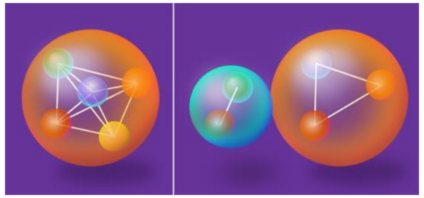


Recent studies of pentaquarks at LHCb

Zhenwei Yang (杨振伟)

Center for High Energy Physics, Peking University

On behalf of the LHCb collaboration

2024.09.26

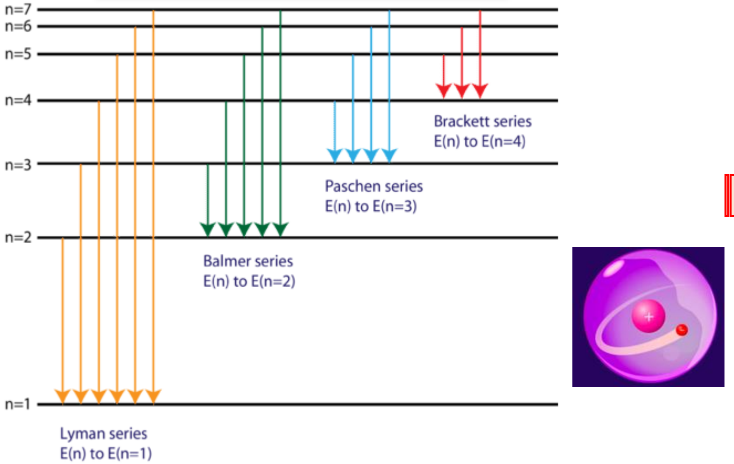
Outline

- Introduction
- Recent results of pentaquarks
  - Observation of $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$ Eur.J.Phys.C84 (2024) 575
  - Observation of $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$ Phys. Rev. D110 (2024) L031104
  - Search for pentaquarks decaying to open-charm hadrons in pp prompt production Phys. Rev. D110 (2024) 032001
- Prospects and summary

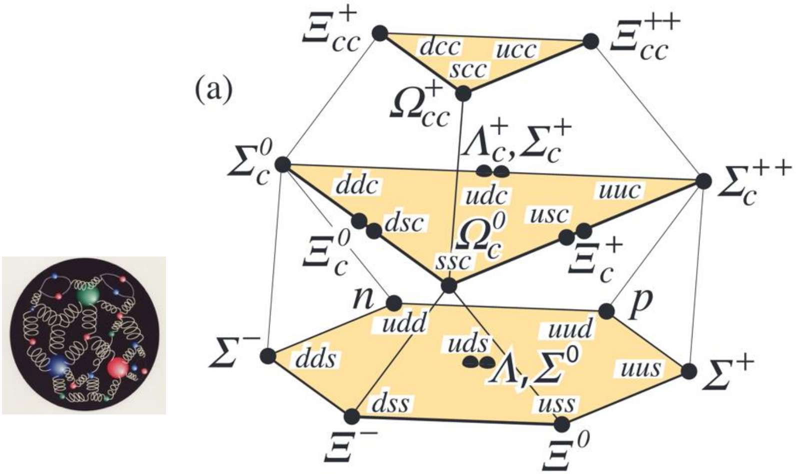
Why spectroscopy?

- Spectroscopy: energy levels and their sorting of a system
- Important approach to unveil dynamics of complex phenomena

light spectra



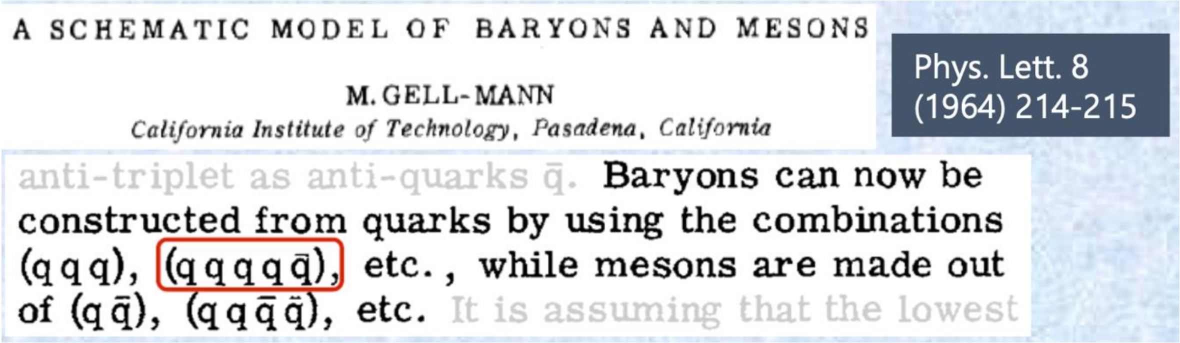
Hadron spectra



Hadron spectroscopy ➔ to understand the strong interaction

Quark model, exotic hadrons, pentaquarks

- In 1964, Gell-Mann and Zweig independently proposed to classify hadrons according to the quark model
- Ordinary hadrons and exotic hadrons


A SCHEMATIC MODEL OF BARYONS AND MESONS

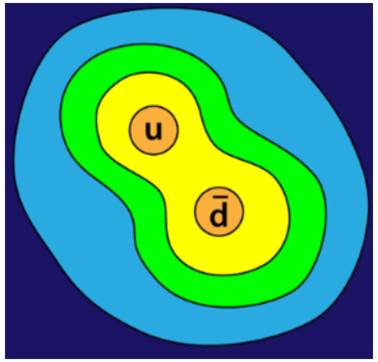
M. GELL-MANN

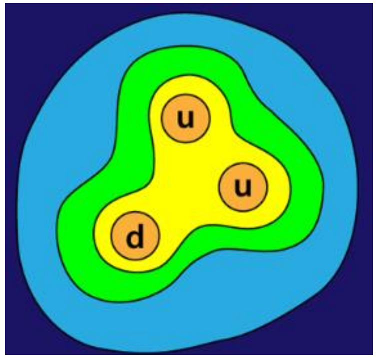
California Institute of Technology, Pasadena, California

Phys. Lett. 8 (1964) 214-215

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. It is assuming that the lowest

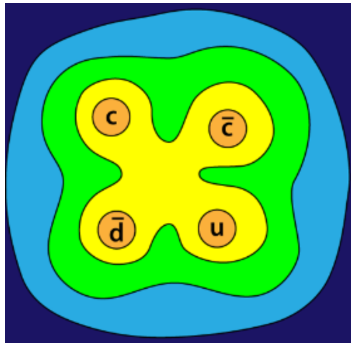
Ordinary

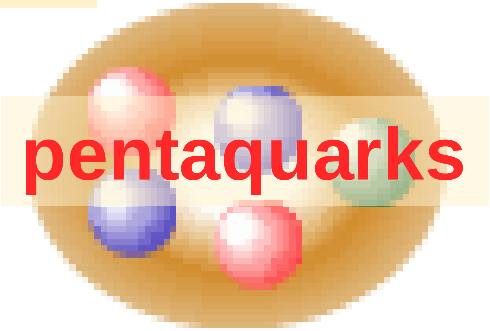




$q\bar{q}$ qqq

Exotic

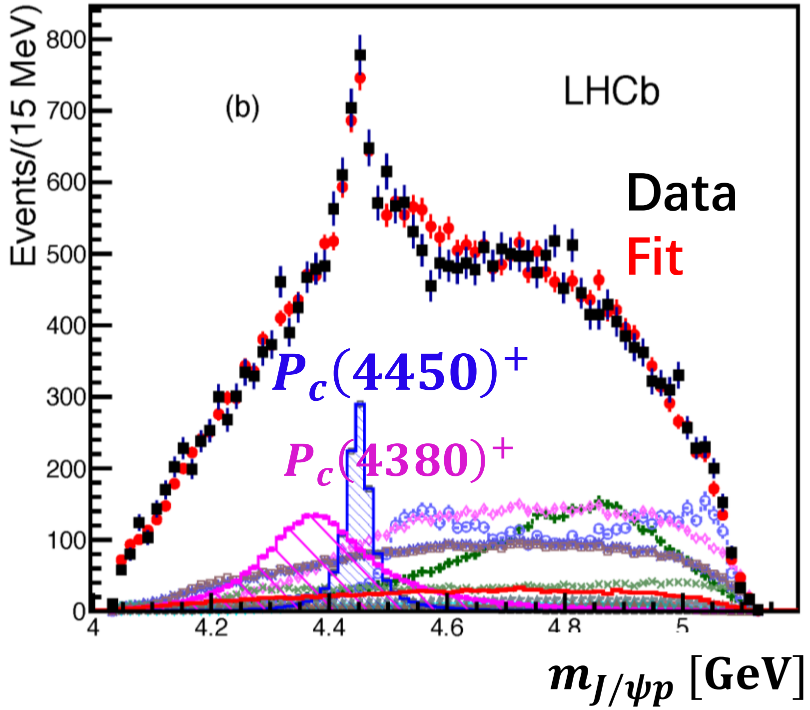




$qq\bar{q}\bar{q}$ $qqqq\bar{q}$

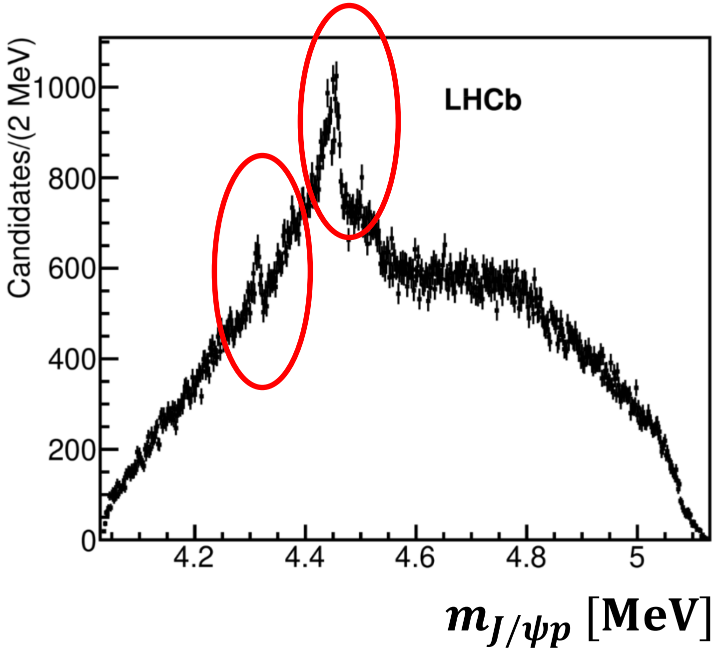
Recap: observation of pentaquark in $\Lambda_b^0 \to J/\psi p K^-$

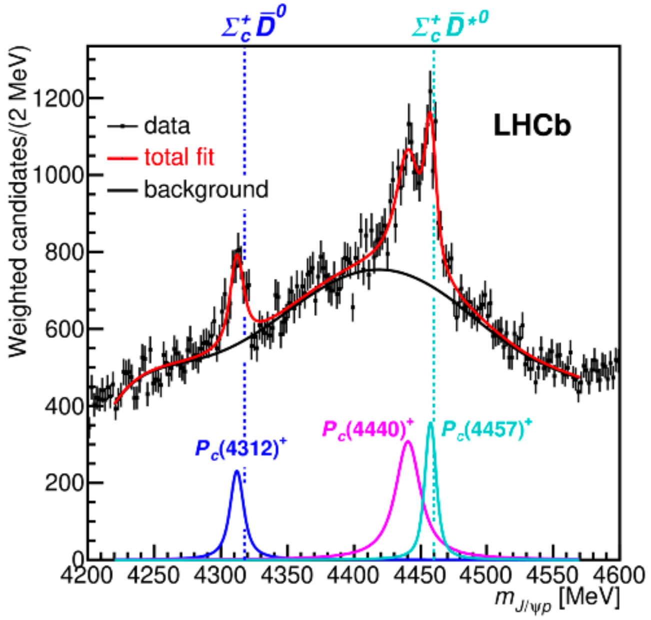
Dataset: 3 fb^{-1}
(2011-2012) PRL 115 (2015) 072001



$P_c^+ \to J/\psi p$
Quark content $(c\bar{c}uud)$

9 fb^{-1}
(2011-2018) PRL 122 (2019) 222001





N_{sig} increases by a factor of 9

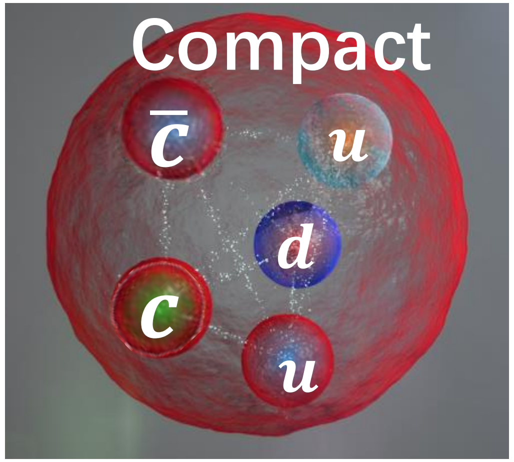
➔ Fine structures observed

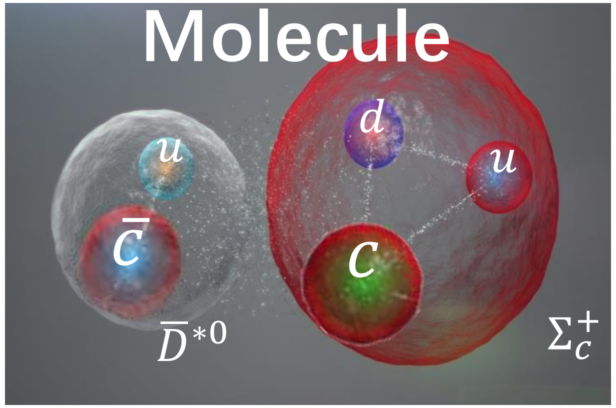
Fruitful studies since 2015

- Synergy between experimentalists and theorists
  - Many new ideas and reviews
- What's the nature of pentaquark?
  - Compact? molecules? Others?
- New decays?
  - $P_c^+ \to$ open-charm hadrons (e.g. $\Lambda_c^+ \bar{D}^{(*)0}$)
- New pentaquarks?
  - e.g. $P_{cs}^0 \to J/\psi\Lambda$

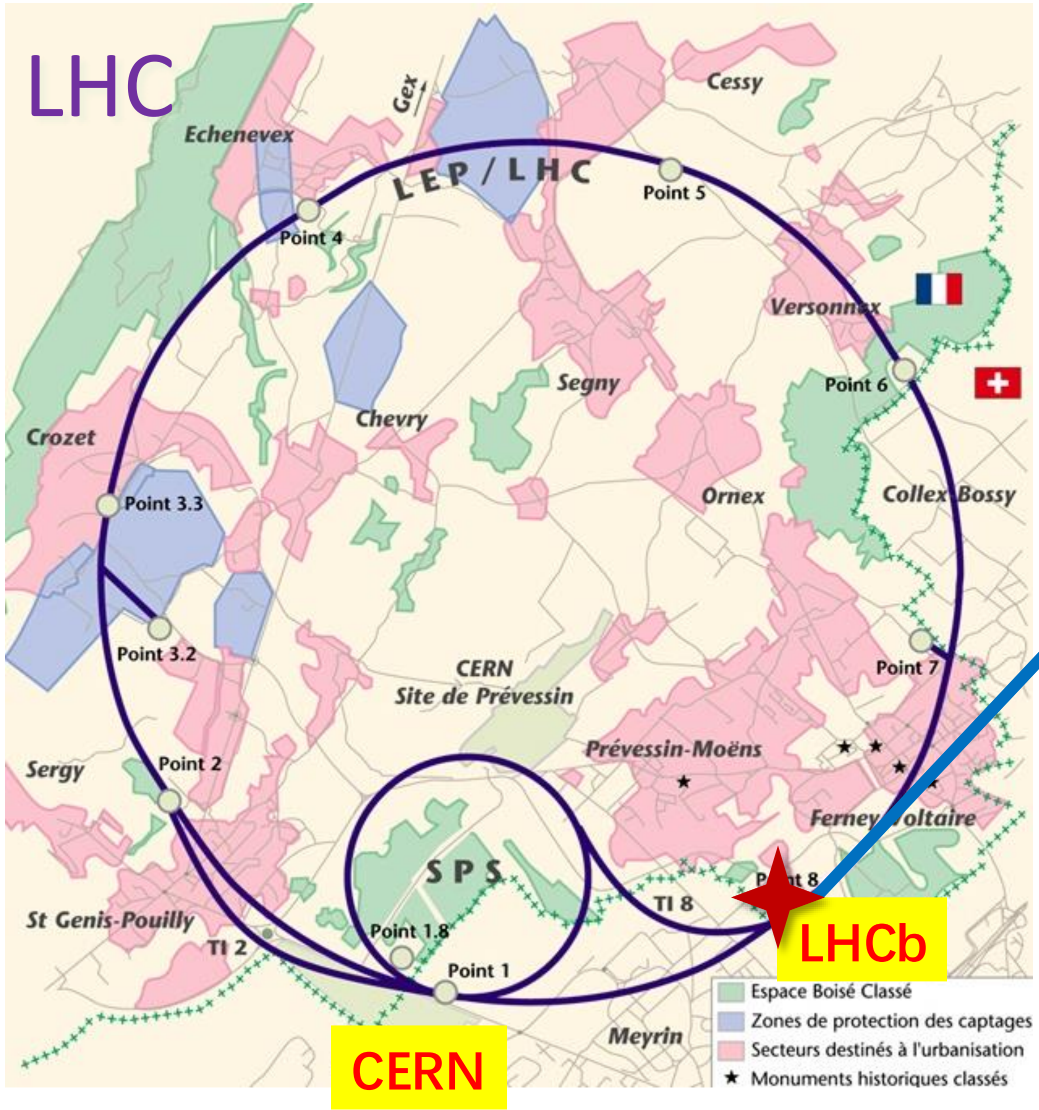
Review papers

H. Chen et al, Phys.Rept. 639 (2016) 1
A. Ali et al, Prog.Part.Nucl.Phys. 97 (2017) 123
A. Esposito et al, Phys.Rept. 668 (2017) 1
R. Lebed et al, Prog.Part.Nucl.Phys. 93 (2017) 143
S. Olsen et al, Rev.Mod.Phys. 90 (2018) 015003
Y. Liu et al, Prog.Part.Nucl.Phys. 107 (2019) 237
N. Brambilla et al, Phys.Rept. 873 (2020) 1
F. Guo et al, Rev.Mod.Phys. 90 (2022) 015004
H. Chen et al, Rept.Prog.Phys. 86 (2023) 026201

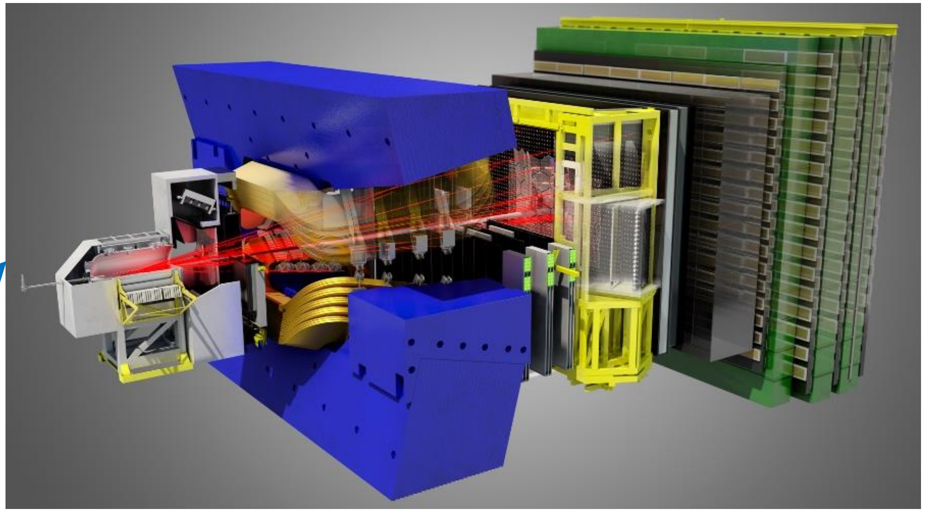




The LHCb experiment



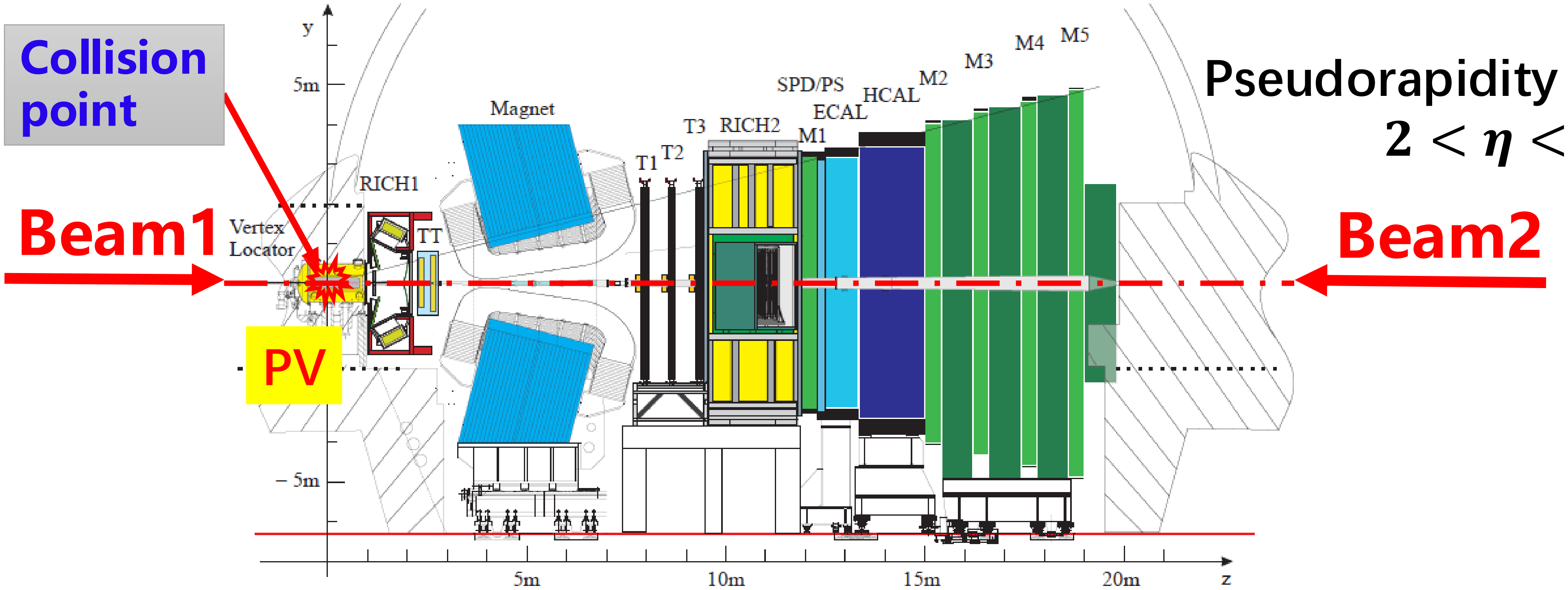
- A forward spectrometer at the LHC designed for the study of heavy flavour physics



- The LHCb collaboration
  - 1710 Members, from 103 institutes in 22 countries (by 26/09/2024)

The LHCb detector and physics

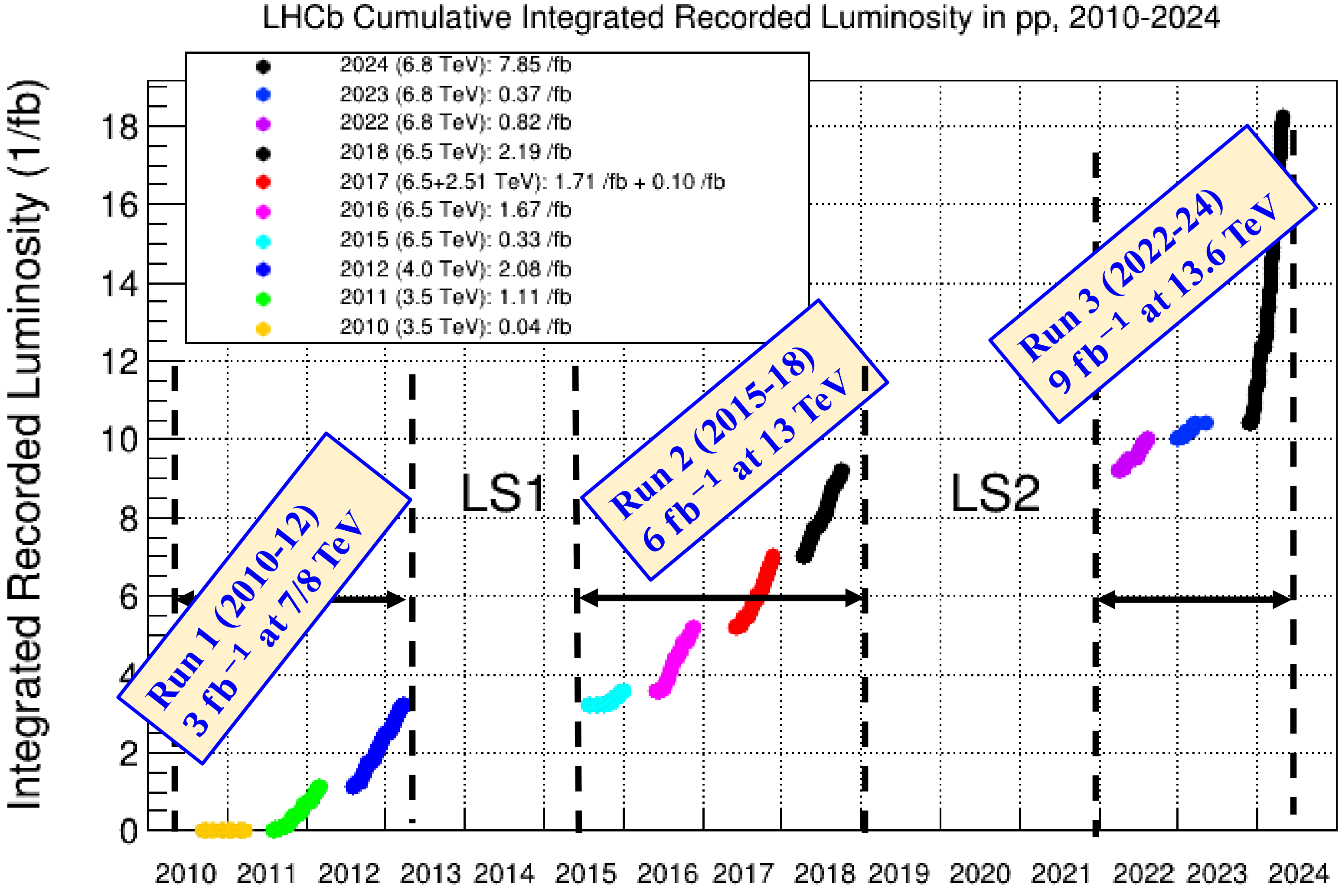
JINST 3 (2008) S08005
Int. J. Mod. Phys. A 30 (2015) 1530022



Pseudorapidity coverage
$2 < \eta < 5$

- Indirect search for New Physics via precision measurements of CKM, CPV and RD
- Direct search of new particles beyond SM
- QCD +EW precision measurements at large rapidity
- Hadron spectroscopy
- Heavy-ion and fixed target physics

Data taking (run1+run2+run3)

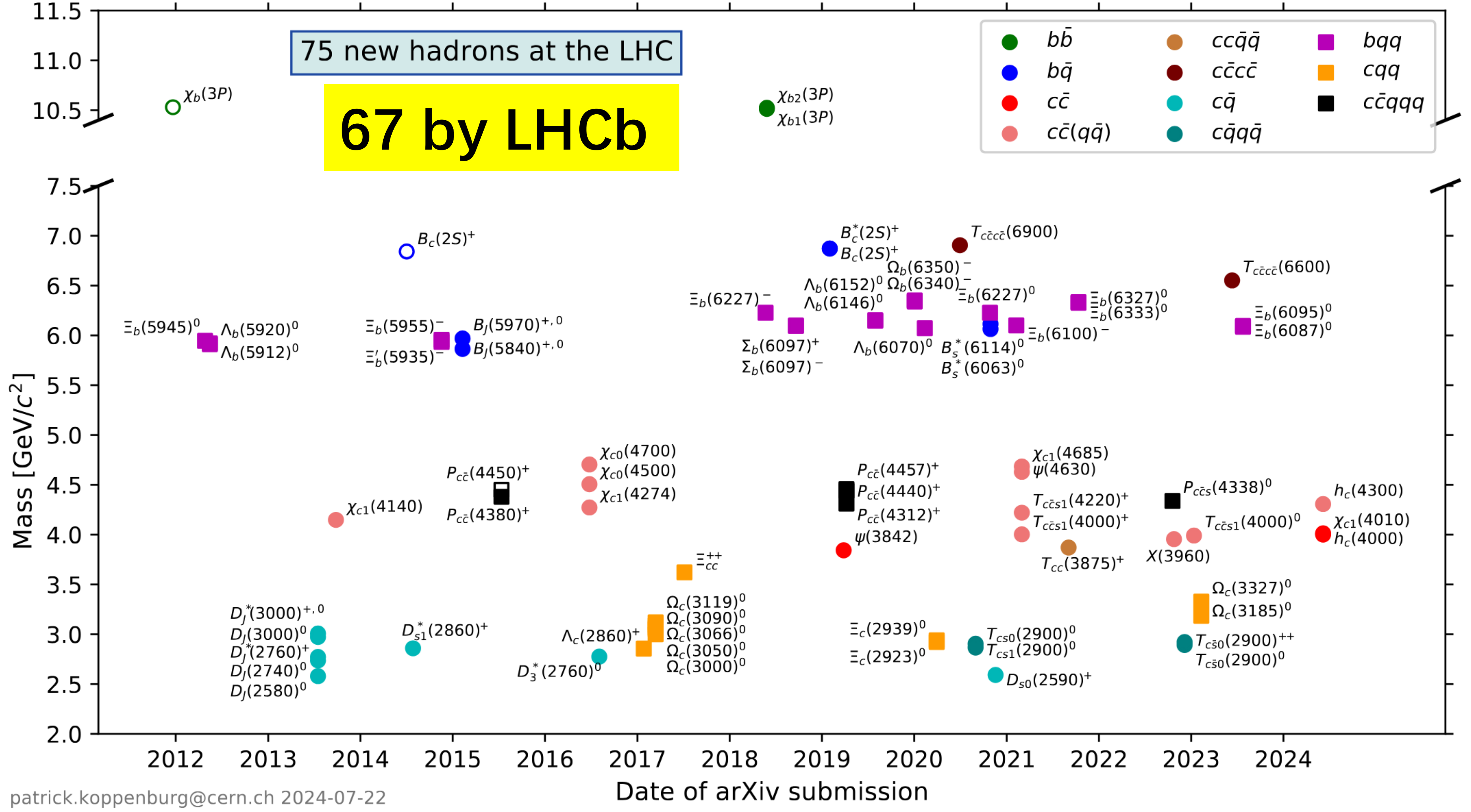


- A huge amount of $b\bar{b}$ and $c\bar{c}$ have been produced
  - $\sim 10^{12}\ b\bar{b}$
  - $\sim 10^{13}\ c\bar{c}$
- Many impressive results have been achieved

$\mathbf{3+6+9\ fb^{-1}}$ **accumulated in Run1+2+3 (2011-2024)**

Results shown today used only (part of) Run1+2

Hadrons observed at LHC(b) (up to 2024-07-22)

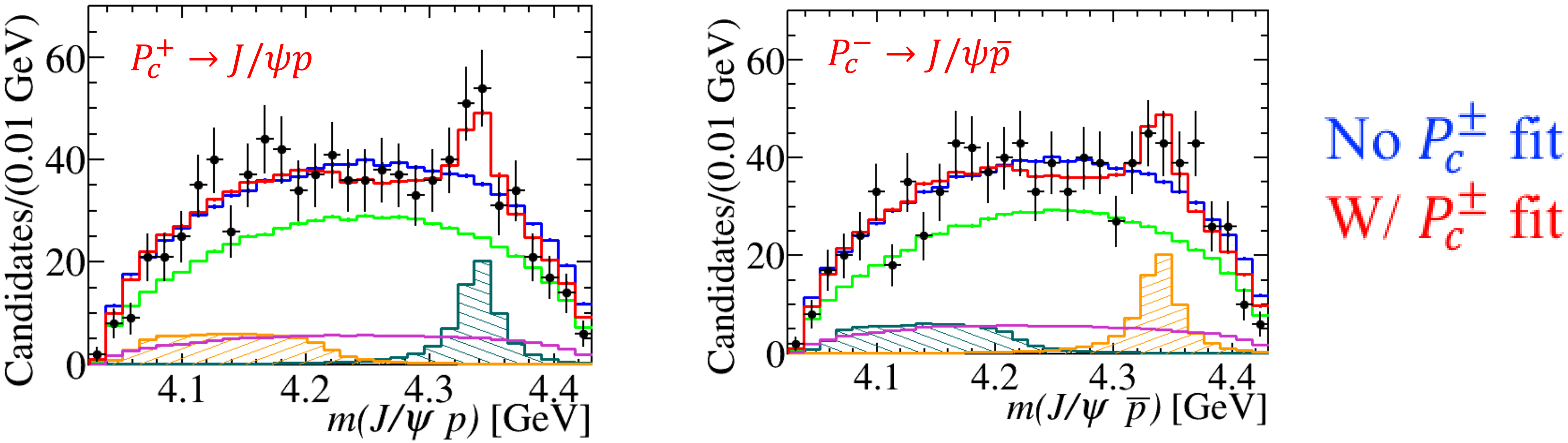


[New particles discovered at the LHC]

Quick reminder of searches for $P_c^{\pm} \to J/\psi p(\bar{p})$

- Amplitude analysis in $B_s^0 \to J/\psi p\bar{p}$ with 2011-2018 data (9 fb^{-1})
- Significance of 3.1σ~3.7σ for $J^P = (\frac{1}{2}^{\pm}, \frac{3}{2}^{\pm})$

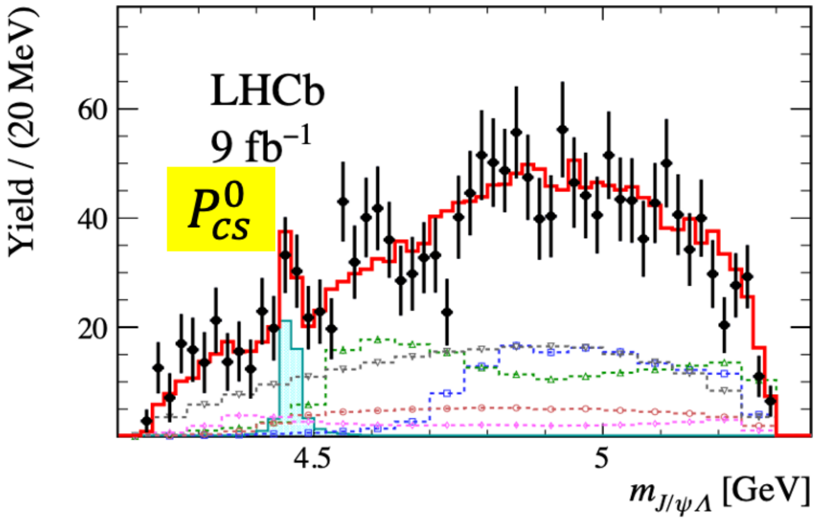
Phys.Rev.Lett. 128 (2022) 062001



$$M_{P_c} = 4337^{+7}_{-4}(\text{stat})^{+2}_{-2}(\text{syst})\ \text{MeV},$$
$$\Gamma_{P_c} = 29^{+26}_{-12}(\text{stat})^{+14}_{-14}(\text{syst})\ \text{MeV},$$

Quick reminder of searches for $P_{cs}^0 \to J/\psi\Lambda$

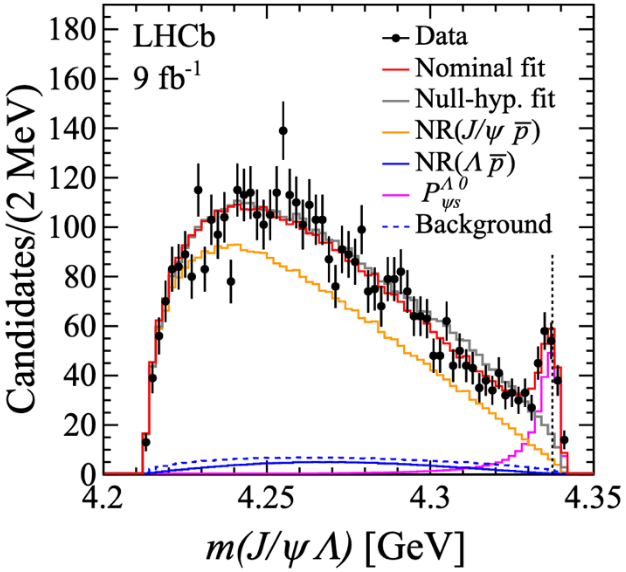
- Amplitude analysis of $\Xi_b^- \to J/\psi K^- \Lambda$ with 2011-2018 data (9 fb^{-1})
- Stat. significance of 4.3σ
  - 3.1σ when syst. considered



$m = 4458.8 \pm 2.9^{+4.7}_{-1.1}$ MeV
$\Gamma = 17.3 \pm 6.5^{+8.0}_{-5.7}$ MeV

Science Bulletin 66 (2021) 1278

- Amplitude analysis of $B^- \to J/\psi\Lambda\bar{p}$ with 2011-2018 data (9 fb^{-1})
- Significance $> 10\sigma$, $J^P = \frac{1}{2}^-$ preferred



$m = 4338.2 \pm 0.7 \pm 0.4$ MeV
$\Gamma = 7.0 \pm 1.2 \pm 1.3$ MeV

Phys. Rev. Lett. 131 (2023) 031901

Outline

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  - Observation of $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$ Phys. Rev. D110 (2024) L031104
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- Prospects and summary

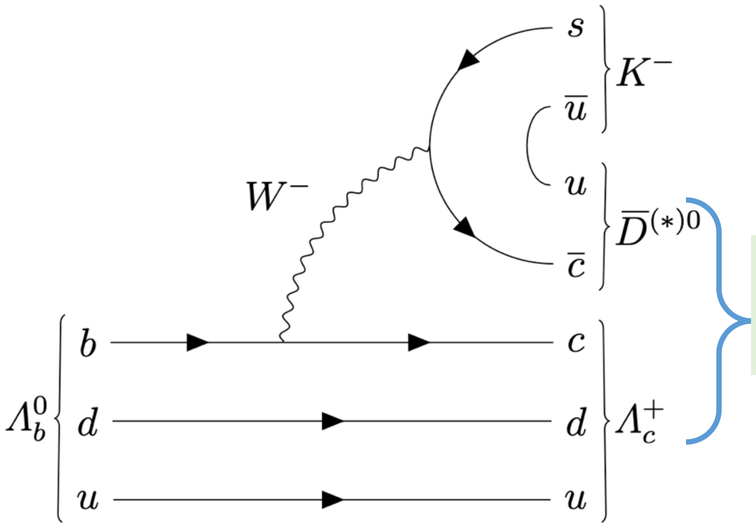
Observation of $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$

Eur.J.Phys.C84 (2024) 575

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

Eur.J.Phys.C84 (2024) 575

- Comparable decay with $\Lambda_b^0 \to J/\psi p K^-$ with possible
- 2016-2018 data (5.4 fb^{-1})
- MVA-based selection for charmed hadrons
- Partially reconstruction for $D^{*0} \to D^0\gamma/\pi^0$
  - Signal shapes determined by KDE from simulation



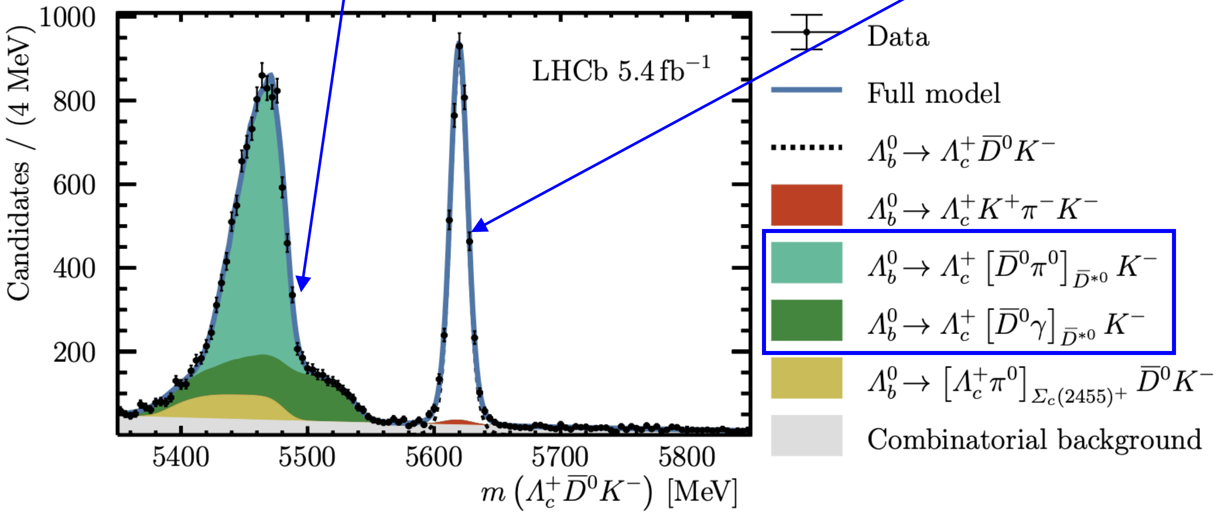
Possible $P_c^+ \to \Lambda_c^+ \overline{D}^{(*)0}$

$N(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{*0} K^-) = 10560^{+310}_{-290}$

$N(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{0} K^-) = 4010 \pm 70$

partial reconstruction for $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{*0} K^-$

$\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{0} K^-$



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

Eur.J.Phys.C84 (2024) 575

- Branching fractions measured

statistical Intermediate decay BF

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

systematic

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

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

w.r.t the normalisation channel

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

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

w.r.t the P_c-observation channel

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

Systematic uncertainties dominated by fit model and samples for efficiency determination

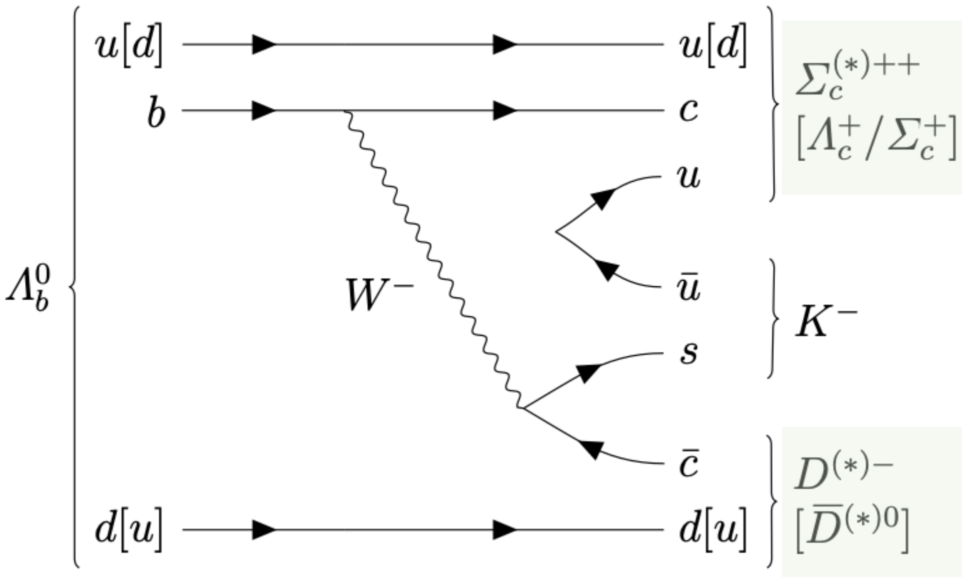
Observation of $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$

Phys. Rev. D110 (2024) L031104

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

Phys. Rev. D110 (2024) L031104

- Color-suppressed compared with $\Lambda_b^0 \to J/\psi p K^-$ and $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-$
- 2015-2018 data (6 fb^{-1})
- $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-$ used for reference to measure branching fractions

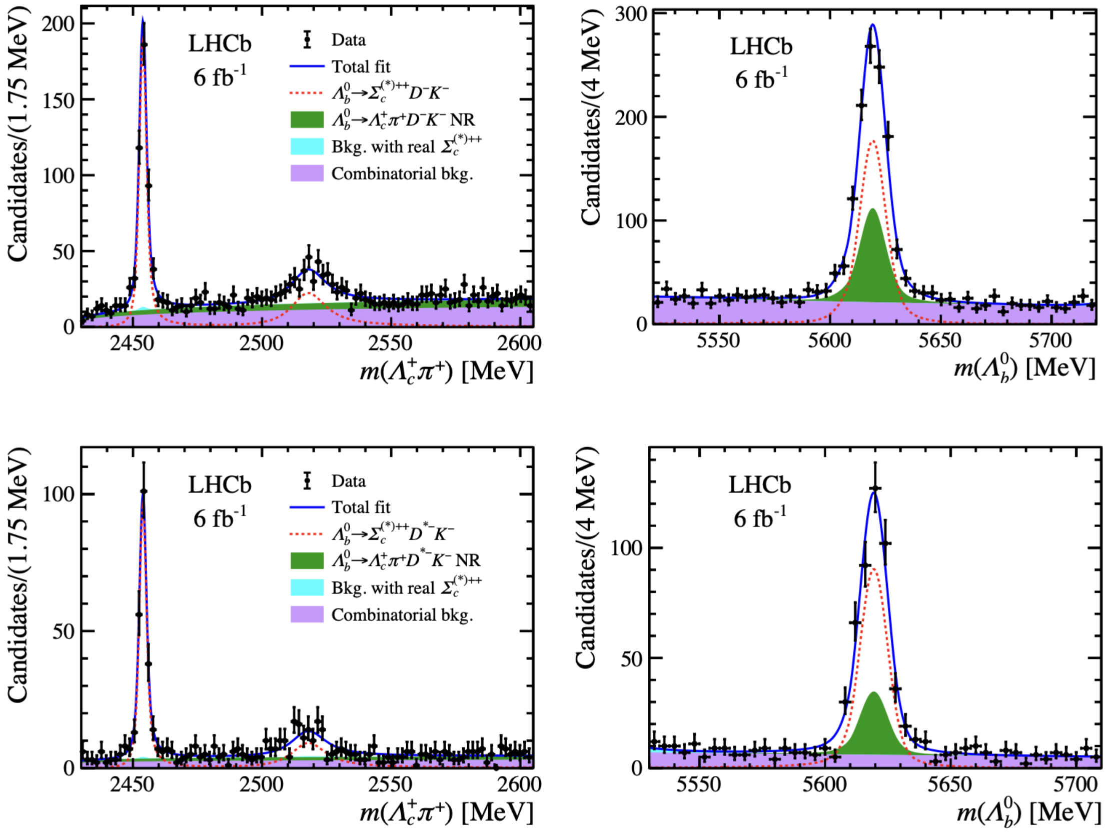


Possible
$P_c^+ \to \Sigma_c^{(*)++} D^{(*)-}$

Observation of $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$ (cont.)

Phys. Rev. D110 (2024) L031104

- Mass fit to extract signals
  - 2D fit, with primary-vertex and mass constraints



Observation of $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$ (cont.)

Phys. Rev. D110 (2024) L031104

- Branching fractions

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

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{*++} D^- K^-)}{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{++} D^- K^-)} = 0.460 \pm 0.052 \pm 0.028,$$

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

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

The first uncertainties are statistical,
the second systematic,
the third due to branching fractions of intermediate decays

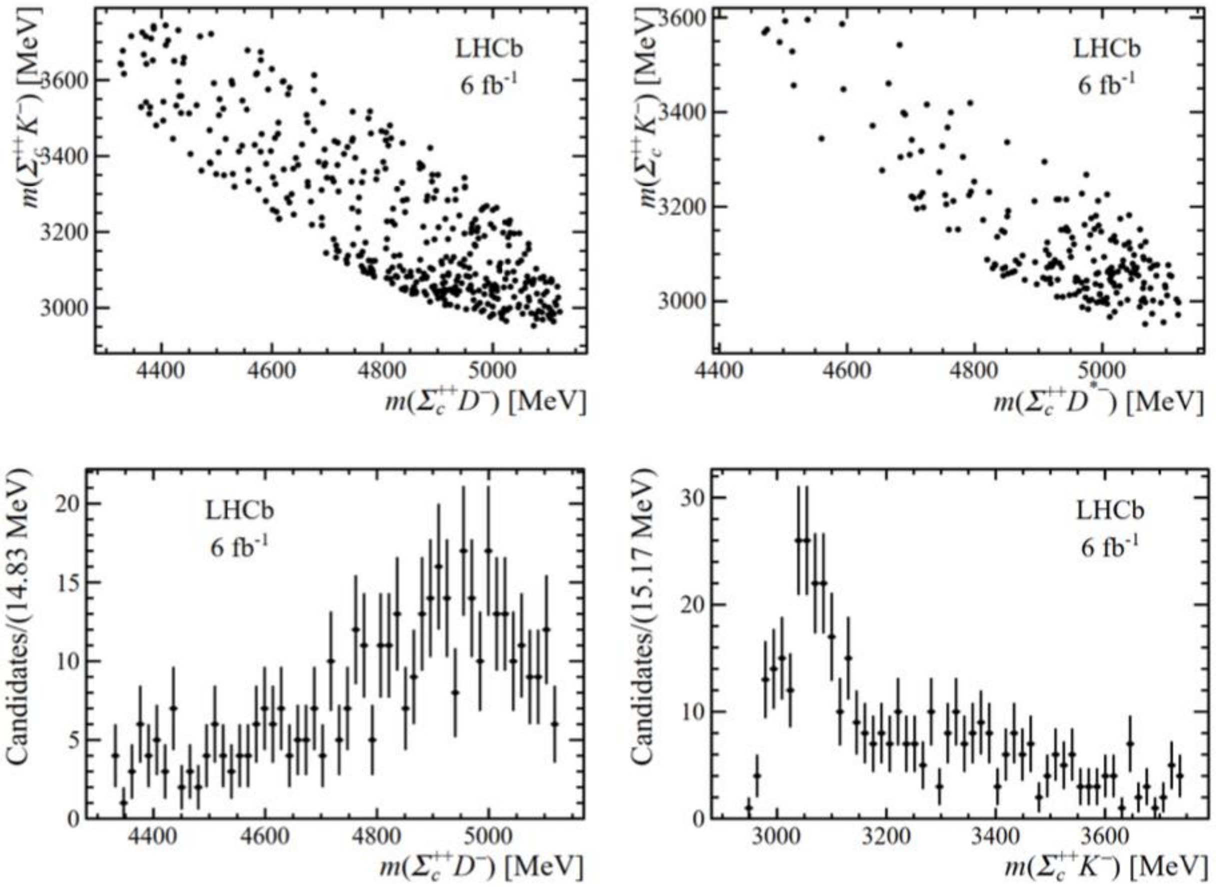
Source	$\frac{\mathcal{B}(\Lambda_b^0\to\Sigma_c^{++}D^-K^-)}{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+\bar{D}^0K^-)}$	$\frac{\mathcal{B}(\Lambda_b^0\to\Sigma_c^{*++}D^-K^-)}{\mathcal{B}(\Lambda_b^0\to\Sigma_c^{++}D^-K^-)}$	$\frac{\mathcal{B}(\Lambda_b^0\to\Sigma_c^{++}D^{*-}K^-)}{\mathcal{B}(\Lambda_b^0\to\Sigma_c^{++}D^-K^-)}$	$\frac{\mathcal{B}(\Lambda_b^0\to\Sigma_c^{*++}D^{*-}K^-)}{\mathcal{B}(\Lambda_b^0\to\Sigma_c^{++}D^-K^-)}$
Track reconstruction	3.22%	–	–	–
Trigger efficiency	0.77%	–	–	–
PID correction algorithm	0.20%	0.05%	0.06%	0.28%
Fitting model	1.36%	3.67%	2.00%	1.29%
Kinematic reweight	0.05%	$< 0.01\%$	$< 0.01\%$	$< 0.01\%$
Statistics of simulated samples	2.71%	4.01%	3.59%	5.58%
NDC backgrounds	1.66%	2.44%	0.71%	2.10%
Modeling of Λ_c^+ decay amplitude	1.28%	0.09%	1.58%	0.41%
Multiple candidates	0.06%	1.51%	0.38%	3.44%
Total	5.64%	6.21%	5.70%	7.35%

Systematic uncertainties dominated by fit model, samples for efficiency determination, and non-doubly-charmed backgrounds

Observation of $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$ (cont.)

Phys. Rev. D110 (2024) L031104

- Any hint of $P_c^+ \to \Sigma_c^{++} D^{(*)-}$?



- No clear $P_c^+ \to \Sigma_c^{++} D^{(*)-}$ observed
- Amplitude analysis will be performed when larger data sample available
- The newly measured branching ratios of $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$ and $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-$ might be helpful for calculations in the molecular picture

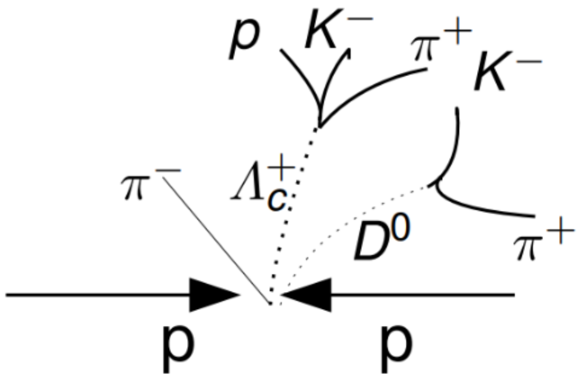
Search for pentaquarks decaying to open-charm hadrons in pp prompt production

Phys. Rev. D110 (2024) 032001

Pentaquark searches in prompt production

Phys. Rev. D110 (2024) 032001

- Pentaquark might be produced in prompt production in pp collisions
- Searches could be performed in combinations of hadron combinations, e.g. $J/\psi p$, $J/\psi \Lambda$, or open-charmed hadrons
  - Challenging due to very high and complicated backgrounds
- The following combinations studied
- 2016-2018 data ($5.7\ \mathrm{fb}^{-1}$)



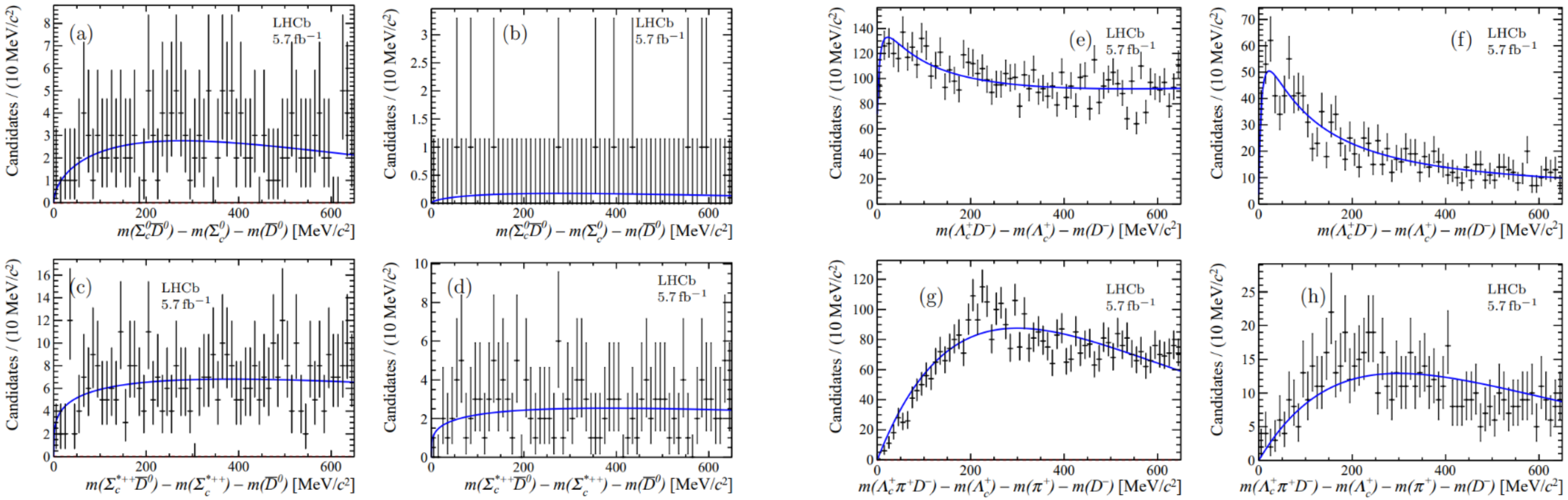
$\Sigma_c^{++}\bar{D}^0$	~~$\Sigma_c^{++}D^0$~~	$\Sigma_c^{++}D^-$	~~$\Sigma_c^{++}D^+$~~	~~$\Sigma_c^{++}D^{*-}$~~	~~$\Sigma_c^{++}D^{*+}$~~
$\Sigma_c^{0}\bar{D}^0$	~~$\Sigma_c^{0}D^0$~~	$\Sigma_c^{0}D^-$	~~$\Sigma_c^{0}D^+$~~	~~$\Sigma_c^{0}D^{*-}$~~	~~$\Sigma_c^{0}D^{*+}$~~
$\Sigma_c^{*++}\bar{D}^0$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

- 10 modes too statistically limited to set UL
- 32 modes studied

Pentaquark searches in prompt production

Phys. Rev. D110 (2024) 032001

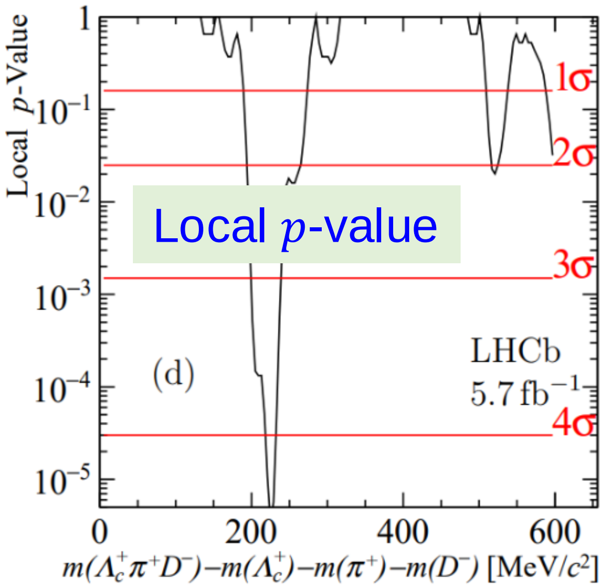
- Example fits for the background-only hypothesis
  - $\Sigma_c^{(*)}D$ and $\Lambda_c^+\pi D$ modes: threshold function
  - Λ_c^+D modes: 1st order Chebyshev polynomial summed with log-normal distribution



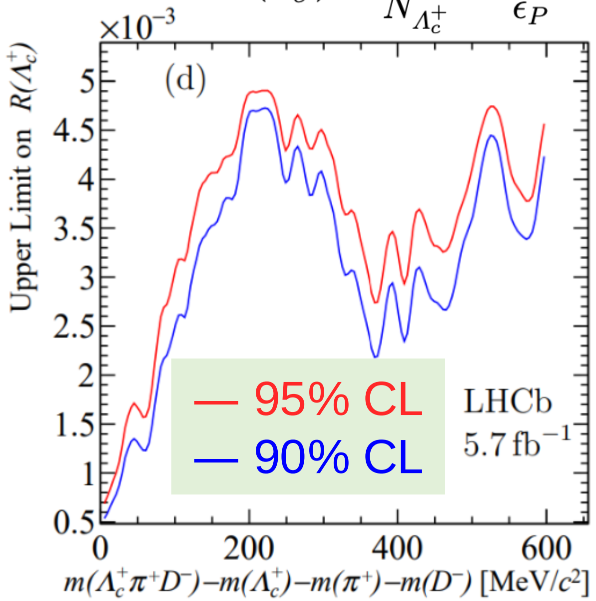
Pentaquark searches in prompt production

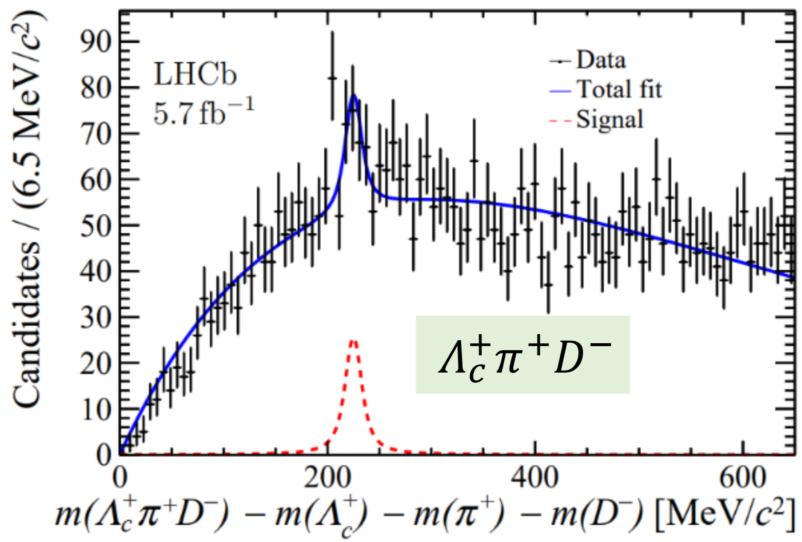
Phys. Rev. D110 (2024) 032001

- Signal model: Gaussian, 5, 10, 15 Voigtians
  - The likelihood convoluted with a Gaussian to consider systematics
  - LEE effect considered
- The most significant deviation from H0 is seen in the $\Lambda_c^+\pi^+D^-$ mode (3.6σ)



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





Pentaquark searches in prompt production

Phys. Rev. D110 (2024) 032001

- No hints for know pentaquark states ➔ setting ULs

Decay Mode	Pentaquark Hypothesis	p-value	Significance (σ)	Signal Yield	Upper Limit ($\times 10^{-3}$) (90% CL)	(95% CL)
$\Lambda_c^+ \ \overline{D}^0$	$P_c(4312)^+$	0.32	0.48	19.78 ± 22.27	1.17	1.29
	$P_c(4440)^+$	0.44	0.15	26.91 ± 28.17	1.41	1.53
	$P_c(4457)^+$	0.53	0.00	6.20 ± 13.60	1.27	1.43
$\Lambda_c^+ \ \pi^+ \ D^{*-}$	$P_c(4440)^+$	1.00	0.00	0.00 ± 0.96	0.72	0.91
	$P_c(4457)^+$	1.00	0.00	0.00 ± 1.73	0.77	0.97
$\Lambda_c^+ \ \pi^- \ D^{*-}$	$P_c(4440)^+$	1.00	0.00	0.00 ± 0.80	0.63	0.80
	$P_c(4457)^+$	1.00	0.00	0.00 ± 0.74	0.59	0.74
$\Lambda_c^+ \ \pi^+ \ D^-$	$P_c(4312)^+$	1.00	0.00	0.00 ± 1.56	0.69	0.88
	$P_c(4440)^+$	0.65	0.00	4.43 ± 11.67	3.71	4.24
	$P_c(4457)^+$	0.65	0.00	5.94 ± 12.68	3.13	3.61
$\Lambda_c^+ \ \pi^- \ D^-$	$P_c(4312)^+$	1.00	0.00	0.00 ± 1.42	0.67	0.86
	$P_c(4440)^+$	0.53	0.00	12.52 ± 15.89	3.91	4.37
	$P_c(4457)^+$	0.53	0.00	8.60 ± 12.22	3.10	3.51
$\Sigma_c^0 \ D^-$	$P_c(4440)^+$	1.00	0.00	0.00 ± 2.47	0.82	1.03
	$P_c(4457)^+$	1.00	0.00	0.00 ± 1.05	0.63	0.81
$\Sigma_c^{++} \ D^-$	$P_c(4440)^+$	0.80	0.00	0.61 ± 4.52	1.13	1.37
	$P_c(4457)^+$	0.59	0.00	0.66 ± 1.79	0.80	0.99
$\Sigma_c^{*0} \ D^-$	$P_c(4440)^+$	0.31	0.49	3.23 ± 3.53	1.89	2.24
	$P_c(4457)^+$	1.00	0.00	0.00 ± 3.09	0.91	1.13
$\Sigma_c^{*++} \ D^-$	$P_c(4440)^+$	0.75	0.00	1.20 ± 3.81	1.38	1.67
	$P_c(4457)^+$	1.00	0.00	0.00 ± 5.74	0.87	1.08

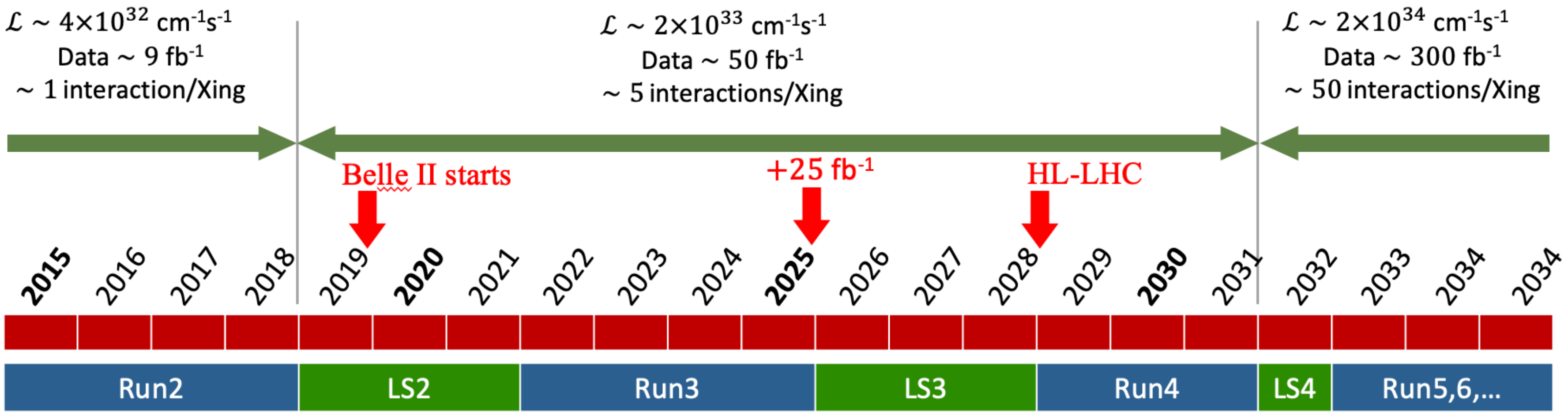
$$R(\Lambda_c^+) = \frac{N_P}{N_{\Lambda_c^+}} \times \frac{\epsilon_{\Lambda_c^+}}{\epsilon_P}$$

Outline

- Introduction
- Recent results of pentaquarks
  - Observation of $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$ Eur.J.Phys.C84 (2024) 575
  - Observation of $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$ Phys. Rev. D110 (2024) L031104
  - Search for pentaquarks decaying to open-charm hadrons in pp prompt production Phys. Rev. D110 (2024) 032001
- Prospects and summary

Prospects

The LHCb Upgrade: status and plan



- 9 fb^{-1} accumulated in Run1+Run2 (2010-2018)
- Upgrade performed in LS2 (2019-2021)
  - 50 fb^{-1} expected after Run4
- Upgrade 2 (LS4)
  - 300 fb^{-1} in total expected after Run5

Summary

- Great progress since the observation of the pentaquarks in 2015
- Recent results of pentaquarks reported
  - Observation of $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$
  - Observation of $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$
  - Search for pentaquarks decaying to open-charm hadrons in pp prompt production
- While exploiting the full Run1+Run2 data, data from Run3 increasing rapidly, with $50\ \mathrm{fb}^{-1}$ expected after Run4 and $300\ \mathrm{fb}^{-1}$ after Run5
- New data are coming, stay tuned for new results from LHCb

Thank you!