

# Analysis of $T_{cc}^+$ including three-body cuts

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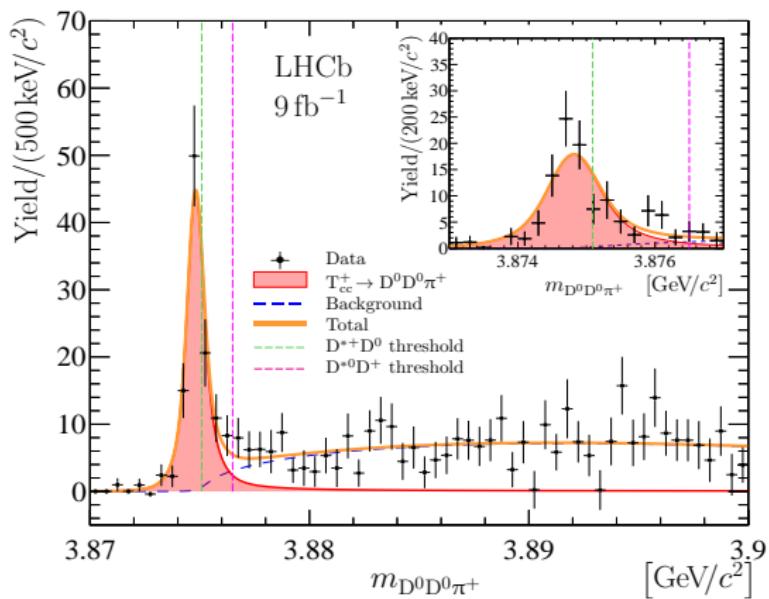
Based on PRD105 (2022) 014024, and arXiv: 2110.07484

The workshop of the B.3 subproject of CRC110

# Doubly charmed tetraquark $T_{cc}^+$ ( $cc\bar{u}\bar{d}$ )

LHCb, arXiv: 2109.01038

## Breit-Wigner fit



Parameter	Value
$N$	$117 \pm 16$
$\delta m_{\text{BW}}$	$-273 \pm 61$ keV
$\Gamma_{\text{BW}}$	$410 \pm 165$ keV

$$\delta m = m_{T_{cc}^+} - m_{D^{*+}} - m_{D^0}$$

- significance  $> 10\sigma$
- $\delta m_{\text{BW}} < 0$  ( $4.3\sigma$ )

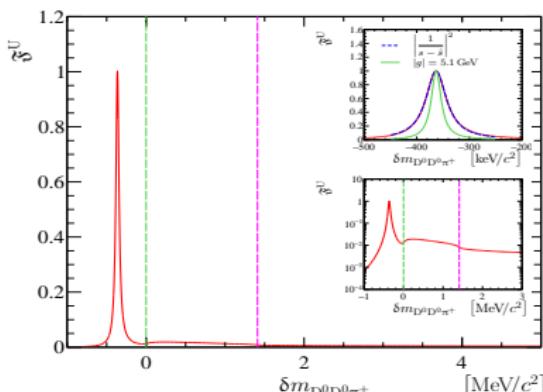
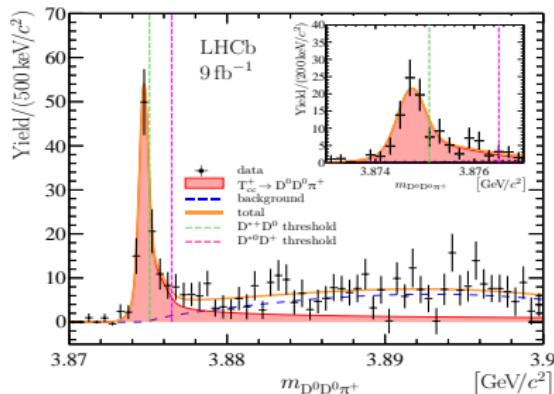
•  $\Re \sim 400$  keV.

$$\begin{aligned} \Re = & 0.778 \mathcal{G}(\sigma = 276 \text{ keV}) \\ & + 0.222 \mathcal{G}(\sigma = 666 \text{ keV}) \end{aligned}$$

# Doubly charmed tetraquark $T_{cc}^+$

Unitarized and analytical model fit to the spectrum

LHCb, arXiv: 2109.01056



$$\delta m_{\text{pole}} = -360 \pm 40^{+4}_{-0} \text{ keV}$$

$$\Gamma_{\text{pole}} = 48 \pm 2^{+0}_{-14} \text{ keV}$$

☞  $I = 0$  : isoscalar

↪  $D^+ D^0 \pi^+$ ,  $D^+ D^+$  ✗

☞ Weinberg compositeness:

$$1 - Z = \sqrt{\frac{1}{1 + 2|r/\Re a|}}$$

$$a = [-(7.16 \pm 0.51) + i(1.85 \pm 0.28)] \text{ fm},$$

$-r < 11.9(16.9)$  fm at 90 (95)% CL,

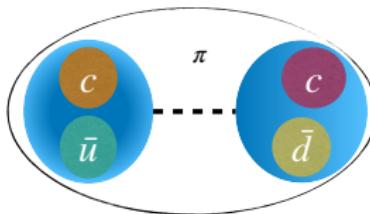
$Z < 0.52(0.58)$  at 90 (95)% CL.

$Z = 0$  : composite,

$Z = 1$  : elementary.

☞ Consistent with molecule

# $T_{cc}^+$ as a hadronic molecule



- ☞  $T_{cc}^+$  resides near  $D^*D$  thresholds  
→ approximate 90% of  $D^0 D^0 \pi^+$  events contain a  $D^{*+}$ . LHCb, arXiv: 2109.01056

A Feynman diagram showing the  $T_{cc}^+$  molecule as a sum of terms. On the left, a square vertex labeled  $T$  is connected to three external lines. This is followed by an equals sign and a sum of four terms. The first term shows a vertex  $V$  connected to three lines. The second term shows a vertex  $V$  connected to a loop of two gluons ( $G$ ) and three lines. The third term shows a vertex  $V$  connected to a loop of three gluons ( $G$ ) and three lines. The fourth term shows a vertex  $V$  connected to a loop of four gluons ( $G$ ) and three lines. The sequence continues with an ellipsis (...).

- ☞  $D^*D$  isoscalar ( $I = 0$ ) and isovector ( $I = 1$ )  
 $|D^*D, I = 0\rangle = -\frac{1}{\sqrt{2}}(D^{*+}D^0 - D^{*0}D^+),$   
 $|D^*D, I = 1\rangle = -\frac{1}{\sqrt{2}}(D^{*+}D^0 + D^{*0}D^+),$

$$V_{\text{CT}}^{I=0}(D^*D \rightarrow D^*D; J^P = 1^+) = v_0,$$

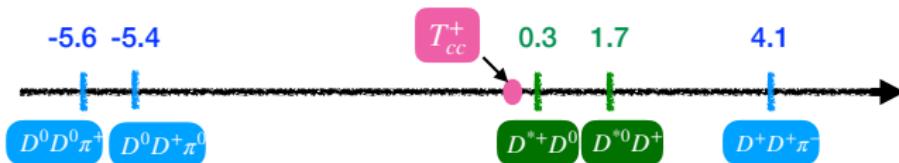
$$V_{\text{CT}}^{I=1}(D^*D \rightarrow D^*D; J^P = 1^+) = v_1.$$

- ☞ In the particle basis  $\{D^{*+}D^0, D^{*0}D^+\}$

$$V_{\text{CT}}^{I=0}[D^*D, 1^+] = \frac{1}{2} \begin{pmatrix} v_0 & -v_0 \\ -v_0 & v_0 \end{pmatrix}$$

# Including three-body cuts

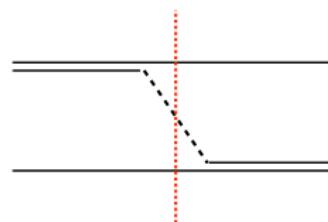
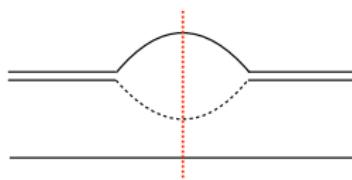
- ☞ A coupled-channel analysis using an EFT approach



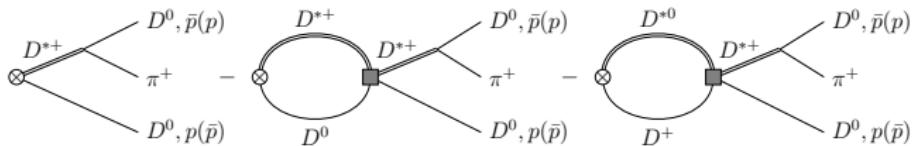
- ☞ LO Chiral Lagrangian ( $g$  determined from  $D^* \rightarrow D\pi$ )

$$\mathcal{L} = \frac{1}{4} g \operatorname{Tr} \left( \vec{\sigma} \cdot \vec{u}_{ab} H_b H_a^\dagger \right)$$

- ☞ Three-body cuts



# $D^0 D^0 \pi^+$ mass distribution



☞  $U_\alpha(M, p) = P_\alpha - \sum_\beta \int \frac{d^3 \vec{q}}{(2\pi)^3} V_{\alpha\beta}(M, p, q) G_\beta(M, q) U_\beta(M, q)$

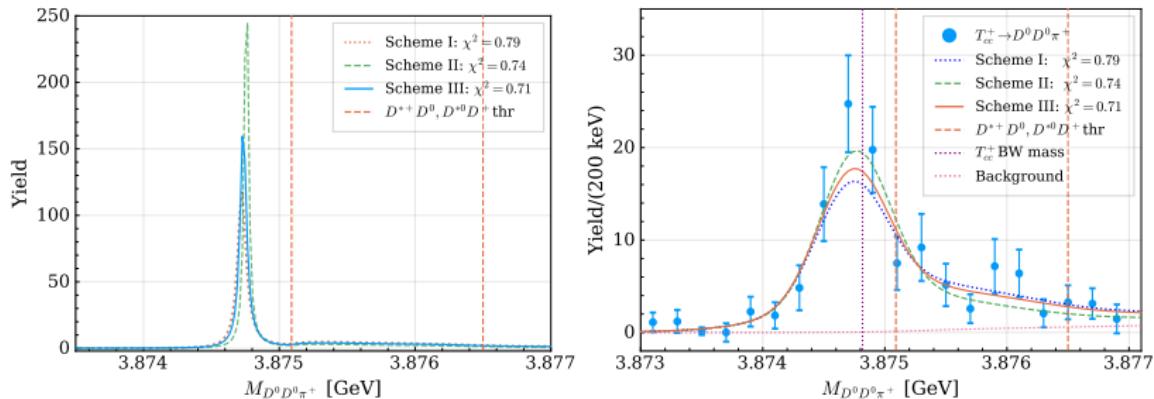
↪  $G_\alpha(M, p) = \frac{1}{m_\alpha^* + m_\alpha + \frac{p^2}{2\mu_\alpha} - M - \frac{i}{2}\Gamma_\alpha(M, p)}$

☞ Fit Schemes:

- ▶ Scheme I (No 3-body cut):  
↪ no OPE,  $\Gamma_c(M, p) = 82.5$  keV,  $\Gamma_0(M, p) = 53.7$  keV
  - ▶ Scheme II (partial 3-body cut):  
↪ no OPE, dynamical widths of  $D^*$  (self-energy)
  - ▶ Scheme III (complete 3-body cut):  
↪ OPE + dynamical widths of  $D^*$
- ☞ Only two free parameters:  $\mathcal{N}$ ,  $v_0$

checked for  $\Lambda = [0.3 - 1.2]$  GeV

# Fit to the $D^0 D^0 \pi^+$ mass distribution $\Lambda = 0.5$ GeV



Scheme	III	II	I
Pole [keV]	$-356^{+39}_{-38} - i(28 \pm 1)$	$-333^{+41}_{-36} - i(18 \pm 1)$	$-368^{+43}_{-42} - i(37 \pm 0)$

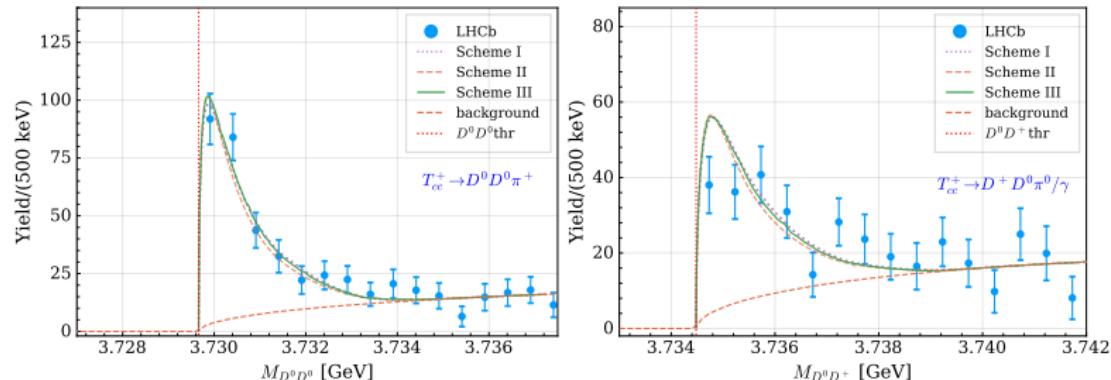
☞ The width of  $T_{cc}^+$

$$56 \text{ keV} \xrightarrow[\text{OPE}]{\text{remove}} 36 \text{ keV} \xrightarrow[\text{M-dep. of } \Gamma^*]{\text{remove}} 74 \text{ keV}$$

Scheme III → Scheme II → Scheme I

Two-body approx. 75 keV [M. Albaldejo, 2110.02944]

# Predictions for the $D^0D^0$ and $D^0D^+$ line shapes



☞ Effective coupling  $g_\alpha$  to the channel  $\alpha$  ( $\Lambda = 0.5$  GeV)

$$g_\alpha g_\beta = \lim_{M \rightarrow M_{\text{pole}}} (M^2 - M_{\text{pole}}^2) T_{\alpha\beta}(M)$$

Scheme	I	II	III
$g_{D^*D}^{(I=0)}(S)$	$-1.45 \pm 0.04$	$-1.42 \pm 0.03$	$-1.43 \pm 0.03$
$g_{D^*D}^{(I=1)}(S)$	0	0	$-0.03 \pm 0.00$
$g_{D^*D}^{(I=0)}(D)$	—	—	$0.02 \pm 0.00$
$g_{D^*D}^{(I=1)}(D)$	—	—	$-0.00 \pm 0.00$

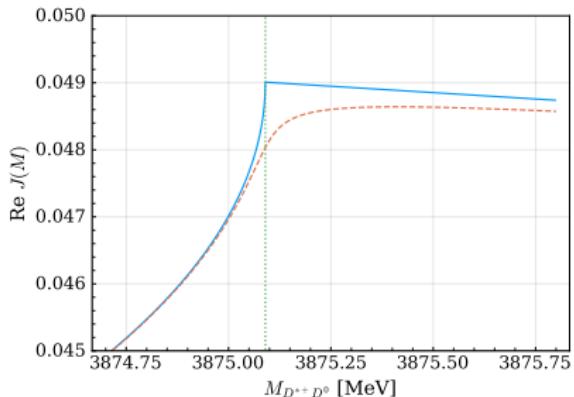
# Low energy expansion of the scattering amplitude

$$T_{D^*+D^0 \rightarrow D^*+D^0}(k) = -\frac{2\pi}{\mu_{c0}} \left( \frac{1}{a_0} + \frac{1}{2} r_0 k^2 - ik + \mathcal{O}(k^4) \right)^{-1}$$

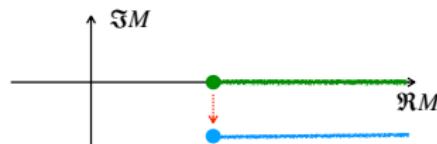
☞ A single-channel with a constant potential:

$$T^{-1}(M) = V_{\text{CT}}^{-1} + J(M), \quad J(M) = \int \frac{d^3 \vec{p}}{(2\pi)^3} G(M, p)$$

☞  $r_0 \propto -\Re \frac{dJ(M)}{dM} \Big|_{M=M_{\text{thr}}+0^+}$



☞  $M = m_c^* - i\Gamma_c/2 + m_0 + \frac{k^2}{2\mu_{c0}}$



# Isospin violation: infinitely narrow $D^*$ limit

☞ Only contact potential (Scheme I):

$$T_{D^*+D^0 \rightarrow D^*+D^0}^{-1}(M) = \frac{2}{v_0} + (J_1(M) + J_2(M))$$

☞  $r_0 = -\frac{2\pi}{\mu^2} \left. \frac{d(J_1(M) + J_2(M))}{dM} \right|_{M=M_{\text{thr},1}+0^+}$  E = M - M\_{\text{thr},1}

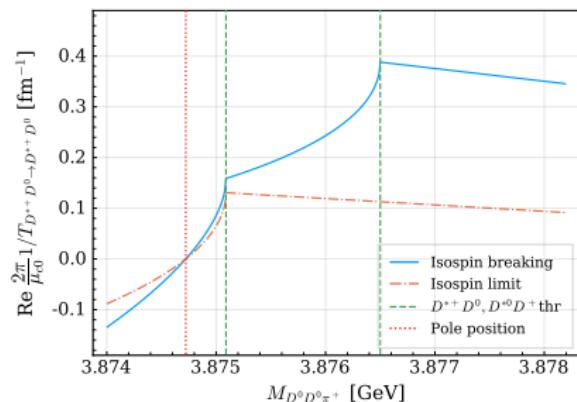
$$J_1(E) = \frac{\Lambda\mu}{\pi^2} - \frac{2\mu^2 E}{\pi^2 \Lambda} + i \frac{\sqrt{2\mu E}\mu}{2\pi} + \mathcal{O}(E^2),$$

$$J_2(E) = \frac{\Lambda\mu}{\pi^2} - \frac{2\mu^2 E}{\pi^2 \Lambda} + \frac{2\Delta\mu^2}{\pi^2 \Lambda} - \frac{\mu\sqrt{2\mu\Delta}}{2\pi} + \frac{\mu E \sqrt{2\mu\Delta}}{4\pi\Delta} + \mathcal{O}(E^2)$$

☞  $r_0 = \frac{8}{\pi\Lambda} - \frac{1}{\sqrt{2\mu\Delta}}$

☞  $r_0 \rightarrow$  regulator and OPE

talk by Baru on Wednesday



# Composite or Compact? $(\Delta r_{\text{IV}} = -\sqrt{\frac{1}{2\mu\Delta}} = -3.78 \text{ fm})$

☞ Compositeness  $\bar{X}_A = 1 - Z$

$$\bar{X}_A = \left(1 + 2 \left| \frac{r'_0}{\Re a_0} \right| \right)^{-1/2}, \quad r'_0 = r_0 - \Delta r_{\text{IV}}$$

☞

	$a_0$ [fm]	$r_0$ [fm]	$r'_0$ [fm]	$\bar{X}_A$
I	$\begin{pmatrix} -6.31^{+0.36} \\ -0.45 \\ \pm 0.27 \end{pmatrix} + i \begin{pmatrix} 0.05^{+0.01} \\ -0.01 \\ \pm 0.00 \end{pmatrix}$	$-2.78 \pm 0.01$ $\pm 0.66$	$1.00 \pm 0.01$ $\pm 0.66$	$0.87 \pm 0.01$ $\pm 0.07$
II	$\begin{pmatrix} -6.64^{+0.36} \\ -0.50 \\ \pm 0.27 \end{pmatrix} - i \begin{pmatrix} 0.10^{+0.01} \\ -0.02 \\ \pm 0.01 \end{pmatrix}$	$-2.80 \pm 0.01$ $\pm 0.59$	$0.98 \pm 0.01$ $\pm 0.59$	$0.88 \pm 0.01$ $\pm 0.06$
III	$\begin{pmatrix} -6.72^{+0.36} \\ -0.45 \\ \pm 0.27 \end{pmatrix} - i \begin{pmatrix} 0.10^{+0.03} \\ -0.03 \\ \pm 0.03 \end{pmatrix}$	$-2.40 \pm 0.01$ $\pm 0.85$	$1.38 \pm 0.01$ $\pm 0.85$	$0.84 \pm 0.01$ $\pm 0.06$

☞ OPE contribution to  $r_0$ : 0.4 fm

# Prediction: HQSS partner

☞ In the heavy quark limit

$$V^{I=0}(D^* D^* \rightarrow D^* D^*, J^P = 1^+) = V^{I=0}(D^* D \rightarrow D^* D, J^P = 1^+)$$

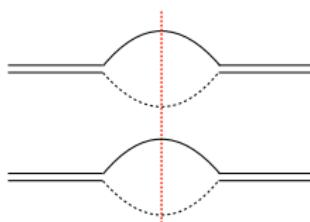
☞ ?  $V^{I=0}(D^* D \rightarrow D^* D^*, J^P = 1^+)$

☞ renormalization of OPE

→ regulator dependent ↔ higher order counter terms

Baru et al, PRD99(2019)074023; Du et al, JHEP08(2021)157

☞ Four-body cuts



☞ Neglecting  $D^* D - D^* D^*$  and widths of  $D^*$  ( $\Lambda = 0.5$  GeV)

$$\delta_{cc}^{*+} = m_{T_{cc}^{*+}} - m_{D^*+} - m_{D^*0}$$

Scheme I:  $\delta_{cc}^{*+} = -1444(61)$  keV,

Scheme II:  $\delta_{cc}^{*+} = -1138(50)$  keV,

Scheme III:  $\delta_{cc}^{*+} = -503(40)$  keV.

two-body approx., two  $\Lambda$ 's, M. Albaladejo, 2110.02944

width & strangeness Dai, 2110.15270

# Summary

- $T_{cc}^+$  is the first doubly charmed (heavy quark) meson ( $cc\bar{u}\bar{d}$ )
- $m_{T_{cc}^+} > m_{DD\pi} \rightarrow$  three-body cuts  
     $\hookrightarrow$  one-pion exchange + self-energy of  $D^*$
- The width of  $T_{cc}^+$  is sensitive to the details

$$56 \text{ keV} \xrightarrow[\text{OPE}]{\text{remove}} 36 \text{ keV} \xrightarrow[\text{M-dep. of } \Gamma^*]{\text{remove}} 74 \text{ keV}$$

- ★ Low-energy parameters ( $a_0, r_0$ )  
 $\hookrightarrow$  a finite width:  $k_{\text{eff}} = \sqrt{2\mu(E + i\Gamma/2)}$   
 $\hookrightarrow$  isospin coupled-channel:  $r_{\text{IV}} = -\sqrt{\frac{1}{2\mu\Delta}}$
- ★ Compositeness:  $\bar{X}_A = 0.87, 0.88, 0.84$
- ★ Properties of  $T_{cc}^+$  consistent with a shallow  $D^*D$  molecule

Thank you very much for your attention!