# Overview of Exotic Spectroscopy at LHCb

on behalf of LHCb collaboration

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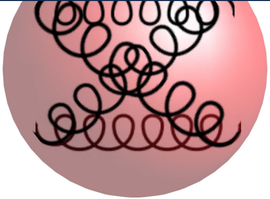
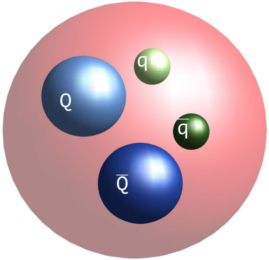
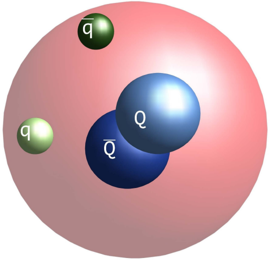
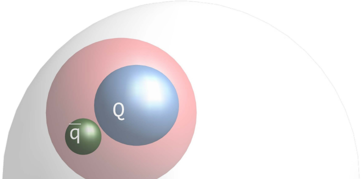
# Outline

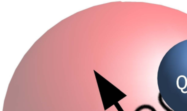
- The LHCb experiment.
- Current landscape of hadron spectroscopy at LHCb.
- Recap on the nature of exotic hadrons.
- Observation of an exotic narrow doubly charmed tetraquark.
- Study of the doubly charmed tetraquark $T_{cc}^{+}$.



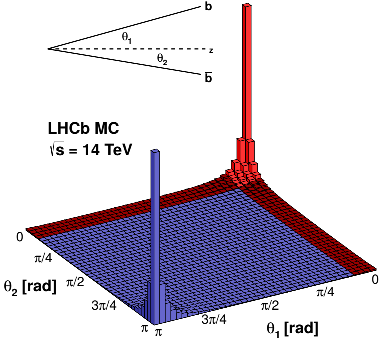


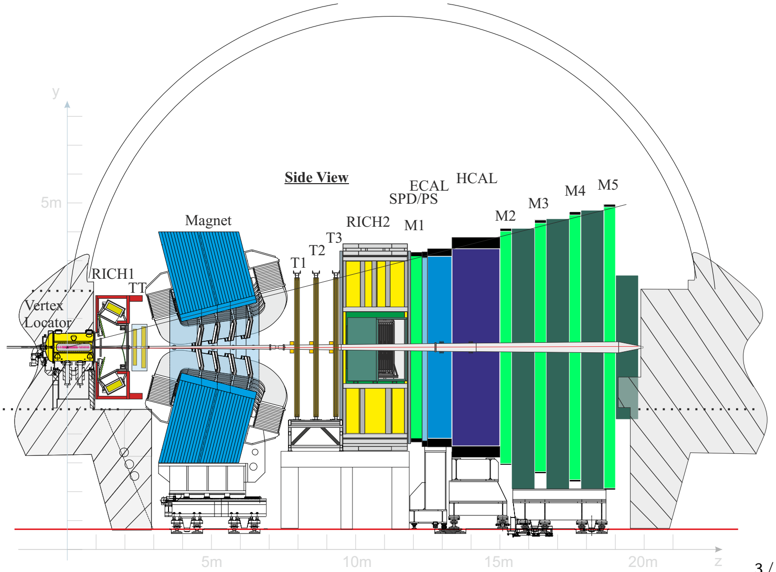



# The LHCb Experiment




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

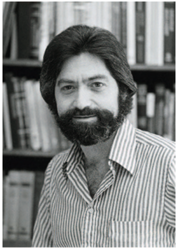
| | | |
|---|---|---|
| Vertex: | $\sigma_{IP}$ | $\sim 20\ \mu m$ |
| Time: | $\sigma_\tau$ | $\sim 45\ fs$ |
| PID: | $\varepsilon(K \to K)$ | $\sim 95\%$ |

# 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**.

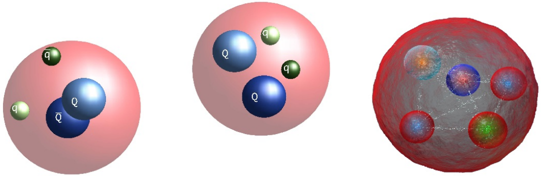


6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons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

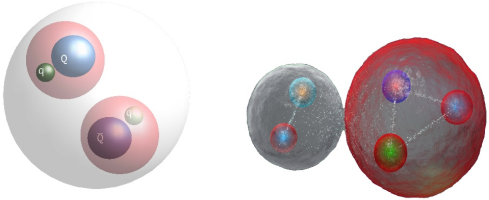
George Zweig

# The nature of exotic hadrons

Tightly bound (compact) states

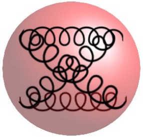


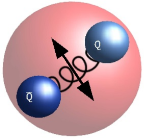

Molecular states




## Other states

Glueball

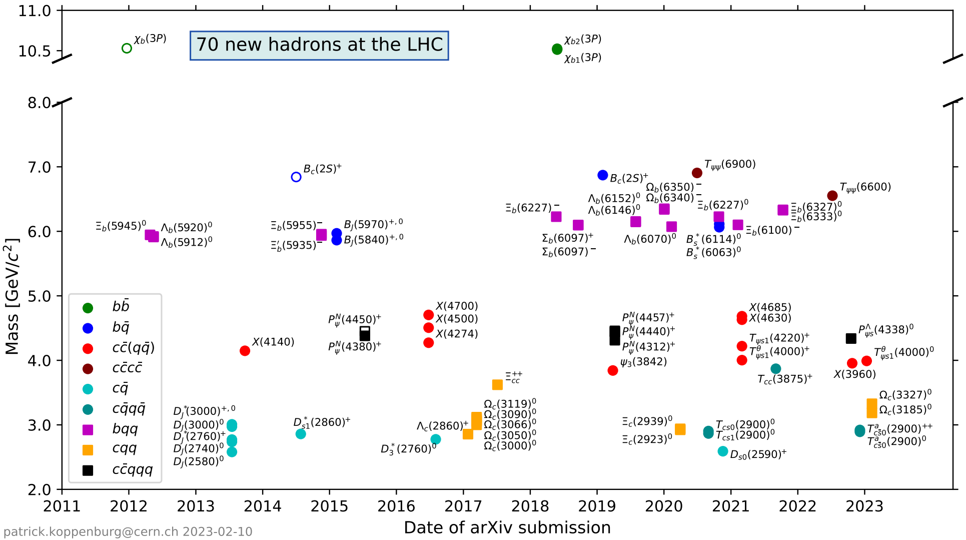





Hybrid

Soeren Lange / CERN graphics

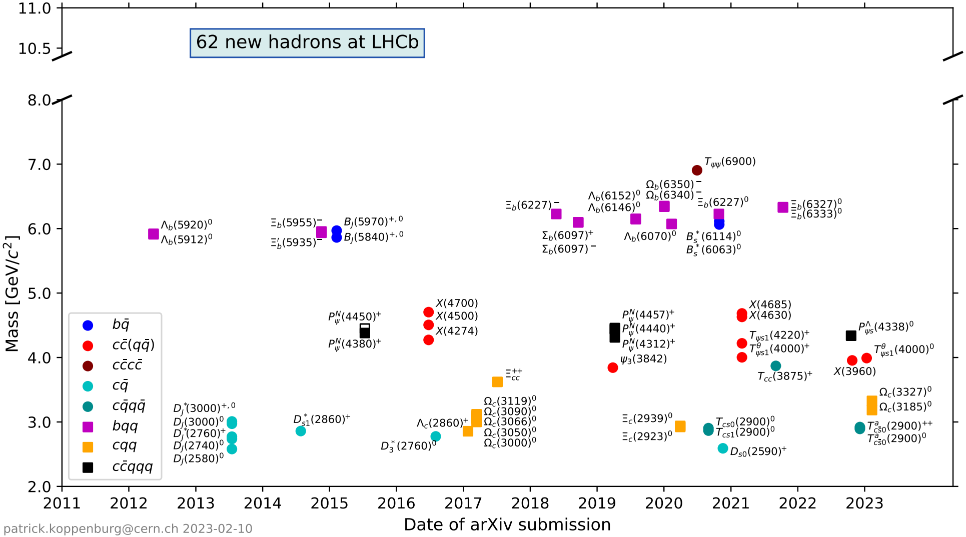
# Hadron spectroscopy at the LHC




[P. Koppenburg web page]

↑ End of Run2

# Hadron spectroscopy at the LHCb




[P. Koppenburg web page]

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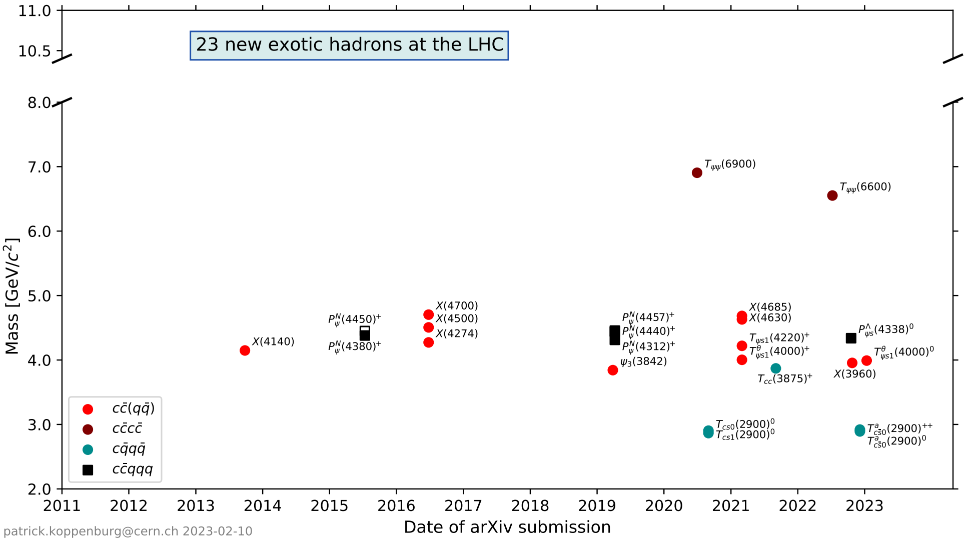
# New exotic hadrons at the LHC

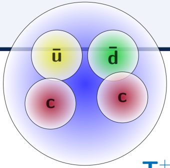



[P. Koppenburg web page]

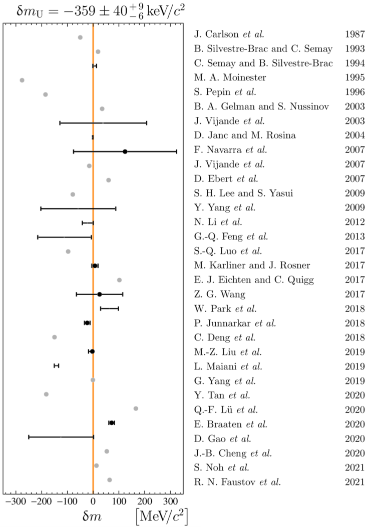
↑ End of Run2

- 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.
- $QQ\bar{q}\bar{q}$ 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.

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

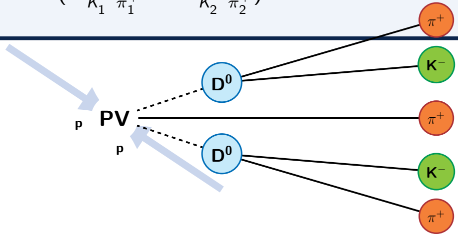


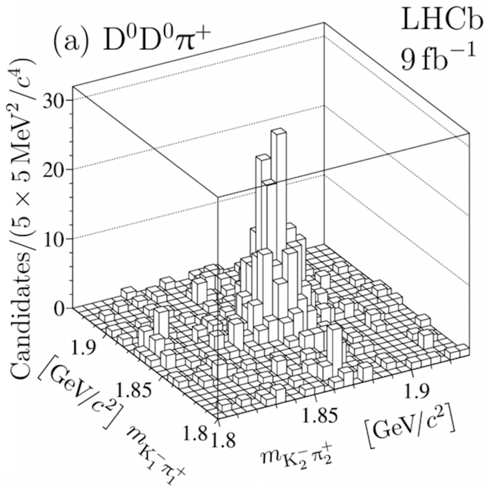

$T_{cc}^{+}$



# 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 $p_{\mathrm{T}}$.
- 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 $m_{K_2^- \pi_2^+}$).

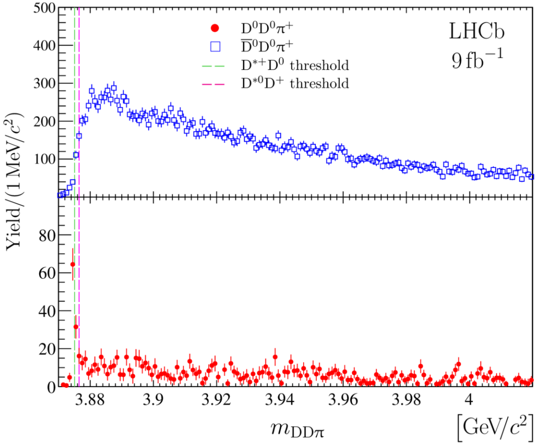



[LHCb Collaboration. Observation of an exotic narrow doubly charmed tetraquark. Nat. Phys. 18, 751–754 (2022).]

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

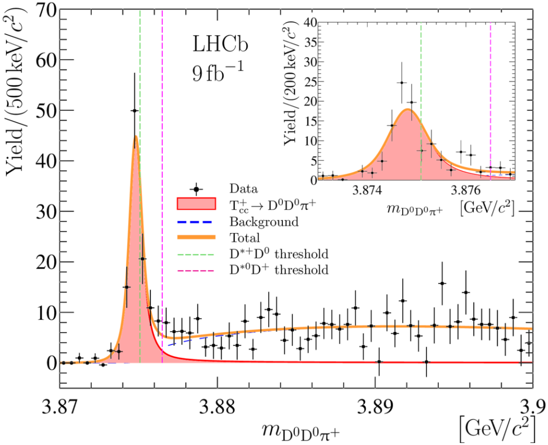
- Narrow peak observed in $D^0 D^0 \pi^+$.
- As a cross-check $D^0 \bar{D}^0 \pi^+$ spectrum investigated.
- No peak observed in $D^0 \bar{D}^0 \pi^+$.
- A narrow hypothetical charmonium like state in $D^0 \bar{D}^0 \pi^+$ followed by a transition $\bar{D}^0. \to D^0$ would produce a narrow peak in $D^0 D^0 \pi^+$ 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

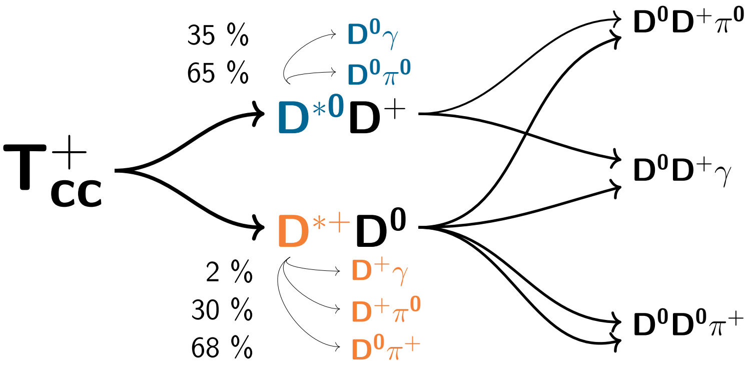
- Signal model:
  Relativistic Breit-Wigner $*$ Resolution.
- Phase space background.
- Signal significance $> 10\sigma$.
- Peak below $D^{*+}D^0$ established with $4.3\sigma$ significance.
- Model too naive $\rightarrow$ proximity to threshold.

| Parameter | Value |
|---|---|
| N | $117 \pm 16$ |
| $\delta m_{BW}$ | $-273 \pm 61$ keV |
| $\Gamma_{BW}$ | $410 \pm 165$ keV |




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

# Constructing unitarized amplitude model



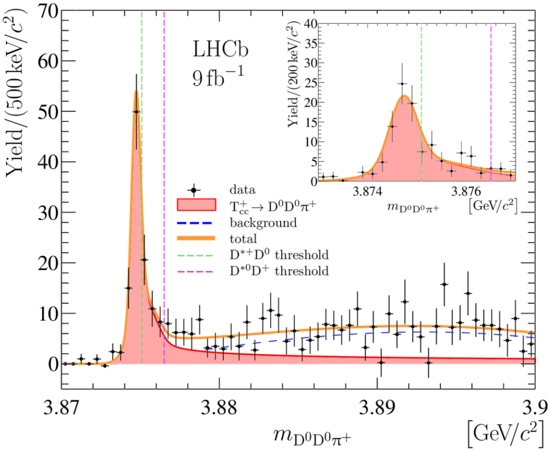

Model assumptions:

- $J^P = 1^+$ : S-wave decay to $DD^*$.
- $T_{cc}^+$ is an isoscalar: $|\mathbf{T_{cc}^+}\rangle_{\mathcal{I}=0} = \left(|\mathbf{D^{*0}D^+}\rangle - |\mathbf{D^{*+}D^0}\rangle\right)/\sqrt{\mathbf{2}}$.
- 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 $9\sigma$ significance.
- Shape does not depend on $T_{cc}^+ \to DD^*$ coupling $|g|$ for large values.

| Parameter | Value |
|---|---|
| N | $186 \pm 24$ |
| $\delta m_U$ | $-359 \pm 40$ keV |
| $\lvert g \rvert$ | $3 \times 10^4$ keV (fixed) |

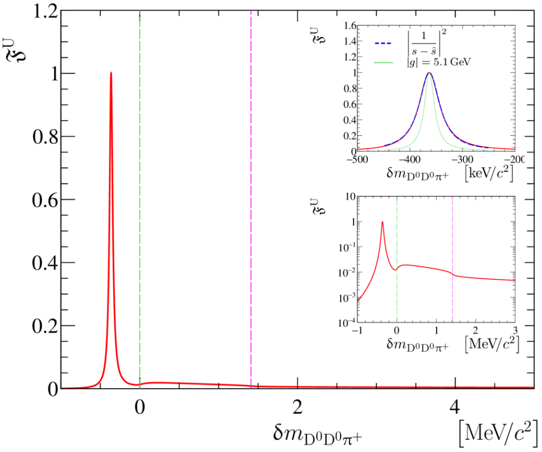



$$\delta m_U \equiv m_{T_{cc}^+} - (m_{D^{*+}} + m_{D^0})$$

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

# Features of the unitarized amplitude model

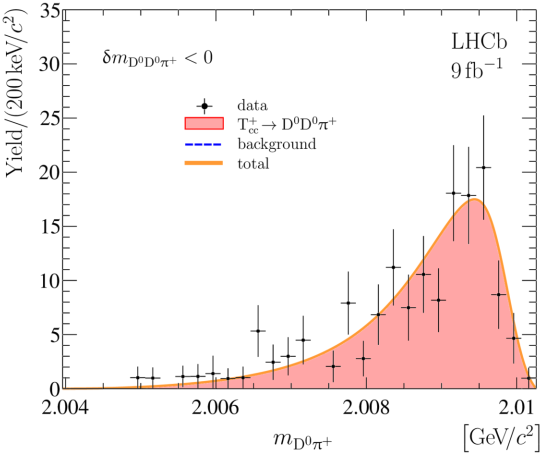
- Nearly isolated resonance below $D^{*+}D^0$ threshold.
- Best precision on peak position below threshold.
- FWHM: $47.8 \pm 1.9$ keV.
- Lifetime: $\tau \approx 10^{-20}$ s.
    - Compared to other exotic hadrons, lifetime is very large.
- Long tail observed.
- Threshold cusps observed at $D^{*+}D^0$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




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

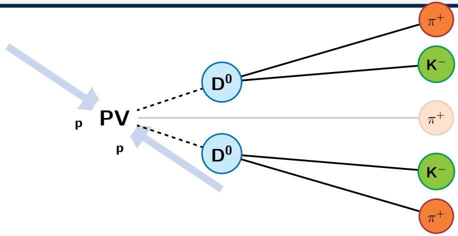
# Crosscheck of the model on $D^0\pi^+$

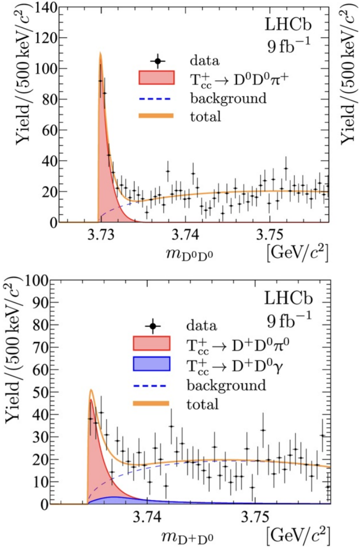
- Unitarized model integrated over $D^0D^0\pi^+$ and $D^0D^0$ masses to obtain $D^0\pi^+$ shape
- Only floating parameter is the yield
- Perfect agreement confirms:
  - $T_{cc}^+ \to DD^*$ is decaying via off-shell $D^*$ resonance
  - $J^P$ assignment for $T_{cc}^+$ is correct
- Future amplitude analysis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

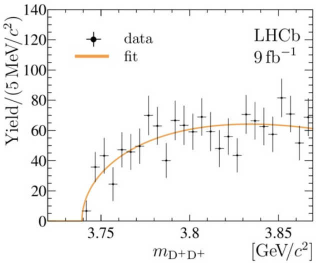
- If $T_{cc}^{+}$ was a part of $\mathcal{I} = 1$ triplet:

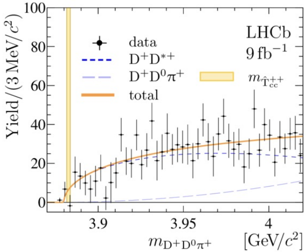
$$\begin{array}{ll} T_{cc}^{0} & cc\overline{dd} \\ T_{cc}^{+} & cc\overline{u}\overline{d} \\ T_{cc}^{++} & cc\overline{uu} \end{array}$$

- 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 $\Sigma_c^0$, $\Sigma_c^+$, $\Sigma_c^{++}$)



# Analytic continuation to the complex plane

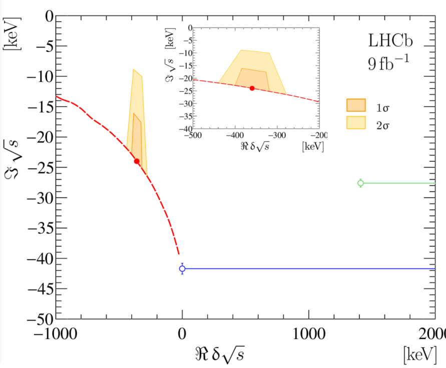
- Pole position can be obtained from the model:

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

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

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

- $\delta m_{pole} = -360 \pm 40^{+4}_{-0}$ 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: $0 \leq -r < 11.9(16.9)$ 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.
- This is an exciting new chapter of exotic hadron spectroscopy, with many intriguing results already obtained.
- $T_{cc}^{+}$ is the first state of $\mathcal{QQ}\bar{q}\bar{q}$ 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 to accommodate precision measurements of exotic states.

# End of talk

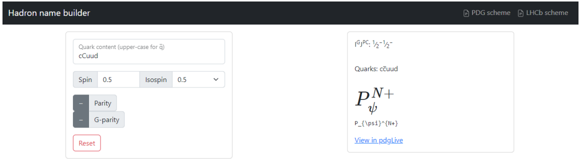
Thank You for your attention

# 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/]