Long-range structure of T_{cc}^{+} state

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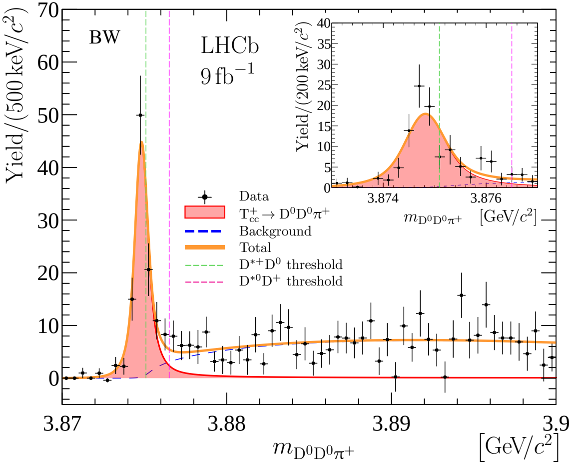
Contents

Amazing results in LHCb: observation of T_{cc}^+



EPS-HEP conference, Ivan Polyakov's talk,29/07/2021; Nature Physics,22'

- Prompt production of 3-BODY final states: $D^0D^0\pi^+$
- Fitting with Breit-Wigner function

$$\delta m_{\text{BW}} = -273 \pm 61\text{keV}, \quad \Gamma_{\text{BW}} = 410 \pm 165\text{keV}$$

- The second doubly charmed hadron
  - $\Rightarrow$ manifestly exotic $(cc\bar{u}\bar{d})$, tetraquark !
- $QQ\bar{q}\bar{q}$ anticipated and debated for 40 yrs !!!
- Analog of $X(3872)$
  - $\Rightarrow$ Very close to $D^{*+}D^0$ threshold
  - $\Rightarrow$ Very narrow resonance

- Our work: The width $(410 \pm 165$keV) is over-estimated .

arXiv:2107.14784, Release in 30/07/2021,PRD104,L051502

  - $\Rightarrow$ Long-range properties can be determined with little uncertainty in NREFT

History: $QQ\bar{q}\bar{q}$ is potential STABLE tetraquark state

- The potential stable $QQ\bar{q}\bar{q}$ was first proposed in 1980s J.P. Ader, J.M. Richard, P. Taxi,PRD25(1982) 2370

  "...*On the other hand, the genuine exotic* $QQ\bar{Q}'\bar{Q}'$ *can be stable against dissociation if the ratio of the quark masses is large enough.*"

- Further developments J. Carlson et al, PRD37,744; B. Silvestre-Brac et al,Z.Phys.C57,273-282; Valcarce et al, PLB393,119-123...

- In 2017, the observation of Ξ_{cc}^{++} in LHCb incited a new round discussions on $QQ\bar{q}\bar{q}$

  $\Rightarrow$ Quark model Luo et al,EPJC7710,709; Karliner et al,PRL119,202001; Eichten et al,PRL119,202002; W.Park et al,NPA983,1-19,...

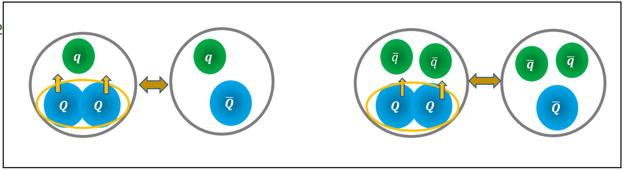
  $\Rightarrow$ Lattice QCD A. Francis et al,PRL118,142001; P. Junnarkar et al PRD99,034507; Hadron Spectrum Collaboration, JHEP11,033,...

  $\Rightarrow$ ...

- E.g: when $M_Q/m_q \sim \infty$ Eichten et al, PRL119,202002

  heavy-diquark-heavy-antiquark symmtry

$$(QQ\bar{q}\bar{q}) = (QQq) + (Qqq) - (Q\bar{q})$$



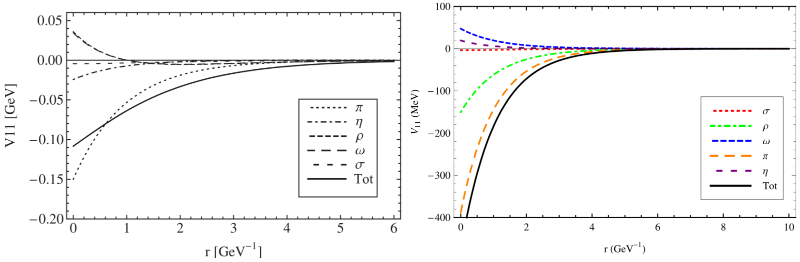
History: analog of $X(3872)$

- The D^*D molecular states: analog of $X(3872)$⇒close to $D^{*+}D^0$ threshold
- In the isospin symmetry: the same one-pion-exchange interaction (long-range interaction)

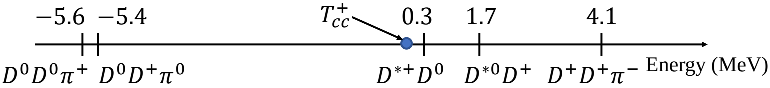
$$V[\bar{D}^*D/\bar{D}D^*; I(J^{PC})=0(1^{++})] = V[D^*D; I(J^P)=0(1^+)]$$

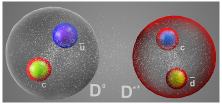
- E.g 1: QCD sum rules: almost degenerate T_{cc} and $X(3872)$ J.M.Dias, S.Narison et al, PLB703(2011)274-280
- E.g 2: One-boson-exchange potential $\pi, \eta, \rho, \omega, \sigma$ N.Li, S.-L Zhu et al, PRD86(2012)074022, PRD88(2013)114008

⇒ Reproduce the $X(3872)$ first and predict an D^*D molecule with $E_b \sim$ 400 keV



Effective field theory: scales and power counting





- Power counting: Naive dimensional analysis

S. Weinberg

$\Rightarrow$ Small scale: Q, large scale m_π

Diagram: $D^*D \to D^*D$

(LO)

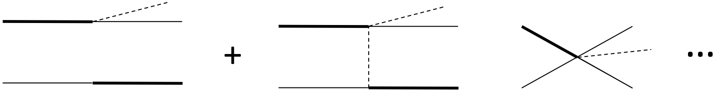
$Q \sim \sqrt{2\delta m_{T_{cc}}\mu_{DD^*}} \sim 20-60$ MeV

m_π is the large scale

Pion can be integrated out

OPE subleading order

Diagram: $D^*D \to DD\pi$



(LO)

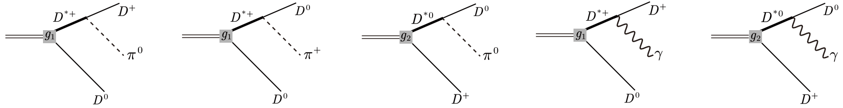
LO decays: One-body operator

$v_D \sim 0.075$:

Non-relativistic dynamics

Isospin violation effect

Strong and radiative decays



(s_a) (s_b) (s_c) (r_a) (r_b)

- $|1\rangle \equiv |D^{*+}D^0\rangle, \quad |2\rangle \equiv |D^{*0}D^+\rangle$
- Parameters g_1, g_2, g_π, g_γ

  $\Rightarrow$ g_π extracted from $D^{*+} \to D^+\pi^0$ and $D^{*+} \to D^0\pi^+$

  $\Rightarrow$ g_γ extracted from the partial decay widths of $D^{*+,0} \to D^{+,0}\gamma$, take $\Gamma_{D^{*0}} =$ 40-80 keV

  $\Rightarrow$ g_1 and g_2 extract from the D^*D scattering or bound state wave function
- Calculation

Similar calculation for $X(3872)$: M.B. Voloshin,...

$$\mathcal{A}[D^{*+} \to D^+\pi^0] = g_\pi q_\pi \cdot \epsilon_{D^*}, \quad \mathcal{A}[T_{cc}^+ \to D^+D^0\pi^0] = \frac{g_1 \epsilon_T^\mu (g_{\mu\nu} - \frac{p_{12\mu}p_{12\nu}}{m_{D^*}^2}) g_\pi p_2^\nu}{p_{12}^2 - m_{D^*}^2 + i m_{D^*}\Gamma_{D^*}}$$

D^*D scattering: Coupled-channel EFT

- Extracting g_1 and g_2 from residues of T-matrix: $\lim_{E\to E_0}(E-E_0)t_{ij}\sim g_j$
- Contact interaction with $V(\boldsymbol{p},\boldsymbol{p}')=\begin{bmatrix} v_{11} & v_{12} \\ v_{12} & v_{11}\end{bmatrix}\Theta(\Lambda-p)\Theta(\Lambda-p')$,
- Λ-dependence of $v_{ij}(\Lambda)$ is determined explicitly make the T-matrix free of cutoff Phys.Lett.B 588 (2004) 57-66

$$t=v+vGt,$$

$$G_i(E)=\int^{\Lambda}\frac{d^3\boldsymbol{q}}{(2\pi)^3}\frac{1}{E-E_{i,q}+i\epsilon},\ E_{i,q}=\delta_i+\frac{q^2}{2\mu}$$

$$\text{Pole}:\ E_0,\ \kappa_i\equiv\sqrt{2\mu(-E_0+\delta_i)}$$

$$(H_0+V)|\psi\rangle=E_0|\psi\rangle$$

$$\langle\boldsymbol{p}|\psi\rangle=\cos\theta\phi_1(p)|1\rangle+\sin\theta\phi_2(p)|2\rangle,$$

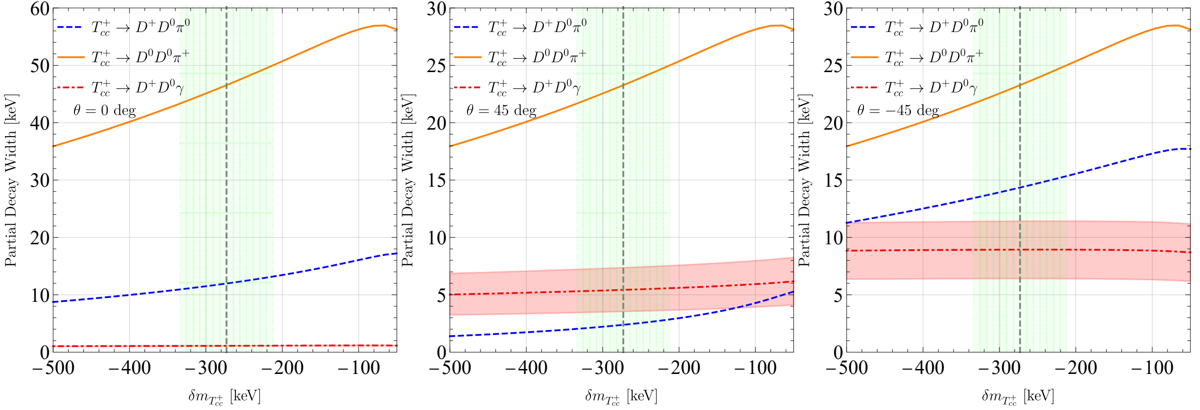
$$\phi_i(p)\sim\Theta(\Lambda-p)(E_0-\frac{p^2}{2\mu}-\delta_i)^{-1}$$

- Two parameters $\{v_{11},v_{12}\}\to\{E_0,\theta\}\to\{g_1,g_2\}$

$$g_1\sim\sqrt{\kappa_1}\cos\theta,\quad g_2\sim\sqrt{\kappa_2}\sin\theta.$$

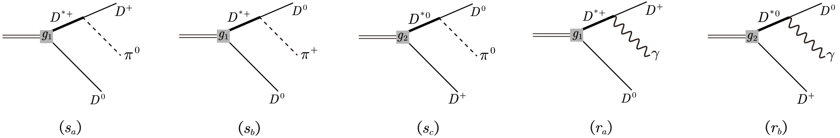
- 1) Renormalization group invariant 2) coupled-channels 3) explicit isospin violation δ_i

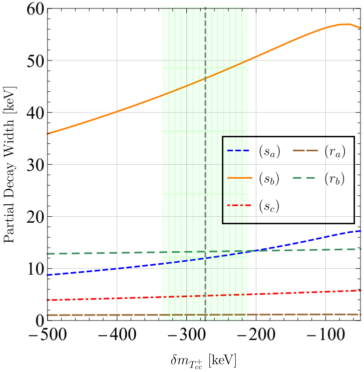
Numerical results



- $\theta = 0$: $D^{*+}D^{0}$single channel (Left) ; $\theta = 45$, $I = 1$(Middle); $\theta = -45$: $I = 0$ (Right).
- The uncertainties: $\delta m_{T_{cc}^{+}}$, $\Gamma[D^{*0} \to D^{0}\gamma]$
- The dominant decay mode is $T_{cc}^{+} \to D^{0}D^{0}\pi^{+}$ (observation channel in experiment)

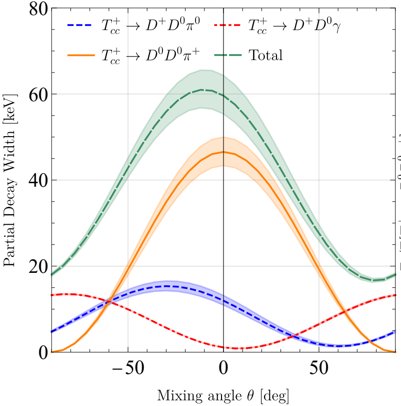
Amplitude analysis

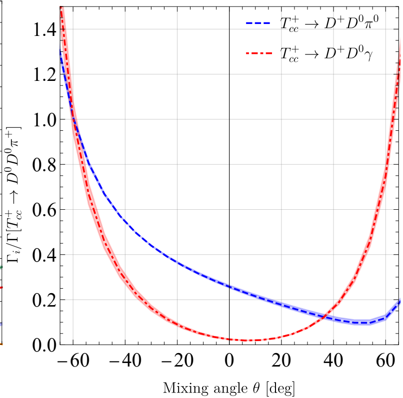




- Dominant diagrams to the strong interaction (s_b):
  - $\Rightarrow$ Extra isospin factor $\sqrt{2}$ and constructive interference effect
- Dominant diagrams to the radiative interaction:(r_b)
  - $\Rightarrow$ M1 radiative transition roughly proportional to the electric charge of the light quarks

Final results





- Our results are inconsistent with the BW fitting
- The ratio of partial decay widths is sensitive to the mixing angle

$$\Gamma_{\text{str}} + \Gamma_{\text{EM}} = \begin{cases} 46.7^{+2.7}_{-2.9}\ \text{keV} & I = 0 \\ 59.7^{+4.6}_{-4.4}\ \text{keV} & I = 1 \\ 31.2^{+2.2}_{-2.4}\ \text{keV} & D^{*+}D^0 \end{cases} \quad \text{VS} \quad \Gamma_{\text{BW}} = 410 \pm 165\text{keV}$$

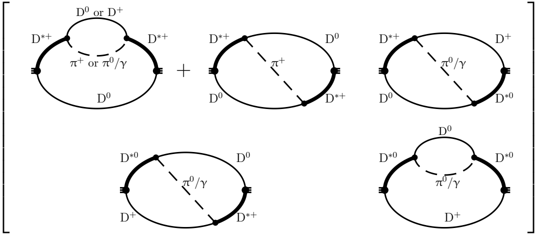
Related works

- Similar calculations: assuming $I = 0$ of T_{cc}^{+}; relativistic framework PLB826,136897;PRD104,116010
- Subleading effects:2-body operator, DD FSI, compact tetraquark effect M.-J Yan et al, PRD105,014007
- The second analysis from LHCb considering unitary: LHCb, Nature Commun. 13 (2022) 1, 3351

$$\mathfrak{F}_f^U(s) = \rho_f(s) \left| [m_U^2 - s - |g|^2 \Sigma(s)]^{-1} \right|^2$$

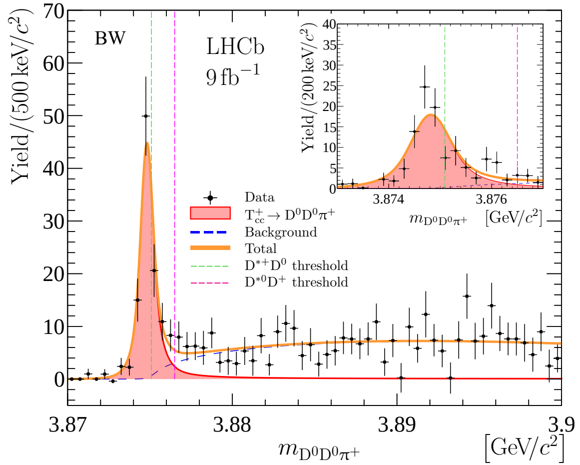
where $f \in \{D^0 D^0 \pi^+, D^0 D^+ \pi^0, D^0 D^+ \gamma\}$ $\quad \rho_f(s)$: 3-body phase space,

$$|g|^2 \Sigma(s) = (g^* \quad -g^*) G \begin{pmatrix} g \\ -g \end{pmatrix}$$

$G =$ 

- $\delta m_{pole}^U = -360 \pm 40_{-0}^{+4}$ keV, $\Gamma_{pole}^U = 48 \pm 2_{-14}^{+0}$keV

Related works



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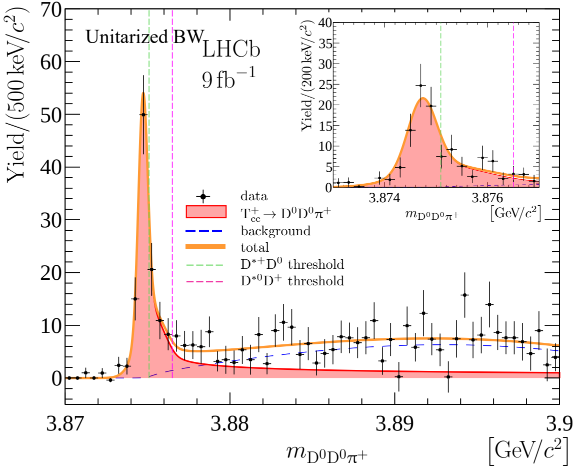

LHCb, Nature Commun. 13 (2022) 1, 3351

$$\Gamma_{BW} = 410 \pm 165\text{keV} \quad \text{VS} \quad \Gamma^{U}_{pole} = 48 \pm 2^{+0}_{-14} \text{ keV} \quad \text{VS} \quad \Gamma^{I=0} = 46.7^{+2.7}_{-2.9} \text{ keV}$$

Molecular state VS compact tetraquark state

- The present result supports the molecular interpretation
- The closeness to thresholds (~200 keV) need fine-tuning mechanisms Discussions for X(3872):PRD69,074005

  ⇒ Mechanism 1: fine-tuning of D^*D potential

  ⇒ Mechanism 2: fine-tuning of the mass of compact core
- The low-energy properties can not reflect the short structures

  ⇒ E.g. universal low energy properties for system ($\frac{1}{a_s} \sim \sqrt{2\mu E_B} \ll m_\pi$) PRD69,074005
- The proportion of the compact core could be small (decreasing with approaching to threshold), but it could be important to generate the bound state PRD105,116024
- To uncover the short-range structure $\rightarrow$ processes associated with higher energy scale

Outlook

- In the molecular scheme, the strong and radiative decays of T_{cc}^+ are investigated

$$\Gamma_{BW} = 410 \pm 165\text{keV} \quad \text{VS} \quad \Gamma^U_{pole} = 48 \pm 2^{+0}_{-14}\ \text{keV} \quad \text{VS} \quad \Gamma^{I=0} = 46.7^{+2.7}_{-2.9}\ \text{keV}$$

  ⇒ Inconsistent with the original experimental analysis (even considering the uncertainties)

  ⇒ Coincide with the unitarized analysis

- Coupled channel EFT: 1) Λ-independent 2) coupled-channels 3) explicit isospin violation
- The separation of the long-range dynamics and short-range dynamics

  ⇒ The long-range dynamics can be determined by only two parameters E_b and θ

  ⇒ Two edge sword: the short-range structure is hard to detect

- Remaining puzzles

  ⇒ Prompt production, relation of X(3872) and T_{cc}, fine-tuning mechanisms, short range interaction and structures,...

Thanks for your attention!