Experimental aspects of Spectroscopy and Phenomenology at LHCb

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on behalf of the LHCb collaboration

STRONG: September 2021

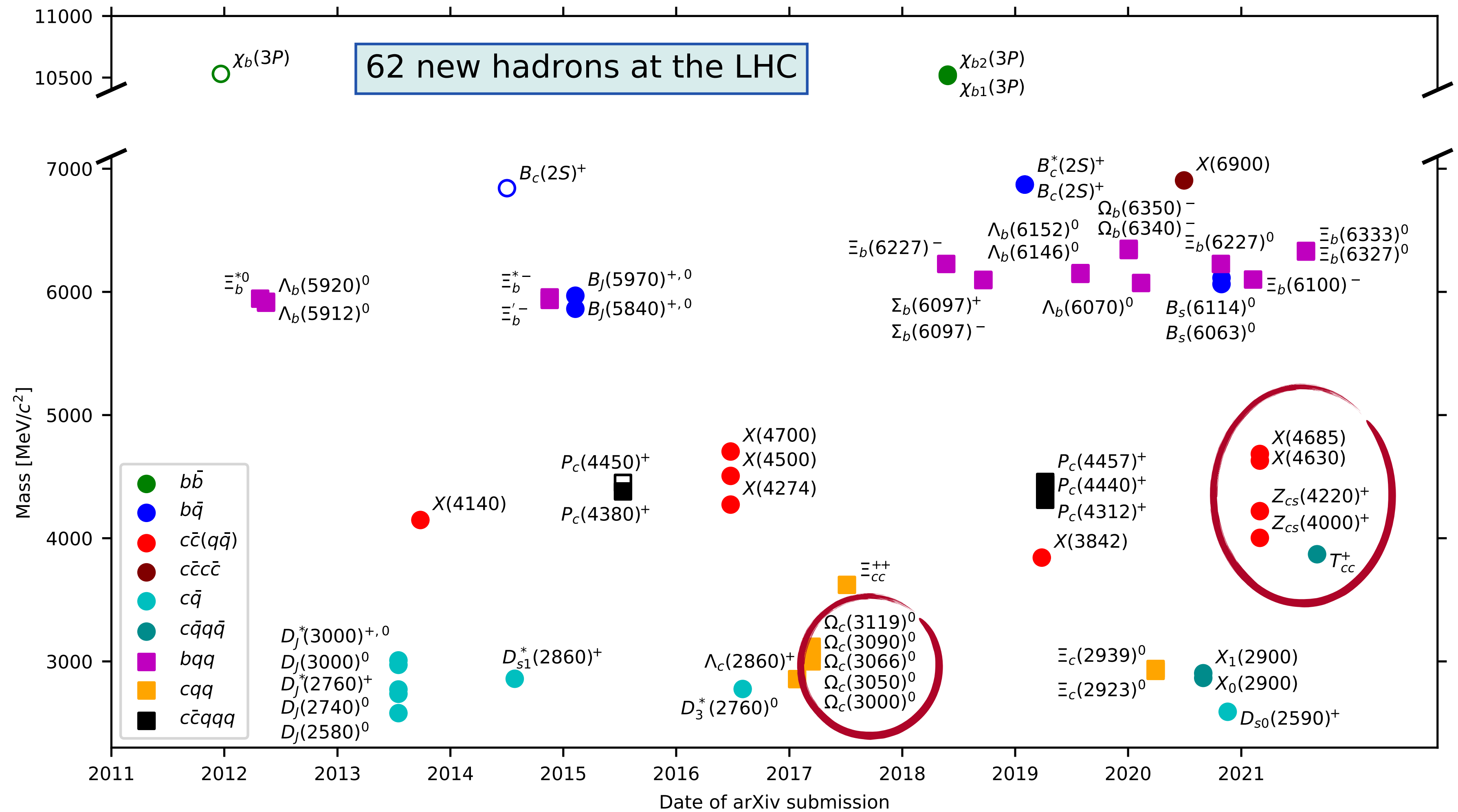
Introduction

- Over the past 10 years the LHC has discovered 62 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.

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

62 new hadrons



Recent Results

- Observation of new resonances decaying to $J/\psi K^+$ and $J/\psi\phi$
  LHCb-PAPER-2020-044 (published in PRL: Phys. Rev. Lett. 127, 082001)

- Evidence for a new structure in the $J/\psi p$ and $J/\psi\bar{p}$ systems in $B_s^0 \to J/\psi p\bar{p}$ decays
  LHCb-PAPER-2021-018 (submitted to PRL: arXiv:2108.04720)

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

- Observation of an exotic narrow doubly charmed tetraquark
  LHCb-PAPER-2021-031 (arXiv:2109.01038, arXiv:2109.01056)

Observation of new resonances decaying to $J/\psi K^+$ and $J/\psi\phi$

Run 1 Analysis: Phys. Rev. Lett. 118, 022003 (2017)
This analysis: Phys. Rev. Lett. 127, 082001 (2021)
[LHCb-PAPER-2020-044]

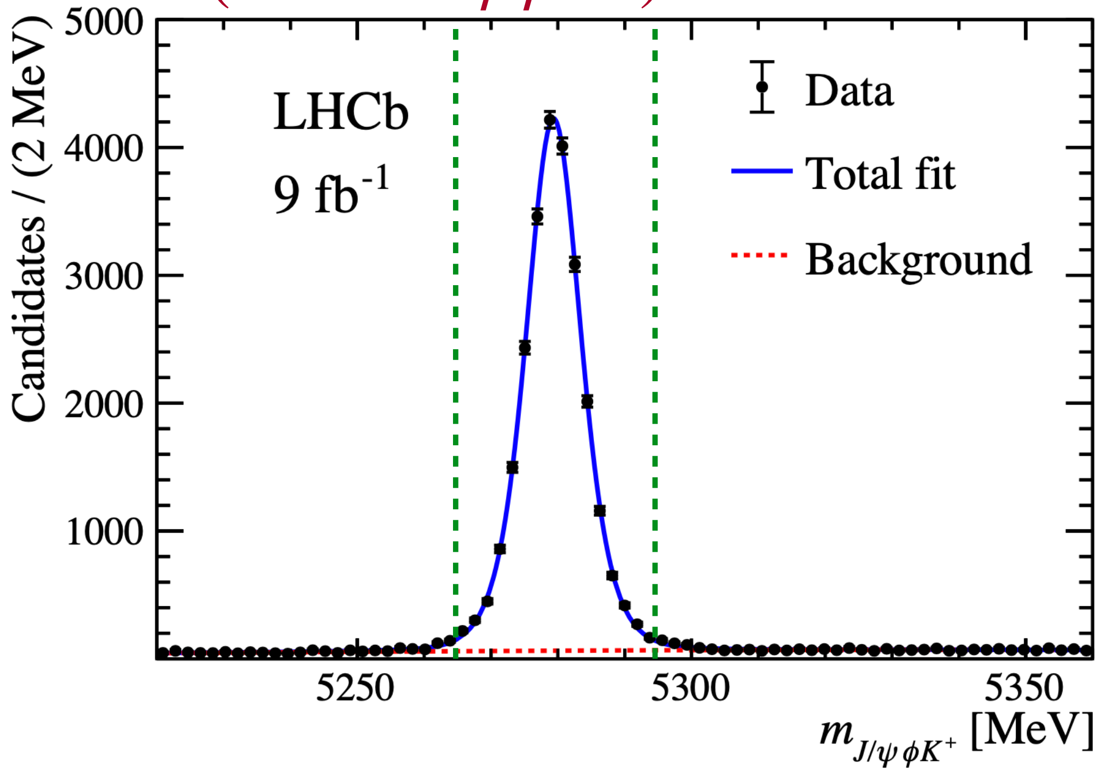
New Exotic States: Z_{cs}^{+}

- The previous Run 1 analysis found four X ($\rightarrow J/\psi\phi$) structures with a significance of over 5σ.

Signal Decay: $B^+ \rightarrow J/\psi\phi K^+$

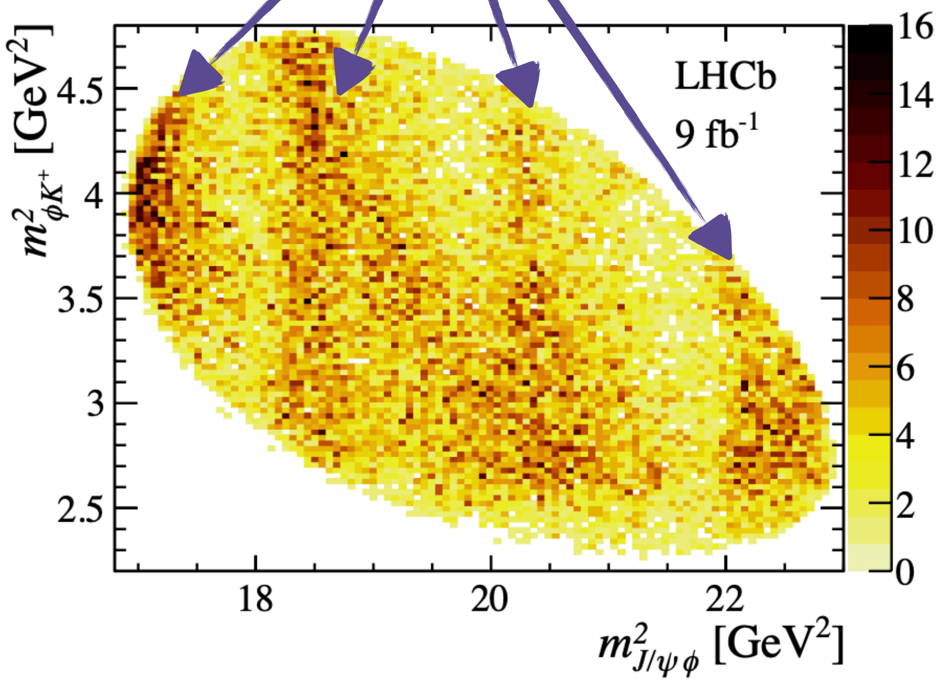
- Including Run 2 and improving the selection efficiency provides an increase of ~ 6 times larger statistics.

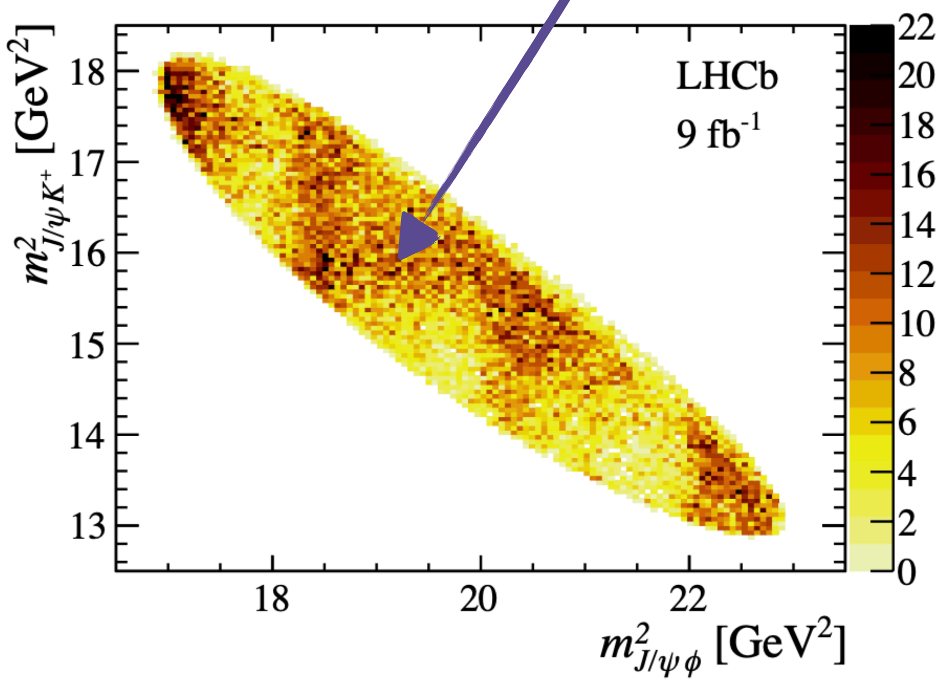
$N(B^+ \rightarrow J/\psi\phi K^+) = 24220 \pm 170$



Previously observed

Distinct band in $J/\psi K^+$





- Candidates in region of ± 15 MeV of B^+ mass peak.
- To investigate structures a full amplitude fit is performed.

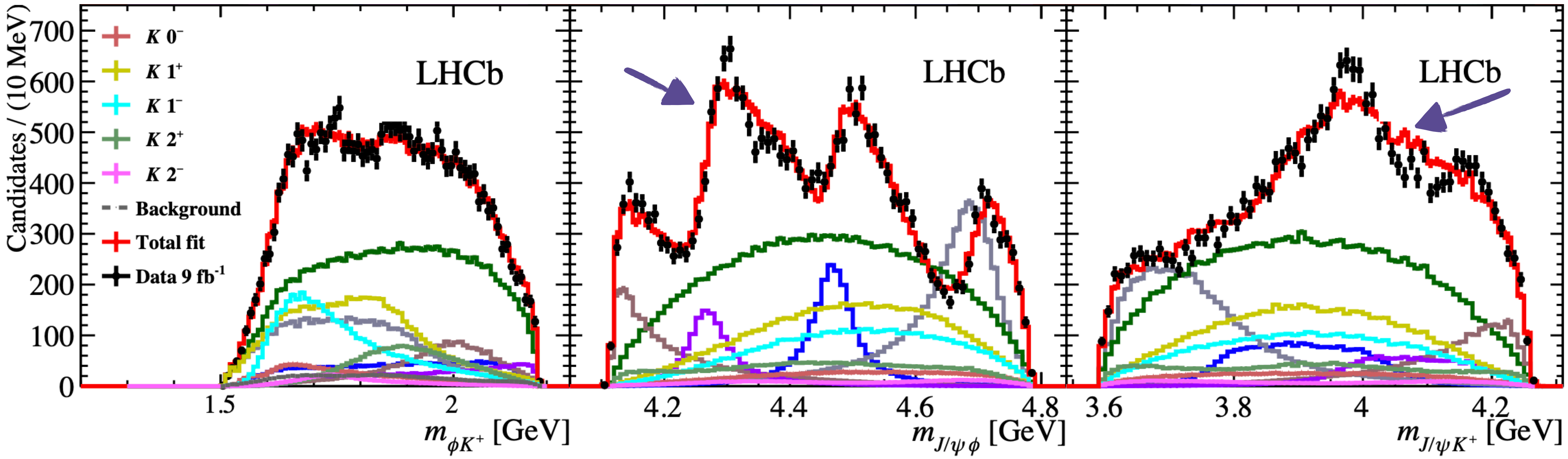
New Exotic States: Z_{cs}^{+}

Run 1 Analysis: Phys. Rev. Lett. 118, 022003 (2017)
This analysis: Phys. Rev. Lett. 127, 082001 (2021)
[LHCb-PAPER-2020-044]

- Signal decay is described in the helicity formalism by three decay chains:

$K^{*+}(\to \phi K^{+})J/\psi$ $\quad$ $X(\to J/\psi\phi)K^{+}$ $\quad$ $Z_{cs}^{+}(\to J/\psi K^{+})\phi$

Model from Run 1 Analysis:



- Clear discrepancies are observed.

- Run 1 model needs to be improved.

Run 1 Analysis: Phys. Rev. Lett. 118, 022003 (2017)
This analysis: Phys. Rev. Lett. 127, 082001 (2021)
[LHCb-PAPER-2020-044]

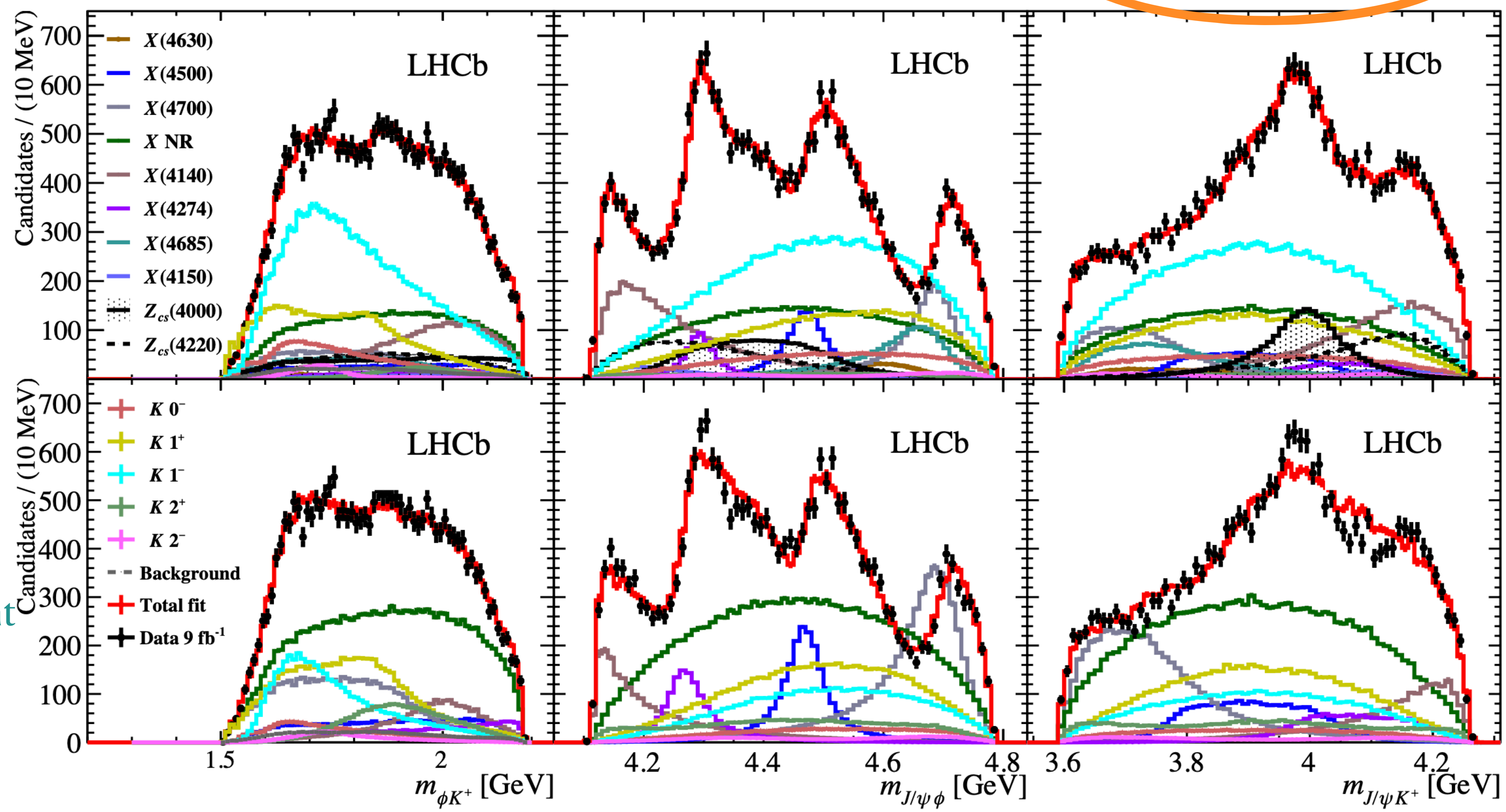
New Exotic States: Z_{cs}^{+}

- Resolve the modelling issues with the inclusion of more exotic states.

$Z_{cs}(4000)^{+}$

$Z_{cs}(4220)^{+}$

$K^{*+}(\to \phi K^{+})J/\psi$ $\quad X(\to J/\psi\phi)K^{+}$ $\quad Z_{cs}^{+}(\to J/\psi K^{+})\phi$



New Model

Improvement to model

- In total: nine K^{*+}, seven X, two Z_{cs}^{+} and one $J/\psi\phi$ NR component are taken as the default model, all have a statistical significance of over 5σ.

New Exotic States: Z_{cs}^{+}

Run 1 Analysis: Phys. Rev. Lett. 118, 022003 (2017)
This analysis: Phys. Rev. Lett. 127, 082001 (2021)
[LHCb-PAPER-2020-044]

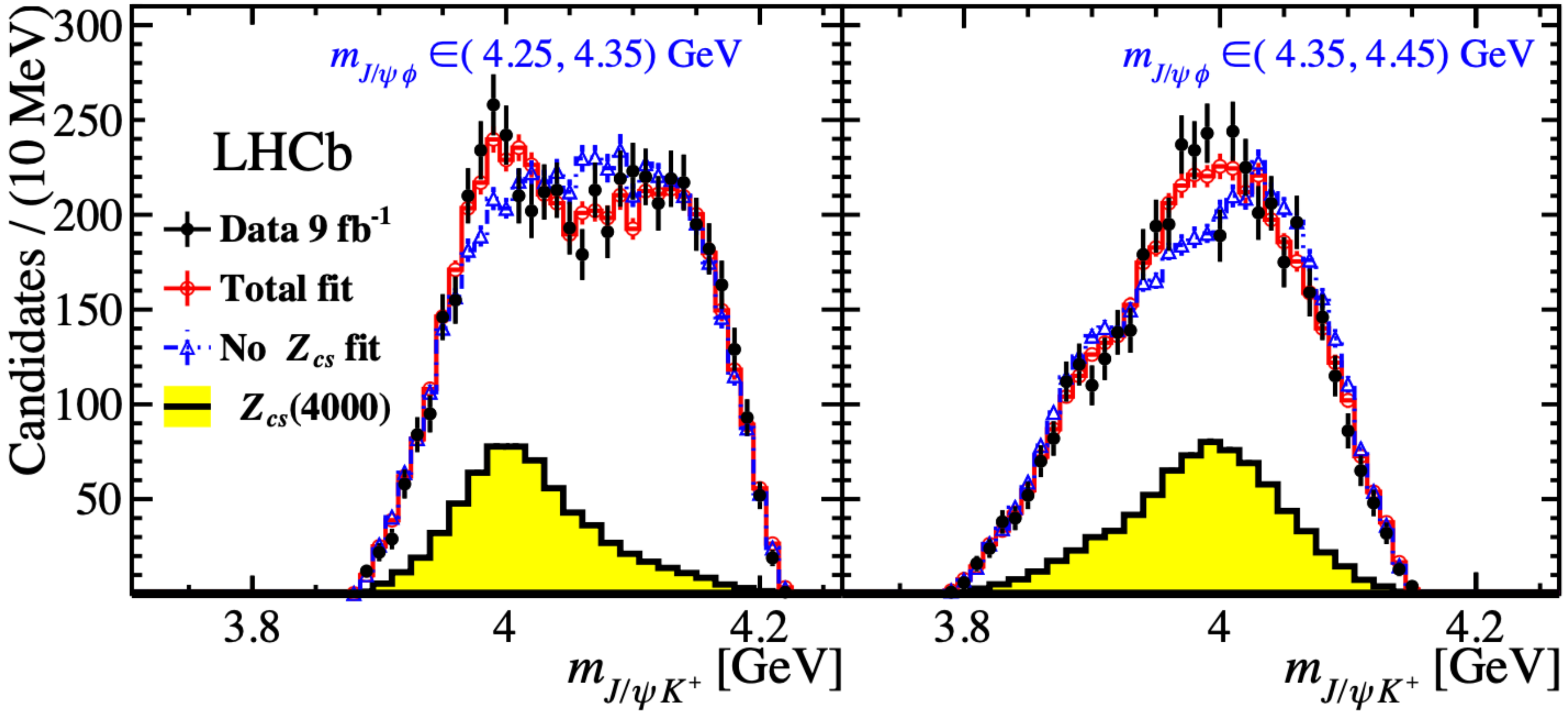
	Contribution	Significance $[\times\sigma]$	M_0 [MeV]	Γ_0 [MeV]	FF [%]
	All $K(1^+)$				$25 \pm 4\,^{+\ 6}_{-15}$
2^1P_1	$K(1^+)$	4.5 (4.5)	$1861 \pm 10\,^{+16}_{-46}$	$149 \pm 41\,^{+231}_{-\ 23}$	
2^3P_1	$K'(1^+)$	4.5 (4.5)	$1911 \pm 37\,^{+124}_{-\ 48}$	$276 \pm 50\,^{+319}_{-159}$	
1^3P_1	$K_1(1400)$	9.2 (11)	1403	174	$15 \pm 3\,^{+\ 3}_{-11}$
	All $K(2^-)$				$2.1 \pm 0.4\,^{+2.0}_{-1.1}$
1^1D_2	$K_2(1770)$	7.9 (8.0)	1773	186	
1^3D_2	$K_2(1820)$	5.8 (5.8)	1816	276	
	All $K(1^-)$				$50 \pm 4\,^{+10}_{-19}$
1^3D_1	$K^*(1680)$	4.7 (13)	1717	322	$14 \pm 2\,^{+35}_{-\ 8}$
2^3S_1	$K^*(1410)$	7.7 (15)	1414	232	$38 \pm 5\,^{+11}_{-17}$
	$K(2^+)$				
2^3P_2	$K_2^*(1980)$	1.6 (7.4)	$1988 \pm 22\,^{+194}_{-\ 31}$	$318 \pm 82\,^{+481}_{-101}$	$2.3 \pm 0.5 \pm 0.7$
	$K(0^-)$				
2^1S_0	$K(1460)$	12 (13)	1483	336	$10.2 \pm 1.2\,^{+1.0}_{-3.8}$
	$X(2^-)$				
	$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28\,^{+59}_{-30}$	$2.0 \pm 0.5\,^{+0.8}_{-1.0}$
	$X(1^-)$				
	$X(4630)$	5.5 (5.7)	$4626 \pm 16\,^{+\ 18}_{-110}$	$174 \pm 27\,^{+134}_{-\ 73}$	$2.6 \pm 0.5\,^{+2.9}_{-1.5}$
	All $X(0^+)$				$20 \pm 5\,^{+14}_{-\ 7}$
	$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6\,^{+10}_{-\ 8}$	$5.6 \pm 0.7\,^{+2.4}_{-0.6}$
	$X(4700)$	17 (18)	$4694 \pm 4\,^{+16}_{-\ 3}$	$87 \pm 8\,^{+16}_{-\ 6}$	$8.9 \pm 1.2\,^{+4.9}_{-1.4}$
	$\mathrm{NR}_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8\,^{+19}_{-11}$
	All $X(1^+)$				$26 \pm 3\,^{+\ 8}_{-10}$
	$X(4140)$	13 (16)	$4118 \pm 11\,^{+19}_{-36}$	$162 \pm 21\,^{+24}_{-49}$	$17 \pm 3\,^{+19}_{-\ 6}$
	$X(4274)$	18 (18)	$4294 \pm 4\,^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5\,^{+0.8}_{-0.4}$
	$X(4685)$	15 (15)	$4684 \pm 7\,^{+13}_{-16}$	$126 \pm 15\,^{+37}_{-41}$	$7.2 \pm 1.0\,^{+4.0}_{-2.0}$
	All $Z_{cs}(1^+)$				$25 \pm 5\,^{+11}_{-12}$
	$Z_{cs}(4000)$	15 (16)	$4003 \pm 6\,^{+\ 4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
	$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24\,^{+43}_{-30}$	$233 \pm 52\,^{+97}_{-73}$	$10 \pm 4\,^{+10}_{-\ 7}$

Five new exotic states included in the default fit model.

New Exotic States: Z_{cs}^{+}

Run 1 Analysis: Phys. Rev. Lett. 118, 022003 (2017)
This analysis: Phys. Rev. Lett. 127, 082001 (2021)
[LHCb-PAPER-2020-044]

- Splitting the $m_{J/\psi\phi}$ plot into two slices demonstrates the necessity of the $Z_{cs}(4000)^{+}$ state. Where the inclusion of this state provides an improvement in the fit quality. This new narrow state is observed with a high significance.



- Spin and parity of each exotic state is probed by testing alternative J^{P} hypotheses and comparing the fit likelihood values.

- Previously reported J^{P} assignments for the four X states are confirmed with high significance.
  - $X(4675)$ and $Z_{cs}(4000)$ states are 1^{+} at over 15σ significance.
  - $Z_{cs}(4220)$ is either 1^{+} or 1^{-} within 2σ.
  - Other X states cannot be uniquely determined.

Evidence for a new structure in the $J/\psi p$ and $J/\psi \bar{p}$ systems in $B_s^0 \to J/\psi p \bar{p}$ decays

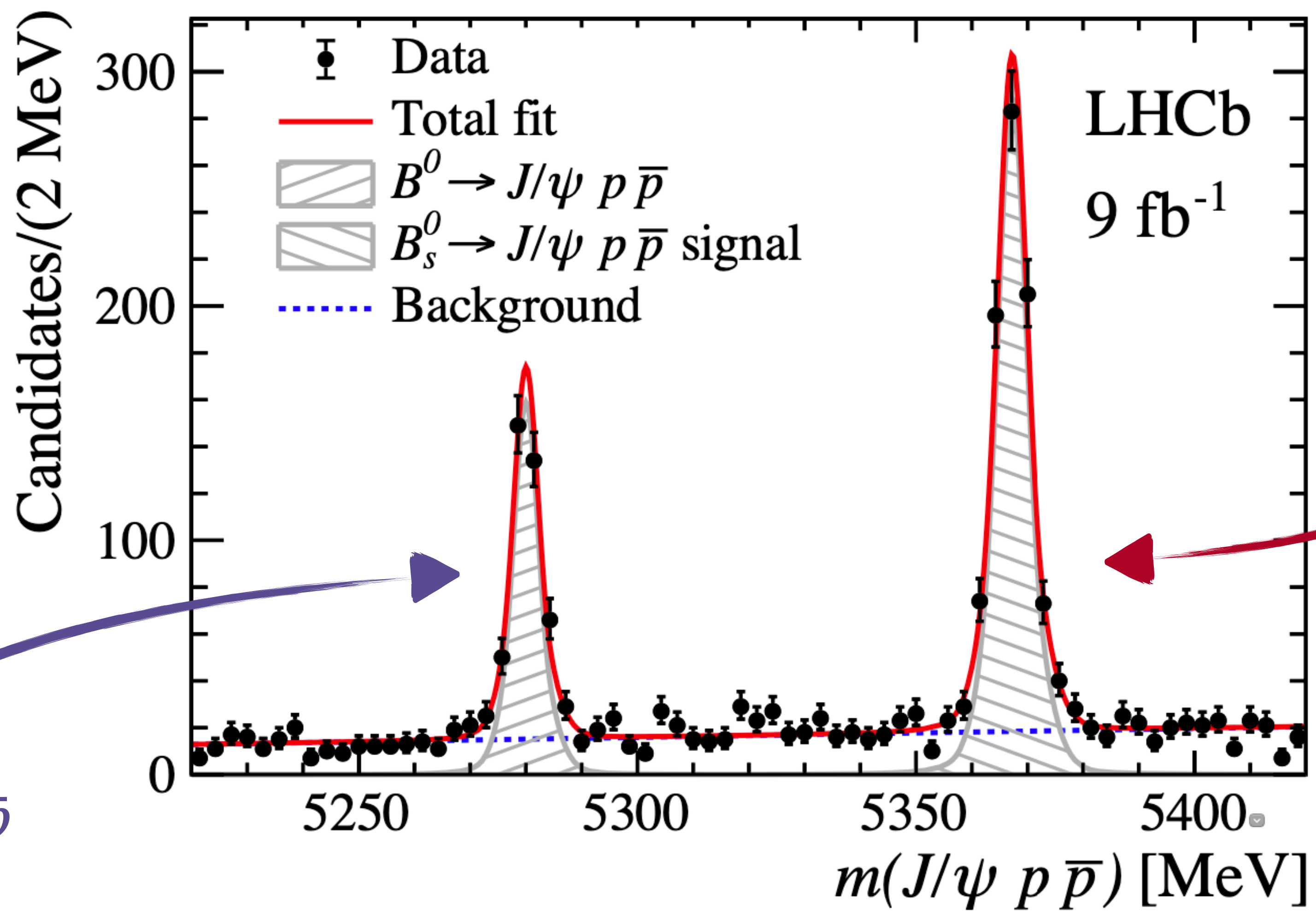
Evidence for a new structure in $J/\psi p$ and $J/\psi\bar{p}$

- Interest in exotic spectroscopy is increasing due to the observation of pentaquark candidates (P_c) in $J/\psi p$ final states produced in $\Lambda_b^0 \to J/\psi p K^-$ decays. Phys. Rev. Lett. 115, 072001 (2015) Phys. Rev. Lett. 122, 222001 (2019)

- The $B_s^0 \to J/\psi p\bar{p}$ decay was first observed in 2019 by the LHCb experiment, this decay may have sensitivity to resonant P_c structures. Phys. Rev. Lett. 122, 191804 (2019)

- This decay mode offers a clean environment to search for new resonant structures.

Signal peaks modelled by the sum of two Crystal Ball functions.



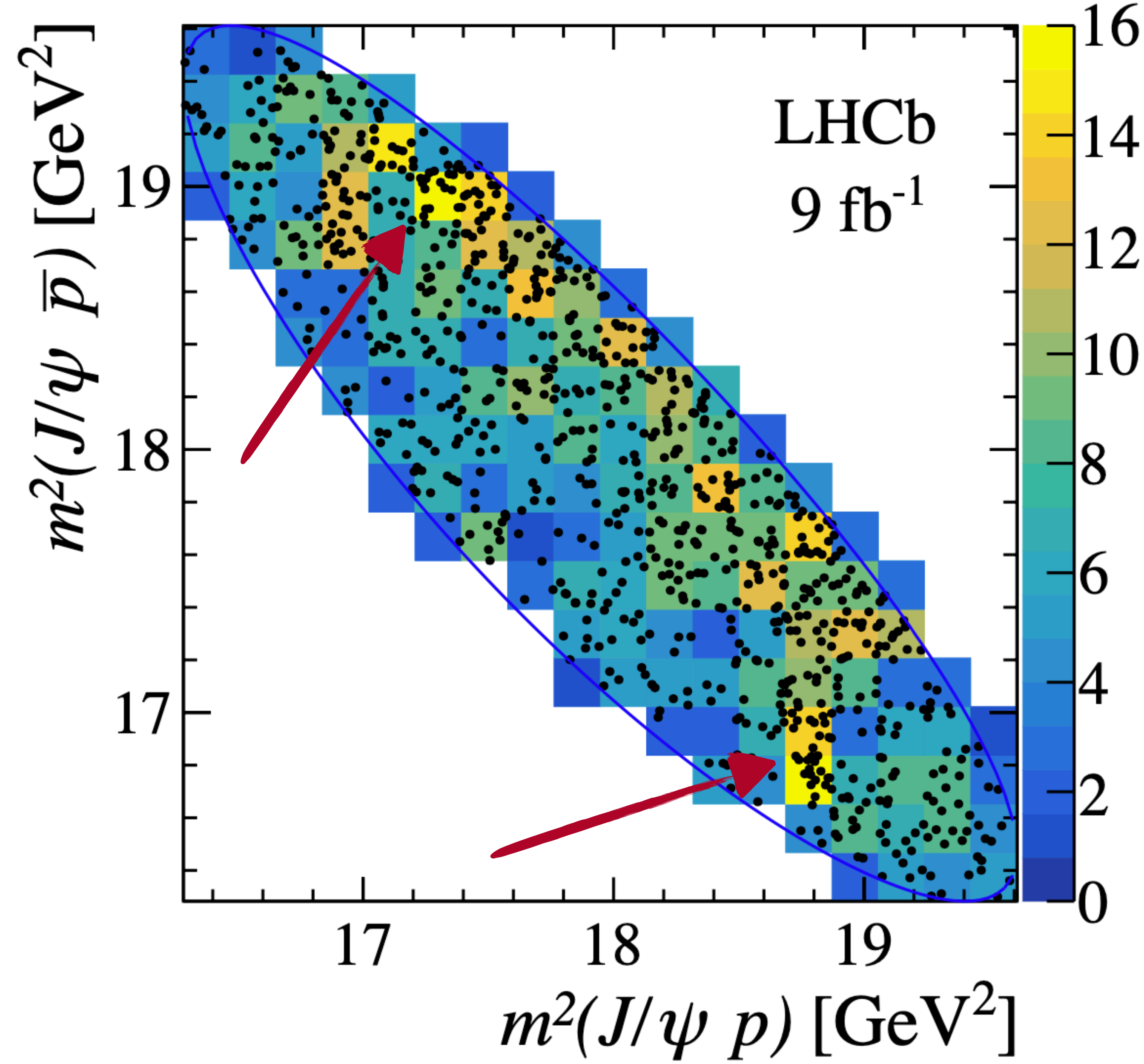
$N(B_s^0) = 797 \pm 31$

$B_s^0 \to J/\psi p\bar{p}$

$B^0 \to J/\psi p\bar{p}$

Evidence for a new structure in $J/\psi p$ and $J/\psi\bar{p}$

- Hints of horizontal and vertical bands in the region around $(18.8 - 19.0)$ GeV^2 in the $m^2(J/\psi p)$ and $m^2(J/\psi\bar{p})$ distributions.



- These enhancements are not compatible with the pure phase-space hypothesis.
- Three interfering decay sequences are considered:

$$B_s^0 \rightarrow J/\psi X(\rightarrow p\bar{p})$$

$$B_s^0 \rightarrow P_c^+(\rightarrow J/\psi p)\bar{p}$$

$$B_s^0 \rightarrow P_c^-(\rightarrow J/\psi\bar{p})p$$

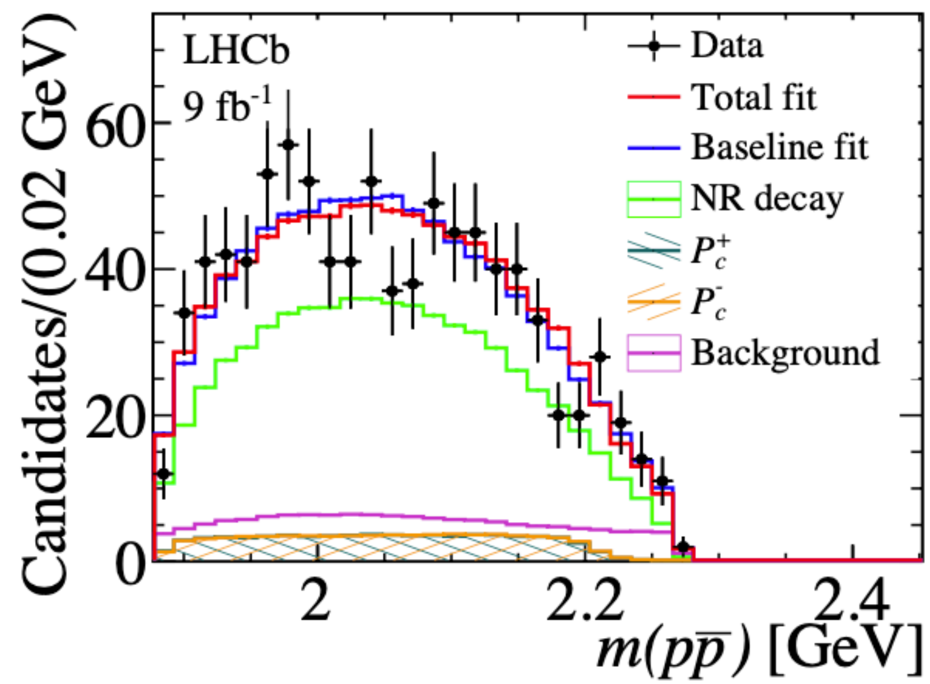
- This analysis is sensitive to the sum of contributions from P_c^+ and P_c^- pentaquark candidates, denoted P_c.

Flavour untagged

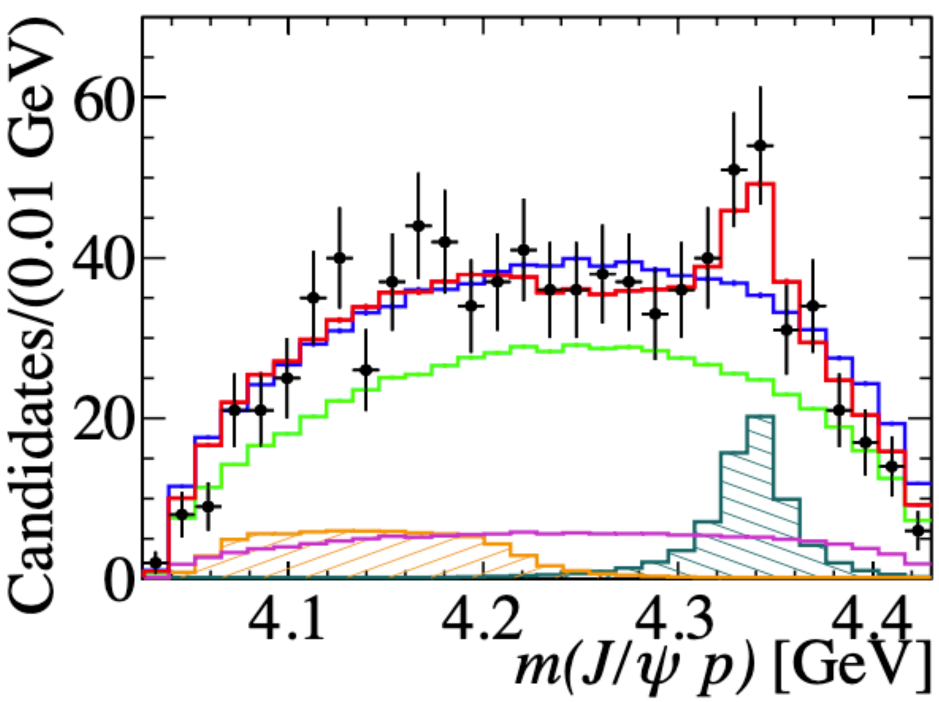
CP symmetry is assumed

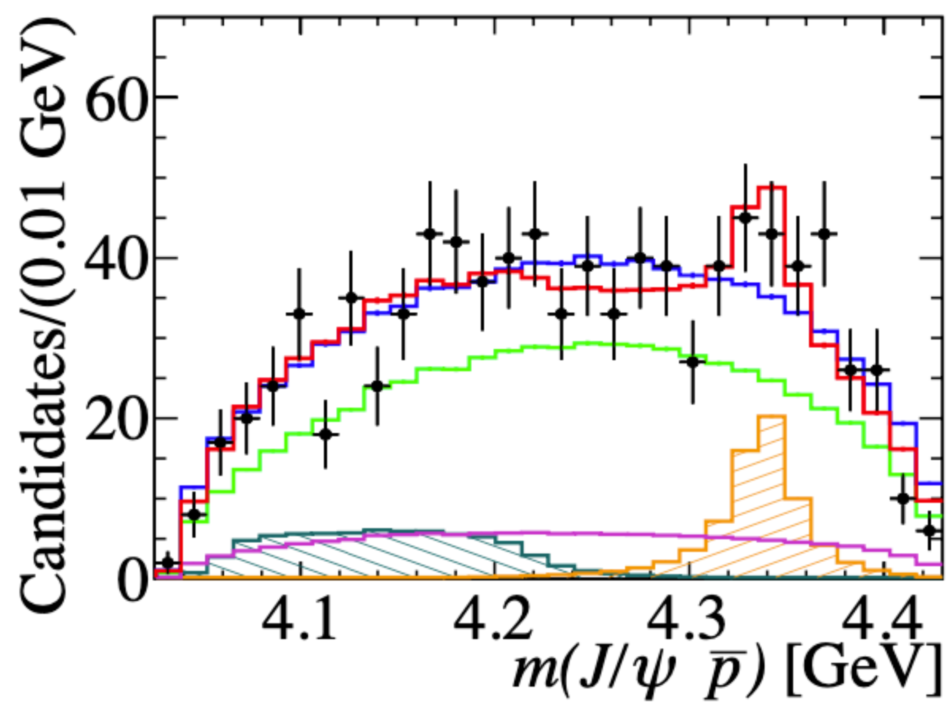
Evidence for a new structure in $J/\psi p$ and $J/\psi\bar{p}$

- The baseline fit is the simplest model, in which no resonant contributions are considered.
- The baseline fit does not describe the data well, two resonant contributions P_c^+ and P_c^- are added.
- The default model includes a new $P_c^\pm$ state.



Statistical significance in the range of $3.1 - 3.7\sigma$, depending on assigned J^P hypothesis ($1/2^\pm$, $3/2^\pm$).





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

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

No hints of the previously seen P_c states are observed.

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

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

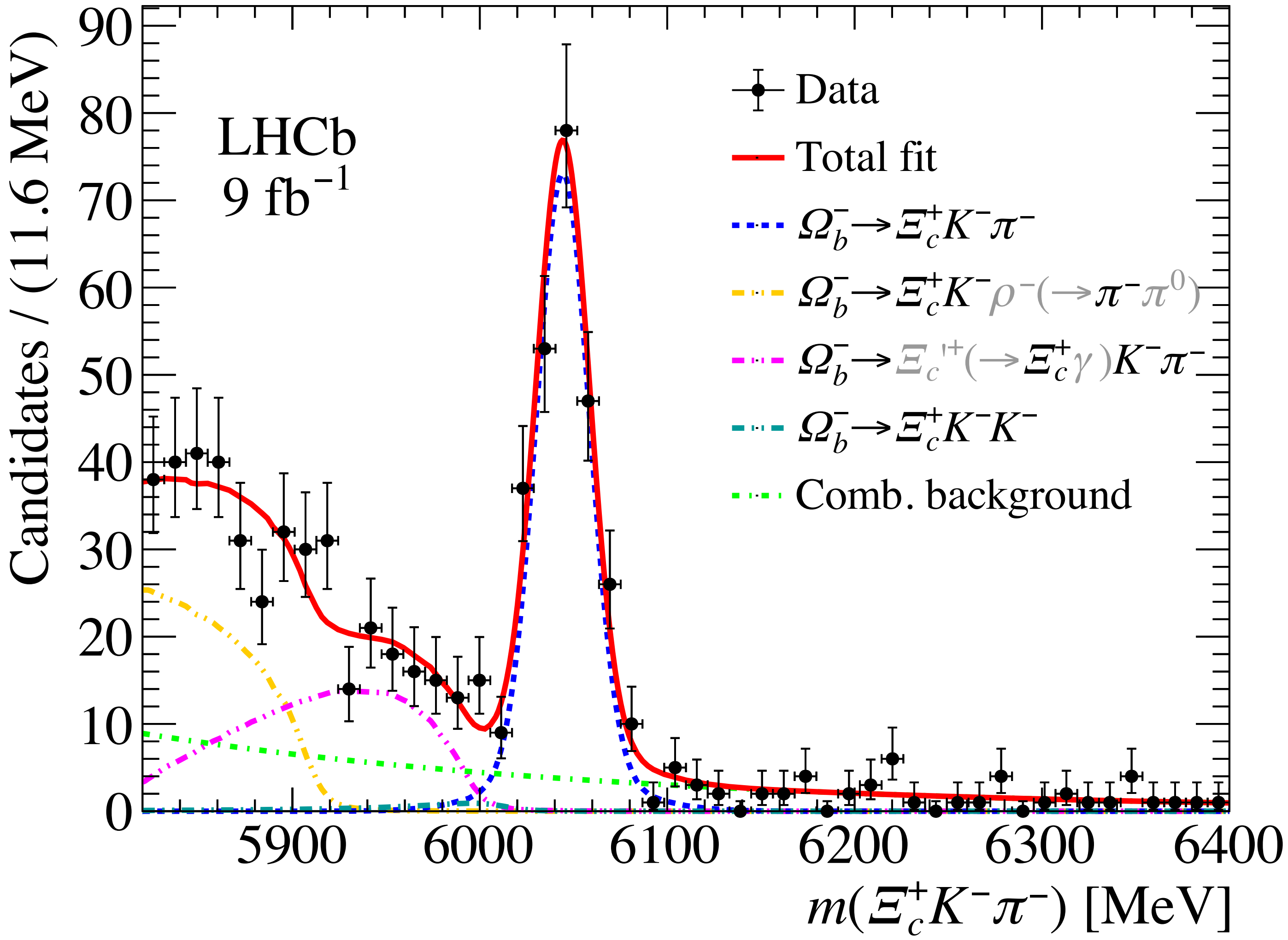
- In 2017 there was an observation of five new resonances of Ω_c^0 (css) decaying as $\Omega_c^{**0} \to \Xi_c^+ K^-$: Now cited over 200 times!

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 a precise Ω_b^- mass:

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

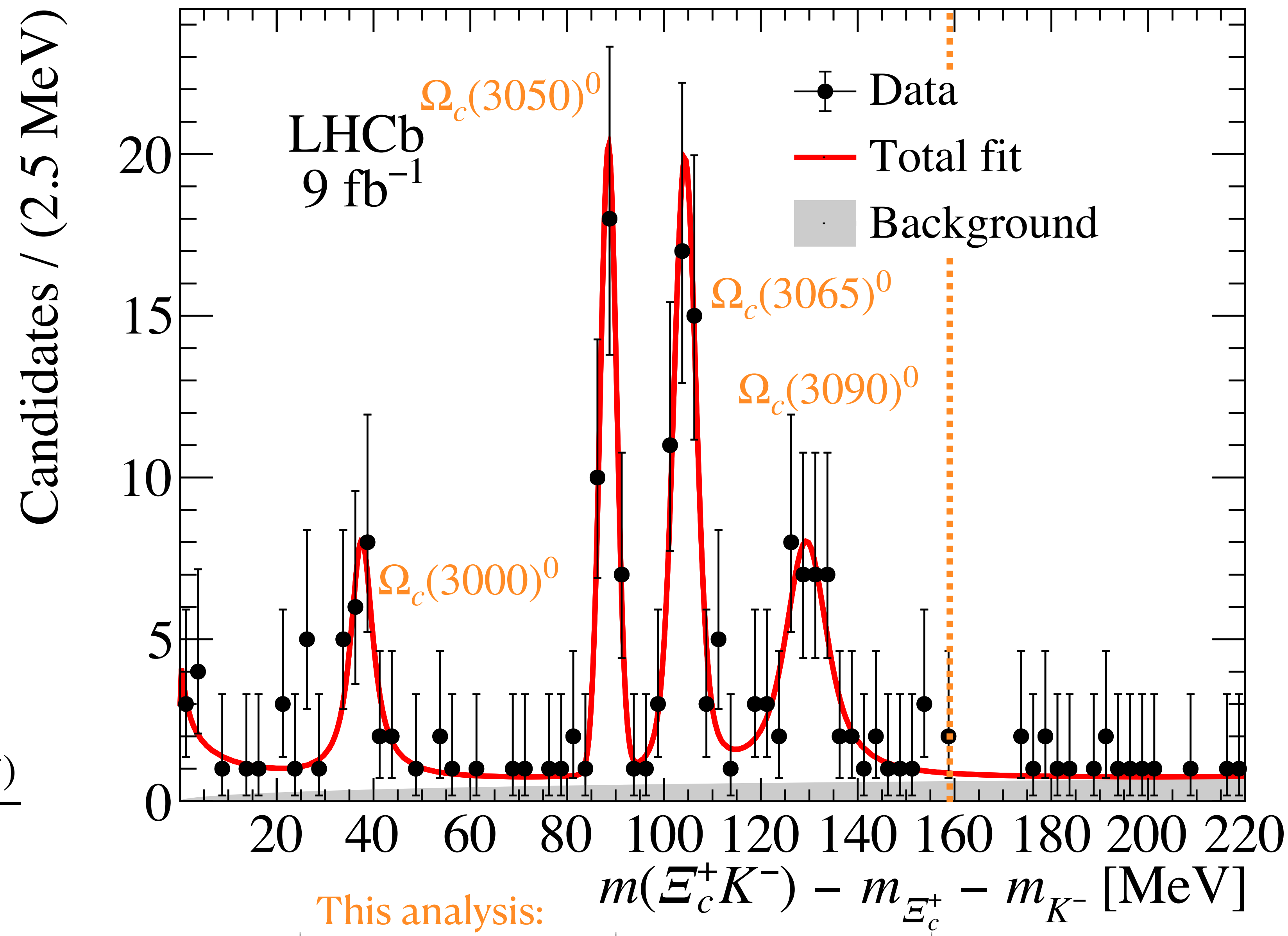
Observation of the Excited Ω_c^0 States

- 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:

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

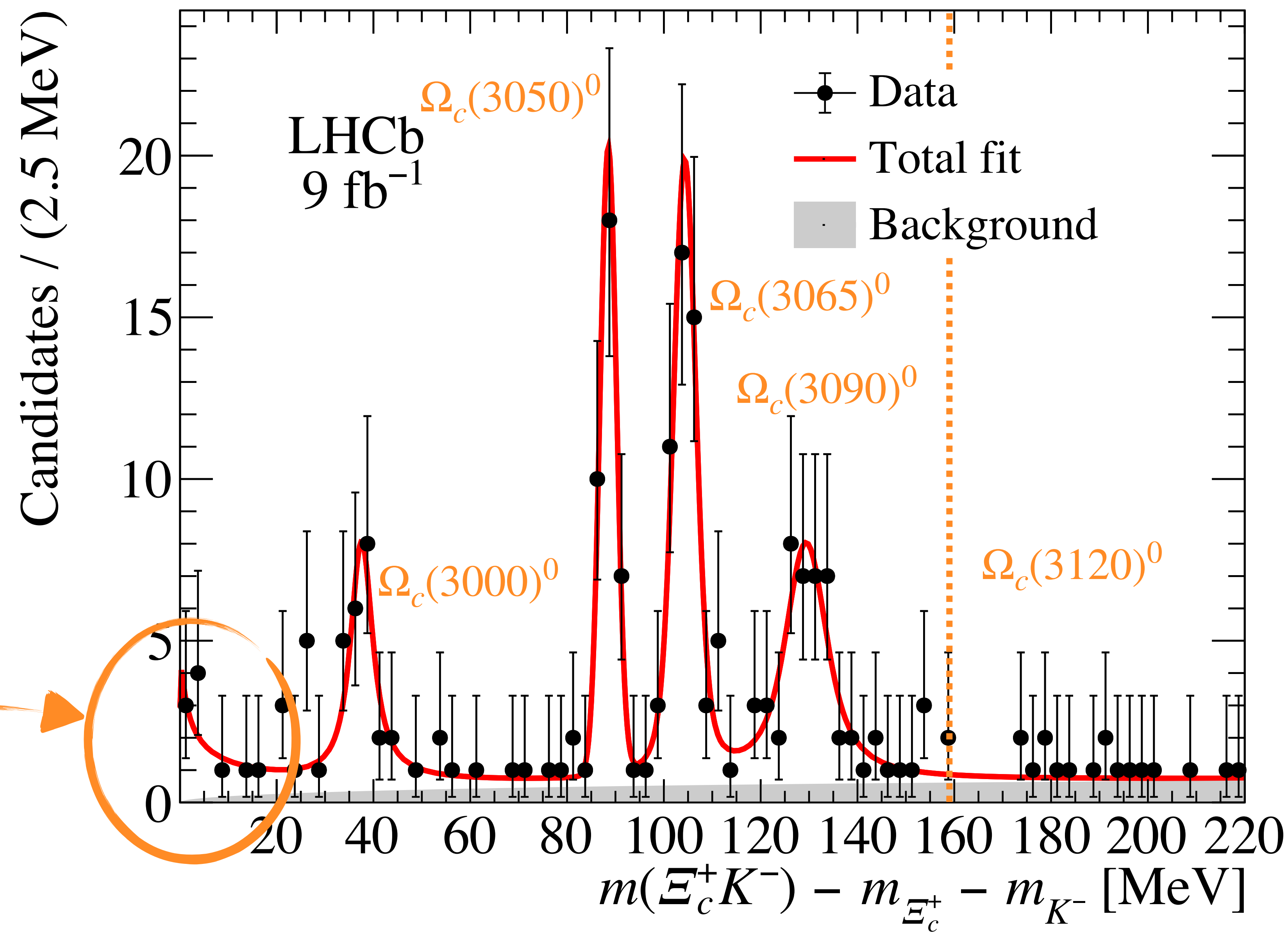


	Prompt analysis:		This analysis:		
Resonance	Mass [MeV]	Γ [MeV]	Mass [MeV]	Γ [MeV]	P
$\Omega_c(3000)^0$	3000.4 ± 0.2 ± 0.1	4.5 ± 0.6 ± 0.3	2999.2 ± 0.9 ± 0.9	4.8 ± 2.1 ± 2.5	0.11 ± 0.02 ± 0.04
$\Omega_c(3050)^0$	3050.2 ± 0.1 ± 0.1	0.8 ± 0.2 ± 0.1	3050.1 ± 0.3 ± 0.2	< 1.6 @ 95% CL	0.15 ± 0.02 ± 0.02
$\Omega_c(3065)^0$	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

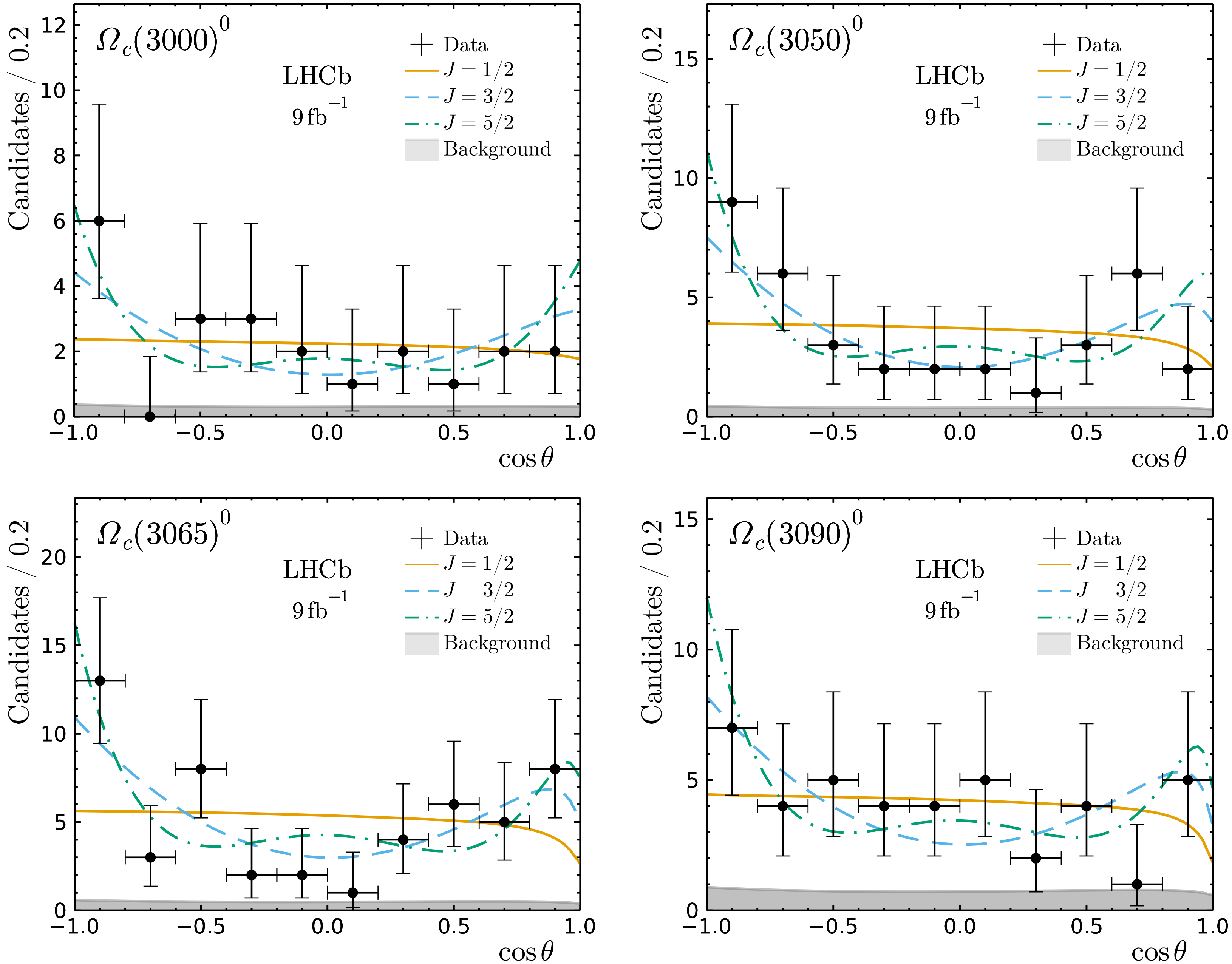


- Enhancement seen at $\Xi_c^+ K^-$ threshold with a significance larger than 4σ, further studies needed to determine its nature. A similar structure was seen in the prompt $\Xi_c^+ K^-$ spectrum and was interpreted as the partially reconstructed decay $\Omega_c(3065)^0 \rightarrow \Xi_c'^+(\rightarrow \Xi_c^+ \gamma) K^-$.
  - 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 an exotic narrow doubly charmed tetraquark

Observation of T_{cc}^{+}

LHCb-PAPER-2021-031
arXiv:2109.01038

Phys. Rev. Lett. 199, 112001 (2017)
Science Bulletin 65 (2020) 1983

- The search of the T_{cc}^{+} state is motivated by the observation of the Ξ_{cc}^{++} baryon and the new fully charmed tetraquark which decays to two J/ψ mesons by the LHCb experiment.

Quark content: $cc\bar{u}\bar{d}$

Quark content: ccu

- The measured mass of the Ξ_{cc}^{++} baryon implies that the mass of the $cc\bar{u}\bar{d}$ tetraquark is close to the D^0D^{*+} threshold.

- Theoretical predictions of δm relative to the D^0D^{*+} mass threshold lie in the range $-300 < \delta m < 300$ MeV.

$$\delta m \equiv m_{T_{cc}^{+}} - (m_{D^{*+}} + m_{D^0})$$

Searching for the T_{cc}^{+} state in the $D^0D^0\pi^+$ mass spectrum.

Observation of T_{cc}^{+}

LHCb-PAPER-2021-031
arXiv:2109.01038

- Signal component is modelled by the combination of the detector resolution and a relativistic Breit-Wigner (P-wave) function.

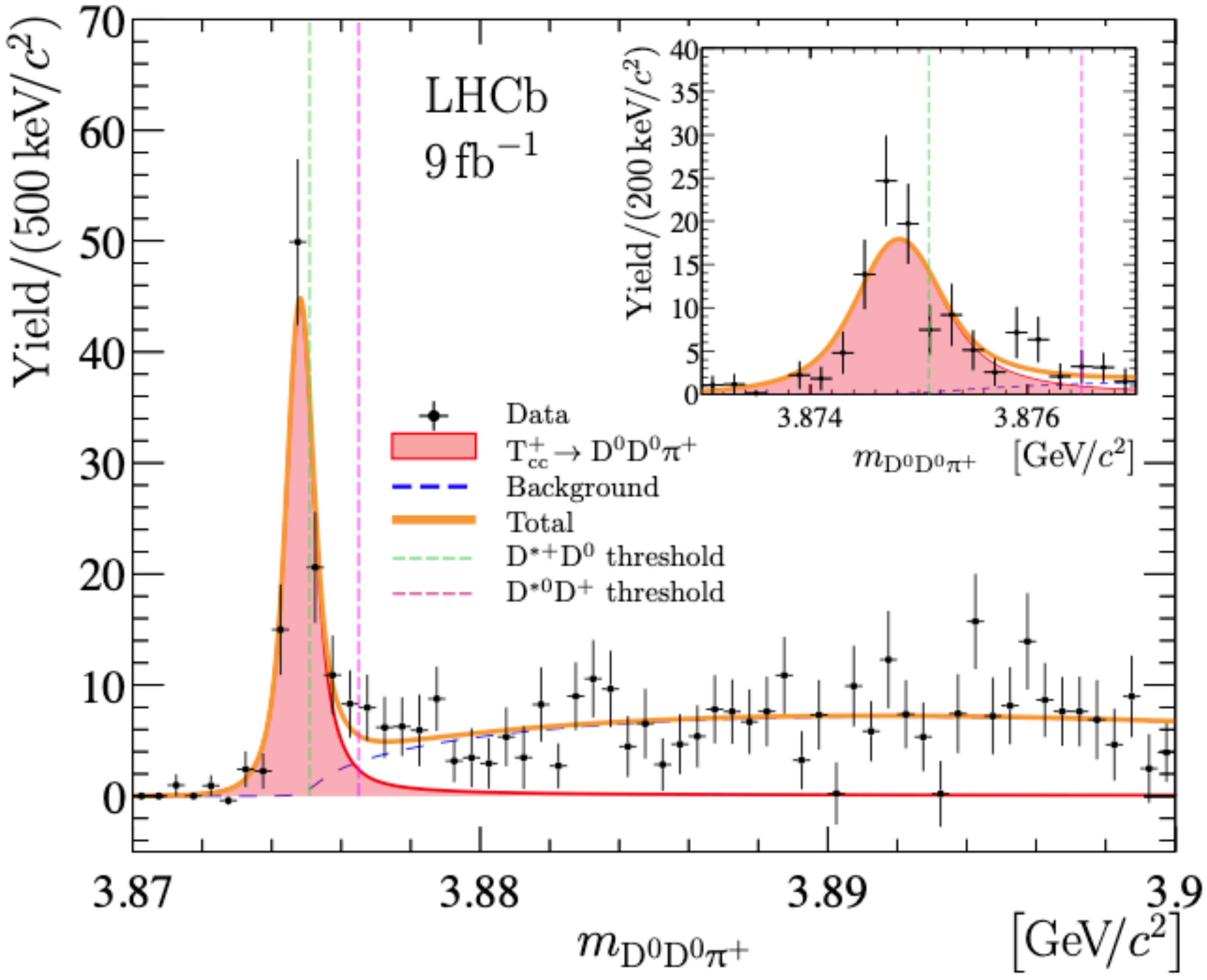
Expected $J^P = 1^+$

- The statistical significance is estimated using Wilks' theorem, it is found to be 22σ.

- A more sophisticated model is used to determine the properties of T_{cc}^{+}, more information can be found here: arXiv:2109.01056

$$\delta m_{pole} = -360 \pm 40^{+4}_{-0}\ \mathrm{keV/c^2}$$

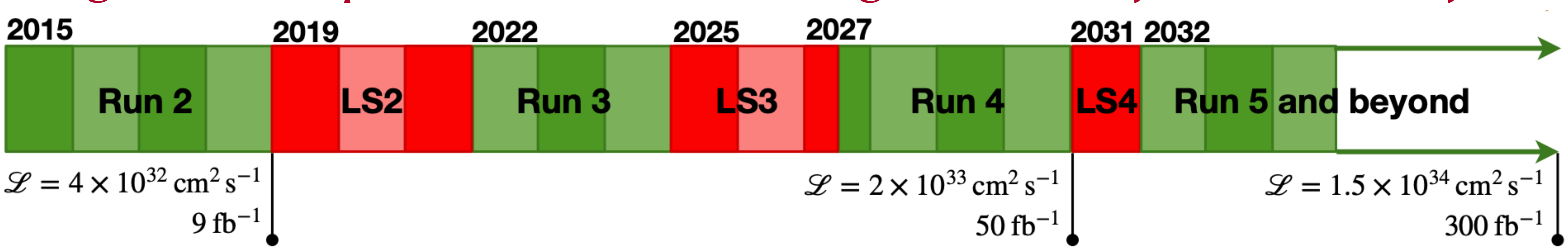
$$\Gamma_{pole} = 48 \pm 2^{+0}_{-14}\ \mathrm{keV}$$



Summary

- Lots of new particles and excited states have been discovered at LHCb!
  - Including the tetraquarks $X(4685)$, $X(4150)$, $X(4630)$, $Z_{cs}(4000)^+$, $Z_{cs}(4220)^+$ and T_{cc}^+.
- 1^+ assignment favoured for new $X(4685)$ state, $Z_{cs}(4000)^+$ state determined to be 1^+ and $Z_{cs}(4220)^+$ could be 1^+ or 1^-
- Evidence found for a pentaquark like state at a mass of $4337^{+7}_{-4} \pm 2$ MeV.
- 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 a significance of 3.5σ.

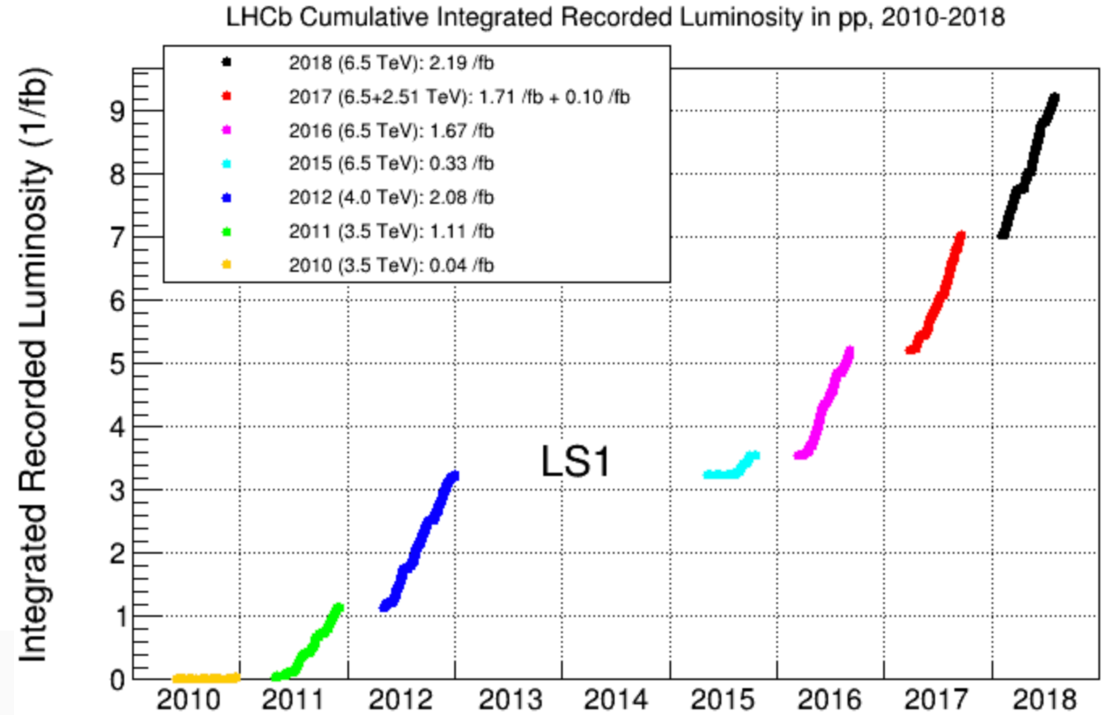
In the LHCb upgrade we plan to collect about 50 fb⁻¹ of data by 2030, further searches with larger data samples should increase the signal sensitivity for these decay modes!



Thanks for Listening!

Backup

The LHCb Detector

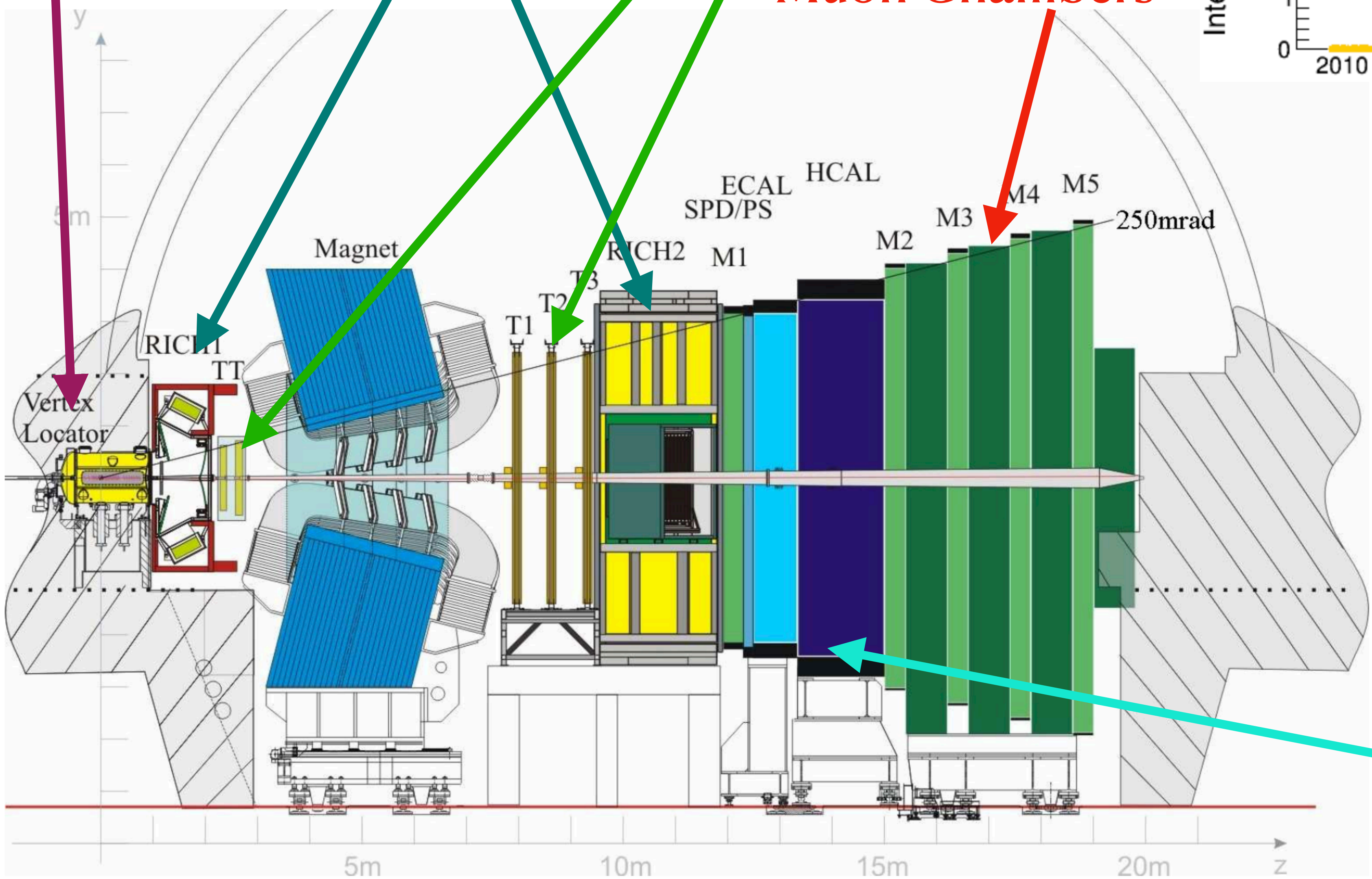


Ring Imaging Cherenkov Detectors (RICH)

Trackers

Vertex Locator

Muon Chambers



Calorimeters

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

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.

$\Lambda_b(5920)^0$
$\Lambda_b(5912)^0$
$\Lambda_b(6072)^0$
$\Lambda_b(6146)^0$
$\Lambda_b(6152)^0$

$\Lambda_b^0\pi^+\pi^-$

- 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

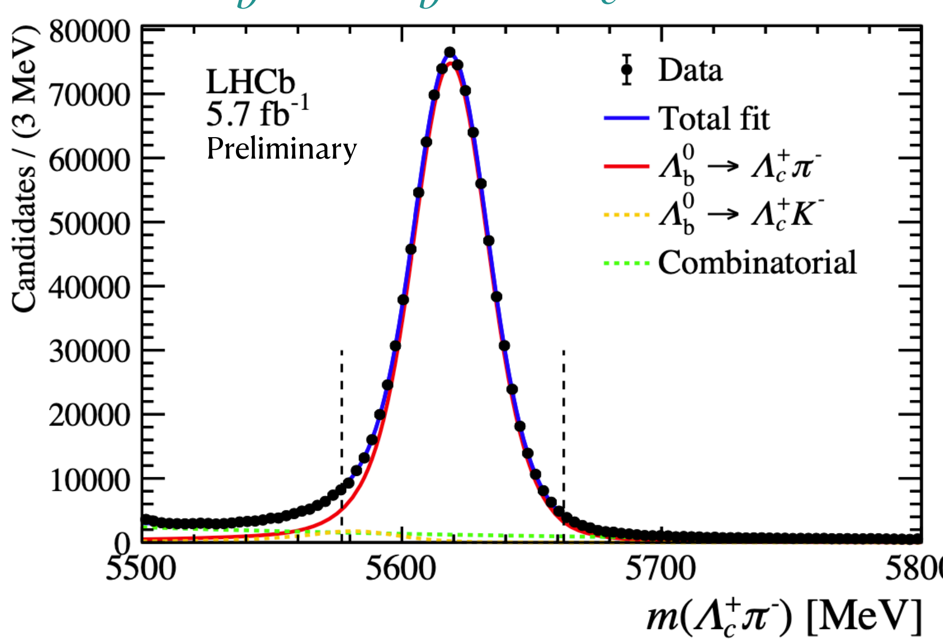
$\Xi_b(6227)^- \to \Lambda_b^0 K^-$ $\quad$ $\Xi_b(6227)^- \to \Xi_b^0 \pi^-$ $\quad$ $\Xi_b(6227)^0 \to \Xi_b^- \pi^+$

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

Phys. Rev. Lett. 126 (2021) 252003

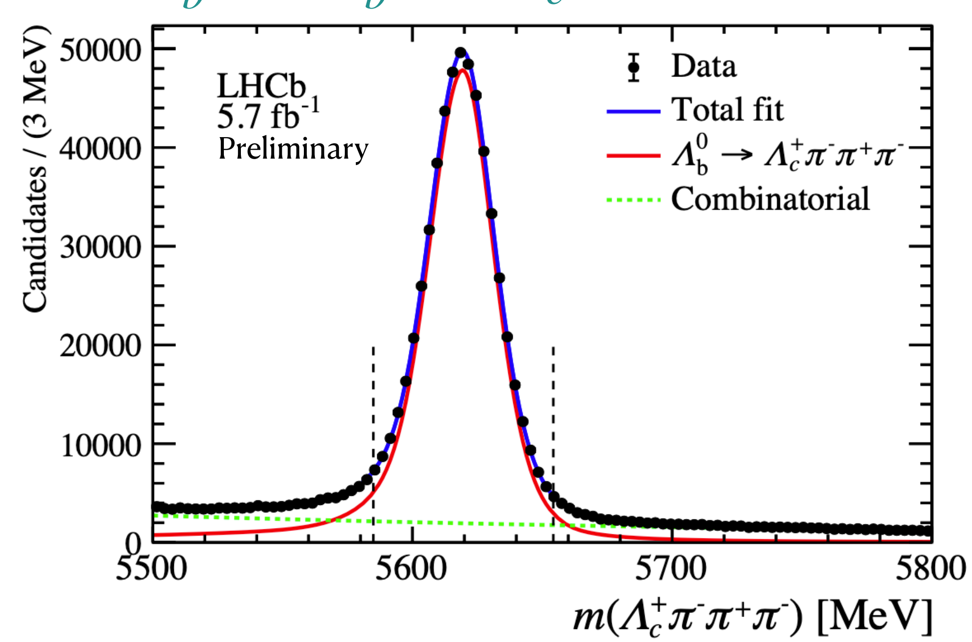
- Two 1D Ξ_b^0 states are predicted with decays dominated by the $\Sigma_b^{(*)}K$ and $\Xi_b^{*,\prime}\pi$ modes.

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



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

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

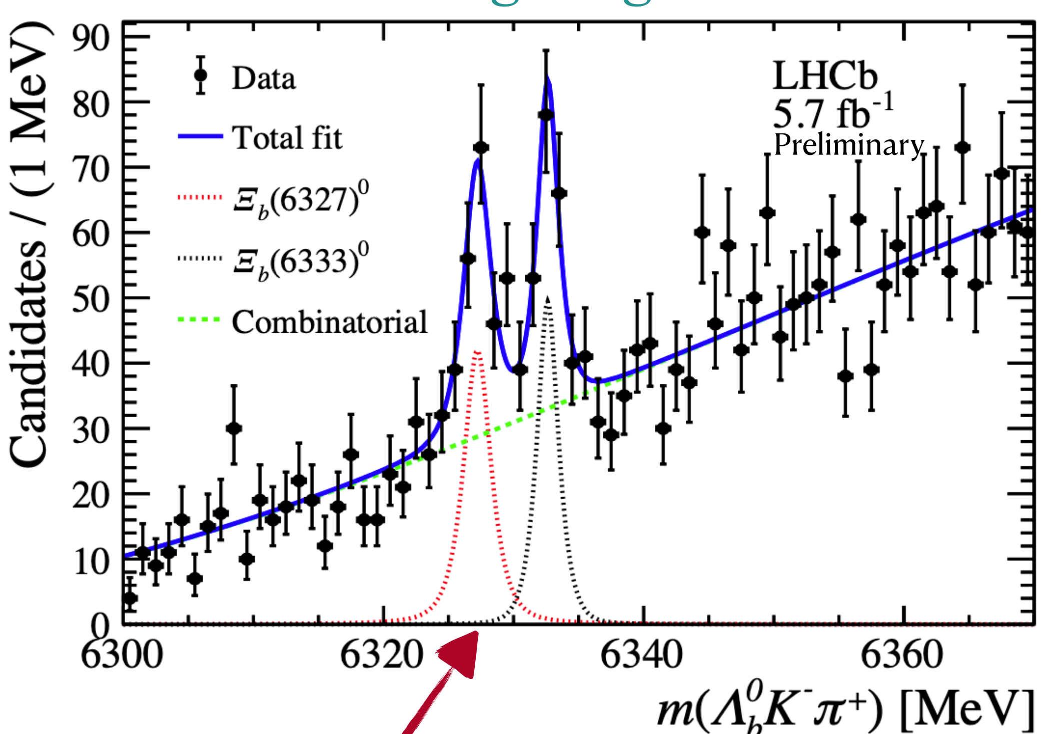


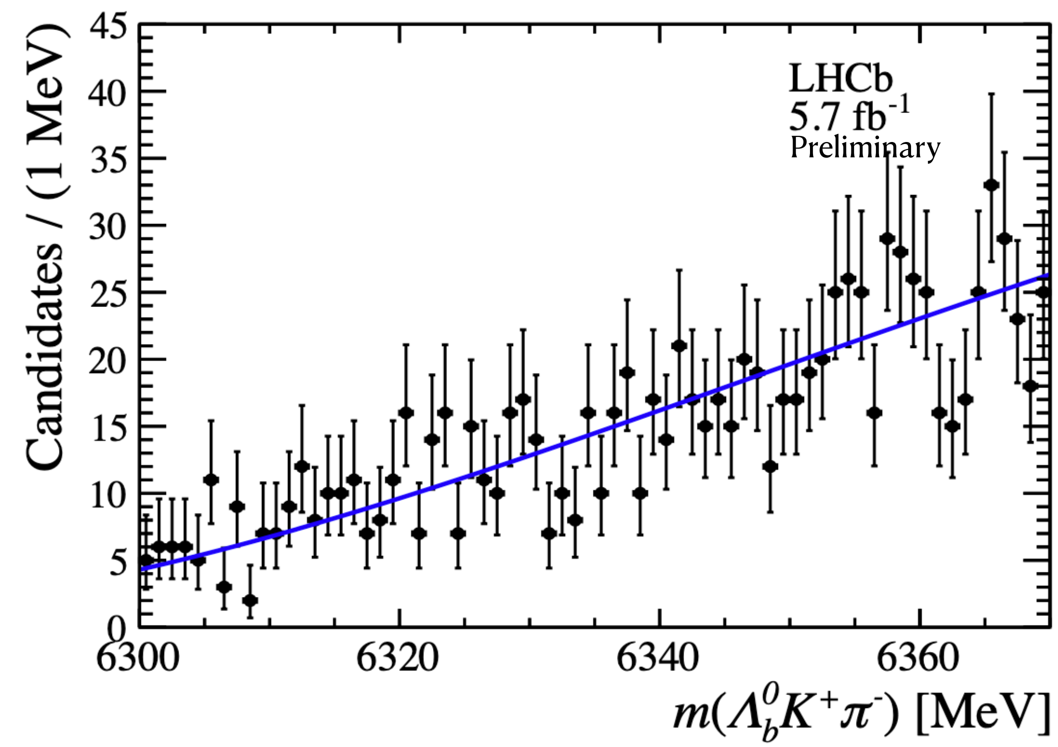
$N(\Lambda_c^+\pi^-\pi^+\pi^-) = (595.9 \pm 3.3) \times 10^3$

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.

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

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

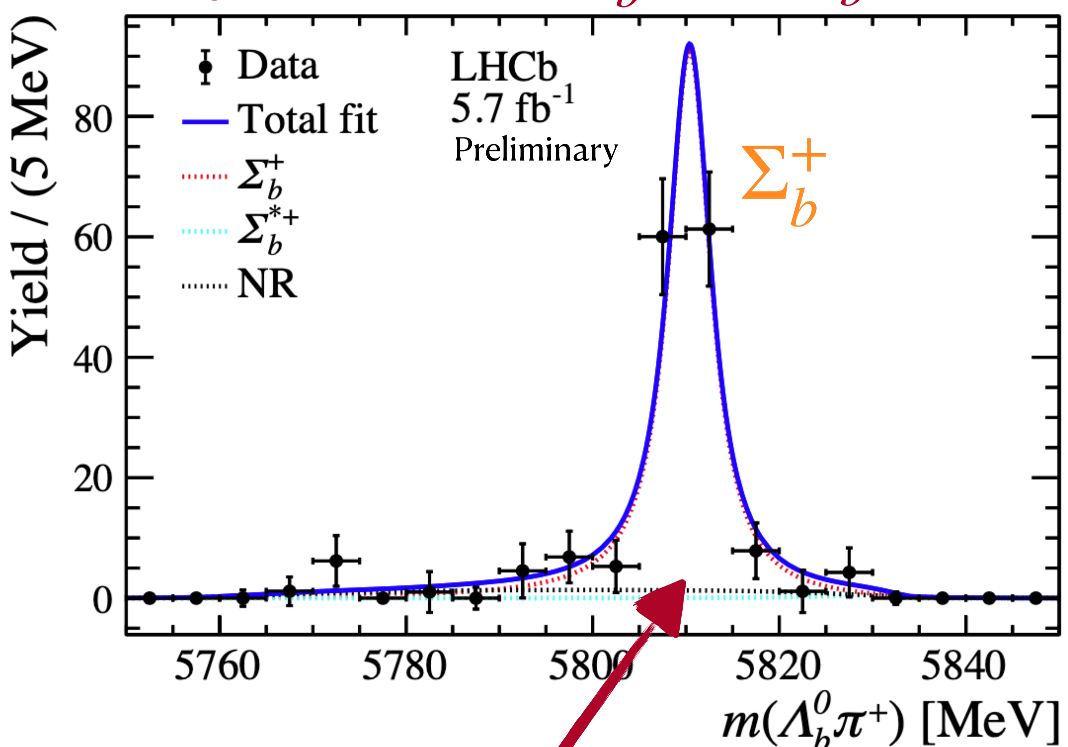
- Statistical significance of two peaking structures is 9.3σ.

Observation of the excited Ξ_b^0 states

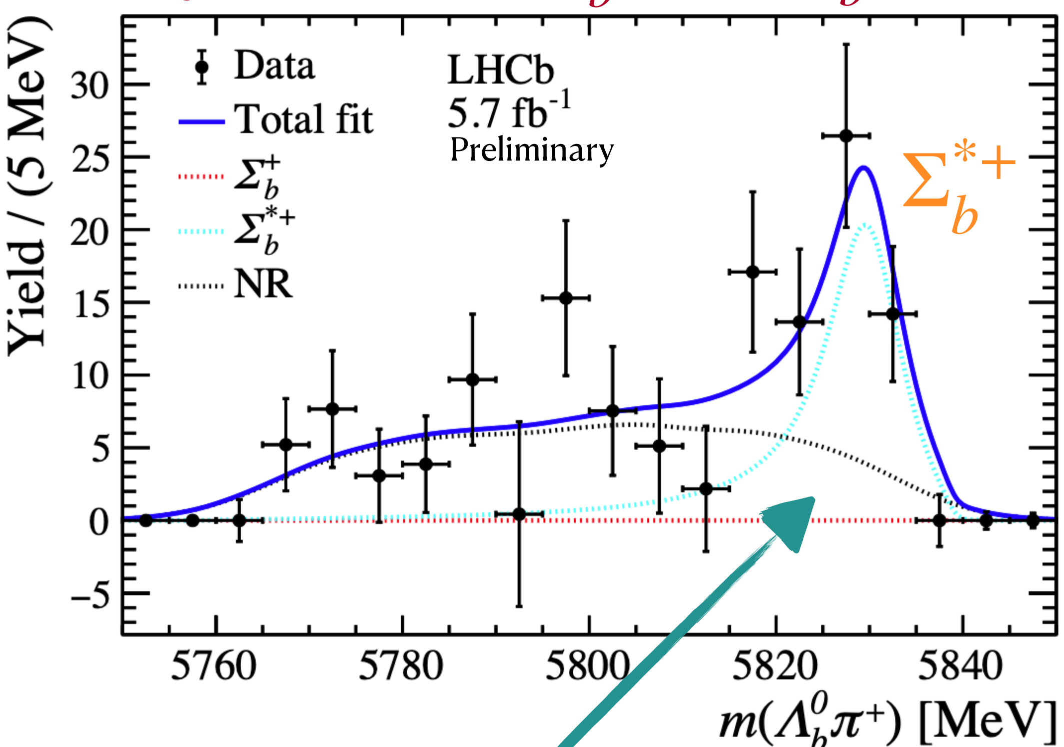
- Resonance structures in excited Ξ_b^0 decays are studied by performing many $\Lambda_b^0 K^- \pi^+$ mass fits in 5 MeV wide slices of the $\Lambda_b^0 \pi^+$ mass spectrum.
- Mass and width parameters of the two Ξ_b^0 states are fixed to the nominal fit values.

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

$\Xi_b(6327)^0 \to \Sigma_b^+(\to \Lambda_b^0 \pi^+) K^-$



$\Xi_b(6333)^0 \to \Sigma_b^{*+}(\to \Lambda_b^0 \pi^+) K^-$



$\Sigma_b^+ \to \Lambda_b^0 \pi^+$ 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.

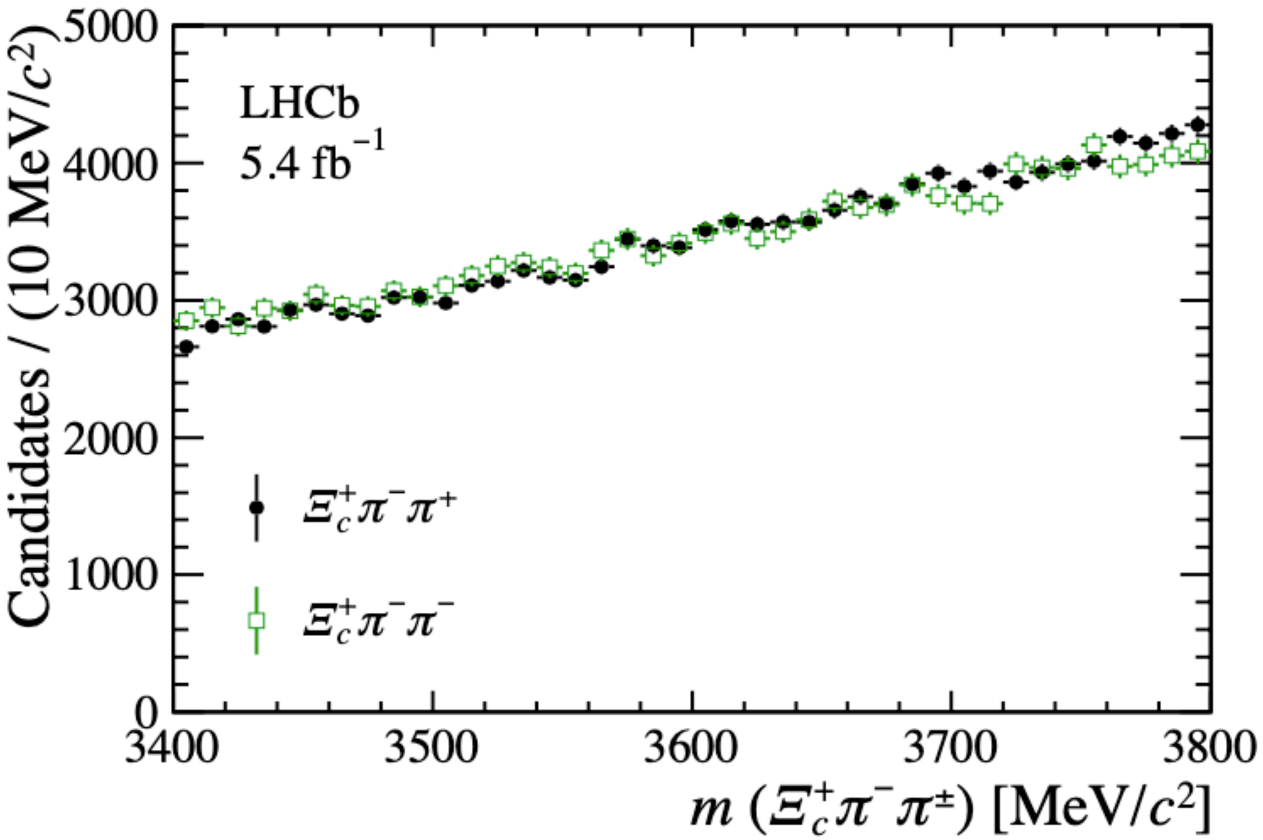
Search for the doubly charmed baryon Ξ_{cc}^{+} in the $\Xi_c^{+}\pi^{-}\pi^{+}$ final state

Search for the doubly charmed baryon Ξ_{cc}^{+}

- First evidence of Ξ_{cc}^{+} was reported by the SELEX collaboration in the $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$ and $\Xi_{cc}^{+} \to pD^+K^-$ decays, future searches by the FOCUS, BaBar, and Belle experiments show no evidence for this baryon. The LHCb collaboration performed a search for the Ξ_{cc}^{+} baryon in $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$ decays, no significant signal was observed.

- In 2017 the first observation of the Ξ_{cc}^{++} baryon in the $\Lambda_c^+ K^- \pi^+ \pi^+$ invariant mass spectrum, it was later confirmed in the $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ decay.

Signal decay: $\Xi_{cc}^{+} \to \Xi_c^+ \pi^- \pi^+$



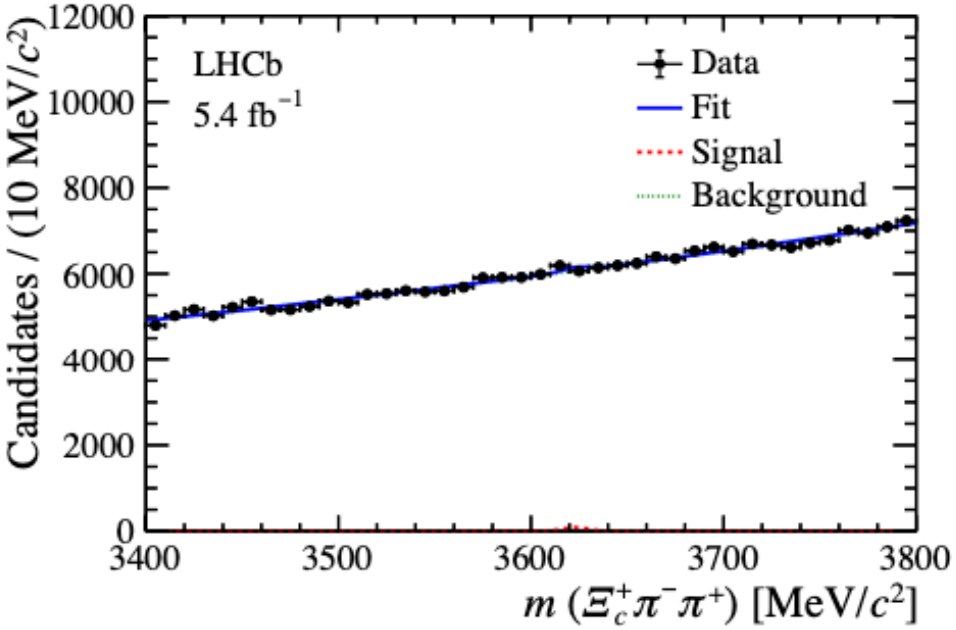
Normalisation mode: $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$

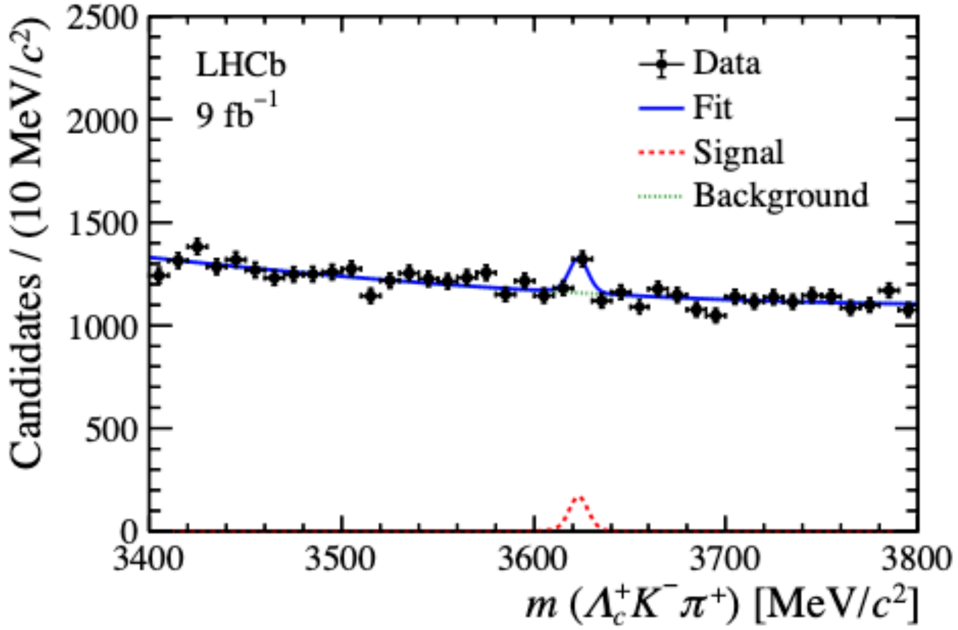
$$R = \frac{\epsilon_{norm}}{\epsilon_{sig}} \frac{N_{sig}}{N_{norm}}$$

- No significant signal excess is seen.

- This mass spectrum is used to evaluate the upper limit on R.

Search for the doubly charmed baryon Ξ_{cc}^{+}





- Combine results with the search in the $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$ decay.

Combined local and global significance is 4.0σ and 2.9σ respectively (at a mass of 3623 MeV).

- Curves determined by generating 3×10^5 pseudoexperiments.
- Mass of Ξ_{cc}^{+} range from 3400 – 3800 MeV in steps of 2 MeV for four lifetime hypotheses.
- R varies between 2 and 5 at 95 % CL.