Nature of T_{cc} with effective field theory

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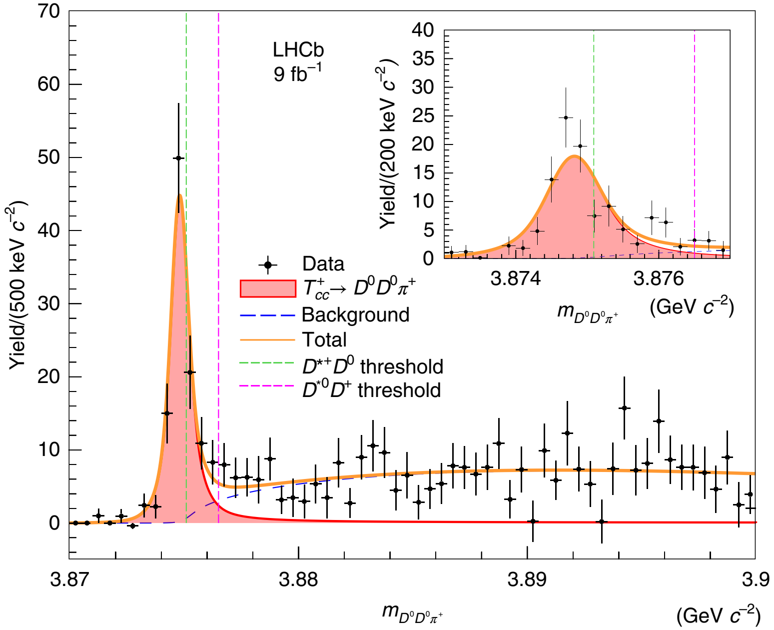
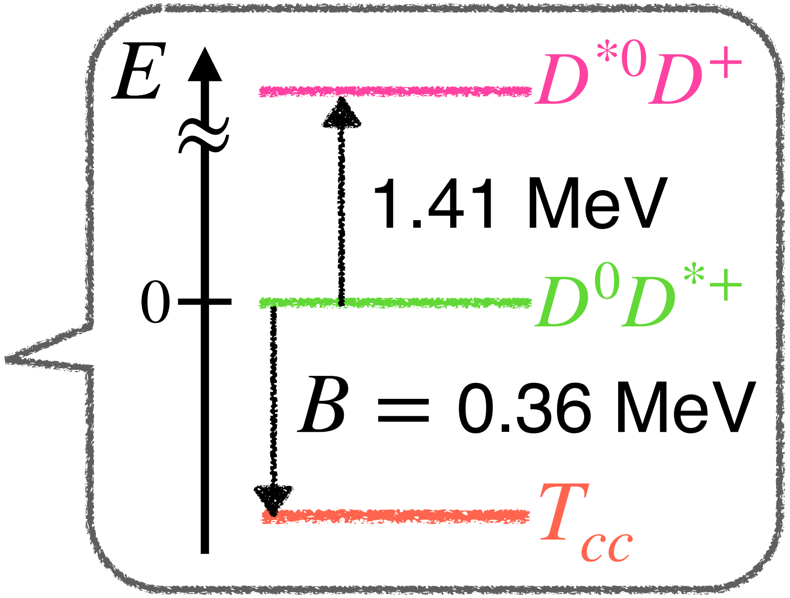
Background

T_{cc} (in 2021)



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

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

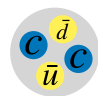


$T_{cc} \to D^0 D^0 \pi^+ \ (c\bar{u}c\bar{u}u\bar{d})$

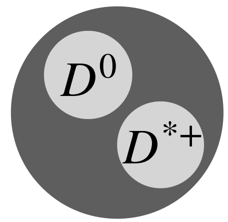
→ minimum quark content is $cc\bar{u}\bar{d}$!

exotic hadron

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



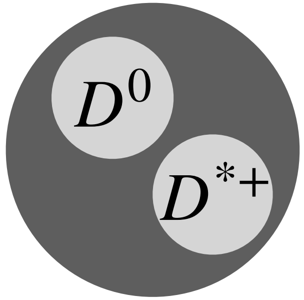
multiquarks

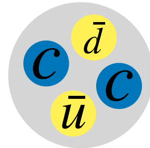


hadronic molecules

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 **elementariness**

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

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

◉ how to calculate?

S. Weinberg, Phys. Rev. 137, B672 (1965);
Y. Kamiya and T. Hyodo, PTEP 2017, 023D02 (2017);
T. Kinugawa and T. Hyodo, Phys. Rev. C 106, 015205 (2022).

1. weak-binding relation (model-independent)

$$a_0 = R\left\{\frac{2X}{1+X} + \mathcal{O}\left(\frac{R_{\rm typ}}{R}\right)\right\}$$

a_0 : scattering length

$R \equiv (2\mu B)^{-1/2}$, B : binding energy

$$R_{\rm typ} = \max\{R_{\rm int}, r_e, \cdots\}$$ ($R_{\rm int}$: interaction range, r_e : effective range)

2. model calculation❗ ⟵ this work

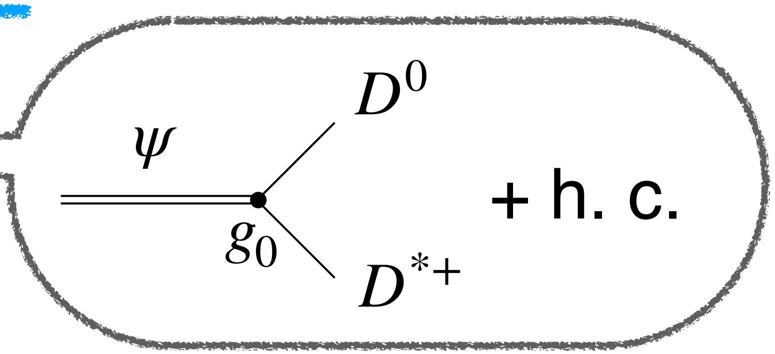
Model

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

● single-channel resonance model

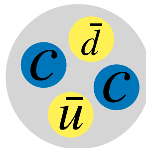
$$\mathscr{H}_{\rm free} = \underbrace{\frac{1}{2m_{D^0}}\nabla D^{0\dagger}\cdot\nabla D^0 + \frac{1}{2m_{D^{*+}}}\nabla D^{*+\dagger}\cdot\nabla D^{*+}}_{①} + \frac{1}{2m_\Psi}\nabla\psi^\dagger\cdot\nabla\psi + \nu_0\psi^\dagger\psi,$$

$$\mathscr{H}_{\rm int} = \underbrace{g_0(\psi^\dagger D^0 D^{*+} + D^{0\dagger}D^{*+\dagger}\psi)}_{②}\,.$$



① single-channel scattering

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



● scattering amplitude

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

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

Model parameters

- cutoff Λ : 140 MeV = m_π (π exchange)
- 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 $f^{-1} = 0$ $\kappa = \sqrt{2\mu B}$.

  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).

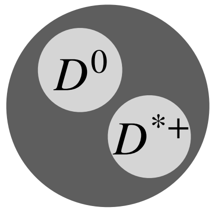
$$\longrightarrow X = \frac{G'(-B)}{G'(-B) - [V^{-1}(-B)]'}, \quad \alpha'(E) = d\alpha/dE$$

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

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

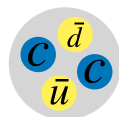
compositeness X as a function of ν_0

$X > 0.5$



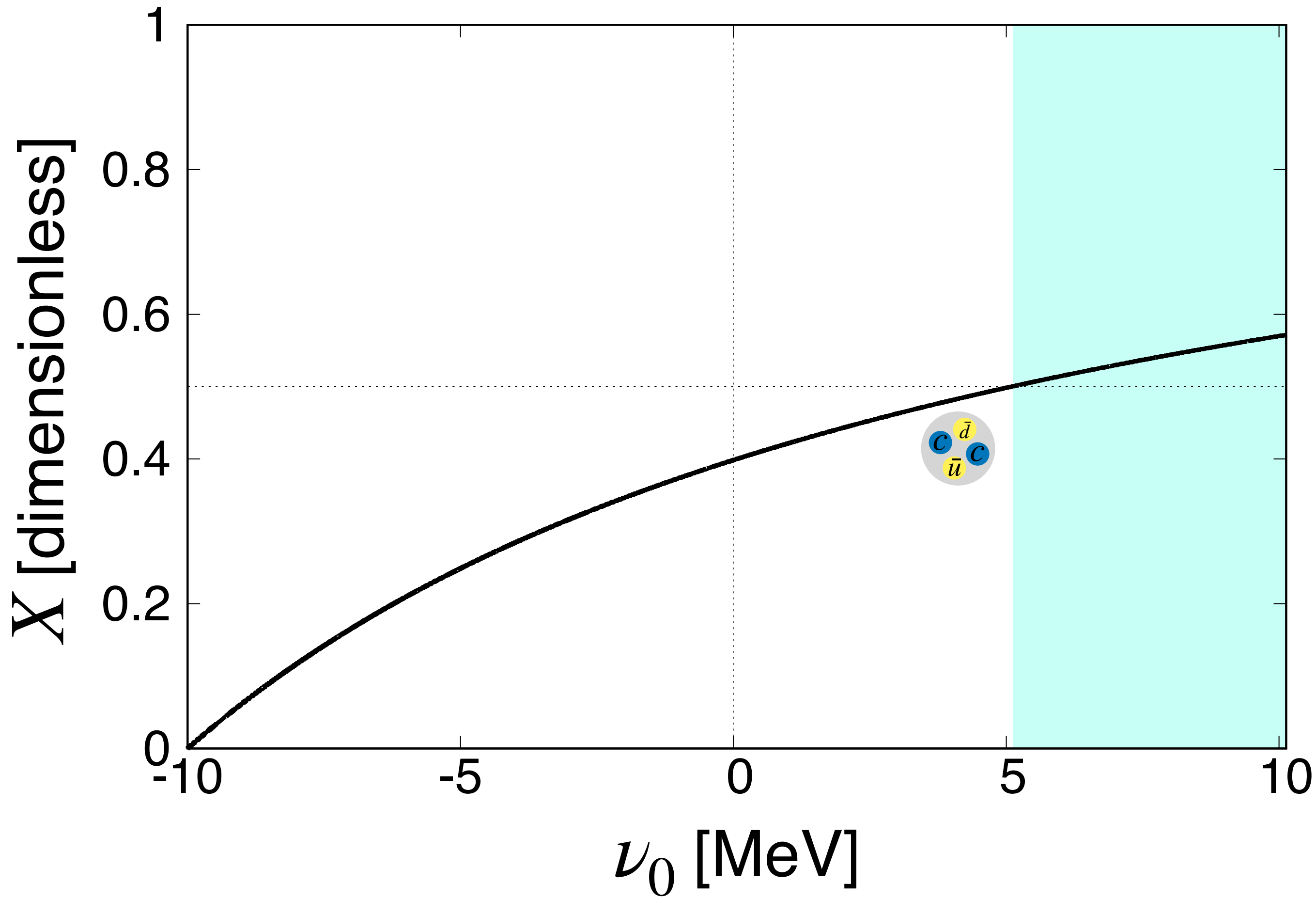
or

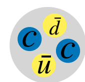
$X < 0.5$



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

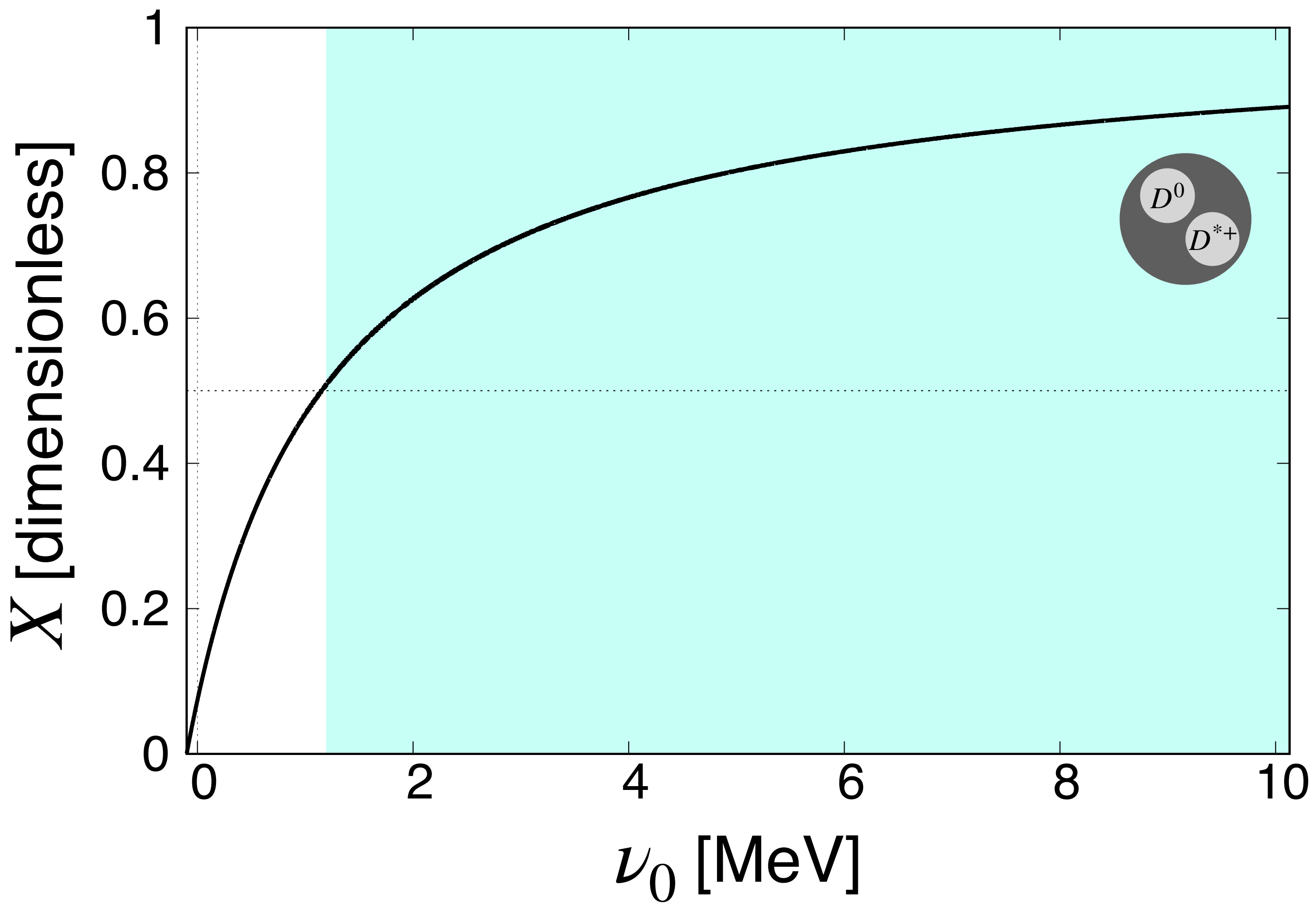
◉ X as a function of ν_0 for natural energy scale



- 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 

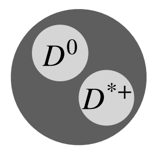
∵ **bare state origin**

◉ X as a function of ν_0 for shallow bound state



- weakly-bound state : $B_{\rm nat} \gg B_{\rm wb} = 0.1$ MeV,
  $\Lambda = 140$ MeV (π exchange)

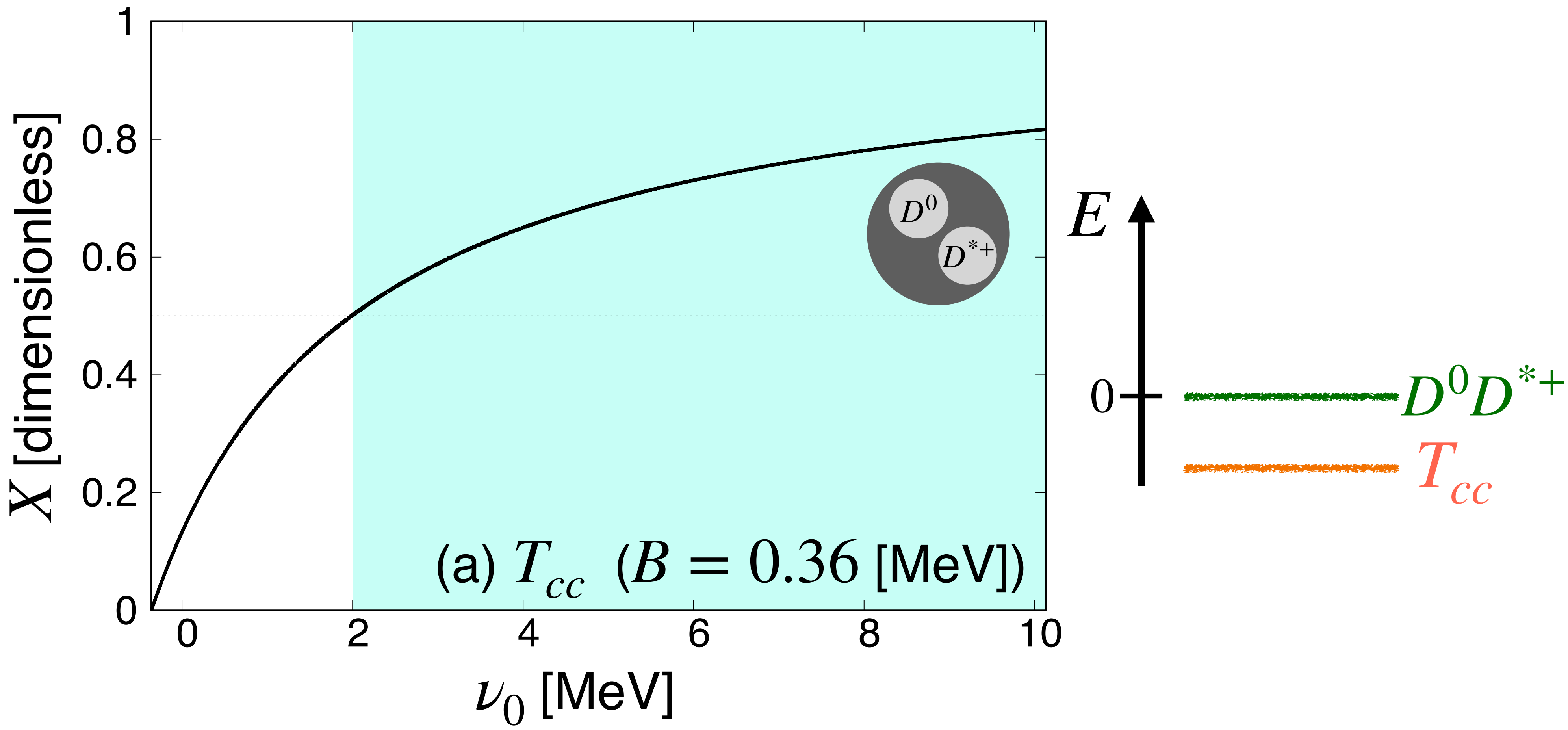
- $X > 0.5$ for $88\ \%$ of ν_0 = composite dominant



∵ **low-energy universality !**

Application to T_{cc}

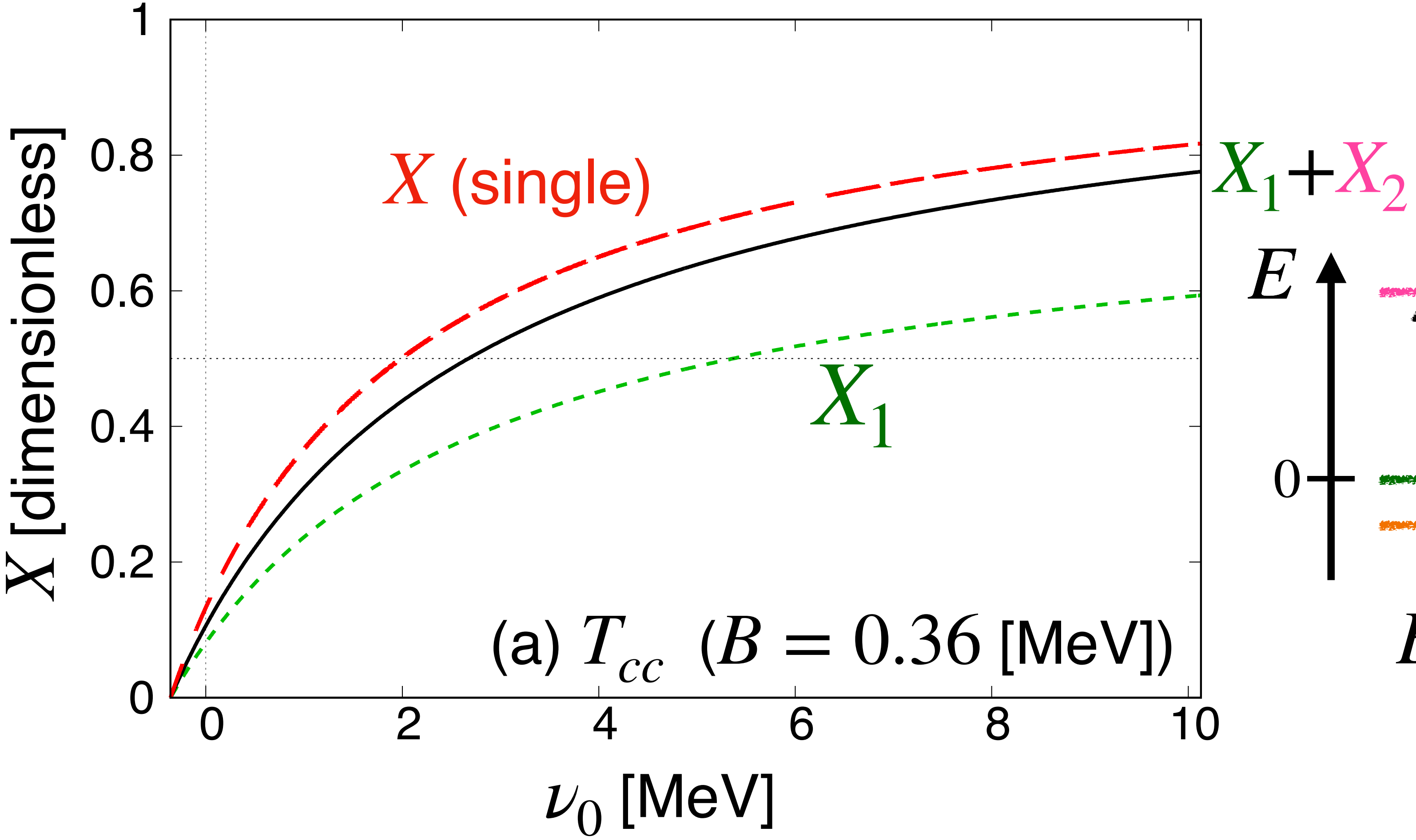
◉ single-channel

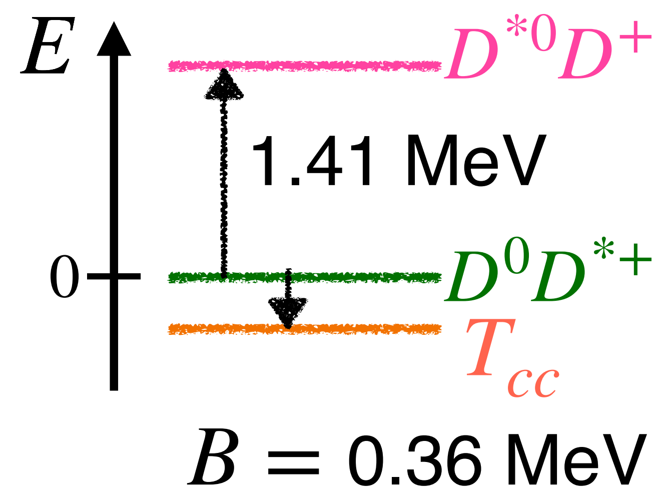


- $X > 0.5$ for 78 % of ν_0 = composite dominant
- fine tuning is necessary to realize $X < 0.5$

Application to T_{cc}

◉ coupled-channel





- X (single) $\sim X_1 + X_2$
- composite nature is shared by both channels

∵ threshold energy difference cannot be neglected

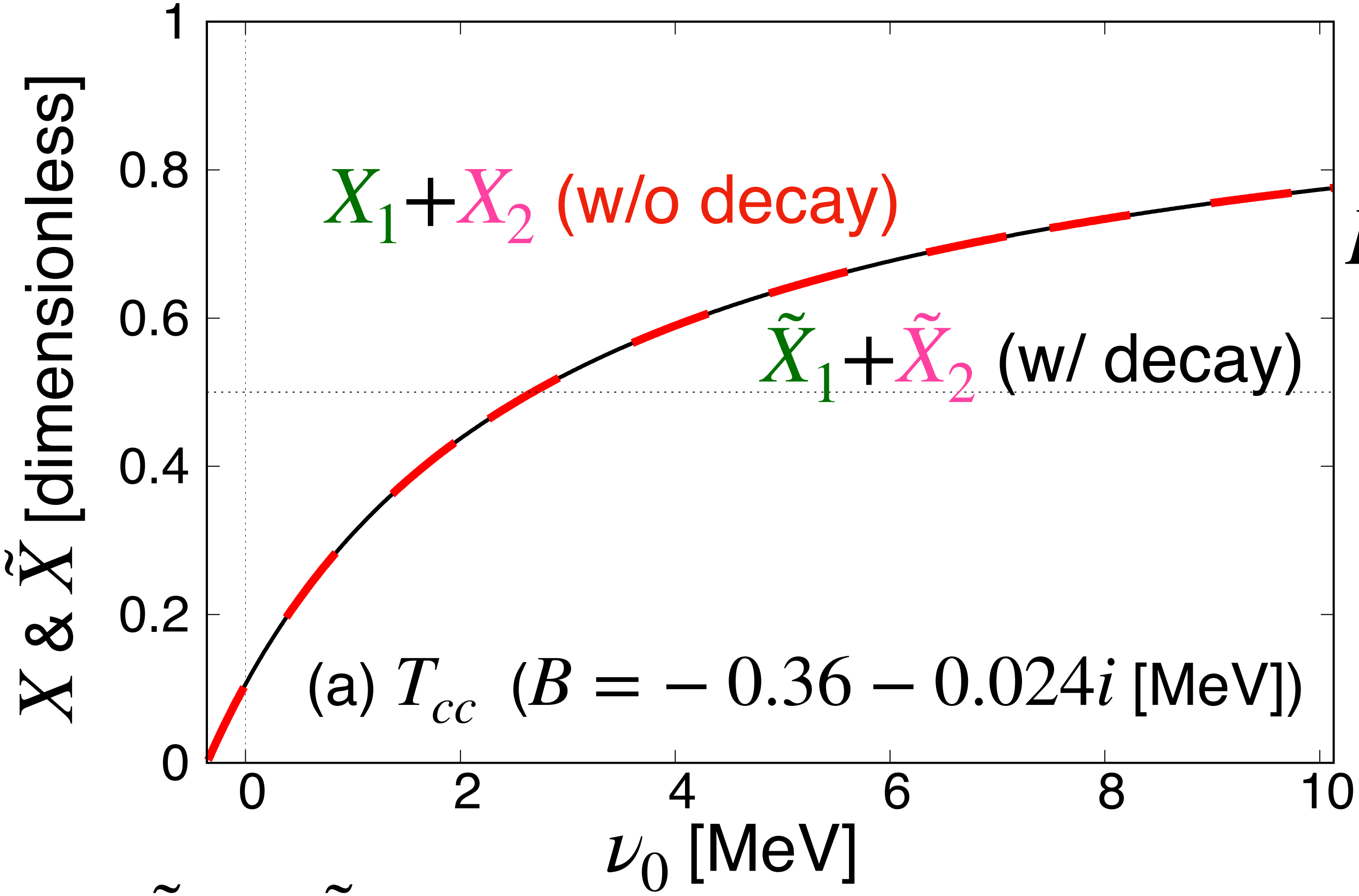
Application to T_{cc}

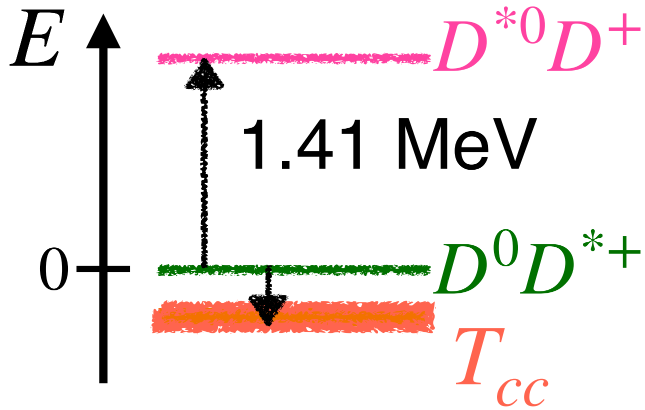
$$\tilde{X}_i = \frac{|X_i|}{|X_1| + |X_2| + |Z|}$$

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

◉ coupled-channel and decay

$g_0 \in \mathbb{C}$





B = 0.36 MeV
Γ = 0.048 MeV

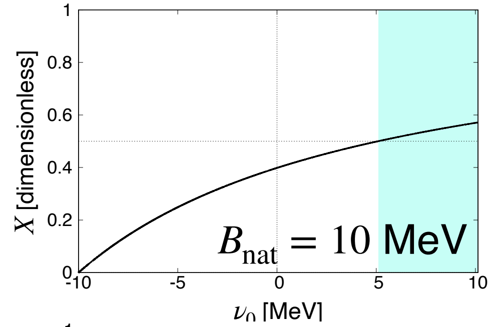
- $\tilde{X}_1 + \tilde{X}_2$ (w/ decay) $\sim X_1 + X_2$ (w/o decay)

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

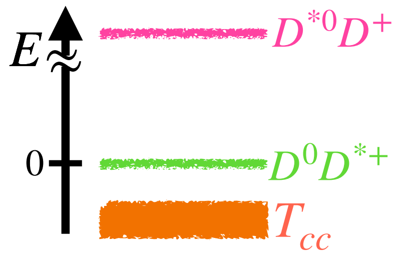
Summary

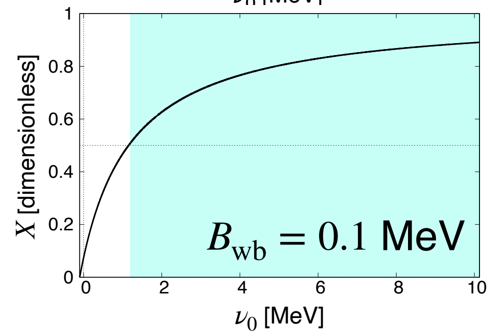
- internal structure of T_{cc} ⟵ EFT & compositeness
- model with bare 4-quark state coupled to the scattering state
- shallow bound state is composite dominant even from bare state

  ∵ low-energy universality



- T_{cc} is composite dominant for most of ν_0 for 1channel





- composite nature is shared by both channels with coupled channel effect

- T_{cc} is composite dominant even with decay

Nature of T_{cc} with effective field theory

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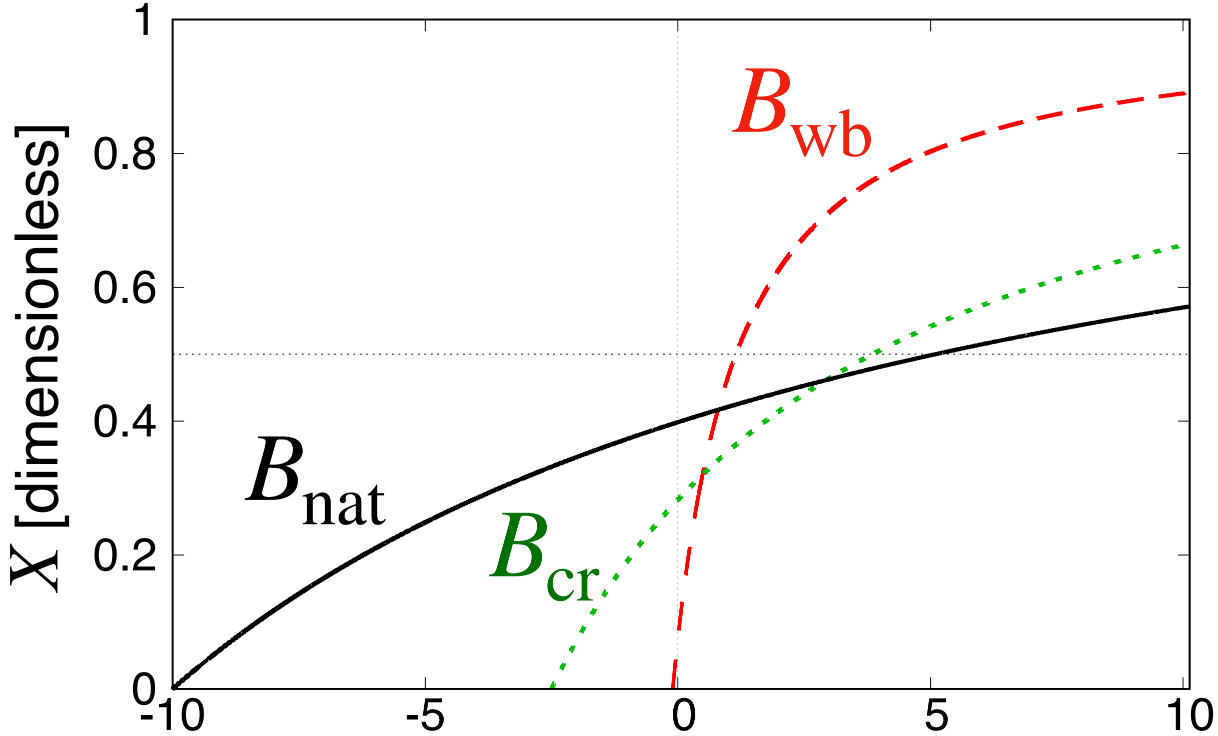
Calculation

X & low-energy universality

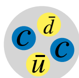


- natural energy scale

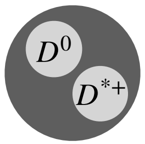
$$B_{\rm nat} = \Lambda^2/(2\mu) \sim 10 \text{ MeV}$$

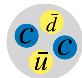
$X > 0.5$ for 25 % of ν_0

= elementary dominant

∵ **bare state origin** 

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



: 

= 1:1

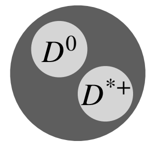
- weakly-bound state

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

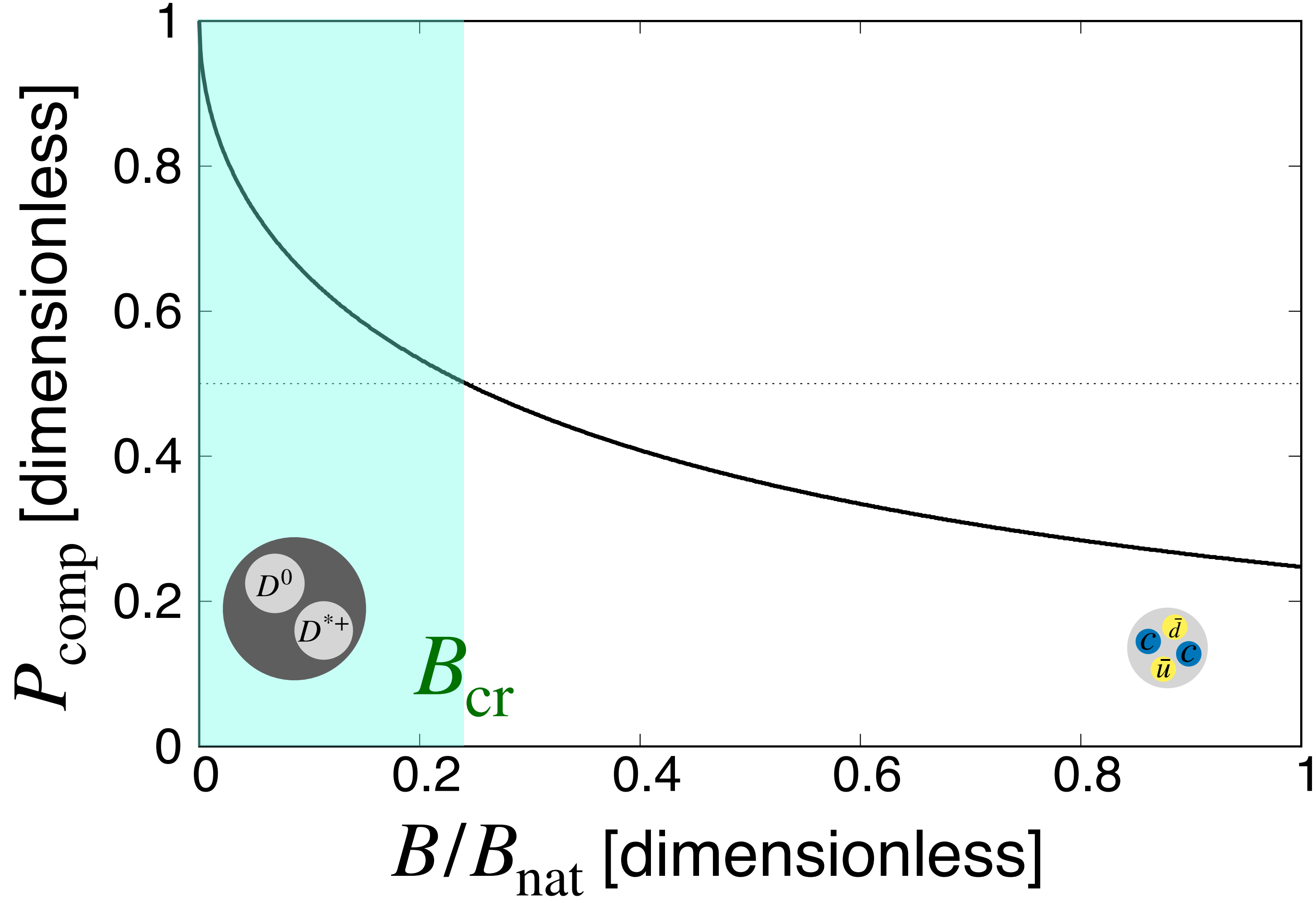
$X > 0.5$ for 88 % of ν_0

= composite dominant

∵ **low-energy universality !**



Calculation



composite dominant

∵ **low-energy universality !**

natural energy scale

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