Compositeness of exotic hadrons with decay and coupled-channel effects

arXiv:2303.07038 [hep-ph]

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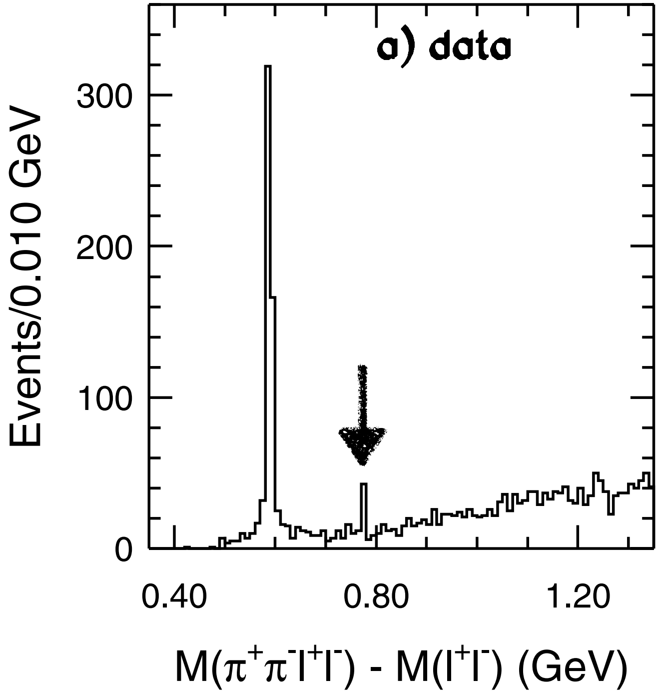
March. 16th, 3rd J-PARC HEF-ex WS

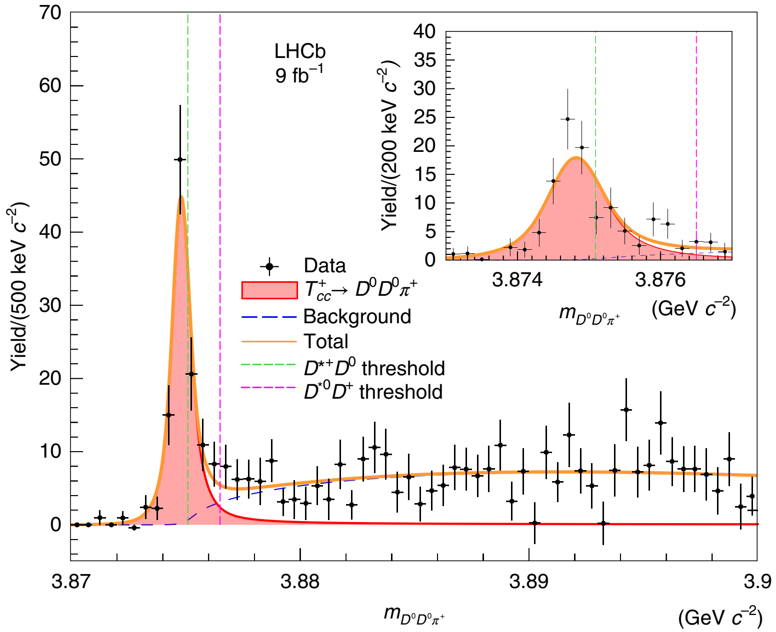
Near-threshold exotic hadrons

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



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

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



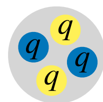
LHCb Collaboration, Nature Phys. **18** (2022) no.7, 751-754;

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

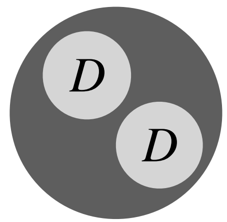
internal structure?

exotic hadron

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

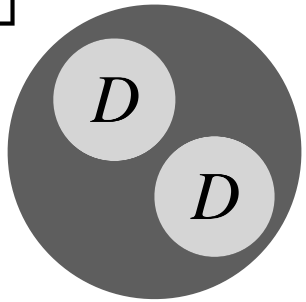


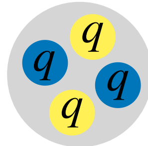
multiquarks



hadronic molecules

Compositeness





◉ 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**

◉ model calculation

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

compositeness X ⟵ residue of scattering amplitude

Low-energy universality

- scattering length $a_0 \gg$ typical length scale of system R_{typ}

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

→ length scales are written only by $|a_0|(\to \infty)$

for bound states ?

$$a_0 = R \qquad R = 1/\sqrt{2\mu B} \qquad a_0 \to \infty \longrightarrow B \to 0$$

→ universality holds for weakly-bound states!!

- compositeness $X = 1$ in $B \to 0$ limit T. Hyodo, Phys. Rev. C **90**, 055208 (2014) .

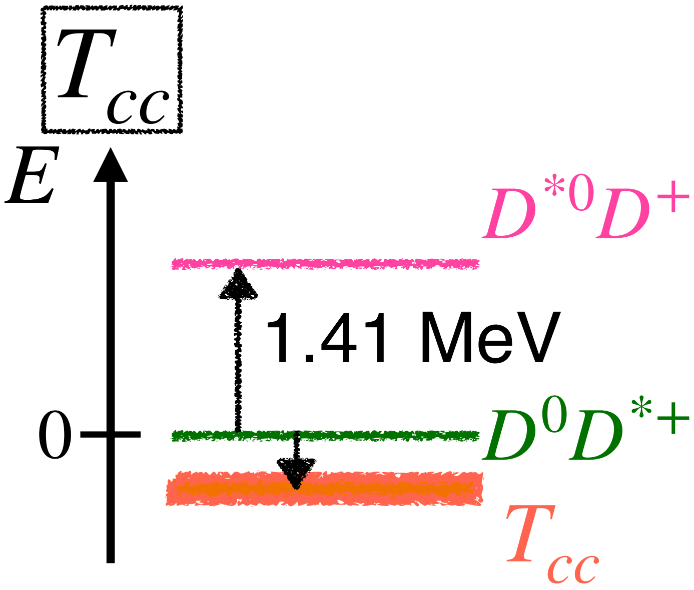
→ near threshold poles = composite dominant ?

e.g. $^{8}\mathrm{Be}$, $^{12}\mathrm{C}$ → α cluster? H. Horiuchi, K. Ikeda, and Y. Suzuki, Prog. Theor. Phys. Suppl. **52**, 89 (1972) .

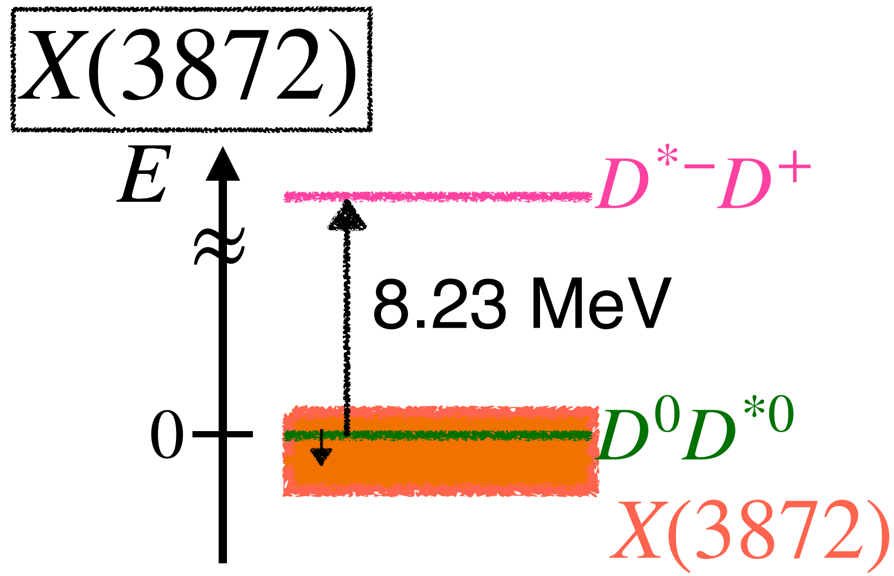
Decay & coupled ch. effects

However…

actual exotic hadrons ⟶ decay and coupled channel



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



PDG

other ch. than threshold ch. make deviation from $X = 1$

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

This work…
study those deviations quantitatively!

Model

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

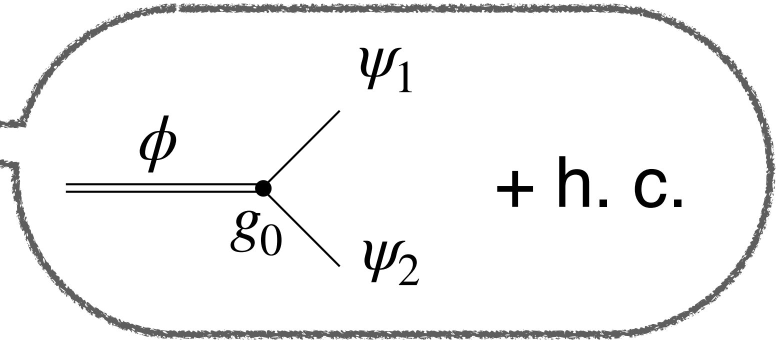
◉ single-channel resonance model

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

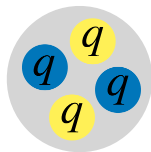
1.

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

2.



1. single-channel scattering
2. coupling with compact state ϕ



◉ scattering amplitude

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

Λ : 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 : $g_0^2(B, \nu_0, \Lambda) = \dfrac{\pi^2}{\mu}(B+\nu_0)\Big[\Lambda - \kappa\arctan(\Lambda/\kappa)\Big]^{-1}$

∵ 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 EFT

Calculation

◉ compositeness X

scattering amplitude : $T = \dfrac{1}{V^{-1} - G}$

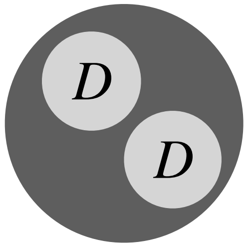
Y. Kamiya and T. Hyodo, PTEP 2017, 023D02 (2017).

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

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

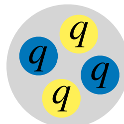
- ν_0 region : $-B/E_{\mathrm{typ}} \le \nu_0/E_{\mathrm{typ}} \le 1$

$X > 0.5$



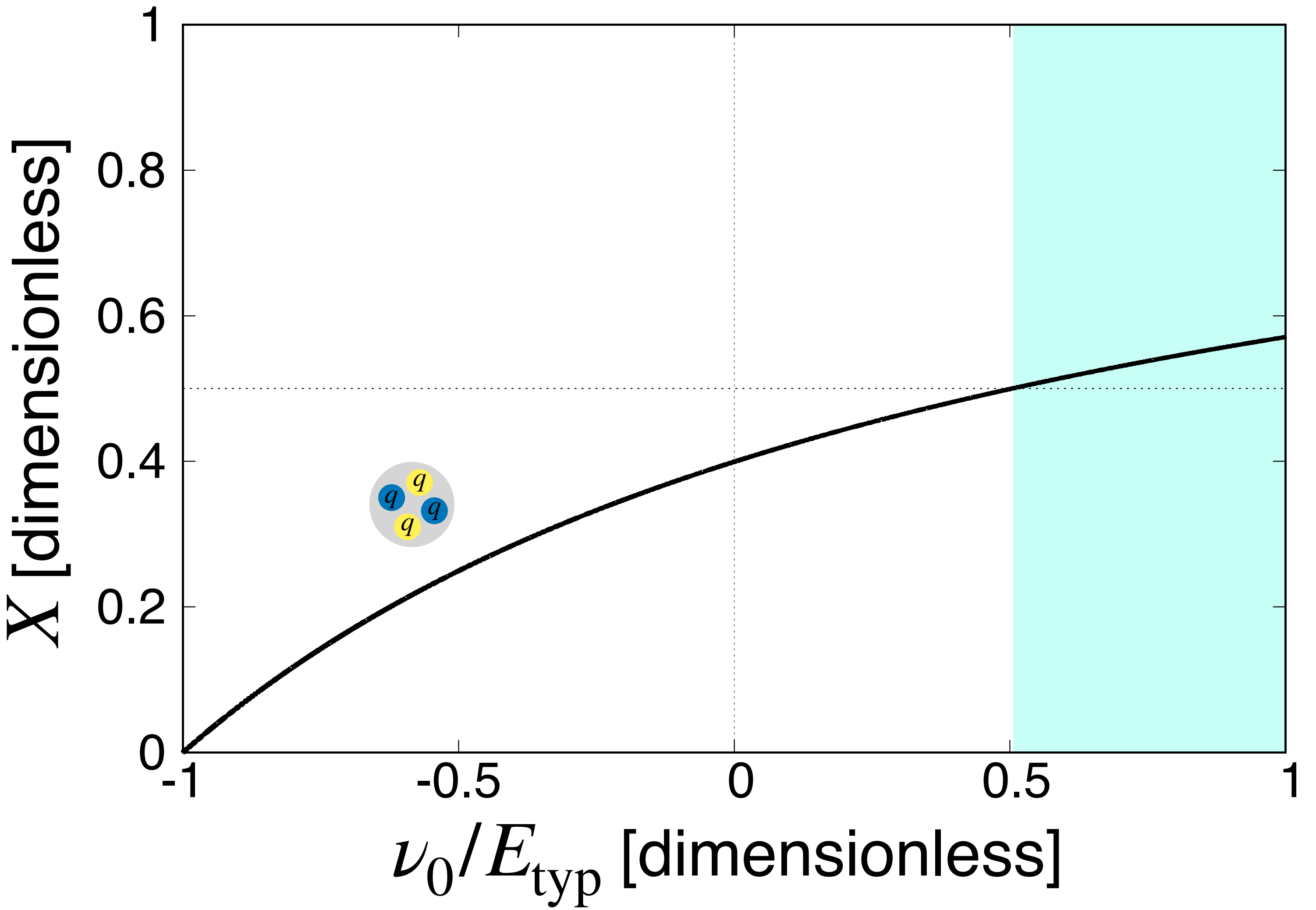
compositeness X as a function of ν_0 or

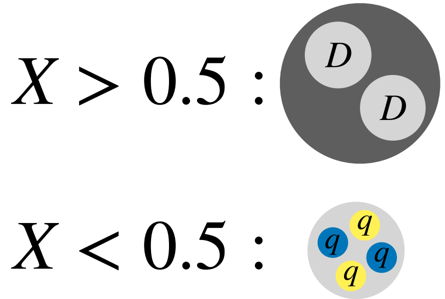
$X < 0.5$



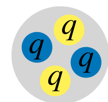
$\longrightarrow$ internal structure of bound state?

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



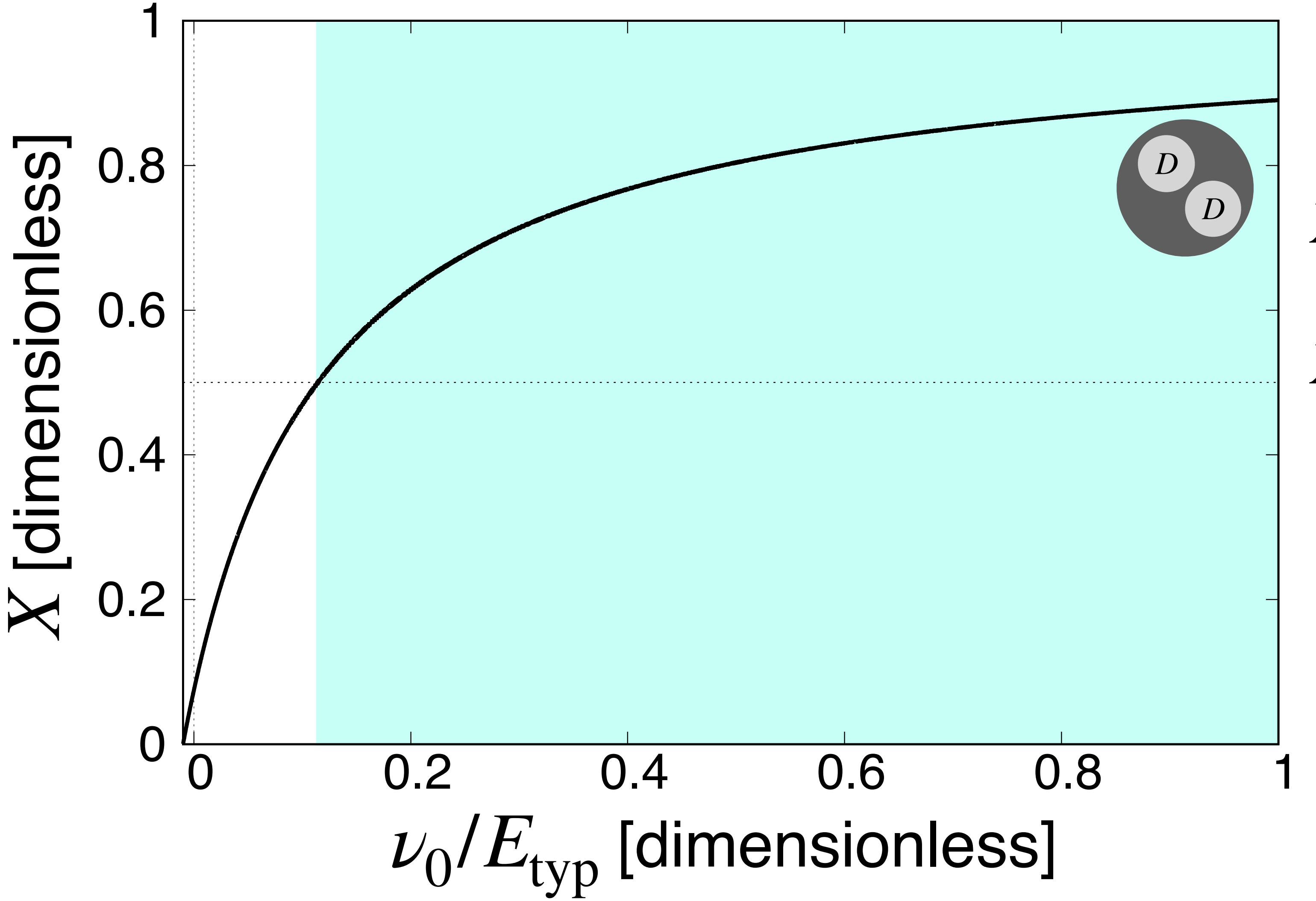


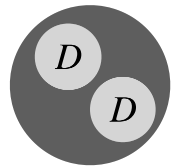
- typical energy scale : $B = E_{\rm typ} = \Lambda^2/(2\mu)$

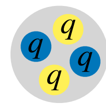
- $X > 0.5$ only for $25\ \%$ of ν_0 = elementary dominant 

∵ **bare state origin**

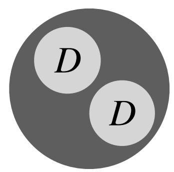
◉ X as a function of $\nu_0/E_{\rm typ}$ of bound state $B = 0.01E_{\rm typ}$



$X > 0.5$: 

$X < 0.5$: 

- weakly-bound state : $B = 0.01E_{\rm typ}$
- $X > 0.5$ for $88\ \%$ of ν_0 = composite dominant



∵ **low-energy universality !**

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

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

compositeness

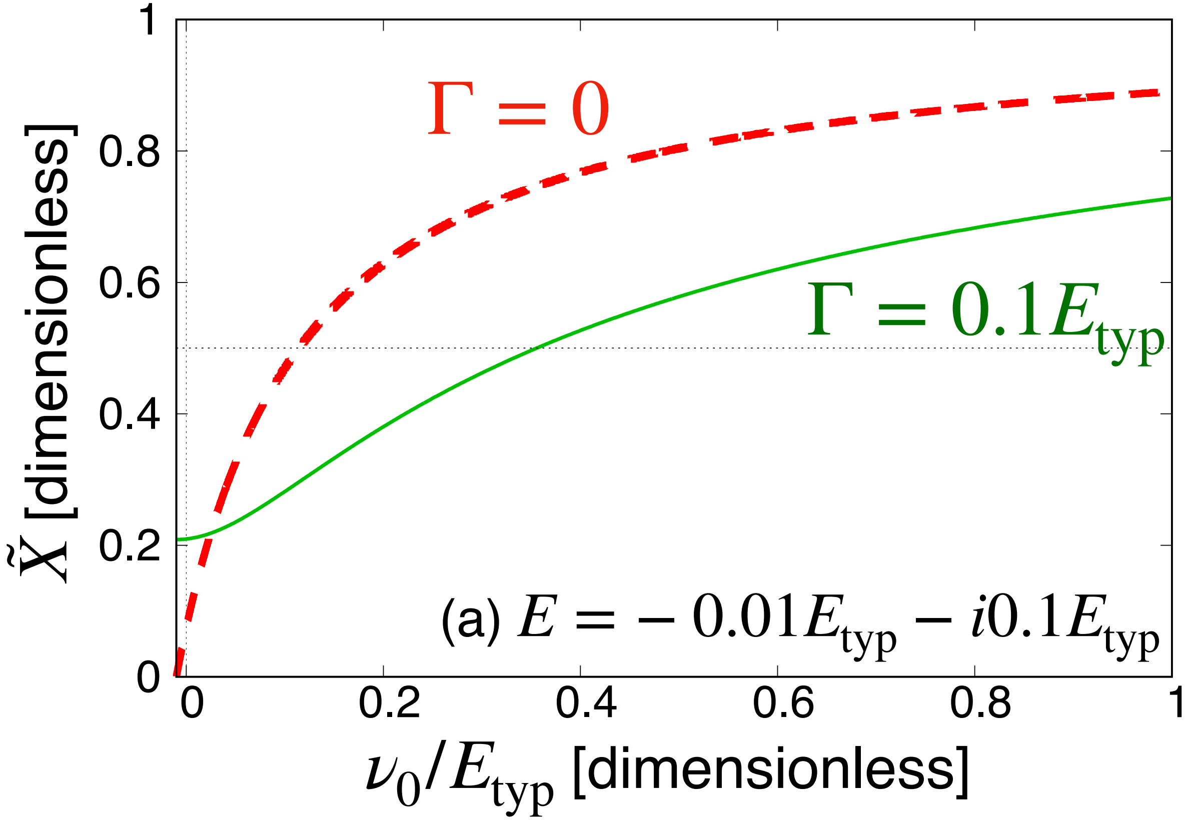
$$X \in \mathbb{R} \longrightarrow X \in \mathbb{C}$$

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

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

Effect of decay

◉ compositeness $\tilde{X}$



- $\tilde{X}$ is suppressed by $\Gamma \neq 0$

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

Effect of coupled channel

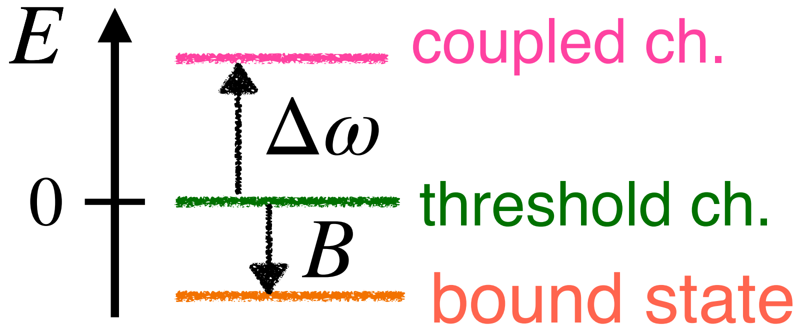
◉ introducing coupled channel $\Psi_1\Psi_2$

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

X_1 : threshold ch. compositeness

X_2 : coupled ch. compositeness

- threshold energy difference $\Delta\omega$



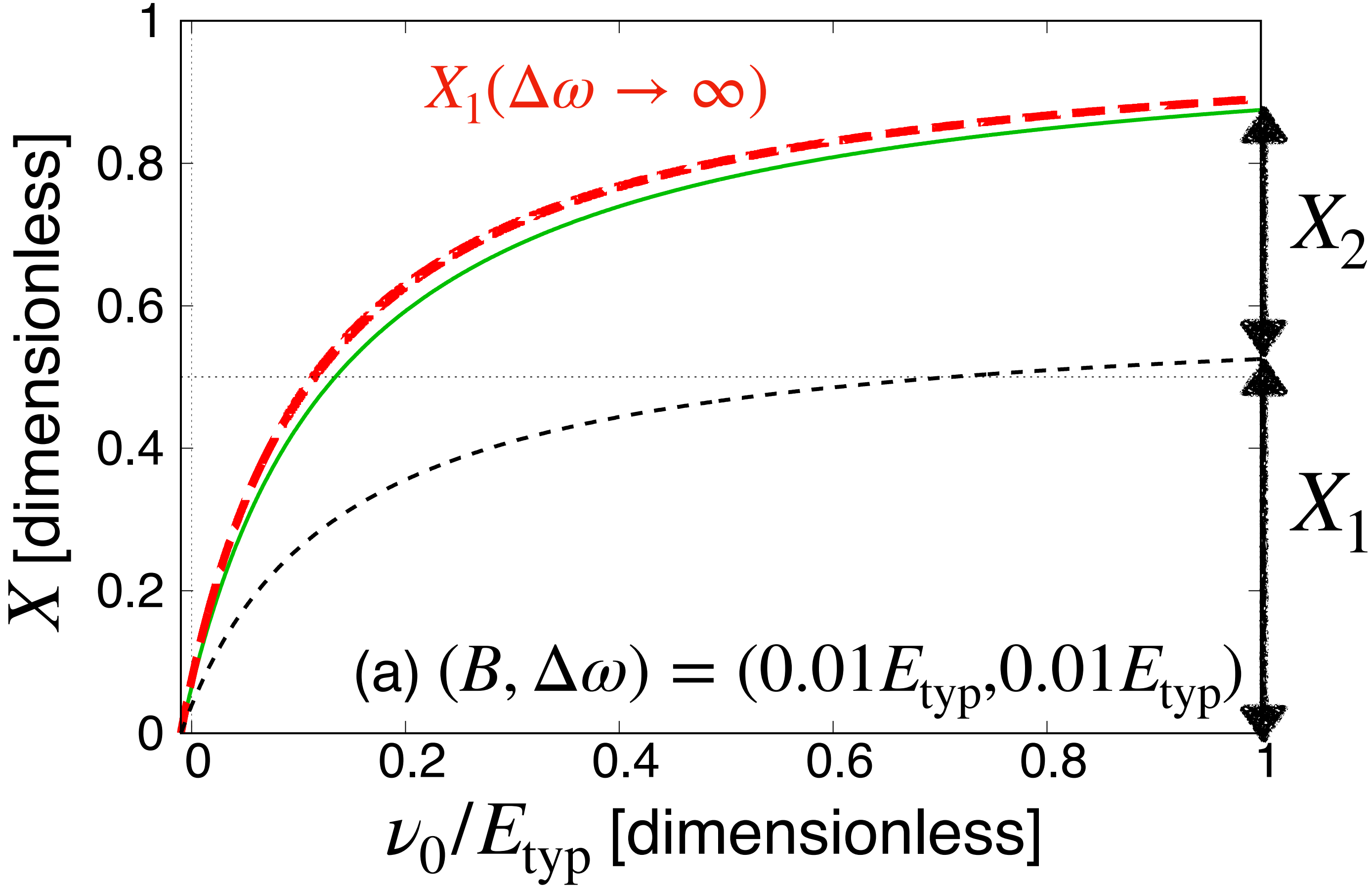
- low-energy universality with coupled-channel effect

$X_1 \sim 1$ (threshold channel)

$X_2 \sim 0$ (other channel) $Z \sim 0$ (other channel)

Effect of coupled channel

◉ compositeness X_1 and X_2

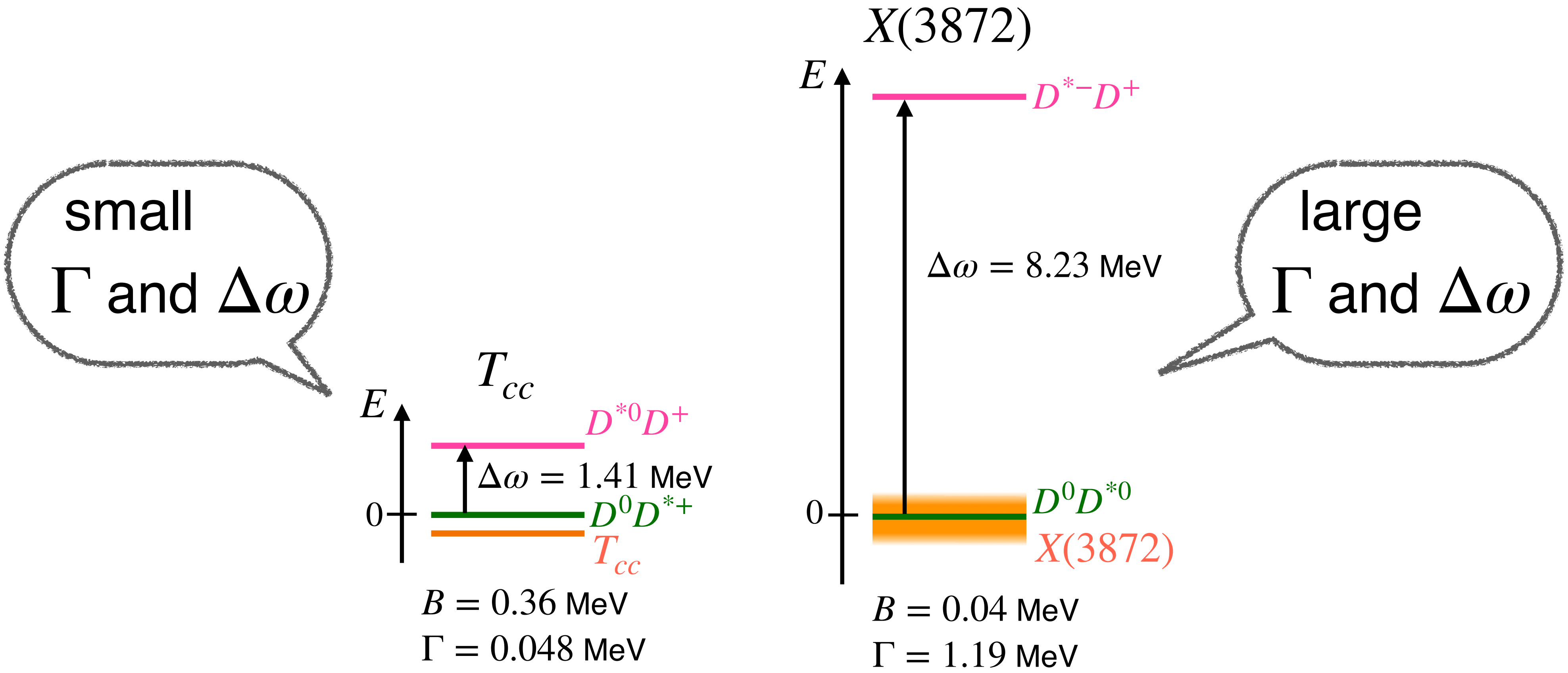


- X_1 is suppressed by $\Delta\omega$

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

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

◉ <u>exotic hadron</u> ← decay and coupled channel



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

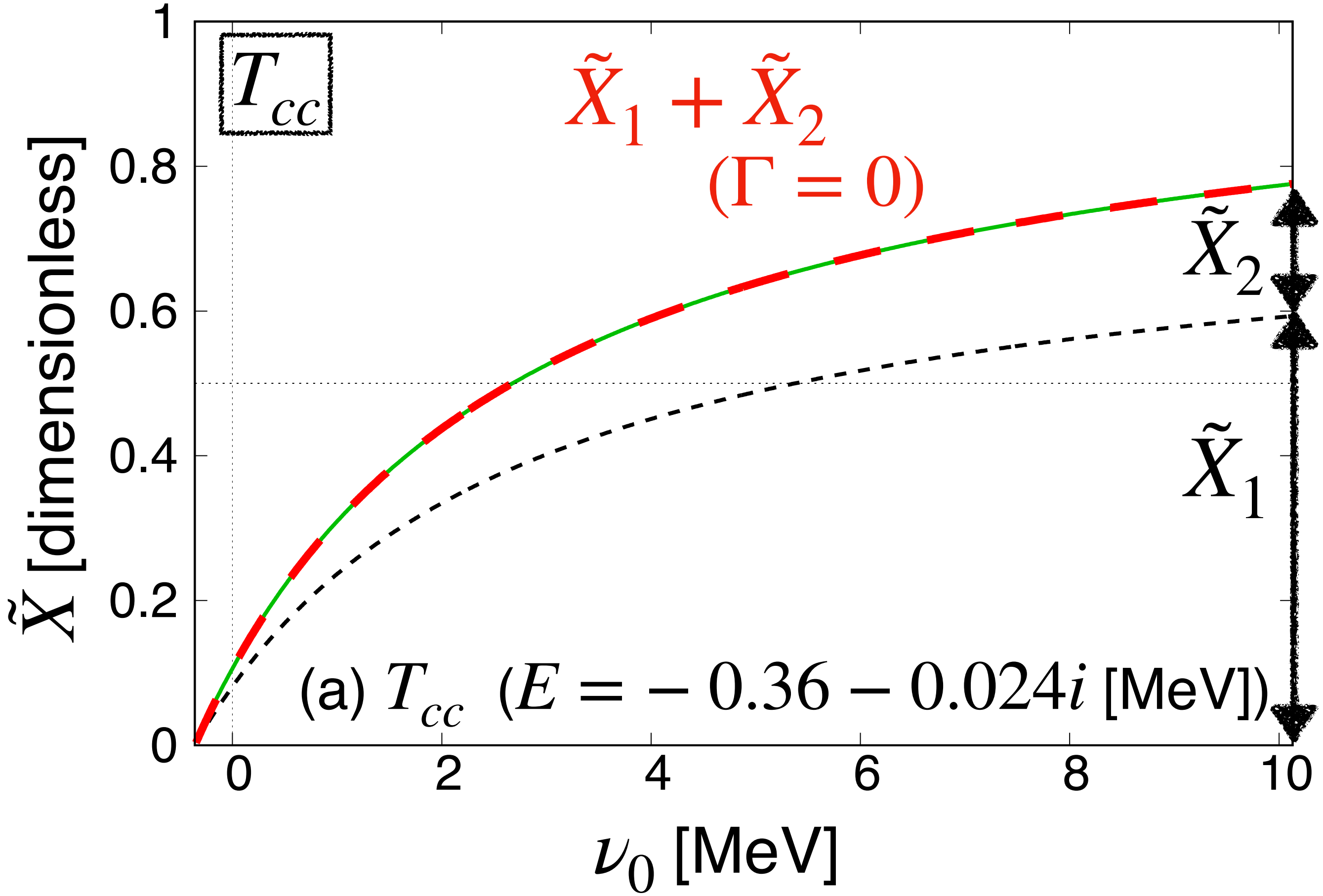
◉ <u>compositeness</u> T. Sekihara, *et. al.*, PRC 93, 035204 (2016).

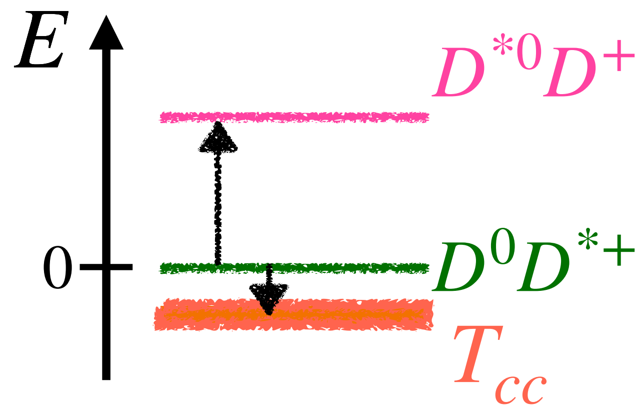
$$\tilde{X}_j = \frac{|X_j|}{\sum_j |X_j| + |Z|}, \quad (j = 1,2)$$

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

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

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





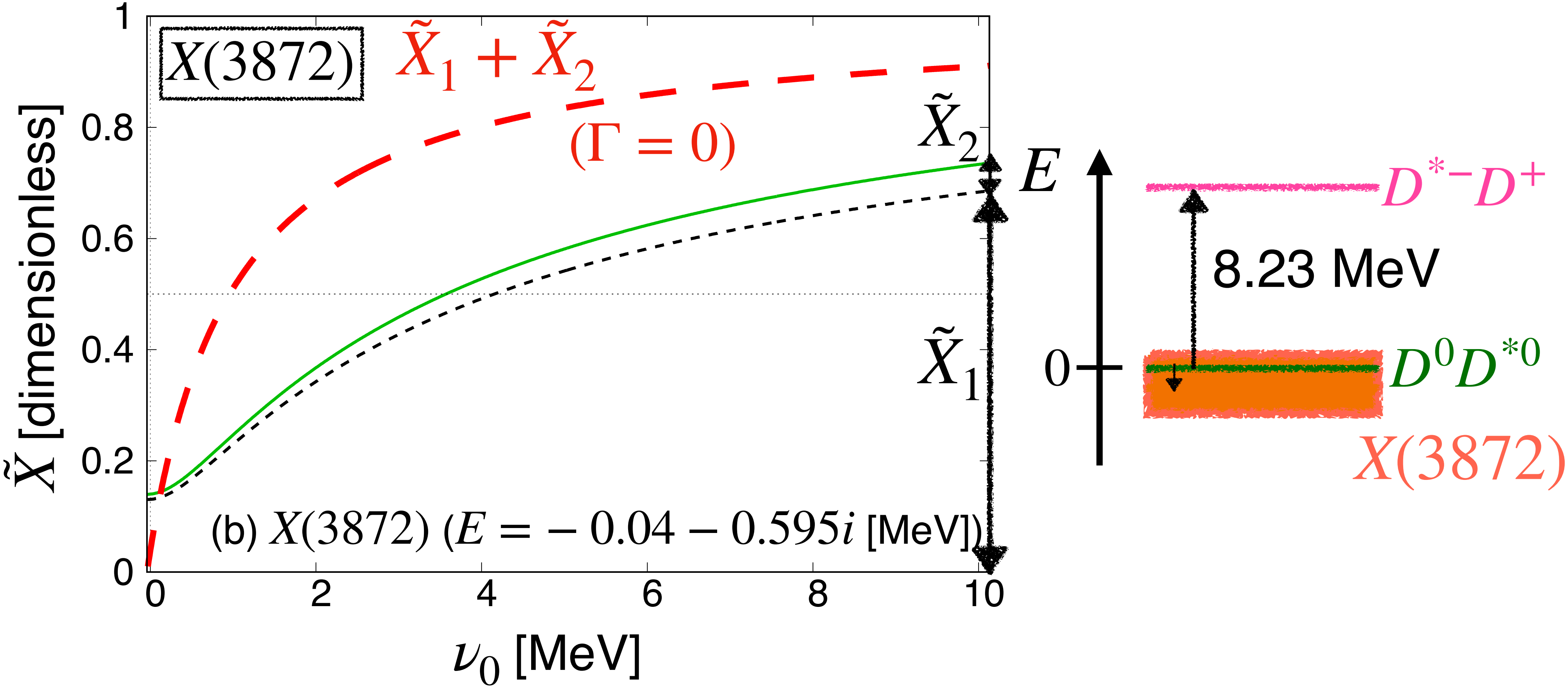
- $\tilde{X}_2$ is not negligible

  ∵ 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 $X(3872)$



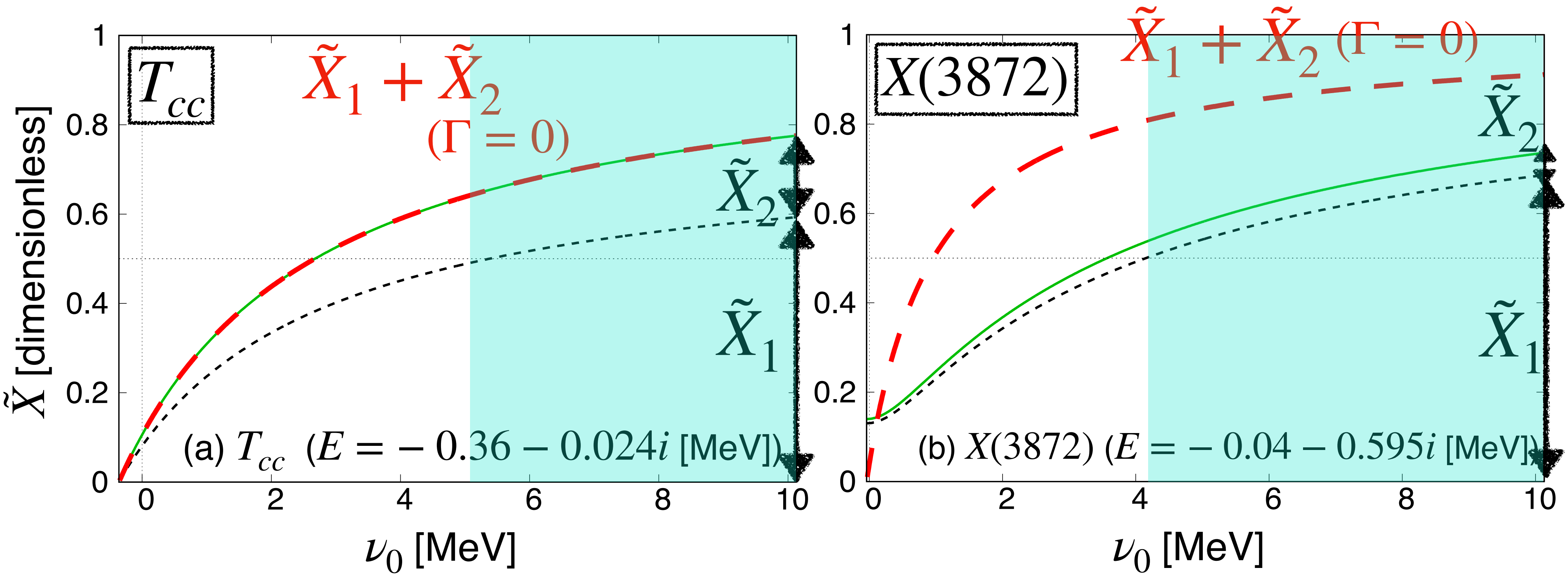
- difference of $\tilde{X}_1 + \tilde{X}_2(\Gamma = 0)$ and $\tilde{X}_1 + \tilde{X}_2$ is large

  ∵ large decay width contribution

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

  → coupled ch. effect is small

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



- T_{cc} : $\tilde{X}_1 > 0.5$ for $55\ \%$ of ν_0 region
- $X(3872)$: $\tilde{X}_1 > 0.5$ for $41\ \%$ of ν_0 region
- coupled ch. effect is more important for T_{cc} than $X(3872)$
- decay effect is more important for $X(3872)$ than T_{cc}

Summary arXiv:2303.07038 [hep-ph]

- internal structure of exotic hadrons ← EFT & compositeness

- model with bare state coupled to the scattering state

- shallow bound state is composite dominant even from bare state

  ∵ low-energy universality

- decay and coupled channel effects are introduced

→ both decay and coupled ch. effect suppress compositeness

- X of T_{cc} and $X(3872)$ are calculated 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

Compositeness of exotic hadrons with decay and coupled-channel effects

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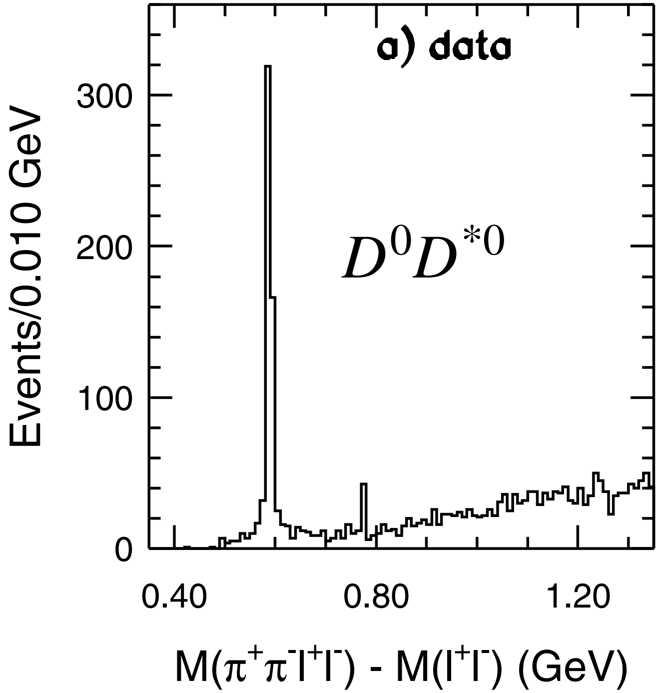
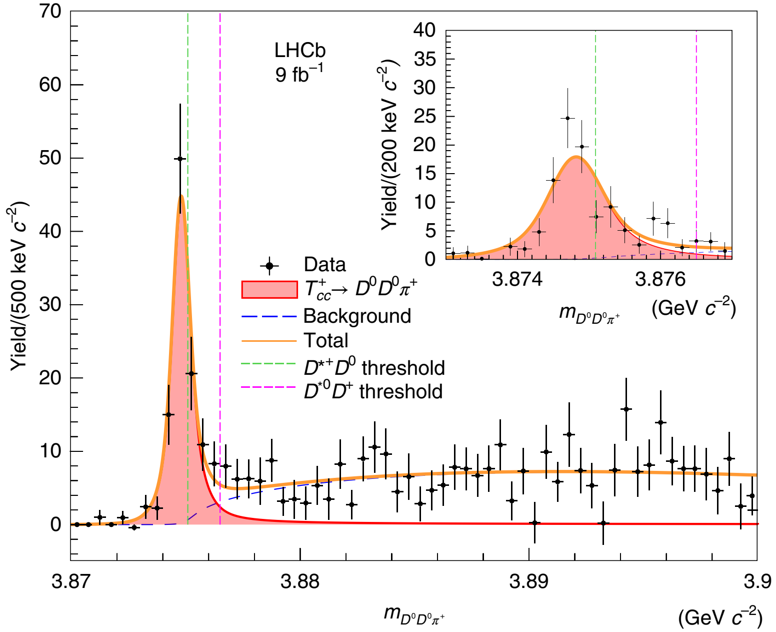
Near-threshold exotic hadrons

$X(3872) \to K^{\pm}\pi^{+}\pi^{-}J/\psi$



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

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



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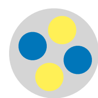
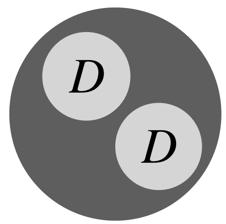
exotic hadron

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



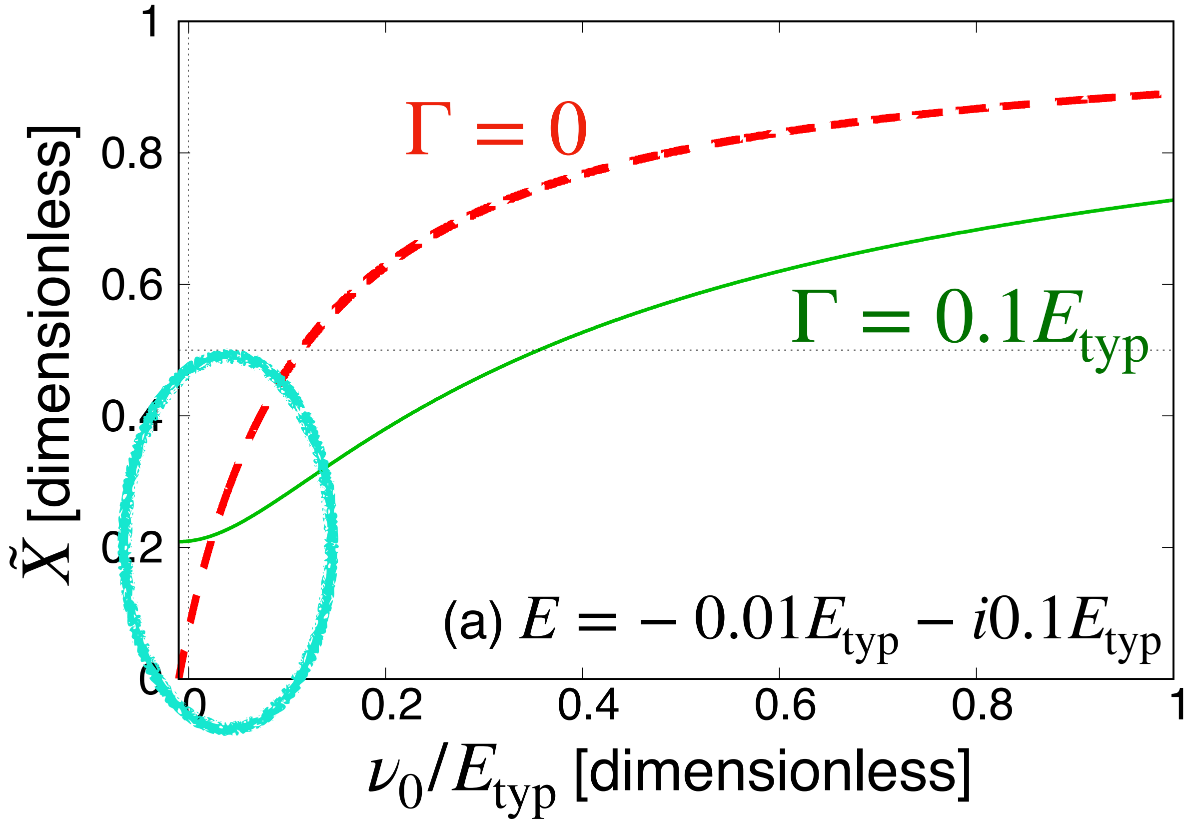
multiquarks



hadronic molecules

internal structure ? ← EFT & compositeness

Effect of decay



- $X \neq 0$ with $\Gamma \neq 0$
  $\because\ g_0 \neq 0$ at $\nu_0 = -B$

c.f. $g_0 = 0$ at $\nu_0 = -B$
with $\Gamma = 0$

$$g_0^2\left(-\nu_0 + i\frac{\Gamma}{2}; \nu_0, \Lambda\right) = \frac{\pi^2}{\mu}\left(-i\frac{\Gamma}{2}\right)\left[\Lambda - \kappa \arctan\left(\frac{\Lambda}{\kappa}\right)\right]^{-1} \neq 0$$

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

Compositeness for two-channel case

$$V(k) = \begin{pmatrix} v(k) & v(k) \\ v(k) & v(k) \end{pmatrix}, \ v(k) = \frac{g_0^2}{\frac{k^2}{2\mu_1} - \nu_0}.$$

$$G(k) = \begin{pmatrix} G_1(k) & 0 \\ 0 & G_2(k) \end{pmatrix}, \quad G_1(k) = -\frac{\mu_1}{\pi^2}\left[\Lambda + ik \arctan\left(-\frac{\Lambda}{ik}\right)\right],$$

$$G_2(k') = -\frac{\mu_2}{\pi^2}\left[\Lambda + ik' \arctan\left(-\frac{\Lambda}{ik'}\right)\right].$$

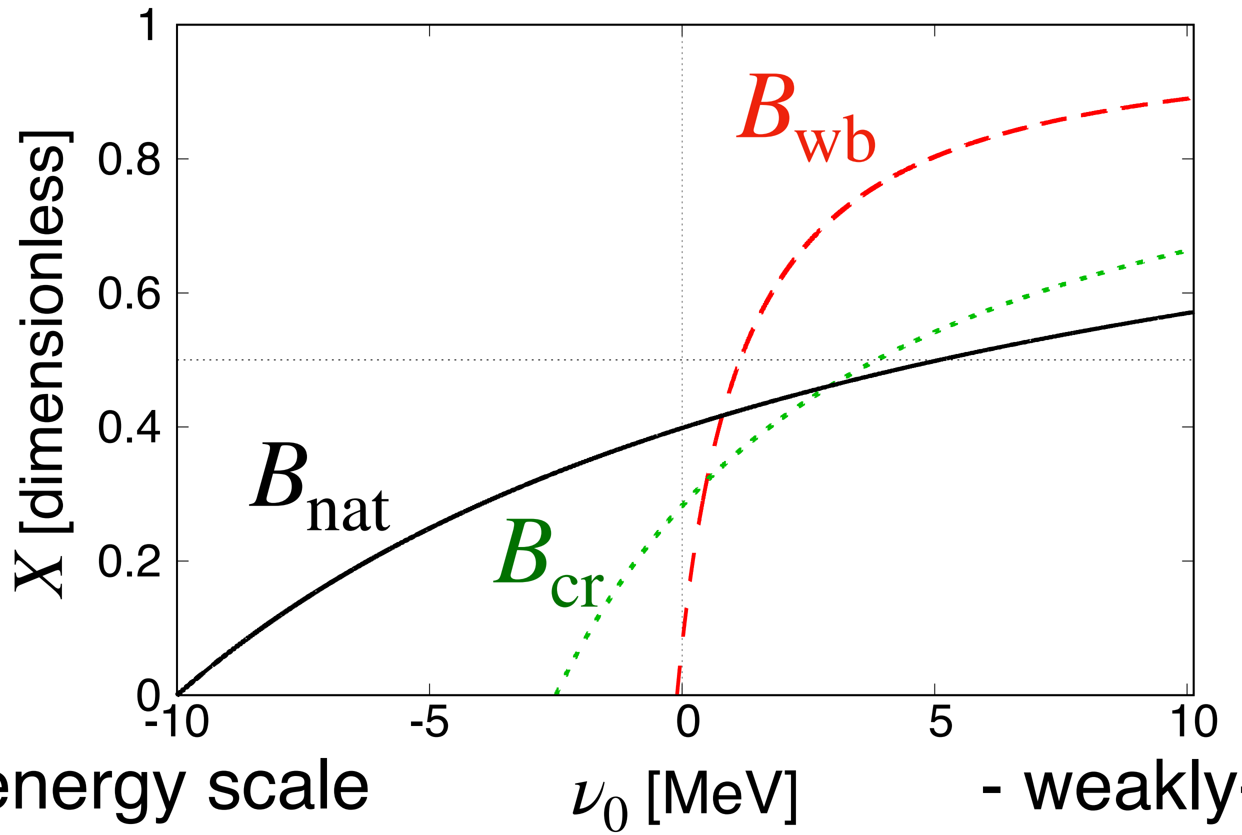
$$k = \sqrt{2\mu_1 E}, \quad k'(k) = \sqrt{2\mu_2(E - \Delta\omega)} = \sqrt{\frac{\mu_2}{\mu_1}k^2 - 2\mu_2\Delta\omega}.$$

$$\longrightarrow \quad X_1 = \frac{G_1'}{(G_1' + G_2') - [v^{-1}]'},$$

$$X_2 = \frac{G_2'}{(G_1' + G_2') - [v^{-1}]'}.$$

Calculation

X & low-energy universality

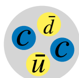


- natural energy scale

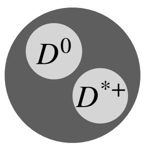
$$B_{\rm nat} = \Lambda^2/(2\mu)$$
$$\sim 10 \text{ MeV}$$

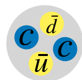
$X > 0.5$ for 25 % of ν_0

= elementary dominant

∵ **bare state origin** 

$B_{\rm cr} \sim 2.5$ MeV



: 

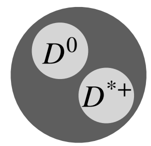
= 1:1

- weakly-bound state

$B_{\rm wb} = 0.1$ MeV

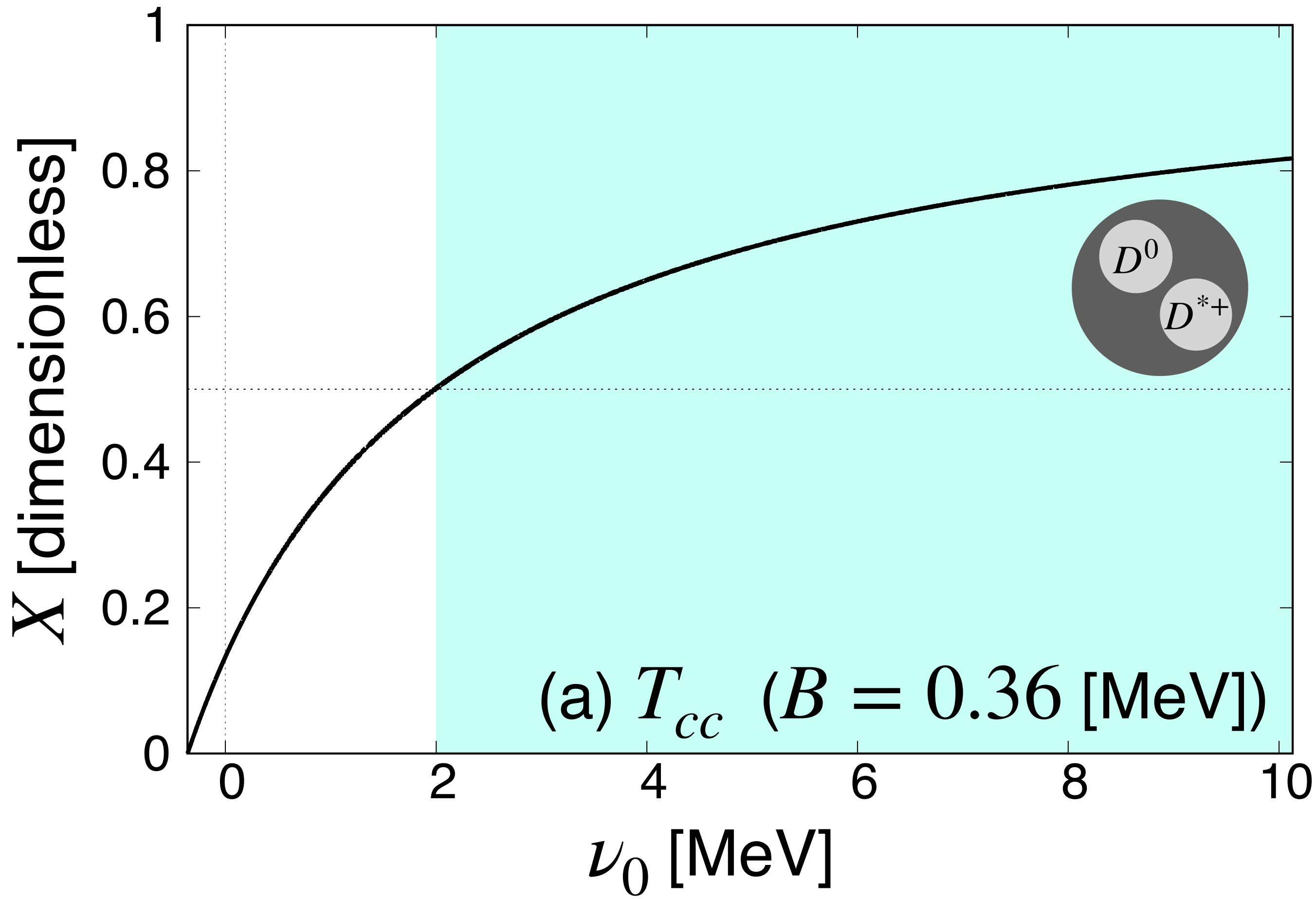
$X > 0.5$ for 88 % of ν_0

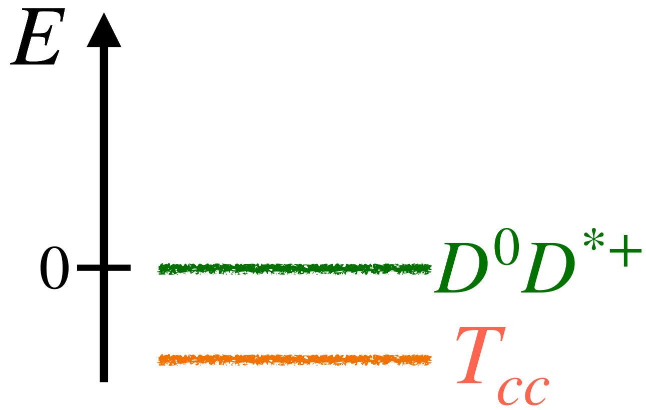
= composite dominant

∵ **low-energy universality !** 

Application to T_{cc}

◉ <u>single-channel</u>





- $X > 0.5$ for $78\ \%$ of ν_0 = composite dominant
- fine tuning is necessary to realize $X < 0.5$