Nature of T_{cc} with effective field theory

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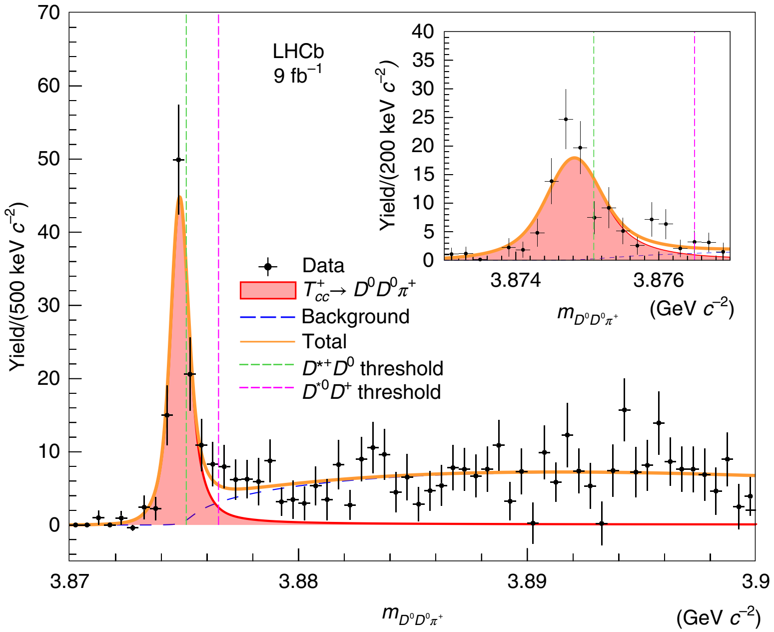
October 27th SNP school 2022

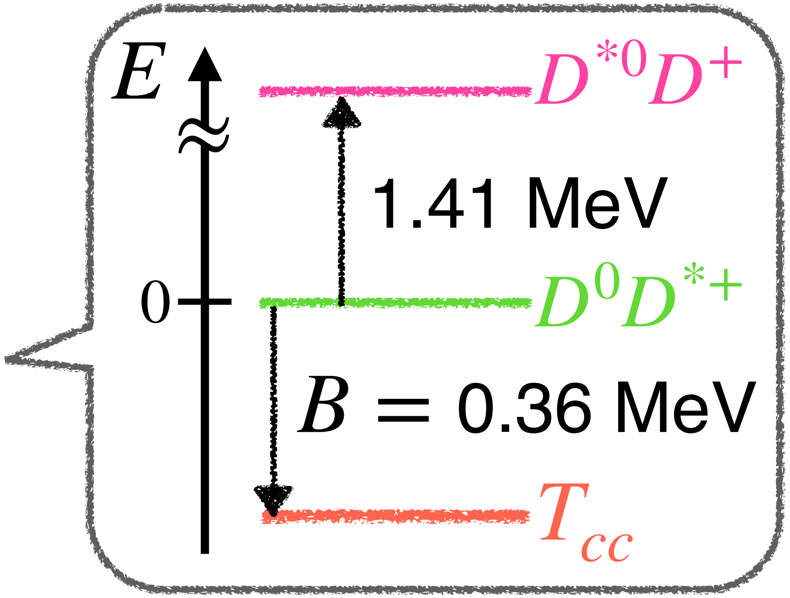
Background

T_{cc} (in 2021)



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

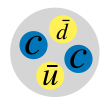
LHCb Collaboration, Nat. Commun **13** 3351 (2022).



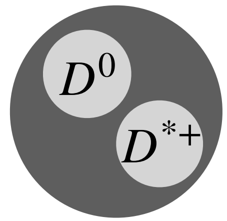
$T_{cc} \to D^0 D^0 \pi^+ \ (c\bar{u}c\bar{u}u\bar{d})$

→ minimum quark content is $cc\bar{u}\bar{d}$!

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



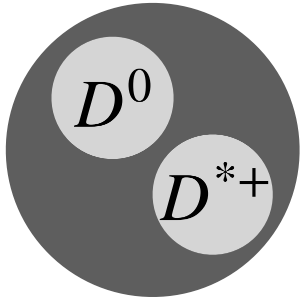
multiquarks

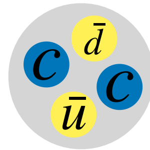


hadronic molecules

internal structure of T_{cc} ← effective field theory & compositeness

Compositeness





hadron wavefunction

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

compositeness (weight of hadronic molecule)

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

T. Hyodo, Int. J. Mod. Phys. A 28, 1330045 (2013).
T. Kinugawa and T. Hyodo, Phys. Rev. C 106, 015205 (2022).
E. Braaten, M. Kusunoki, and D. Zhang, Annals Phys. 323, 1770 (2008).

Model calculation

$$\mathscr{H}_{\text{free}} = \frac{1}{2m_{D^0}}\nabla D^{0\dagger}\cdot\nabla D^0 + \frac{1}{2m_{D^{*+}}}\nabla D^{*+\dagger}\cdot\nabla D^{*+} + \frac{1}{2m_\Psi}\nabla\psi^\dagger\cdot\nabla\psi + \nu_0\psi^\dagger\psi,$$

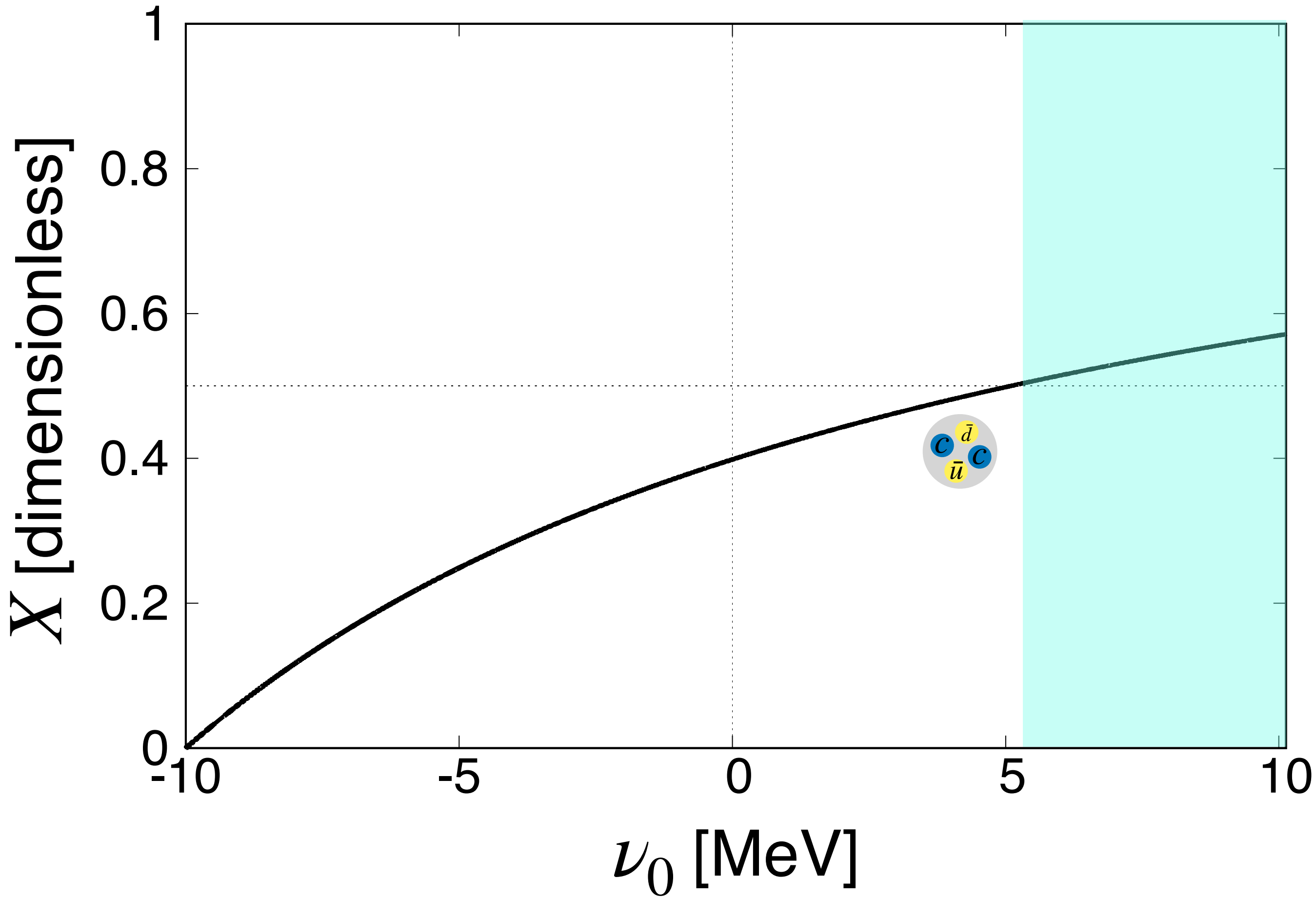
$$\mathscr{H}_{\text{int}} = g_0(\psi^\dagger D^0 D^{*+} + D^{0\dagger}D^{*+\dagger}\psi)\,.$$

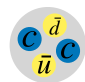
single-channel & bare state ψ

- ν_0 region : $-B \leq \nu_0 \leq \Lambda^2/(2\mu)$, ⟵ $g_0 \in \mathbb{R}$, Λ : cutoff

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

◉ X as a function of ν_0



- natural energy scale : $B_{\rm nat} = \Lambda^2/(2\mu) \sim 10$ MeV,
  $\Lambda = 140$ MeV (π exchange)
- $X > 0.5$ only for $25\ \%$ of ν_0 = elementary dominant 

∵ **bare state origin**

Application to T_{cc}

- shallow bound state

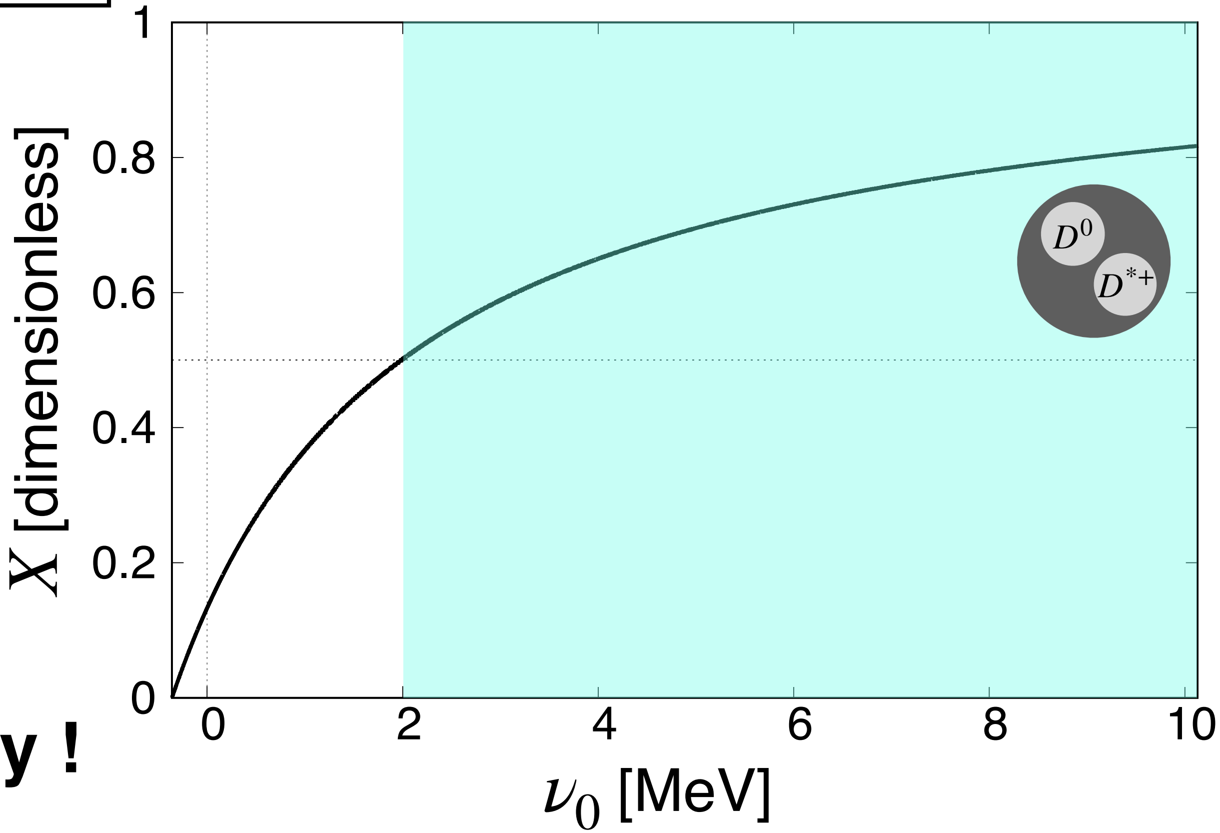
  $B = 0.36$ MeV

- $X > 0.5$ for $78\ \%$ of ν_0

  = composite dominant

- fine tuning is necessary to realize $X < 0.5$ for T_{cc}

  ∵ **low-energy universality !**



Summary

- internal structure of T_{cc} ⟵ EFT & compositeness
- shallow bound state is composite dominant even from bare state
- T_{cc} is composite dominant for most of ν_0

Back up

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Model

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

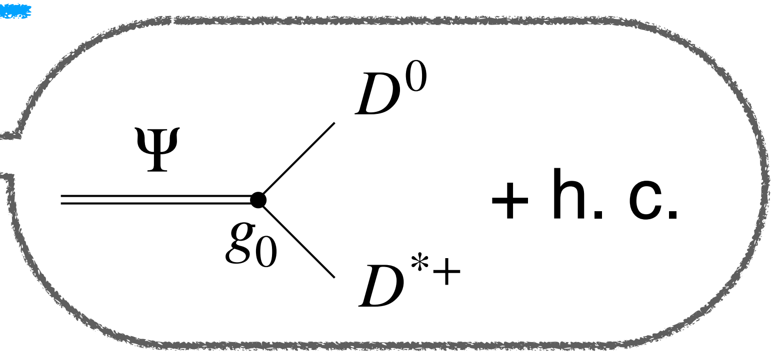
● single-channel resonance model

$$\mathscr{H}_{\text{free}} = \frac{1}{2m_{D^0}} \nabla D^{0\dagger} \cdot \nabla D^0 + \frac{1}{2m_{D^{*+}}} \nabla D^{*+\dagger} \cdot \nabla D^{*+} + \frac{1}{2m_\Psi} \nabla \psi^\dagger \cdot \nabla \psi + \nu_0 \psi^\dagger \psi,$$

①

$$\mathscr{H}_{\text{int}} = g_0 (\psi^\dagger D^0 D^{*+} + D^{0\dagger} D^{*+\dagger} \psi) .$$

②



① single-channel scattering

② coupling with compact four-quark state Ψ $(cc\bar{u}\bar{d})$

● 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

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

Model parameters

・ cutoff Λ : 0.14 GeV = m_π (π exchange)

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

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

T_{cc} : $B = 0.36$ MeV LHCb Collaboration, Nature Phys. **18** (2022) no.7, 751-754.

・ energy of bare 4-quark state ν_0

- determined by other models : e.g. $\nu_0 = 7$ MeV (quark model)
M. Karliner and J. L. Rosner, PRL 119, 202001 (2017)

- **varied in the region** : $-B \leq \nu_0 \leq \Lambda^2/(2\mu)$

∵ to have $g_0^2 \geq 0$ & applicable limit of EFT

fixed B, Λ $\xrightarrow[\text{bound state condition}]{g_0^2(\Lambda, \nu_0, B)}$ ν_0 : free parameter

Calculation

◉ compositeness X

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

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

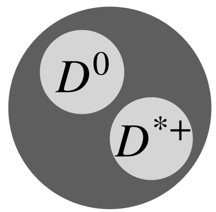
$$\longrightarrow X = \frac{G'(-B)}{G'(-B) - [V^{-1}(-B)]'}, \quad \alpha'(E) = d\alpha/dE$$

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

$$(-B \leq \nu_0 \leq \Lambda^2/(2\mu))$$

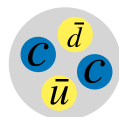
compositeness X as a function of ν_0

$X > 0.5$



or

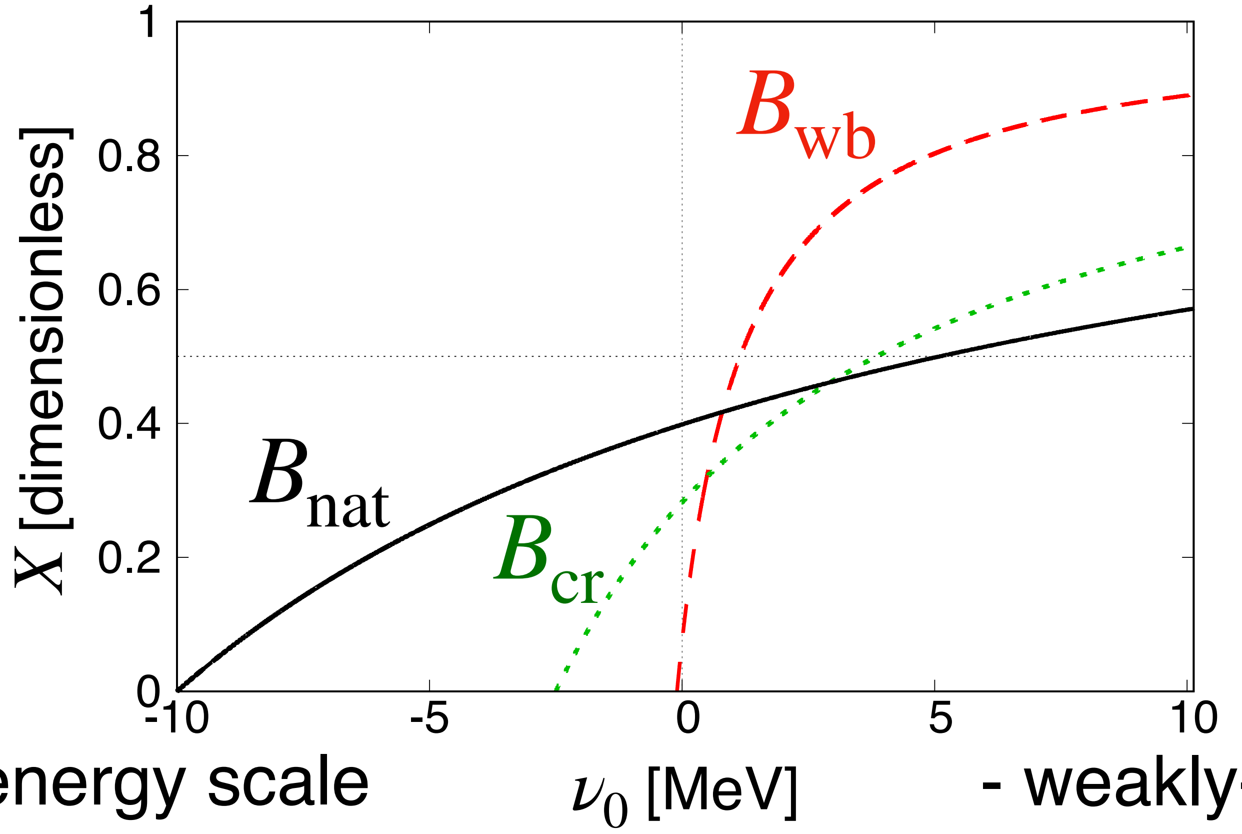
$X < 0.5$



$\longrightarrow$ internal structure of T_{cc}?

Calculation

X & low-energy universality



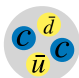
- natural energy scale

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

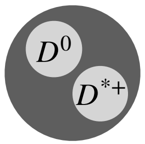
$X > 0.5$ for 25 % of ν_0

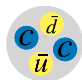
= elementary dominant

∵ **bare state origin**



$$B_{\mathrm{cr}} \sim 2.5 \text{ MeV}$$



: 

= 1:1

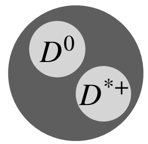
- weakly-bound state

$$B_{\mathrm{wb}} = 0.1 \text{ MeV}$$

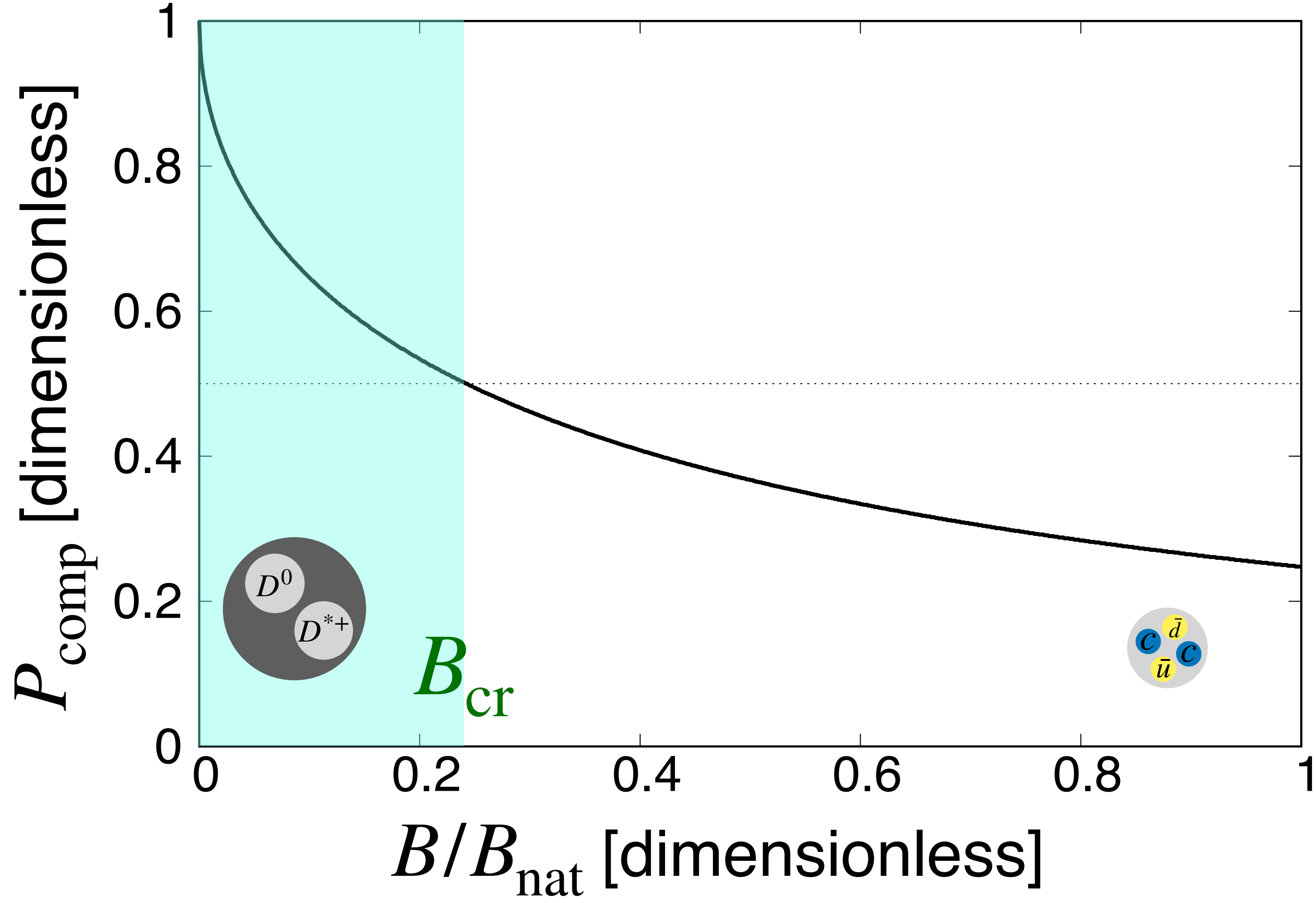
$X > 0.5$ for 88 % of ν_0

= composite dominant

∵ **low-energy universality !**



Calculation



composite dominant

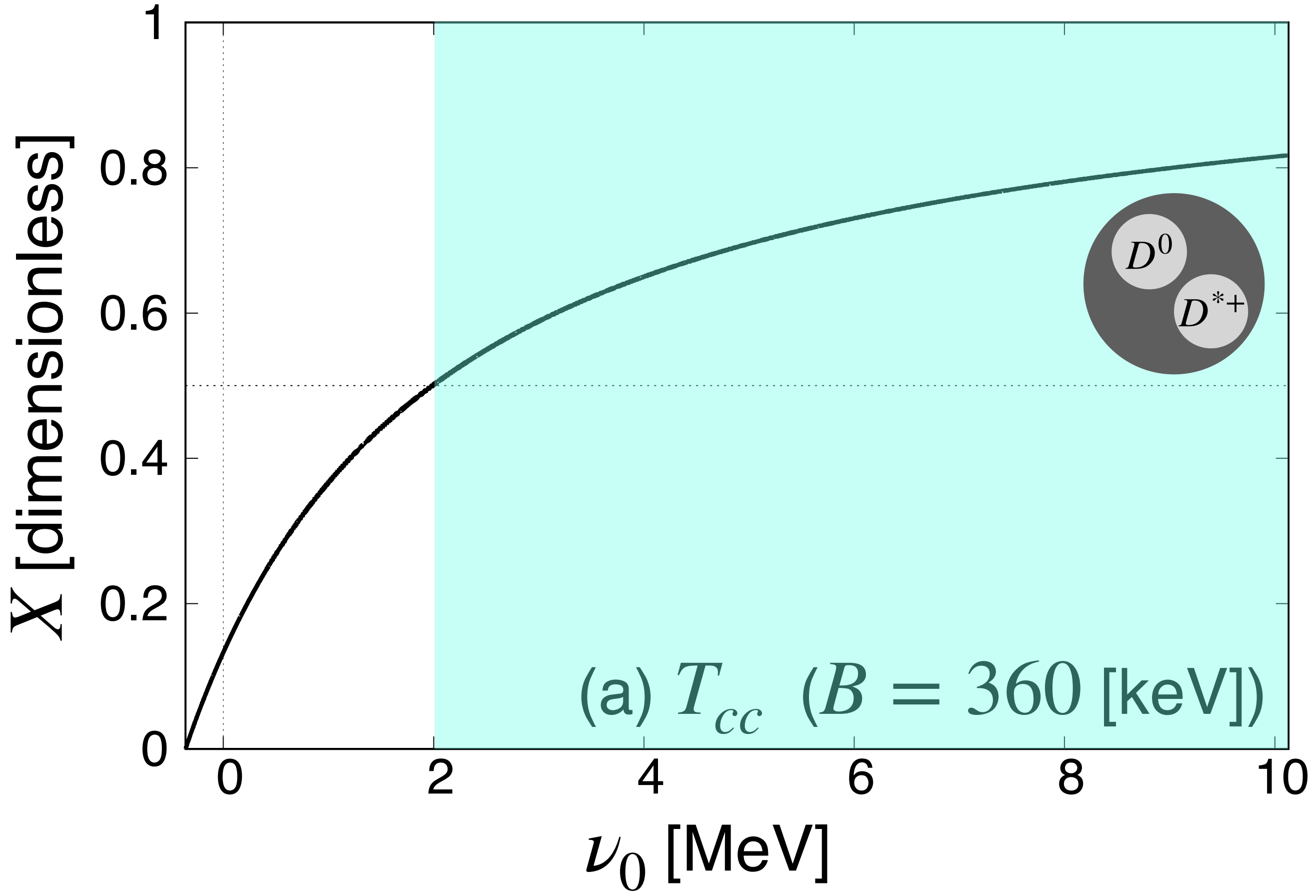
∵ **low-energy universality !**

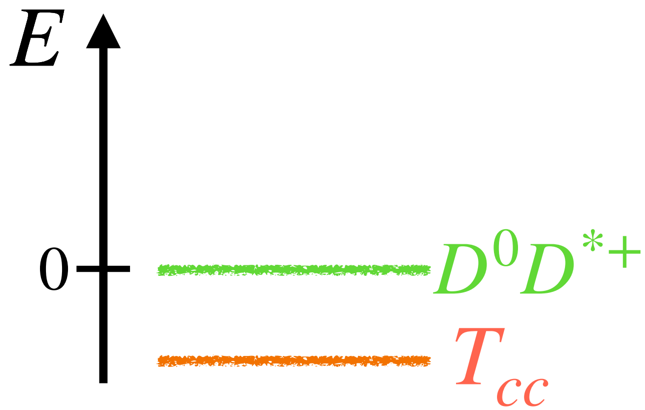
natural energy scale

$$B_{\text{nat}} = \Lambda^2/(2\mu)$$

Application to T_{cc}

◉ single-channel

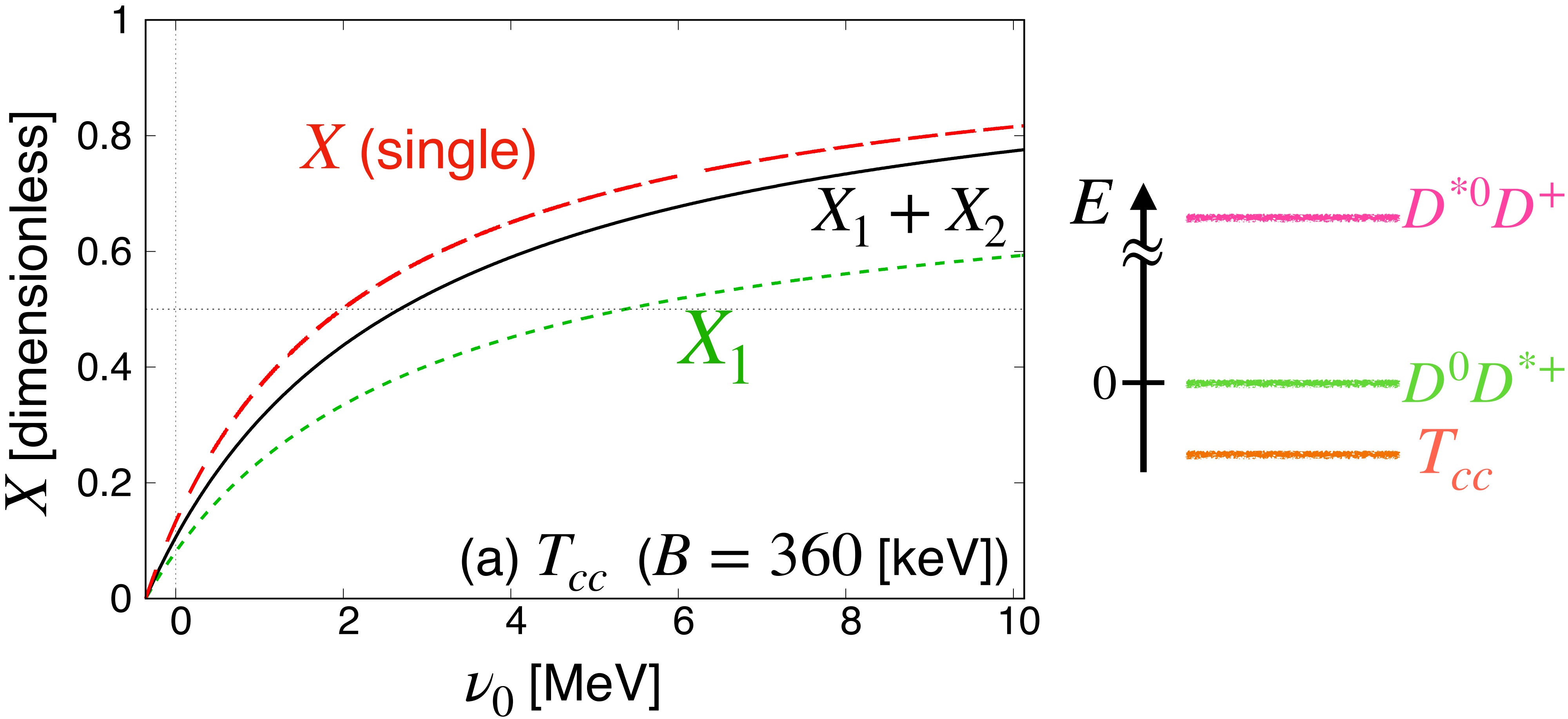




- $X > 0.5$ for 78 % of ν_0 = composite dominant
- fine tuning is necessary to realize $X < 0.5$

Application to T_{cc}

◉ coupled-channel



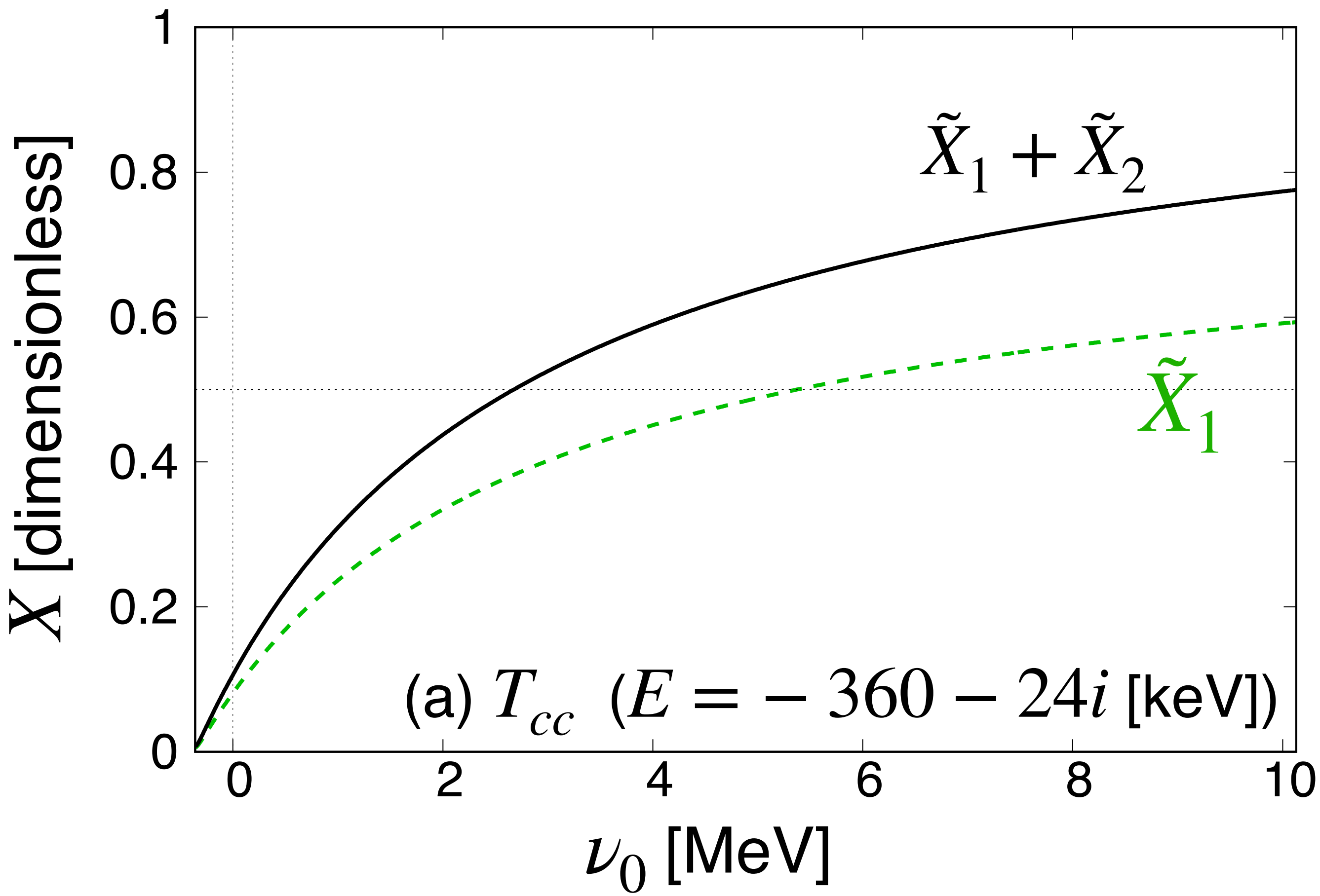
- composite nature is shared by both channels
- X (single) $\sim X_1 + X_2$ $\because$ energy difference of 2 channels $\gg$ binding energy

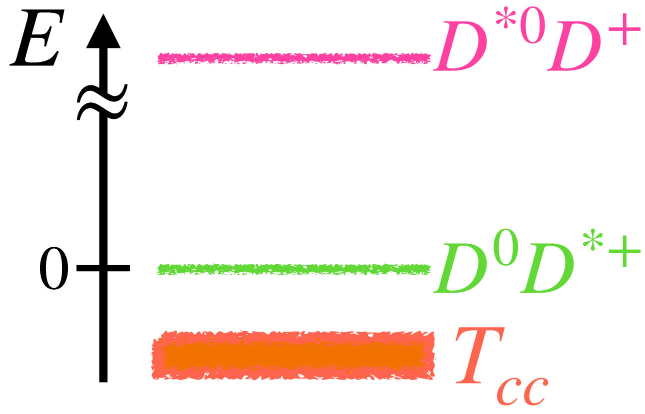
Application to T_{cc}

$$\tilde{X}_i = \frac{|X_i|}{(X_1 + X_2 + \ldots + Z)}$$

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

◉ coupled-channel and decay





- $\tilde{X}_1 + \tilde{X}_2$ (w/ decay) $\sim X_1 + X_2$ (w/o decay)

  ∵ narrow decay width for T_{cc}
- T_{cc} is composite dominant even with decay