Doubly charmed tetraquark at LHCb

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LHCb Collaboration

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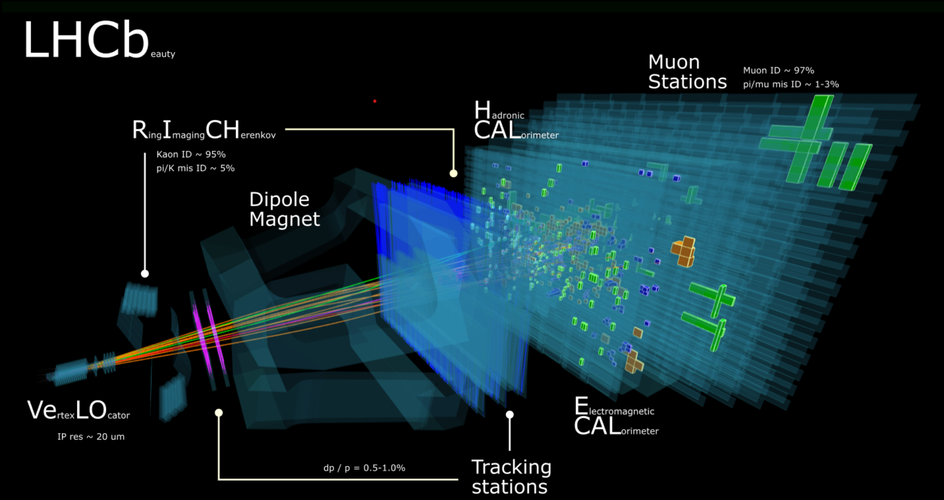
QWG @ Darmstadt

[display]

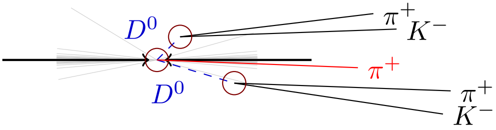


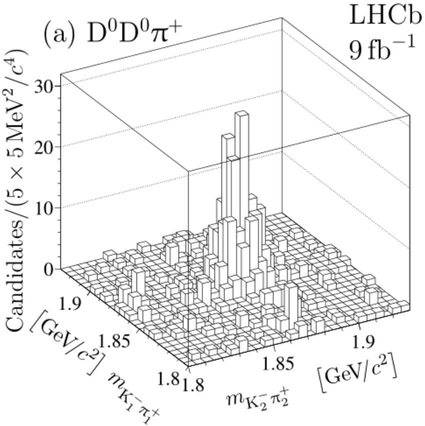
pp collider (7+7 TeV)

Observation of the T_{cc}^{+}

The landmark of 2021: a signal in $D^0D^0\pi^+$ [LHCb, NP 18 (2022)]

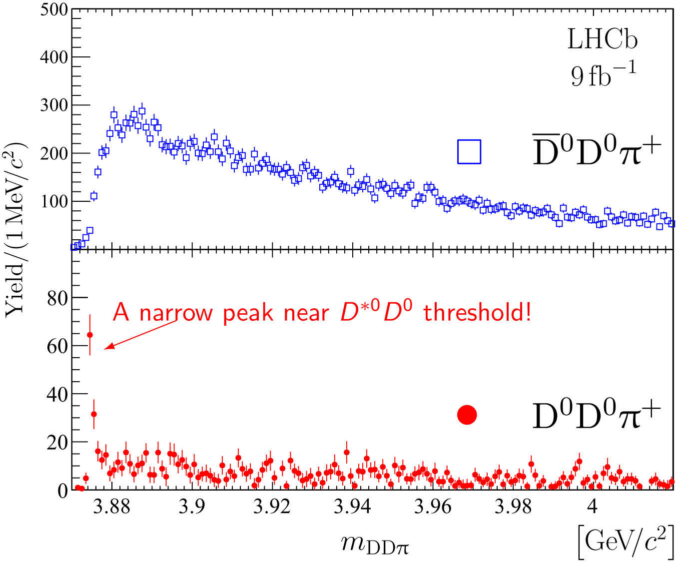
Event selection





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

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



Detailed spectrum and significance

[LHCb, NP 18 (2022) 751-754]

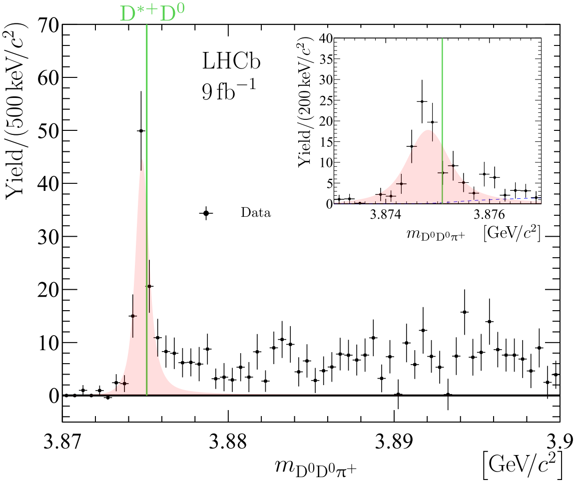
Breit-Wigner model

Too naive model

BW signal [$(DD)_S\,\pi$ P-wave]
+ ph.sp. background

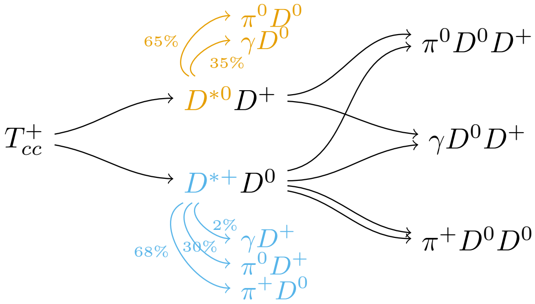
- significance $> 10\sigma$
- peak below (4.3σ)

Parameter	Value
N	117 ± 16
δm_{BW}	-273 ± 61 keV/c^2
Γ_{BW}	410 ± 165 keV



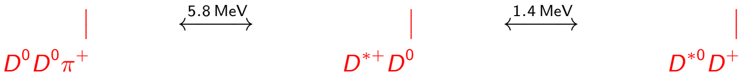
Fundamental properties? Need better model (D^*D threshold)

T_{cc}^{+} decay amplitude



Model assumptions:

- $J^P = 1^+$: S-wave decay to DD^*
- 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 $DD^* \to DD^*$ scattering:

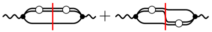
$$T_{2\times 2}(s) = \frac{K}{1-\Sigma K} = \frac{K(m^2-s)}{m^2 - s - i\, g^2\left(\rho_{\text{tot}}(s) + i\xi(s)\right)}$$

where K is the isoscalar potential:

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

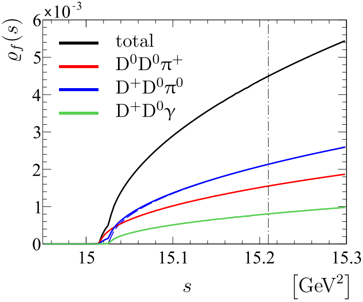
and Σ is the loop function:

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

$= [$  $]$.

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

D^* decays are accounted for.



The construction is guided by Unitarity and Analyticity.

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

Fit to the spectrum

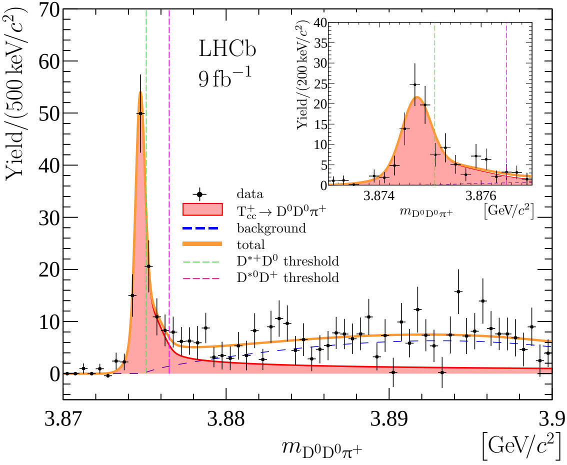
Unitarized model

[LHCb, NC 13 (2022) 3351]

- 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 shape 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)

δm_{U} with respect to $D^{*+}D^0$



Excellent agreement with the data. Reaction amplitude is fully fixed.

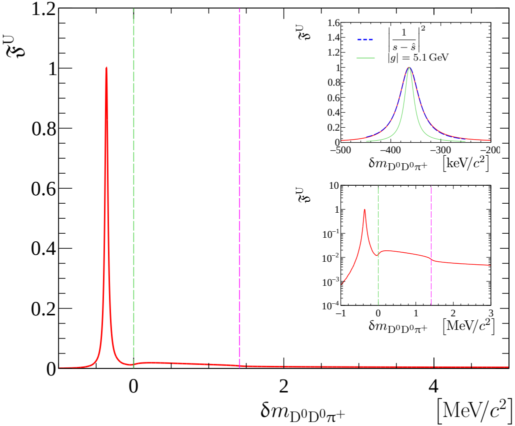
Predicted mass spectrum

[LHCb, NC 13 (2022) 3351]

The 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: $\tau \approx 10^{-20}\,s$.
  (Unprecedentedly large for exotic hadrons)



- Nearly-isolated resonance below the $D^{*+}D^0$ threshold
- Long tail with cusps at the $D^{*+}D^0$ and $D^{*0}D^+$ thresholds

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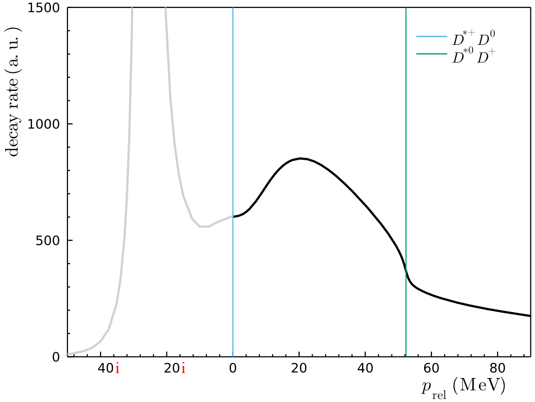


[MM, Tcc2DDpi.jl @ GitHub]

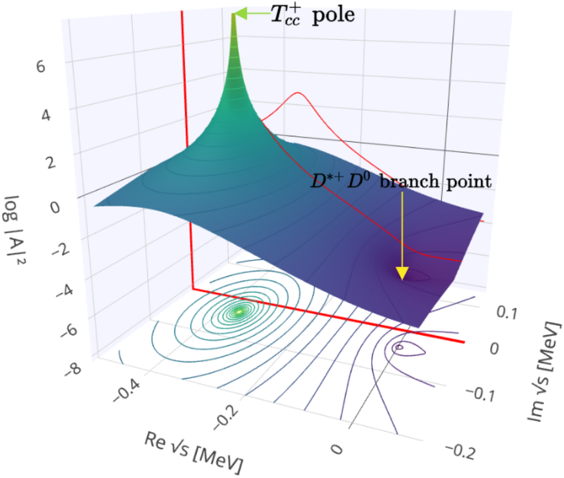
- Nearly-isolated resonance below the $D^{*+}D^{0}$ threshold
- Long tail with cusps at the $D^{*+}D^{0}$ and $D^{*0}D^{+}$ thresholds

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:

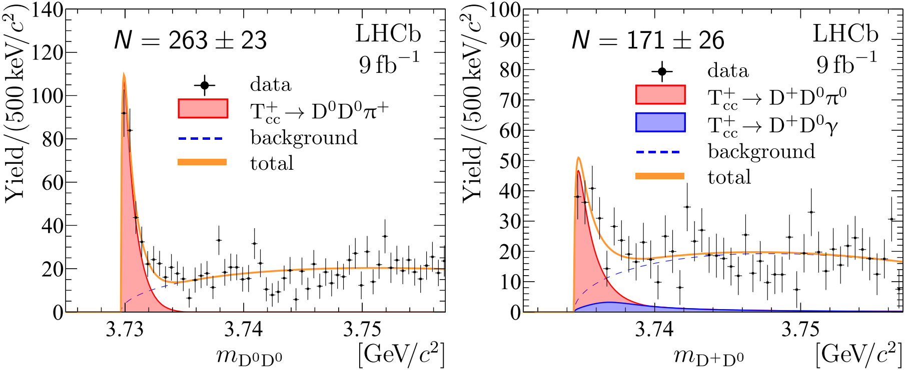
$$\delta m_{\text{pole}} = -360 \pm 40^{+4}_{-0}\,\text{keV}\,,$$

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

Partially-reconstructed decays

[LHCb, NC 13 (2022) 3351]

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?

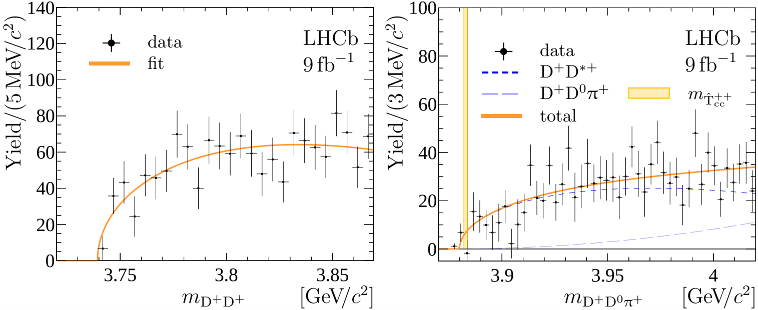
[LHCb, NC 13 (2022) 3351]

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

$$T_{cc}^{0}: \quad cc\bar{d}\bar{d}$$
$$T_{cc}^{+}: \quad cc\bar{u}\bar{d}$$
$$T_{cc}^{++}: \quad cc\bar{u}\bar{u} \qquad \to D^{+}D^{*+}$$

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

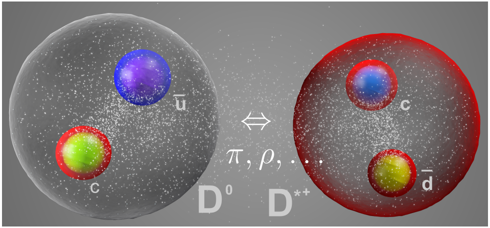
$$m_{T_{cc}^{++}} - (m_{D^{+}} + m_{D^{*+}}) = 2.7 \pm 1.3\,\mathrm{MeV}(\text{using mass of } \Sigma_c^0, \Sigma_c^+, \Sigma_c^{++})$$

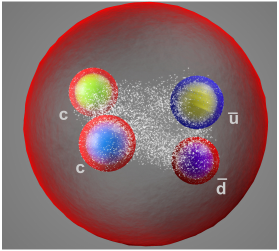


No indication of $I = 1$ family.

Interpretation

T_{cc}^{+} : Two extreme spatial configurations





Molecular configuration:

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

Compact configuration:

- genuine QCD state,
- compact (cc) core,
- there is no limit on lifetime, depends on how much it couples to continuum,
- ? typical hadronic size of 1 fm.

Effective range and Weinberg compositeness

Non-relativistic expansion near the threshold:

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

Scattering length, a

- a characteristic size of the state
- $a > 0$: moderate interaction
- $a < 0$: strong attraction forming a bound state

Effective range, r

- is the second order correction

! always positive in potential scattering

[Landau-Smorodinsky(1944), Esposito(2021)]

Weinberg compositeness: $X \equiv 1 - Z = \sqrt{\dfrac{1}{1 + 2r/a}}$

$X = 1$: composite (molecule) $\qquad X = 0$ elementary

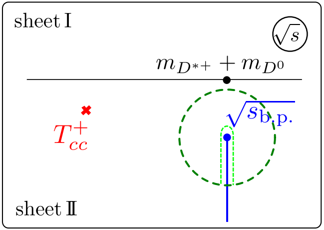
According to the Weinberg's compositeness,

- Any state coupled to continuum (i.e. can decay) has a molecule component
- Non-zero effective range is an indication of the compact component

Scattering parameters for the $D^{*+}D^0$ system [MM, 2203.04622]

$$\mathcal{A}^{-1}_{D^{*+}D^0 \to D^{*+}D^0} = N\left(\frac{1}{a} + r\frac{k^2_{D^{*+}D^0}}{2} + O(k^4_{D^{*+}D^0}) - ik_{D^{*+}D^0}\right)$$

Finite width of D^* shifts the **expansion point** to the complex plane to match the analytic structure.



For the nominal model:

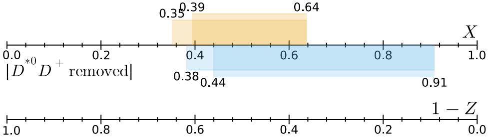
- Large scattering length, $\sim 6\,\mathrm{fm}$,

$$1/a = (-33 \pm 2) + (2 \pm 0.1)i\,\mathrm{MeV}\,,$$

- Negative CL for effective range:

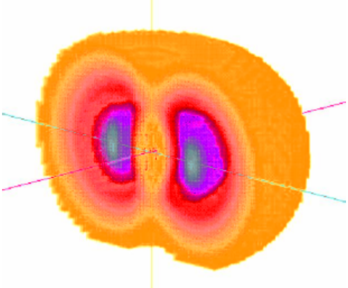
$$-16.2(-21.2) < \mathrm{Re}\,r < -4.3 \text{ at } 90(95)\%\text{ CL}\,.$$

- Large compositeness



Compare to what we know about deuteron [MM, 2203.04622]

Deuteron d^+ [Garcon, Van Orden(2001)]



- Presumably molecule
- Weinberg compositeness $X \approx 1$
- $R_{\text{charge}} = 2.1\,\text{fm}$
- $R_{\text{matter}} = 1.9\,\text{fm}$
- scatt.len. $a = -5.42\,\text{fm}$
- eff.range $r = 1.75\,\text{fm}$

Tetraquark T_{cc}^+

[?]

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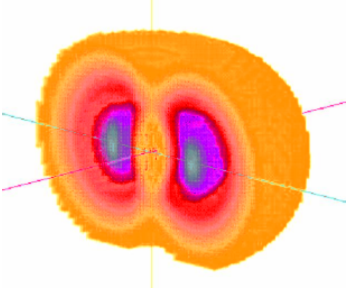

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Tetraquark T_{cc}^+

[?]

- Could well be "compact"
- $0.44 \le X \le 0.91$ at 90% CL
- $R_{\text{charge}} =??$
- $R_{\text{matter}} =??$
- $a = -5.54\,\text{fm}$
- $-16.2 < r < -4.3\,\text{fm}$ at 90% CL

More on the T_{cc}^{+} width

The natural **width** is the key observable of **compositeness**

- The peak position is well fixed, $\sim -400\,\mathrm{keV}$ below $D^{*+}D^{0}$
- effective range (or g) is the only shape parameter
- $g \to 0 \Rightarrow$ small compositeness (the natural width is zero)
- $g \to \infty \Rightarrow$ large compositeness ($\Gamma_{T_{cc}^{+}}$ goes to the **saturation limit**)
- How different $\Gamma_{T_{cc}^{+}}$ from the **saturation limit** determines the compositeness

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- How different $\Gamma_{T_{cc}^{+}}$ from the **saturation limit** determines the compositeness
- But what is this limit value?
  - 48 keV: not-iterated OPE (LHCb model) [LHCb, NC 13 (2022) 3351]
  - 30 keV: no OPE at all [MM, Tcc2DDpi.jl @ GitHub]
  - 75 keV: in two-body approximation [Albaladejo, M. (2021)]
  - 56 keV: with all three-body effects [Meng-Lin Du et al. (2021)]

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  - 56 keV: with all three-body effects [Meng-Lin Du et al. (2021)]
- Experimentally: the fit pushes the width to higher values.
  - Low limit in the default model, $\Gamma_{T_{cc}^+} > 20\,\text{keV}$ at 95% CL.
  - BW model: the fit with the free-parameter width gives $410 \pm 165\,\text{keV}$.

A plausible model

Warning: my personal choice among many competing interpretations

Non-relativistic quark model. T_{cc}^{+} wave function

- Solve Heisenberg equation. Interaction between **every pair** of quarks

$$H = \sum_i \left(m_i + \frac{p^2}{2m_i}\right) - \frac{3}{16}\sum_{i<j} v_{ij}(r_{ij}), \text{ with } r_{ij} = |\vec{r}_i - \vec{r}_j|$$

- Different variants for potential are used ("Bhaduri" and "Grenoble")

$$v_{ij}^{(\text{Bhaduri})}(r_{ij}) = \overbrace{\tilde{\lambda}_i^C \tilde{\lambda}_j^C}^{\text{color}} \left[\Lambda - \underbrace{\frac{\kappa}{r}}_{\text{Columnb}} + \underbrace{\lambda r}_{\text{confinement}} + \underbrace{\frac{\kappa}{m_i m_j} \frac{\exp(-r/r_0)}{r r_0^2} \sigma_i \sigma_j}_{\text{spin-spin interaction}}\right],$$

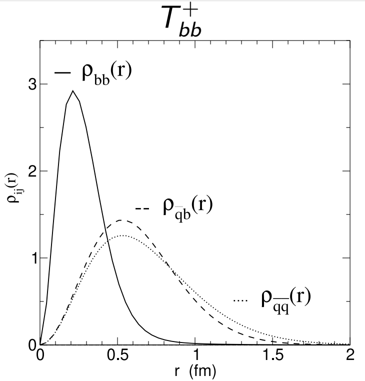
with parameters adjusted by fit to conv. states.

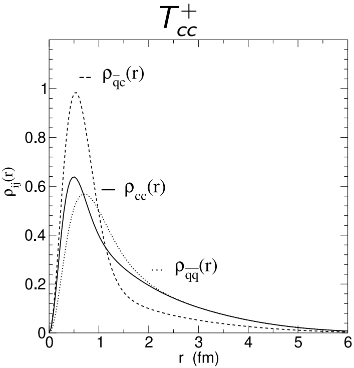
- T_{bb}^{+} is bound well below the lowest threshold. Stable (bb) in triplet, $J_{(bb)} = 1$.
- T_{cc}^{+} is near the threshold: (cc) in (sixt.), $J_{(cc)} = 0, 1$.
  - $\delta m \in \{-1, 0, 11, 13\}$ MeV [Semay, Silvestre-Brac (1993)]
  - $\delta m \in \{-2.7, -0.6\}$ MeV [Janc, Rosina (2004)]

Distributions of QQ component

[Janc, Rosina, FBS35 (2004)]

- Matter wave function: ρ_{QQ} shows how close QQ together
- Color wave function: $3 \otimes 3 = \bar{3} \oplus 6$
  - compact (QQ) is in triplet $\sim \bar{Q}$.
  - $(\mathrm{Meson}_Q\ \mathrm{Meson}_Q)$ has QQ in sixtet





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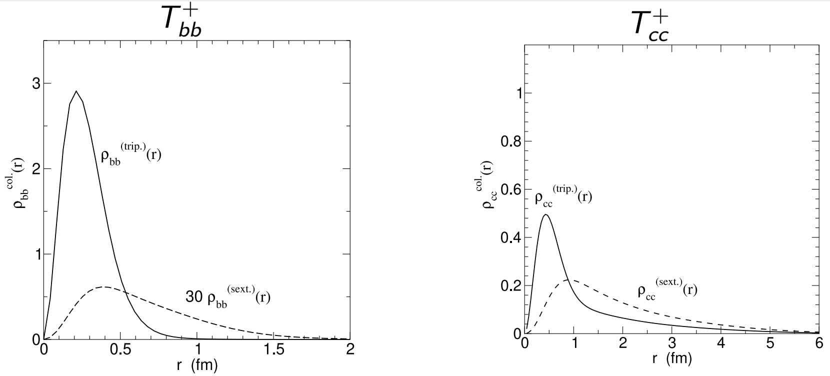

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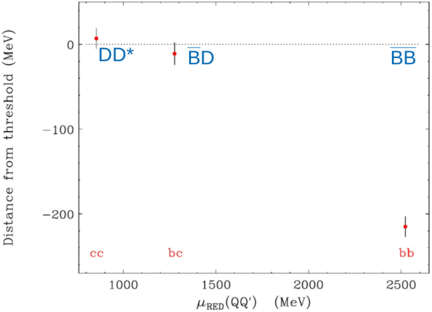
Do other hadrons of the $(QQ'qq')$ family exist?

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

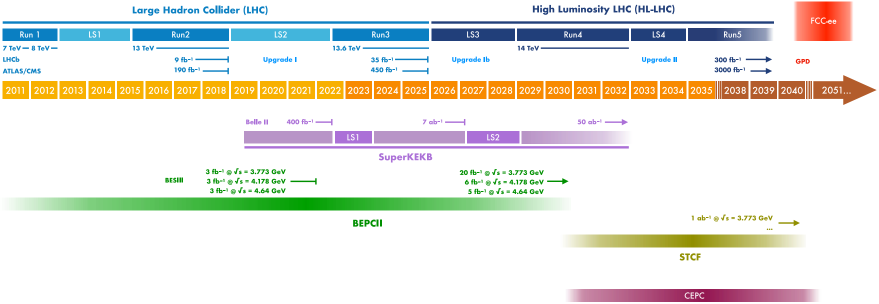
- $T^+_{bb}(bb\bar{u}\bar{d})$ are likely **stable** with respect to QCD
- $T^+_{cb}(cb\bar{u}\bar{d})$ is either stable or almost
- ? Radial and orbital excitations of isoscalar T^*_{QQ}
- ? Isovector T_{QQ} and its family



[Karliner, Rosner (2017)]

Updated timeline for LHC

[W. Altmannshofer, F. Archilli, arXiv:2206.11331]



LHCb:

- ramping up after major Upgrade I
- $\times 5$ statistics in Run 3(2023-2025) @13.6 TeV + Run 4(2029-2032) @14 TeV

Summary

- We observed a clear evidence that QCD is richer than $(q\bar{q})$ and (qqq).
- There is a zoo of exotic hadrons: compact multiquark states, molecule!

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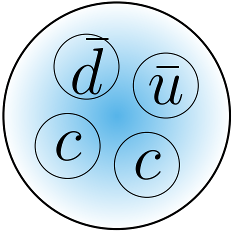

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- Almost stable with respect to the strong interaction
- Supports existence of stable(!) T_{bb}^{-}

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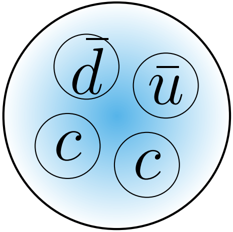

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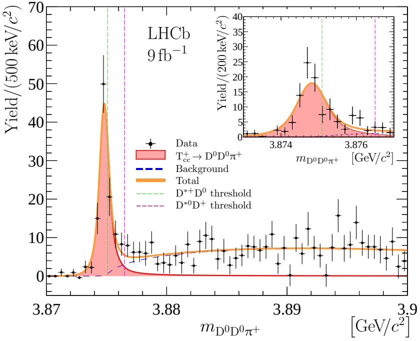
More results to come!

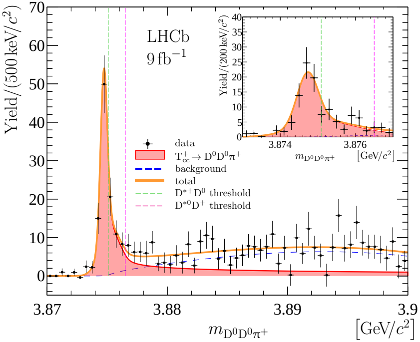
Two models

Naive model is of similar quality but yeilds incorrect parameters

Naive model ($\Gamma_{BW} = 410 \pm 165\,\text{MeV}$)



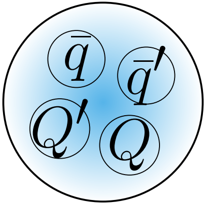
Complete model
($\Gamma_{pole} = 48 \pm 2^{+0}_{-14}$ MeV)



The reason: background and resolution. Confirmed by MC studies.

Predictions of $T_{QQ'}$

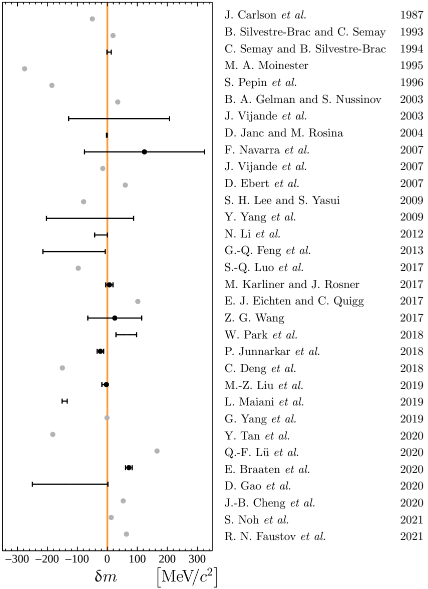
Anticipated open-flavor exotic hadron



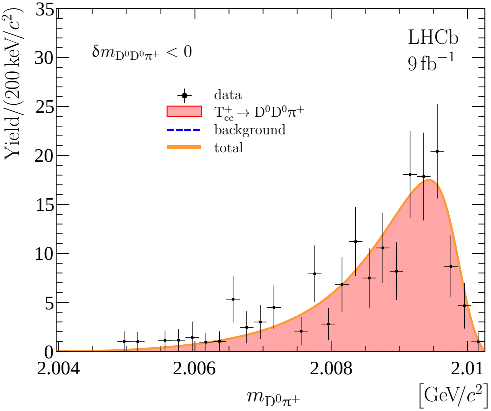
- Ground state: $(QQ'\bar{u}\bar{d})$, $J^P = 1^+$, isospin 0
- Exists?
  - T_{bb}^-: most theorists believe that it exists.
  - T_{cc}^+: there was no consensus

Mass of T_{cc}^+

$\delta m_{\mathrm{U}} = -359 \pm 40\,^{+9}_{-6}\,\mathrm{keV}/c^2$



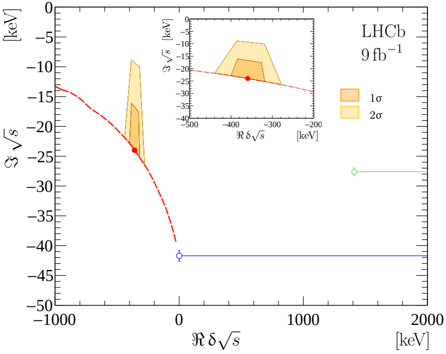
Does T_{cc}^{+} decay via off-shell D^*?

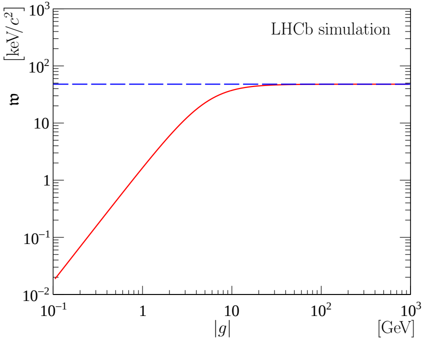


- Peak at high mass requires D^* propagator
- P-wave behavior on the left limit
- S-wave behavior on the right limit

Width saturation

Complex plane





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