New results from LHCb

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on behalf of LHCb collaboration

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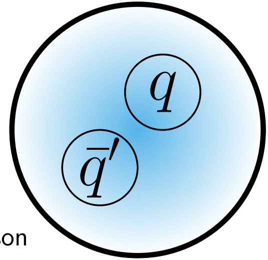
Joint Physics Analysis Center

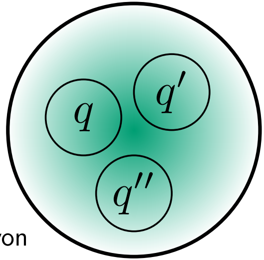
October 25st, 2021
Showmass RF7

Image credit: Samuel Velasco / Quanta Magazines

Conventional hadrons

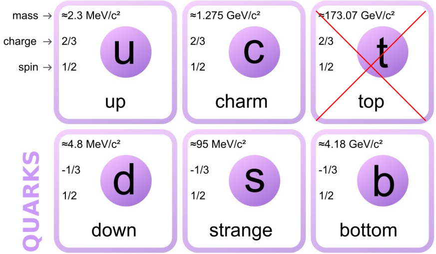


meson



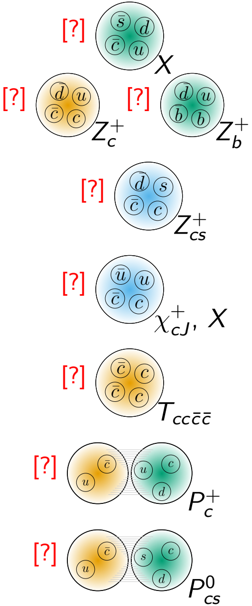
baryon

$\otimes$



$\Rightarrow \sim$ 10 classes (+excitations) of mesons and
$\sim$ 20 classes (+excitations) of baryons

Growing evidence of exotic states



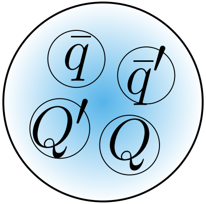
- All but one with hidden flavor: $(c\bar{c})$ or $(b\bar{b})$
- Complex discovery, controversial interpretation

States
$X_0(2900)$, $X_1(2900)$ [22,23]
$\chi_{c1}(3872)$ [7]
$Z_c(3900)$ [24], $Z_c(4020)$ [25,26], $Z_c(4050)$ [27], $X(4100)$ [28], $Z_c(420$ [29], $Z_c(4430)$ [30,31,32,33], $R_{c0}(4240)$ [32]
$Z_{cs}(3985)$ [34], $Z_{cs}(4000)$, $Z_{cs}(4220)$ [35]
$\chi_{c1}(4140)$ [36,37,38,39], $\chi_{c1}(4274)$, $\chi_{c0}(4500)$, $\chi_{c0}(4700)$ [39 $X(4630)$, $X(4685)$ [35], $X(4740)$ [40]
$X(6900)$ [15]
$Z_b(10610)$, $Z_b(10650)$ [41]
$P_c(4312)$ [42], $P_c(4380)$ [43], $P_c(4440)$, $P_c(4457)$ [42], $P_c(4357)$ [44]
$P_{cs}(4459)$ [45]

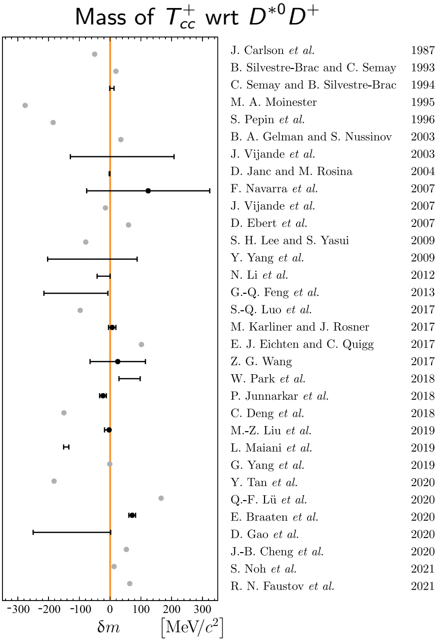
Milestones: 1) **X**YZ 2) P_c^+ 3) T_{cc}^+

Meet $T_{QQ'}$: new class

"hypothetical" before August 2021



- Ground state: $(QQ'\bar{u}\bar{d})$, $J^P = 1^+$, isospin 0
- Exists?
  - T_{bb}^-: most theorists believe that it exists.
  - T_{cc}^+: no consensus
- in experiment: it does not exist before observed

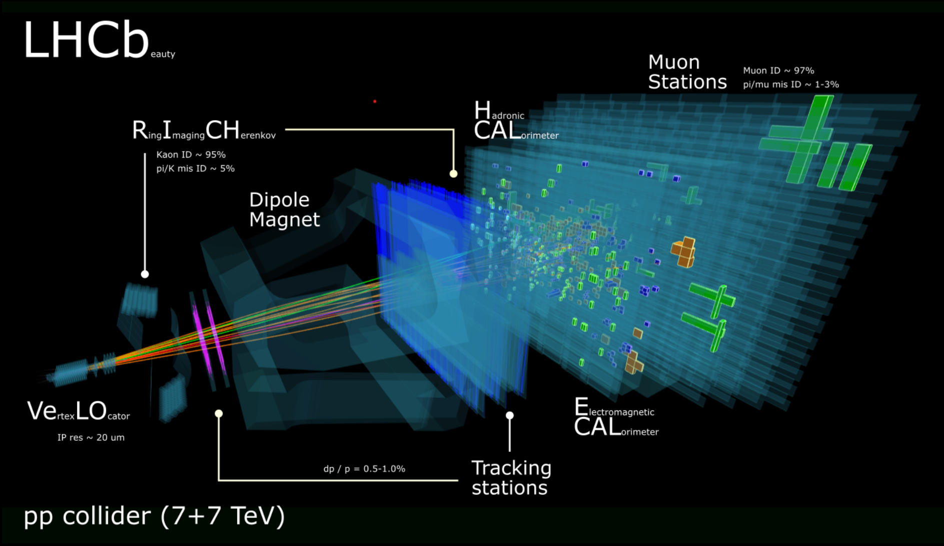


Observation of T_{cc}^{+}

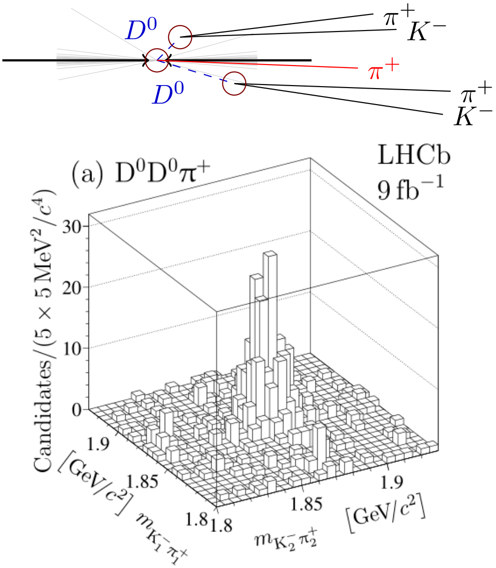
[LHCb, arXiv:2109.01038]

[Image: Maximilien Brice/CERN]

[display]

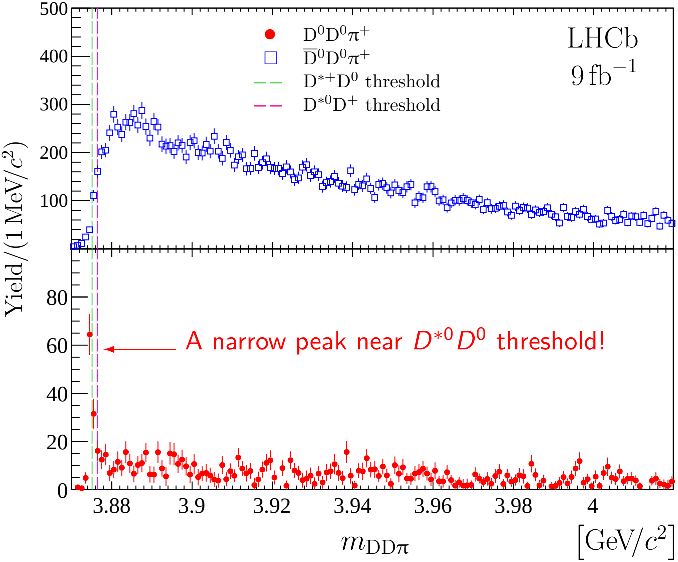

LHCb eauty
Muon Stations
Muon ID ~ 97%
pi/mu mis ID ~ 1-3%
RingImagingCHerenkov
Kaon ID ~ 95%
pi/K mis ID ~ 5%
Hadronic CALorimeter
Dipole Magnet
VertexLOcator
IP res ~ 20 um
Electromagnetic CALorimeter
dp / p = 0.5-1.0%
Tracking stations
pp collider (7+7 TeV)

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 $D^0 \bar{D}^0 \pi^+$



Spectrum fit and significance

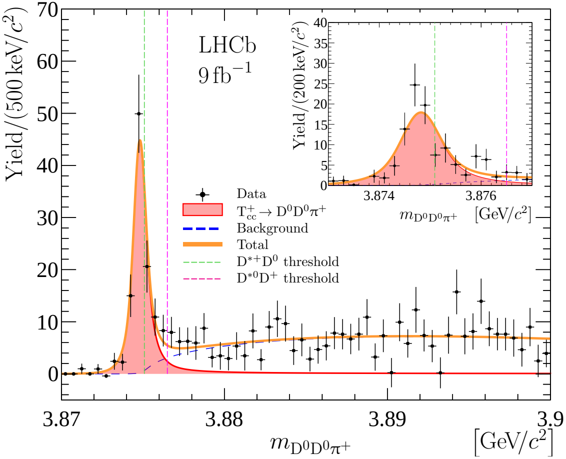
Breit-Wigner model

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
$\delta m_{\rm BW}$	-273 ± 61 keV/c^2
$\Gamma_{\rm BW}$	410 ± 165 keV

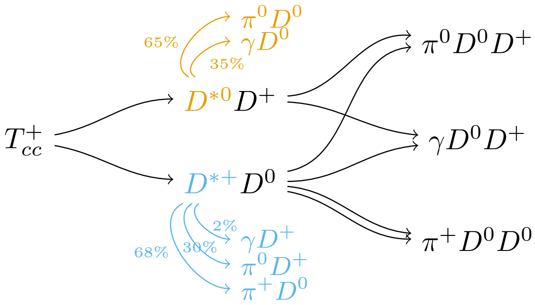


Fundamental properties? Need better model (D^*D threshold)

Extracting T_{cc}^{+} parameters

[LHCb, arXiv:2109.01056]

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:

$$T_{2\times2}(s) = K + K\,\Sigma\,K + K\,\Sigma\;K\,\Sigma\,K + \dots$$

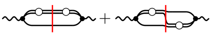
where K is the isoscalar potential:

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

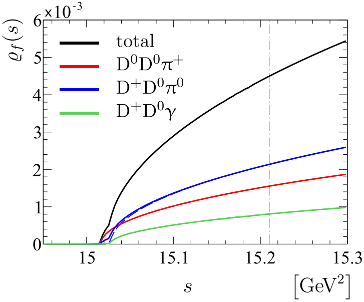
and Σ is the loop function:

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

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



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



D^* decays are accounted for.

Unitarity and Analyticity principles are fulfilled.

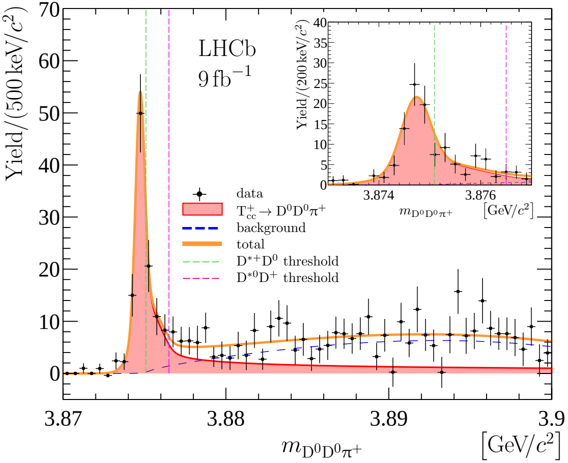
Model parameters: $|g|^2$ **and** m^2 **– bare mass and coupling**

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)



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

Predicted mass spectrum

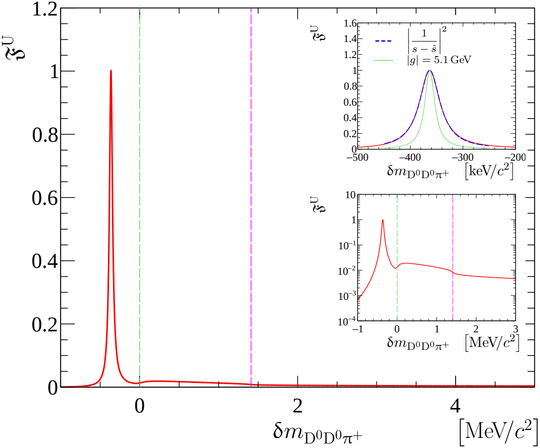
resolution removed

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)



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

Fundamental resonance parameters [interactive]

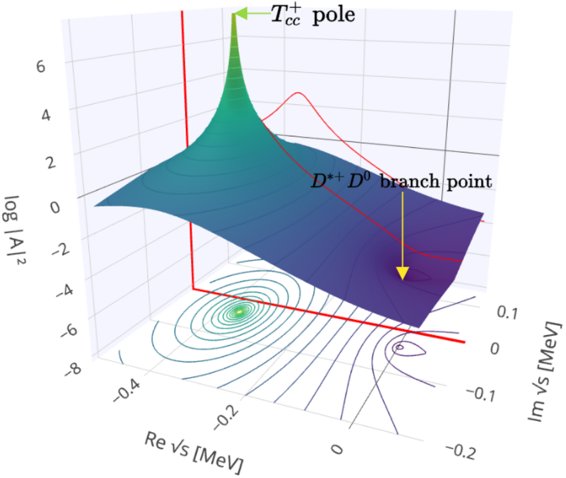
Mass and width – position of the complex pole of the reaction amplitude

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

The pole parameters:

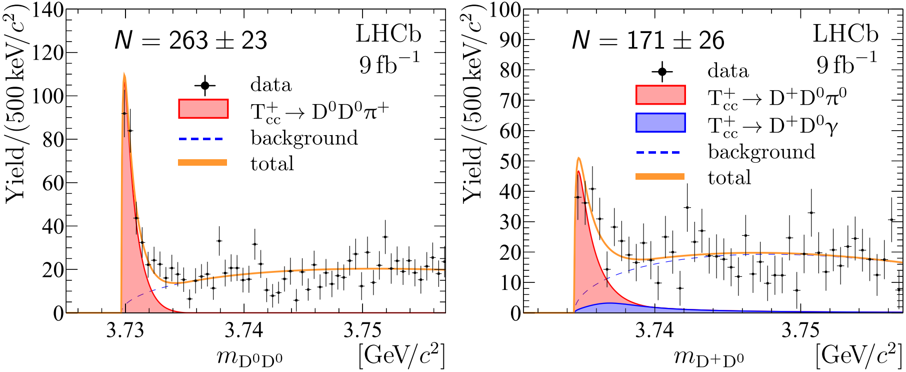
$$\delta m_{\text{pole}} = -360 \pm 40^{+4}_{-0}\,\text{keV}\,,$$

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



Partially-reconstructed decays

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

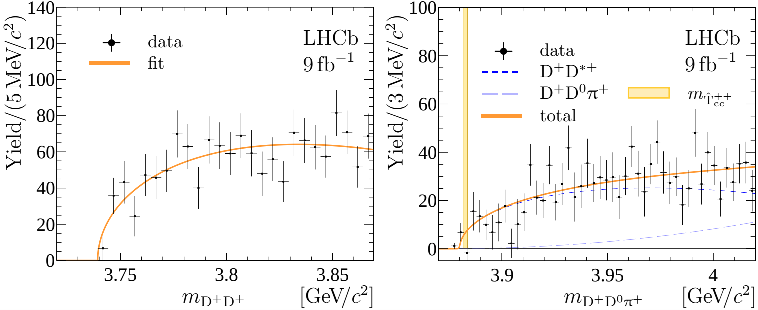
Isospin partners?

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

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

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

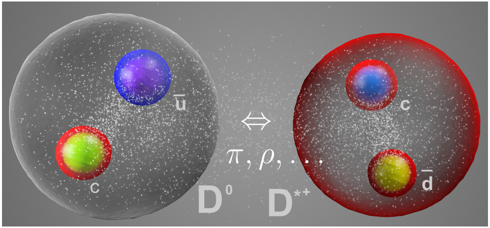
$$m_{T_{cc}^{++}} - (m_{D^+} + m_{D^{*+}}) = 2.7 \pm 1.3\,\text{MeV}(\text{using mass of } \Sigma_c^0, \Sigma_c^+, \Sigma_c^+ +)$$

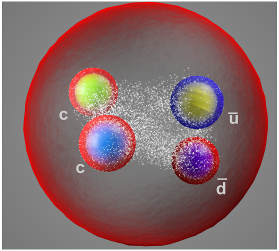


No indication of $I = 1$ family.

Interpretation

Two extreme spatial configurations





"Molecule" configuration:

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

? spatially-extended object.

"Atomic" configuration:

- genuine QCD state,
- bound by naked color forces
- lifetime low limit is set by $\tau(D^{*0})$, 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:

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

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)]

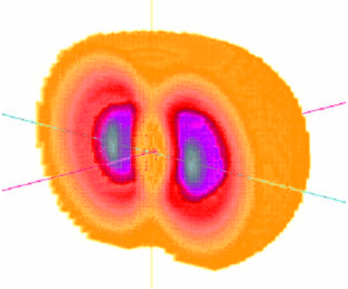
Weinberg compositeness: $1 - Z = \sqrt{\dfrac{1}{1 + 2r/\Re a}}$

$1 - Z = 1$: composite (molecule) $\quad$ $1 - Z = 0$ elementary

- T_{cc}^{+}: $a = (-7.16 \pm 0.51) + i(1.85 \pm 0.28)\,\text{fm}$
- T_{cc}^{+}: r is negative in the model: $0 < -r < 11.9(16.9)\,\text{fm}$ at $90(95)\,\%\,\text{CL}$
- T_{cc}^{+}: $1 - Z > 0.48(0.42)$: not-entirely elementary, well

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

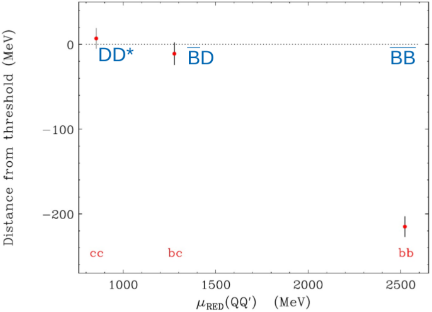
Do other hadrons of the $(QQ'qq')$ family exist?

- 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}^{*}

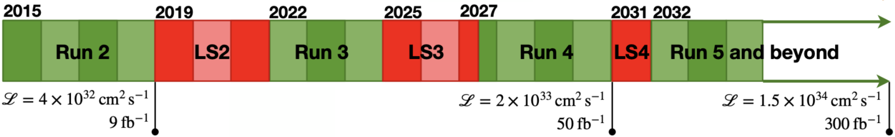
? Isovector T_{QQ} and its family



[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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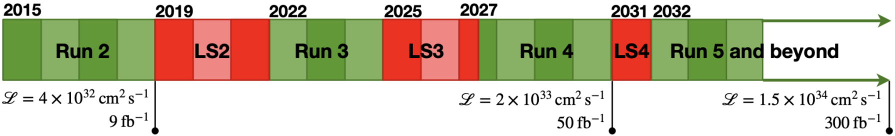

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+Run 3 (2022-2025) :			
+Run 4 (2027-2030) :	$+40\,\mathrm{fb}^{-1}$ @14 TeV	$> 8k$	$> 1k$

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!

Observation of T_{cb}^{0}, T_{bb}^{-}

Based on Steve Blusk estimation [Tcc & beyond workshop]

$$N_{\text{signal}} = \overbrace{\mathcal{L}}^{\text{luminosity}} \times \underbrace{\sigma_{\text{prod}}}_{\text{cross section}} \times \overbrace{\text{Br}}^{T_{QQ}\to B(D)B(D)} \times \prod \underbrace{\text{Br}}_{B/D\text{ decays}} \times \overbrace{\varepsilon}^{\text{efficiency}}$$

Observation of T^0_{cb}, T^-_{bb}

Based on Steve Blusk estimation [Tcc & beyond workshop]

$$N_{\text{signal}} = \overbrace{\mathcal{L}}^{\text{luminosity}} \times \underbrace{\sigma_{\text{prod}}}_{\text{cross section}} \times \overbrace{\text{Br}}^{T_{QQ}\to B(D)B(D)} \times \prod \underbrace{\text{Br}}_{B/D\text{ decays}} \times \overbrace{\varepsilon}^{\text{efficiency}}$$

$$\varepsilon(D^+)\varepsilon(D^{*+}) \approx 0.08$$
$$\varepsilon(D^0 \to K^-\pi^+) \approx 0.17$$

$$\epsilon(B^-) \approx 0.1$$

Observation of T_{cb}^0, T_{bb}^-

Based on Steve Blusk estimation [Tcc & beyond workshop]

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$$\varepsilon(D^+)\varepsilon(D^{*+}) \approx 0.08$$
$$\varepsilon(D^0 \to K^-\pi^+) \approx 0.17$$

$$\epsilon(B^-) \approx 0.1$$

Observing T_{cb}^0

- Cross-section: $\sigma \approx 100\,\text{nb}$

  [Ali et al., PLB785 (2018) 605]
- Rough expectations with $50\,\text{fb}^{-1}$ (by 2030):
  - Strong decay

$N_{\text{signal}}(T_{cb}^0 \to B^- D^+) \sim 300$

  - Weak decay

$N_{\text{signal}}(T_{cb}^0 \to J/\psi D^+ K^-) \sim 7k$

Observing T_{bb}^-

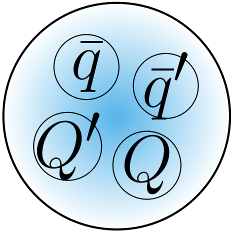
- Cross-section: $\sigma \approx 1\,\text{nb}$
- lifetime: $\tau \approx 0.6\,\text{ps} - 7.6\text{ps}$

  [Agaev et al., EPJA 56, 177 (2020)]

  [Hernandez et al., PLB800, 135073 (2020)]]
- Rough expectations with $50\,\text{fb}^{-1}$ (by 2030):
  - Weak decay

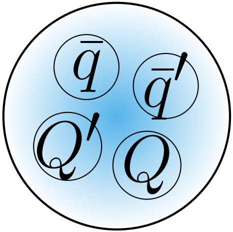
$N_{\text{signal}}(T_{bb}^0 \to B_c^- D^+ K^-) \sim 0.2$

Summary



- T_{cc}^{+} is the first representee of $(QQ'\bar{q}\bar{q}')$ hadrons
- Undoubted proof of hadrons beyond conventional $(q\bar{q})$ and (qqq) scheme
- Almost stable with respect to the strong interaction

Summary



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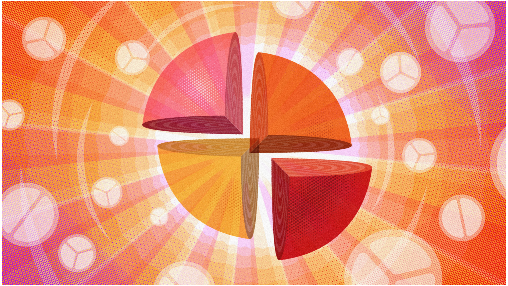
Outlook

- Model assumption are consistent with the data, but need to be proven:
  - Accurate accouning for three-body effects
  - Dalitz-plot analysis and test of J^P
- Analysis of the production cross sections

Remarks

- Two papers are submitted to a good journal
- Wide interest in media
  - $>$ 150 media citations in Russian
  - $>$ 20 in English
  - a few in German, Brazilian, Hebrew, Vietnamese, Turkish, ...
- Publicly available code to build the model in `Julia`



[QuantaMagazine [link]]

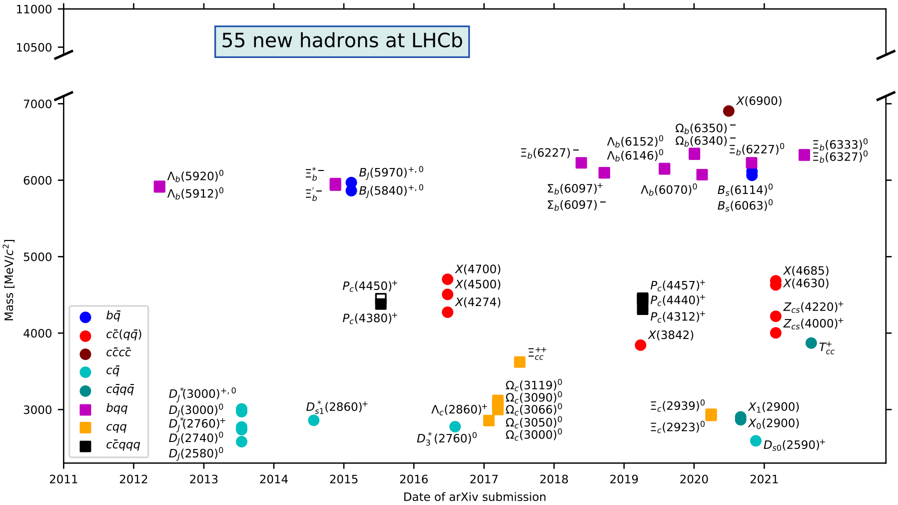
חלקיק תת־אטומי חדש התגלה במאיץ החלקיקים בשווייץ

זמן החיים של החלקיק ארוך משמעותית מאלה שהיו מוכרים עד כה. הגילוי מספק עדות עקיפה חזקה לקיומו של חומר יציב מסוג חדש

גדעון לב

[Haaretz [link]]

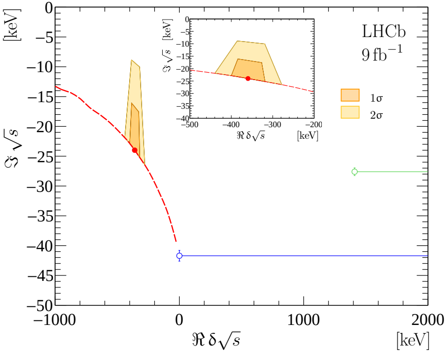
New hadrons observed at LHCb

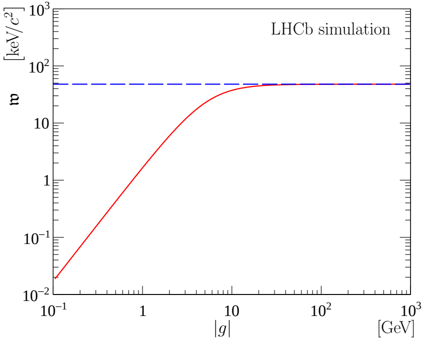


Thank you for the attention

Width saturation

Complex plane

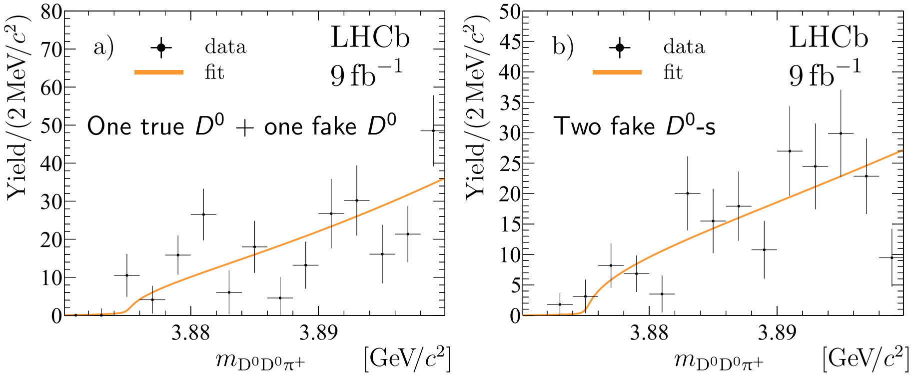




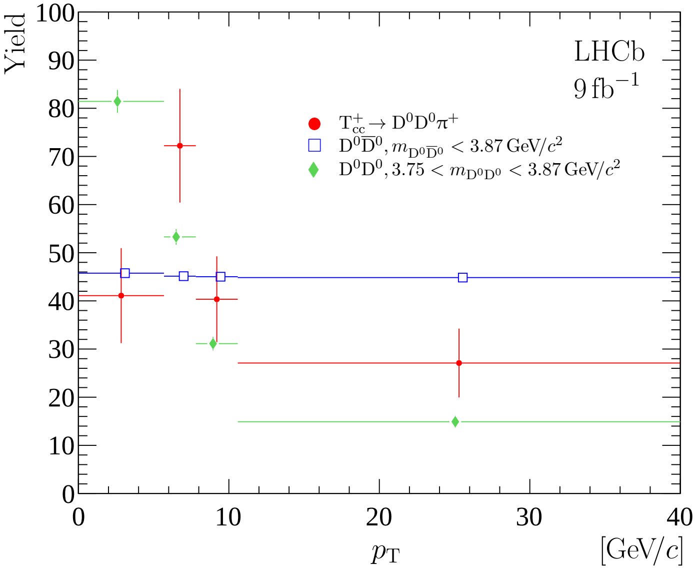
- The D^* width gives the limit to T_{cc}^+ width, $< \Gamma_{T_{cc}^+}^{(\max)}$
- Parameter $|g|$ sets the value in the range $[0, \Gamma_{T_{cc}^+}^{(\max)}]$
- The fit prefers the limit value

Cross-checks

- Different years (2011-2018)
- Different data-taking conditions (magner polarity)
- No signal when using fake D^0

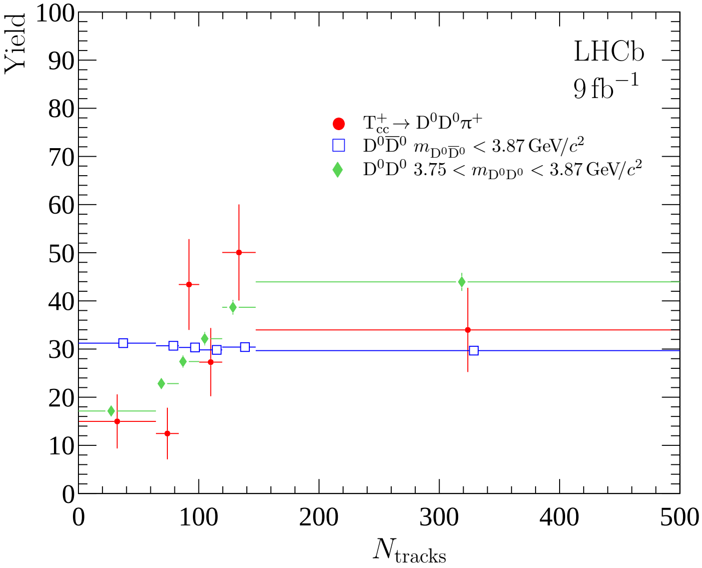


p_t spectrum for T_{cc}^{+}



Multiplicity dependence of T_{cc}^{+} yeild

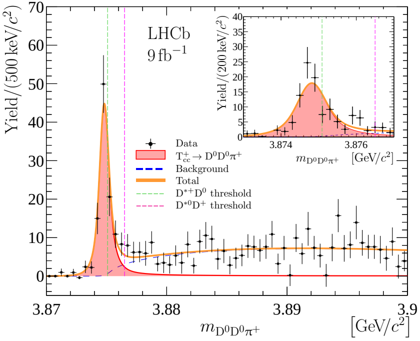
Surprisingly similar to uncorrelated $D^0 D^0$ production (DPS)



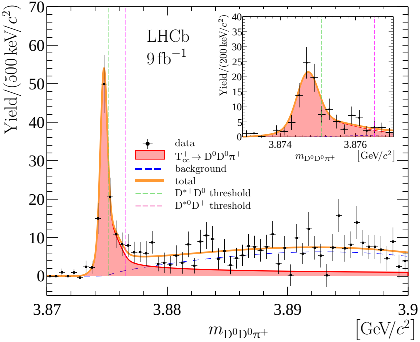
Two models

Naive model is of similar quality but yeilds incorrect parameters

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



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



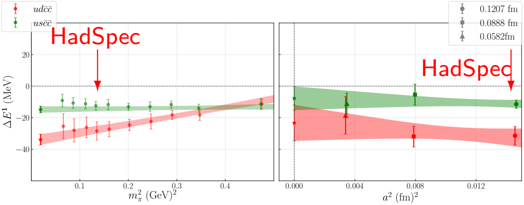
The reason: background and resolution. Confirmed by MC studies.

Lattice QCD

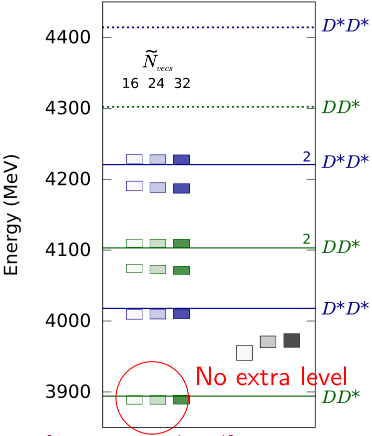
First-principles theoretical (numerical) approach to QCD.

Several calculations are done. The situation is puzzling

- HAL QCD Collaboration (2014): attraction but **no binding**
- Hadron Spectrum Collaboration (2017): **no binding**
- Junnarkar et al. (2018): $-23 \pm 11\,\text{MeV}$ **binding**

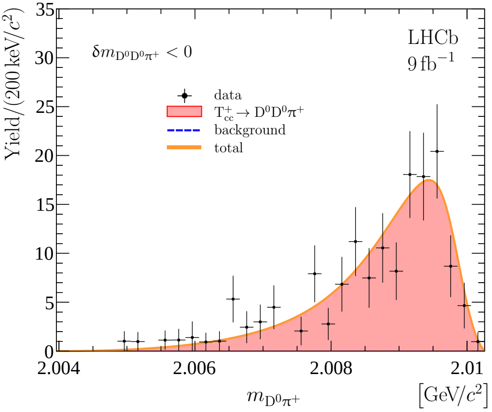


[Junnarkar et al. (2018)]



[Cheung et al., (2017)]

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

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

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

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

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

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

with parameters adjusted by fit to conv. states.

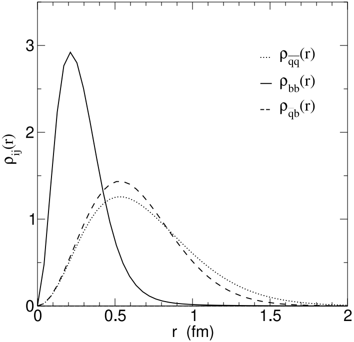
- T_{bb}^{-} is bound well below the lowest threshold. Stable (bb) in triplet, $J_{(bb)} = 1$.
- T_{cc}^{+} is near the threshold: (cc) in (sixt.), $J_{(cc)} = 0, 1$.
  - $\delta m \in \{-1, 0, 11, 13\}$ MeV [Semay, Silvestre-Brac (1993)]
  - $\delta m \in \{-2.7, -0.6\}$ MeV [Janc, Rosina (2004)]

Distributions of QQ component

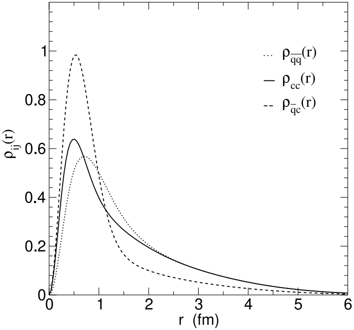
[[Janc, Rosina (2004)]]

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

T^+_{bb}



T^+_{cc}



T^+_{bb} looks atomic like Λ_b, while T^+_{cc} has large $D\bar{D}^*$ component

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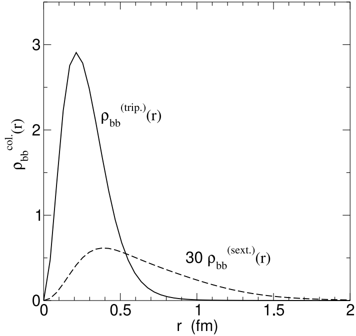
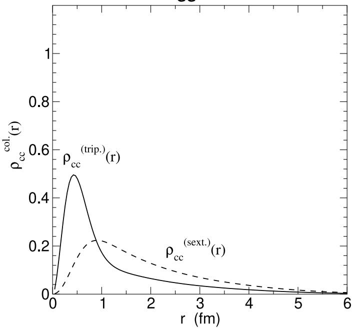
T^+_{bb}



T^+_{cc}



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