Spectroscopy and decays of b-hadrons at LHCb

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on behalf of the LHCb collaboration

HADRON: July 2021

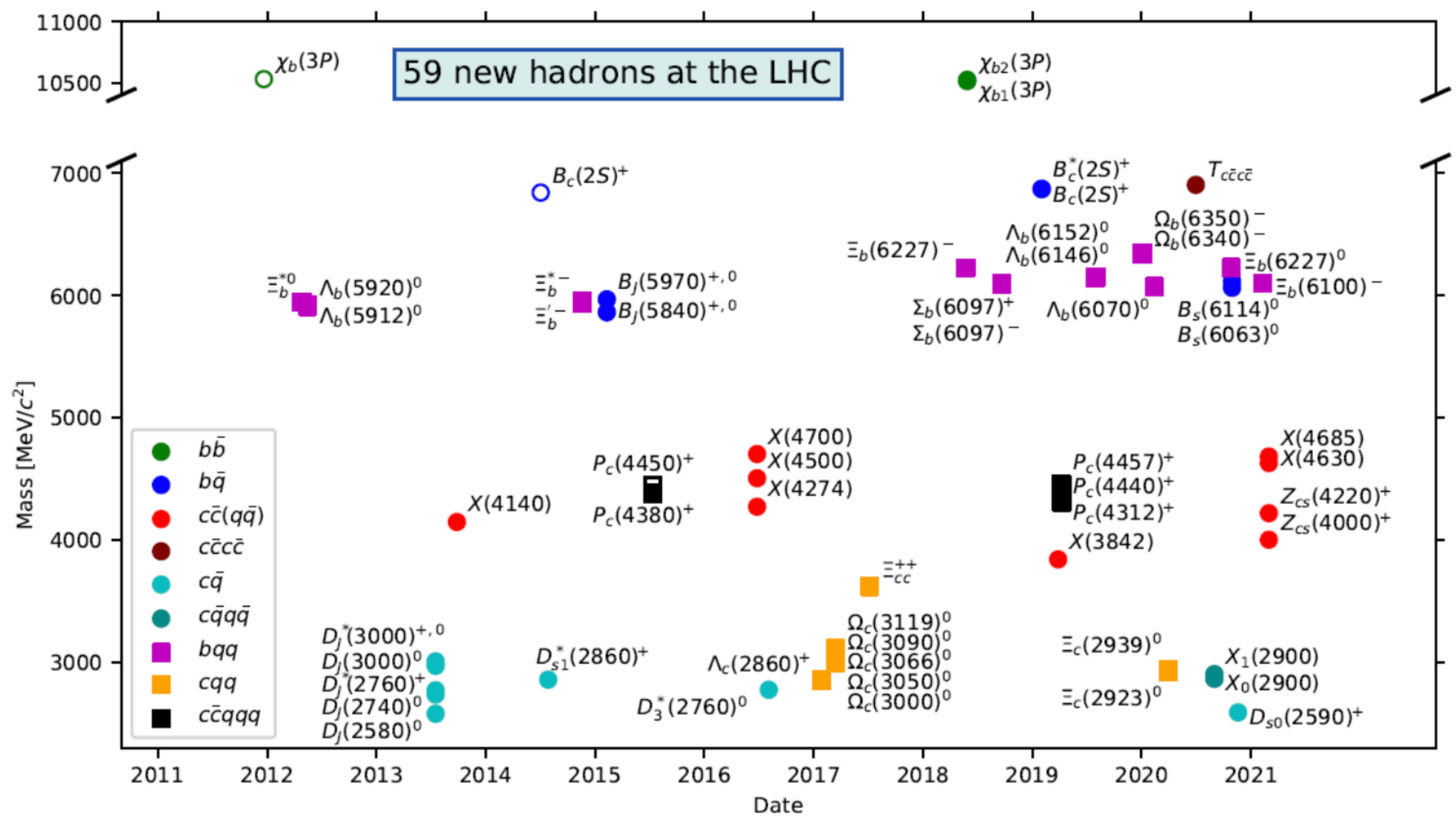
Introduction

- Over the past 10 years the LHC has discovered 59 new hadrons, mainly from LHCb.
- The discovery of new particles provides valuable information on probing the limits of the quark model.

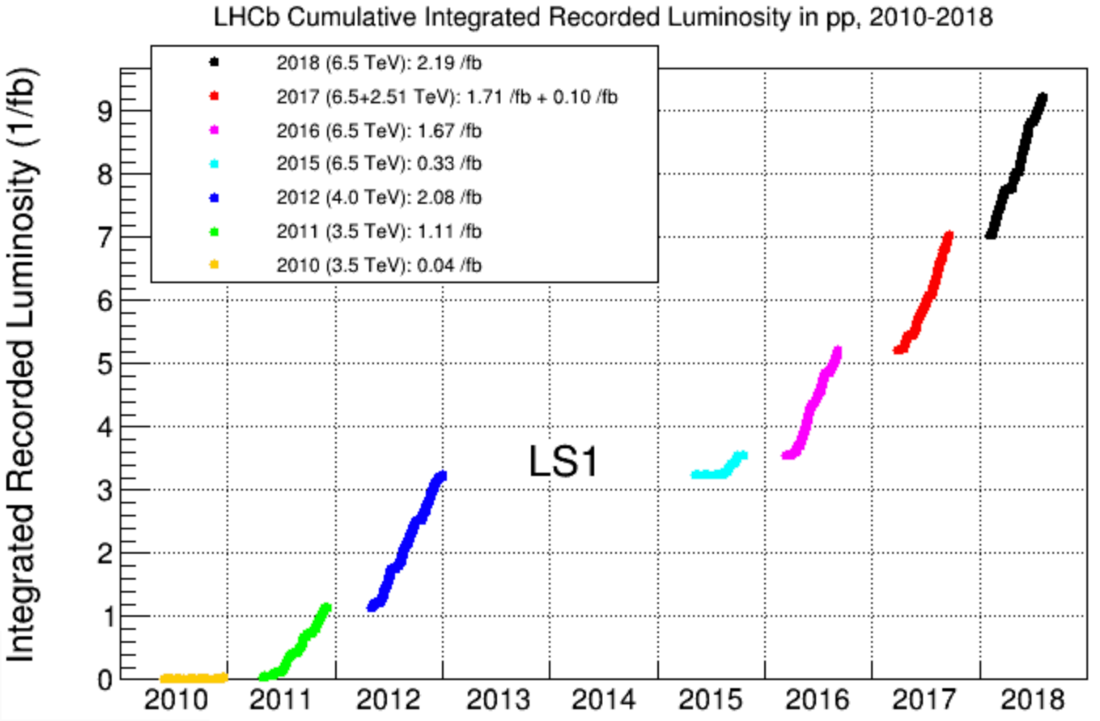
→ Could provide a deeper understanding of the hadronic structure.

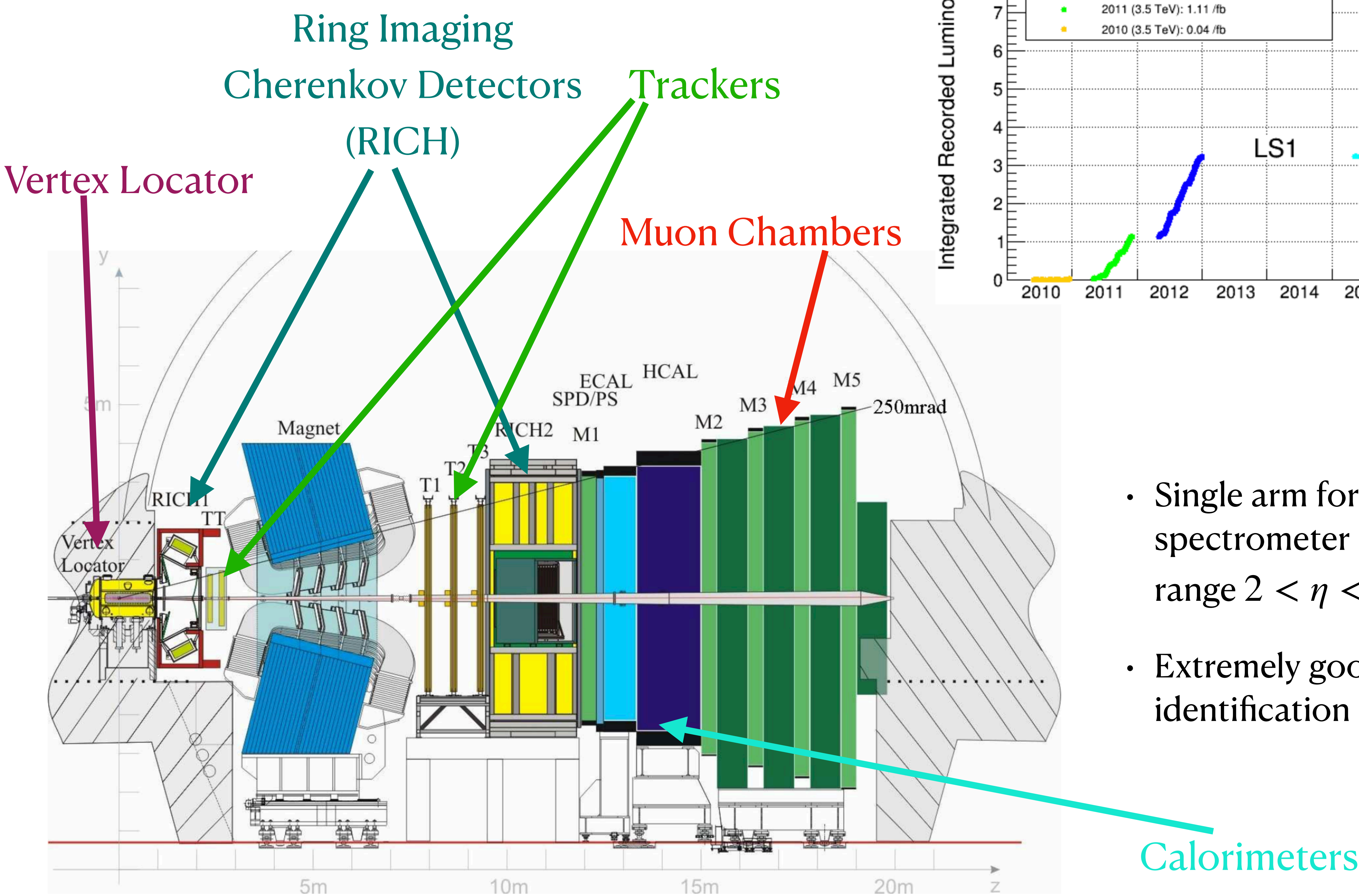
59-new-hadrons

- Studying heavy flavour spectroscopy allows us to further our understanding of how conventional hadrons, tetraquarks and pentaquarks are formed.



The LHCb Detector





- Single arm forward spectrometer covering the range $2 < \eta < 5$.
- Extremely good particle identification and tracking.

Recent Results

- Observation of the excited Ω_c^0 baryons in $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decays
  LHCb-PAPER-2021-012 (submitted to PRD Lett: arXiv:2107.03419)

- Observation of two new excited Ξ_b^0 states decaying to $\Lambda_b^0 K^- \pi^+$ - New result!
  LHCb-PAPER-2021-025

- Observation of the decay $\Lambda_b^0 \to \chi_{c1} p \pi^-$
  LHCb-PAPER-2021-003 (published in JHEP: JHEP 05 (2021) 95)

- Search for doubly heavy baryons Ξ_{bc}^0 and Ω_{bc}^0 decaying to $\Lambda_c^+ \pi^-$ and $\Xi_c^+ \pi^-$
  LHCb-PAPER-2021-002 (accepted by Chin. Phys. C: arXiv:2104.04759)

Observation of excited Ω_c^0 baryons in $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decays

LHCb-PAPER-2021-012
arXiv:2107.03419

Observation of $\Omega_b^- \to \Xi_c^+ K^- \pi^-$

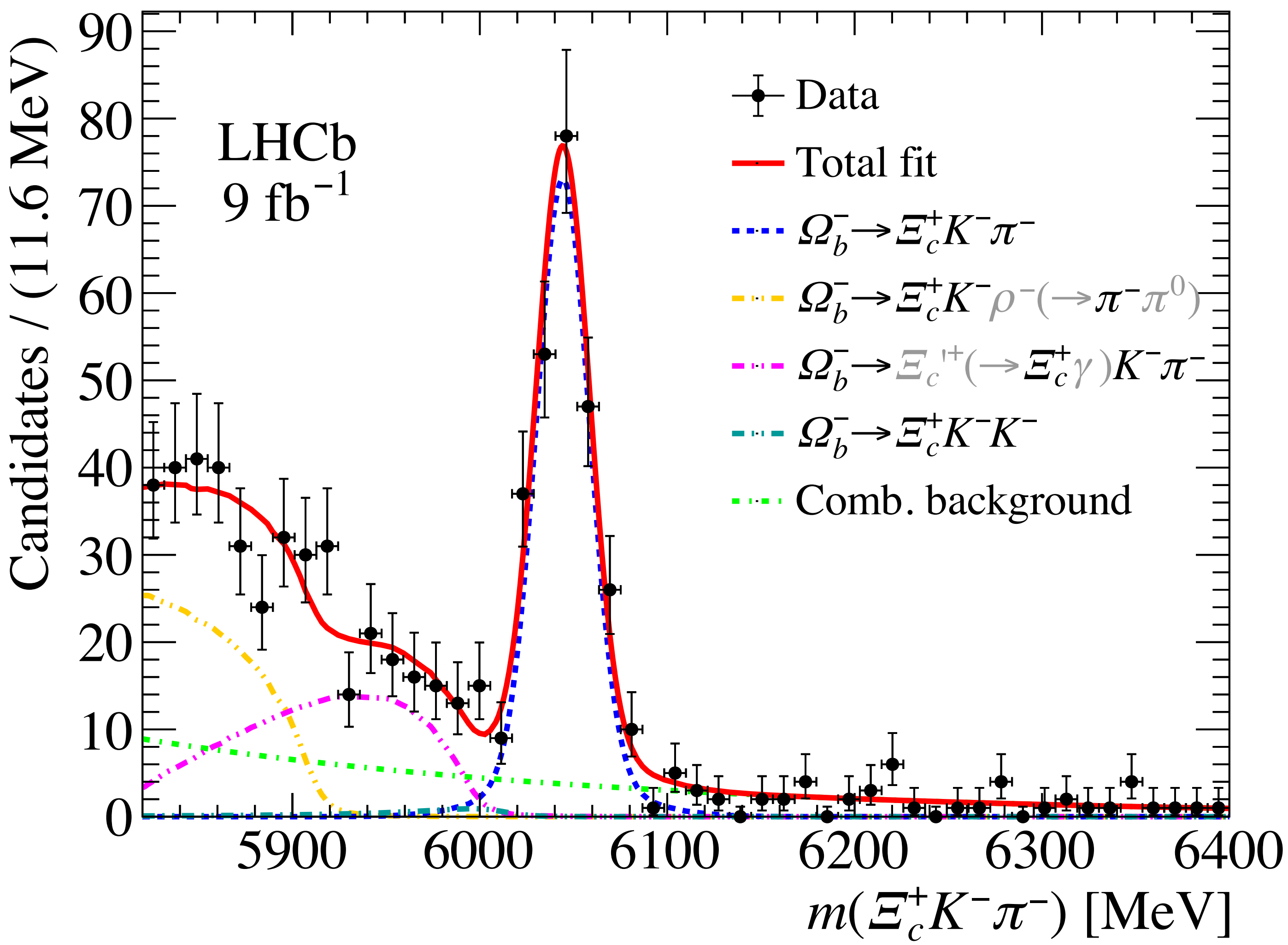
- In 2017 there was an observation of five new resonances of Ω_c^0 (css) decaying as $\Omega_c^{**0} \to \Xi_c^+ K^-$: Now cited over 200 times!

Phys. Rev. Lett. 118 (2017) 182001

- A way to determine the quantum numbers is from studying the decay of a known hadron (Ω_b^-) into these excited states.

Signal Decay: $\Omega_b^- \to \Xi_c^+ K^- \pi^-$

$N(\Omega_b^- \to \Xi_c^+ K^- \pi^-) = 240 \pm 17$



- First observation of $\Omega_b^- \to \Xi_c^+ K^- \pi^-$.
- Branching fraction relative to $\Omega_b^- \to \Omega_c^0 \pi^-$ is measured.

$$\frac{\mathcal{B}(\Omega_b^- \to \Xi_c^+ K^- \pi^-)\mathcal{B}(\Xi_c^+ \to p K^- \pi^+)}{\mathcal{B}(\Omega_b^- \to \Omega_c^0 \pi^-)\mathcal{B}(\Omega_c^0 \to p K^- K^- \pi^+)} = 1.35 \pm 0.11 \pm 0.05$$

- Mass measurement from this analysis:

$$m(\Omega_b^-) = 6044.3 \pm 1.2 \pm 1.1 \text{ MeV}$$

- Averaging all LHCb measurements gives:

$$m(\Omega_b^-) = 6044.8 \pm 1.3 \text{ MeV}$$

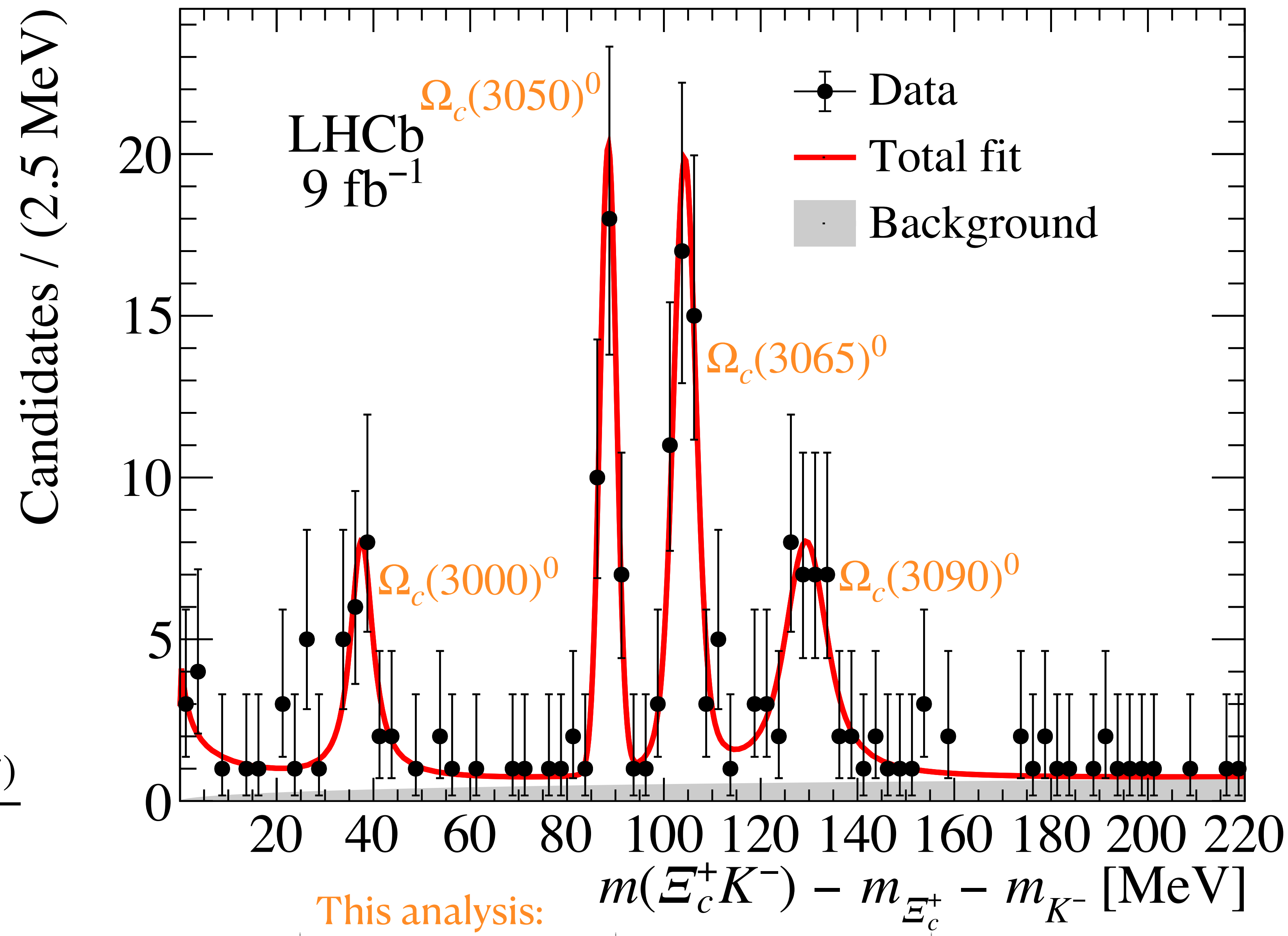
Observation of the Excited Ω_c^0 States

- Four signals are consistent with those of the previously observed $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3065)^0$ and $\Omega_c(3090)^0$ baryons.

- Modelled with a relativistic Breit Wigner (S-wave) convolved with a Gaussian. Threshold modelled with S-wave Breit Wigner.

- Production fraction:

$$P \equiv \frac{\mathcal{B}(\Omega_b^- \to \Omega_c^{**0}\pi^-)\mathcal{B}(\Omega_c^{**0} \to \Xi_c^+ K^-)}{\mathcal{B}(\Omega_b^- \to \Xi_c^+ K^- \pi^-)}$$

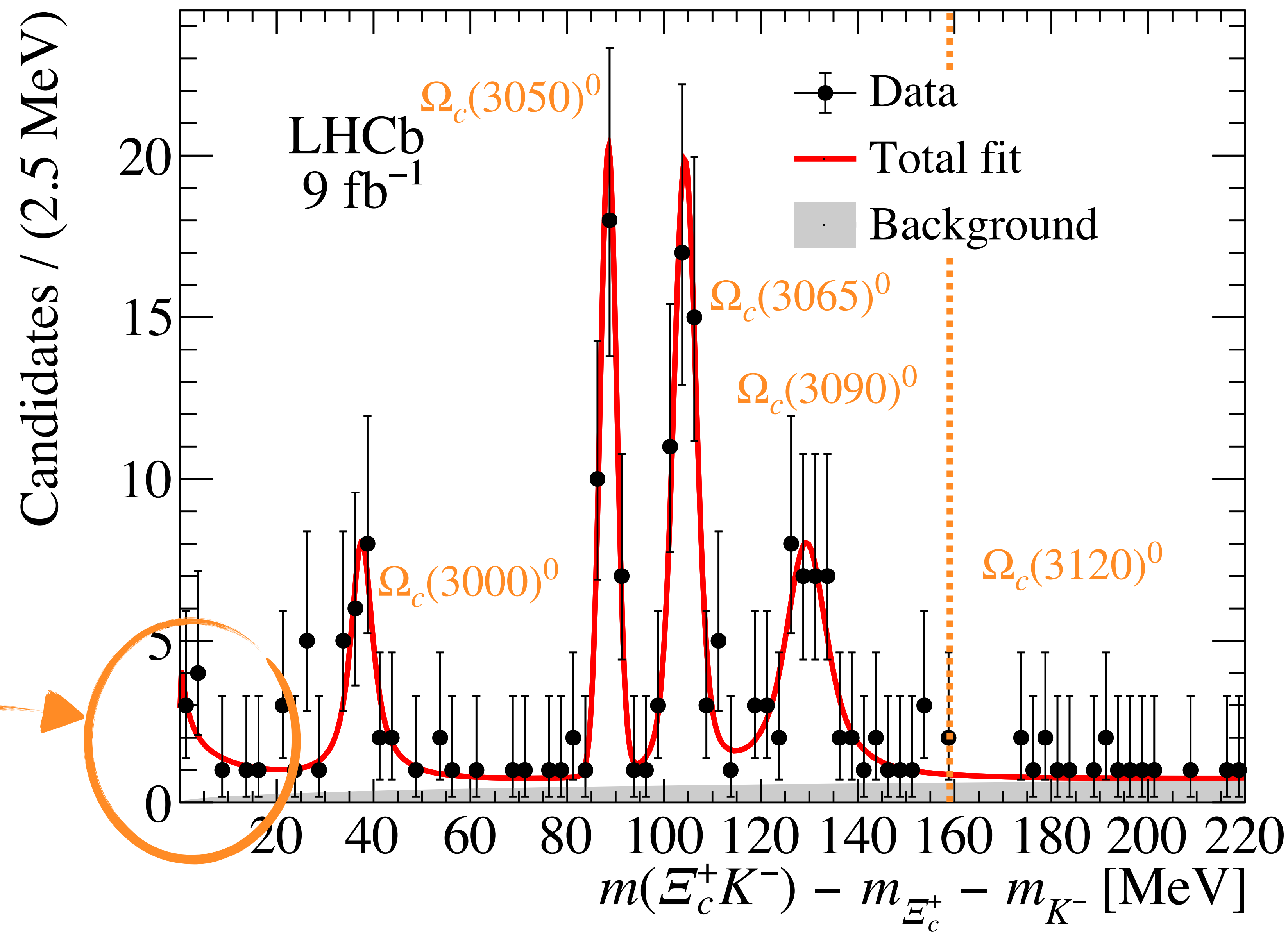


	Prompt analysis:		This analysis:		
Resonance	Mass [MeV]	Γ [MeV]	Mass [MeV]	Γ [MeV]	P
$\Omega_c(3000)^0$	3000.4 ± 0.2 ± 0.1	4.5 ± 0.6 ± 0.3	2999.2 ± 0.9 ± 0.9	4.8 ± 2.1 ± 2.5	0.11 ± 0.02 ± 0.04
$\Omega_c(3050)^0$	3050.2 ± 0.1 ± 0.1	0.8 ± 0.2 ± 0.1	3050.1 ± 0.3 ± 0.2	< 1.6 @ 95% CL	0.15 ± 0.02 ± 0.02
$\Omega_c(3065)^0$	3065.6 ± 0.1 ± 0.3	3.5 ± 0.4 ± 0.2	3065.9 ± 0.4 ± 0.4	1.7 ± 1.0 ± 0.5	0.23 ± 0.02 ± 0.02
$\Omega_c(3090)^0$	3090.2 ± 0.3 ± 0.5	8.7 ± 1.0 ± 0.8	3091.0 ± 1.1 ± 1.0	7.4 ± 3.1 ± 2.8	0.19 ± 0.02 ± 0.04

Observation of the Excited Ω_c^0 States

- The significance exceeds 6σ for each of the four main states.
- Upper limit on the production fraction is set for the missing $\Omega_c(3120)^0$ state:

$P(\Omega_c(3120)^0) < 0.03$, 95 % CL

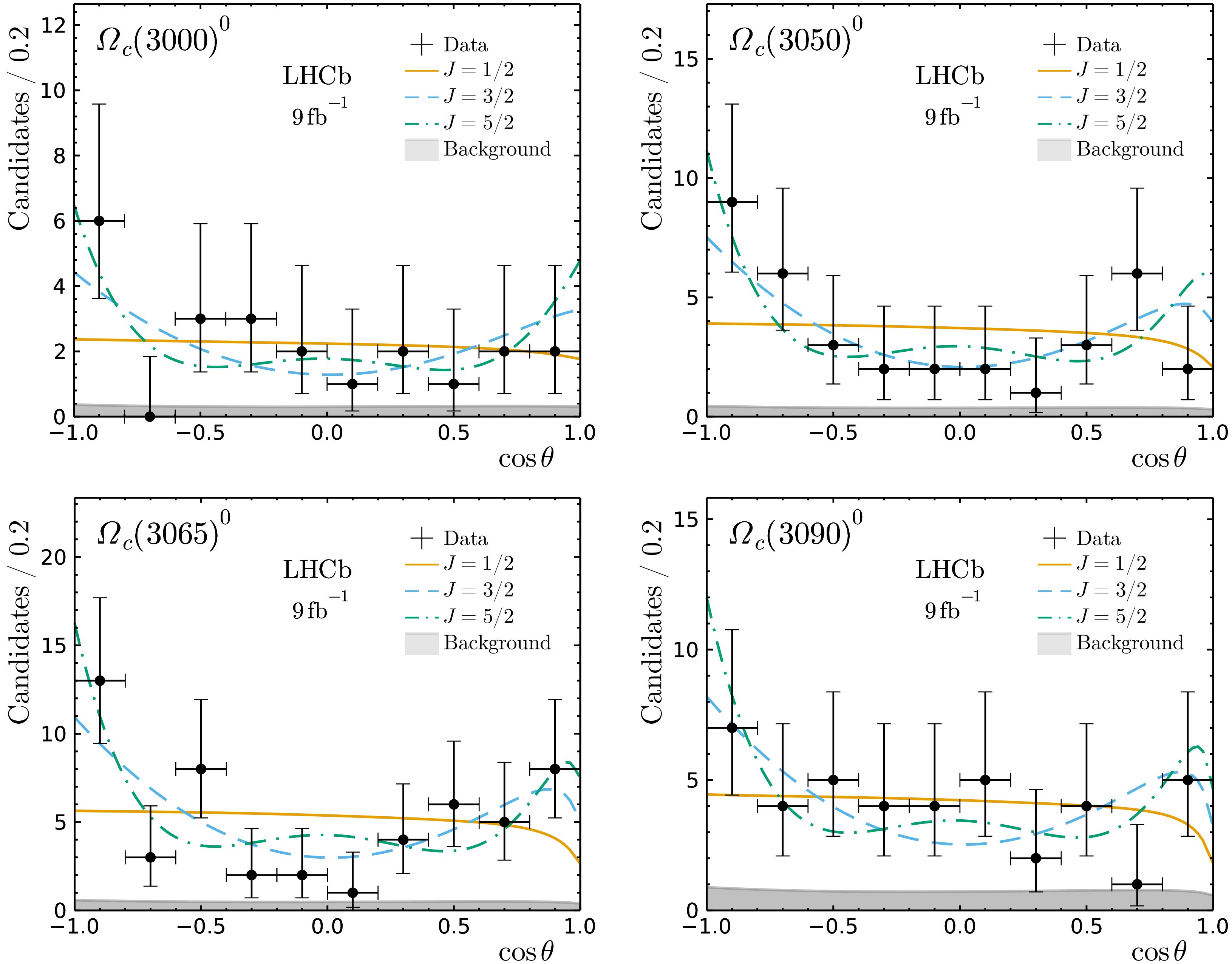


- Enhancement seen at $\Xi_c^+ K^-$ threshold with a significance larger than 4σ, further studies needed to determine its nature. A similar structure was seen in the inclusive $\Xi_c^+ K^-$ spectrum and was interpreted as the partially reconstructed decay $\Omega_c(3065)^0 \to \Xi_c'^+(\to \Xi_c^+ \gamma)K^-$.
  - This interpretation has been ruled out in this analysis due to cuts on the Ω_b^- mass.

LHCb-PAPER-2021-012
arXiv:2107.03419

Observation of the Excited Ω_c^0 States

- Three-body decay provides a way to determine the quantum numbers by exploiting angular distributions.



- The spin of a state is determined by comparing the value of the observable with the expected values under different hypotheses.
- $\Omega_c(3050)^0$ and $\Omega_c(3065)^0$ are not spin-1/2 with 2.2σ and 3.6σ significance.

- Reject common interpretation of spin assignment J = 1/2, 1/2, 3/2, 3/2 with 3.5σ significance.

Observation of two new excited Ξ_b^0 states decaying to $\Lambda_b^0 K^- \pi^+$

Observation of the excited Ξ_b^0 states

- Several excited Λ_b^0 states have been observed, leading to the investigation of the excited Ξ_b states due to their similar properties.

$\Lambda_b(5920)^0$
$\Lambda_b(5912)^0$
$\Lambda_b(6072)^0$ → $\Lambda_b^0\pi^+\pi^-$
$\Lambda_b(6146)^0$
$\Lambda_b(6152)^0$

- Recently the LHCb collaboration reported the observation of the $\Xi_b(6227)^-$ baryon and its isospin partner $\Xi_b(6227)^0$.

Phys. Rev. Lett. 121 (2018) 072002
Phys. Rev. D 103 (2021) 012004

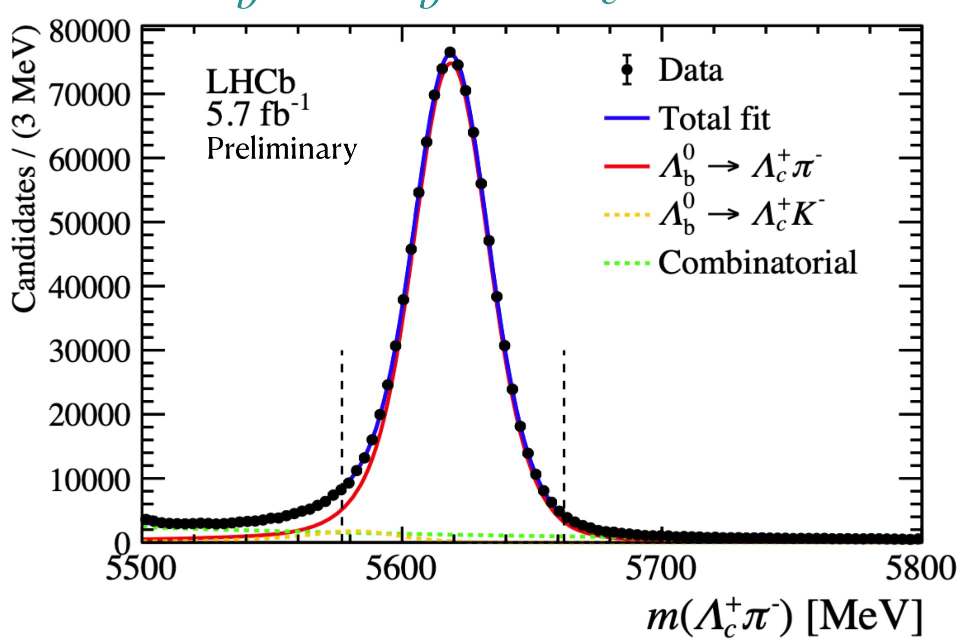
$\Xi_b(6227)^- \to \Lambda_b^0 K^-$ $\Xi_b(6227)^- \to \Xi_b^0\pi^-$ $\Xi_b(6227)^0 \to \Xi_b^-\pi^+$

- The CMS collaboration reported an observation of the $\Xi_b(6100)^-$ baryon.

Phys. Rev. Lett. 126 (2021) 252003

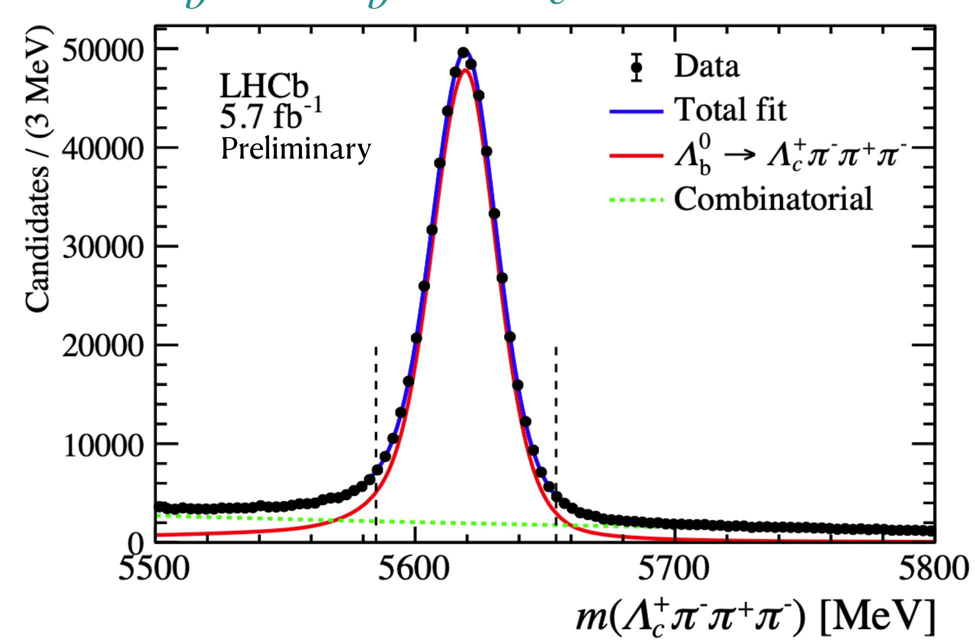
- Two 1D Ξ_b^0 states are predicted with decays dominated by the $\Sigma_b^{(*)}K$ and $\Xi_b^{*,\prime}\pi$ modes.

$\Xi_b^{*0} \to \Lambda_b^0(\to \Lambda_c^+\pi^-)K^-\pi^+$



$N(\Lambda_c^+\pi^-) = (1017.2 \pm 1.3) \times 10^3$

$\Xi_b^{*0} \to \Lambda_b^0(\to \Lambda_c^+\pi^-\pi^+\pi^-)K^-\pi^+$

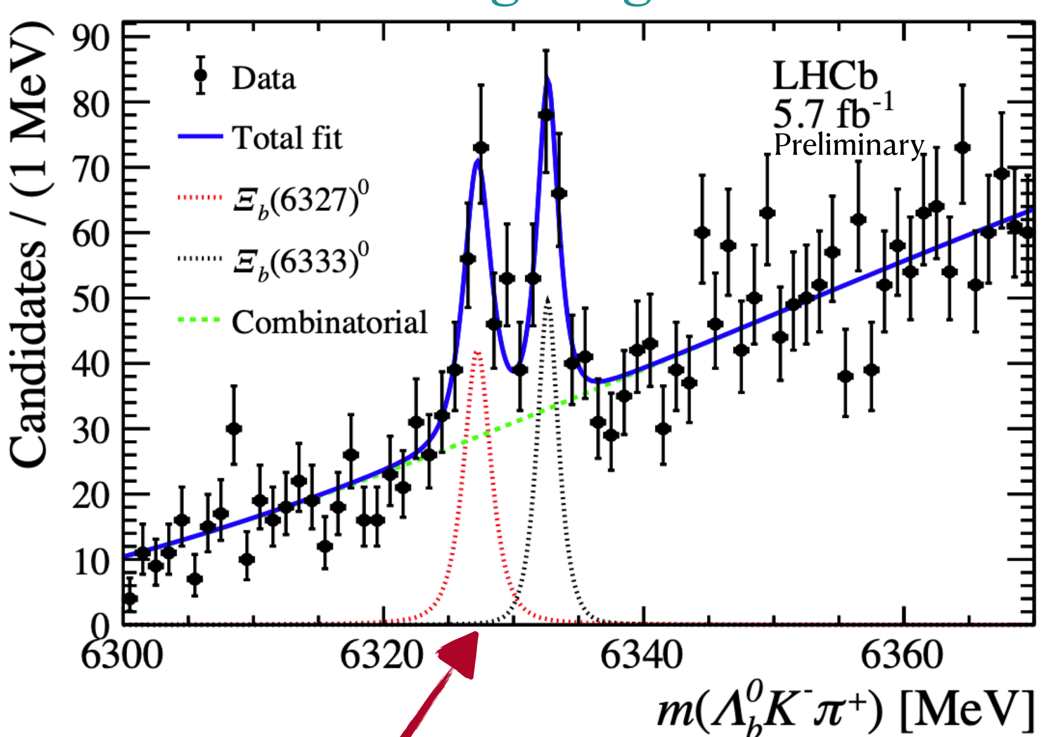


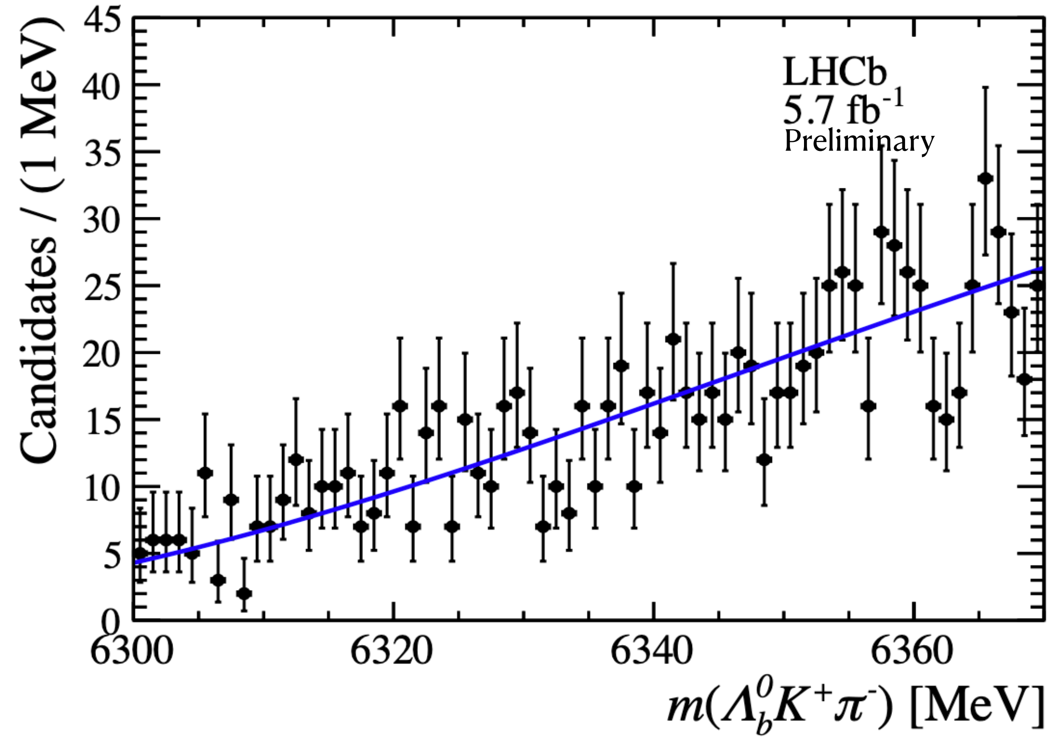
$N(\Lambda_c^+\pi^-\pi^+\pi^-) = (595.9 \pm 3.3) \times 10^3$

Observation of the excited Ξ_b^0 states

- Candidates with mass in a 2.5σ window around the Λ_b^0 mass are used to form $\Lambda_b^0 K^- \pi^+$.
- To estimate the background generated from random combinations, the wrong sign candidates are reconstructed with a $\Lambda_b^0 K^+ \pi^-$ final state.

Right sign





Peaks modelled based on relativistic Breit-Wigner function, convolved with a resolution function.

$$m_{\Xi_b(6327)^0} = 6327.26^{+0.23}_{-0.21} \pm 0.08 \pm 0.24 \text{ MeV}$$

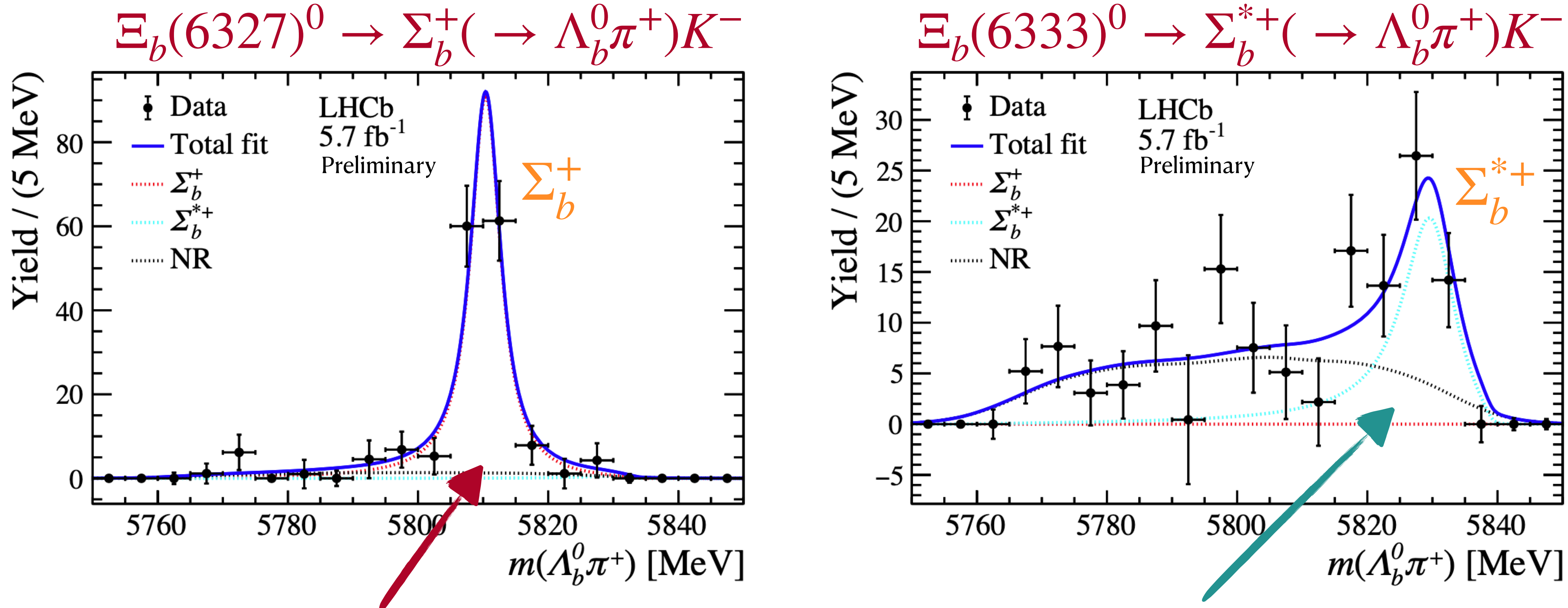
$$m_{\Xi_b(6333)^0} = 6332.67^{+0.17}_{-0.18} \pm 0.03 \pm 0.22 \text{ MeV}$$

- Statistical significance of two peaking structures is 9.3σ.

Observation of the excited Ξ_b^0 states

- Resonance structures in excited Ξ_b^0 decays are studied by performing many $\Lambda_b^0 K^- \pi^+$ mass fits in 5 MeV wide slices of the $\Lambda_b^0 \pi^+$ mass spectrum.
- Mass and width parameters of the two Ξ_b^0 states are fixed to the nominal fit values.

Signal yield of the $\Xi_b(6327)^0$ and $\Xi_b(6333)^0$ states as a function of the $\Lambda_b^0\pi^+$ mass:



$\Sigma_b^+ \to \Lambda_b^0\pi^+$ contributes to most of the $\Xi_b(6327)^0$ decays.

A large fraction of the $\Xi_b(6333)^0$ baryons decay without $\Lambda_b^0\pi^+$ resonances.

- Resonance structures consistent with the theoretical predictions to the 1D excited Ξ_b^0 doublets.

Observation of the decay $\Lambda_b^0 \to \chi_{c1} p \pi^-$

Observation of the decay $\Lambda_b^0 \to \chi_{c1} p \pi^-$

- Hidden-charm pentaquarks have been found in the $J/\psi p$ system of the beauty-baryon decays $\Lambda_b^0 \to J/\psi p K^-$.
- Evidence for a pentaquark contribution in the same $J/\psi p$ mass region was found in the study of the $\Lambda_b^0 \to J/\psi p \pi^-$ decay.
- Hidden-charm pentaquarks have only been observed in the $J/\psi p$ and $J/\psi \Lambda$ systems, motivating the investigation into other systems, such as $\eta_c p$, $\chi_{c1} p$ and $\chi_{c2} p$.

Cabibbo-suppressed

Normalisation mode: $\Lambda_b^0 \to \chi_{c1,2}(\to J/\psi \gamma) p K^-$

Signal mode: $\Lambda_b^0 \to \chi_{c1,2}(\to J/\psi \gamma) p \pi^-$

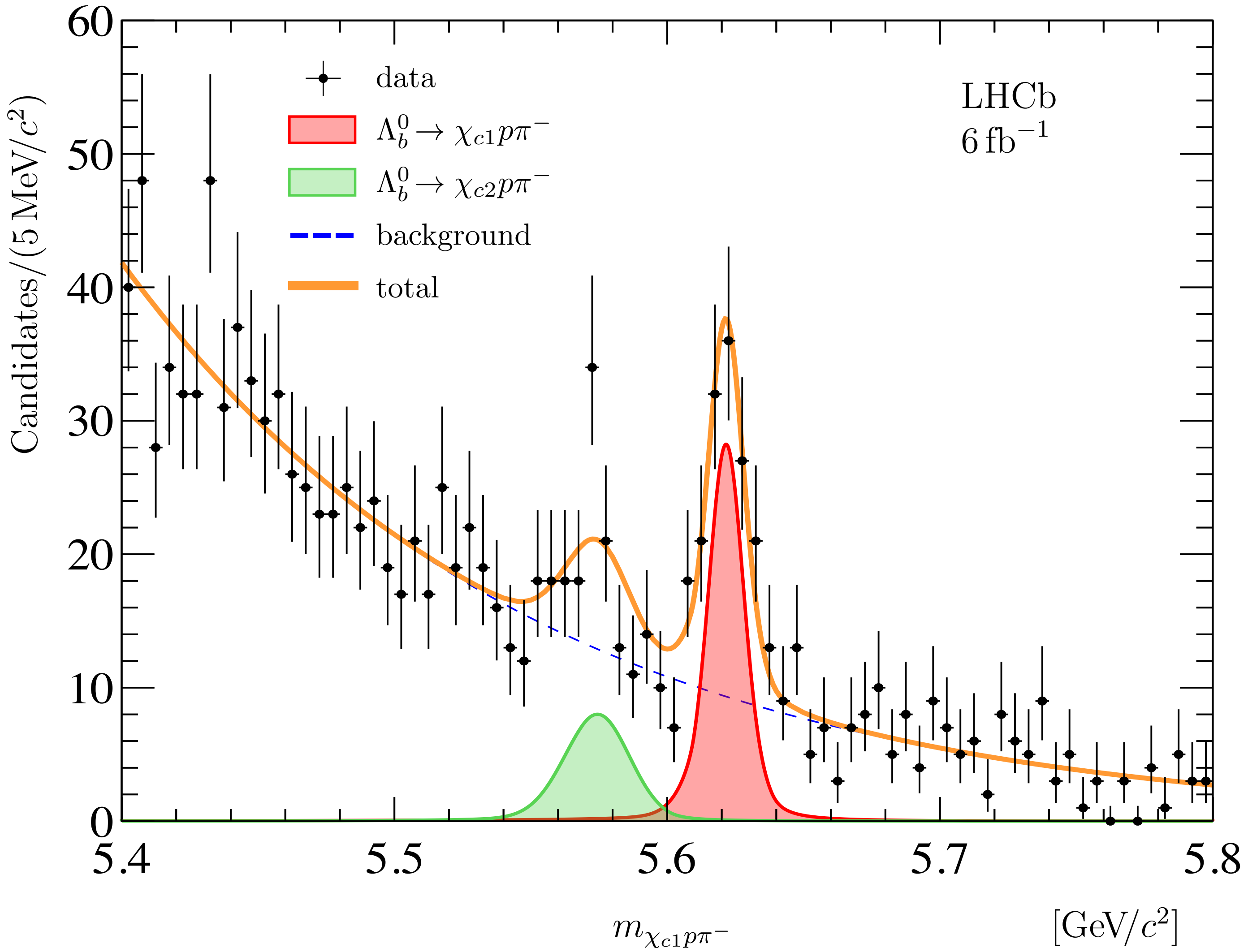
- The normalisation mode is used to determine the ratio of branching fractions:

$$\mathcal{R}_{\pi/K} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p \pi^-)}{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)} \qquad \mathcal{R}_{2/1}^{\pi} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p \pi^-)}{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p \pi^-)} \qquad \mathcal{R}_{2/1}^{K} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)}$$

Observation of the decay $\Lambda_b^0 \to \chi_{c1} p \pi^-$

- Each signal component is described by the sum of two Crystal Ball functions with a common mean, with the ratio of the widths and the tail parameters fixed by simulation.

- The significance of $\Lambda_b^0 \to \chi_{c1,2} p \pi^-$ is estimated from Wilks' theorem and the significance of $\Lambda_b^0 \to \chi_{c2} p \pi^-$ is tested by simulating a large number of pseudoexperiments.



- Statistical significance is found to be 9.6σ and 3.8σ for $\Lambda_b^0 \to \chi_{c1} p \pi^-$ and $\Lambda_b^0 \to \chi_{c2} p \pi^-$ respectively.

$$N(\Lambda_b^0 \to \chi_{c1} p \pi^-) = 105 \pm 16$$

$$N(\Lambda_b^0 \to \chi_{c2} p \pi^-) = 51 \pm 16$$

Observation of the decay $\Lambda_b^0 \to \chi_{c1} p \pi^-$

- Each signal component of the normalisation channel is modelled in the same way as the signal mode.

$$N(\Lambda_b^0 \to \chi_{c1} p K^-) = 3133 \pm 75$$

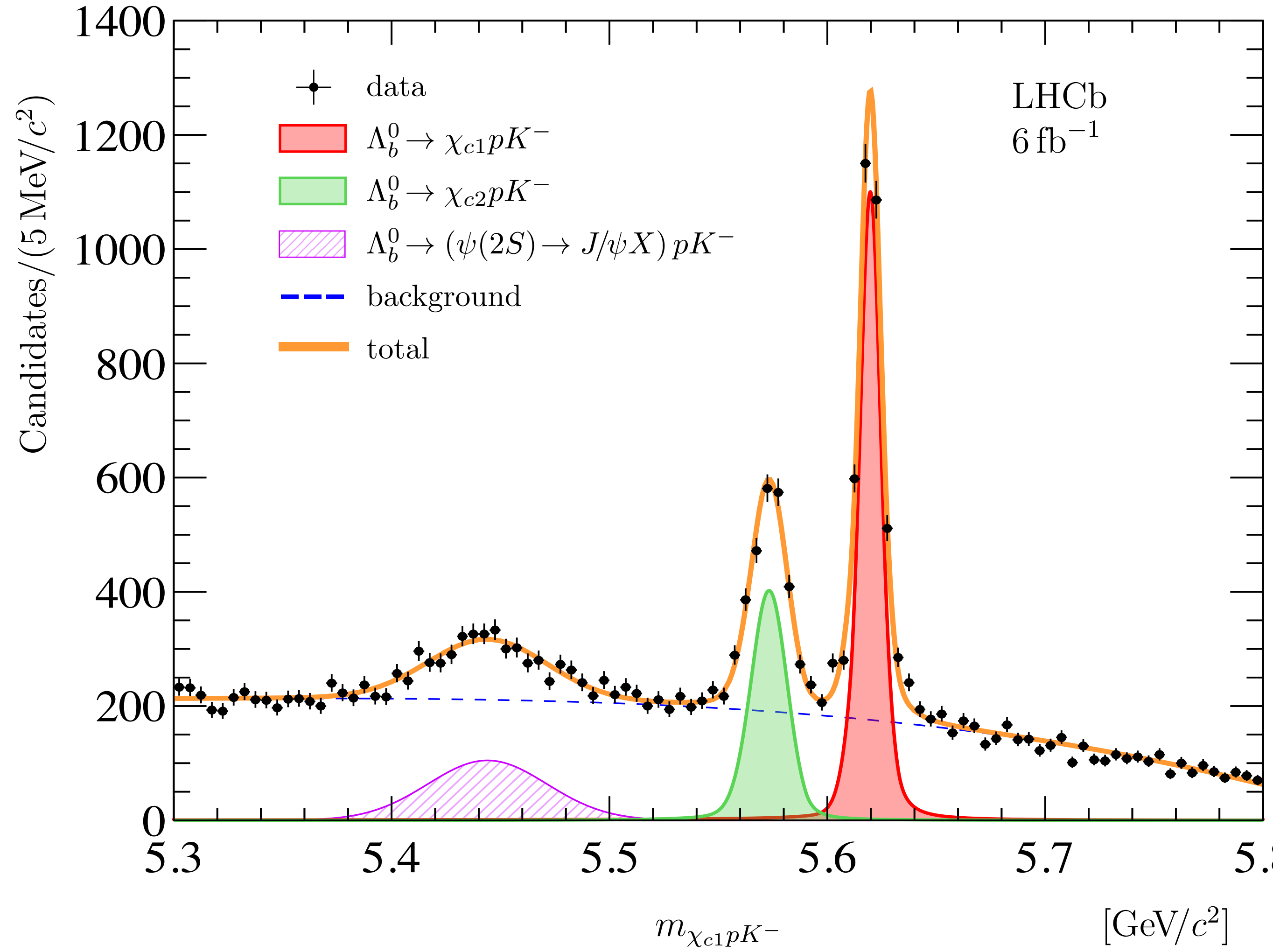
$$N(\Lambda_b^0 \to \chi_{c2} p K^-) = 1766 \pm 71$$

- Branching fractions:

$$R_{\pi/K} = (6.59 \pm 1.01 \pm 0.22) \times 10^{-2}$$

$$R^{\pi}_{2/1} = 0.95 \pm 0.30 \pm 0.04 \pm 0.04$$

$$R^{K}_{2/1} = 1.06 \pm 0.05 \pm 0.04 \pm 0.04$$



- Background subtracted $\chi_{c1} p$, $\chi_{c1} \pi^-$ and $p\pi^-$ distributions from the $\Lambda_b^0 \to \chi_{c1} p \pi^-$ decay are investigated and consistent with the phase space model. No evidence for exotic states is found.

Search for doubly heavy baryons Ξ_{bc}^{0} and Ω_{bc}^{0} decaying to $\Lambda_c^+\pi^-$ and $\Xi_c^+\pi^-$

LHCb-PAPER-2021-002
arXiv:2104.04759

Doubly heavy baryons: Ξ_{bc}^0/Ω_{bc}^0

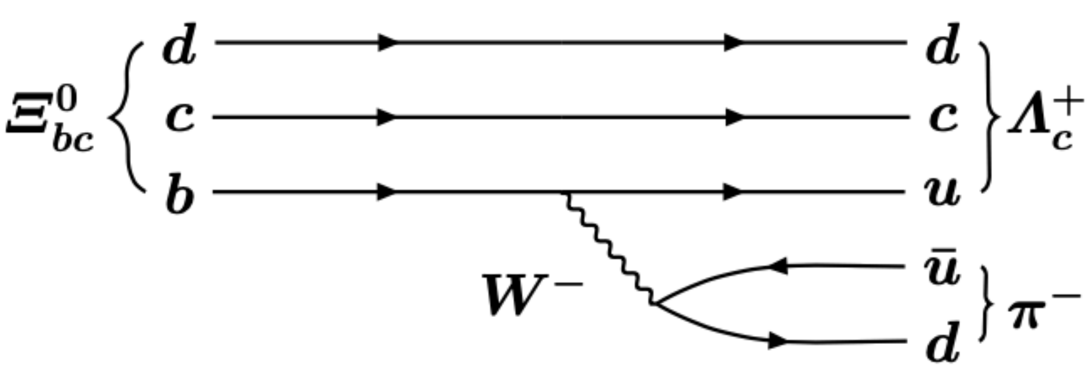
- To date, no baryons containing one b and one c quark have been observed experimentally.
- This is the first search for the Ω_{bc}^0 baryon at LHCb and a new search for the Ξ_{bc}^0 baryon, both decay to $\Lambda_c^+\pi^-$ and $\Xi_c^+\pi^-$.

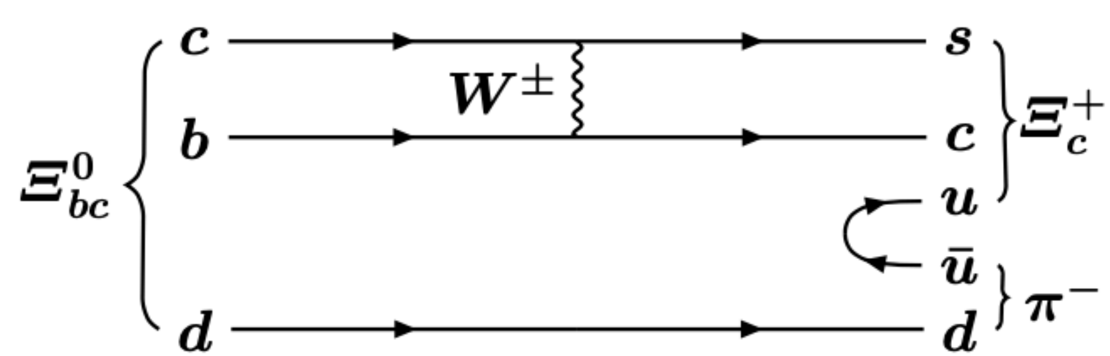
Previous search: $\Xi_{bc}^0 \to D^0pK^-$
JHEP11(2020)095

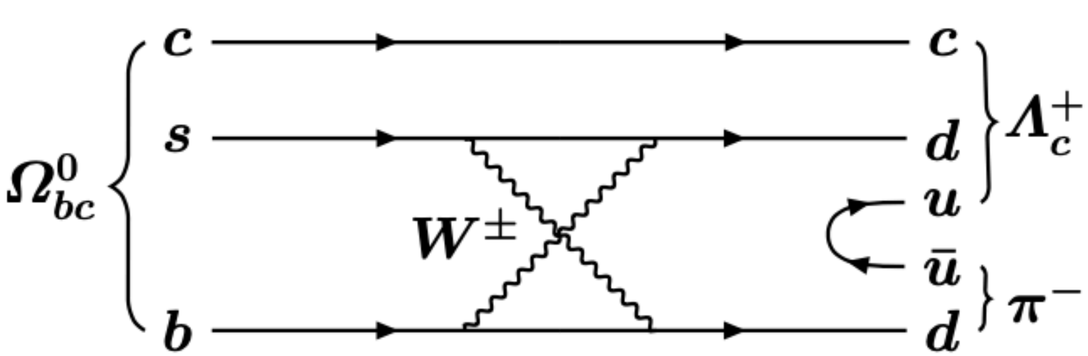
Production ratios:

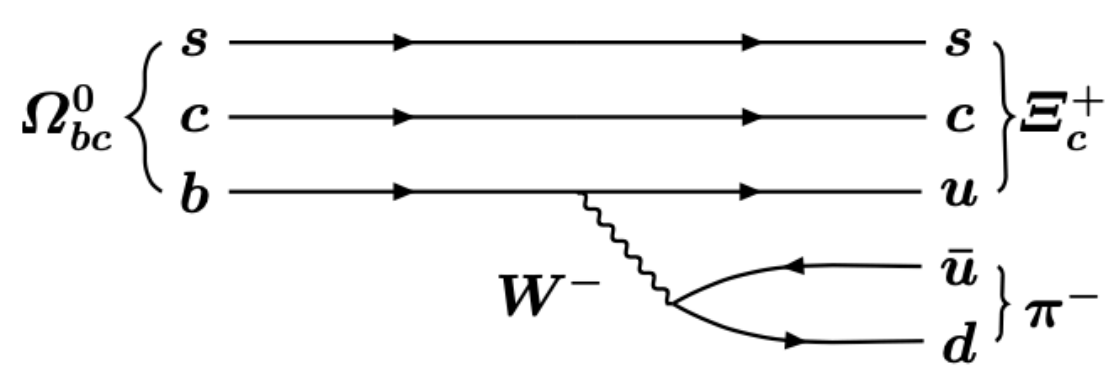
$$R(\Lambda_c^+\pi^-) = \frac{N(\Xi_{bc}^0/\Omega_{bc}^0 \to \Lambda_c^+\pi^-)}{N(\Lambda_b^0 \to \Lambda_c^+\pi^-)} \frac{\epsilon(\Lambda_b^0)}{\epsilon(\Xi_{bc}^0/\Omega_{bc}^0)}$$

$$R(\Xi_c^+\pi^-) = \frac{N(\Xi_{bc}^0/\Omega_{bc}^0 \to \Xi_c^+\pi^-)}{N(\Xi_b^0 \to \Xi_c^+\pi^-)} \frac{\epsilon(\Xi_b^0)}{\epsilon(\Xi_{bc}^0/\Omega_{bc}^0)}$$





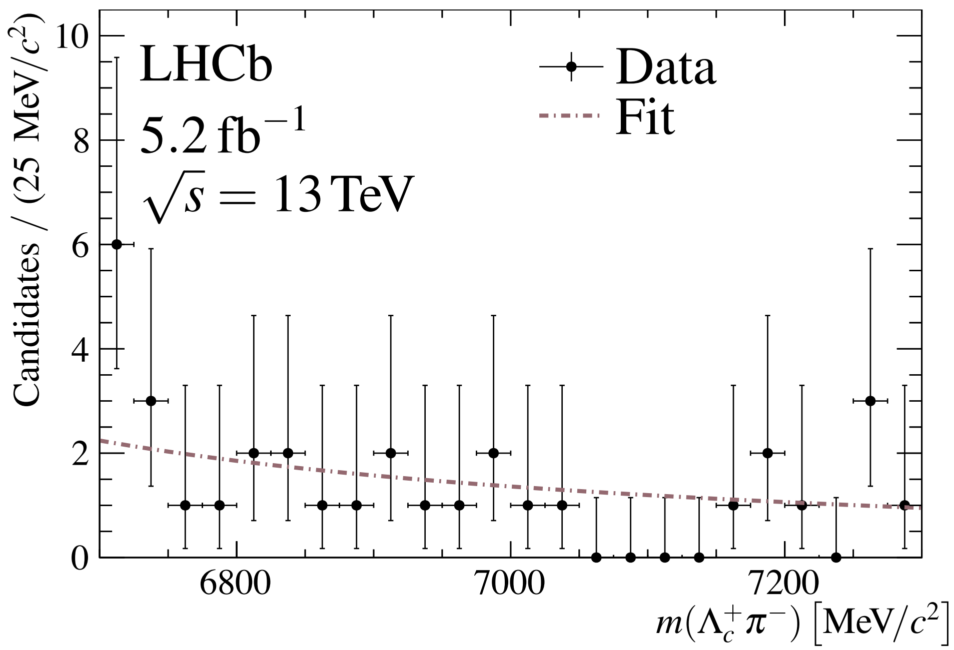


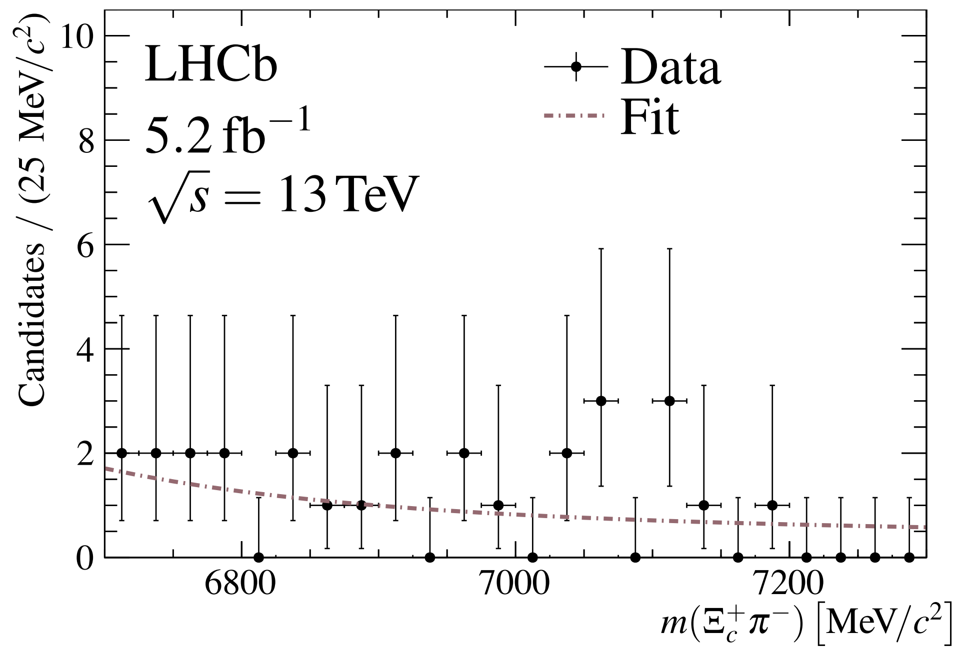


LHCb-PAPER-2021-002
arXiv:2104.04759

Doubly heavy baryons: Ξ_{bc}^0/Ω_{bc}^0

- No significant signal excess is seen, upper limits at 95% confidence level are set on the ratios $R(\Lambda_c^+\pi^-)$ and $R(\Xi_c^+\pi^-)$.



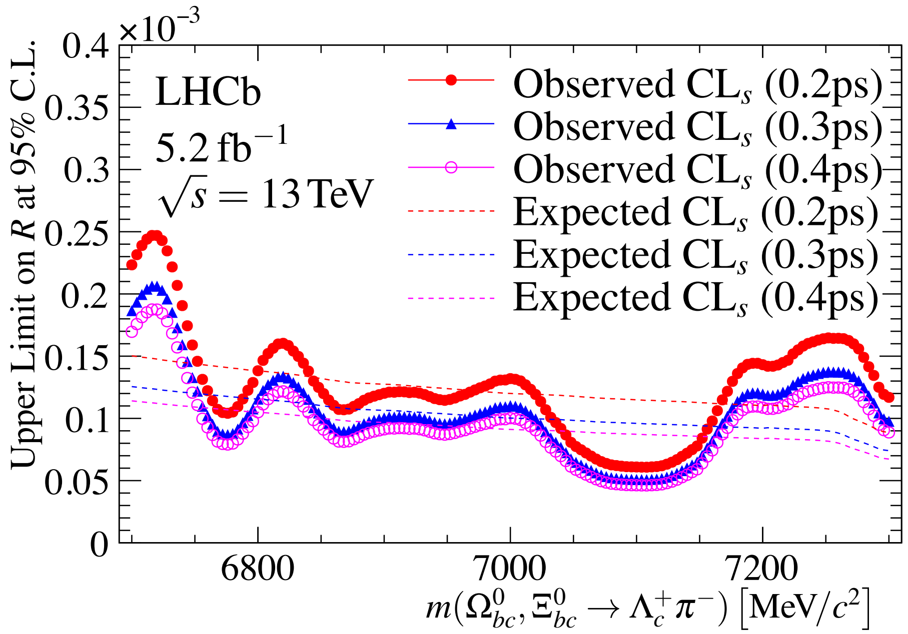


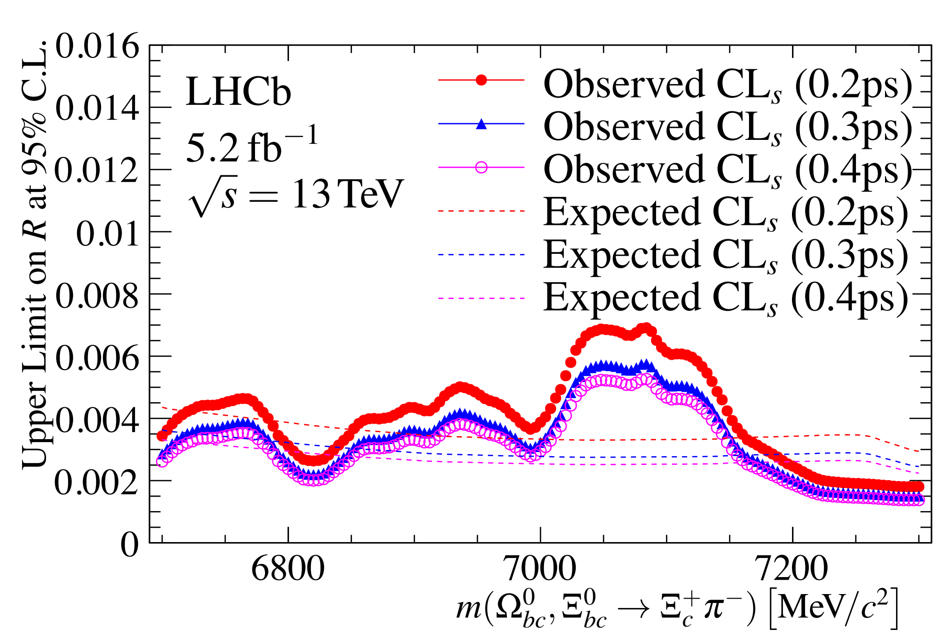
- The assumed mass of Ξ_{bc}^0 is varied from 6700 to 7300 MeV with a step size of 4 MeV, and its lifetime is varied from 0.2 to 0.4 ps.

Upper limit ranges on R:

$\Xi_{bc}^0(\Omega_{bc}^0) \to \Lambda_c^+\pi^-$:
0.5×10^{-4} to 2.5×10^{-4}

$\Xi_{bc}^0(\Omega_{bc}^0) \to \Xi_c^+\pi^-$:
1.4×10^{-3} to 6.9×10^{-3}





Summary

- Lots of new particles and excited states have been discovered at LHCb!
- First observation of the decay $\Omega_b^- \to \Xi_c^+ K^- \pi^-$.
- Precise measurement of the Ω_b^- mass: $m(\Omega_b^-) = 6044.8 \pm 1.3$ MeV.
- Four excited Ω_c^0 states observed with a significance over 6σ. Rejected common interpretation of spin assignment $J = 1/2, 1/2, 3/2, 3/2$ with 3.5σ confidence.
- Two excited Ξ_b^0 states are observed with a significance over 9σ (compared to no peak hypothesis) and 5σ (compared to one-peak hypothesis).
  - Properties are in good agreement with the theoretical predictions of the 1D excited Ξ_b^0 doublet.
- First observation of the decay $\Lambda_b^0 \to \chi_{c1} p \pi^-$ with a significance of over 9σ. Evidence is found for the $\Lambda_b^0 \to \chi_{c2} p \pi^-$ decay with a significance of 3.8σ.
- Upper limits on R at 95 % confidence level are found for Ξ_{bc}^0 and Ω_{bc}^0.

Thanks for Listening!