Exceptionally charming tetraquark T_{cc}^{+}

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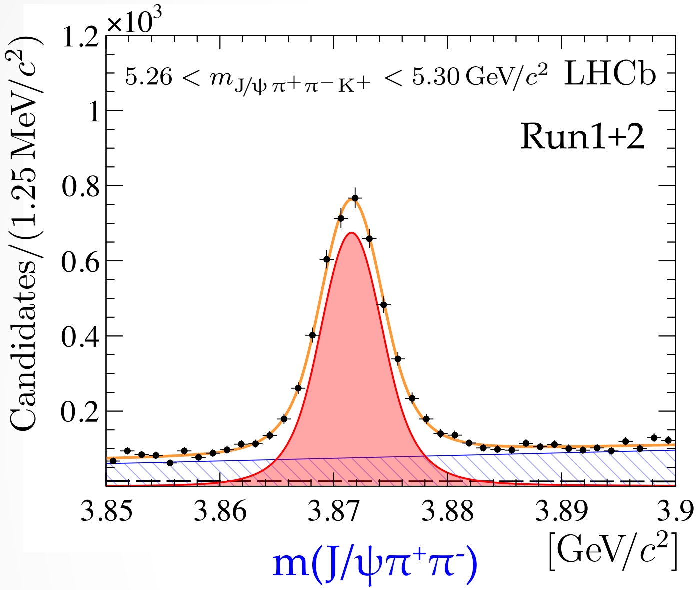
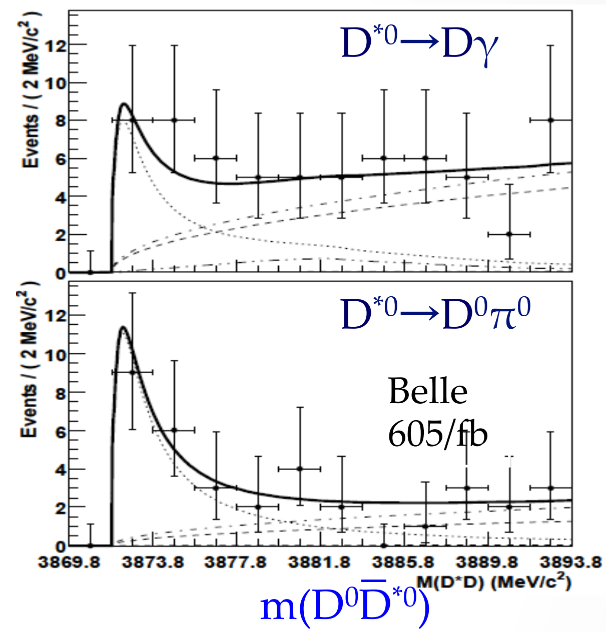
Outline

- Motivations & predictions for $QQ\bar{q}\bar{q}$ states
- Experimental observation of $T_{cc}^{+} \rightarrow D^0 D^{*+}$
- Studies of the T_{cc}^{+} properties

Golden Age of spectroscopy: beginning

- 2003: Belle observes $X(3872)\rightarrow J/\psi\pi^+\pi^-$ Belle PRL91 262001 (2003)

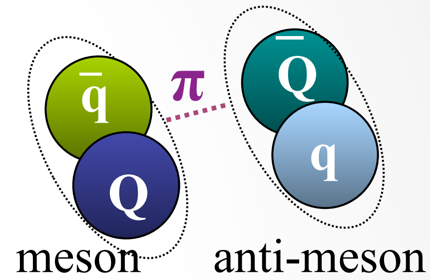




- $\Gamma_{BW}(X) = 0.96 \pm 0.19 \pm 0.20$ MeV LHCb JHEP08 123 (2020)
- $m(X) = 3871.59 \pm 0.06 \pm 0.03 \pm 0.01$ MeV $\cong m_{D0}+m_{D^{*0}}$
- Below/above $D\bar{D}^*$ threshold? bound/virtual state?
- 10×larger BF of $X(3872)\rightarrow D^0\bar{D}^{*0}$ Belle PRD81 031103 (2010)
- Charmonium assignment: $\chi_{c1}(2P)$ [based on $J^{PC}=1^{++}$ and mass]
- Most likely a mixture of $c\bar{c}$ and $D\bar{D}^*$ molecule

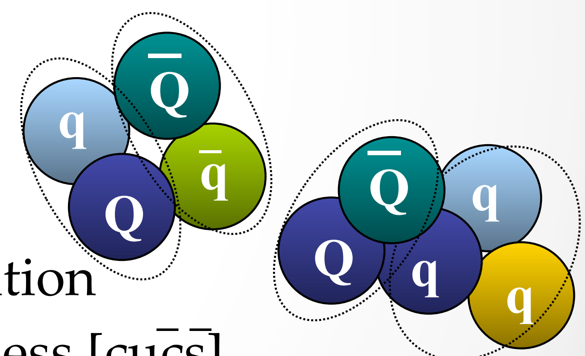
Conventional and exotic particles

- Quark Model by Gell-Mann and Zweig (1964):
  mesons and baryons = conventional states
  States more complex = exotics also predicted



- **Molecule**

Meson-antimeson loosely bound by pion exchange
Mass ≈ sum of meson masses
Decay: dissociation into constituent particles

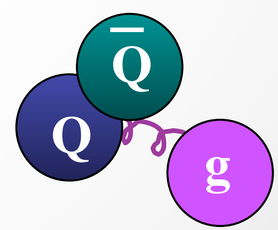


- **Tetraquark, pentaquark**

Quarks tightly bound by gluon exchange
Decay: rearrange into mesons/baryons ⇨ dissociation
Can have non-zero charge $[cu\bar{c}\bar{d}]$ and/or strangeness $[cu\bar{c}\bar{s}]$

- **Hybrid**: $Q\bar{Q}$ + constituent excited gluons

Can have exotic J^{PC} : 0^{+-}, 1^{-+}, 2^{+-}…
Large widths for hadronic transitions ($\psi\pi\pi$, $\psi\omega$)



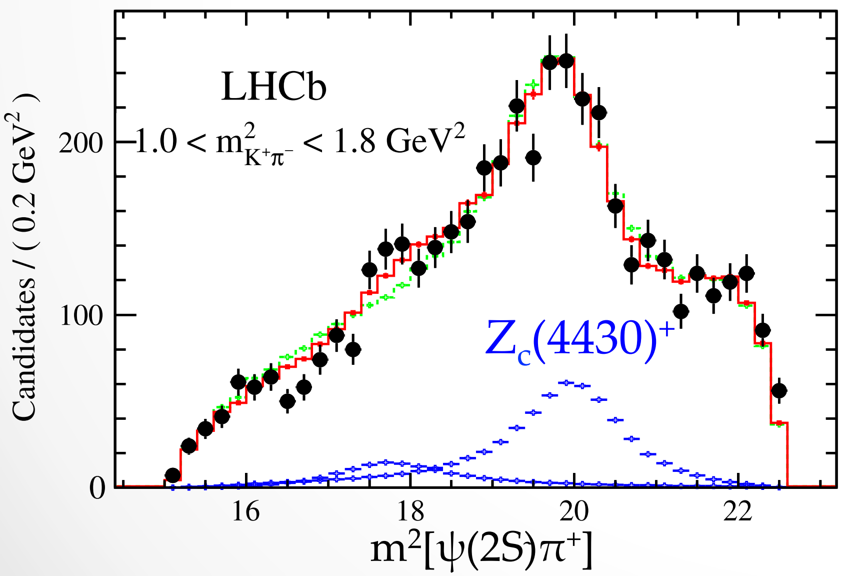
Golden Age of spectroscopy: exotics

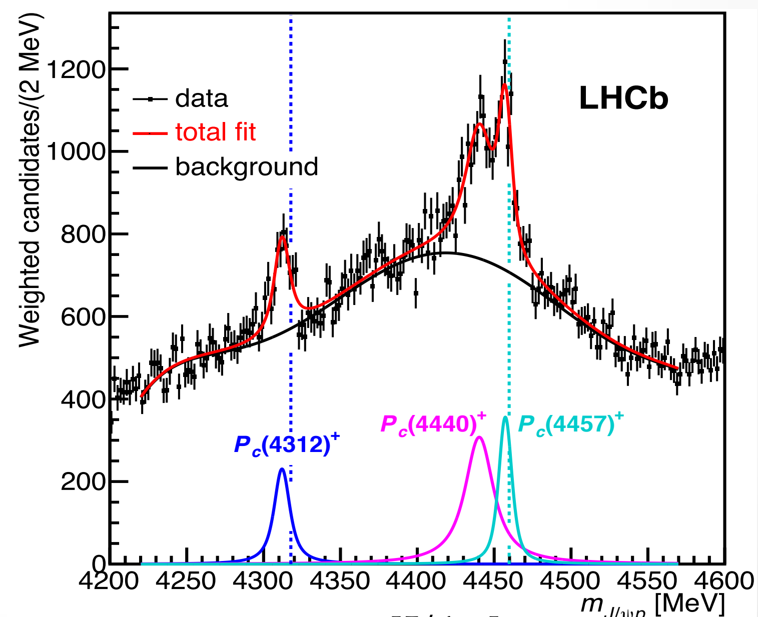
- About 30 candidates for exotics with heavy quark(s)
- Some of them manifestly exotic
- Charged charmonia: $Z_c(3900)^+$, $Z_c(4430)^+ \rightarrow \psi(2S)\pi^+$

  Belle PRL100 142001 (2008), Belle PRD80 031104 (2009), LHCb PRL112 222002 (2014)

  Belle PRL110 252002 (2013), BESIII PRL110 252001 (2013)
- Pentaquarks: $P_c(4312)^+$, $P_c(4440)^+$, $P_c(4457)^+ \rightarrow J/\psi p$

  LHCb PRL115 072001 (2015), LHCb PRL122 222001 (2019)





m[J/ψp]

Candidates for exotic particles

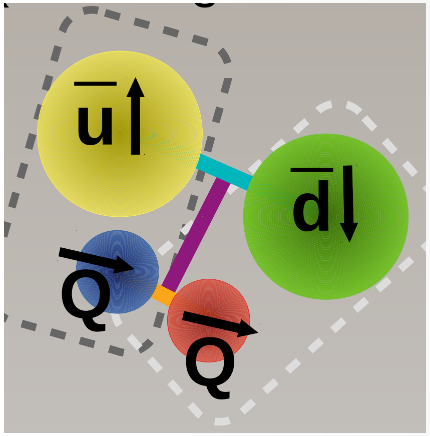
- Most of them contain $Q\bar{Q}$ ($c\bar{c}$ or $b\bar{b}$)
- Molecular or compact objects? Resonance nature?
- Close to mass thresholds of meson-meson or meson-baryon
- Large widths of O(10-100) MeV
- How about long-lived exotic states?

States	Quark content
$X_0(2900)$, $X_1(2900)$ [21, 22]	$\bar{c}du\bar{s}$
$\chi_{c1}(3872)$ [6]	$c\bar{c}q\bar{q}$
$Z_c(3900)$ [23], $Z_c(4020)$ [24, 25], $Z_c(4050)$ [26], $X(4100)$ [27], $Z_c(4200)$ [28], $Z_c(4430)$ [29–32], $R_{c0}(4240)$ [31]	$c\bar{c}u\bar{d}$
$Z_{cs}(3985)$ [33], $Z_{cs}(4000)$, $Z_{cs}(4220)$ [34]	$c\bar{c}u\bar{s}$
$\chi_{c1}(4140)$ [35–38], $\chi_{c1}(4274)$, $\chi_{c0}(4500)$, $\chi_{c0}(4700)$ [38], $X(4630)$, $X(4685)$ [34], $X(4740)$ [39]	$c\bar{c}s\bar{s}$
$X(6900)$ [14]	$c\bar{c}c\bar{c}$
$Z_b(10610)$, $Z_b(10650)$ [40]	$b\bar{b}u\bar{d}$
$P_c(4312)$ [41], $P_c(4380)$ [42], $P_c(4440)$, $P_c(4457)$ [41], $P_c(4357)$ [43]	$c\bar{c}uud$
$P_{cs}(4459)$ [44]	$c\bar{c}uds$

For references see arXiv:2109.01056

Any chance for long-lived exotic state?

- $QQ\bar{q}\bar{q}$ states, at $m_Q \to \infty$ limit, are prime candidates
- QQ forms a compact color anti-triplet object
  ⇨ $QQ\bar{q}\bar{q}$ similar to $\bar{\Lambda}_c$ or $\bar{\Lambda}_b$ antibaryon



Predictions from various models & lattice QCD:

- $[bb\bar{u}\bar{d}]$ state should be deeply bound,
  mass: ~200 MeV below BB* threshold
- Unclear about $[bc\bar{u}\bar{d}]$ and $[cc\bar{u}\bar{d}]$
- T_{cc}^{+} ground state with $[cc\bar{u}\bar{d}]$
  $J^P=1^+$, $I=0$
  mass: $-300 < \delta m < 300$ MeV, where $\delta m = m(T_{cc}^{+}) - [m(D^0) + m(D^{*+})]$
- No consensus if T_{cc}^{+} exists and is narrow enough to be detected

Learning from doubly-charmed baryon

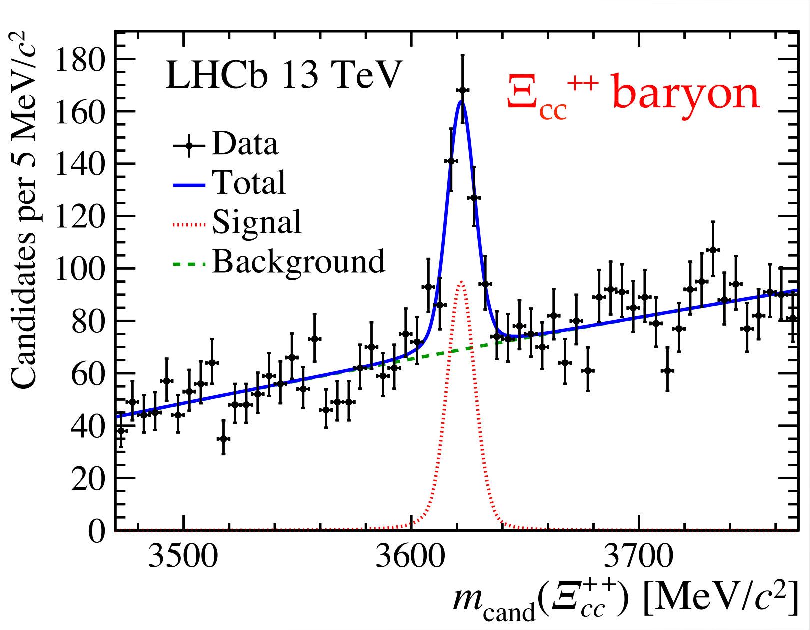
- Recently observed $\Xi_{cc}^{++} \to \Lambda_c K^- \pi^+ \pi^+$ LHCb PRL119 112001 (2017)

  $m(\Xi_{cc}^{++}) = 3621.55 \pm 0.23 \pm 0.30$ MeV LHCb JHEP 02 049 (2020)

- Relationship between properties of Ξ_{cc}^{++} [ccu] and T_{cc}^{+} [$cc\bar{u}\bar{d}$]

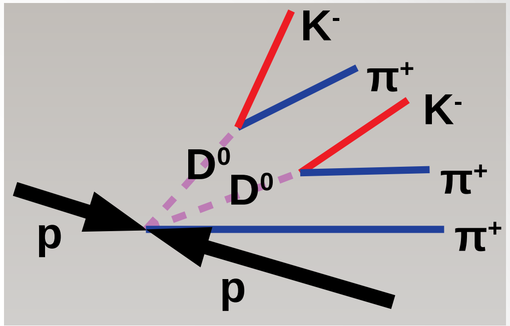
  $m(cc\bar{u}\bar{d}) \approx m(\Xi_{cc}^{++}) + [m(\Lambda_c) - m(D^0)]$ + kinematic corrections (~few MeV)

- Predictions using Ξ_{cc}^{++} mass
  - ⇨ $\delta m < 100$ MeV
  - ⇨ T_{cc}^{+} close to D^0D^{*+} threshold

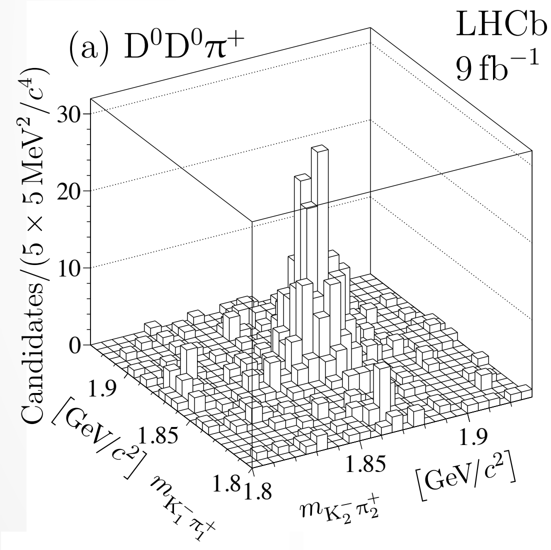


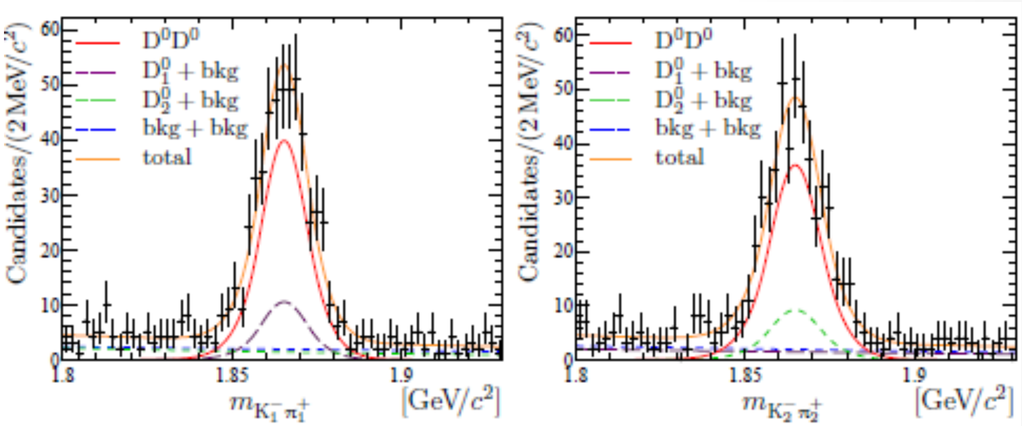
LHCb arXiv:2109.01038

Search for T_{cc}^+



- LHCb Run1+2 data, 9/fb, at √s=7,8,13 TeV
- Reconstructed $D^0D^0\pi^+$ with $D^0 \to K^-\pi^+$
- K/π: p_T>250 MeV, large IP relative to pp collision vertex
- D^0: good vertex, p_T>1GeV, small IP, flight distance >100μm
- non-D^0 background subtracted

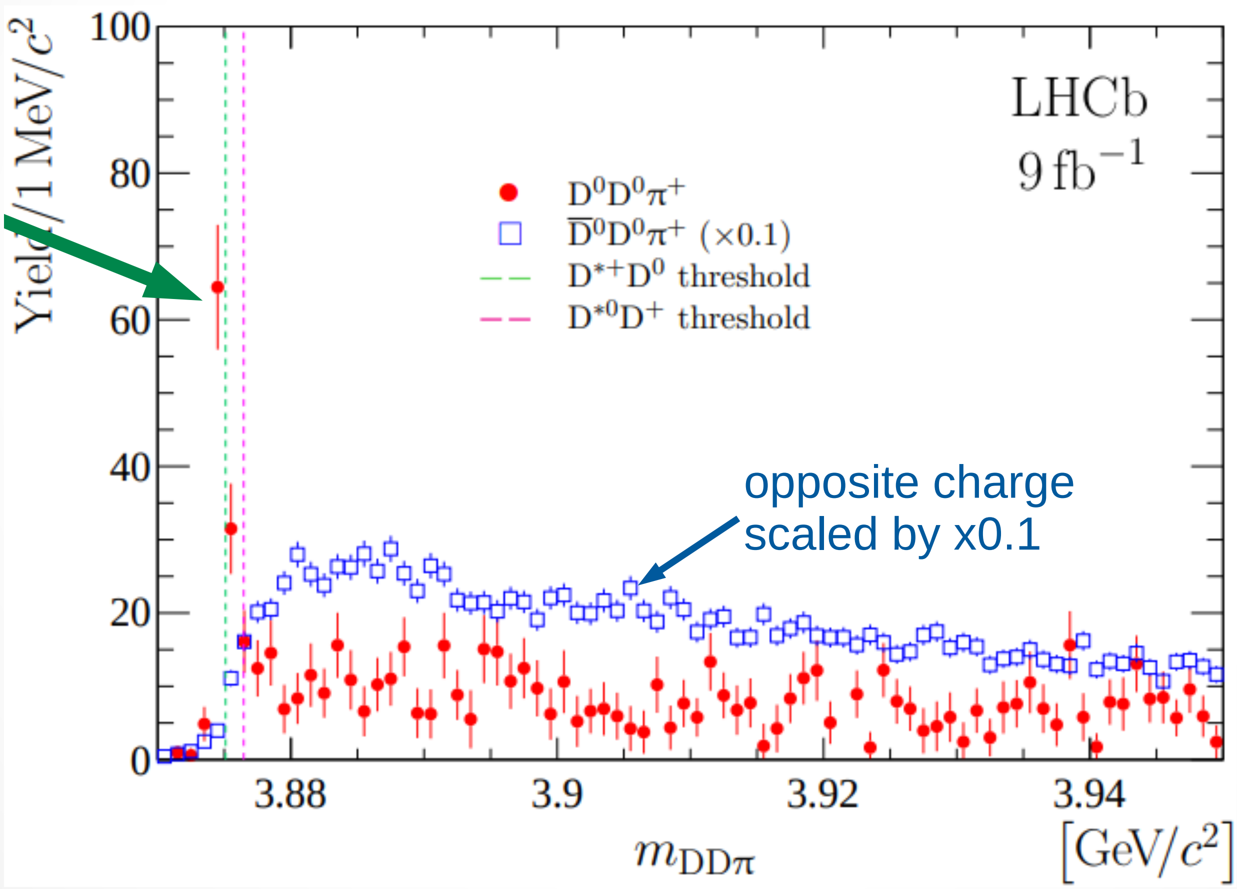




- one $m(D^0\pi^+)$ with mass close to D^{*+} mass
- $m(D^0D^0\pi^+)$ calculated with D^0 inv. mass constrained to D^0 mass

Reconstructed $m(D^0D^0\pi^+)$

- Narrow peak in $m(D^0D^0\pi^+)$ close to D^0D^{*+} threshold
- No such structure in $m(\bar{D}^0D^0\pi^+)$



Fit to m($D^0D^0\pi^+$)

- T_{cc}^+ shape: P-wave relativistic Breit-Wigner
- Convolved with exp. resolution: double-Gaussian
- Simulation-based resolution ~400 keV

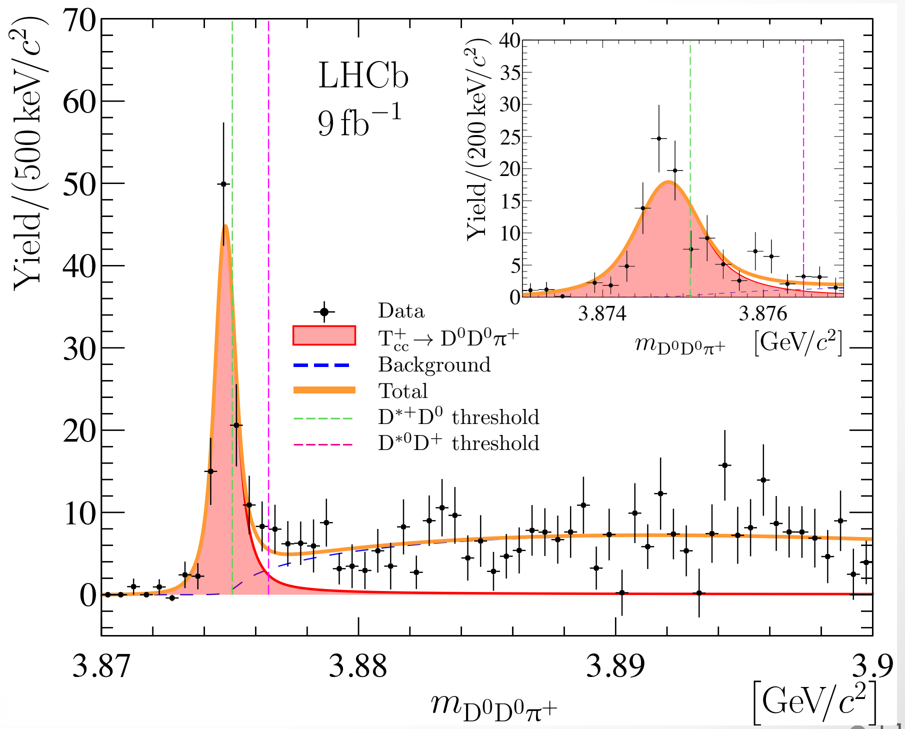
  [×1.05 correction from control channels in data]
- Background: random combinations of true D^{*+} and D^0

  ⇨ two-body phase-space

- T_{cc}^+ yield: 117 ± 16 (22σ)

$$\begin{aligned} \delta m_{\mathrm{BW}} &= -273 \pm 61 \pm 5 \,^{+11}_{-14}\ \mathrm{keV}/c^2 \\ \Gamma_{\mathrm{BW}} &= 410 \pm 165 \pm 43 \,^{+18}_{-38}\ \mathrm{keV}\,, \end{aligned}$$

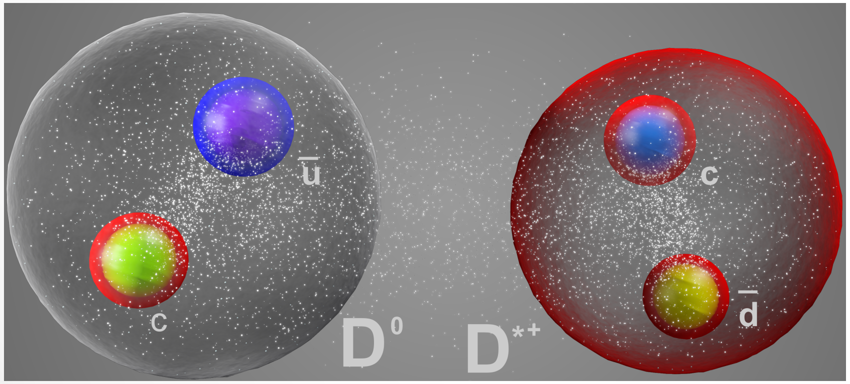
- Mass below D^0D^{*+} threshold!
- Narrowest exotic state!
- Quark composition $[cc\bar{u}\bar{d}]$

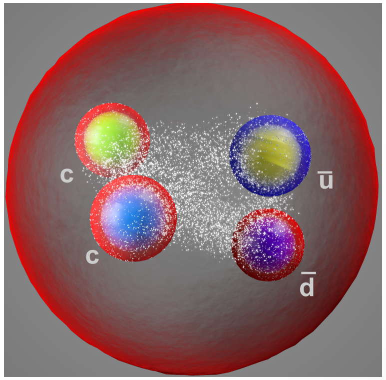


Study of the T_{cc}^{+} properties

- Is it isoscalar or isovector? T_{cc}^{0} and T_{cc}^{++} partners exist?
- Decay structure: Decay via D^{*+}?
- Lineshape? Impact of nearby mass thresholds
- How its production in pp compares to other states?
- Quark structure:

loosely-bound DD* molecule or compact 4-quark?





Unitarised Breit-Wigner descritpion

- State with $J^P=1^+$, I=0 and strongly coupling to DD^* is:

$$\boxed{\left|\mathrm{T}_{\mathrm{cc}}^{+}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|\mathrm{D}^{*+}\mathrm{D}^{0}\right\rangle - \left|\mathrm{D}^{*0}\mathrm{D}^{+}\right\rangle\right)}$$

- Consider coupling g to both DD^* and couplings to $D^* \to D\pi/\gamma$
- Decay amplitudes: $T_{cc}^{+} \to D^0D^0\pi^+$, $D^0D^+\pi^0$, $D^0D^+\gamma$
- Breit-Wigner function for D^* decay
- Unitarised Breit-Wigner function for given final state f

$$\boxed{\begin{aligned} \mathfrak{F}_f^{\mathrm{U}}(s) &= \varrho_f(s)\left|\mathcal{A}_{\mathrm{U}}(s)\right|^2, \\ \mathcal{A}_{\mathrm{U}}(s) &= \frac{1}{m_{\mathrm{U}}^2 - s - i m_{\mathrm{U}}\hat{\Gamma}(s)} \end{aligned}}$$

Phase-space integrated decay amplitude:

$$\varrho_f(s) = \frac{1}{(2\pi)^5}\frac{\pi^2}{4s}\iint ds_{12}ds_{23}\frac{\left|\mathfrak{M}_f(s, s_{12}, s_{23})\right|^2}{|g|^2}$$

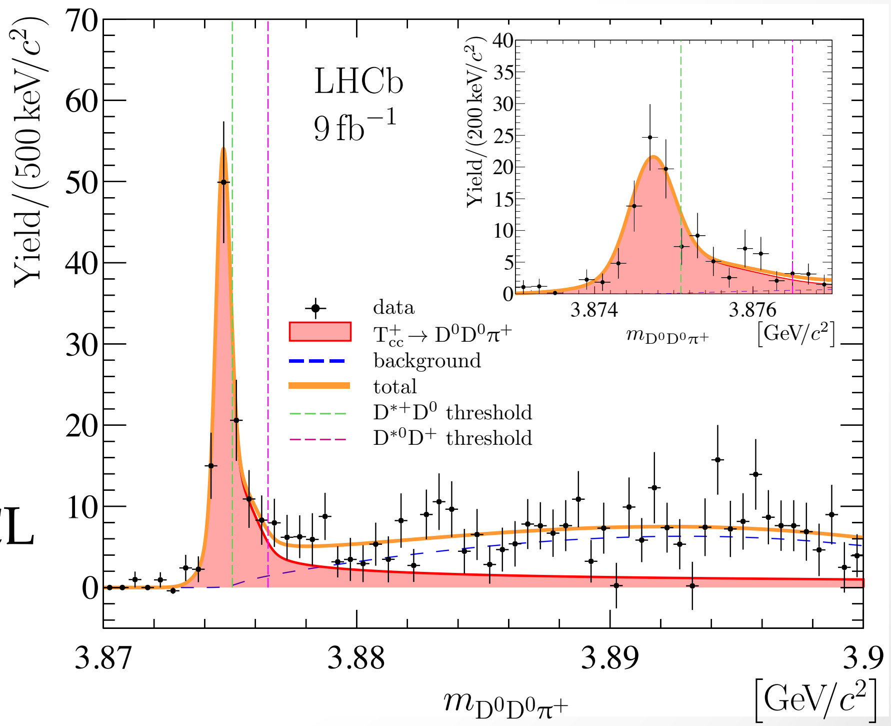
- Parameters

- peak location m_U = mass value where $Re(A_U)$ vanishes
- coupling g related to width $\boxed{i m_{\mathrm{U}}\hat{\Gamma}(s) \equiv |g|^2\,\Sigma(s)}$

Fit to m($D^0D^0\pi^+$) with unitarised BW

- Similar to BW around the peak; long tail above DD* thresholds
- For small coupling, T_{cc}^+ width determined by |g|
- With increasing g, the width asymptotically reaches D* width

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

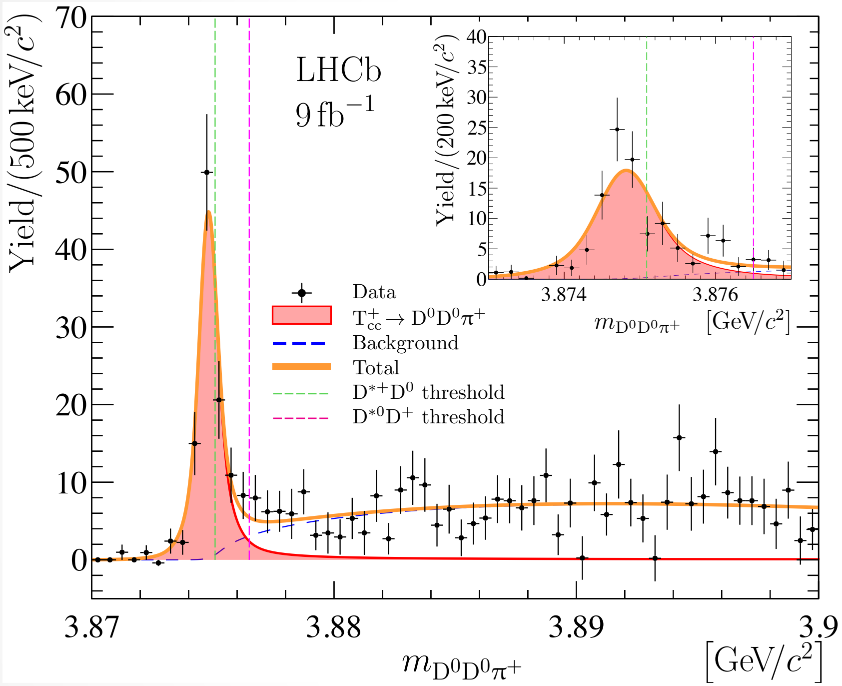


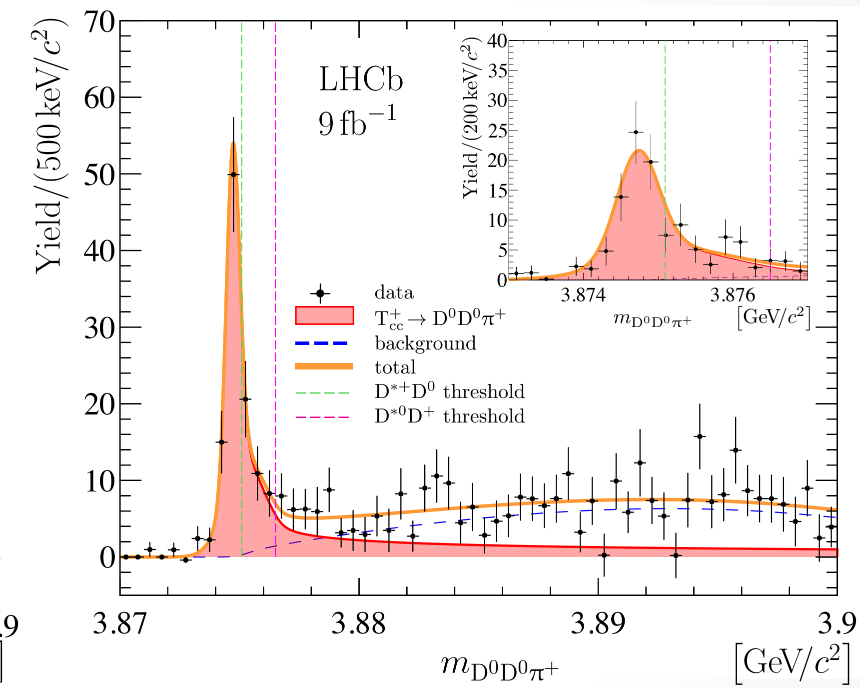
- |g| fixed by D* width
- |g|> 7.7 (6.2) GeV @90 (95)% CL
- m_U below D^0D^{*+} threshold (9σ)
- m_U systematics: $^{+9}_{-6}$ keV

T_{cc}^+ lineshape comparison

- Breit-Wigner shape

Unitarised Breit-Wigner





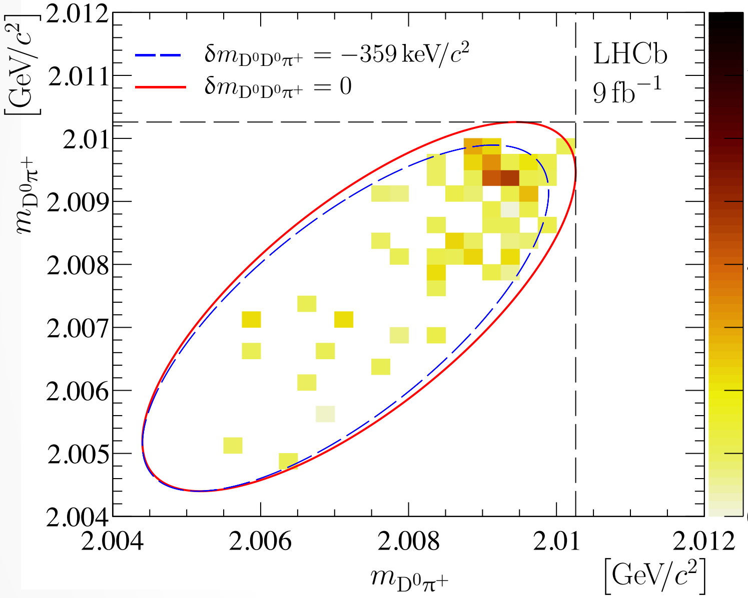
- Compare visible peak parameters: mode and FWHM
- Parameters consistent

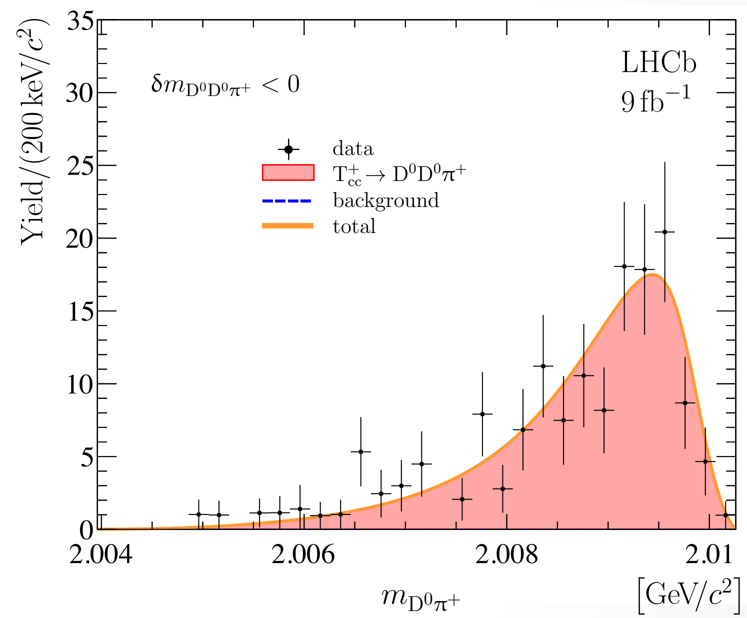
(tested with pseudoexperiments)

	$\delta\mathfrak{m}$ [keV/c^2]	$\mathfrak{w}$ [keV/c^2]
$\mathfrak{F}^{BW}$	-279 ± 59	409 ± 163
$\mathfrak{F}^{U}$	-361 ± 40	47.8 ± 1.9

$T_{cc}^{+} \to D^0 D^0 \pi^+$ proceeds via D^{*+}?

- At least one $m(D^0\pi^+)$ required to have mass close to D^{*+} mass
- What is decay structure for $m(D^0D^0\pi^+)$ below D^0D^{*+} threshold?

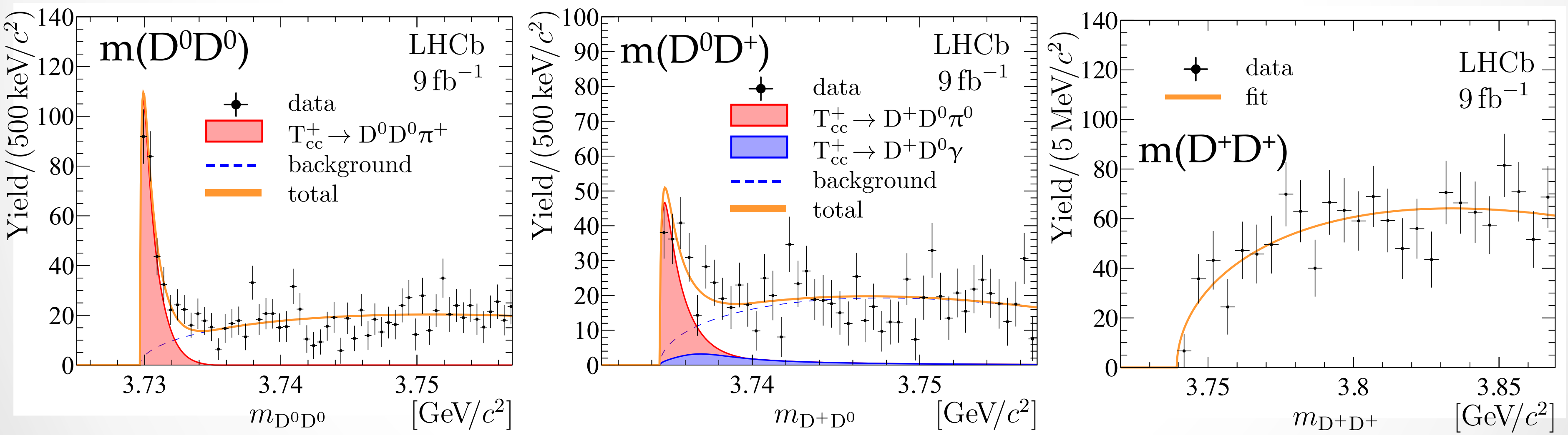




- Signal shape from unitarised BW model, convolved with resolution
- Decay proceeds via off-shell D^{*+} intermediate state
- Supports $J^P=1^+$ assignment

Is the T_{cc}^{+} an isosinglet state?

- For isovector expected triplet: T_{cc}^{0} [$cc\bar{u}\bar{u}$] T_{cc}^{+} [$cc\bar{u}\bar{d}$] T_{cc}^{++} [$cc\bar{d}\bar{d}$]
- Mass splitting relative to T_{cc}^{+} of ±3 MeV
- Requires studying all $DD\pi/\gamma$ combinations:
  $m(D^0D^0\pi^0/\gamma)$, $m(D^0D^+\pi^0/\gamma)$, $m(D^0D^+\pi^+)$, $m(D^+D^+\pi^0/\gamma)$
- Look for T_{cc} reconstructed with missing π/γ

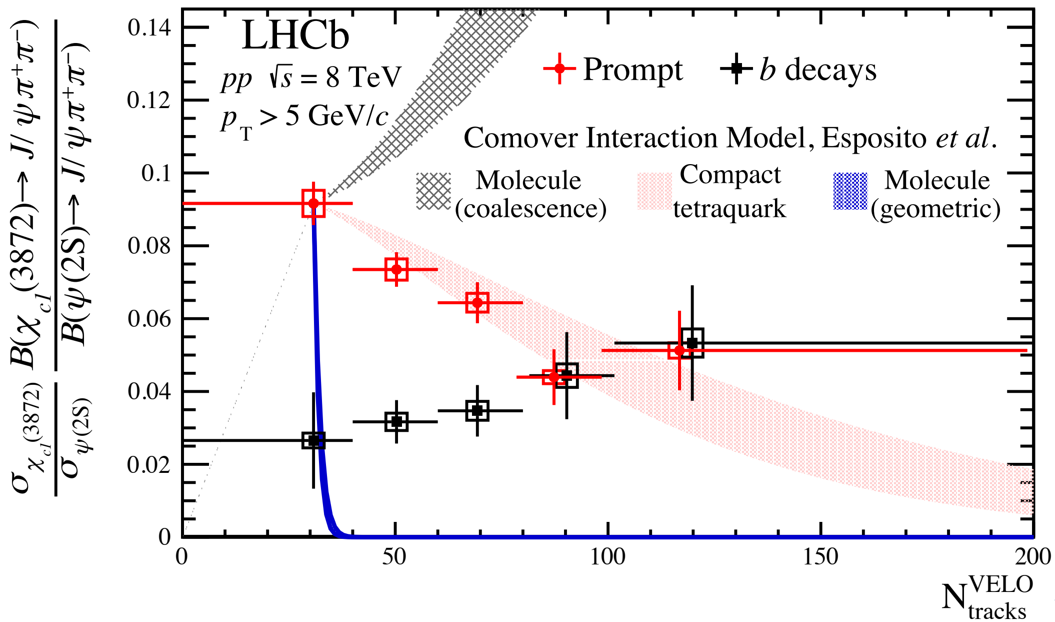


- Peaks consistent with partially reconstructed $T_{cc}^{+} \to D^0D^0\pi^+$, $D^+D^0\pi^0/\gamma$
- No evidence for T_{cc}^{0} or T_{cc}^{++}

Production of T_{cc}^+ similar to X(3872)?

- Properties of T_{cc}^+ similar to that of X(3872)
- How about T_{cc}^+ hadroproduction from pp?
- Suppression of X(3872) relative to ψ(2S) at large track multiplicity

LHCb PRL126 092001 (2021)

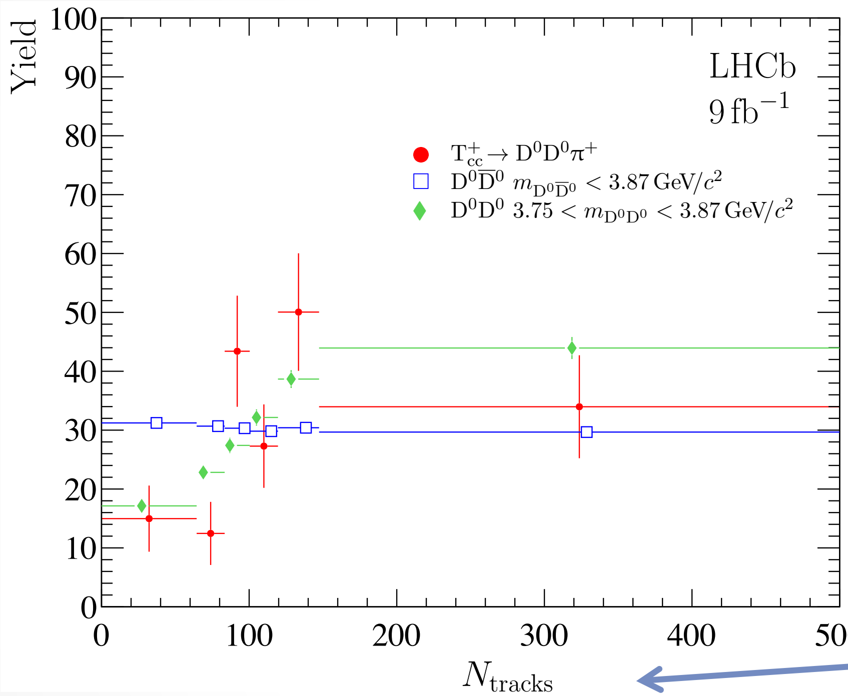


Number of tracks reconstructed in the vertex detector

- Explained by Comover Interaction Model: nearby pions/gluons cause X(3872) breakup

Production of T_{cc}^+

- Comparison of T_{cc}^+ yield with low-mass D^0D^0 and $D^0\bar{D}^0$ pairs



Dominant production mechanisms:

- T_{cc}^+ from single parton scattering
- D^0D^0 from double parton scattering
- $D^0\bar{D}^0$ from $pp \to c\bar{c}X$

Number of tracks reconstructed in the vertex detector

- Similar behaviour for T_{cc}^+ and D^0D^0. Unexpected
- No T_{cc}^+ suppression with large number of tracks. Unlike X(3872)

Summary and outlook

- T_{cc}^+ opens new class of exotic hadrons: $[QQ\bar{q}\bar{q}]$
- Manifestly exotic with $[cc\bar{u}\bar{d}]$
- Below D^0D^{*+} threshold and long-lived

$$\boxed{\begin{aligned} \delta m_{\mathrm{BW}} &= -273 \pm 61 \pm 5\,^{+11}_{-14}\,\mathrm{keV}/c^2 \\ \Gamma_{\mathrm{BW}} &= 410 \pm 165 \pm 43\,^{+18}_{-38}\,\mathrm{keV}\,, \end{aligned}}$$

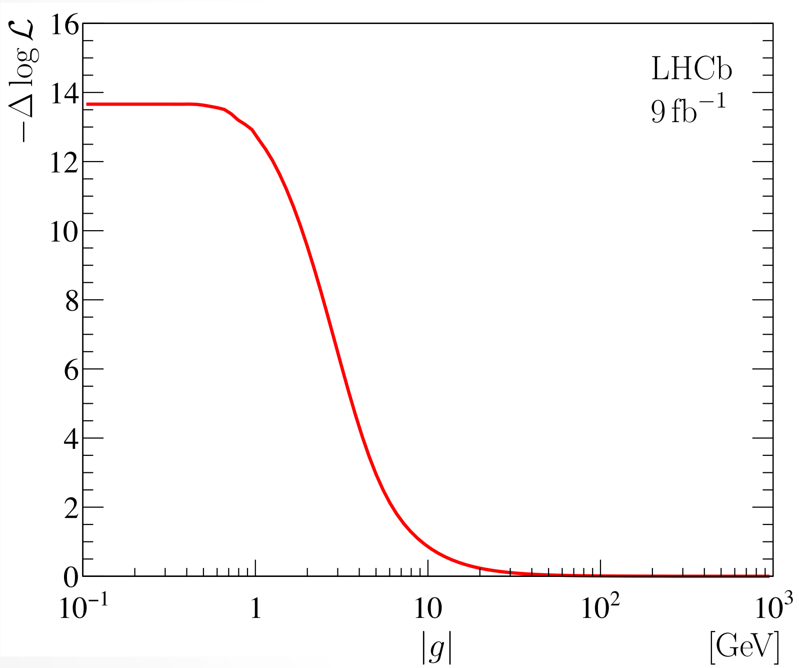
- Consistent with predicted T_{cc}^+ having $J^P=1^+$ and $I=0$

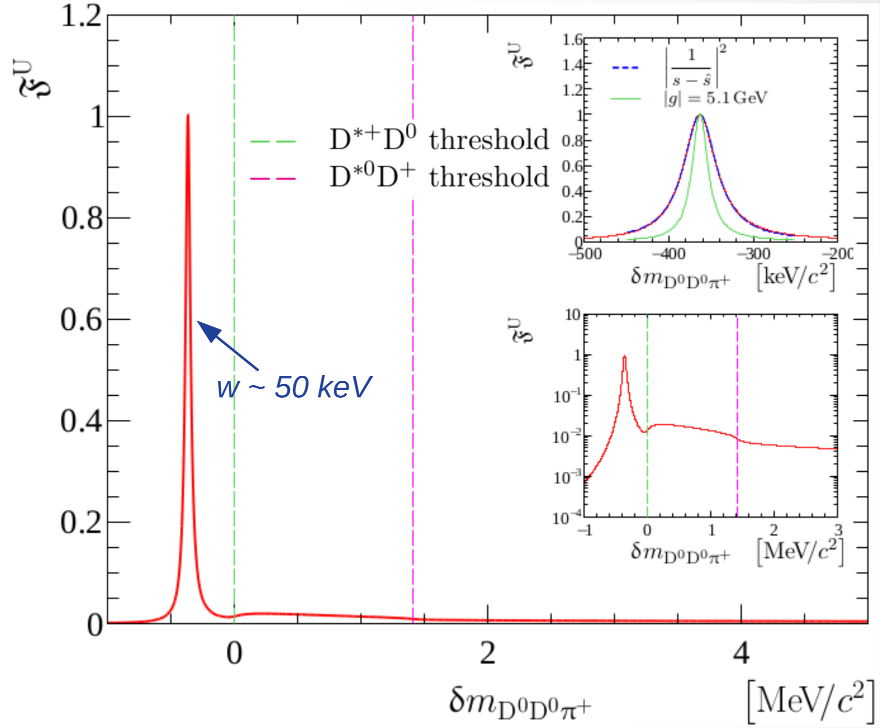
- Future studies to test the T_{cc}^+ nature
  - Production measurements in pp [with X(3872) as a reference]
  - Production in e^+e^-?
  - Dalitz analysis of $T_{cc}^+ \to DD\pi/\gamma$ to confirm J^P
  - Search for T_{bc} and T_{bb}

Backups

T_{cc}^{+} lineshape

- Fitted shape w/o resolution
- Likelihood scan of coupling





- For small g resonance too narrow for resolution. For increasing g T_{cc}^{+} width determined by D* width, then g decouples from the resonance shape

LHCb arXiv:2109.01038

Systematics on BW parameters

Source	$\sigma_{\delta m_{\mathrm{BW}}}$ [keV/c^2]	$\sigma_{\Gamma_{\mathrm{BW}}}$ [keV]
Fit model		
Resolution model	2	7
Resolution correction factor	1	30
Background model	3	30
Model parameters	< 1	< 1
Momentum scale	3	—
Energy loss corrections	1	—
$\mathrm{D}^{*+} - \mathrm{D}^0$ mass difference	2	—
Total	5	43
J^{P} quantum numbers	$^{+11}_{-14}$	$^{+18}_{-38}$

LHCb arXiv:2109.01056

Systematics on m_U

Source	$\sigma_{\delta m_{\mathrm{U}}}$ [keV/c^2]
Fit model	
Resolution model	2
Resolution correction factor	2
Background model	2
Coupling constants	1
Unknown value of $\lvert g \rvert$	$^{+7}_{-0}$
Momentum scaling	3
Energy loss	1
$D^{*+} - D^0$ mass difference	2
Total	$^{+9}_{-6}$

PRL 115, 072001 (2015)

Pentaquarks: at first sight

- $\Lambda_b \to J/\psi pK$; 6-dim amplitude analysis

$P_c(4380)^+$

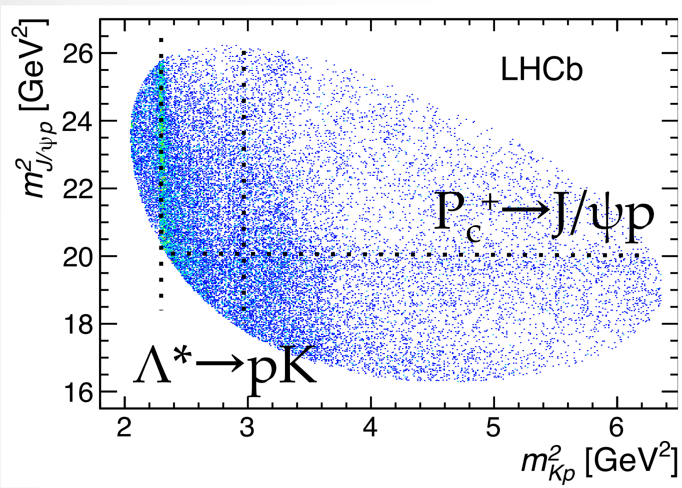
$$M = 4380 \pm 8 \pm 29 \text{ MeV}$$

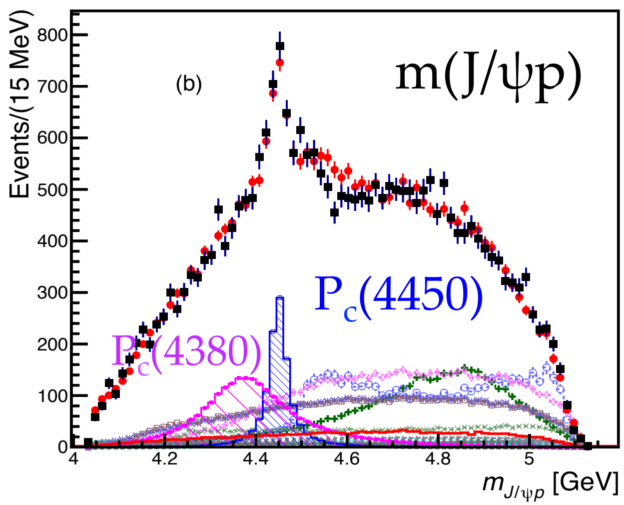
$$\Gamma = 205 \pm 18 \pm 86 \text{ MeV}$$

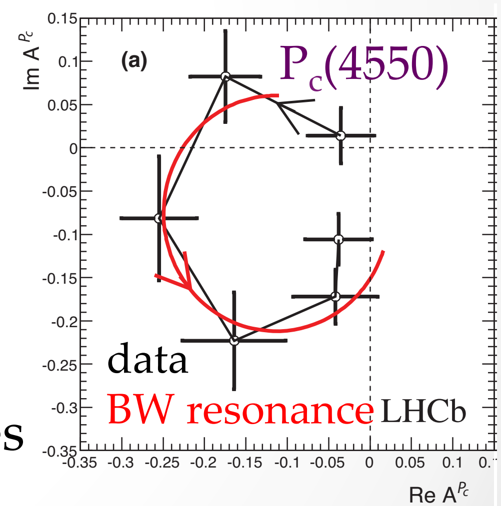
$P_c(4550)^+$

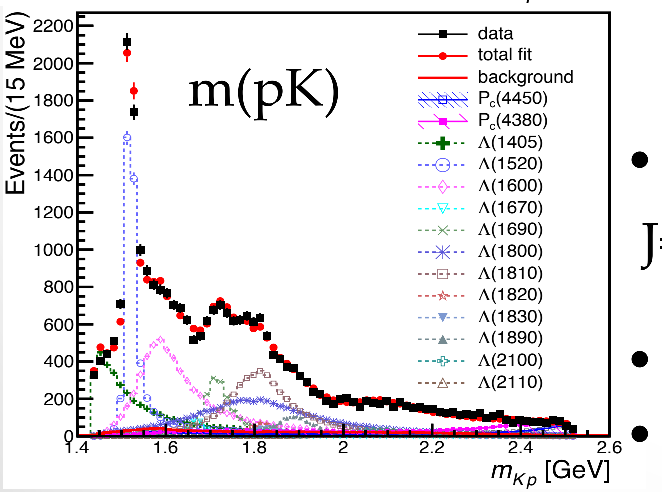
$$M = 4450 \pm 2 \pm 2 \text{ MeV}$$

$$\Gamma = 39 \pm 5 \pm 19 \text{ MeV}$$









- $P_c(4380)$ $P_c(4550)$:

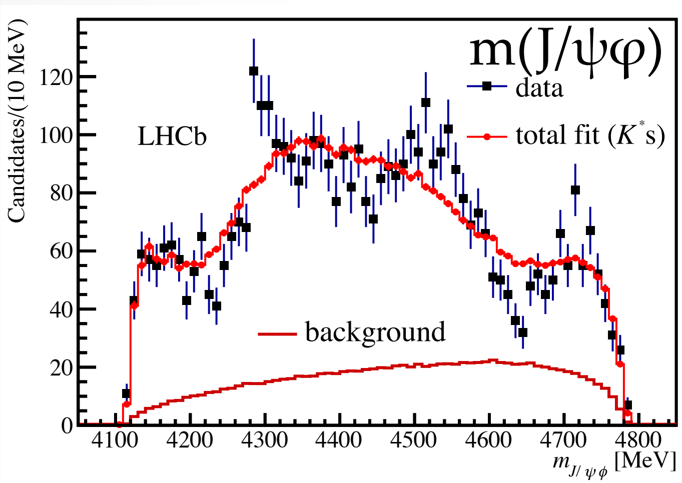
J=3/2, 5/2; opposite P-parities

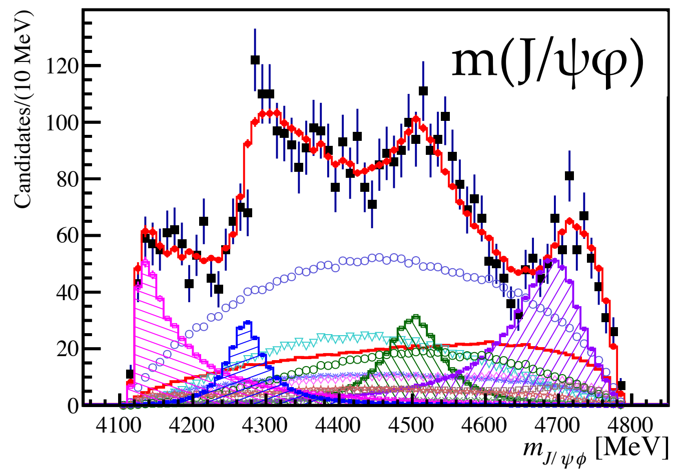
- Min. quark content **[c<u>c</u>uud]**
- Tightly bound or baryon+meson molecule?

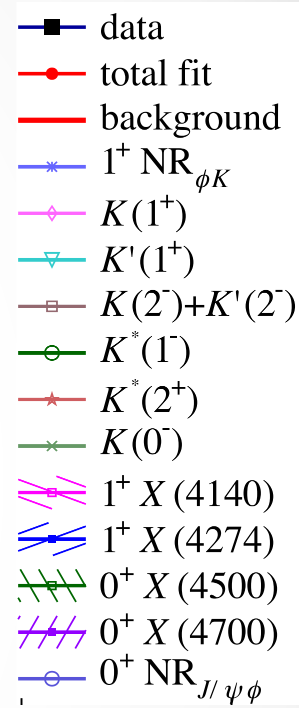
X→J/ψφ Family

PRL 118, 022003 (2017)
PRD 95, 012002 (2017)

- B_s→J/ψφK, 6-dim amplitude analysis
- K*→φK only: don't describe data







- **Four X→J/ψφ needed**; broader than seen by CDF/CMS

State	Signif	J^{PC}	M [MeV]	Γ [MeV]
X(4140)	8.4σ	1^{++}	$4160 \pm 4^{+5}_{-3}$	$83 \pm 21^{+21}_{-14}$
X(4274)	5.8σ	1^{++}	$4273 \pm 8^{+17}_{-4}$	$56 \pm 11^{+8}_{-11}$
X(4500)	6.1σ	0^{++}	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$
X(4700)	5.6σ	0^{++}	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$

- All won't fit $c\underline{c}$ spectrum
- $D_s^*D_s^*$ molecules or tetraquarks?

- No single model can acommodate them all