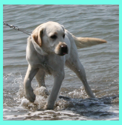


Nature of T_{cc} with effective field theory

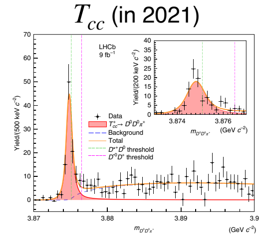
Tomona Kinugawa, Tetsuo Hyodo

Department of Physics, Tokyo Metropolitan University

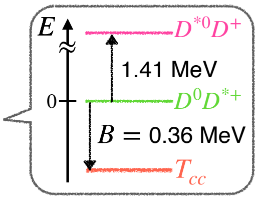
abstract : T_{cc}, observed in 2021, is considered as the exotic state with charm $C=2$. We focus on the internal structure of T_{cc} and study whether it is a hadronic molecule or not. For this purpose, we construct models to reproduce the mass of T_{cc} with the scatterings of the D mesons coupled with the compact four-quark state. The calculations of the compositeness show that T_{cc} is composite dominant without the fine tuning of the energy of the compact four-quark state.

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

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)

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

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

T. Kinugawa and T. Hyodo, Phys. Rev. C 106, 015205 (2022).

Model

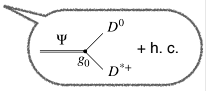
E. Braaten, M. Kusunoki, and D. Zhang, Annals Phys. 323, 1770 (2008).

◉ single-channel resonance model

$$\mathscr{H} = \frac{1}{2m_{D^0}}\nabla D^{0\dagger}\cdot\nabla D^0 + \frac{1}{2m_{D^{*+}}}\nabla D^{*+\dagger}\cdot\nabla D^{*+} + \frac{1}{2m_\Psi}\nabla\psi^\dagger\cdot\nabla\psi + \nu_0\psi^\dagger\psi + g_0(\psi^\dagger D^0 D^{*+} + D^{0\dagger}D^{*+\dagger}\psi).$$

① single-channel scattering

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



◉ scattering amplitude

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

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

◉ parameters

- cutoff Λ : 140 MeV = m_π (π exchange)
- coupling const. g_0 : $g_0^2(B,\nu_0,\Lambda) = \frac{\pi^2}{\mu}(B+\nu_0)\left[\Lambda - \kappa\arctan(\Lambda/\kappa)\right]^{-1}$, $\kappa = \sqrt{2\mu B}$.

  ∵ bound state condition $f^{-1}=0$

  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. ν_0 = 7 MeV (quark model) M. Karliner and J. L. Rosner, PRL 119, 202001 (2017)
  - **varied in the region** : $-B \le \nu_0 \le \Lambda^2/(2\mu)$

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

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

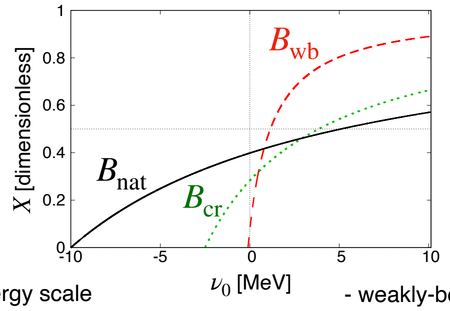
◉ compositeness X Y. Kamiya and T. Hyodo, PTEP 2017, 023D02 (2017).

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

compositeness X as a function of ν_0 ⟶ internal structure of T_{cc}?

Calculation

Λ = 140 MeV, $-B \le \nu_0 \le \Lambda^2/(2\mu)$



- natural energy scale $B_{\rm nat} = \Lambda^2/(2\mu) \sim 10$ MeV

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

  ∵ **bare state origin**

$B_{\rm cr} \sim 2.5$ MeV ; D^0D^{*+} : quarks = 1:1

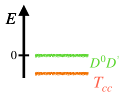
- weakly-bound state $B_{\rm wb}$ = 0.1 MeV

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

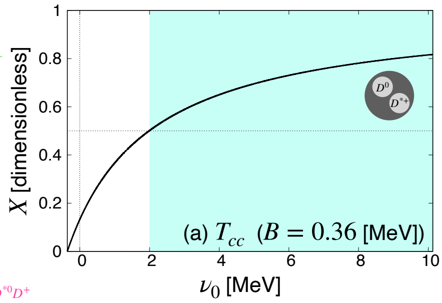
  ∵ **low-energy universality !**

Application to T_{cc}

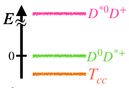
◉ single-channel



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

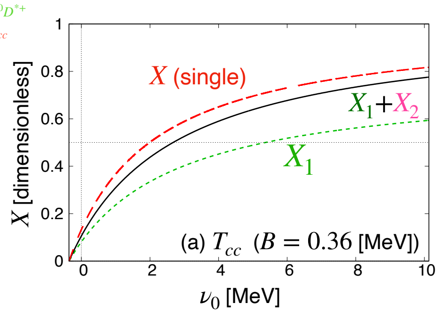


◉ coupled-channel



- composite nature is shared by 2 channels
- X (single) $\sim X_1 + X_2$

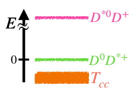
∵ threshold energy difference ≫ binding energy



◉ coupled-channel & decay

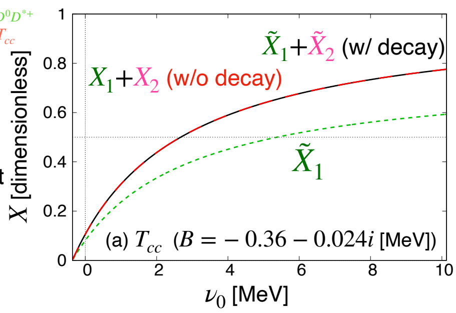
$$\tilde{X}_i = \frac{|X_i|}{(|X_1|+|X_2|+|Z|)}$$

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



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

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



Summary

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

  ∵ low-energy universality
- T_{cc} is composite dominant for most of ν_0 with single-channel
- coupled channel & decay effects do not dramatically change X