b-baryon decays at LHCb

俞洁晟（湖南大学）

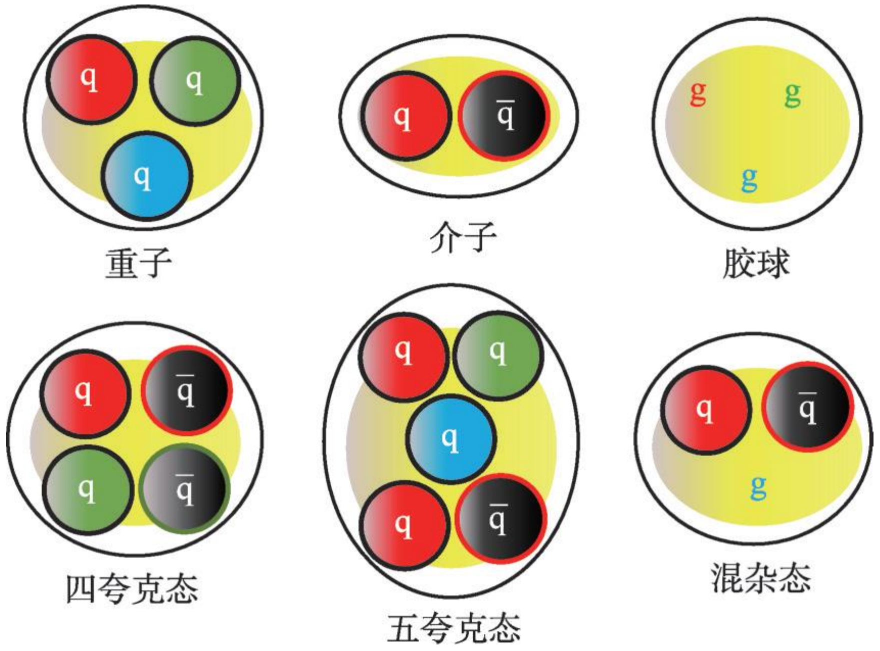
第21届 全国重味物理与CP破坏研讨会
2024年10月25-29日 衡阳
南华大学、湖南大学

Outline

- Introduction
- b-baryon FCNC
  - $\Lambda_b^0 \to pK^-\mu^+\mu^-$
- $b \to c\bar{c}s$ decays
  - $\Lambda_b^0 \to \Lambda_c^+\bar{D}^{(*)0}K^-$, $\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}$, $\Lambda_b^0 \to \Sigma_c^{(*)++}\bar{D}^{(*)-}K^-$, $\Lambda_b^0 \to D\bar{D}\Lambda$,
- $b \to c$ decays
  - b-baryon $\to \Lambda_c^+ hh$

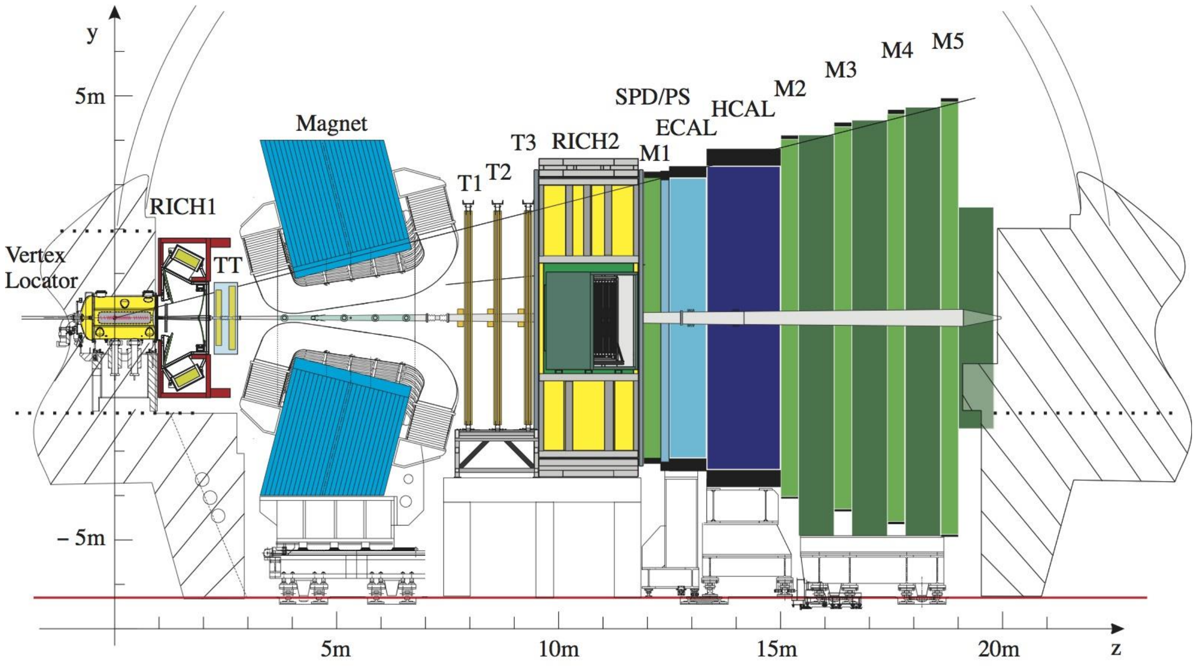
Why baryons?

- The main constituents of the universe
- More sensitive to non-perturbative QCD: test effective models
- ***b***-baryons have enough energy to search these states



LHCb experiment

LHCb collaboration： 21 counties, 96 institutes, 1600 members



中国单位(9个)：
清华大学
华中师范大学
中国科学院大学
武汉大学
高能物理研究所
华南师范大学
北京大学
湖南大学
兰州大学

- Understand matter-antimatter imbalance (CP violation)
- Search for new physics (Rare decays)
- Explore and understand QCD (Hadron properties, exotic hadrons)

b-baryon FCNC

$$\Lambda_b^0 \rightarrow pK^-\mu^+\mu^-$$

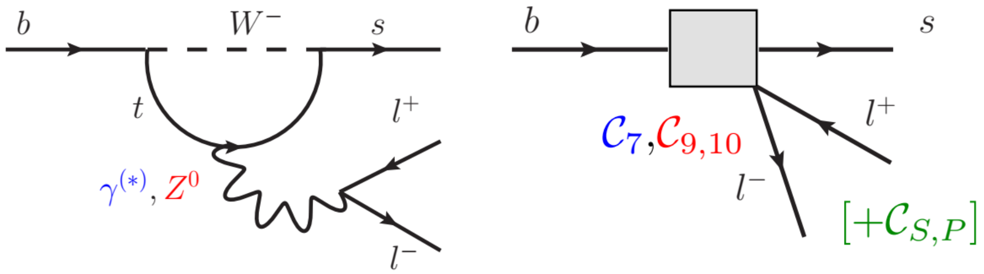
$b \to s l^+ l^-$ decays

- $b \to s l^+ l^-$ decays described by effective Hamiltonian

$$H = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i O_i + \frac{K}{\Lambda_{NP}^2} O_j^{(6)}$$

New physics can affect Wilson coefficients C_i or add new operators O_j

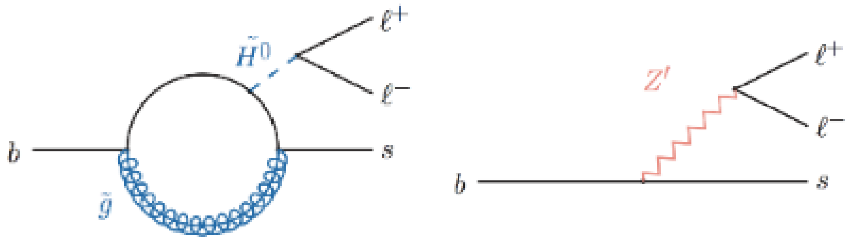
- Sensitivity to Wilson coefficients



- $B^0_{(s)} \to l^+ l^-$ $[\mathcal{C}_{10}, \mathcal{C}_S, \mathcal{C}_P]$
- $b \to s l^+ l^-$ $[\mathcal{C}_7, \mathcal{C}_9, \mathcal{C}_{10}]$

7: photon penguin; 9,10: EW penguin; S,P: (pseudo-) scalar penguin

- Theoretically clean probes of NP
  - Pure leptonic decays
  - Special angular observables
  - Ratio between $e/\mu/\tau$

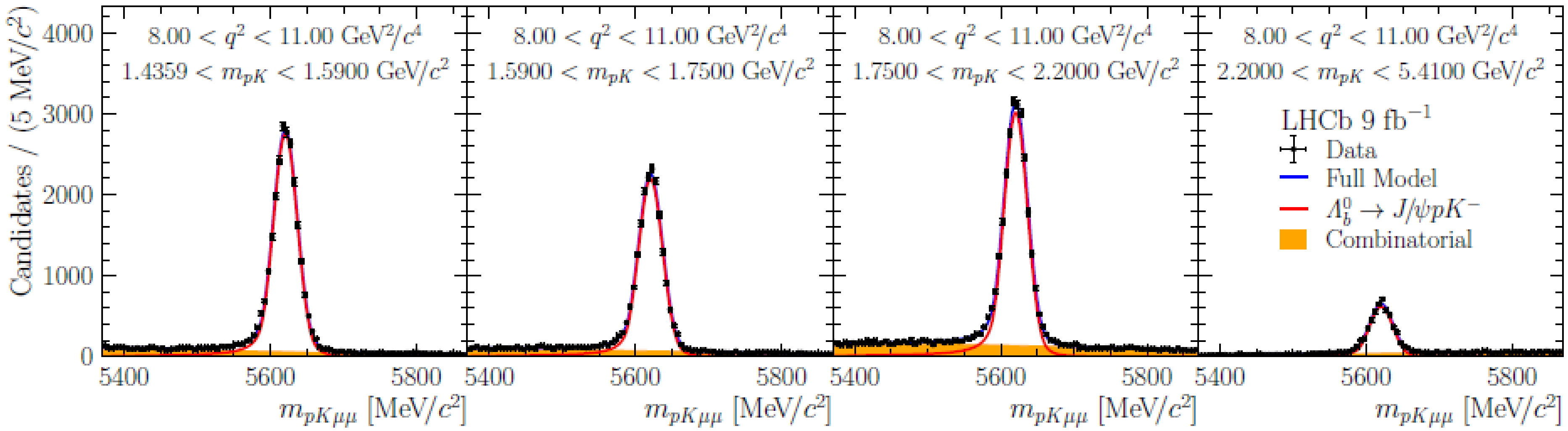


Measurement of the $\Lambda_b^0 \to pK^-\mu^+\mu^-$ differential branching fraction

- $\Lambda_b \to pK^- J/\psi(\to \mu^+\mu^-)$ as normalization channel

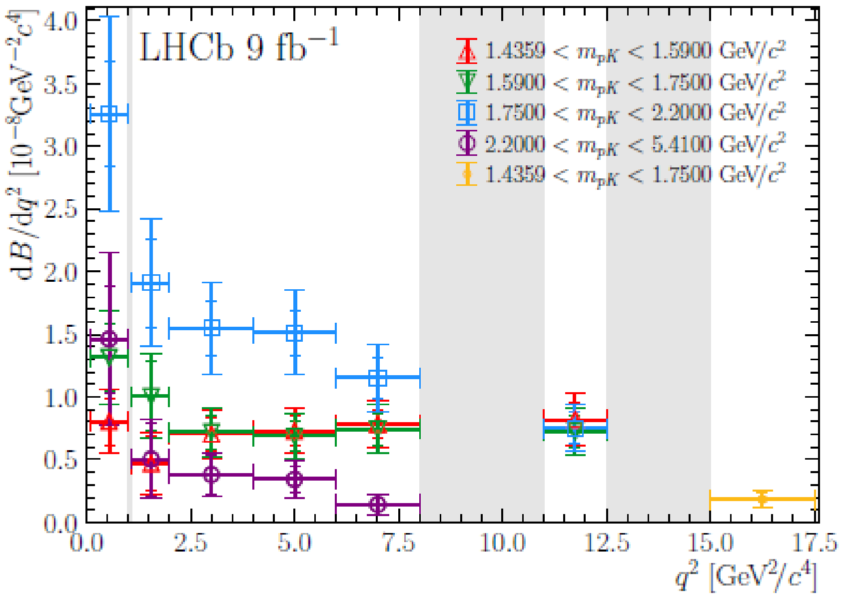
$$\frac{d^2\mathcal{B}(\Lambda_b^0 \to pK^-\mu^+\mu^-)}{dq^2 dm_{pK}^2} = \frac{N_{\Lambda_b^0\to pK^-\mu^+\mu^-}}{N_{\Lambda_b^0\to J/\psi pK^-}} \frac{\mathcal{B}(\Lambda_b^0 \to J/\psi pK^-)\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\Delta(q^2, m_{pK}^2)}$$

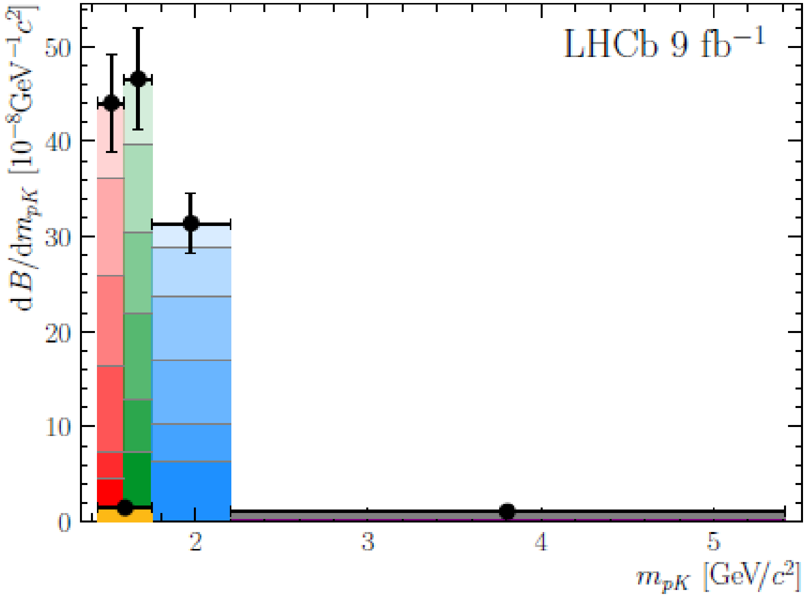
arXiv:2409.12629



q^2 \ m_{pK}	[1.4359, 1.5900]	[1.59, 1.75]	[1.75, 2.20]	[2.20, 5.41]
[0.10, 0.98]	$5.22 \pm 1.21 \pm 0.43 \pm 0.98$	$8.22 \pm 1.69 \pm 0.38 \pm 1.54$	$7.24 \pm 0.92 \pm 0.52 \pm 1.36$	$0.46 \pm 0.13 \pm 0.14 \pm 0.09$
[1.1, 2.0]	$3.05 \pm 1.45 \pm 0.51 \pm 0.57$	$6.27 \pm 1.71 \pm 0.40 \pm 1.18$	$4.24 \pm 0.78 \pm 0.16 \pm 0.80$	$0.16 \pm 0.09 \pm 0.02 \pm 0.03$
[2.0, 4.0]	$4.56 \pm 0.90 \pm 0.26 \pm 0.86$	$4.50 \pm 0.86 \pm 0.21 \pm 0.84$	$3.44 \pm 0.47 \pm 0.08 \pm 0.64$	$0.12 \pm 0.05 \pm 0.02 \pm 0.02$
[4.0, 6.0]	$4.72 \pm 0.76 \pm 0.15 \pm 0.89$	$4.29 \pm 0.73 \pm 0.20 \pm 0.81$	$3.36 \pm 0.41 \pm 0.07 \pm 0.63$	$0.11 \pm 0.03 \pm 0.02 \pm 0.02$
[6.0, 8.0]	$5.08 \pm 0.76 \pm 0.12 \pm 0.95$	$4.65 \pm 0.79 \pm 0.34 \pm 0.87$	$2.56 \pm 0.36 \pm 0.05 \pm 0.48$	$0.04 \pm 0.02 \pm 0.01 \pm 0.01$
[11, 12.5]	$5.32 \pm 0.86 \pm 0.20 \pm 1.00$	$4.53 \pm 0.80 \pm 0.16 \pm 0.85$	$1.67 \pm 0.28 \pm 0.03 \pm 0.31$	—
[15.0, 17.5]	$0.59 \pm 0.19 \pm 0.07 \pm 0.11$		—	—

Measurement of the $\Lambda_b^0 \to pK^-\mu^+\mu^-$ differential branching fraction





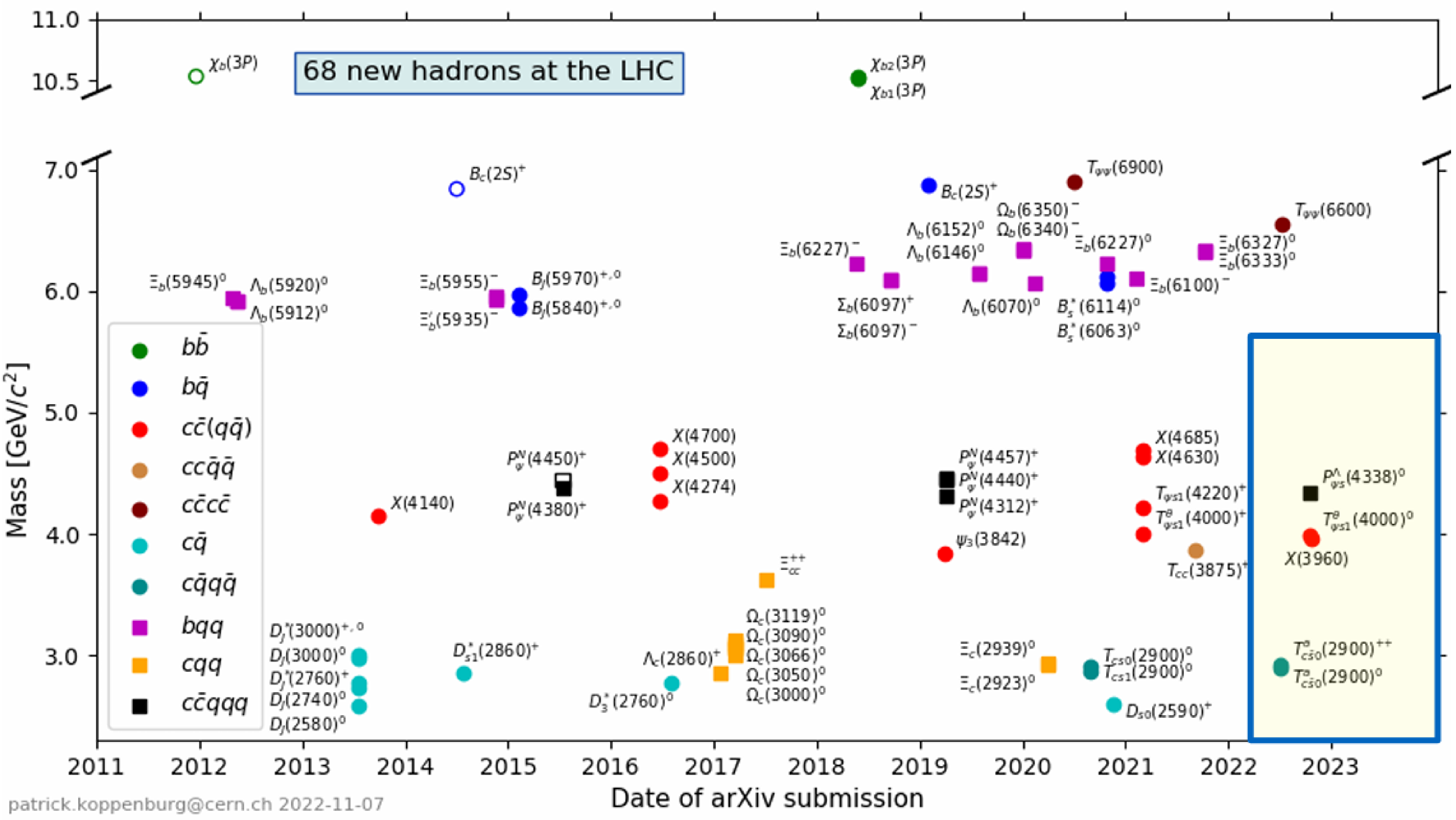
arXiv:2409.12629

- The pattern of measurements appears consistent with SM expectations.
- However, a detailed interpretation of the results requires a more complete understanding of the hadronic system and the different contributing states.

$b \to c\bar{c}s$ decays

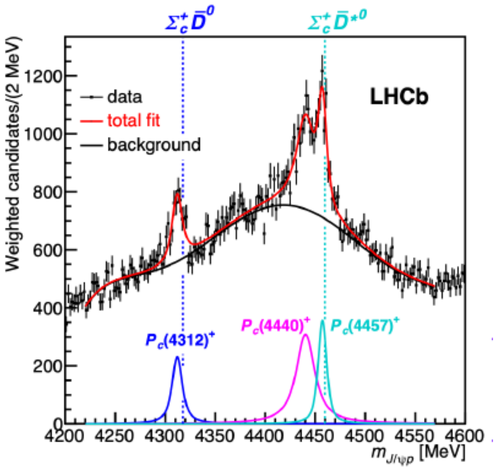
$$\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-,\ \Lambda_b^0 \to \Lambda_c^+ D_s^{*-},$$
$$\Lambda_b^0 \to \Sigma_c^{(*)++} \bar{D}^{(*)-} K^-,\ \Lambda_b^0 \to D\bar{D}\Lambda,$$

Heavy hadron Spectroscopy

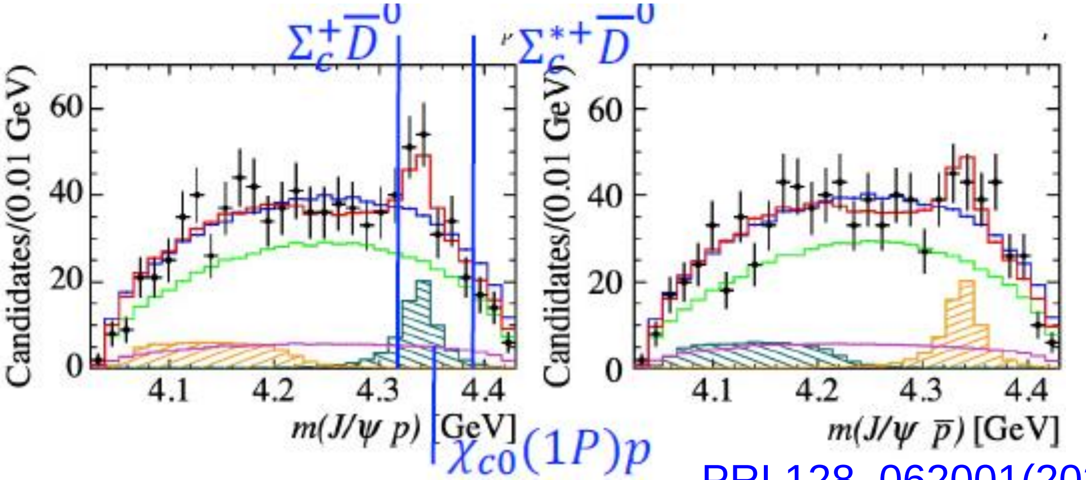


Pentaquark states at LHCb

- ➢ Observation of $[c\bar{c}uud]$ pentaquarks: $P_c(4312)^+$, $P_c(4440)^+$, $P_c(4457)^+$

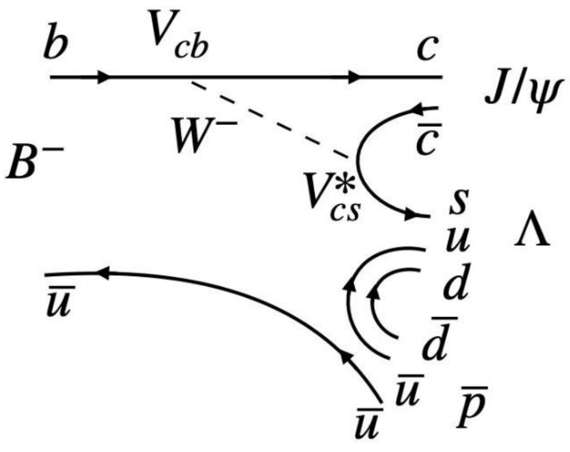


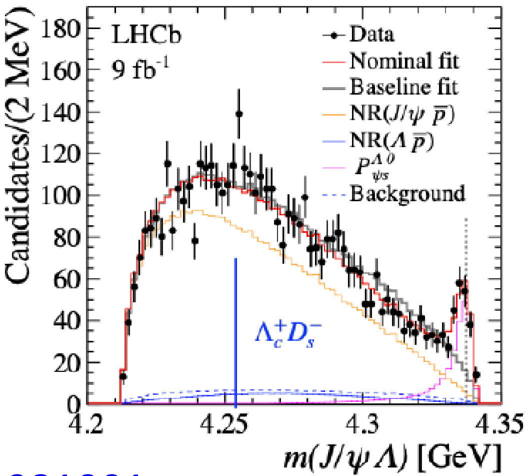
PRL122, 222001(2019)



PRL128, 062001(2022)

- ➢ Observation of $[c\bar{c}uds]$ pentaquark candidate with strangeness: $P_{cs}(4338)^0$





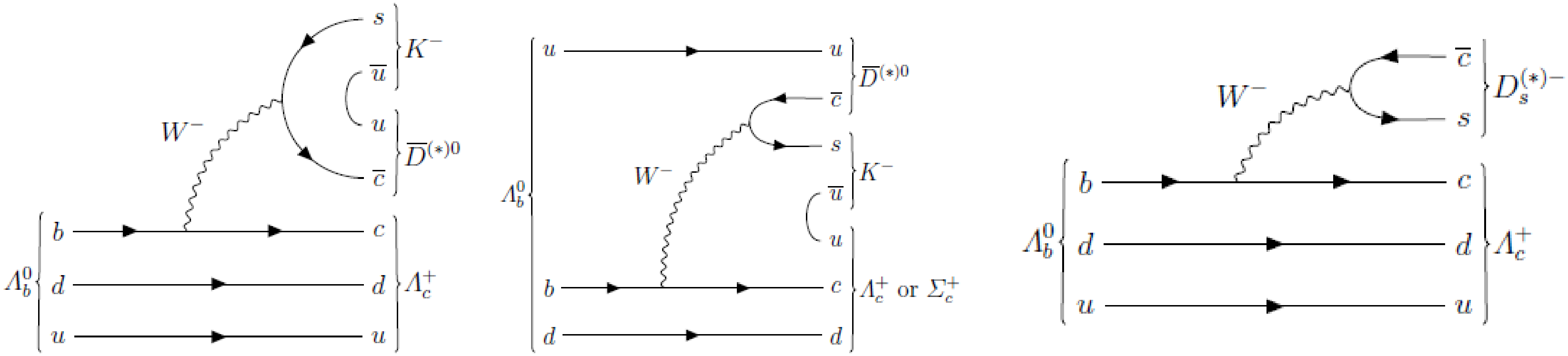
Phys. Rev. Lett. 131, 031901

First observation of $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-$ with Run II data

- P_c decay to $\Lambda_c^+ \bar{D}^{(*)0}$ are anticipated in many models

  Phys. Lett. B793 (2019) 144, Phys. Rev. D100 (2019) 014021, Phys. Rev. D100 (2019) 016014…

- The theory predict: $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^{*-})/\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)$ in range 0.75–2.2



- $\Lambda_b^0 \to \Lambda_c^+ D_s^-$ as normalization channel

$$\frac{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ D_s^-\right)} = \frac{N^{\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-}}{N^{\Lambda_b^0 \to \Lambda_c^+ D_s^-}} \frac{\epsilon^{\Lambda_b^0 \to \Lambda_c^+ D_s^-}}{\epsilon^{\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-}} \frac{\mathcal{B}\left(D_s^- \to K^- K^+ \pi^-\right)}{\mathcal{B}\left(\bar{D}^0 \to K^+ \pi^-\right)},$$

$$\frac{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ D_s^-\right)} = \frac{N^{\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}}}{N^{\Lambda_b^0 \to \Lambda_c^+ D_s^-}} \frac{\epsilon^{\Lambda_b^0 \to \Lambda_c^+ D_s^-}}{\epsilon^{\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}}},$$

First observation of $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$ with Run II data

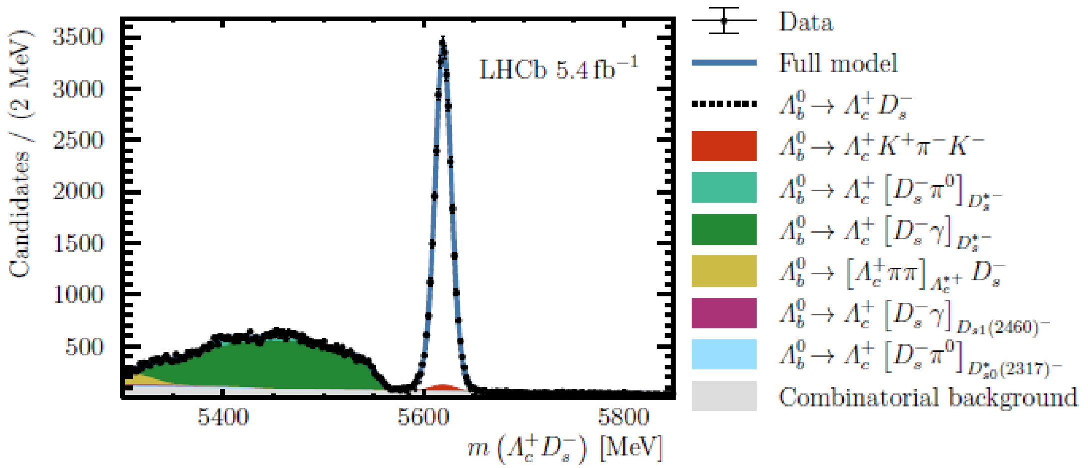
$$\frac{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ D_s^-\right)} = 0.1908^{+0.0036+0.0016}_{-0.0034-0.0018} \pm 0.0038,$$

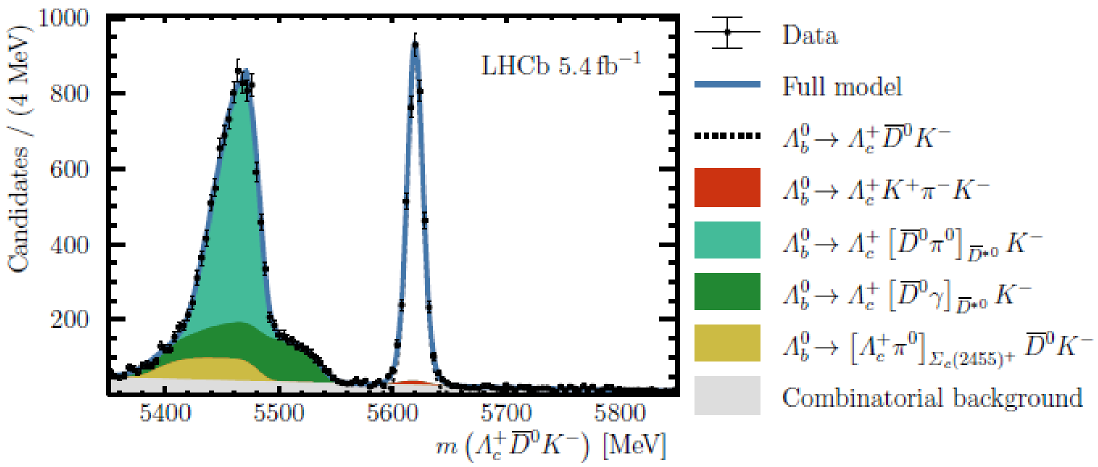
$$\frac{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{*0} K^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ D_s^-\right)} = 0.589^{+0.018+0.017}_{-0.017-0.018} \pm 0.012,$$

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

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

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





- $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^{*-})/\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)$ is compatible with several predictions: Mod. Phys. Lett. A13 (1998) 23, Chin. Phys.C42 (2018) 093101, Eur. Phys. J. C79 (2019) 540, Phys. Rev. D100 (2019) 034025

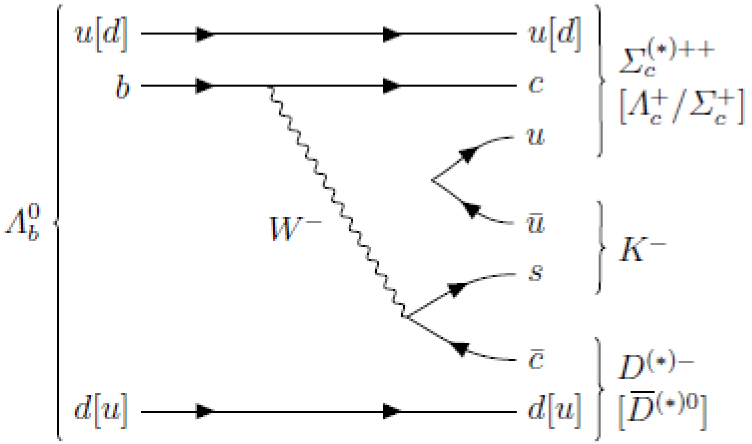
EPJC 84 (2024) 575

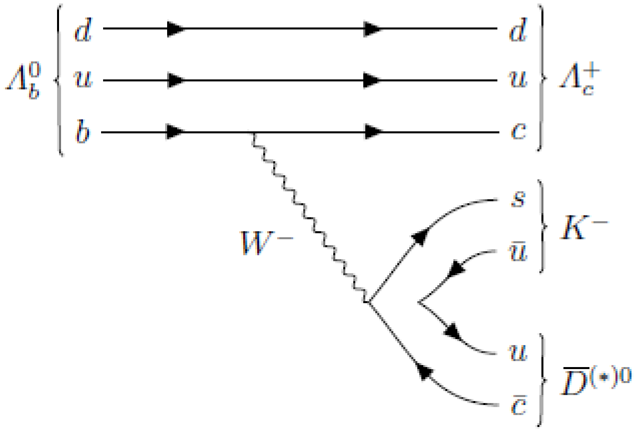
First observation of $\Lambda_b^0 \to \Sigma_c^{(*)++}\overline{D}^{(*)-}K^-$ with Run II data

- P_c with $3/2^-$ spin parity would decay substantially into $\Sigma_c^{(*)}\overline{D}$

  JHEP 08 (2021) 157, Eur. Phys. J. A 58 (2022) 68, Eur. Phys. J. C 79 (2019) 887, Phys. Rev. D 108 (2023) 114022…

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

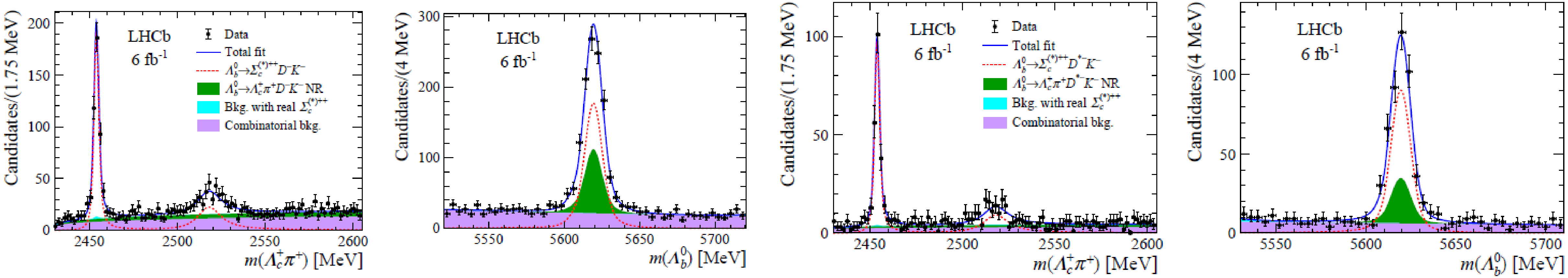




First observation of $\Lambda_b^0 \to \Sigma_c^{(*)++} \overline{D}^{(*)-} K^-$ with Run II data

➢ Two-dimensional invariant mass fits

Phys. Rev. D 110, L031104



Channel	Signal yields
$\Lambda_b^0 \to \Sigma_c^{++} D^- K^-$	480 ± 25
$\Lambda_b^0 \to \Sigma_c^{*++} D^- K^-$	279 ± 26
$\Lambda_b^0 \to \Sigma_c^{++} D^{*-} K^-$	243 ± 17
$\Lambda_b^0 \to \Sigma_c^{*++} D^{*-} K^-$	116 ± 15
$\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-$	4032 ± 75

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

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

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

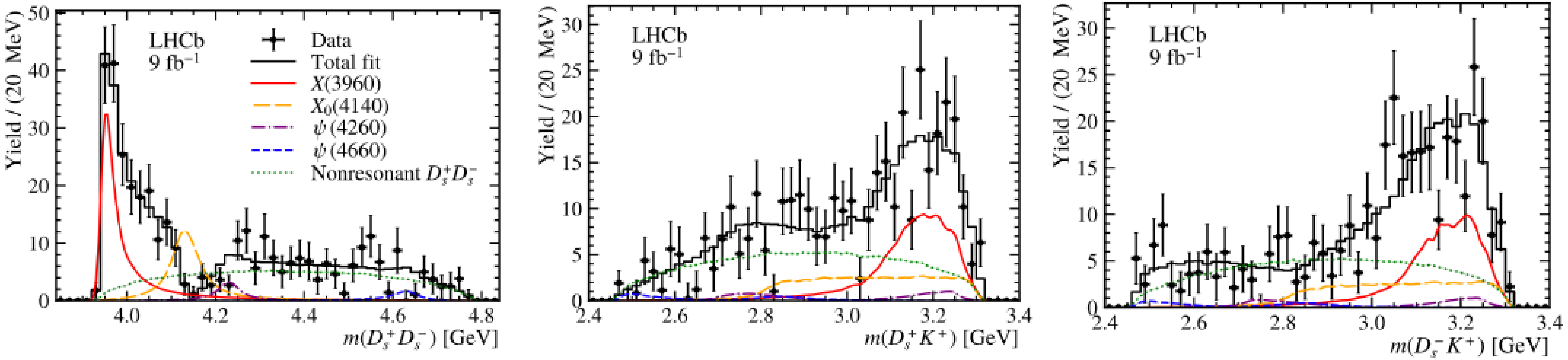
$$\frac{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{*++} D^{*-} K^-)}{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{++} D^- K^-)} = 0.896 \pm 0.137 \pm 0.066 \pm 0.018,$$

➢ Important inputs for theoretical studies of pentaquark production

New $[c\bar{c}s\bar{s}]$ state in $D_s^+D_s^-$

- Near threshold structure X(3960):

Phys. Rev. D 108 (2023) 034012
Phys. Rev. Lett. 131, 071901 (2023)

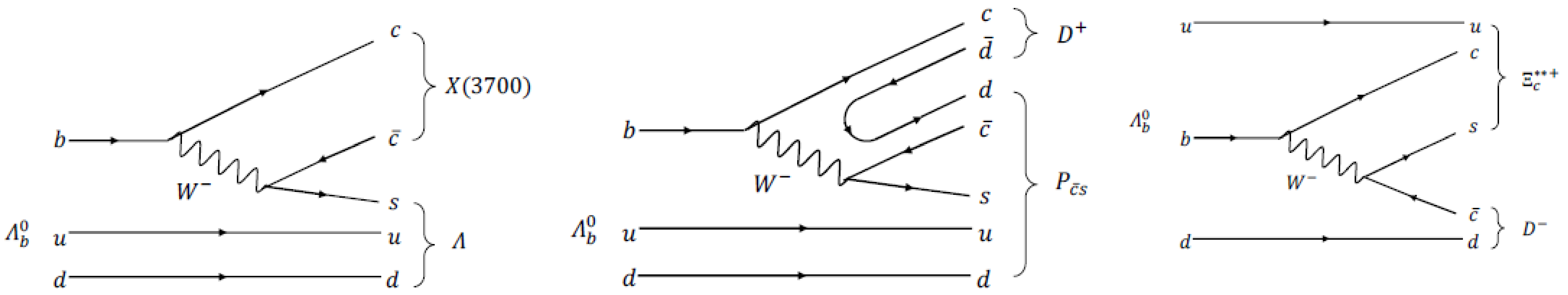


Components	J^{PC}	Mass (MeV)	Width (MeV)	Fit fraction (%)	Significance (σ)
$X(3960)$	0^{++}	$3956 \pm 5 \pm 10$	$43 \pm 13 \pm 8$	$25.4 \pm 7.7 \pm 5.0$	12.6 (14.6)
$X_0(4140)$	0^{++}	$4133 \pm 6 \pm 6$	$67 \pm 17 \pm 7$	$16.7 \pm 4.7 \pm 3.9$	3.8 (4.1)
$\psi(4260)$	1^{--}	4230 (fixed)	55 (fixed)	$3.6 \pm 0.4 \pm 3.2$	3.2 (3.6)
$\psi(4660)$	1^{--}	4633 (fixed)	64 (fixed)	$2.2 \pm 0.2 \pm 0.8$	3.0 (3.2)
NR	S-wave	–	–	$46.1 \pm 13.2 \pm 11.3$	3.1 (3.4)

dip at 4.14 GeV via interference

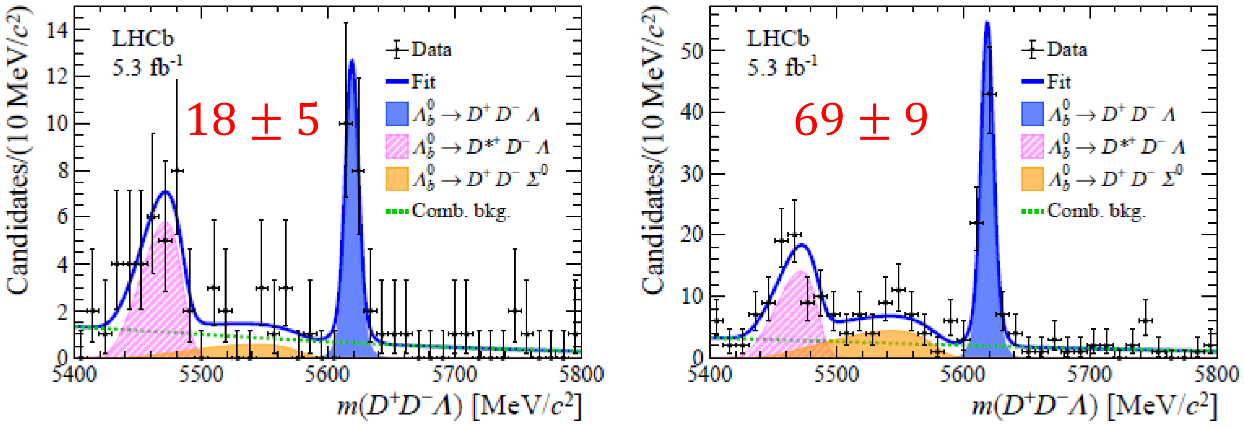
First observation of $\Lambda_b^0 \to D\bar{D}\Lambda$ with Run II data

- $\Lambda_b^0 \to D\bar{D}\Lambda$ can proceed via two types of two-body intermediate states: $X(3700)$ in D^+D^- and P_{cs} in $D^+\Lambda$



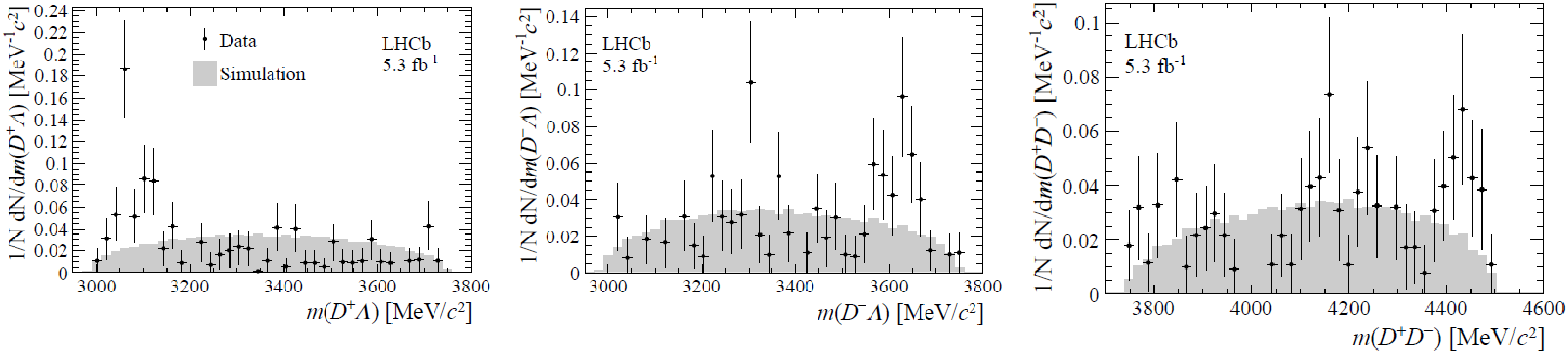
- $B^0 \to D\bar{D}K_s$ as normalization channel

First observation of $\Lambda_b^0 \to D\bar{D}\Lambda$ with Run II data



$$\mathcal{R} = \frac{\sigma_{\Lambda_b^0}}{\sigma_{B^0}} \times \frac{\mathcal{B}(\Lambda_b^0 \to D^+D^-\Lambda)}{\mathcal{B}(B^0 \to D^+D^-K_S^0)} = 0.179 \pm 0.022 \pm 0.014,$$

- $\mathcal{B}(\Lambda_b^0 \to D\bar{D}\Lambda) = (1.24 \pm 0.15 \pm 0.10 \pm 0.28 \pm 0.11) \times 10^{-4}$



- $\Xi_c(3055)$ in $m(D^+\Lambda)$
- $X(3700)$ may exist

JHEP 07 (2024) 140

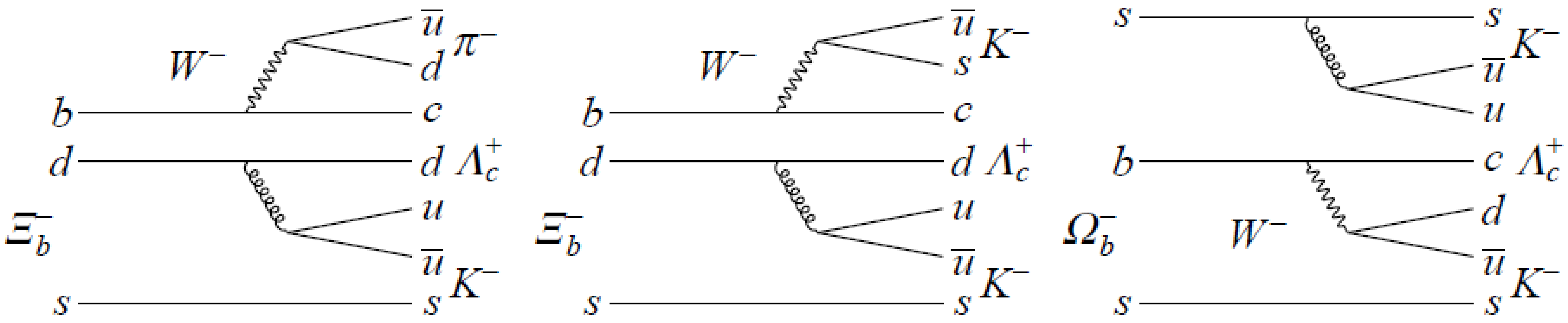
$b \to c$ decays

$$\Xi_b^- \to \Lambda_c^+ K^- \pi^-, \Xi_b^- \to \Lambda_c^+ K^- K^-, \Omega_b^- \to \Lambda_c^+ K^- K^-$$

Study of b−baryon → $\Lambda_c^+ hh$ with Run I&II data

- A few of Ξ_b^- and Ω_b^- decays observed

- Test QCD models



Cabibbo-favoured | Cabibbo-suppressed | Cabibbo-favoured

- $B^- \to \Lambda_c^+ \bar{p} \pi^-$ as normalization channel

$$\frac{\mathcal{B}(X_b \to Y)}{\mathcal{B}(X_b \to Z)} = \frac{N(Y)/\langle\epsilon(Y)\rangle}{N(Z)/\langle\epsilon(Z)\rangle} = \frac{\sum_{i=0}^{n_Y} w_i^Y/\epsilon_i^Y}{\sum_{i=0}^{n_Z} w_i^Z/\epsilon_i^Z} = \frac{N^{\text{corr}}(Y)}{N^{\text{corr}}(Z)} .$$

Study of b−baryon → $\Lambda_c^+ hh$ with Run I&II data

JHEP 08 (2024) 132

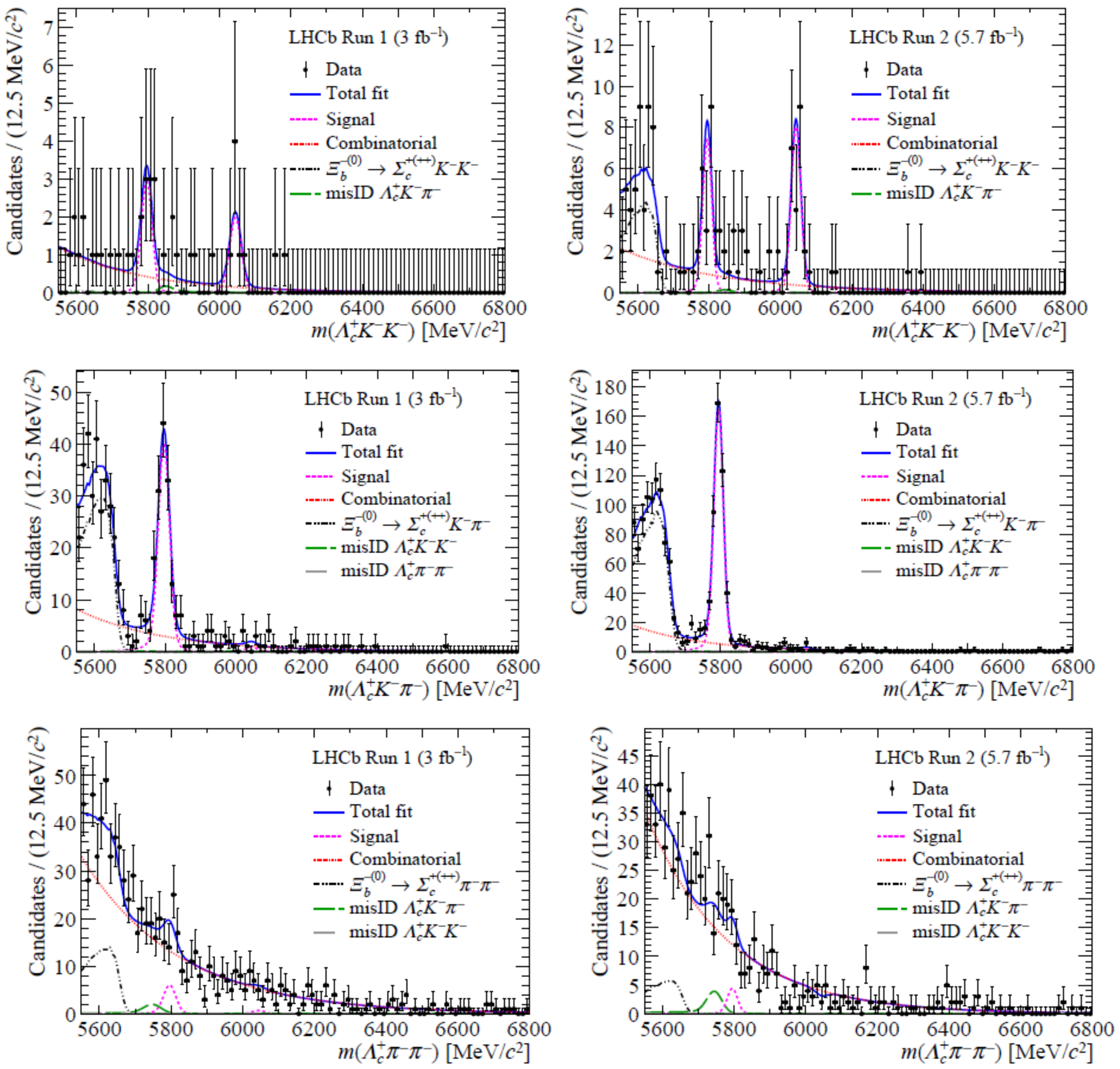
$$\frac{\mathcal{B}(B^- \to \Lambda_c^+ \bar{p} K^-)}{\mathcal{B}(B^- \to \Lambda_c^+ \bar{p} \pi^-)} = 0.0397 \pm 0.0023\,(\text{stat}) \pm 0.0012\,(\text{syst})\,,$$

$$\frac{\mathcal{B}(\Xi_b^- \to \Lambda_c^+ K^- K^-)}{\mathcal{B}(\Xi_b^- \to \Lambda_c^+ K^- \pi^-)} = 0.045 \pm 0.011\,(\text{stat}) \pm 0.005\,(\text{syst})\,,$$

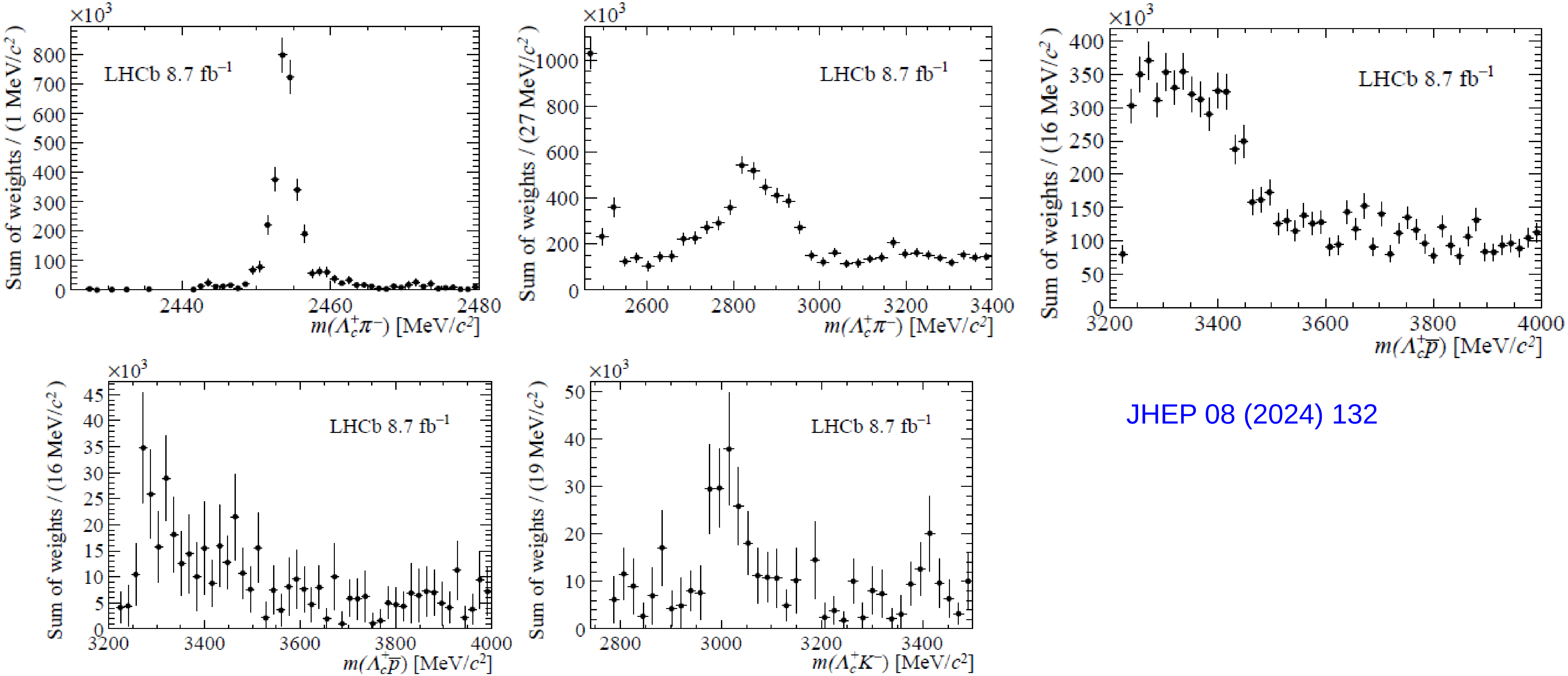
$$\frac{\mathcal{B}(\Xi_b^- \to \Lambda_c^+ \pi^- \pi^-)}{\mathcal{B}(\Xi_b^- \to \Lambda_c^+ K^- \pi^-)} = 0.025 \pm 0.013\,(\text{stat}) \pm 0.019\,(\text{syst})\,,$$

$$\frac{\mathcal{B}(\Omega_b^- \to \Lambda_c^+ K^- \pi^-)}{\mathcal{B}(\Omega_b^- \to \Lambda_c^+ K^- K^-)} = 0.19 \pm 0.12\,(\text{stat}) \pm 0.10\,(\text{syst})\,,$$

Decay	Run 1	Run 2	Combined
Statistical uncertainties only			
$\Xi_b^- \to \Lambda_c^+ K^- K^-$	3.6	5.5	6.3
$\Omega_b^- \to \Lambda_c^+ K^- K^-$	4.2	7.9	8.8
Including systematic uncertainties			
$\Xi_b^- \to \Lambda_c^+ K^- K^-$	3.5	5.2	5.9
$\Omega_b^- \to \Lambda_c^+ K^- K^-$	3.6	6.9	7.5



Study of b−baryon → $\Lambda_c^+ hh$ with Run I&II data



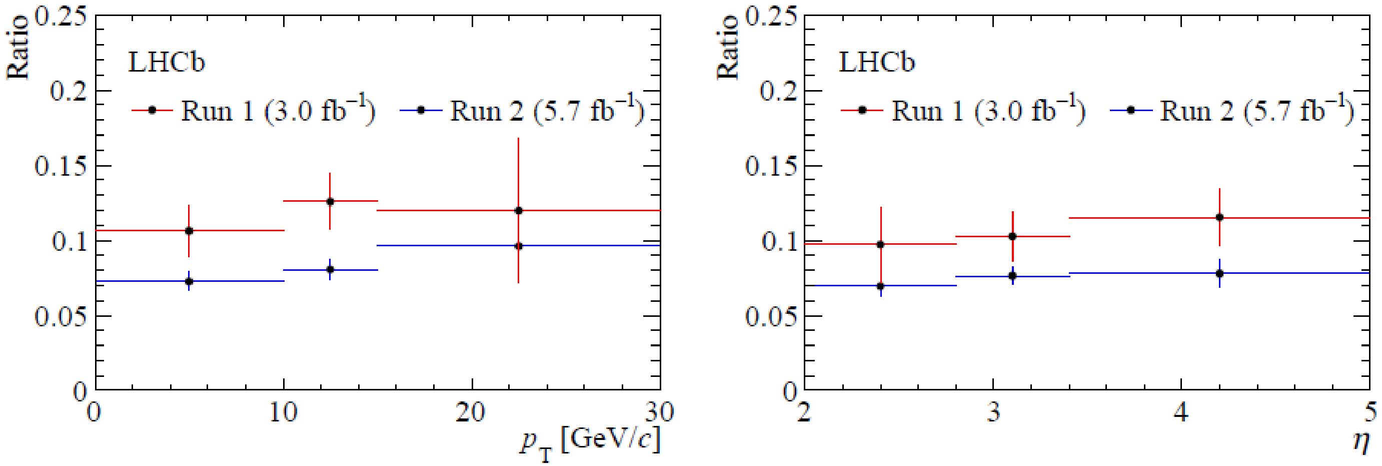
JHEP 08 (2024) 132

- Both $B^- \to \Lambda_c^+ \bar{p} \pi^-$ and $B^- \to \Lambda_c^+ \bar{p} K^-$ observed threshold enhancement

Study of b−baryon → $\Lambda_c^+ hh$ with Run I&II data

- The CPV JHEP 08 (2024) 132

$$\mathcal{A}_{\text{meas}}\left(X_b \to Y\right) = \frac{\sum_{i=0}^{n_Y} \frac{w_i}{\epsilon_i} - \sum_{i=0}^{n_{\bar{Y}}} \frac{w_i}{\bar{\epsilon}_i}}{\sum_{i=0}^{n_Y} \frac{w_i}{\epsilon_i} + \sum_{i=0}^{n_{\bar{Y}}} \frac{w_i}{\bar{\epsilon}_i}} = \frac{N^{\text{corr}}(X_b \to Y) - N^{\text{corr}}(\bar{X}_b \to \bar{Y})}{N^{\text{corr}}(X_b \to Y) + N^{\text{corr}}(\bar{X}_b \to \bar{Y})},$$
$$= \mathcal{A}_{CP}\left(X_b \to Y\right) + \mathcal{A}_{\text{prod}}\left(X_b\right).$$



$$\mathcal{A}_{\text{prod}}(\Xi_b^-;\text{Run 1}) = -0.10 \pm 0.10\,(\text{stat}) \pm 0.03\,(\text{syst}),$$
$$\mathcal{A}_{\text{prod}}(\Xi_b^-;\text{Run 2}) = -0.10 \pm 0.05\,(\text{stat}) \pm 0.02\,(\text{syst}),$$

- The A_{prod} consistent with zero and with previous measurements

Summary and prospects

- **LHCb provides ideal environment to search NP and test QCD**
  - FCNC: $\Lambda_b^0 \to pK^-\mu^+\mu^-$
  - Observed many new Λ_b^0 decay modes

- **Opportunities with Run 3&4 (30 $\mathbf{fb^{-1}}$)**
  - Wider scope for exploitation
  - Improvement on understanding multi-quark states natures

Thank you