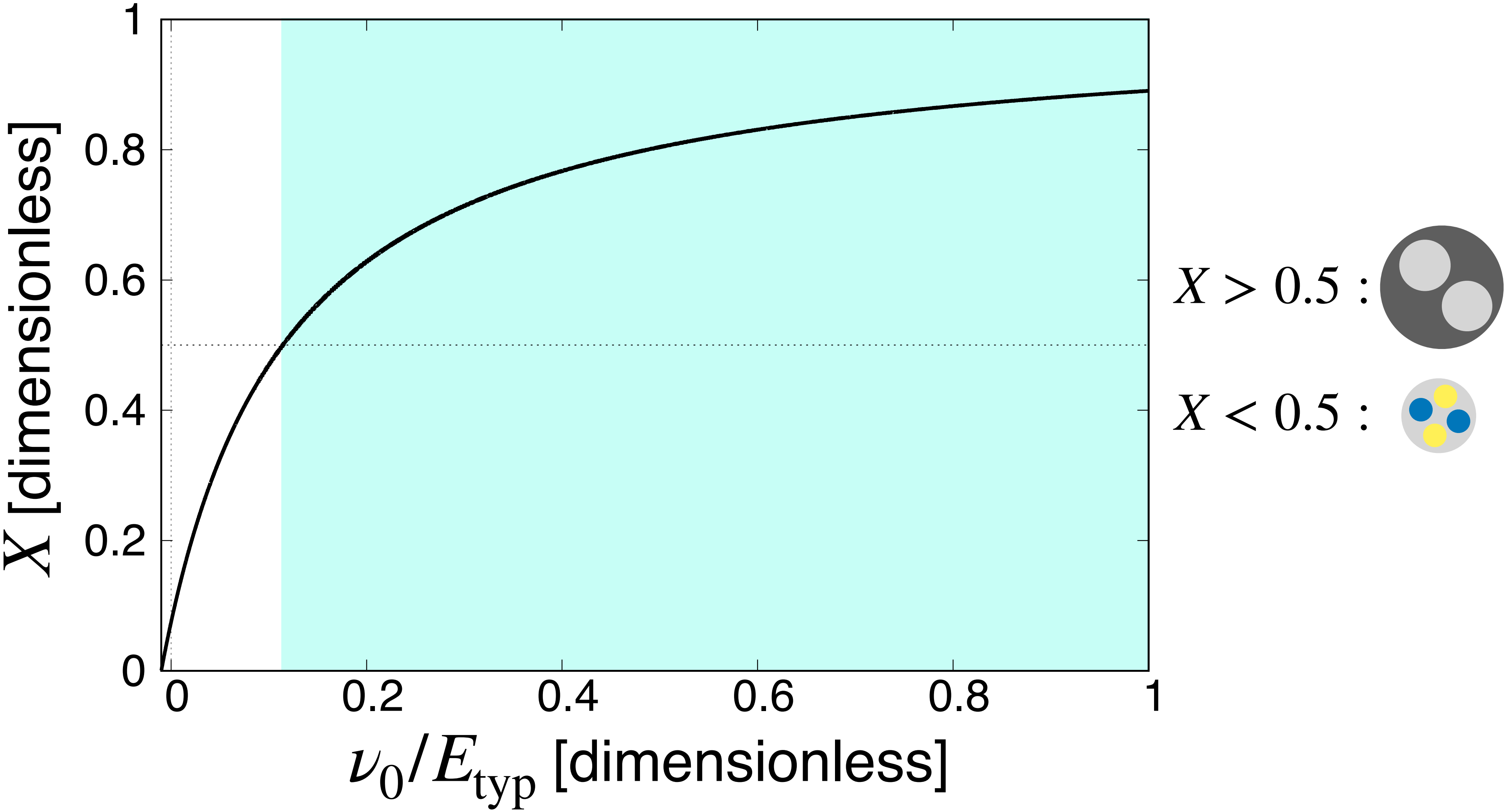
$X > 0.5$: 

$X < 0.5$: 

- typical energy scale : $B = E_{\rm typ} = \Lambda^2/(2\mu)$

- $X > 0.5$ only for $25\ \%$ of ν_0 $\because$ **bare state origin** 

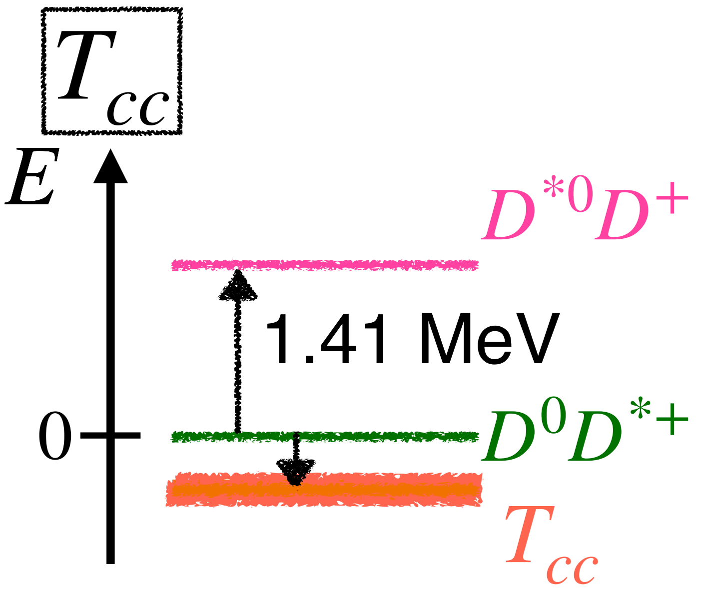
◉ X as a function of $\nu_0/E_{\rm typ}$ of bound state $B = 0.01E_{\rm typ}$



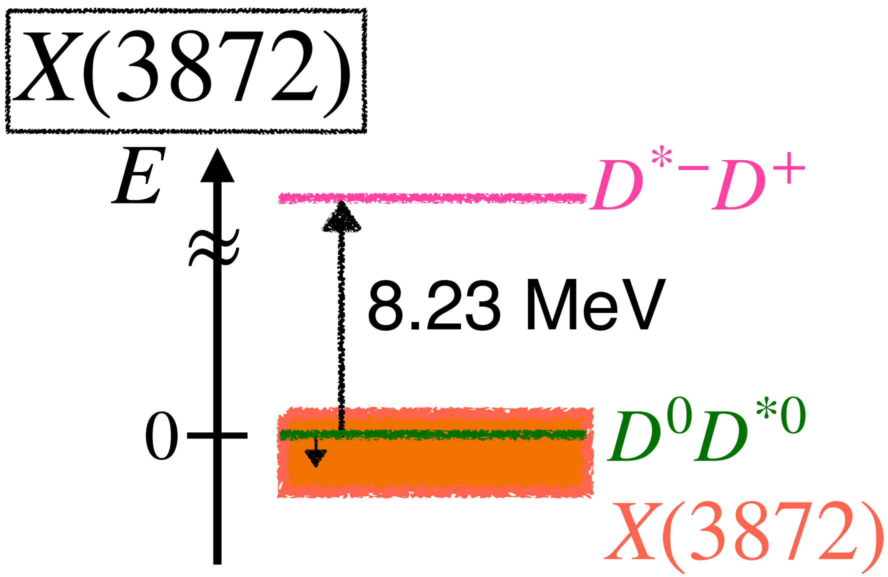
- weakly-bound state : $B = 0.01E_{\rm typ}$
- $X > 0.5$ for $88\ \%$ of ν_0 ⟶ **realization of universality**
- elementary dominant state can be realized with fine tuning

Decay & coupled ch. effects

actual exotic hadrons ⟶ decay and coupled channels



LHCb Collaboration, Nat. Commun **13** 3351 (2022).



PDG

other channels than threshold channel make deviation from $X = 1$

Y. Kamiya and T. Hyodo, PTEP 2017, 023D02 (2017).

In this work, we study those deviations quantitatively!

Effect of decay

◉ introducing decay effect

- formally : introducing decay channel in lower energy region than binding energy

  ⟶ eigenenergy becomes complex

- effectively : coupling const. $g_0 \in \mathbb{C}$! ⟵ this work

$$\mathscr{H}_{\rm int} = g_0(\phi^\dagger \psi_1 \phi_2 + \phi_1^\dagger \psi_2^\dagger \phi)\,.$$

$$E = -B \longrightarrow E = -B - i\Gamma/2$$

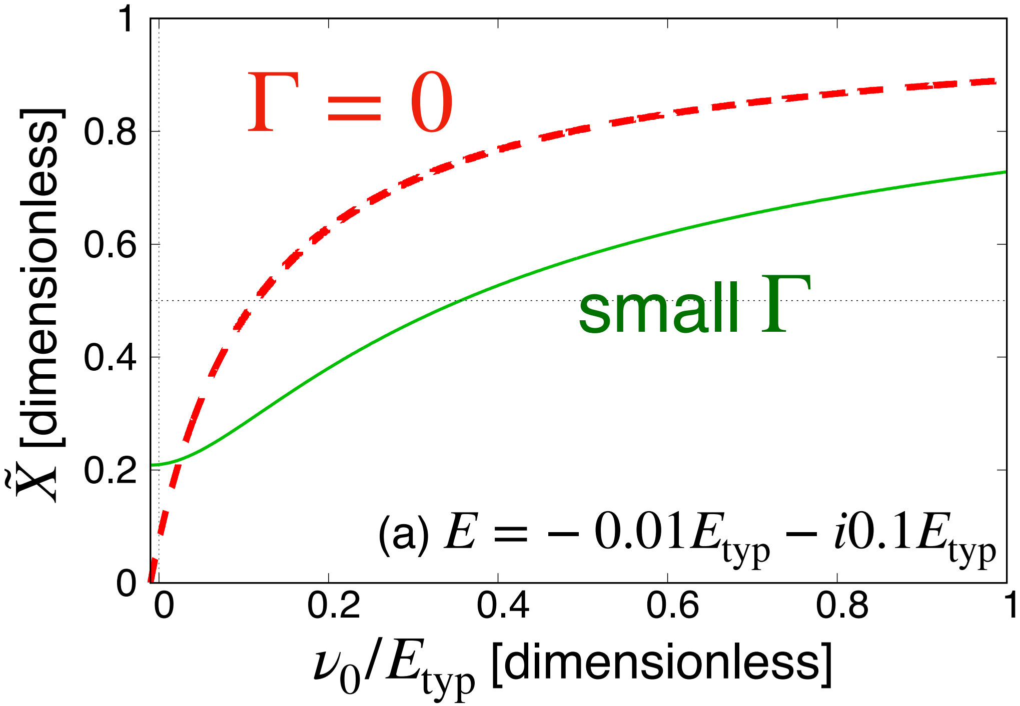
compositeness T. Sekihara, T. Arai, J. Yamagata-Sekihara and S. Yasui, PRC 93, 035204 (2016).

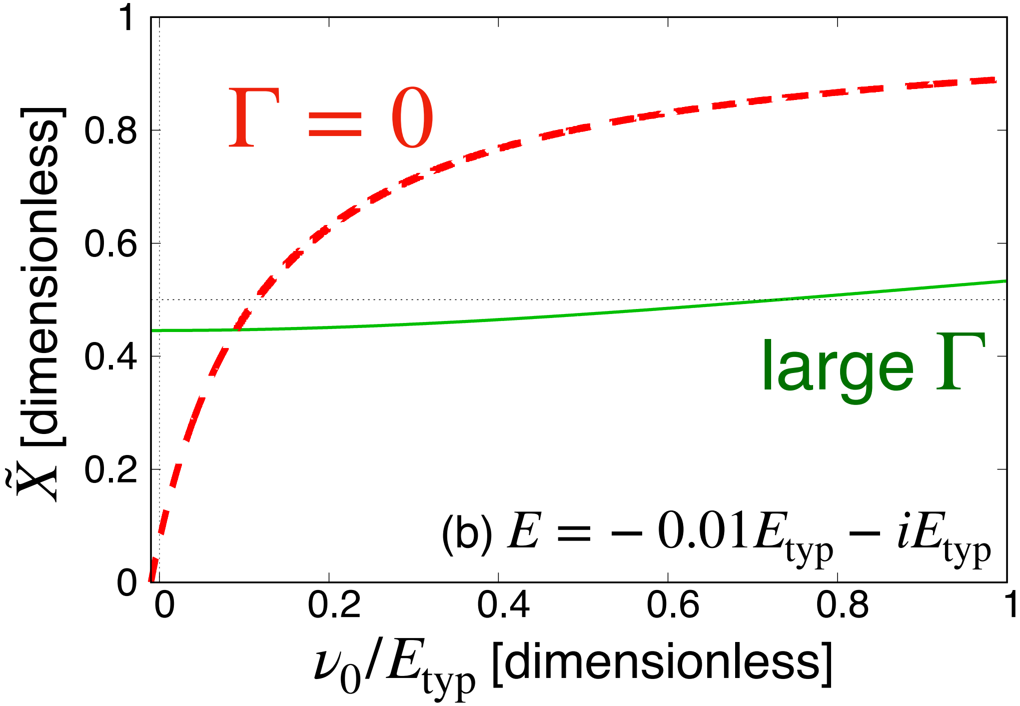
$$X \in \mathbb{R} \longrightarrow X \in \mathbb{C}$$

$$\tilde{X} = \frac{|X|}{|X| + |1 - X|}$$

Effect of decay

$E = -0.01E_{\rm typ} - i0.1E_{\rm typ}$ $\qquad$ $E = -0.01E_{\rm typ} - iE_{\rm typ}$

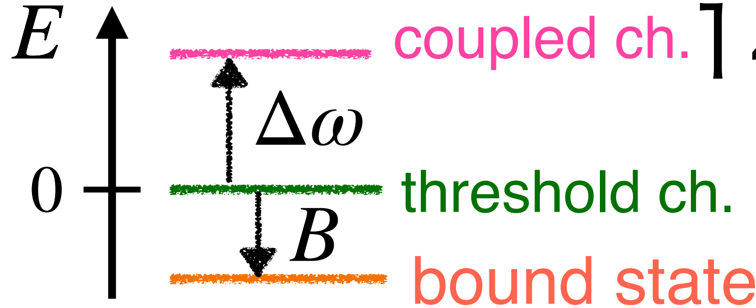




- $\tilde{X}$ is suppressed by decay effect

∵ threshold ch. component ($\tilde{X}$) decreases with inclusion of decay ch. component ($1 - \tilde{X}$)

Effect of coupled channel



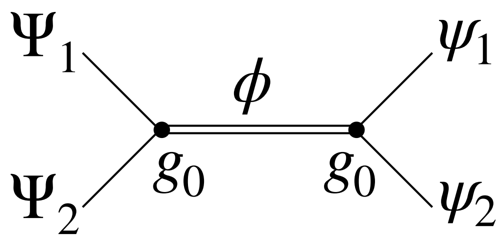
◉ introducing coupled channel $\Psi_1\Psi_2$

$$|\Psi\rangle = \sqrt{X_1}\,|\text{threshold ch}\rangle + \sqrt{X_2}\,|\text{coupled ch}\rangle + \sqrt{1-(X_1+X_2)}\,|\text{others}\rangle$$

$$\mathcal{H}_{\text{free}} = (\text{kinetic terms of } \psi_{1,2}, \Psi_{1,2}, \phi) + \omega_1 \Psi_1 \Psi_1^\dagger + \omega_2 \Psi_2 \Psi_2^\dagger + \nu_0 \phi^\dagger \phi,$$

$$\mathcal{H}_{\text{int}} = g_0(\phi^\dagger \psi_1 \psi_2 + \psi_1^\dagger \psi_2^\dagger \phi + \phi^\dagger \Psi_1 \Psi_2 + \Psi_1^\dagger \Psi_2^\dagger \phi)\,.$$

- threshold energy difference $\Delta\omega = \omega_1 + \omega_2$
- ch. 1 couples to ch. 2 through ϕ with same coupling const.



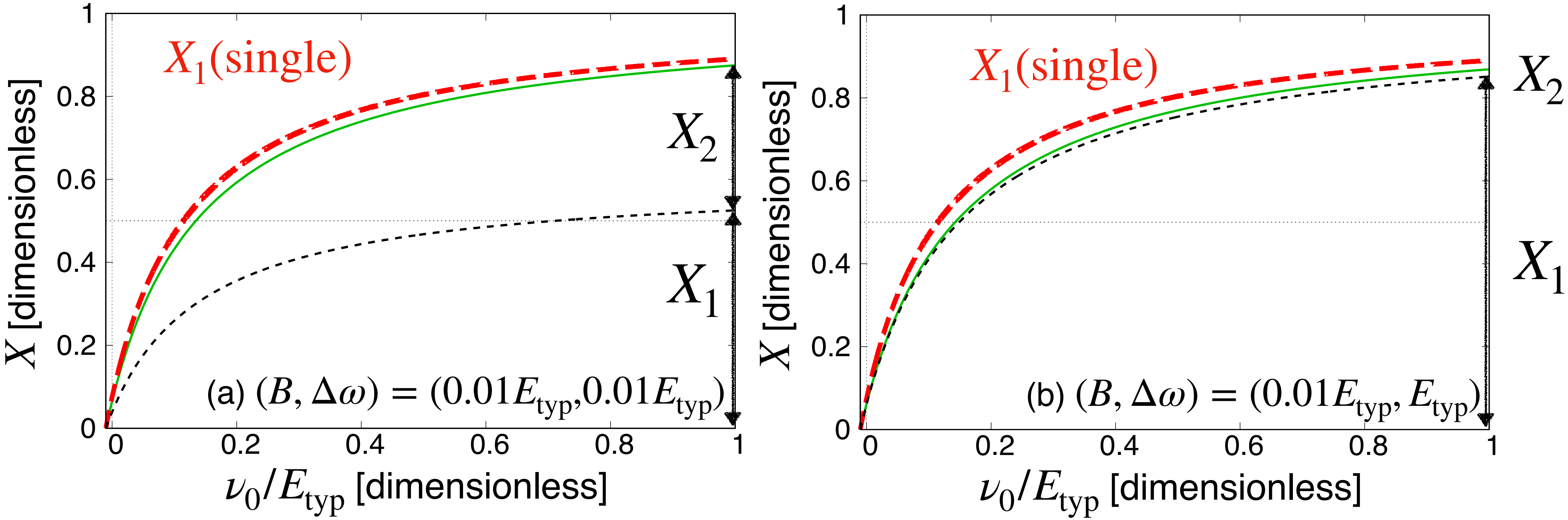
- low-energy universality with coupled-channel effect ($B \to 0$)

  $X_1 \to 1$ (threshold channel)

  $X_2 \to 0$ and $Z \to 0$ (other channel)

Effect of coupled channel

$(B, \Delta\omega) = (0.01E_{\rm typ}, \underline{0.01E_{\rm typ}})$ $(B, \Delta\omega) = (0.01E_{\rm typ}, \underline{E_{\rm typ}})$



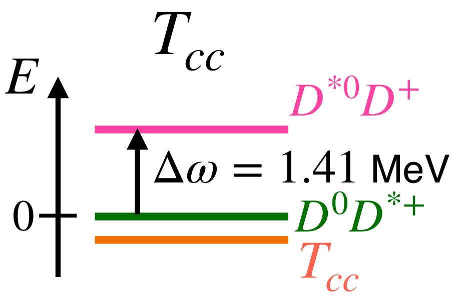
- X_1 is suppressed by channel coupling

∵ threshold ch. component (X_1) decreases with inclusion of coupled ch. component (X_2)

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

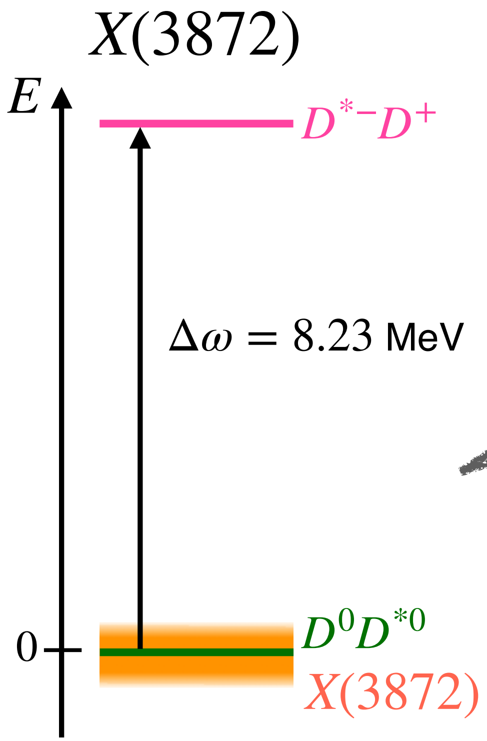
◉ exotic hadron ⟵ decay and coupled channel

small Γ and $\Delta\omega$



$B = 0.36$ MeV
$\Gamma = 0.048$ MeV

LHCb Collaboration, Nat. Commun **13** 3351 (2022).



$B = 0.04$ MeV
$\Gamma = 1.19$ MeV

PDG

large Γ and $\Delta\omega$

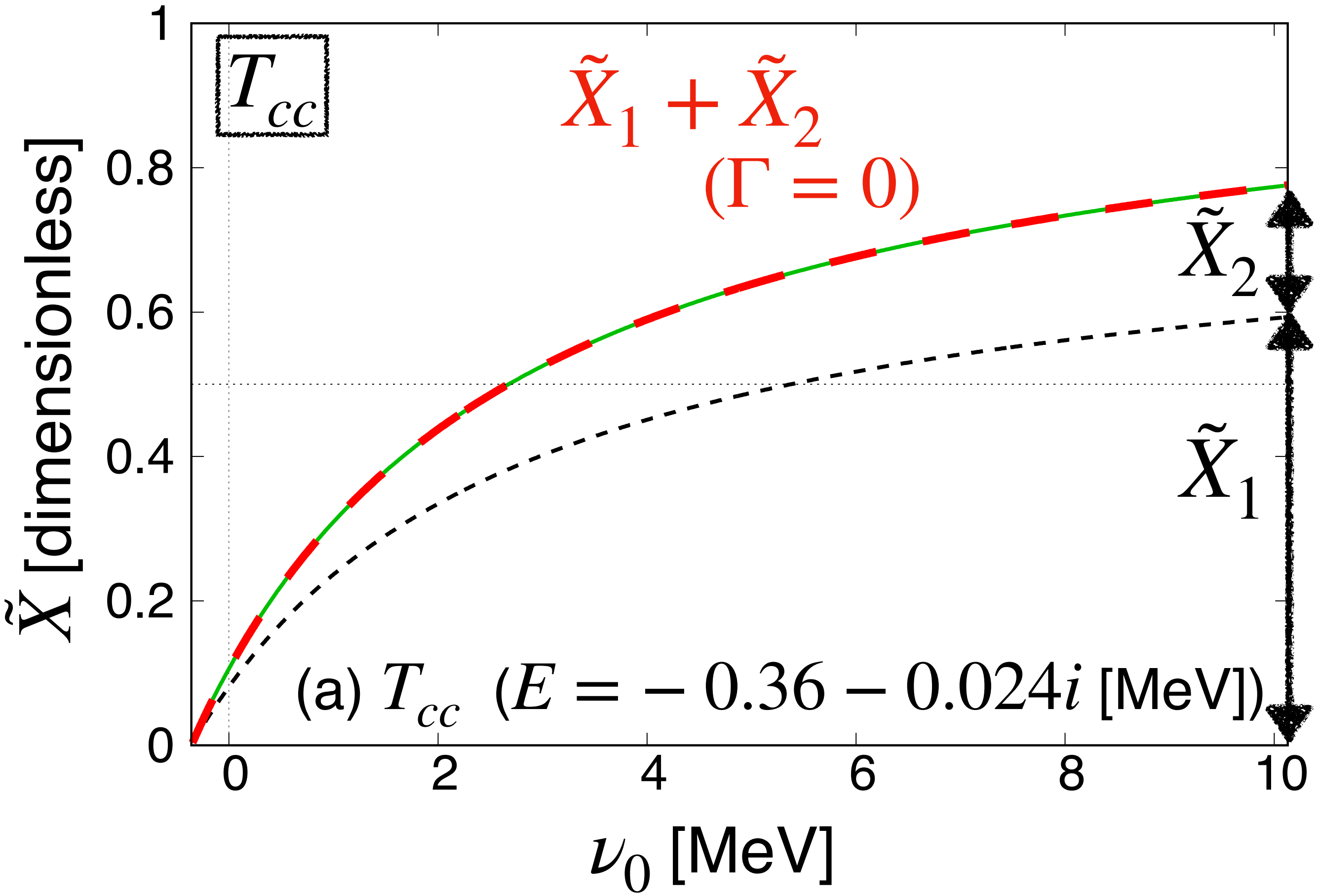
◉ compositeness T. Sekihara, T. Arai, J. Yamagata-Sekihara and S. Yasui, PRC 93, 035204 (2016).

$$\tilde{X}_j = \frac{|X_j|}{\sum_j |X_j| + |Z|}, \quad (j = 1,2)$$

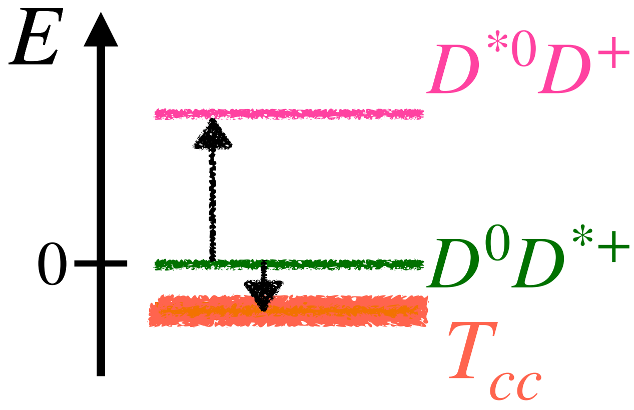
$\tilde{X}_1$: threshold ch. compositeness

$\tilde{X}_2$: coupled ch. compositeness

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



$\Lambda = 140$ MeV
(π meson)



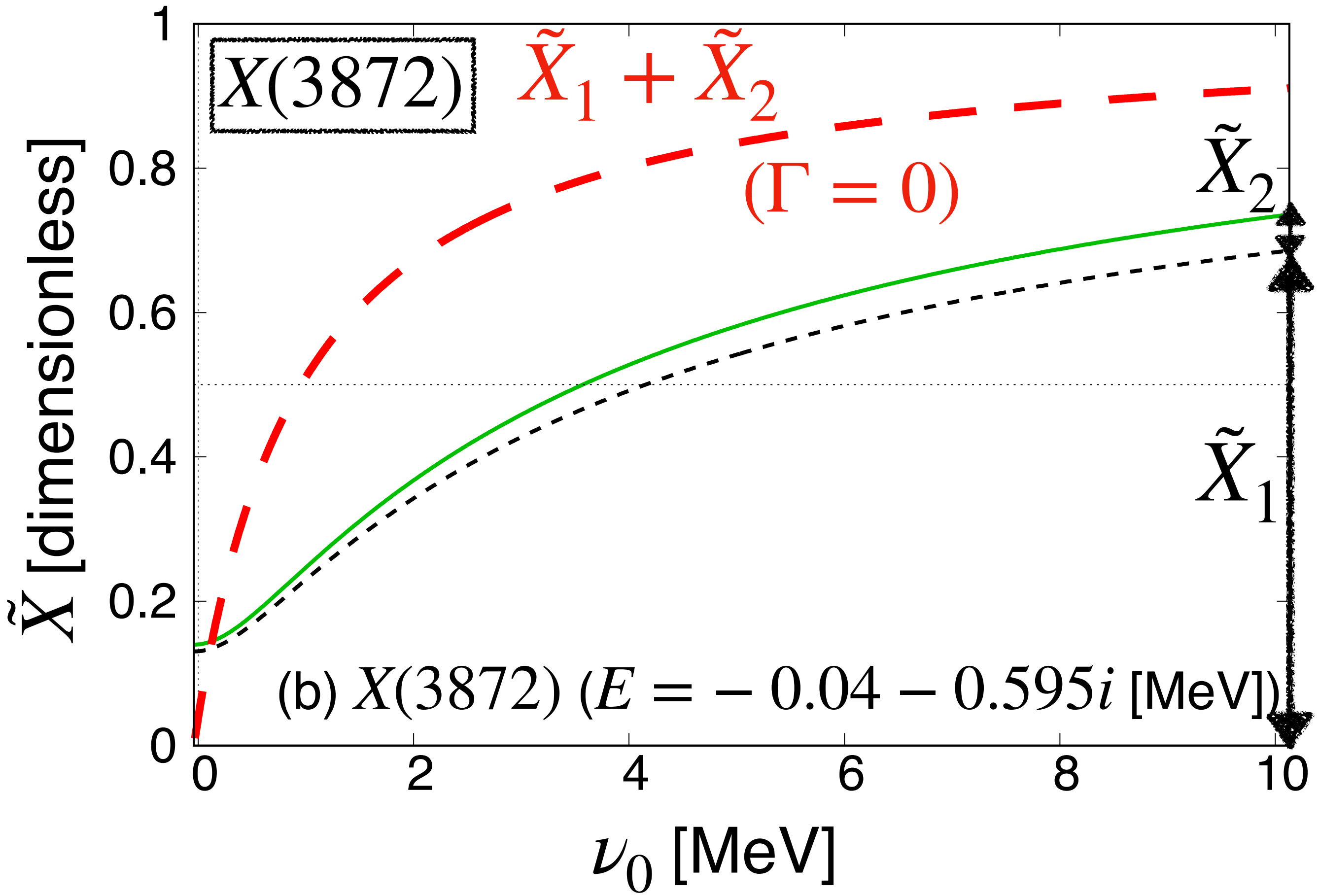
- $\tilde{X}_2$ is not negligible

  ∵ coupled ch. contribution (small $\Delta\omega$)

- difference of $\tilde{X}_1 + \tilde{X}_2(\Gamma = 0)$ and $\tilde{X}_1 + \tilde{X}_2$ is too small

  → We can neglect decay contribution ∵ $\Gamma \ll B$

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



$\Lambda = 140$ MeV
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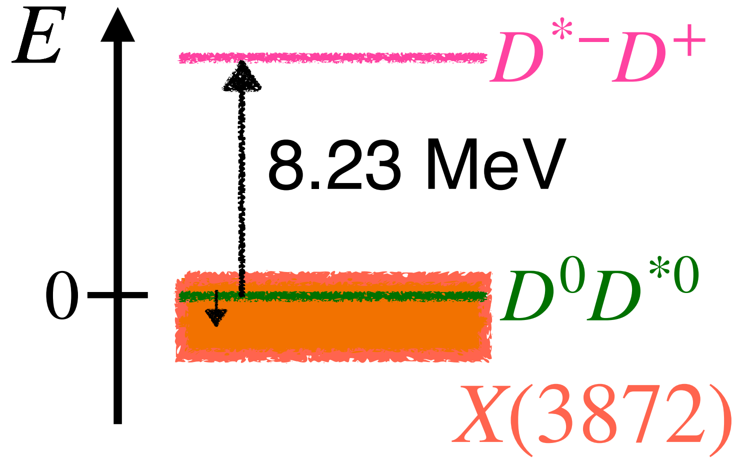

- difference of $\tilde{X}_1 + \tilde{X}_2(\Gamma = 0)$ and $\tilde{X}_1 + \tilde{X}_2$ is large

  ∵ large decay width contribution

- $\tilde{X}_2$ is much smaller than $\tilde{X}_1$

  ⟶ coupled ch. effect is small

Summary

T. Kinugawa and T. Hyodo, arXiv:2303.07038 [hep-ph]

- internal structure of exotic hadrons ← compositeness

- shallow bound state

→ fine tuning is necessary to realize elementary dominant state

- decay and coupled channel effects are introduced

→ both decay and coupled ch. effects suppress compositeness

- T_{cc} and $X(3872)$ with decay and coupled ch. effects

T_{cc} : important coupled ch. effect with negligible decay effect

$X(3872)$: important decay effect with negligible coupled ch. effect