Recent Results in Pentaquark Studies at LHCb

Gary Robertson
On Behalf of the LHCb Collaboration

NSTAR 2024

19^{th} June 2024

University of Glasgow
gary.robertson@cern.ch

University of Glasgow

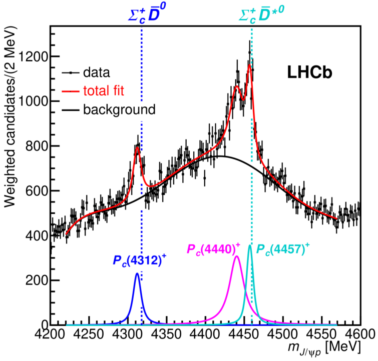
VIA VERITAS VITA

LHCb

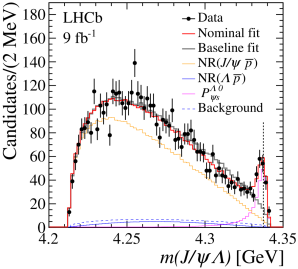
- Search for pentaquarks in wide range of charm hadron combinations (32 in total). - Accepted by PRD (arXiv:2404.07131).
- Observation of $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$ and $\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}$ Decays. - Published in EPJ C 84 (2024) 575.
- First observation of $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$ decays and measurement of their relative branching fractions. - Accepted by PRD Lett. (arXiv:2404.19510)
- Prospects in Run 3 and beyond.

Motivation

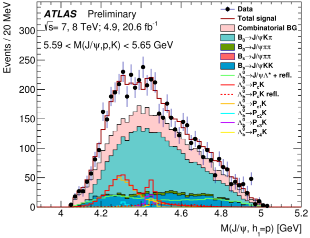
- Exotic hadrons are ones which have quark content that is not $q\bar{q}$ or qqq.
- Proposed by Gell–Mann's (Phys. Lett.(**8**) 3 (1964)) and Zweig (CDS (1964)).
- First observation of a pentaquark was by LHCb in 2015 in $J/\psi p$ ($c\bar{c}uud$) mass spectrum. (PRL (**115**), 072001 (2015))



PRL (**122**), 222001 (2019)

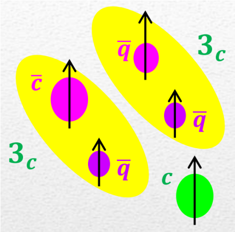


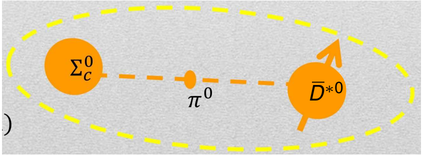
- First pentaquark with strangeness in $J/\psi\Lambda$ mass spectrum (PRL (**131**) 031901).



- 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?





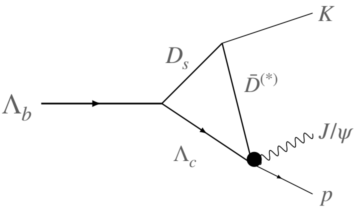
Compact model:

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

Molecular model:

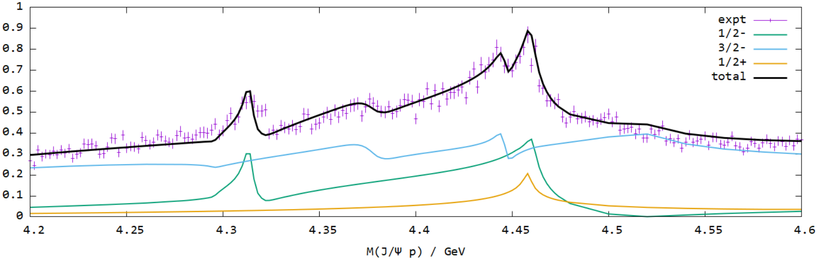
- Proximity to threshold is natural.
- States are mostly unrelated to each other.
- States would be an order of 10x larger than compact counterparts.

- Possibly charmonium-like states?

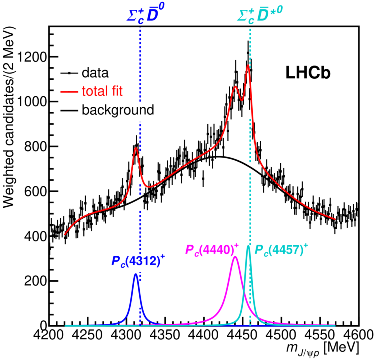


- Triangle singularities can also potentially explain apparent peaks.

PRD (**106**) 054029 (2022)

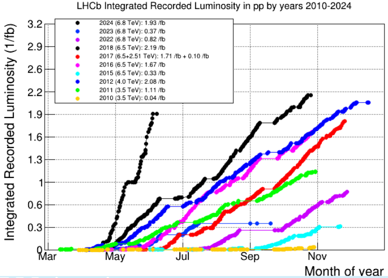


- The three analyses focused on are sensitive to pentaquark contributions to their open-charm hadron final states.
- Prompt and non-prompt production.
- Predicted by many theorists, but not yet observed.
- Important test of our theories on pentaquark production mechanisms.

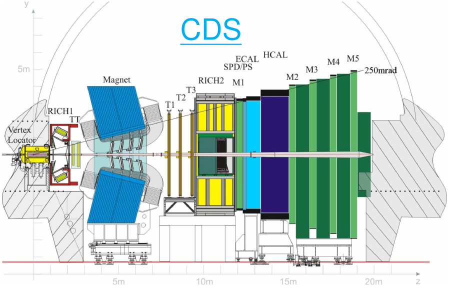


PRL (**122**), 222001 (2019)

- Largest heavy–flavour dataset collected – 3 + 6 fb^{-1} with Run 1+2.
- Large production cross–sections of *b* and *c* hadrons.
- Specialised trigger for hadronic decays.



CDS



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

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

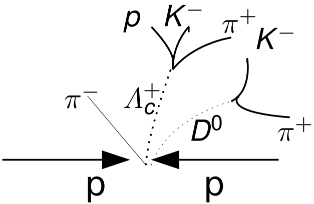
- Observed pentaquarks are close to mass threshold of some charm baryon-meson combinations.
  PRD **(101)**, 074030 (2020)
- Structure is not clear - could they be molecules (PRD (**101**), 054037 (2020)) or are they compact (EPJ A (**56**), 142 (2020)) states?
- Goal was to search for pentaquark decays 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.

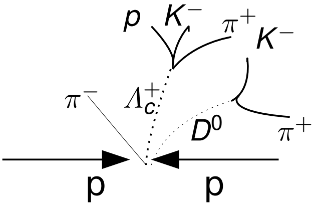
$\Sigma_c^{++}\bar{D}^0$ $\Sigma_c^{0}\bar{D}^0$	$\Sigma_c^{++}D^0$ $\Sigma_c^{0}D^0$	$\Sigma_c^{++}D^-$ $\Sigma_c^{0}D^-$	$\Sigma_c^{++}D^+$ $\Sigma_c^{0}D^+$	$\Sigma_c^{++}D^{*-}$ $\Sigma_c^{0}D^{*-}$	$\Sigma_c^{++}D^{*+}$ $\Sigma_c^{0}D^{*+}$
$\Sigma_c^{*++}\bar{D}^0$ $\Sigma_c^{*0}\bar{D}^0$	$\Sigma_c^{*++}D^0$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

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

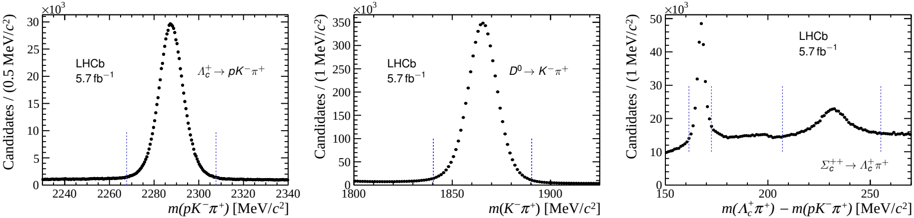


$\Sigma_c^{++}\bar{D}^0$	~~$\Sigma_c^{++}D^0$~~	$\Sigma_c^{++}D^-$	~~$\Sigma_c^{++}D^+$~~	~~$\Sigma_c^{++}D^{*-}$~~	~~$\Sigma_c^{++}D^{*+}$~~
$\Sigma_c^{0}\bar{D}^0$	~~$\Sigma_c^{0}D^0$~~	$\Sigma_c^{0}D^-$	~~$\Sigma_c^{0}D^+$~~	~~$\Sigma_c^{0}D^{*-}$~~	~~$\Sigma_c^{0}D^{*+}$~~
$\Sigma_c^{*++}\bar{D}^0$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

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

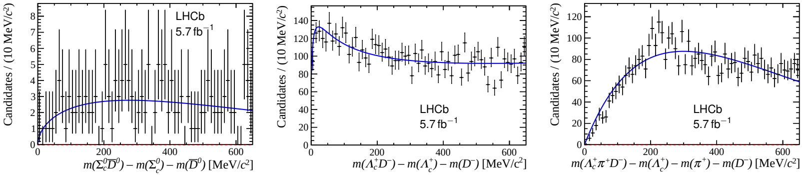


- 2016 - 2018 data set (5.7 fb^{-1}).
- Baryons/mesons are built in high level trigger selection, and optimised individually. Optimisation then applied in signal combination.
- Simulation samples used to optimise selection and train multivariate algorithms.
- $\Sigma_c^{++(0)} \to \Lambda_c^+ \pi^{+(-)}$,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



Fitting Procedure

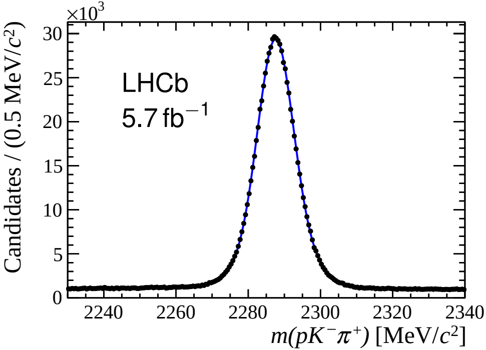
- Fit is done simultaneously to open-charm signal and sideband samples.
- $\Sigma_c^{(*)} D$ and $\Lambda_c^+ \pi D$ modes use threshold function for background.
- $\Lambda_c^+ D$ modes use Chebyshev polynomial summed with log normal distribution for background.



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

Normalisation Channel

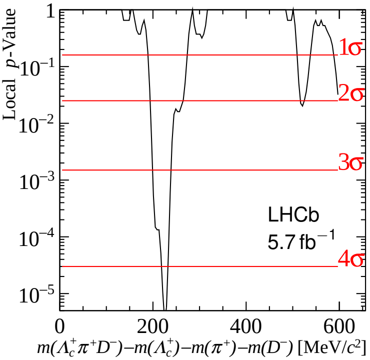
- $\Lambda_c^+ \to pK^-\pi^+$ decay is modelled using sum of Gaussian with Crystal Ball function.
- 1^{st} order Chebyshev polynomial for combinatorial background.

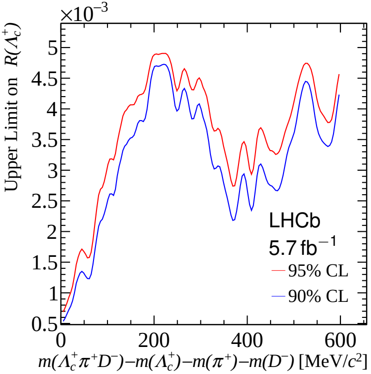


- Yield of $789,200 \pm 1,300$.

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.
- **Local** *p*–value is corrected for look elsewhere effect.



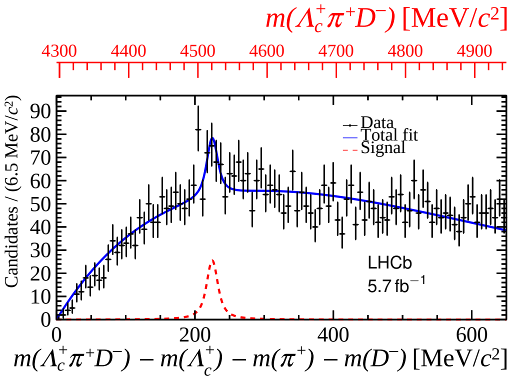


Results

Decay Mode	Width (MeV)	Lowest p–value Local	Lowest p–value Corrected	Significance (σ) Local	Significance (σ) Corrected	Q-value (MeV/c^2)	Signal Yield	UL ($\times 10^{-3}$) 90% CL	UL ($\times 10^{-3}$) 95% CL
$\Lambda_c^+ \pi^- D^-$	0	3.9×10^{-4}	0.03	3.36	1.90	257	38.1 ± 12.4	4.28	4.56
	5	5.71×10^{-5}	3.33×10^{-3}	3.86	2.71	253	62.1 ± 17.1	4.62	4.83
	10	1.45×10^{-5}	6.92×10^{-4}	4.18	3.20	249	83.7 ± 21.2	4.72	4.88
	15	4.59×10^{-6}	1.83×10^{-4}	4.44	3.56	249	103.5 ± 24.6	4.77	4.92
$\Lambda_c^+ \pi^- D^{*-}$	0	4.4×10^{-3}	0.31	2.62	0.48	197	12.0 ± 5.3	3.11	3.45
	5	7.1×10^{-3}	0.31	2.45	0.51	197	16.8 ± 7.3	4.08	4.53
	10	8.6×10^{-3}	0.27	2.38	0.61	197	21.2 ± 9.1	4.69	5.15
	15	8.9×10^{-3}	0.22	2.37	0.78	197	25.5 ± 10.8	5.11	5.56
$\Sigma_c^{*++} \overline{D}^0$	0	1×10^{-2}	0.75	2.32	0.00	37	5.0 ± 2.8	0.96	1.09
	5	1.2×10^{-2}	0.62	2.24	0.00	37	7.8 ± 4.0	1.32	1.49
	10	2.7×10^{-2}	0.92	1.92	0.00	205	7.0 ± 20.6	1.57	1.78
	15	2.7×10^{-2}	0.73	1.92	0.00	485	12.5 ± 6.7	2.23	2.49
$\Sigma_c^{*++} D^-$	0	1.2×10^{-3}	0.11	3.03	1.21	537	6.5 ± 3.3	1.63	1.82
	5	1.6×10^{-3}	0.10	2.95	1.30	497	11.8 ± 5.0	2.52	2.79
	10	2.5×10^{-3}	0.11	2.81	1.24	497	13.0 ± 5.7	2.82	3.12
	15	4.3×10^{-3}	0.14	2.63	1.07	497	13.9 ± 6.3	3.02	3.37
$\Sigma_c^{*++} D^{*-}$	0	2.3×10^{-2}	1.40	2.00	0.00	193	2.5 ± 1.8	1.08	1.23
	5	3.5×10^{-2}	1.44	1.81	0.00	449	2.9 ± 2.1	1.26	1.45
	10	3.5×10^{-2}	1.08	1.81	0.00	453	3.2 ± 2.3	1.36	1.57
	15	4.1×10^{-2}	0.99	1.74	0.00	453	3.3 ± 2.4	1.45	1.66

Decay Mode	Width (MeV)	Lowest p–value Local	Lowest p–value Corrected	Significance (σ) Local	Significance (σ) Corrected	Q-value (MeV/c^2)	Signal Yield	UL ($\times 10^{-3}$) 90% CL	UL ($\times 10^{-3}$) 95% CL
$\Lambda_c^+ \pi^- D^-$	0	3.9×10^{-4}	0.03	3.36	1.90	257	38.1 ± 12.4	4.28	4.56
	5	5.71×10^{-5}	3.33×10^{-3}	3.86	2.71	253	62.1 ± 17.1	4.62	4.83
	10	1.45×10^{-5}	6.92×10^{-4}	4.18	3.20	249	83.7 ± 21.2	4.72	4.88
	15	4.59×10^{-6}	1.83×10^{-4}	4.44	3.56	249	103.5 ± 24.6	4.77	4.92
$\Lambda_c^+ \pi^- D^{*-}$	0	4.4×10^{-3}	0.31	2.62	0.48	197	12.0 ± 5.3	3.11	3.45
	5	7.1×10^{-3}	0.31	2.45	0.51	197	16.8 ± 7.3	4.08	4.53
	10	8.6×10^{-3}	0.27	2.38	0.61	197	21.2 ± 9.1	4.69	5.15
	15	8.9×10^{-3}	0.22	2.37	0.78	197	25.5 ± 10.8	5.11	5.56
$\Sigma_c^{*++} \overline{D}^0$	0	1×10^{-2}	0.75	2.32	0.00	37	5.0 ± 2.8	0.96	1.09
	5	1.2×10^{-2}	0.62	2.24	0.00	37	7.8 ± 4.0	1.32	1.49
	10	2.7×10^{-2}	0.92	1.92	0.00	205	7.0 ± 20.6	1.57	1.78
	15	2.7×10^{-2}	0.73	1.92	0.00	485	12.5 ± 6.7	2.23	2.49
$\Sigma_c^{*++} D^-$	0	1.2×10^{-3}	0.11	3.03	1.21	537	6.5 ± 3.3	1.63	1.82
	5	1.6×10^{-3}	0.10	2.95	1.30	497	11.8 ± 5.0	2.52	2.79
	10	2.5×10^{-3}	0.11	2.81	1.24	497	13.0 ± 5.7	2.82	3.12
	15	4.3×10^{-3}	0.14	2.63	1.07	497	13.9 ± 6.3	3.02	3.37
$\Sigma_c^{*++} D^{*-}$	0	2.3×10^{-2}	1.40	2.00	0.00	193	2.5 ± 1.8	1.08	1.23
	5	3.5×10^{-2}	1.44	1.81	0.00	449	2.9 ± 2.1	1.26	1.45
	10	3.5×10^{-2}	1.08	1.81	0.00	453	3.2 ± 2.3	1.36	1.57
	15	4.1×10^{-2}	0.99	1.74	0.00	453	3.3 ± 2.4	1.45	1.66

- In five channels, corrected significances $> 3\sigma$ observed.



- Correction within modes is applied (see Slide 35), but nothing to account for across all modes.

- Using 1,000 background-only pseudo-datasets, the scan was repeated for every mode.
- Using Voigtian signal model with 15 MeV/c^2.
- Fluctuations above 3σ can be counted and averaged across all modes.

- Average number of fluctuations above 3σ: 6.97.
- Standard deviation: 4.99.
- Thus, five significances reported in previous slide **are** consistent with background fluctuations.

- 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)	$P_c(4440)^+$
	$P_c(4457)^+$

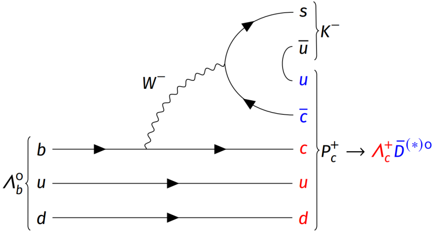
$P_c(4312)^+$	$M = 4311.9\,\text{MeV}, \Gamma = 10\,\text{MeV}$
$P_c(4440)^+$	$M = 4440\,\text{MeV}, \Gamma = 21\,\text{MeV}$
$P_c(4457)^+$	$M = 4457.3\,\text{MeV}, \Gamma = 6.4\,\text{MeV}$

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

- Search carried out over many modes.
- No strong evidence of pentaquark signal.
- Significances seen are consistent with background data.
- No evidence for existing pentaquark states.

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

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



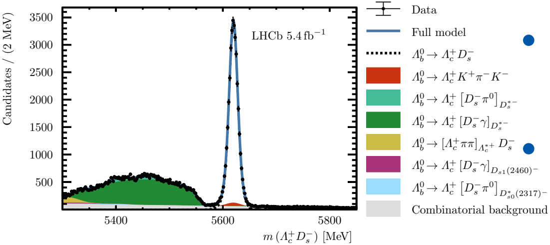
- To probe, we need:
  - Fit fraction - the fraction of $P_c \to \Lambda_c^+ \bar{D}^{(*)0}$ in $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-$.
  - $\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-)}$

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

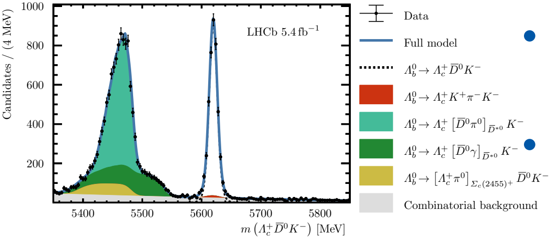
- 2016-18 Run 2 dataset (5.4 fb^{-1}).
- Measure $\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = \frac{N_{\Lambda_c^+ \bar{D}^{(*)0} K^-}}{N_{\Lambda_c^+ D_s^-}} \frac{\epsilon_{\Lambda_c^+ \bar{D}^{(*)0} K^-}}{\epsilon_{\Lambda_c^+ D_s^-}} \frac{\mathcal{B}(D_s^- \to K^- K^+ \pi^-)}{\mathcal{B}(\bar{D}^0 \to K^+ \pi^-)}$
- 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 $\Lambda_c^+ \to p K^- \pi^+$ 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

EPJ C 84 (2024) 575



- $\Lambda_c^+ \bar{D}^{*0} K^-$ 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?

Results

$$N^{\Lambda_b^0 \to \Lambda_c^+ \bar{D}^0 K^-} / N^{\Lambda_b^0 \to \Lambda_c^+ D_s^-} = 0.1132^{+0.0021}_{-0.0020}(stat.)^{+0.0006}_{-0.0007}(syst.)$$

$$N^{\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{*0} K^-} / N^{\Lambda_b^0 \to \Lambda_c^+ D_s^-} = 0.298^{+0.009}_{-0.008}(stat.)^{+0.008}_{-0.009}(syst.)$$

- 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 (2019)):

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

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.

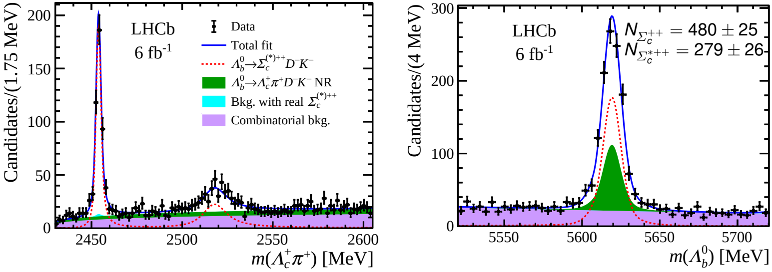
$$N^{\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}} / N^{\Lambda_b^0 \to \Lambda_c^+ D_s^-} = 1.309 \pm 0.017^{+0.047}_{-0.043}$$

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

- Results are consistent with theoretical predictions for $\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^{*-})}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)}$.
- Branching fractions of $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$ relative to $\Lambda_b^0 \to J/\psi p K^-$ are measured - important ingredient for pentaquark studies.
- Future analysis to measure the pentaquark fit fractions will give last missing ingredient and allow models for branching fractions relative to $J/\psi p$ to be tested.

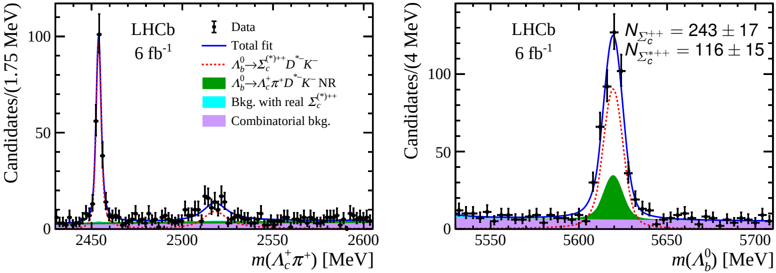
First observation of $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$ decays

- 2015 - 2018 dataset ($6\,\text{fb}^{-1}$).
- Use $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^0 K^-$ decay as normalisation channel.
- Aim to measure $\frac{\Lambda_b^0 \to \Sigma_c^{++} D^- K^-}{\Lambda_b^0 \to \Lambda_c^+ \bar{D}^0 K^-}$, $\frac{\Lambda_b^0 \to \Sigma_c^{*++} D^- K^-}{\Lambda_b^0 \to \Sigma_c^{++} D^- K^-}$, $\frac{\Lambda_b^0 \to \Sigma_c^{++} D^{*-} K^-}{\Lambda_b^0 \to \Sigma_c^{++} D^- K^-}$, $\frac{\Lambda_b^0 \to \Sigma_c^{*++} D^{*-} K^-}{\Lambda_b^0 \to \Sigma_c^{++} D^- K^-}$.
- Using $\Lambda_b^0 \to \Sigma_c^{++} D^- K^-$ as normalisation cancels many systematics - simplifies measurement.
- Non-Doubly-Charmed background (*e.g.* real Σ_c^{++} combined with fake D^0 *etc.*) must be accounted for.
- Backgrounds coming from misidentification are carefully vetoed, *e.g.* $D_s^+ \to \{K^+ \Rightarrow p\} K^- \pi^+$ in Λ_c^+ decay.



$$\frac{\Lambda_b^0 \to \Sigma_c^{++} D^- K^-}{\Lambda_b^0 \to \Lambda_c^+ \bar{D}^0 K^-} = 0.282 \pm 0.016(stat.) \pm 0.016(syst.) \pm 0.005(\mathcal{B})$$

$$\frac{\Lambda_b^0 \to \Sigma_c^{*++} D^- K^-}{\Lambda_b^0 \to \Sigma_c^{++} D^- K^-} = 0.460 \pm 0.052(stat.) \pm 0.028(syst.)$$



$$\frac{\Lambda_b^0 \to \Sigma_c^{++} D^{*-} K^-}{\Lambda_b^0 \to \Sigma_c^{++} D^- K^-} = 2.261 \pm 0.202(stat.) \pm 0.129(syst.) \pm 0.046(\mathcal{B})$$

$$\frac{\Lambda_b^0 \to \Sigma_c^{*++} D^{*-} K^-}{\Lambda_b^0 \to \Sigma_c^{++} D^- K^-} = 0.896 \pm 0.137(stat.) \pm 0.066(syst.) \pm 0.018(\mathcal{B})$$

- New decay channels found with high significance:
  - >10σ - $\Lambda_b^0 \to \Sigma_c^{++} D^- K^-$
  - >10σ - $\Lambda_b^0 \to \Sigma_c^{++} D^{*-} K^-$
  - >10σ - $\Lambda_b^0 \to \Sigma_c^{*++} D^- K^-$
  - 9σ - $\Lambda_b^0 \to \Sigma_c^{*++} D^{*-} K^-$
- No pentaquark signal.
- BFs will provide important input into theoretical studies.
- Only $\mathcal{O}(100)$ candidates in dataset - insufficient for amplitude analysis.
- Run 3 to the rescue!

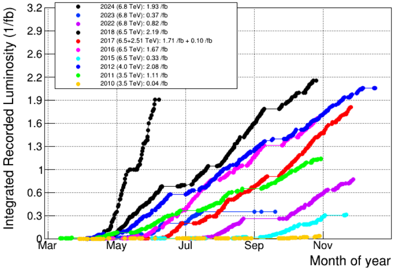
Conclusions

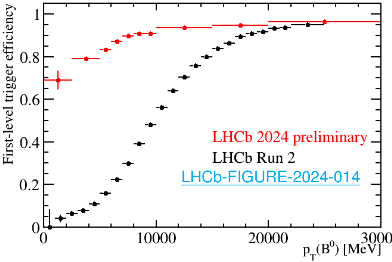
- Search for pentaquarks in wide range of signal channels (arXiv:2404.07131).
  - No strong evidence of signal.
  - Five channels with $> 3\sigma$ corrected p–value.
  - Found to be consistent with background fluctuations.
  - No signal seen for decays from known pentaquark states.
- Observation of $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$ and $\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}$ Decays (EPJ C 84 (2024) 575).
  - $\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^0 K^-)} = 0.152^{+0.032}_{-0.028}$
  - $\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{*0} K^-)} = 0.049^{+0.011}_{-0.009}$
  - $\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^{*-})}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = 1.668 \pm 0.022(stat.)^{+0.061}_{-0.055}(syst.)$ - consistent with several theory predictions.
  - First search for pentaquark signal in $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$ decay.

- First observation of $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$ decays (arXiv:2404.19510).
    - No pentaquark signal seen.
    - BFs measured, important for future studies and predictions regarding pentaquarks.
    - Full amplitude analysis can be carried out with Run 3 data.

- First observation of $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$ decays (arXiv:2404.19510).
  - No pentaquark signal seen.
  - BFs measured, important for future studies and predictions regarding pentaquarks.
  - Full amplitude analysis can be carried out with Run 3 data.
- Three analyses discussed here.
  - All sensitive to pentaquark signals - yet no *significant* signal seen.
- Why have pentaquarks not been observed decaying into these open-charm hadron final states?
  - Is there an underlying process suppressing the production in these channels?
  - Is it just a case of needing a larger dataset?

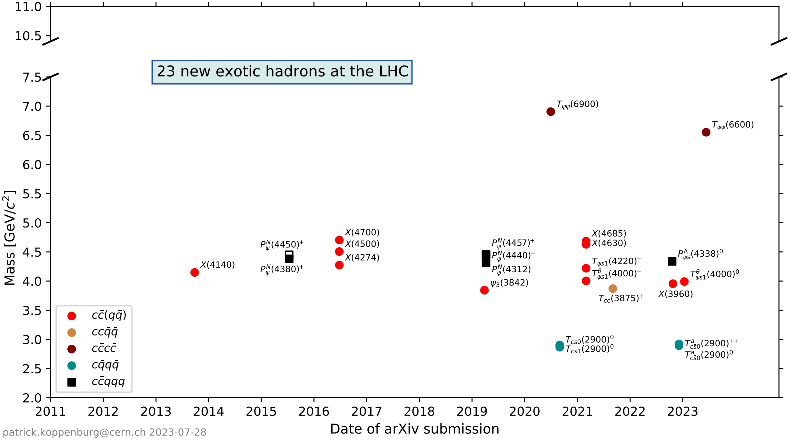
- More results still to come from LHCb Run 2 dataset.
  - Other pentaquark analyses nearing completion.
- LHCb Run 3 ongoing:
  - On track for $\sim 7\,\text{fb}^{-1}$ by the end of the year.
  - Improved trigger means higher efficiency for hadronic events.
  - Statistically limited pentaquark searches will be possible.





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).



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

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

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

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

- p–value is corrected to account for look elsewhere effect:

$$p_{corr} = p_{loc} + \langle N(c_0) \rangle \exp\left(-\frac{c - c_0}{2}\right)$$

- $\langle N(c_0) \rangle$: number of fluctuations in pseudo-data above reference level (c_0).
- c: $2\Delta \ln \mathcal{L}$.
- Accounts for the fact we scan across a large mass range and accommodates the possibility of background fluctuations.