Effective range of T_{cc}^{+} and other parameters

[LHCb, arXiv:2109.01056]

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LHCb collaboration
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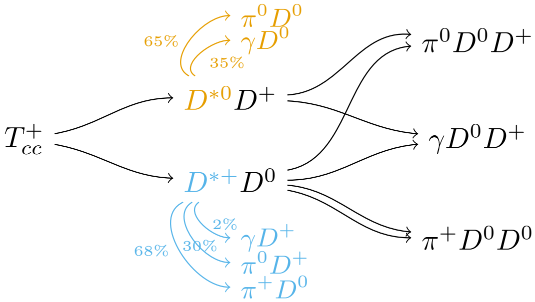
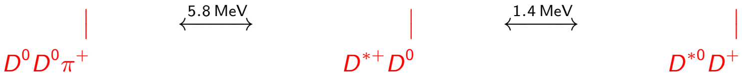
Effective CERN meeting

T_{cc}^{+} decay amplitude



Model assumptions:

- $J^P = 1^+$: S-wave decay to $D^* D$
- T_{cc}^+ is an isoscalar: $|T_{cc}^+\rangle_{I=0} = \left\{ \left| D^{*0} D^+ \right\rangle - \left| D^{*+} D^0 \right\rangle \right\} / \sqrt{2}$
- No isospin violation in couplings to $D^{*+} D^0$ and $D^{*0} D^+$



T_{cc}^+ self-energy and hadronic reaction amplitude

Three-body unitarity [MM et al. (JPAC), JHEP 08 (2019) 080]

Dynamic amplitude of $D^*D \to D^*D$ scattering:

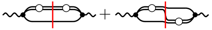
$$T_{2\times 2}(s) = \frac{K}{1 - \Sigma K} = \frac{K(m^2 - s)}{m^2 - s - i\, g^2 \left(\rho_{\text{tot}} + i\xi\right)}$$

where K is the isoscalar potential:

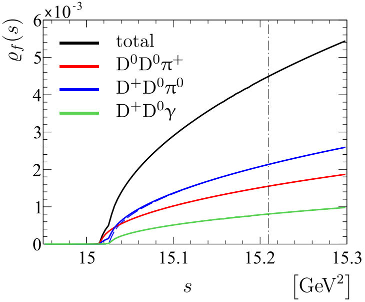
$$K = \frac{1}{m^2 - s} \begin{pmatrix} g\cdot g & -g\cdot g \\ -g\cdot g & g\cdot g \end{pmatrix},$$

and Σ is the loop function:

$$\Sigma(s) = [D^*D \to DD\pi(\gamma) \to D^*D]$$

$= \Big[$  $\Big]$.

$$\text{Im}\left[\begin{pmatrix} g \\ -g \end{pmatrix}^{\dagger} \Sigma(s) \begin{pmatrix} g \\ -g \end{pmatrix}\right] = \rho(s)$$



F

D^* decays are accounted for.

Unitarity and Analyticity guided construction.

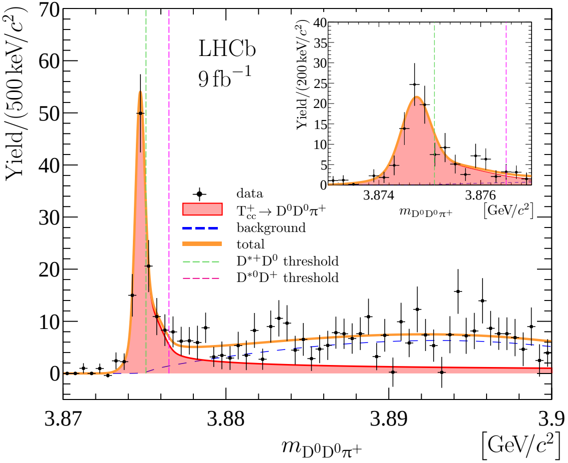
Model parameters: $|g|^2$ and m^2 – bare mass and coupling

Fit to the spectrum

Unitarized model

- The signal shape does not depend on $|g|$ for $|g| \to \infty$.
- The lower limit: $|g| > 7.7(6.2)\,\mathrm{GeV}$ at 90(95)% CL
- δm_U is the only parameter

Parameter	Value
N	186 ± 24
δm_{U}	$-359 \pm 40\,\mathrm{keV}/c^2$
$\lvert g \rvert$	3×10^4 GeV (fixed)



No direct sensitivity to the width, the value is driven by the model

Predicted mass spectrum

resolution removed

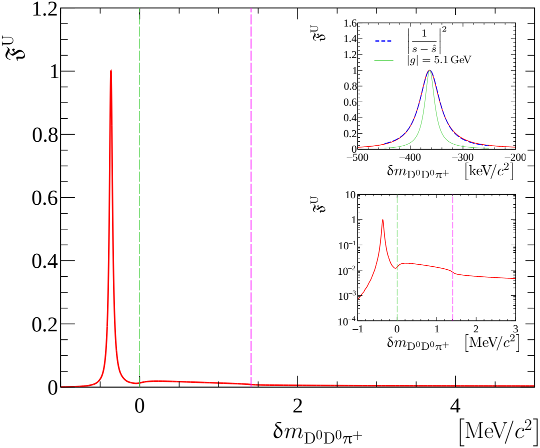
Visible characteristics:

- Peak position: $-359 \pm 40\,\mathrm{keV}$

  (The most precise ever wrt to the threshold)

- FWHM: $47.8 \pm 1.9\,\mathrm{keV}$,
- Lifetime: $\tau \approx 10^{-20}$ s.

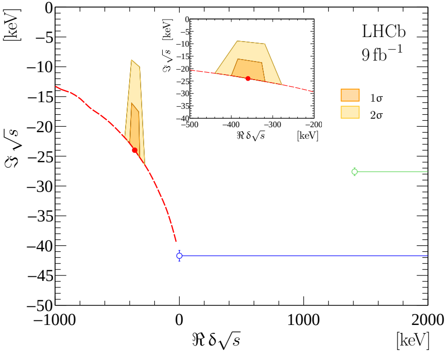
  (Unprecedented for exotic hadrons)

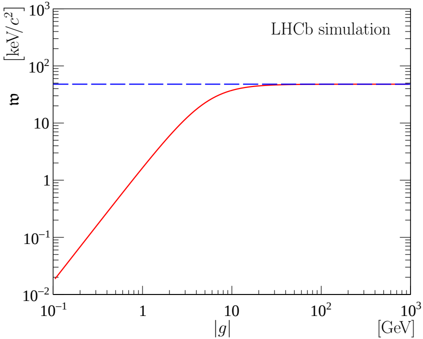


- A bound state below $D^{*+}D^0$ threshold with a narrow width due to D^*
- Still, the NLL scan suggest the low limit to the width, $\Gamma > 10\,\mathrm{keV}$ at 95 CL.

Width saturation

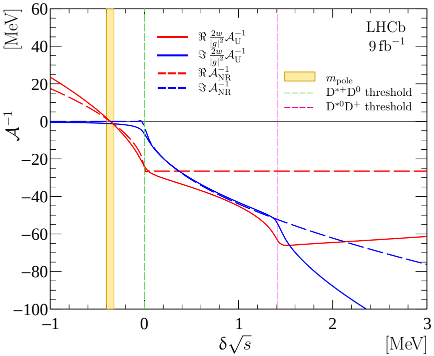
Complex plane





- The D^* width gives the limit to T_{cc}^+ width, $< \Gamma_{T_{cc}^+}^{(\max)}$
- Parameter $|g|$ sets the value in the range $[0, \Gamma_{T_{cc}^+}^{(\max)}]$
- The fit prefers the limit value

Effective range and Weinberg compositeness



$$\mathcal{A}_{\mathrm{NR}}^{-1} = \frac{1}{a} + r\frac{k^2}{2} - ik + \mathcal{O}(k^4)\,,$$

$$\frac{2}{|g|^2}\mathcal{A}_{\mathrm{U}}^{-1} = -\left[\xi(s) - \xi(m_{\mathrm{U}}^2)\right] + 2\frac{m_{\mathrm{U}}^2 - s}{|g|^2} - i\varrho_{\mathrm{tot}}$$

Matching:

- $r = 16w/|g|^2$, where w is a normalization factor between ρ and k
- w excludes the contribution of the second threshold
- does not have the $1/\sqrt{\delta}$ term

- T_{cc}^{+}: $a = (-7.16 \pm 0.51) + i(1.85 \pm 0.28)\,\mathrm{fm}$
- T_{cc}^{+}: r is negative in the model: $0 < -r < 11.9(16.9)\,\mathrm{fm}$ at $90(95)\,\%\,\mathrm{CL}$
- T_{cc}^{+}: $1 - Z > 0.48(0.42)$. T_{cc}^{+} is consistent with the molecule

Two extreme spatial configurations

$$1 - Z = \sqrt{\frac{1}{1 + 2r/\Re a}} \approx 1 - \frac{r}{a}, \quad \Rightarrow \quad Z \propto \frac{1}{|g|^2} \text{ when } |g| \to \infty$$

"Molecule" configuration:

- two mesons are well separated,
- bound by forces similarly to el.mag. van der Waals,
- **entirely coupled to $D^{*+}D^0$,**

$\sim$ **T_{cc}^+ lives until D^{*0} decays,**

? spatially-extended object.

"Atomic" configuration:

- genuine QCD state,
- bound by direct color forces

$\sim$ **T_{cc}^+ cannot live shorter than D^{*0}, $\tau_{T_{cc}^+}$ can be arbitrary large (uncoupled from continuum)**

? typical hadronic size of 1 fm.

How the width is made

Components of the model:

- Coupled $D^{*+}D^0/D^{*0}D^+$ channels
- One-particle exchange
- $D^* \to D\pi$ decay

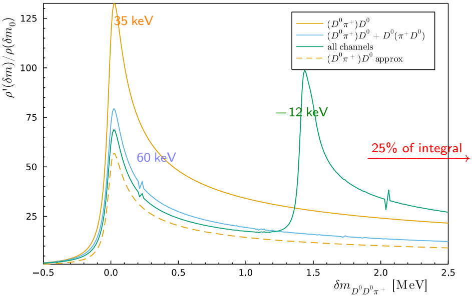
Analytic expression for the width:

$$\frac{1}{\Gamma} = \frac{1}{2\pi}\,\mathrm{P}\int_{\mathrm{th}}^{\infty} \frac{\rho'(e)/\rho(\delta m_0)}{e-\delta m_0}\mathrm{d}e$$

- 48 keV: default model
- −12 keV if not consider the $D^{*0}D^+$
- ∼ 15 keV is controlled by the tail

$$48\,\mathrm{keV} \xrightarrow[\text{OPE}]{\text{remove}} 30\,\mathrm{keV} \xrightarrow[D^*\to D\pi]{\text{remove}} 75\,\mathrm{keV}$$

Two-body approx. [Albaladejo, M. (2021)]



Complete of the three-body effects gives 56 keV [Meng-Lin Du et al. (2021)]

Summary

* Procedure of measuring r is important

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But moreover:

- Experimental observable of compositeness is the T_{cc}^{+} width
  - Limiting value corresponds to $1 - Z = 1$
  - The smaller width – indication of the compact component
- Having correct the limiting value of $\Gamma_{T_{cc}^{+}}$ is the key question.
  - ? contribution of OPE
  - ? three-body cut

Backup

Fundamental resonance parameters

[interactive]

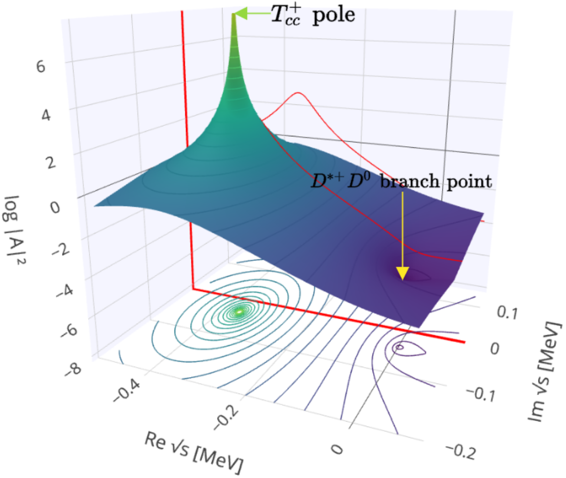
Mass and width – position of the complex pole of the reaction amplitude

- Analytic continuation is non-trivial due to three-body decays [MM et al. (JPAC), PRD 98 (2018) 096021]

The pole parameters:

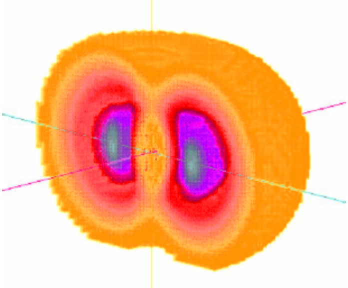
$$\delta m_{\text{pole}} = -360 \pm 40^{+4}_{-0}\,\text{keV}\,,$$

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



Comparison to the deuteron

Deuteron [Garcon, Van Orden(2001)]



- Presumably molecule
- $1 - Z \approx 1$
- $R_{\text{charge}} = 2.1\,\text{fm}$
- $R_{\text{matter}} = 1.9\,\text{fm}$
- $a = -5.42\,\text{fm}$
- $r = 1.75\,\text{fm}$

Tetraquark T_{cc}^{+} [LHCb, arXiv:2109.01056]

[compact cc core]

[$\bar{u}\bar{d}$ cloud]

- Expected to be atomic
- $1 - Z \geq 0.48$ at 90% CL
- $R_{\text{charge}} = ??$
- $R_{\text{matter}} = ??$
- $a = -7.16\,\text{fm}$
- $r > -11.9\,\text{fm}$ at 90% CL