Studies of open-double-charm exotic states at LHCb

on behalf of LHCb collaboration

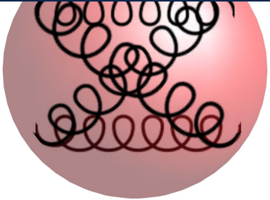
Mindaugas Šarpis

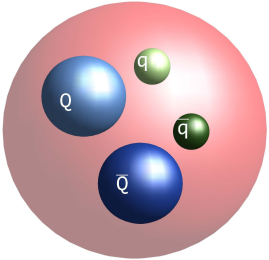
University of Bonn

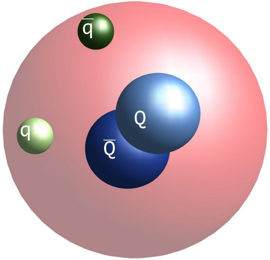
June 15, 2023

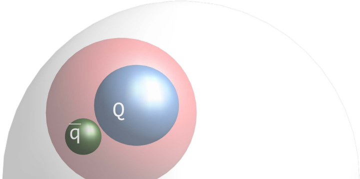
Outline

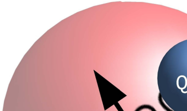
- The LHCb experiment
- Current landscape of hadron spectroscopy at LHCb
- Recap on the nature of exotic hadrons
- Observation of an exotic narrow doubly charmed tetraquark
- Study of the doubly charmed tetraquark T_{cc}^{+}



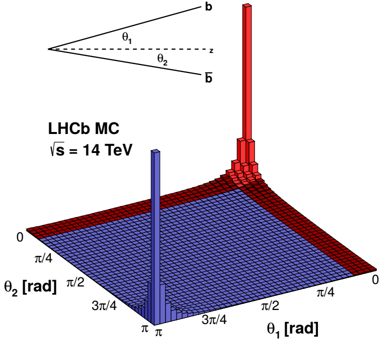


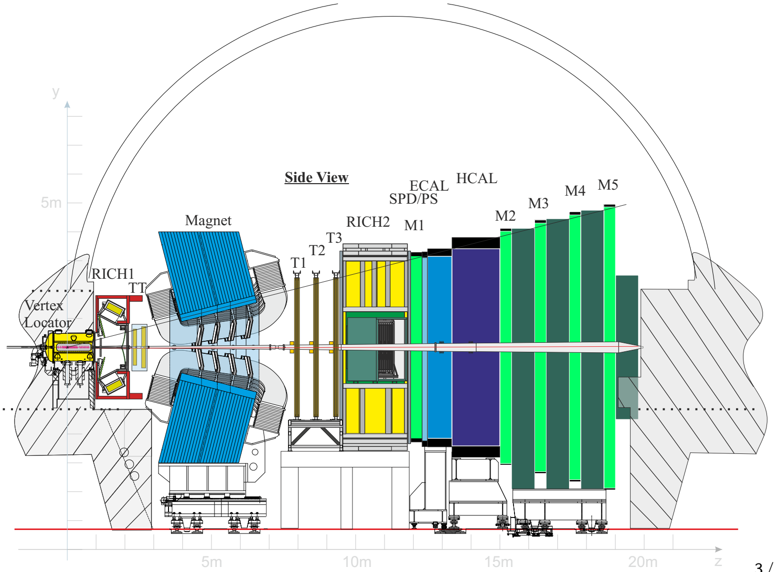






The LHCb Experiment





LHCb is a single-arm forward spectrometer covering $2 < \eta < 5$

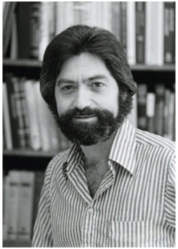
Vertex:	σ_{IP}	$\sim 20\ \mu m$
Time:	σ_τ	$\sim 45\ fs$
PID:	$\varepsilon(K \to K)$	$\sim 95\%$

Exotic hadrons in the quark model

We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc.

Murray Gell-Mann

Multiquark hadrons other than conventional meson and baryon states (containing 2 and 3 quarks respectively) are considered to be **Exotic Hadrons**.

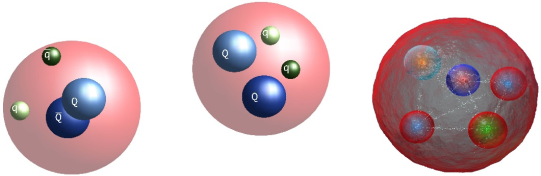


6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

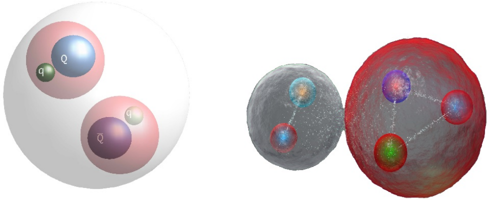
George Zweig

The nature of exotic hadrons

Tightly bound (compact) states

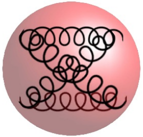


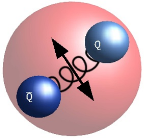
Molecular states



Other states

Glueball

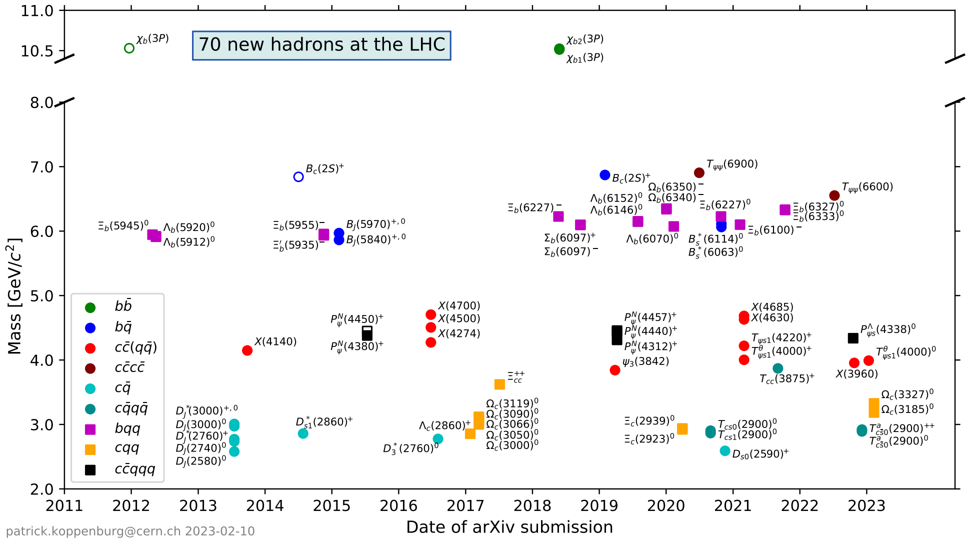




Hybrid

Soeren Lange / CERN graphics

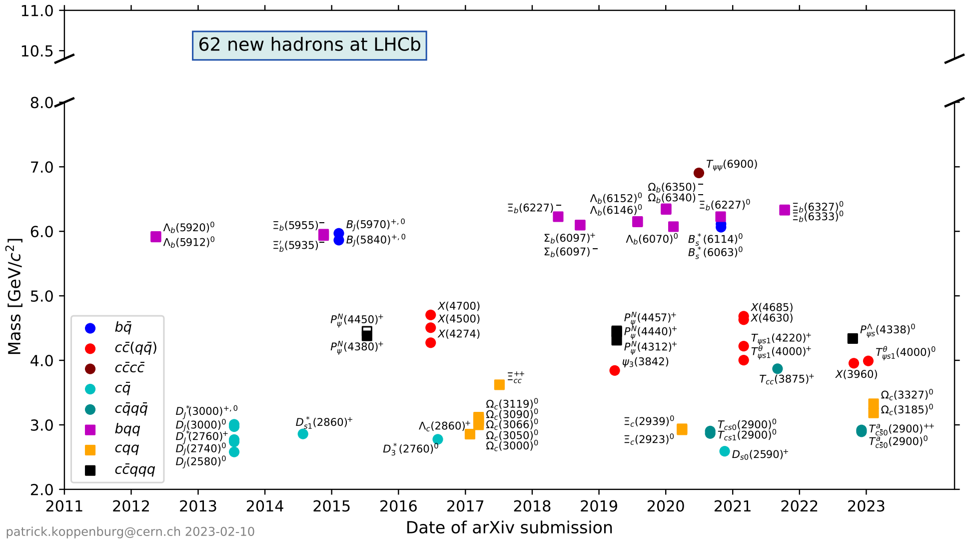
Hadron spectroscopy at the LHC



[P. Koppenburg web page]

↑ End of Run2

Hadron spectroscopy at the LHCb

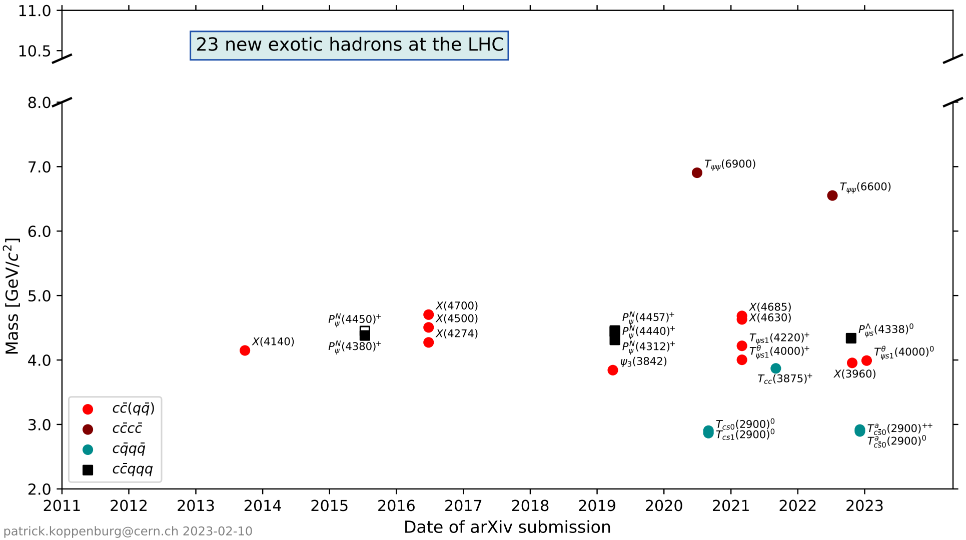


patrick.koppenburg@cern.ch 2023-02-10

[P. Koppenburg web page]

↑ End of Run2

New exotic hadrons at the LHC



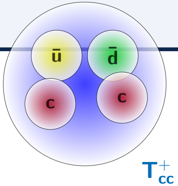
[P. Koppenburg web page]

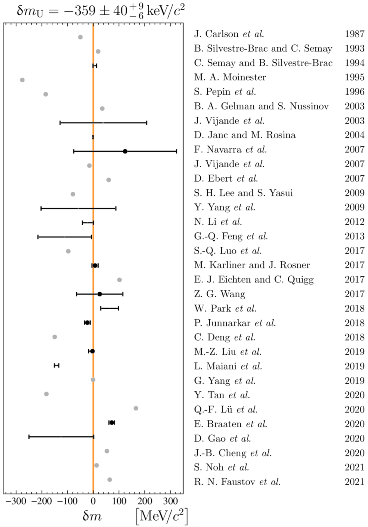
↑ End of Run2

Motivation for T_{cc}^{+} studies — Double open-charm Tetraquark

- Highly non-perturbative regime makes QCD calculations difficult
- Hadronic spectroscopy is driven by experimental input
- Abundance of tetraquark and pentaquark states discovered
- All discovered exotic hadrons predominantly decay via strong interaction
- A long-lived exotic state stable wrt. strong interaction would be very intriguing
- $\mathcal{Q}\mathcal{Q}\bar{q}\bar{q}$ hadron is a prime candidate for such a state
- $bb\bar{u}\bar{d}$ state expected to be stable, but no consensus on $bc\bar{u}\bar{d}$ or $cc\bar{u}\bar{d}$ states

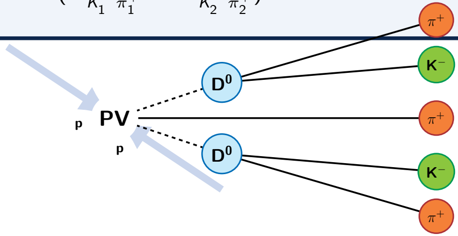
$$\delta m \equiv m_{T_{cc}^{+}} - (m_{D^{*+}} + m_{D^{0}})$$

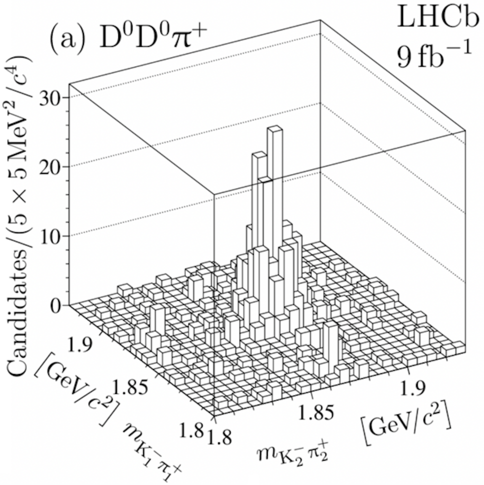




Selection of $D^0 D^0 \pi^+$ candidates

- Prompt $D^0 D^0 \pi^+$ candidates selected
- Ensuring D^0 detached vertices
- Detached $K^- \pi^+$ with high p_{T}
- Good track, vertex and PID quality required
- Ensure no reflections via mis-ID
- Remove D^0 combinatorial background using 2D with $(m_{K_1^- \pi_1^+}$ vs $m_{K_2^- \pi_2^+})$

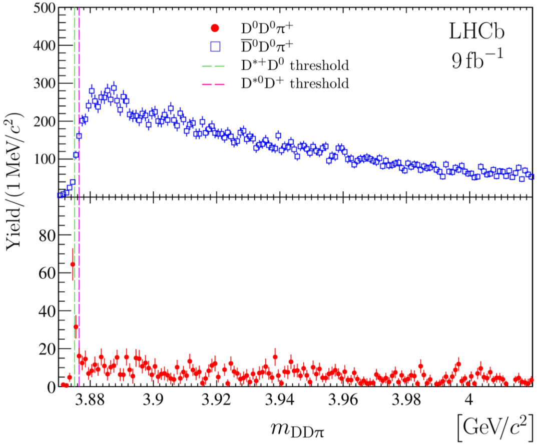




[LHCb Collaboration. Observation of an exotic narrow doubly charmed tetraquark. Nat. Phys. 18, 751–754 (2022).]

$D^0 D^0 \pi^+$ inv. mass spectrum

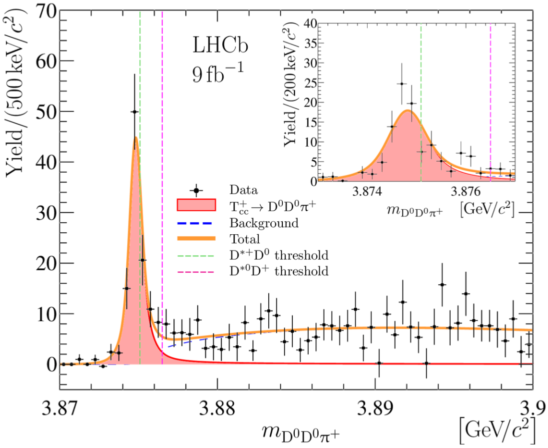
- Narrow peak observed in $D^0 D^0 \pi^+$
- As a cross-check $D^0 \bar{D}^0 \pi^+$ spectrum investigated
- No peak observed in $D^0 \bar{D}^0 \pi^+$
- A narrow hypothetical charmonium like state in $D^0 \bar{D}^0 \pi^+$ followed by a transition $\bar{D}^0 \rightarrow D^0$ would produce a narrow peak in $D^0 D^0 \pi^+$ but a much larger peak in $D^0 \bar{D}^0 \pi^+$
- The peak in $D^0 D^0 \pi^+$ appears just under $D^{*+} D^0$ threshold
- Tetraquark in close proximity to meson-meson threshold suggests a molecular - loosely bound nature of the state



Fit to $D^0 D^0 \pi^+$ inv. mass spectrum — Simple model

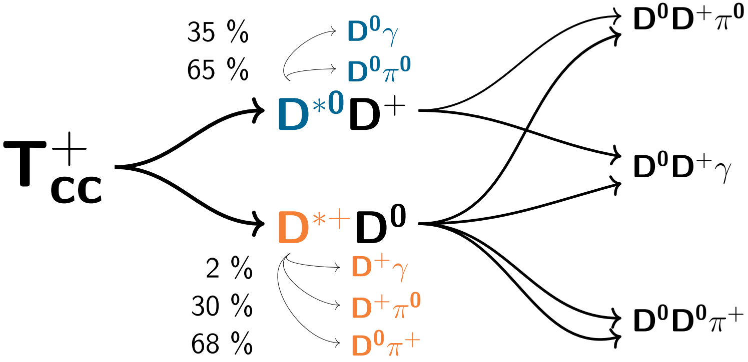
- Signal model:
  Relativistic Breit-Wigner $*$ Resolution
- Phase space background
- Signal significance $> 10\sigma$
- Peak below $D^{*+}D^0$ established with 4.3σ significance
- Model too naive $\rightarrow$ proximity to threshold

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



$$\delta m_{BW} \equiv m_{T_{cc}^+} - (m_{D^{*+}} + m_{D^0})$$

Constructing unitarized amplitude model



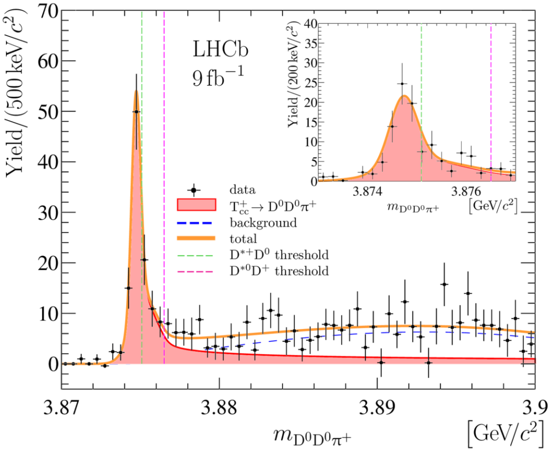
Model assumptions:

- $J^P = 1^+$: S-wave decay to DD^*
- T_{cc}^+ is an isoscalar: $|\mathbf{T}_{cc}^+\rangle_{\mathcal{I}=0} = \left(|\mathbf{D}^{*0}\mathbf{D}^+\rangle - |\mathbf{D}^{*+}\mathbf{D}^0\rangle\right)/\sqrt{2}$
- Isospin conserved in $D^{*0}D^+$ and $D^{*+}D^0$ couplings.

Fit to $D^0 D^0 \pi^+$ inv. mass spectrum unitarized amplitude model

- Signal model:
  Advanced 3-body Breit-Wigner model
- 3-body phase-space calculated via of $X \to DD^*[\to D\pi/\gamma]$ matrix element over $D^0 D^{0/+}\pi^+/\gamma$ Dalitz plot
- Peak below $D^{*+}D^0$ established with 9σ significance
- Shape doesn't depend on $T_{cc}^+ \to DD^*$ coupling $|g|$ for large values

Parameter	Value
N	186 ± 24
δm_U	-359 ± 40 keV
$\lvert g \rvert$	3×10^4 keV (fixed)

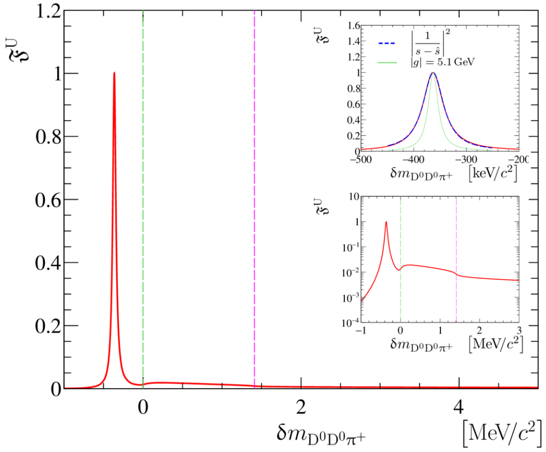


$$\delta m_U \equiv m_{T_{cc}^+} - (m_{D^{*+}} + m_{D^0})$$

[LHCb collaboration. Study of the doubly charmed tetraquark T_{cc}^+. Nat Commun 13, 3351 (2022).]

Features of the unitarized amplitude model

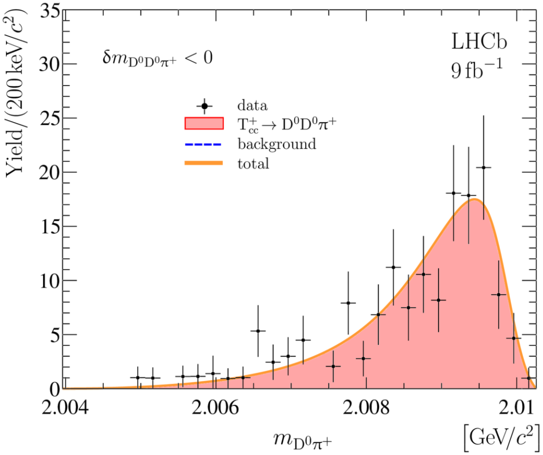
- Nearly isolated resonance below $D^{*+}D^0$ threshold
- Best precision on peak position below threshold
- FWHM: 47.8 ± 1.9 keV
- Lifetime: $\tau \approx 10^{-20}$ s
  - Compared to other exotic hadrons, lifetime is very large
- Long tail observed
- Threshold cusps observed at $D^{*+}D^0$ and $D^{*0}D^+$



[LHCb collaboration. Study of the doubly charmed tetraquark T_{cc}^{+}. Nat Commun 13, 3351 (2022).]

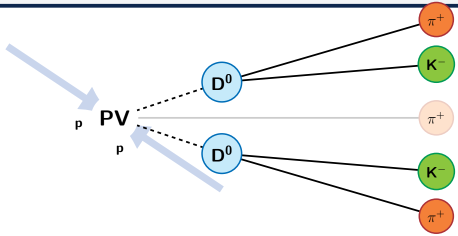
Crosscheck of the model on $D^0\pi^+$

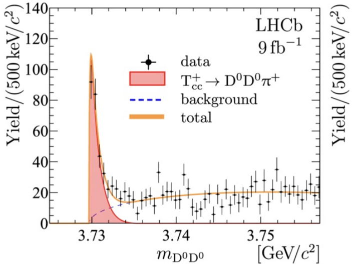
- Unitarized model integrated over $D^0D^0\pi^+$ and D^0D^0 masses to obtain $D^0\pi^+$ shape
- Only floating parameter is the yield
- Perfect agreement confirms:
  - $T_{cc}^+ \to DD^*$ is decaying via off-shell D^* resonance
  - J^P assignment for T_{cc}^+ is correct
- Future amplitude analysis of the Dalitz plot will exclude all other possibilities for J^P

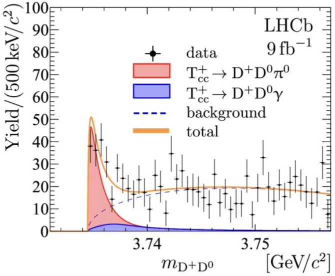


Crosscheck of the model on partially reconstructed decays

- Energy release in $D^* \to D^0\pi^0/\gamma$ is small
- Even without reconstructing π^0 or γ, a narrow peak should be observed in D^0D^0 and D^+D^0 mass spectra
- Independent selection is performed to obtain prompt D^0D^0 and D^+D^0 signal
- Only floating parameter in the fits is the yield
- Relative yields are in agreement with expectations







Checking $\mathcal{I} = 1$ hypothesis

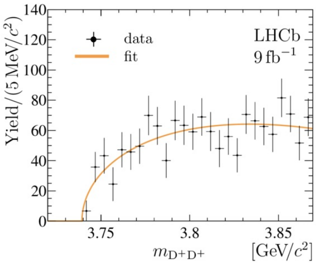
- If T_{cc}^{+} was a part of $\mathcal{I} = 1$ triplet:

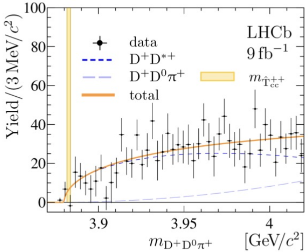
$$\begin{array}{ll} T_{cc}^{0} & cc\overline{d}\overline{d} \\ T_{cc}^{+} & cc\overline{u}\overline{d} \\ T_{cc}^{++} & cc\overline{u}\overline{u} \end{array}$$

- Isospin partners should have roughly the same mass.

$$m_{T_{cc}^{++}} - (m_{D^+} + m_{D^{*+}}) = 2.7 \pm 1.3 \text{ MeV}$$

(using mass of Σ_c^0, Σ_c^+, Σ_c^{++})





Analytic continuation to the complex plane

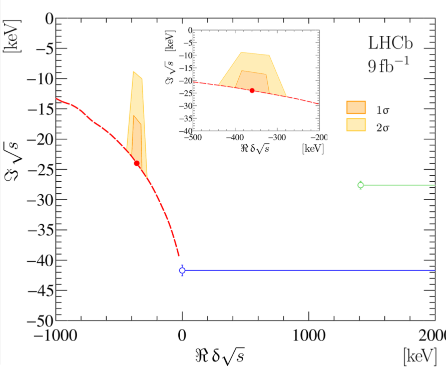
- Pole position can be obtained from the model:

$$\frac{1}{\mathcal{A}^{H}_{U}\hat{s}} = 0$$

$$\sqrt{\hat{s}} \equiv m_{pole} - \frac{i}{2}\Gamma_{pole}$$

$$\delta\sqrt{s} \equiv \sqrt{s} - (m_{D^{*+}} + m_{D^0})$$

- $\delta m_{pole} = -360 \pm 40^{+4}_{-0}$ keV
- $\Gamma_{pole} = 48 \pm 2^{+0}_{-14}$ keV
- By expansion near pole low-energy scattering parameters can be extracted:
  - Scattering length: $a = [-(7.16 \pm 0.51) + i(1.85 \pm 0.28)]$ fm
  - Characteristic size: $R_a \equiv -\mathcal{R}_a = 7.16 \pm 0.51$ fm
  - Effective range: $0 \le -r < 11.9(16.9)$ fm at 90(95)% CL
  - Weinberg compositeness: $Z < 0.52(0.58)$ at 90(95)% CL
  - Size of D^0D^{*+} molecule: $R_{\Delta E} \equiv \frac{1}{\gamma} = 7.5 \pm 0.4$ fm



Summary

- Clear experimental evidence that QCD is richer than qq and qqq baryons
- There is a new *Particle Zoo 2.0* starting of exotic hadrons
- T_{cc}^{+} is the first state of $\mathcal{Q}\mathcal{Q}\bar{q}\bar{q}$ family
- T_{cc}^{+} is isoscalar, no indication of $\mathcal{I} = 1$ family found
- Unitarized amplitude model crosschecked in $D^0\pi^+$ and partially reconstructed decays $\rightarrow$ very good agreement
- Studies of Open-double-charm and other exotic states will help to obtain a better description of QCD inner workings
- Run3, Run4 and future runs of the LHC will provide more statistics at better resolution to push the field of exotic hadron spectroscopy further

End of talk

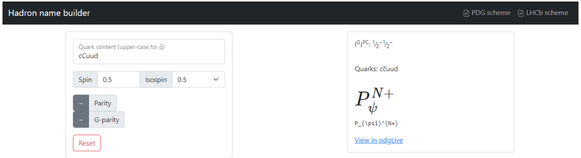
Thank You for your attention

Modern hadron naming scheme

- Current naming scheme is not sufficient to unambiguously index exotic hadrons
- There is no clear solution of how to name some of the states (and how to indicate their quantum numbers) (eg. $cs\bar{u}\bar{d}$ or $J/\psi\Sigma$ states)
- With the future prospects of more multi-quark states being discovered, a new naming scheme has to be introduced
- Proposal of [Exotic hadron naming convention]

Minimal quark content	Current name	$I^{(G)}$, $J^{P(C)}$	Proposed name
$c\bar{c}$	$\chi_{c1}(3872)$	$I^G = 0^+$, $J^{PC} = 1^{++}$	$\chi_{c1}(3872)$
$c\bar{c}u\bar{d}$	$Z_c(3900)^+$	$I^G = 1^+$, $J^P = 1^+$	$T^b_{\psi 1}(3900)^+$
$c\bar{c}u\bar{d}$	$Z_c(4100)^+$	$I^G = 1^-$	$T_\psi(4100)^+$
$c\bar{c}u\bar{d}$	$Z_c(4430)^+$	$I^G = 1^+$, $J^P = 1^+$	$T^b_{\psi 1}(4430)^+$
$c\bar{c}u\bar{s}$	$Z_{cs}(4000)^+$	$I = \frac{1}{2}$, $J^P = 1^+$	$T^\theta_{\psi s1}(4000)^+$
$c\bar{c}u\bar{s}$	$Z_{cs}(4220)^+$	$I = \frac{1}{2}$, $J^P = 1^?$	$T_{\psi s1}(4220)^+$
$c\bar{c}c\bar{c}$	$X(6900)$	$I^G = 0^+$, $J^{PC} = ?^{?+}$	$T_{\psi\psi}(6900)$
$cs\bar{u}\bar{d}$	$X_0(2900)$	$J^P = 0^+$	$T_{cs0}(2900)^0$
$cs\bar{u}\bar{d}$	$X_1(2900)$	$J^P = 1^-$	$T_{cs1}(2900)^0$
$cc\bar{u}\bar{d}$	$T_{cc}(3875)^+$		$T_{cc}(3875)^+$
$b\bar{b}u\bar{d}$	$Z_b(10610)^+$	$I^G = 1^+$, $J^P = 1^+$	$T^b_{\Upsilon 1}(10610)^+$
$c\bar{c}uud$	$P_c(4312)^+$	$I = \frac{1}{2}$	$P^N_\psi(4312)^+$
$c\bar{c}uds$	$P_{cs}(4459)^0$	$I = 0$	$P^\Lambda_{\psi s}(4459)^0$

Work in Progress: Hadron naming tool



A. Morris [https://hadron-names.web.cern.ch/]