Recent studies on pentaquark states from LHCb

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10th XYZ workshop

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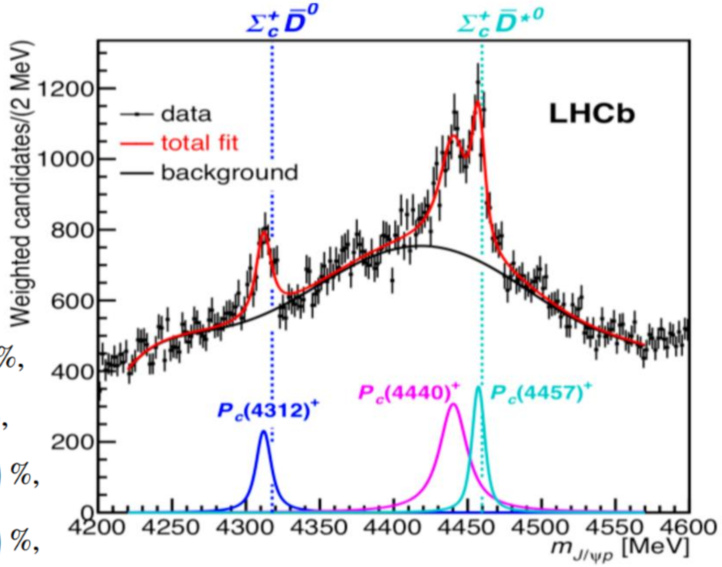
Review of main results before 2024

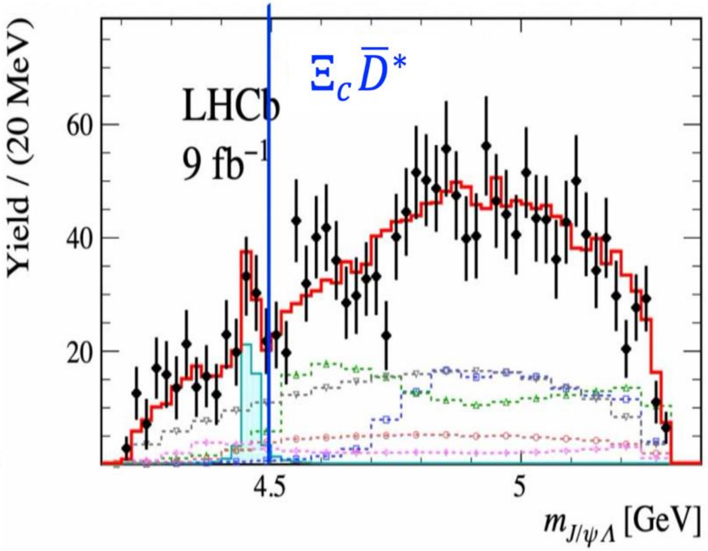
- 2015 Run1: $P_{c\bar{c}}(4380)^+ \& P_{c\bar{c}}(4450)^+$ observed from Amplitude Analysis
- 2019 Run1&2: 1D fit to $\cos\theta_{P_{c\bar{c}}}$-weighted $J/\psi p$ projections
  - $P_{c\bar{c}}(4312)^+$ observed. $P_{c\bar{c}}(4450)^+$ resolved into $P_{c\bar{c}}(4440)^+$ & $P_{c\bar{c}}(4457)^+$
  - $P_{c\bar{c}}(4380)^+$ need to be confirmed. (1D fit not sensitive to broader resonance)

$$f_{pJ/\psi}\left(P_c(4312)^+\right) = \left(0.3 \pm 0.07^{+0.34}_{-0.09}\right)\%,$$
$$f_{pJ/\psi}\left(P_c(4380)^+\right) = (8.4 \pm 0.7 \pm 4.2)\%,$$
$$f_{pJ/\psi}\left(P_c(4440)^+\right) = \left(1.11 \pm 0.33^{+0.22}_{-0.11}\right)\%,$$
$$f_{pJ/\psi}\left(P_c(4457)^+\right) = \left(0.53 \pm 0.16^{+0.15}_{-0.13}\right)\%,$$



$P_{c\bar{c}}$ in $\Lambda_b^0 \to J/\psi p K^-$

PRL 122 (2019) 222001



Evidence of $P_{c\bar{c}s}$ in $\Xi_b^0 \to J/\psi \Lambda K^-$

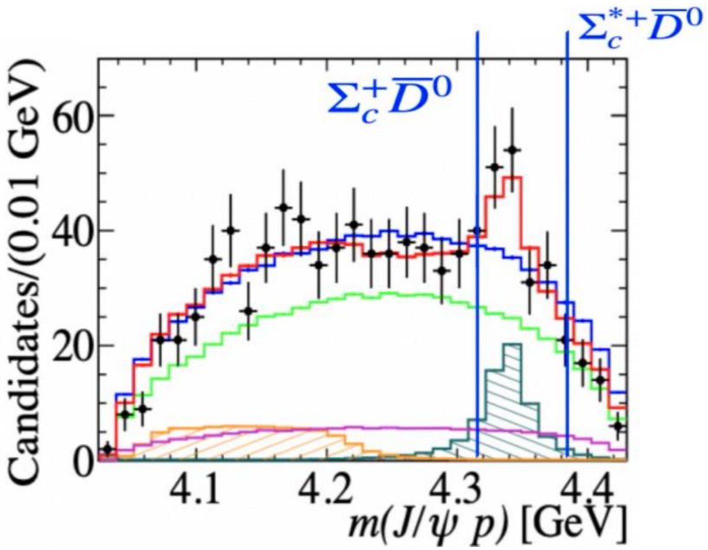
Sci.Bull.66 (2021) 1278

$$m\left(P_{cs}(4459)^0\right) = 4458.8 \pm 2.9(\text{stat.})^{+4.7}_{-1.1}(\text{syst.})\ \text{MeV},$$
$$\Gamma\left(P_{cs}(4459)^0\right) = 17.3 \pm 6.5\ (\text{stat.})^{+8.0}_{-5.7}(\text{syst.})\ \text{MeV},$$

- 2021: Evidence of pentaquark with strangeness $P_{c\bar{c}s}(4459)^0 \to J/\psi\Lambda$

Review of main results before 2024

- 2022: Evidence of $P_{c\bar{c}}(4337)$, while $P_{c\bar{c}}(4312)^+, P_{c\bar{c}}(4380)^+$ not seen
- 2023: Observation of $P_{c\bar{c}s}(4338)$ in $B^+ \to J/\psi\bar{\Lambda}p$ decay

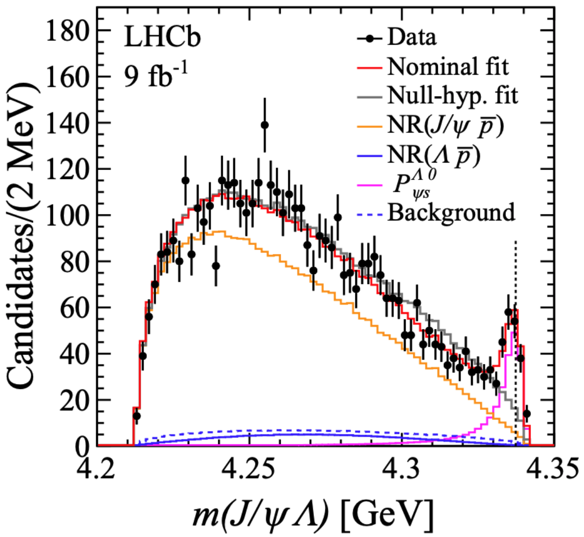


Evidence of $P_{c\bar{c}}$ in $B_s^0 \to J/\psi p\bar{p}$

PRL 128(2022) 062001

$$M_{P_c} = 4337^{+7}_{-4}\,^{+2}_{-2}\ \text{MeV},$$

$$\Gamma_{P_c} = 29^{+26}_{-12}\,^{+14}_{-14}\ \text{MeV},$$



$P_{c\bar{c}s}$ in $B^+ \to J/\psi\bar{\Lambda}p$

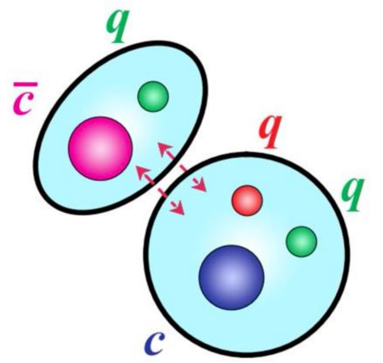
PRL131 (2023) 031901

$$M(P_{c\bar{c}s}) = 4338.2 \pm 0.7 \pm 0.4\text{MeV}$$

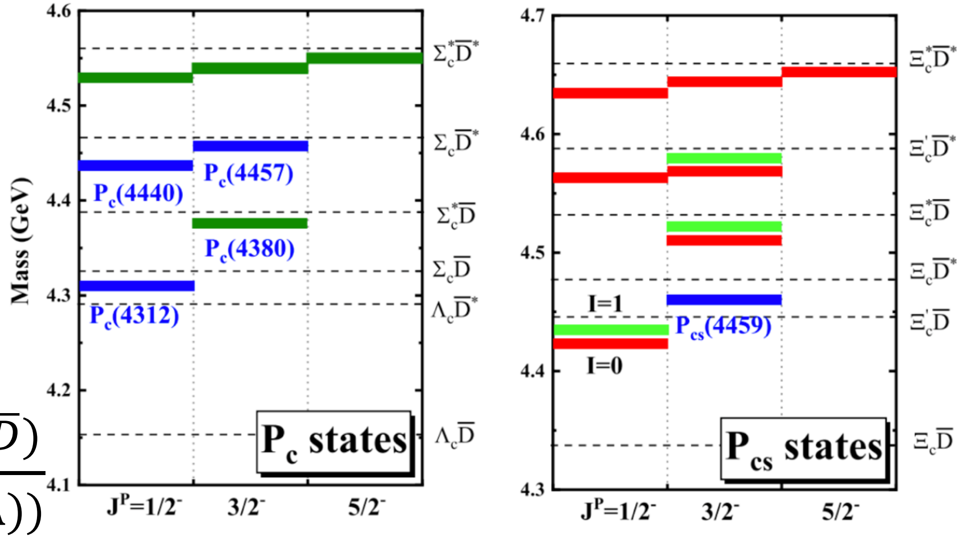
$$\Gamma(P_{c\bar{c}s}) = 7.0 \pm 1.2 \pm 1.3\text{MeV}$$

Review of main results before 2024

- The mass of pentaquarks is found to be close to charm-baryon and charm-meson mass threshold
  - Popular theories: molecular states
  - Other hypothesis (Compact pentaquark, kinematic effects like triangle singularity,…) are not ruled out



- A rough sketch of theoretical predictions
  - Mass and width are consistent with experiment results within uncertainties
  - Most calculations suggest $J^P(P_{c\bar{c}}(4312)^+) = \frac{1}{2}^-$
  - $J^P(P_{c\bar{c}}(4440)^+)$ & $J^P(P_{c\bar{c}}(4457)^+)$ controversial between molecular models and others
  - 1-2 orders of magnitude difference on $\frac{B(P_{c\bar{c}(s)} \to \Sigma_c(\Xi_c)\bar{D})}{B(P_{c\bar{c}(s)} \to J/\psi p(\Lambda))}$
  - Many states are predicted
- Lots of possibilities need to be checked by experiments



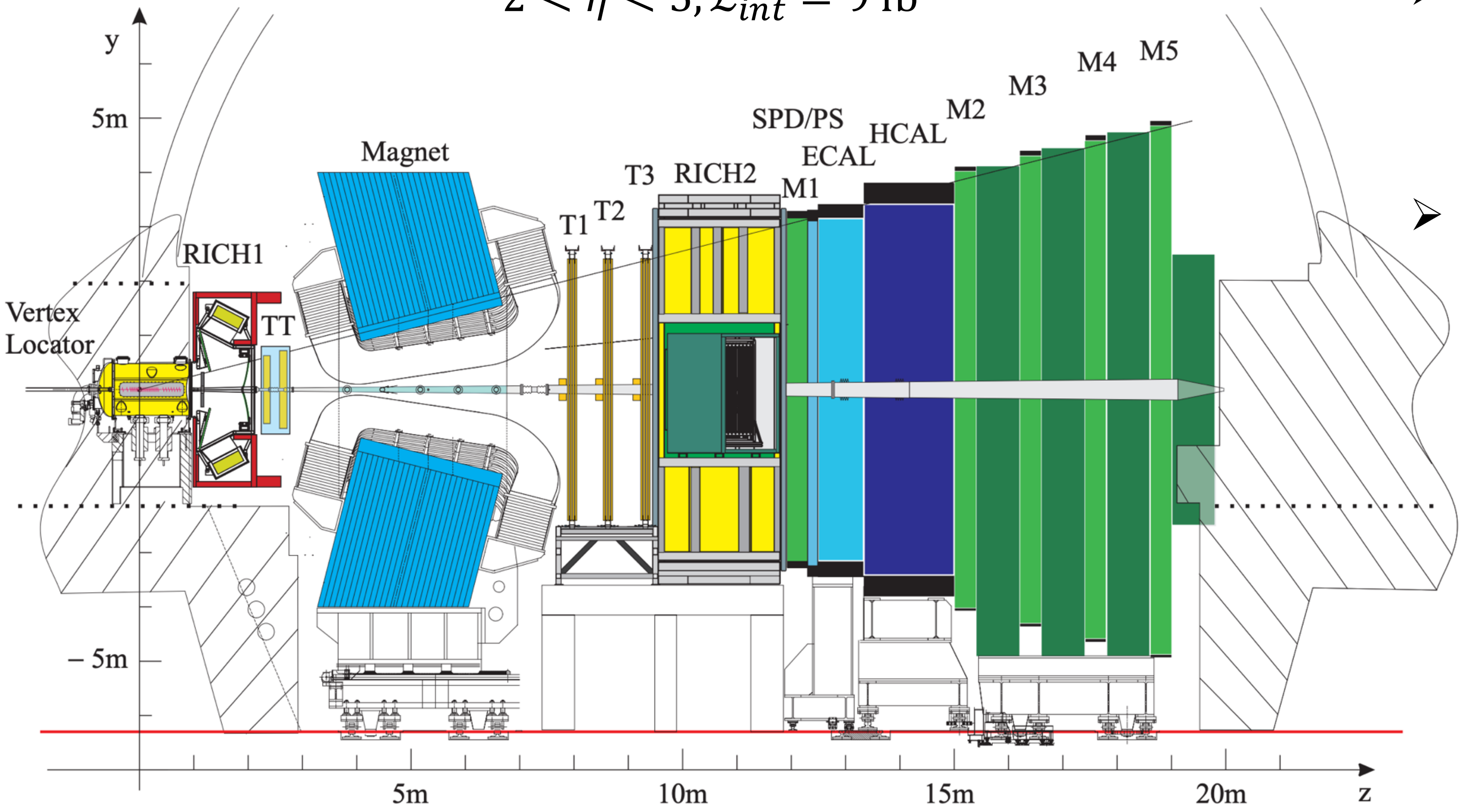
PRD (2022) 105: 014029
PRD (2019) 100: 011502

LHCb detector

➢Single-arm forward. Specially designed for heavy-flavour physics.

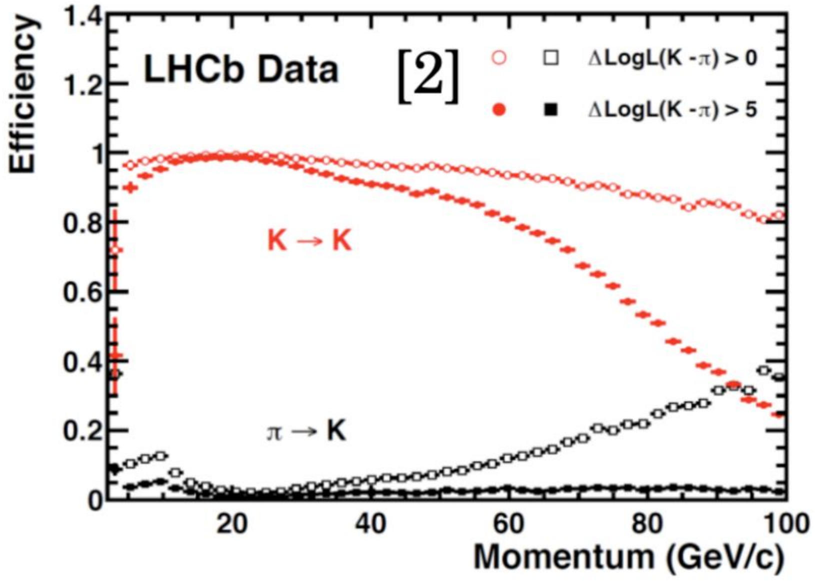
LHCb Run1&2 detector

$2 < \eta < 5, \mathcal{L}_{int} = 9\ \mathrm{fb}^{-1}$



JINST3 (2008) S08005
IJMPA 30 (2015) 1530022

- Excellent tracking and vertexing
  - $\frac{\sigma(p)}{p} < 1\%\ @\epsilon_{track} > 96\%$
  - $\sigma(\mathrm{IP}) = \left(15 + \frac{29}{p_T}\right) \mu m$
- Excellent PID
  - $\epsilon_{PID}(K) \approx 95\%@\mathrm{MisID}(\pi \to K) \approx 5\%$
  - $\epsilon_{PID}(\pi) \approx 97\%@\mathrm{MisID}(\pi \to \mu) \approx 3\%$



Contents of this talk

1. Latest results from LHCb

- Pentaquarks search in pp prompt production
  - Search for pentaquarks in open-charm final states PRD 110 (2024) 032001

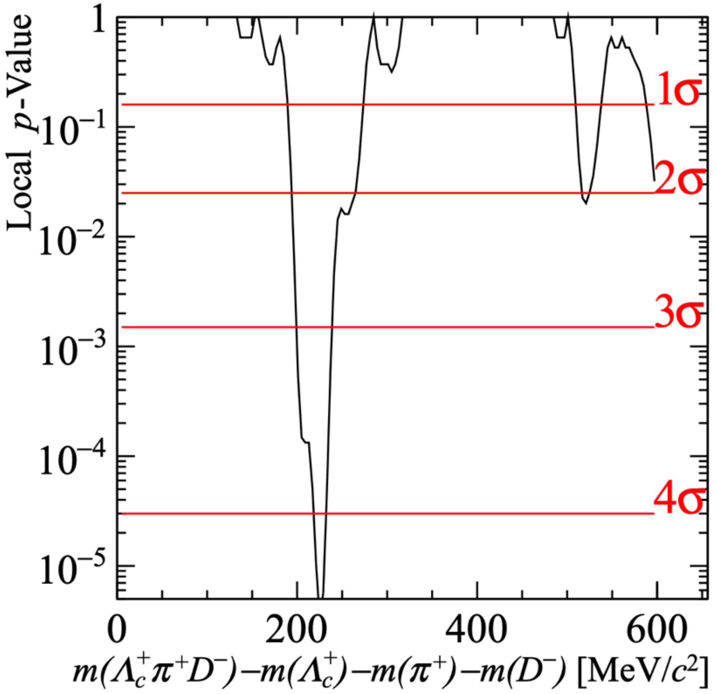
- Pentaquarks search from b-hadron open charm decay
  - Observation of $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$ decay EPJC 84 (2024) 575
  - Observation of $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{*-} K^-$ decay PRD 110 (2024) L031104
  - Observation of $\Lambda_b^0(\Xi_b^0) \to J/\psi \Xi^- K^+(\pi^+)$ decay arXiv:2501.12779

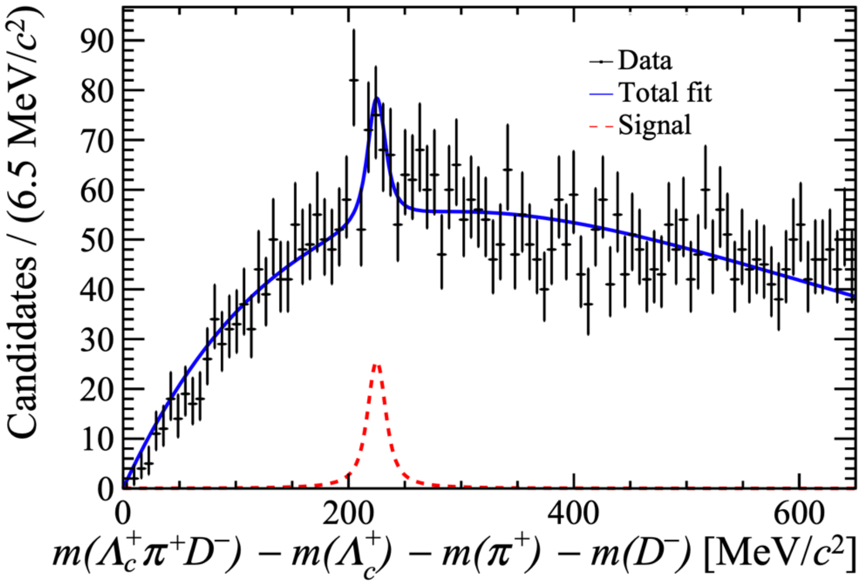
2.Prospects of LHCb Run3

Inclusive Search for Prompt $P_{c\bar{c}}$

- Search $P_{c\bar{c}}/P_{cc}$ directly produced from pp collisions, as opposed to $P_{c\bar{c}}$ produced in b-hadron decays
- Combining final states from: $(\Lambda_c^+, \Sigma_c^{++}, \Sigma_c^0, \Sigma_c^{*++}, \Sigma_c^{*0}, \Lambda_c^+\pi^\pm) \otimes (D^0, \bar{D}^0, D^\pm, D^{*\pm})$
- Scanned for pentaquarks up to $600\ \mathrm{MeV}$ away from mass threshold
- Consistent with background only hypothesis taking Look-Elsewhere effect into account

PRD 110 (2024) 032001

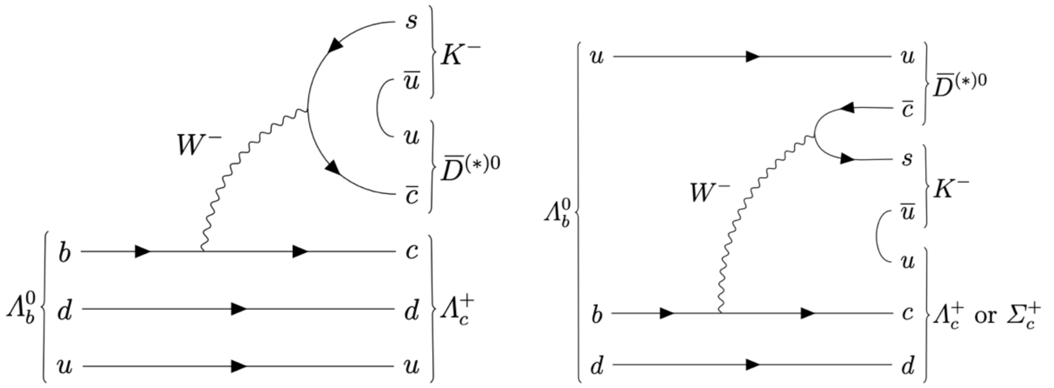


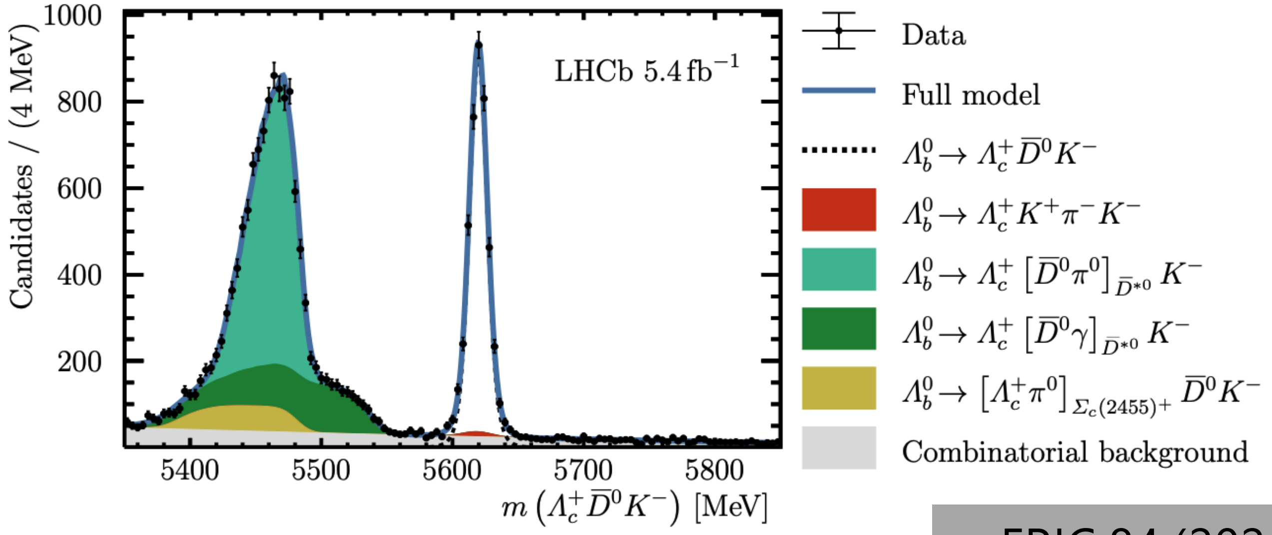


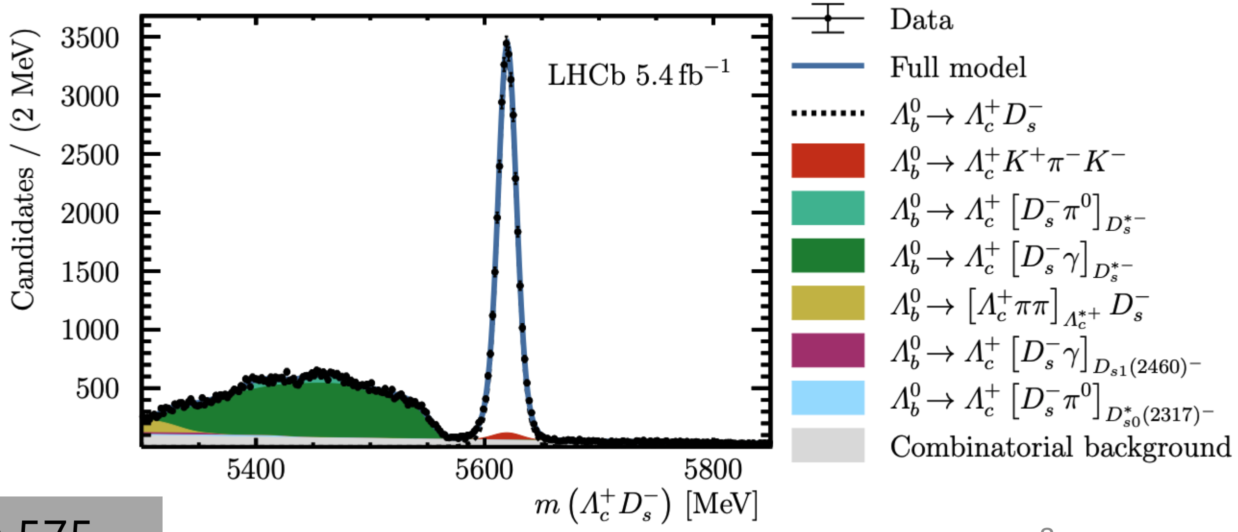
Decay Mode	Pentaquark Hypothesis	Signal Yield	Upper Limit ($\times10^{-3}$) (90% CL)	(95% CL)
$\Lambda_c^+\ \bar{D}^0$	$P_c(4312)^+$	19.78 ± 22.27	1.17	1.29
	$P_c(4440)^+$	26.91 ± 28.17	1.41	1.53
	$P_c(4457)^+$	6.20 ± 13.60	1.27	1.43
$\Lambda_c^+\ \pi^+\ D^{*-}$	$P_c(4440)^+$	0.00 ± 0.96	0.72	0.91
	$P_c(4457)^+$	0.00 ± 1.73	0.77	0.97
$\Lambda_c^+\ \pi^-\ D^{*-}$	$P_c(4440)^+$	0.00 ± 0.80	0.63	0.80
	$P_c(4457)^+$	0.00 ± 0.74	0.59	0.74
$\Lambda_c^+\ \pi^+\ D^-$	$P_c(4312)^+$	0.00 ± 1.56	0.69	0.88
	$P_c(4440)^+$	4.43 ± 11.67	3.71	4.24
	$P_c(4457)^+$	5.94 ± 12.68	3.13	3.61
$\Lambda_c^+\ \pi^-\ D^-$	$P_c(4312)^+$	0.00 ± 1.42	0.67	0.86
	$P_c(4440)^+$	12.52 ± 15.89	3.91	4.37
	$P_c(4457)^+$	8.60 ± 12.22	3.10	3.51
$\Sigma_c^0\ D^-$	$P_c(4440)^+$	0.00 ± 2.47	0.82	1.03
	$P_c(4457)^+$	0.00 ± 1.05	0.63	0.81
$\Sigma_c^{++}\ D^-$	$P_c(4440)^+$	0.61 ± 4.52	1.13	1.37
	$P_c(4457)^+$	0.66 ± 1.79	0.80	0.99
$\Sigma_c^{*0}\ D^-$	$P_c(4440)^+$	3.23 ± 3.53	1.89	2.24
	$P_c(4457)^+$	0.00 ± 3.09	0.91	1.13
$\Sigma_c^{*++}\ D^-$	$P_c(4440)^+$	1.20 ± 3.81	1.38	1.67
	$P_c(4457)^+$	0.00 ± 5.74	0.87	1.08

Branching fraction of $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-$ decay

- Directly search for $P_{c\bar{c}}^+ \to \Lambda_c^+ \bar{D}^{(*)0}$ decay in $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-$
- Measured BF normalized to $\Lambda_b^0 \to \Lambda_c^+ D_s^-$
- Compared to $\mathcal{B}(\Lambda_b \to J/\psi p K^-)$
  - $\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)/\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{*0} K^-) = 0.152^{+0.032}_{-0.028}$
  - $\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)/\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{0} K^-) = 0.049^{+0.011}_{-0.009}$
- Important for future pentaquark searches
  - Extract $P_{c\bar{c}}^+$ fit fraction in $\Lambda_b^0 \to J/\psi p K^-$ and $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-$
  - Test theory predictions on $\mathcal{B}(P_{c\bar{c}}^+ \to J/\psi p)/\mathcal{B}(P_{c\bar{c}}^+ \to \Lambda_c^+ \bar{D}^{(*)0})$





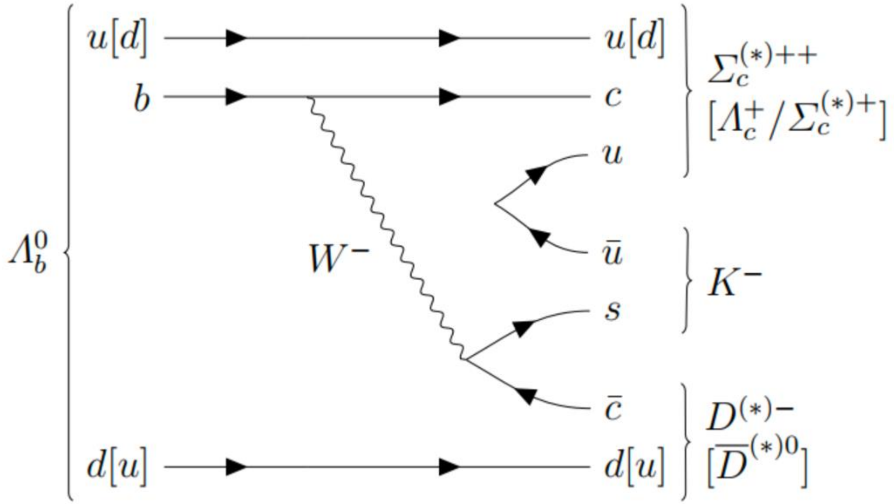


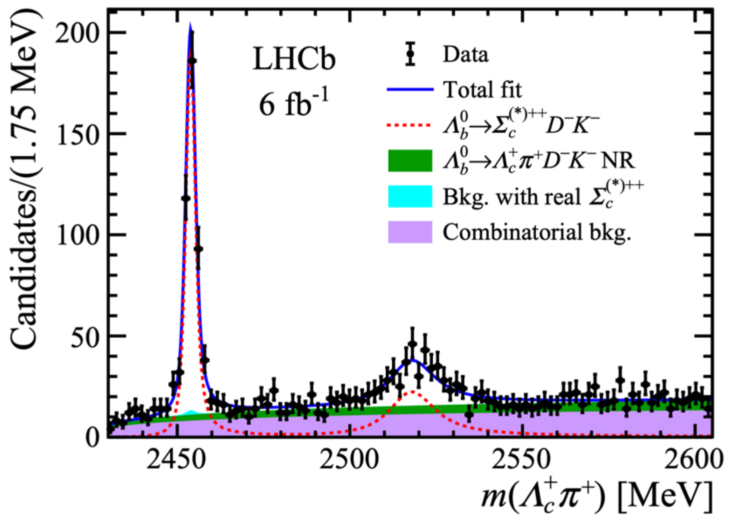
EPJC 84 (2024) 575

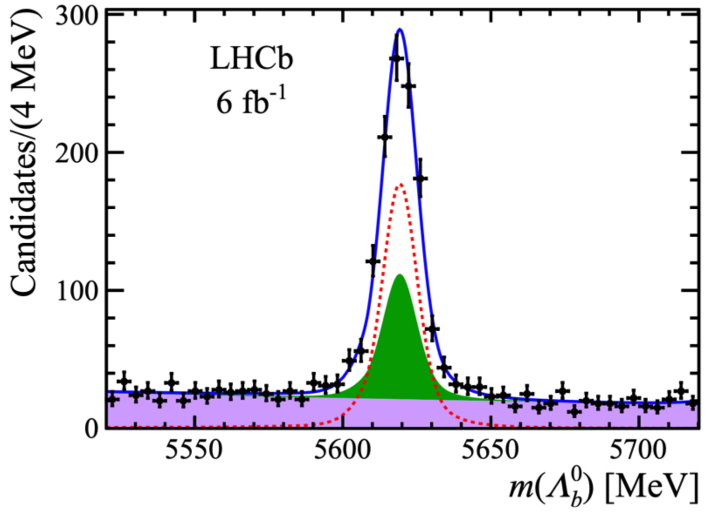
First observation of $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$

PRD 110 (2024) L031104

- Motivations
  - Peak structures slightly below $\Sigma_c D^{(*)}$ in $\Lambda_b^0 \to J/\psi p K^-$
  - Sizeable contributions from $P_{c\bar{c}}^+ \to \Sigma_c^{(*)} D^{(*)}$ decays can enhance the branching fractions of these decays
- Statistics are small
  - $\Lambda_b^0 \to \Sigma_c^{++} D^- K^-: 480 \pm 25$
  - $\Lambda_b^0 \to \Sigma_c^{++} D^{*-} K^-: 279 \pm 26$
  - $\Lambda_b^0 \to \Sigma_c^{*++} D^- K^-: 243 \pm 17$
  - $\Lambda_b^0 \to \Sigma_c^{*++} D^{*-} K^-: 116 \pm 15$
- No obvious peaking structures





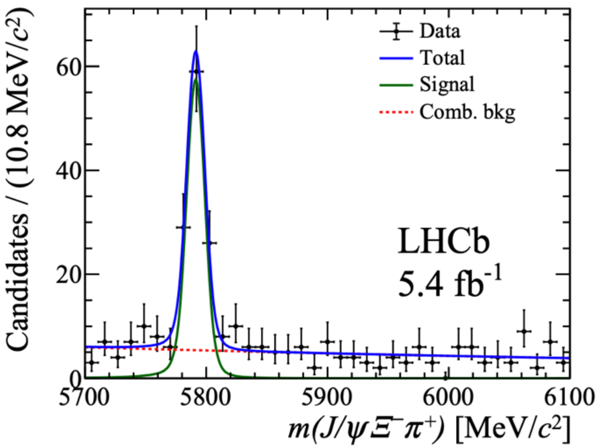


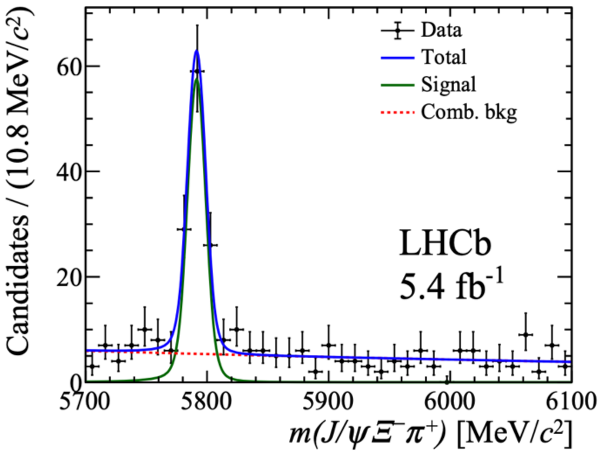
Branching fractions of $\Lambda_b^0(\Xi_b^0) \to J/\psi \Xi^- K^+(\pi^+)$

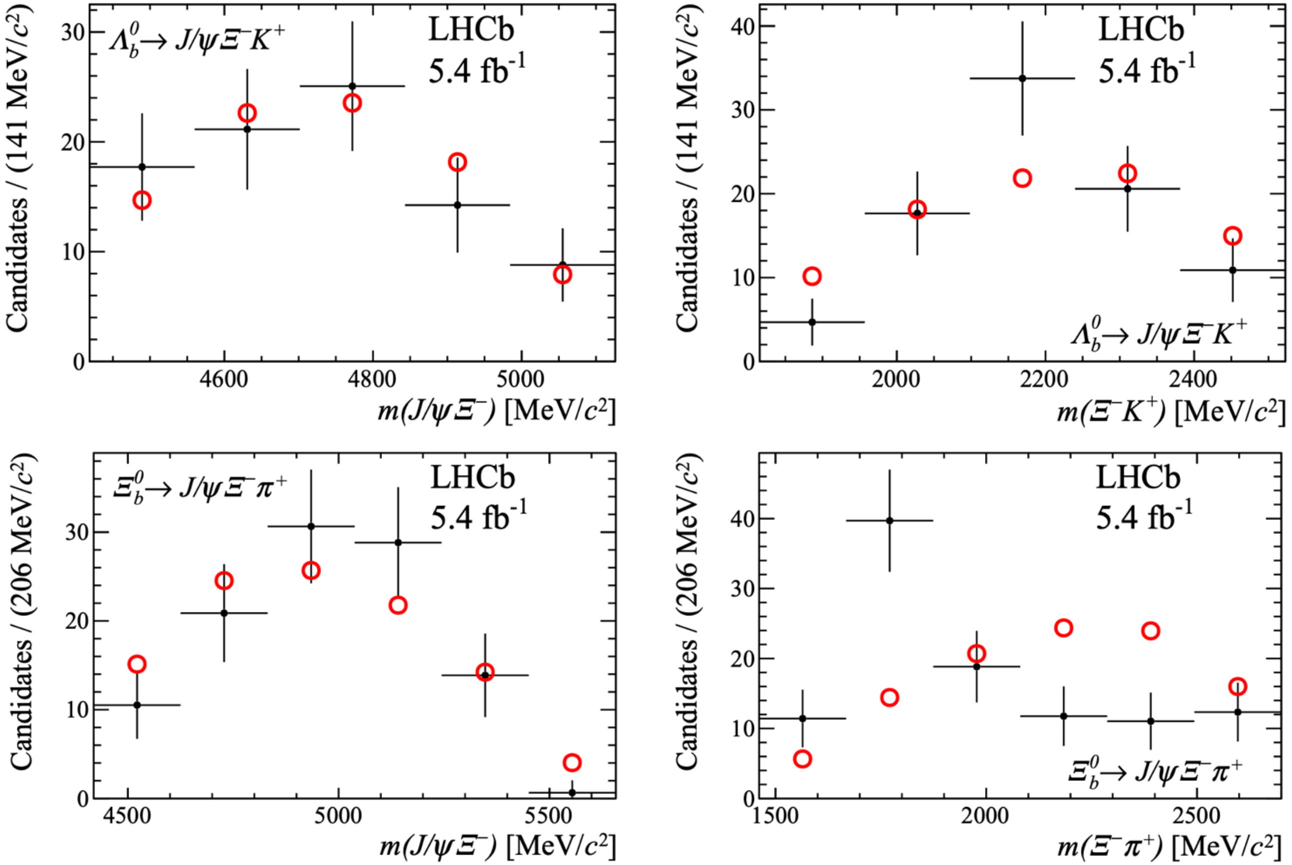
- Motivations: $P_{c\bar{c}}(J/\psi p$:$c\bar{c}uud) \to P_{c\bar{c}s}(J/\psi\Lambda$:$c\bar{c}sud) \to P_{c\bar{c}ss}(J/\psi\Xi^-$:$c\bar{c}ssd)$
- Yields:
  - $\Xi_b^0 \to J/\psi \Xi^- \pi^+$: 107 ± 12
  - $\Lambda_b^0 \to J/\psi \Xi^- K^+$: 84 ± 10

arXiv:2501.12779

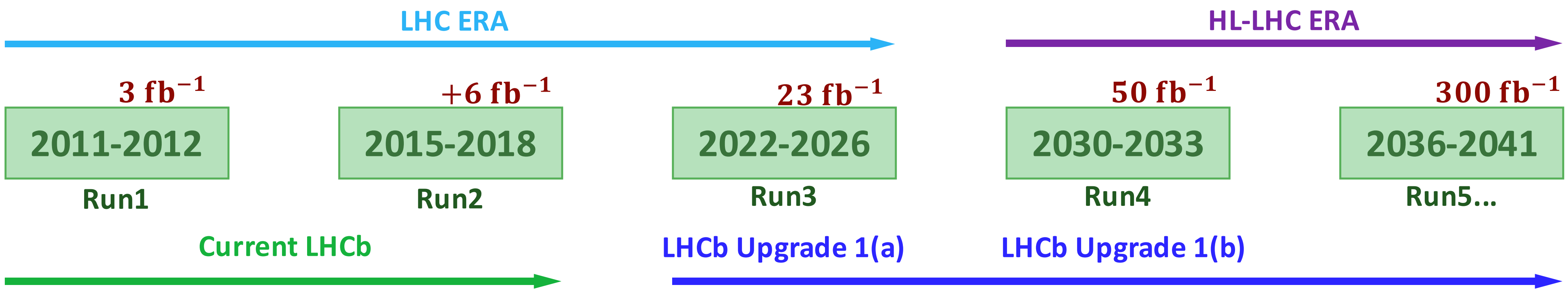
- Branching fractions:
  - $\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi \Xi^- K^+)}{\mathcal{B}(\Lambda_b^0 \to J/\psi \Lambda)} = (1.17 \pm 0.14 \pm 0.08) \times 10^{-2}$
  - $\frac{\mathcal{B}(\Xi_b^0 \to J/\psi \Xi^- \pi^+)}{\mathcal{B}(\Xi_b^0 \to J/\psi \Xi^-)} = (11.9 \pm 1.4 \pm 0.6) \times 10^{-2}$
- No obvious peaking structures



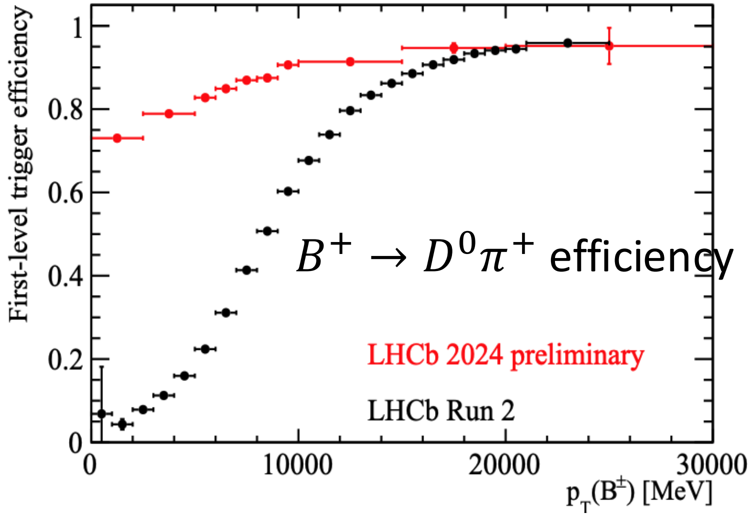




LHCb Run3 and beyond



- Run3: plan to collect $\sim 15\ \mathrm{fb}^{-1}$ pp data (Statistics $\sim 2 \times$ Run1&2)
- Full software trigger
  - Trigger efficiency greatly improved for fully hadron final states
  - $2-3 \times$ for open charm final states
- Higher statistics in upgrade boosts exotics studies @ LHCb
  - Evidence of some states/decay modes→Observation
  - Search for new decay modes of observed pentaquark states(e.g. in open charm decays)
  - Determine J^P and other properties of pentaquark states
  - ….



Summary

- LHCb experiments has published new results:
  - Search for prompt pentaquarks
  - BF measurements of $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$
  - First observation of $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$
  - First observation of $\Lambda_b^0 \to D^+ D^- \Lambda$
- LHCb Run3 will collect more data @higher efficiency especially for open charm channels
  - Expect results in new decay channels

Thanks!

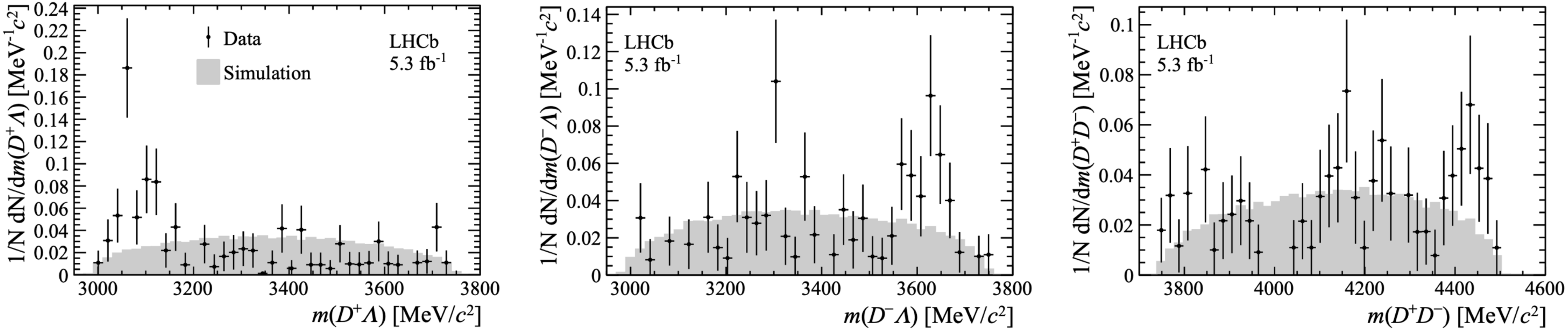
Backups

First observation of $\Lambda_b^0 \to D^+ D^- \Lambda$

- Motivations

JHEP 07 (2024) 140

  - Abundant charmonium structures in $D^+ D^-$ structures
  - Possibility of $P_{c\bar{s}}$ in $D\Lambda$ system, like $T_{cs1}^*(2900)^0$ &$T_{cs0}^*(2900)^0$
- ~ 90 candidates observed while rich structures in invariant mass spectrum discovered compared to phase space



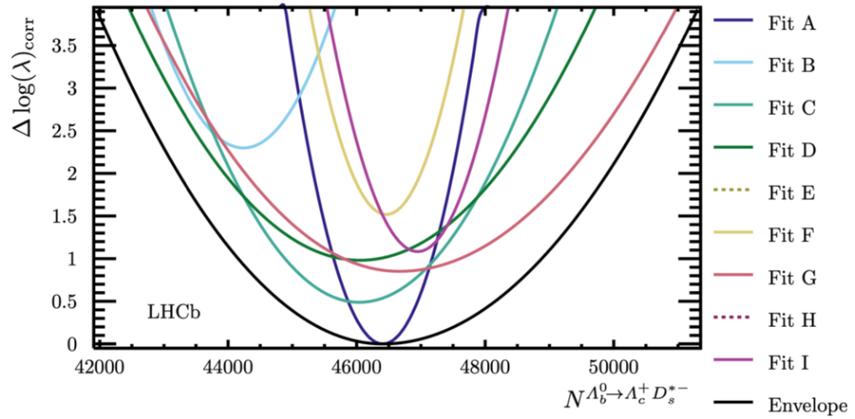
Observation of $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$ decay and BR measurements

- Systematical uncertainties

EPJC 84 (2024) 575

Source / relative to	$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)}$ [%]	$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{*0} K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)}$ [%]	$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^{*-})}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)}$ [%]
Fit model	$^{+0.5}_{-0.6}$	$^{+2.8}_{-3.0}$	$^{+3.6}_{-3.3}$
Weighting	0.1	0.1	0.0
Multiple candidates	0.0	0.0	0.1
Size of the simulated samples	0.4	0.3	0.2
Size of the generated samples	0.6	0.6	0.6
Total	0.9	$^{+2.9}_{-3.1}$	$^{+3.7}_{-3.3}$
Statistical	1.8	2.8	1.3

Systematics are studied by finding the *envelope likelihood*. JINST 10 P04015



- Branching ratios

(w.r.t. to the normalization decay mode)

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

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

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

(w.r.t. to the $P_{c\bar{c}}$-observation decay mode)

$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-)} = 0.152^{+0.032}_{-0.028},$$

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

Theory predictions on relative BF

Table 1.3 Summary of theoretical calculation of the $P_c(4312)$ decay fractions.

Model	$\frac{\mathcal{B}(P_c^+\to\Sigma_c\bar{D})}{\mathcal{B}(P_c^+\to pJ/\psi)}$	$\frac{\mathcal{B}(P_c^+\to\Sigma_c\bar{D}^*)}{\mathcal{B}(P_c^+\to pJ/\psi)}$	Remarks
Moleculer	0.51 ± 1.69, 0.38 ± 1.06 and 0.25 ± 1.65	N.A.	ERE, results depend on the total compositeness $X=1,0.8,0.5$[102]
Molecular	4.54	0.67	HQSS, coupled channels, assume $I=\frac{1}{2}$, $J^P=\frac{1}{2}^-$, subtraction constant $a(1\text{ GeV})=-2.09$[125]
Compact pentaquark	0(forbidden)	0(forbidden)	Extended chromomagnetic, assume $I(J^P)=\frac{1}{2}(\frac{1(3)}{2}^-)$[126]
Molecular	allowed	N.A.	HQSS, no estimated values in the paper[127]
Molecular	0(forbidden)	0(forbidden), prefer $\Lambda_c\bar{D}^*$	Effective Lagrangian, relativistic (f_1,f_3) and no-relativistic (f_2,f_3) form-factors, f_i is cut-off dependent,assume $J^P=\frac{1}{2}^-$[115]
Molecular	0(forbidden), prefer $\Lambda_c^+\bar{D}^{*0}$	N.A.	Fierz rearrangement, assume $J^P=\frac{1}{2}^-$[111]
Molecular	0(forbidden)	0(forbidden), prefer $\eta_c N$	HQSS, chiral unitary, coupled channels, assume $J^P=\frac{1}{2}^-$, depends one a_μ and $q_{\max}$[128]

Model	$\frac{\mathcal{B}(P_c^+\to\Sigma_c\bar{D})}{\mathcal{B}(P_c^+\to pJ/\psi)}$	$\frac{\mathcal{B}(P_c^+\to\Sigma_c\bar{D}^*)}{\mathcal{B}(P_c^+\to pJ/\psi)}$	Remarks
Moleculer	N.A.	0.16 ± 0.47, 0.20 ± 0.44, and 0.11 ± 0.25	ERE, results depend on the total compositeness $X=1,0.8,0.5$[102]
Molecular	0.15	2.28	HQSS, coupled channels, assume $I=\frac{1}{2}$, $J^P=\frac{1}{2}^-$, subtraction constant $a(1\text{ GeV})=-2.09$[125]
Compact pentaquark	For $\Sigma_c^*\bar{D}$:$0.16t$	$1.9t$	Extended chromomagnetic, assume $I(J^P)=\frac{1}{2}(\frac{3}{2}^-)$,$t=\frac{\mathcal{B}(P_c^+\to\Lambda_c\bar{D}^*)}{\mathcal{B}(P_c^+\to pJ/\psi)}$, this article predicts the $\mathcal{B}(P_c^+\to\Lambda_c\bar{D}^*)$ as baseline[126]
Molecular	N.A.	suppressed if compared with $P_c(4312)^+$ and $P_c(4450)^+$	HQSS, $J^P=\frac{3}{2}^-$,no estimated values in the paper[127]
Molecular	113(25), 5.7(0.3)	N.A., and for $\Sigma_c^*\bar{D}$:26.7(270), 1.5(4.1)	Effective Lagrangian, relativistic (f_1,f_3) and no-relativistic (f_2,f_3) form-factors, f_i is cut-off dependent,assume $J^P=\frac{1}{2}^-\left(\frac{3}{2}^-\right)$[115]
Molecular	For $\Sigma_c^{++}D^-$: $0.04t$; For $\Sigma_c^+\bar{D}^0$: $0.08t$	0, prefer $\Lambda_c^+\bar{D}^0$: $1.2t$	Fierz rearrangement, assume $J^P=\frac{1}{2}^-$, depends on $t\geq1$[111]
Molecular	0.04	0(forbidden)	HQSS, chiral unitary, coupled channels, assume $J^P=\frac{1}{2}^-$, depends one a_μ and $q_{\max}$[128]