Search for Pentaquarks Decaying to Open Charm Final States

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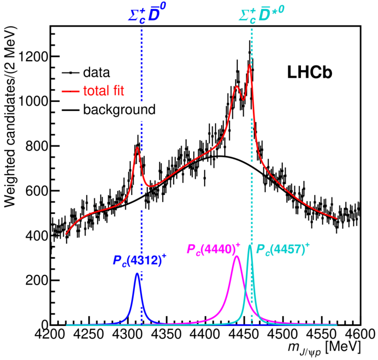
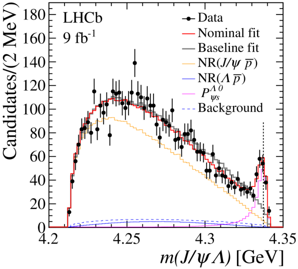
- Search for pentaquarks in wide range of charm hadron combinations (32 in total). - LHCb-PAPER-2023-018 in preparation.
- Observation of $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$ Decay. - LHCb-PAPER-2023-034 in preparation.
- Both in final stages of internal review.
- LHCb public results
- Prospects in Run 3 and beyond.

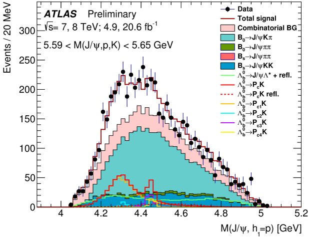
Motivation

- Exotic hadrons are ones which have quark content that is not $q\bar{q}$ or qqq.
- Proposed in Gell–Mann's quark model paper (Phys. Lett.(**8**) 3 (1964)).
- First observation of a pentaquark was by LHCb in 2015 in $J/\psi p$ mass spectrum. (PRL (**115**), 072001 (2015), PRL (**122**), 222001 (2019)).



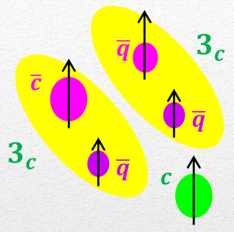
- First pentaquark with strangeness in $J/\psi\Lambda$ mass spectrum (PRL (**131**) 031901).





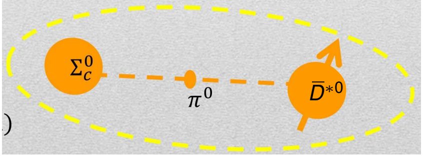
- ATLAS sees states consistent with LHCb pentaquarks (ATLAS-CONF-2019-048).
- Unable to rule out null hypothesis.

What is the structure of the observed pentaquark states?



Compact model:

- Fair understanding of existing spectrum.
- But doesn't explain proximity to threshold.



Molecular model:

- Proximity to threshold is natural.
- States are mostly unrelated to each other.
- States would be an order of 10x larger than compact counterparts.

- Possibly charmonium-like states?

Search for Prompt Production of Pentaquarks in Open-Charm Hadron Final States

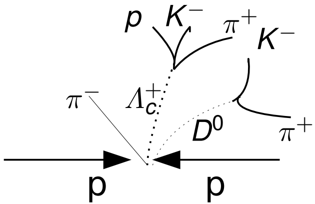
- Observed pentaquarks are close to mass threshold of some charm baryon-meson combinations. PRD **(101)**, 074030
- Structure is not clear - could they be molecules (PRD (**101**), 054037) or are they compact (EPJ A (**56**), 142) states?
- Goal was to search for pentaquark decays into a range of combinations of open-charm Σ_c or Λ_c^+ baryons with D mesons.
- Since no signal was seen, upper limits (ULs) are instead set in each mode (relative to the $\Lambda_c^+ \to pK^-\pi^+$ normalisation channel).

$$R = \frac{N_P}{N_{\Lambda_c^+}} \times \frac{\epsilon_{\Lambda_c^+}}{\epsilon_P}$$

- ULs set as a function of mass.

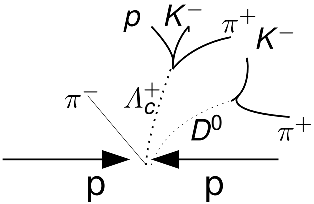
$\Sigma_c^{++}\bar{D}^0$ $\Sigma_c^0\bar{D}^0$	$\Sigma_c^{++}D^0$ $\Sigma_c^0 D^0$	$\Sigma_c^{++}D^-$ $\Sigma_c^0 D^-$	$\Sigma_c^{++}D^+$ $\Sigma_c^0 D^+$	$\Sigma_c^{++}D^{*-}$ $\Sigma_c^0 D^{*-}$	$\Sigma_c^{++}D^{*+}$ $\Sigma_c^0 D^{*+}$
$\Sigma_c^{*++}\bar{D}^0$ $\Sigma_c^{*0}\bar{D}^0$	$\Sigma_c^{*++}D^0$ $\Sigma_c^{*0}D^0$	$\Sigma_c^{*++}D^-$ $\Sigma_c^{*0}D^-$	$\Sigma_c^{*++}D^+$ $\Sigma_c^{*0}D^+$	$\Sigma_c^{*++}D^{*-}$ $\Sigma_c^{*0}D^{*-}$	$\Sigma_c^{*++}D^{*+}$ $\Sigma_c^{*0}D^{*+}$
$\Lambda_c^+\bar{D}^0$	$\Lambda_c^+D^0$	$\Lambda_c^+D^-$	$\Lambda_c^+D^+$	$\Lambda_c^+D^{*-}$	$\Lambda_c^+D^{*+}$
$\Lambda_c^+\bar{D}^0\pi^+$ $\Lambda_c^+\bar{D}^0\pi^-$	$\Lambda_c^+D^0\pi^+$ $\Lambda_c^+D^0\pi^-$	$\Lambda_c^+D^-\pi^+$ $\Lambda_c^+D^-\pi^-$	$\Lambda_c^+D^+\pi^+$ $\Lambda_c^+D^+\pi^-$	$\Lambda_c^+D^{*-}\pi^+$ $\Lambda_c^+D^{*-}\pi^-$	$\Lambda_c^+D^{*+}\pi^+$ $\Lambda_c^+D^{*+}\pi^-$

- Range of cc ($\Lambda_c^+D^0$, Σ_cD^+...) $c\bar{c}$ ($\Lambda_c^+D^-$, $\Sigma_c\bar{D}^0$) modes, as well as range of total charge.
- ULs are not set in all modes - some statistical limitations.

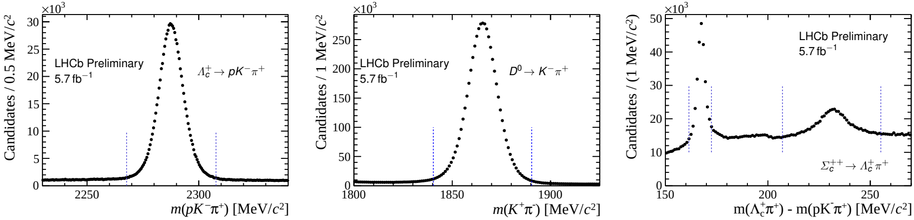


$\Sigma_c^{++}\bar{D}^0$	~~$\Sigma_c^{++}D^0$~~	$\Sigma_c^{++}D^-$	~~$\Sigma_c^{++}D^+$~~	~~$\Sigma_c^{++}D^{*-}$~~	~~$\Sigma_c^{++}D^{*+}$~~
$\Sigma_c^{0}\bar{D}^0$	~~$\Sigma_c^{0}D^0$~~	$\Sigma_c^{0}D^-$	~~$\Sigma_c^{0}D^+$~~	~~$\Sigma_c^{0}D^{*-}$~~	~~$\Sigma_c^{0}D^{*+}$~~
$\Sigma_c^{*++}\bar{D}^0$	$\Sigma_c^{*++}D^0$	$\Sigma_c^{*++}D^-$	$\Sigma_c^{*++}D^+$	$\Sigma_c^{*++}D^{*-}$	~~$\Sigma_c^{*++}D^{*+}$~~
$\Sigma_c^{*0}\bar{D}^0$	$\Sigma_c^{*0}D^0$	$\Sigma_c^{*0}D^-$	$\Sigma_c^{*0}D^+$	$\Sigma_c^{*0}D^{*-}$	~~$\Sigma_c^{*0}D^{*+}$~~
$\Lambda_c^{+}\bar{D}^0$	$\Lambda_c^{+}D^0$	$\Lambda_c^{+}D^-$	$\Lambda_c^{+}D^+$	$\Lambda_c^{+}D^{*-}$	$\Lambda_c^{+}D^{*+}$
$\Lambda_c^{+}\bar{D}^0\pi^+$	$\Lambda_c^{+}D^0\pi^+$	$\Lambda_c^{+}D^-\pi^+$	$\Lambda_c^{+}D^+\pi^+$	$\Lambda_c^{+}D^{*-}\pi^+$	$\Lambda_c^{+}D^{*+}\pi^+$
$\Lambda_c^{+}\bar{D}^0\pi^-$	$\Lambda_c^{+}D^0\pi^-$	$\Lambda_c^{+}D^-\pi^-$	$\Lambda_c^{+}D^+\pi^-$	$\Lambda_c^{+}D^{*-}\pi^-$	$\Lambda_c^{+}D^{*+}\pi^-$

- 10 modes are too statistically limited to set UL.
- Leaves 32.
- *N.B.* Excited doubly charmed baryons could also appear in these spectra.

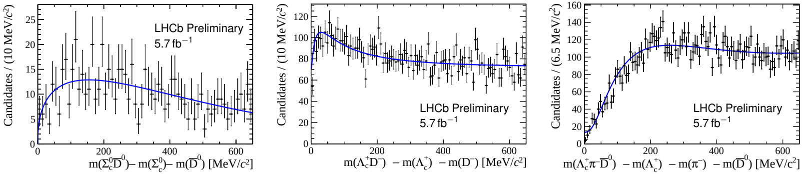


- 2016 - 2018 data set ($5.7\,\mathrm{fb}^{-1}$).
- Baryons/mesons are built in trigger, and optimised individually. Optimisation then applied in signal combination.
- Simulation samples used to optimise selection and train multivariate algorithms.
- $\Sigma_c^{++(0)} \to \Lambda_c^+ \pi^{+(-)}$, $D^{*-} \to \bar{D}^0 \pi^-$, $D^- \to K^+ \pi^- \pi^-$
- Σ_c^{++} (uuc), Λ_c^+ (udc), D^- $(d\bar{c})$, D^0 $(c\bar{u})$



Fitting Procedure

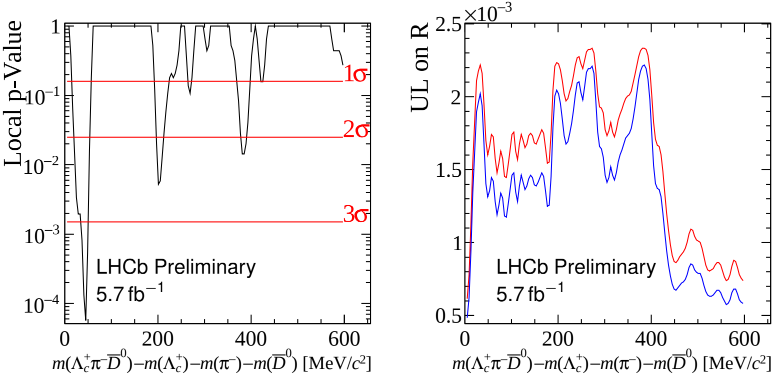
- Fit is done simultaneously to open-charm signal and sideband samples.
- $\Sigma_c^{(*)} D$ modes use threshold function for background.
- $\Lambda_c^+ D$ and $\Lambda_c^+ \pi D$ modes use Chebychev polynomial summed with log normal distribution for background.



- Range of signal models - Gaussian, 5, 10, 15 MeV/c^2 Voigtians.
- Gives some sensitivity to a state with broader width.

Scanning Method

- In 4 MeV/c^2 steps from threshold to +600 MeV/c^2 above.
- Fit simultaneously to signal and sideband regions, split by trigger categories, find **local** *p*–value and UL of fit.
- UL smeared by systematic Gaussian.



Results

- Result is 4 tables (part of 15 MeV/c^2 shown here), with highest local and global significances with corresponding mass.

Decay Mode	Lowest p–value		Significance (σ)		Corresponding	Signal Yield	Upper Limit ($\times 10^{-3}$)	
	Local	Global	Local	Global	Mass (MeV/c^2)		90% CL	95% CL
$\Lambda_c^+ \bar{D}^0$	2.18×10^{-3}	0.16	2.85	1.01	349	46.8 ± 23.4	1.16	1.21
$\Lambda_c^+ D^{*-}$	1.02×10^{-2}	1.00	2.32	0.00	365	15.0 ± 10.3	2.16	2.39
$\Lambda_c^+ \pi^+ D^-$	2.42×10^{-3}	0.16	2.82	0.99	225	68.6 ± 13.3	1.95	2.40
$\Sigma_c^0 \bar{D}^0$	2.85×10^{-2}	1.00	1.90	0.00	65	4.7 ± 4.2	1.02	1.15
$\Lambda_c^+ \pi^- \bar{D}^0$	5.69×10^{-5}	5.23×10^{-3}	3.86	2.56	45	60.1 ± 25.9	1.40	1.70
$\Sigma_c^0 D^-$	2.10×10^{-2}	1.00	2.03	0.00	261	7.0 ± 2.6	0.71	0.89
$\Lambda_c^+ \pi^- D^-$	1.20×10^{-4}	9.49×10^{-3}	3.67	2.35	249	82.8 ± 14.3	2.23	2.67
$\Lambda_c^+ \pi^- D^{*-}$	1.04×10^{-2}	1.00	2.31	0.00	409	23.6 ± 23.0	2.79	3.28
$\Sigma_c^{*++} D^{*-}$	4.10×10^{-2}	1.00	1.74	0.00	453	3.3 ± 2.4	1.24	1.43
$\Sigma_c^{*0} D^-$	3.12×10^{-2}	1.00	1.86	0.00	109	10.7 ± 29.1	1.32	1.59
$\Lambda_c^+ D^+$	5.84×10^{-3}	0.28	2.52	0.59	169	14.9 ± 9.6	1.34	1.50
$\Lambda_c^+ \pi^+ D^0$	6.60×10^{-4}	0.04	3.21	1.72	45	24.8 ± 39.3	0.98	1.18
$\Lambda_c^+ \pi^+ D^{*+}$	3.74×10^{-4}	0.02	3.37	1.99	165	13.8 ± 3.5	0.97	1.22
$\Lambda_c^+ \pi^- D^{*+}$	3.44×10^{-3}	0.28	2.70	0.58	73	5.8 ± 71.3	1.70	1.94
$\Sigma_c^{*++} D^0$	1.76×10^{-2}	1.00	2.11	0.00	113	3.9 ± 2.8	0.87	0.99
$\Sigma_c^{*0} D^+$	1.46×10^{-2}	1.00	2.18	0.00	69	4.7 ± 4.6	1.13	1.32

- Result is 4 tables (part of 15 MeV/c^2 shown here), with highest local and global significances with corresponding mass.

Decay Mode	Lowest p–value Local	Lowest p–value Global	Significance (σ) Local	Significance (σ) Global	Corresponding Mass (MeV/c^2)	Signal Yield	Upper Limit ($\times10^{-3}$) 90% CL	Upper Limit ($\times10^{-3}$) 95% CL
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$\Lambda_c^+\pi^+ D^-$	2.42×10^{-3}	0.16	2.82	0.99	225	68.6 ± 13.3	1.95	2.40
$\Sigma_c^0\bar{D}^0$	2.85×10^{-2}	1.00	1.90	0.00	65	4.7 ± 4.2	1.02	1.15
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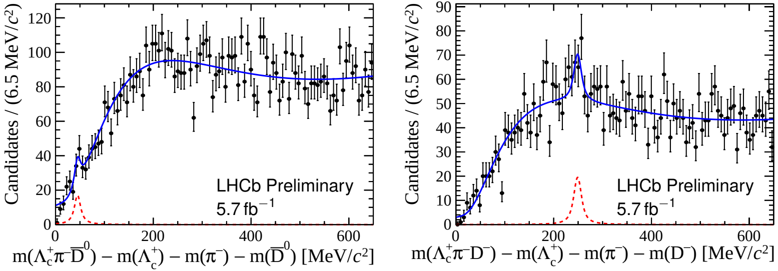
$\Lambda_c^+\pi^- D^-$	1.20×10^{-4}	9.49×10^{-3}	3.67	2.35	249	82.8 ± 14.3	2.23	2.67
$\Lambda_c^+\pi^- D^{*-}$	1.04×10^{-2}	1.00	2.31	0.00	409	23.6 ± 23.0	2.79	3.28
$\Sigma_c^{*++} D^{*-}$	4.10×10^{-2}	1.00	1.74	0.00	453	3.3 ± 2.4	1.24	1.43
$\Sigma_c^{*0} D^-$	3.12×10^{-2}	1.00	1.86	0.00	109	10.7 ± 29.1	1.32	1.59
$\Lambda_c^+ D^+$	5.84×10^{-3}	0.28	2.52	0.59	169	14.9 ± 9.6	1.34	1.50
$\Lambda_c^+\pi^+ D^0$	6.60×10^{-4}	0.04	3.21	1.72	45	24.8 ± 39.3	0.98	1.18
$\Lambda_c^+\pi^+ D^{*+}$	3.74×10^{-4}	0.02	3.37	1.99	165	13.8 ± 3.5	0.97	1.22
$\Lambda_c^+\pi^- D^{*+}$	3.44×10^{-3}	0.28	2.70	0.58	73	5.8 ± 71.3	1.70	1.94
$\Sigma_c^{*++} D^0$	1.76×10^{-2}	1.00	2.11	0.00	113	3.9 ± 2.8	0.87	0.99
$\Sigma_c^{*0} D^+$	1.46×10^{-2}	1.00	2.18	0.00	69	4.7 ± 4.6	1.13	1.32

- Highest **global** significances are 2.56σ and 2.35σ in $\Lambda_c^+\pi^-\overline{D}^0$ and $\Lambda_c^+\pi^-D^-$ modes.



- Modes would be interesting to look at with larger data set in near future.
- Paper available on arXiv very soon!

- Where kinematically possible, the width and mass of the known pentaquarks can be fitted.

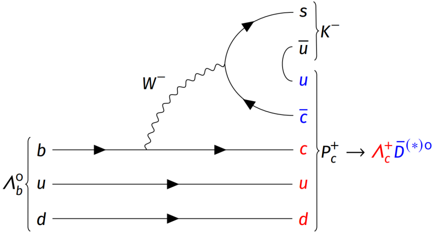
Decay Mode (Threshold)	Pentaquark Hypothesis
$\Lambda_c^+ \overline{D}^0$ (4151.29 MeV)	$P_c(4312)^+$
	$P_c(4440)^+$
	$P_c(4457)^+$
$\Sigma_c^0 D^-$ (4323.41 MeV)	$P_c(4440)^+$
	$P_c(4457)^+$
$\Lambda_c^+ \pi^+ D^{*-}$ (4436.32 MeV)	$P_c(4440)^+$
	$P_c(4457)^+$

$P_c(4312)^+$	$M = 4311.9$ MeV, $\Gamma = 10$ MeV
$P_c(4440)^+$	$M = 4440$ MeV, $\Gamma = 21$ MeV
$P_c(4457)^+$	$M = 4457.3$ MeV, $\Gamma = 6.4$ MeV

- Only consider states with hidden charm content.
- Signal yield consistent with 0 in all cases.
- Full details in paper.

Observation of $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$ Decay

- Comparable to $\Lambda_b^0 \to J/\psi p K^-$ since P_c production is the same.



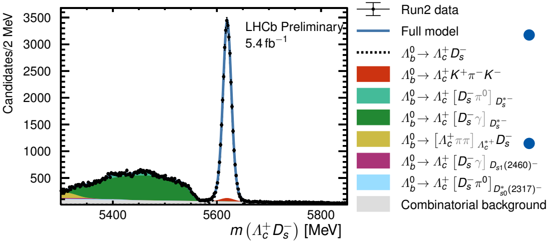
- To probe, we need:
  - Fit fraction - $f_{\Lambda_c^+ \bar{D}^{(*)0}}$
  - $\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-)}$

- BFs relative to $\Lambda_b^0 \to \Lambda_c^+ D_s^-$ found.

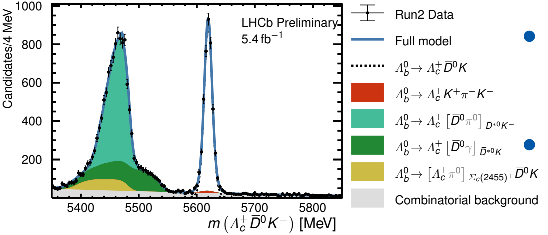
- 2016-18 Run 2 dataset ($5.4\,\text{fb}^{-1}$).
- Measure $\frac{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+\bar{D}^{(*)0}K^-)}{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+D_s^-)} = \frac{N_{\Lambda_c^+\bar{D}^{(*)0}K^-}}{N_{\Lambda_c^+D_s^-}} \frac{\epsilon_{\Lambda_c^+\bar{D}^{(*)0}K^-}}{\epsilon_{\Lambda_c^+D_s^-}} \frac{\mathcal{B}(D_s^-\to K^-K^+\pi^-)}{\mathcal{B}(\bar{D}^0\to K^+\pi^-)}$
- Reconstruction and trigger selection identical between $\Lambda_c^+\bar{D}^{(*)0}K^-$ and $\Lambda_c^+D_s^-$ decay modes.
- Topological and particle identification requirements different between modes.
- BDT used to clean combinatorial background in $\Lambda_c^+\to pK^-\pi^+$ spectrum.
- $\Lambda_c^+\bar{D}^{*0}K^-$ selected with partially reconstructed $\bar{D}^{*0}\to\bar{D}^0\pi^0(\bar{D}^0\gamma)$.
- 4 selection strategies, 3 background subtraction methods, 3 weighting methods - validate result.

Mass Spectrum

LHCb-PAPER-2023-034



- $\Lambda_c^+ \bar{D}^{*0} K^-$ selected with partially reconstructed $\bar{D}^{*0} \to \bar{D}^0 \pi^0 (\bar{D}^0 \gamma)$
- Many other partially reconstructed decays accommodated in the spectra.



- $\Lambda_b^0 \to \Sigma_c(2455)^+ \bar{D}^0 K^-$ is color suppressed, yet shows significant component.
- Possible enhancement from Ξ_c^{*0}, or P_c?

$$N^{\Lambda_b^0\to\Lambda_c^+ D_s^{*-}} = 46\,400 \pm 500(stat.),\ N^{\Lambda_b^0\to\Lambda_c^+ D_s^{-}} = 35\,450^{+200}_{-210}(stat.)$$

$$N^{\Lambda_b^0\to\Lambda_c^+ \bar{D}^{*0} K^-} = 10\,560^{+310}_{-290}(stat.),\ N^{\Lambda_b^0\to\Lambda_c^+ \bar{D}^{0} K^-} = 4\,010 \pm 70(stat.)$$

- Converting to BFs:

$$\frac{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+ D^0 K^-)}{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+ D_s^-)} = 0.1908^{+0.0036}_{-0.0034}(stat.)^{+0.0016}_{-0.0018}(syst.) \pm 0.0038(\mathcal{B})$$

$$\frac{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+ \bar{D}^{*0} K^-)}{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+ D_s^-)} = 0.589^{+0.018}_{-0.017}(stat.)^{+0.017}_{-0.018}(syst.) \pm 0.012(\mathcal{B})$$

- Finally relative to $J/\psi p K^-$ (using PRL 122, 222001):

$$\frac{\mathcal{B}(\Lambda_b^0\to J/\psi p K^-)}{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+ \bar{D}^0 K^-)} = 0.152^{+0.032}_{-0.028}\quad \frac{\mathcal{B}(\Lambda_b^0\to J/\psi p K^-)}{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+ \bar{D}^{*0} K^-)} = 0.049^{+0.011}_{-0.009}$$

Reference	$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^{*-})}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)}$
Z. Phys. C 59, 179	0.75
Phys. Rev. D 56, 2799	0.83
Mod. Phys. Lett. A 13, 23	1.54
Phys. Rev. D 58, 014016	1.46
Prog. Theor. Phys. 101, 959	1.84
Phys. Rev. D 99, 054020	0.85
Chin. Phys. C 42, 093101	1.49
Eur. Phys. J. C 78, 528	1.23
Phys. Rev. D 98, 074011	1.70
Eur. Phys. J. C 79, 540	1.51
Phys. Rev. D 100, 034025	1.47
Eur. Phys. J. C 80, 636	1.29
arXiv:2309.12050	2.25

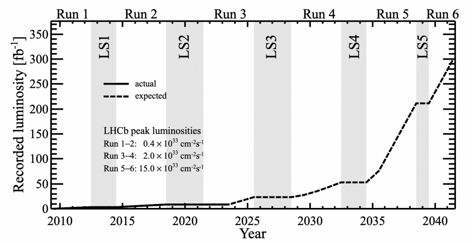
- Also make a measurement of $\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^{*-})}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)}$.
- Consistent with several theory predictions.

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^{*-})}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = 1.668 \pm 0.022(stat.)^{+0.061}_{-0.055}(syst.)$$

Conclusions

- Search for pentaquarks in wide range of signal channels (LHCb-PAPER-2023-018).
  - No substantial evidence of signal.
  - Some hints of interesting areas.
  - 2.35σ in $\Lambda_c^+\pi^-D^-$, 2.56σ in $\Lambda_c^+\pi^-\bar{D}^0$.
  - With Run 3 data a study of these regions could be interesting.
  - No signal seen for decays from known pentaquark states.
- Observation of $\Lambda_b^0 \to \Lambda_c^+\bar{D}^{(*)0}K^-$ decay (LHCb-PAPER-2023-034).
  - $\frac{\mathcal{B}(\Lambda_b^0\to J/\psi pK^-)}{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+\bar{D}^0K^-)} = 0.152^{+0.032}_{-0.028}$
  - $\frac{\mathcal{B}(\Lambda_b^0\to J/\psi pK^-)}{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+\bar{D}^{*0}K^-)} = 0.049^{+0.011}_{-0.009}$
  - $\frac{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+D_s^{*-})}{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+D_s^-)} = 1.668 \pm 0.022(stat.)^{+0.061}_{-0.055}(syst.)$ - consistent with several theory predictions.
  - Future analysis to determine $f_{\Lambda_c^+\bar{D}^{(*)0}}$ will allow to test model predictions.

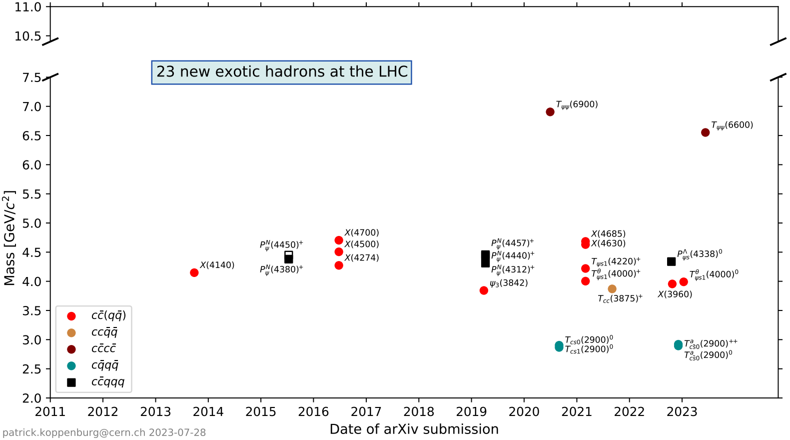
- More results still to come from LHCb Run 2 dataset.
  - Many pentaquark analyses nearing completion.
- LHCb Run 3 has just begun:
  - New data set is on the horizon - will be $\sim$10x (by end of Run 4) larger than the existing dataset.
  - Improved trigger means cleaner hadronic events.
  - Statistically limited pentaquark searches will be within our grasp.



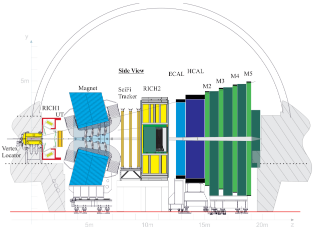
LHCb RUN 3 PROSPECTS

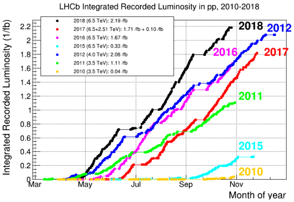
Backup slides

So far, ATLAS, CMS and LHCb have discovered 73 new hadronic states of which 20+ are exotic – majority discovered at LHCb (Plot Source).



- Largest heavy–flavour dataset collected – 9 fb^{-1} with Run 1+2.
- Largest production cross–sections of *b* and *c* hadrons.
- Specialised trigger for hadronic decays.





- Two Ring Imaging CHerenkov (RICH) detectors allow excellent PID.
- VErtex LOcator (VELO) and tracking stations allow precise tracking of particles.

- For $\Sigma_c D$ and $\Sigma_c^* D$ modes the fit model is a threshold function:

$$f(x) = x^{\gamma} \cdot \exp(-p_1 \cdot x) \quad (1)$$

- $\Lambda_c^+ D$ and $D\Lambda_c^+ \pi$ modes use a Chebychev polynomial summed with a log normal distribution:

$$f(x) = f \cdot \frac{1}{2\pi \cdot \ln k * x} \cdot \exp\left(\frac{-\ln^2(\frac{x}{m_0})}{2\ln^2 k} \right) + (1-f) \cdot C(x, x_1) \quad (2)$$