Discovery and study of T_{cc}^{+}

[LHCb, arXiv:2109.01056]

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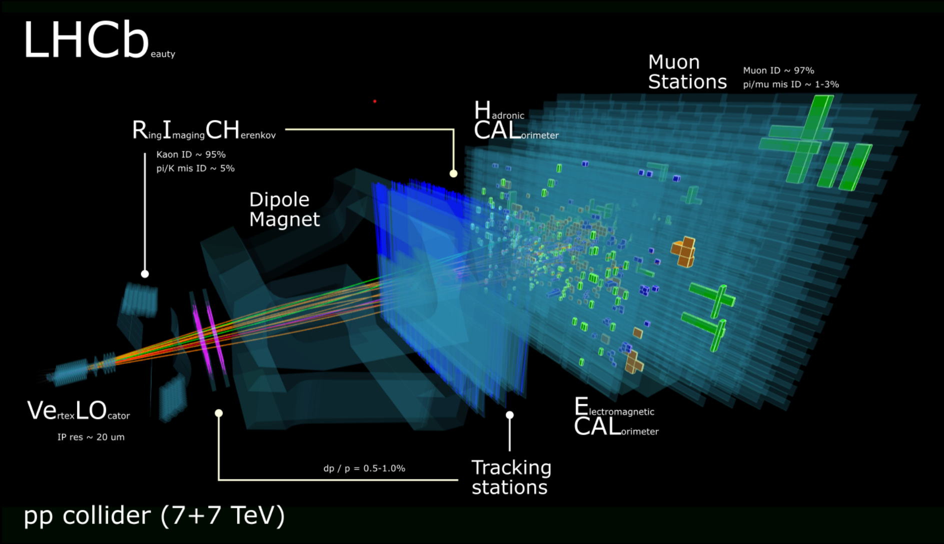
(LHCb collaboration)

dedicated to the memory of **Simon Eidelman**

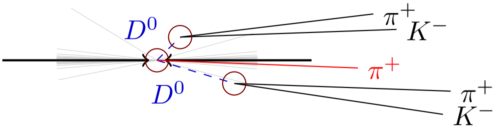
Match 16$^{\text{th}}$, 2022

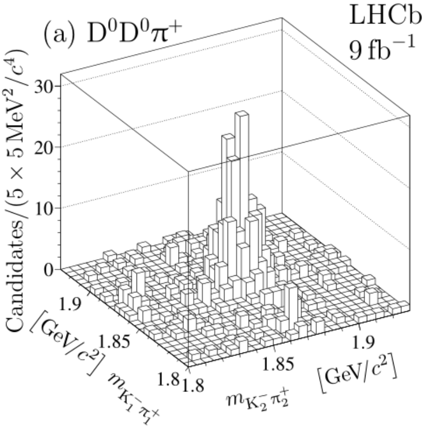
Image credit: Samuel Velasco / Quanta Magazines

[display]


LHCb eauty
Muon Stations
Muon ID ~ 97%
pi/mu mis ID ~ 1-3%
Hadronic CALorimeter
Ring Imaging CHerenkov
Kaon ID ~ 95%
pi/K mis ID ~ 5%
Dipole Magnet
VertexLOcator
IP res ~ 20 um
Electromagnetic CALorimeter
dp / p = 0.5-1.0%
Tracking stations
pp collider (7+7 TeV)

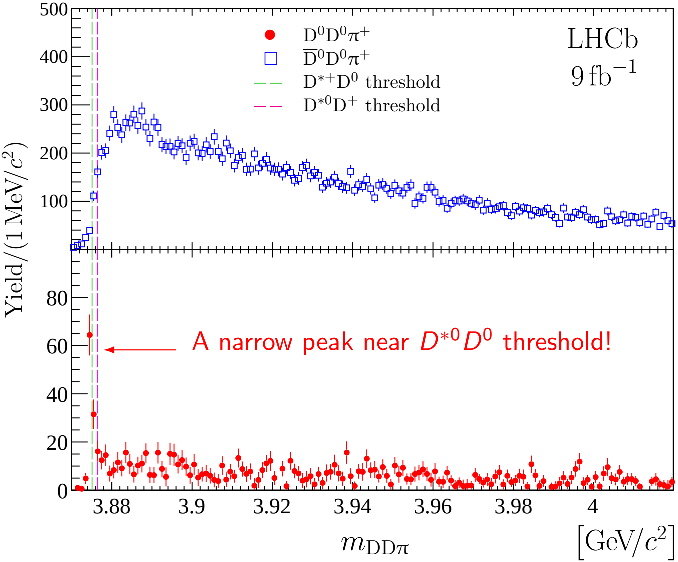
Selection of T_{cc}^{+} in prompt decays to $D^0 D^0 \pi^+$



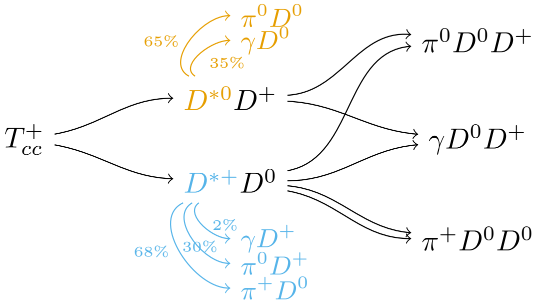


- Select $D^0 D^0 \pi^+$ candidates from primary vertex with detached $D^0 \to K^-\pi^+$
- Require detached $K^-\pi^+$ with high p_T
- Require good quality of tracks, vertexes, and particle ids.
- Ensure no K/π candidates belong to one track (clones)
- Ensure no reflections via mis-ID
- Subtract fake-D background using 2d fit to $(m_{K\pi} \times m_{K\pi})$

The first hint of the signal: $D^0 D^0 \pi^+$ and $D^0 \bar{D}^0 \pi^+$

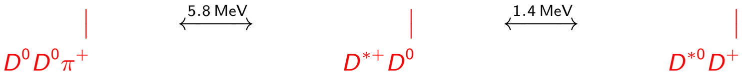


T_{cc}^{+} decay amplitude



Model assumptions:

- $J^P = 1^+$: S-wave decay to $D^* D$
- T_{cc}^{+} is an isoscalar: $\left|T_{cc}^{+}\right\rangle_{I=0} = \left\{\left|D^{*0} D^+\right\rangle - \left|D^{*+} D^0\right\rangle\right\} / \sqrt{2}$
- 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:

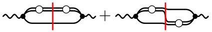
$$T_{2\times 2}(s) = \frac{K}{1-\Sigma\,K} = \frac{K(m^2-s)}{m^2-s-i\,g^2\,(\rho_{\text{tot}}+i\xi)}$$

where K is the isoscalar potential:

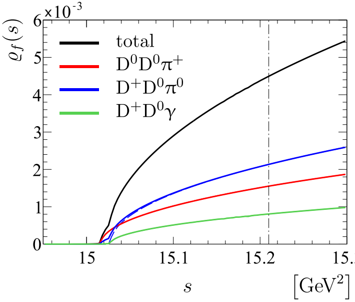
$$K = \frac{1}{m^2-s}\begin{pmatrix} g\cdot g & -g\cdot g \\ -g\cdot g & g\cdot g \end{pmatrix},$$

and Σ is the loop function:

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

$= [$  $]$.

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



F

D^* decays are accounted for.

Unitarity and Analyticity guided construction.

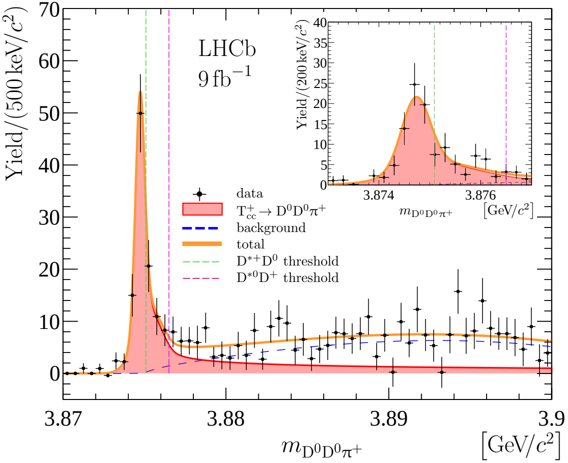
Model parameters: $|g|^2$ **and** m^2 **– bare mass and coupling**

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}	$-359 \pm 40\,\mathrm{keV}/c^2$
$\lvert g \rvert$	$3 \times 10^4\,\mathrm{GeV}$ (fixed)



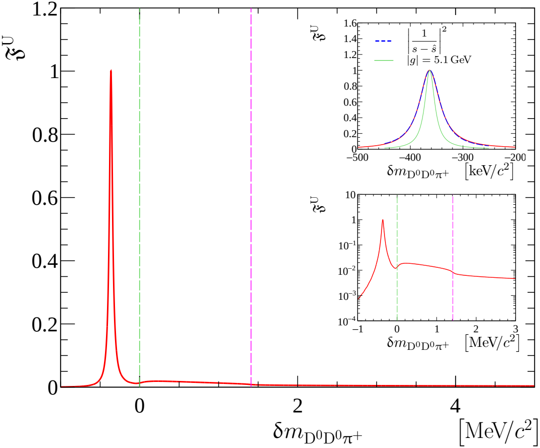
No direct sensitivity to the width, the value is driven by the model

Predicted mass spectrum

resolution removed

Visible characteristics:

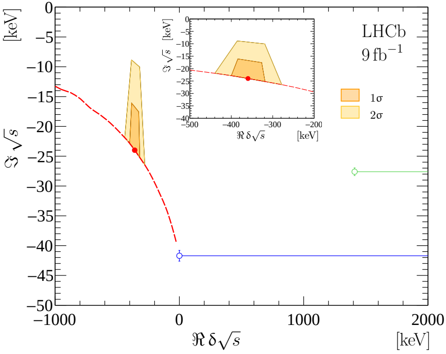
- Peak position: $-359 \pm 40\,\mathrm{keV}$
  (The most precise ever wrt to the threshold)
- FWHM: $47.8 \pm 1.9\,\mathrm{keV}$,
- Lifetime: $\tau \approx 10^{-20}$ s.
  (Unprecedented for exotic hadrons)

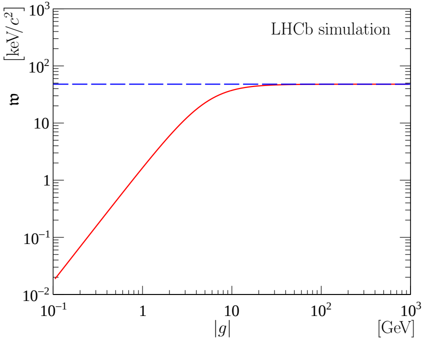


- A bound state below $D^{*+}D^0$ threshold with a narrow width due to D^*
- Still, the NLL scan suggest the low limit to the width, $\Gamma > 10\,\mathrm{keV}$ at 95 CL.

Width saturation

Complex plane





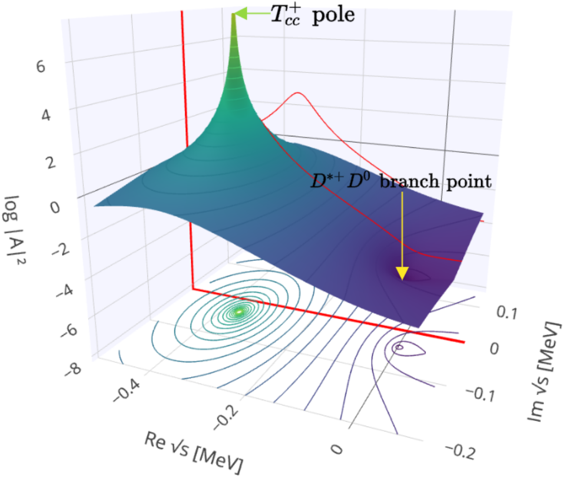
- The D^* width gives the limit (the red dashed line) to T_{cc}^+ width, $< \Gamma^{(\max)}_{T_{cc}^+}(m)$
- Parameter $|g|$ sets the value in the range $[0, \Gamma^{(\max)}_{T_{cc}^+}]$
- The fit prefers the limit value

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]

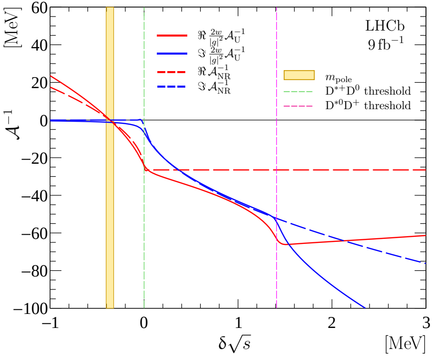


The pole parameters:

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

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

Effective range and Weinberg compositeness



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

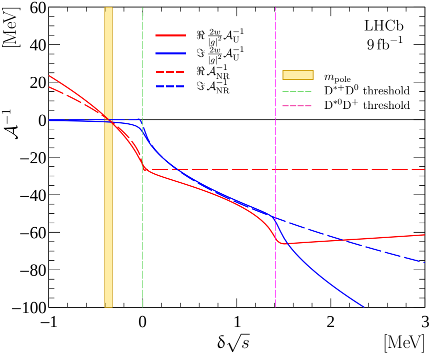
$$\frac{2}{|g|^2}\mathcal{A}_{\mathrm{U}}^{-1} = -\left[\xi(s) - \xi(m_{\mathrm{U}}^2)\right] + 2\frac{m_{\mathrm{U}}^2 - s}{|g|^2} - i\varrho_{\mathrm{tot}}$$

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) % CL
- T_{cc}^+: $1 - Z > 0.48(0.42)$. T_{cc}^+ is consistent with the molecule

Effective range and Weinberg compositeness



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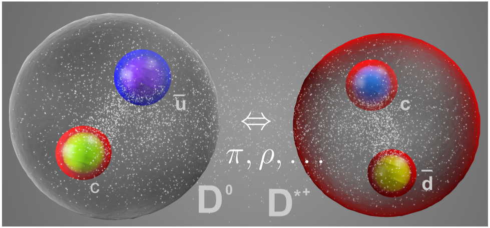
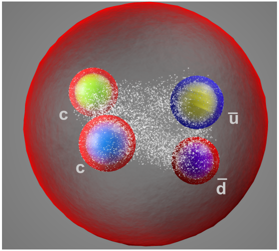
!! The procedure and the values are revisited in [MM, hep-ph/2203.04622]

Two extreme spatial configurations





"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" (©ancient Greek) **configuration:**

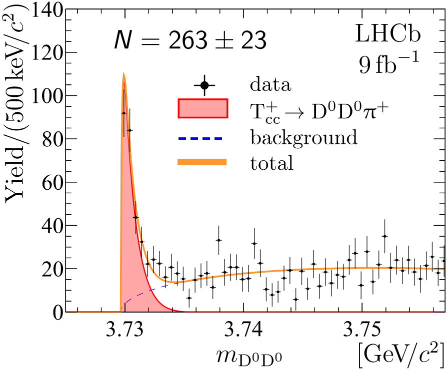
- genuine QCD state,
- bound by direct color forces

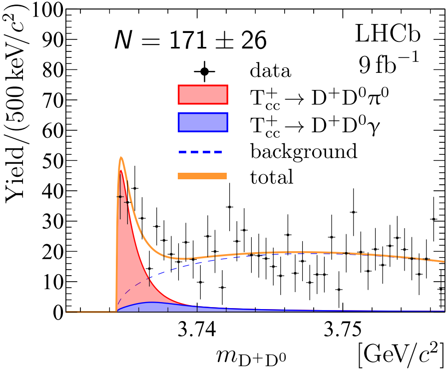
$\sim$ T_{cc}^+ **cannot live shorter than D^{*0}, $\tau_{T_{cc}^+}$ can be arbitrary large (uncoupled from continuum)**

? typical hadronic size of 1 fm.

Partially-reconstructed decays

Independent selection of the prompt $D^0 D^0$ and $D^+ D^0$ events.





- Lineshape of $D^0 D^0$ and $D^+ D^0$ spectra are predicted well by the model
- Relative yeilds of $D^0 D^0$ and $D^0 D^+$ is in good agreement with the model predictions

Isospin partners?

What if the T_{cc}^{+} is a part of the isospin-1 triplet

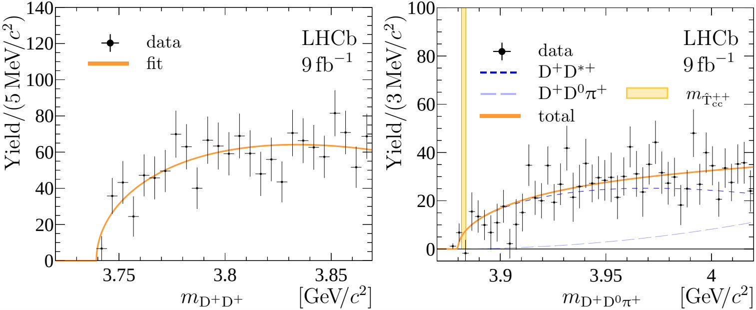
T_{cc}^{0} : $cc\bar{u}\bar{u}$

T_{cc}^{+} : $cc\bar{u}\bar{d}$

T_{cc}^{++} : $cc\bar{d}\bar{\tau}$ $\rightarrow D^{+}D^{*+}$

The partners should be roughly of the same mass, more precise

$$m_{T_{cc}^{++}} - (m_{D^{+}} + m_{D^{*+}}) = 2.7 \pm 1.3\,\text{MeV}(\text{using mass of } \Sigma_c^0, \Sigma_c^+, \Sigma_c^{++})$$

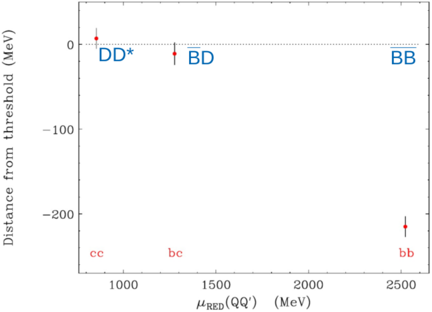


No indication of $I = 1$ family.

Do other hadrons of the $(QQ'qq')$ family exist?

- Exists? Now, we are sure they do, all of them.
- Can be observed? Certainly some. Some might be too broad.

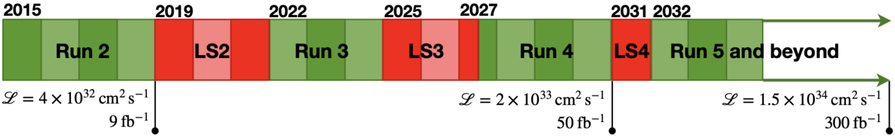
- $T_{bb}^{-}(bb\bar{u}\bar{d})$ are likely stable wrt QCD
- $T_{cb}^{0}(cb\bar{u}\bar{d})$ is either stable or almost, like T_{cc}^{+}
- ? Radial and orbital excitations of isoscalar T_{QQ}^{*}
- ? Isovector T_{QQ} and its family



[Karliner, Rosner (2017)]

Exotic hadrons in the future plans of LHCb

Major LHCb upgrade during LS2 is nearly finished



		P_c^+	T_{cc}^+
Run 1 (2011-2015) :	$+3\,\mathrm{fb}^{-1}$ @7 TeV	~ 100	~ 60
+Run 2 (2015-2019) :	$+6\,\mathrm{fb}^{-1}$ @13 TeV	$\sim 1.5k$	~ 200
+Run 3 (2022-2025) :			
+Run 4 (2027-2030) :	$+40\,\mathrm{fb}^{-1}$ @14 TeV	$> 8k$	$> 1k$

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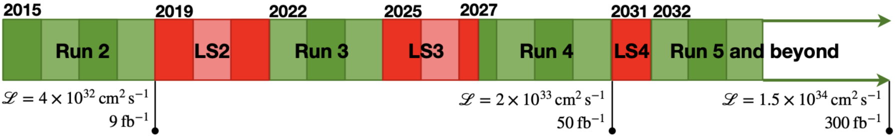

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Run 3 is about to start (2022):

- Same energy, but $\times 4$ intensity: $1.5 \to 5.5$ PV per $\times$-ing
- Uncertainty due to new tracking system, new software trigger

Optimistically, we will be doing 4 years in 1!