Spectroscopy and decays of b-hadrons at LHCb

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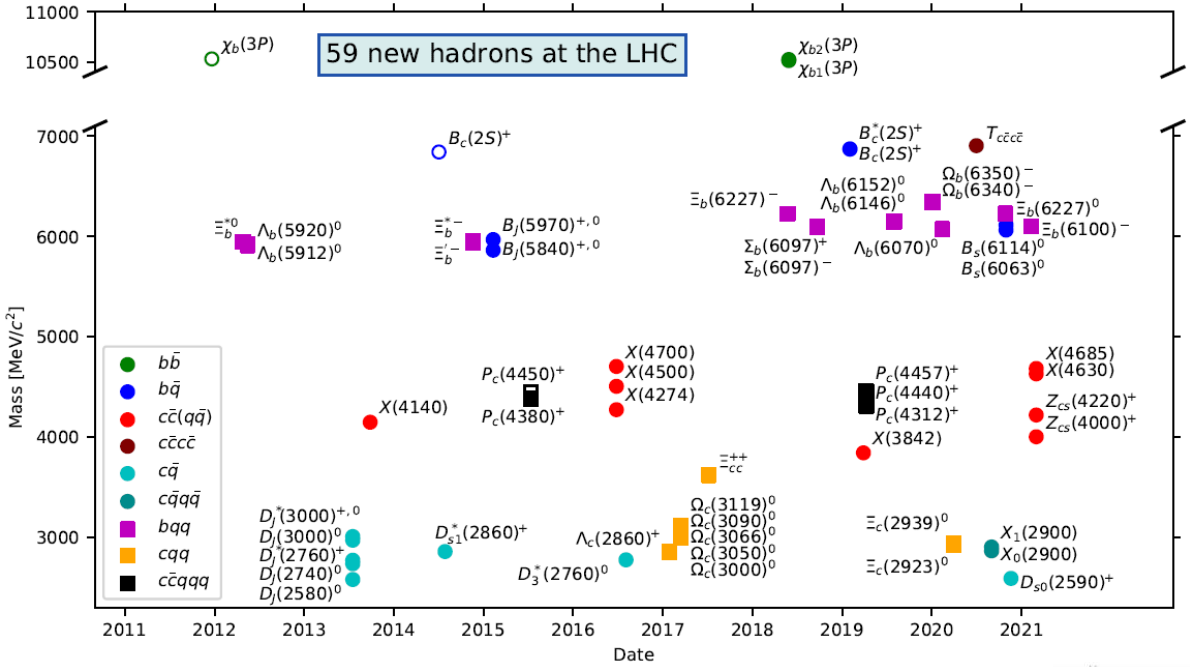
On behalf of LHCb collaboration

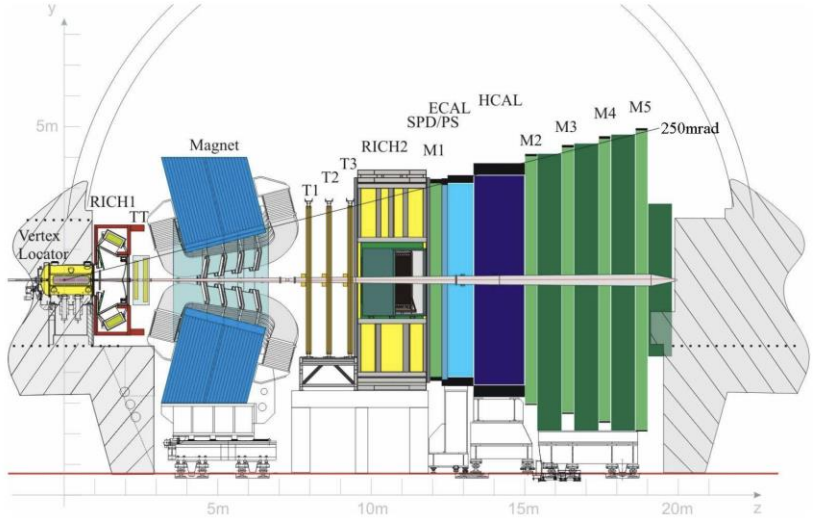
Introduction

lhcb-outreach.web.cern.ch/2021/03/03/lhc-as-a-large-hadron-discovery-factory



- Over the past 10 years the LHC has discovered 59 new hadrons, mainly from LHCb.
- Studying heavy flavour spectroscopy allows us to further our understanding of how conventional hadrons, tetraquarks and pentaquarks are formed.

- Single arm forward spectrometer covering the range $2 < \eta < 5$
- Very good particle identification and tracking
- b-factory: $\sigma_{b\bar{b}} = 144 \pm 21\ \mu b^{-1}$ $(\sqrt{s} = 13\ \text{TeV})$



Outline

- Observation of the decay $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$

  Phys. Rev. Lett. 128, 191803.

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

  Phys. Rev. Lett. 128, 162001.

- Study of the B_c^+ decays into charmonia and three light hadrons

  JHEP 01 (2022) 65

Observation of the decay $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$

arXiv:2201.03497

Published in Phys. Rev. Lett. 128, 191803.

Observation of the decay $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$

- $\mathcal{R}(D^{*+}) \equiv \mathcal{B}(\bar{B}^0 \to D^{*+}\tau^- \bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^- \bar{\nu}_\mu)$ have been measured by LHCb using $\tau^- \to \pi^+\pi^-\pi^-(\pi^0)\nu_\tau$. [Phys. Rev. D 97, 072013 (2018).]
- $\mathcal{R}(\Lambda_c^+) \equiv \mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\tau^- \bar{\nu}_\tau)/\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^- \bar{\nu}_\mu)$ have very precise theory predictions ($\mathcal{R}(\Lambda_c^+) = 0.324 \pm 0.004$) in SM frame. [Phys. Rev. Lett. 121 (2018) 202001.]

- Normalization mode $\Lambda_b^0 \to \Lambda_c^+\pi^+\pi^-\pi^-$ is used to determine the ratio of branching fractions:

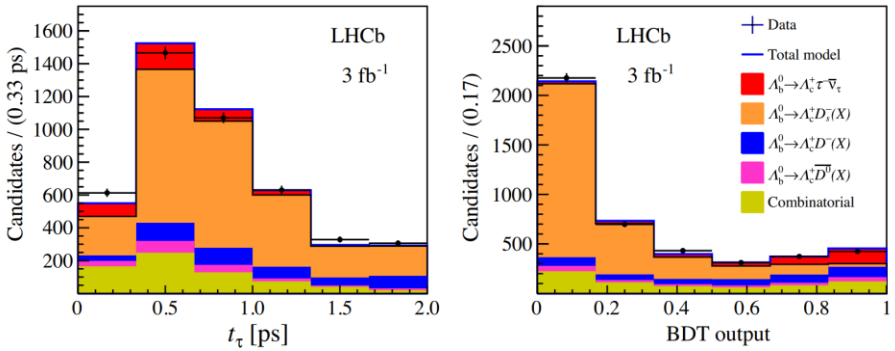
$$\kappa(\Lambda_c^+) = \mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\tau^- \bar{\nu}_\tau)/\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^+\pi^-\pi^-)$$

- Using $\tau^- \to \pi^+\pi^-\pi^-(\pi^0)\nu_\tau$

Observation of the decay $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$

- 3D (q^2, τ, BDT output) binned maximum-likelihood fit to extract signal yield

Phys. Rev. Lett. 128, 191803.



t_τ: lifetime of τ

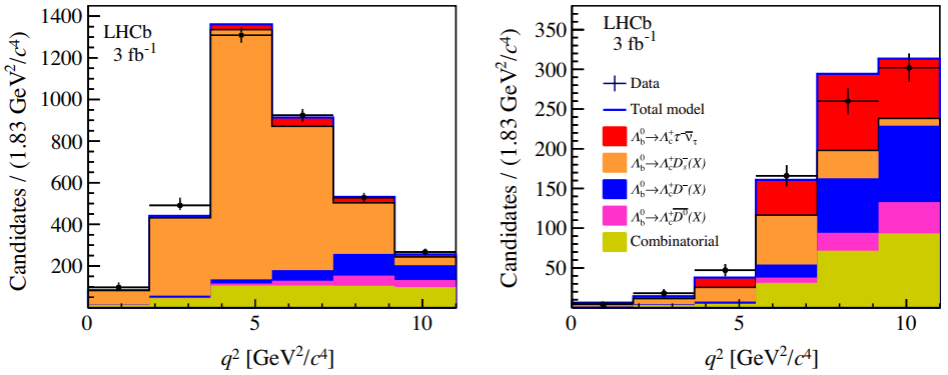
BDT: trained with 15 variables, related to partial reconstruction, isolation techniques, the three π system internal dynamics and kinematics

$$q^2 : m^2(\tau^- \bar{\nu}_\tau) = \left(p_{\Lambda_b^0} - p_{\Lambda_c^+}\right)^2$$

Missing the momentum of $\bar{\nu}_\tau$

$p_{\Lambda_b^0}$ is reconstructed with resolution about 7%

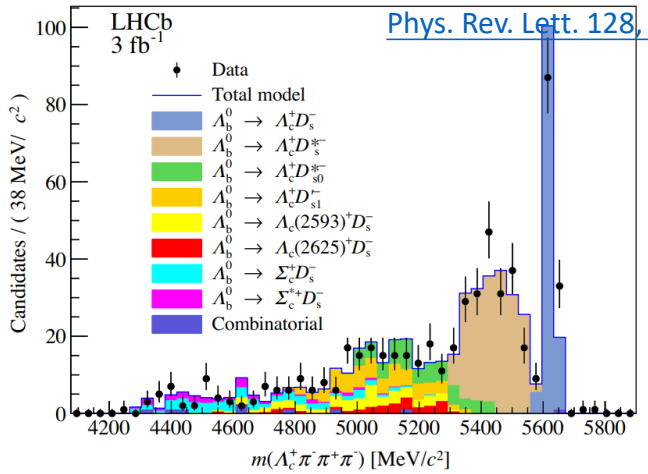
Phys. Rev. Lett. 128, 191803.



Distribution of q^2 with BDT output below(left) and above(right) 0.66

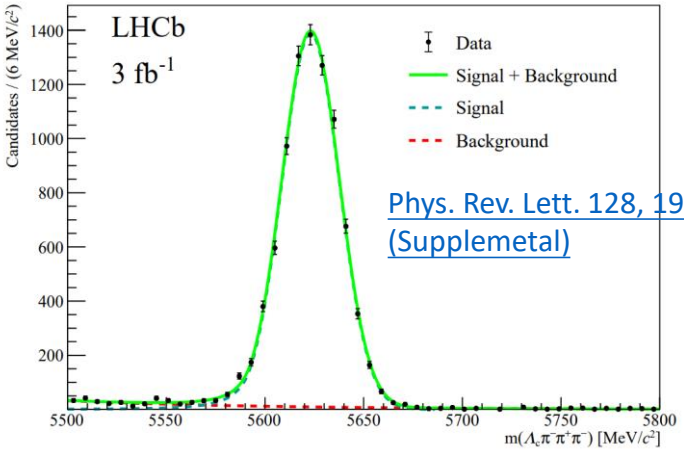
Observation of the decay $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$

- Background $\Lambda_b^0 \to \Lambda_c^+ D_s^- (X)$ is obtained from fit to $m(\Lambda_c^+ \pi^+ \pi^- \pi^-)$ which require $|m(\pi^+ \pi^- \pi^-) - m(D_s^-)| < 45\ \mathrm{MeV}/c^2$.
- The results are used to constrain the relative yields of $\Lambda_b^0 \to \Lambda_c^+ D_s^- (X)$ in 3D fit



Phys. Rev. Lett. 128, 191803.

- Yields of normalization mode $\Lambda_b^0 \to \Lambda_c^+ \pi^+ \pi^- \pi^-$ is obtained with fit to $m(\Lambda_c^+ \pi^+ \pi^- \pi^-)$
- Λ_b^0 signal described with Crystal Ball function



Phys. Rev. Lett. 128, 191803. (Supplemetal)

- Results
- $\kappa(\Lambda_c^+) = 2.46 \pm 0.27 \pm 0.40$
- $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau) = (1.50 \pm 0.16 \pm 0.25 \pm 0.23)\%$
- $\mathcal{R}(\Lambda_c^+) = 0.242 \pm 0.026 \pm 0.040 \pm 0.059$, lower than but agree with SM prediction

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

arXiv:2110.04497

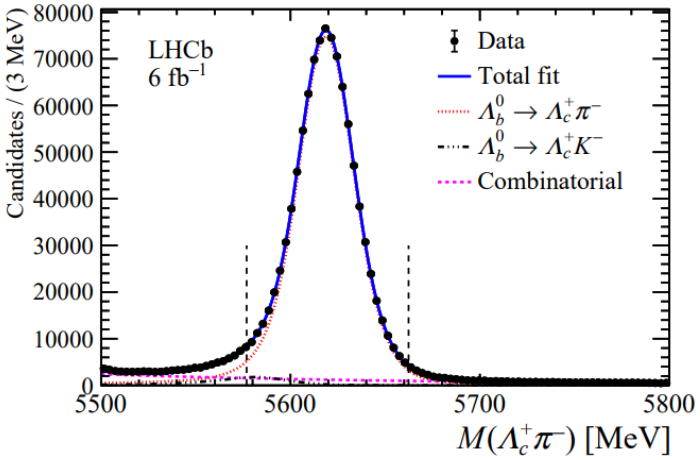
Published in Phys. Rev. Lett. 128, 162001.

Observation of two new excited Ξ_b^0 states

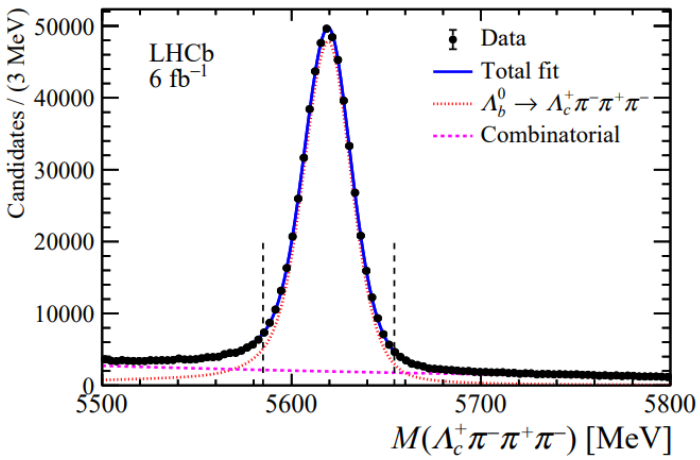
- Several excited Λ_b^0 states have been observed, leading to the investigation of the excited Ξ_b states due to their similar properties.
- Recently the LHCb collaboration reported the observation of the $\Xi_b(6227)^-$ [Phys. Rev. Lett. 121, 072002] and $\Xi_b(6227)^0$ [Phys. Rev. D 103, 012004]

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

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



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

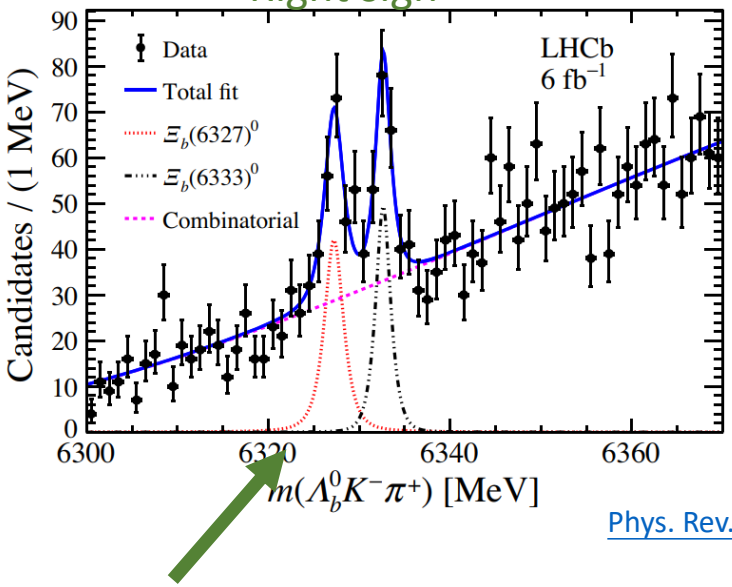


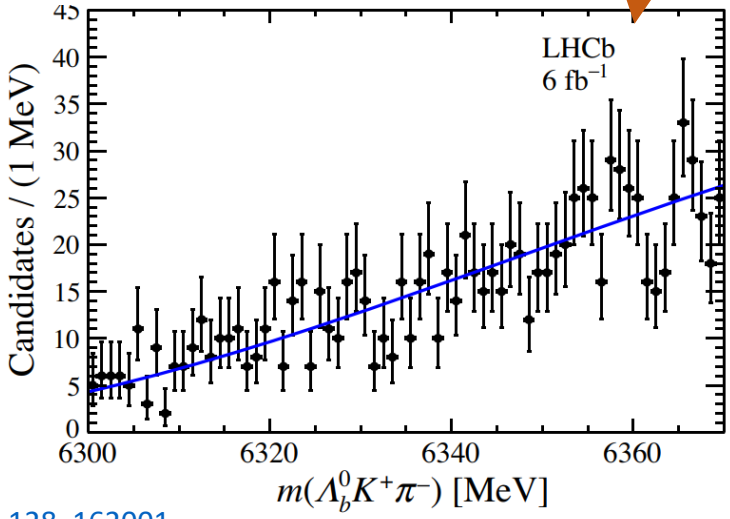
Phys. Rev. Lett. 128, 162001

Observation of two new 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 combinatorial background, the wrong sign candidates are reconstructed with a $\Lambda_b^0 K^- \pi^+$ final state.

Right sign





Phys. Rev. Lett. 128, 162001

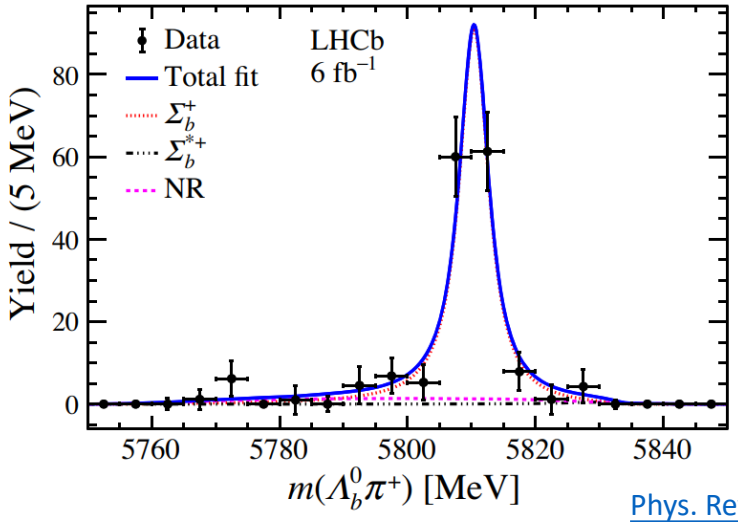
Peaks modelled by relativistic Breit-Wigner function convolved with a resolution function.

$$m_{\Xi_b(6327)^0} = 6327.26^{+0.23}_{-0.21} \pm 0.08 \pm 0.24 \text{ MeV}$$
$$m_{\Xi_b(6333)^0} = 6332.67^{+0.17}_{-0.18} \pm 0.03 \pm 0.22 \text{ MeV}$$

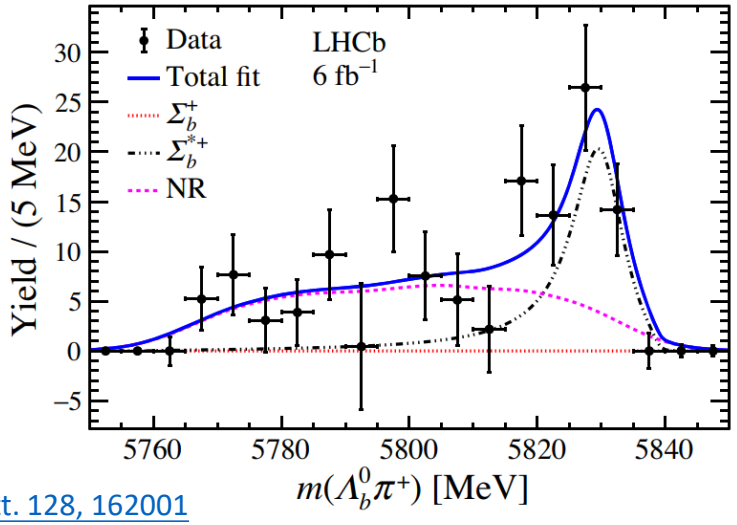
Observation of two new excited Ξ_b^0 states

- Resonance structures in excited Ξ_b^0 decays are studied by mass fits to data samples in 5 MeV slices of the $m(\Lambda_b^0\pi^+)$
- Mass and width parameters of the two Ξ_b^0 states are fixed to the nominal fit values.

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



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



Phys. Rev. Lett. 128, 162001

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

$\Sigma_b^{*+} \to \Lambda_b^0\pi^+$ contributes to part of $\Xi_b(6333)^0$, and no resonances part contributes a lot

- Resonance structures consistent with the theoretical predictions of a doublet of 1D Ξ_b^0 states with $J^P = 3/2^+$ and $5/2^+$ [Phys. Rev. D 100, 094032] [Phys. Rev. D 98, 076015]

Study of the B_c^+ decays into charmonia and three light hadrons

arXiv:2111.03001

Published in JHEP 01 (2022) 65

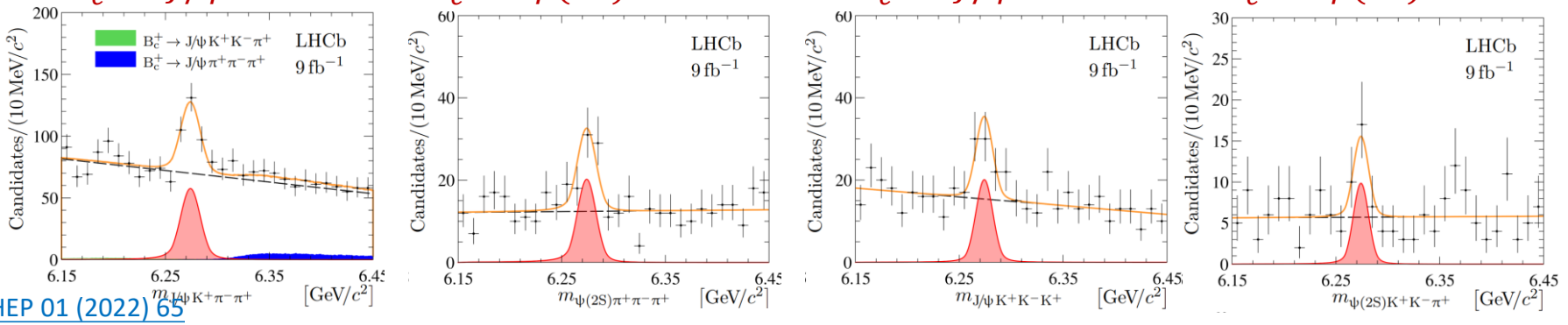
Study of the $B_c^+ \to \psi 3h$

- Only 3 decay modes of $B_c^+ \to \psi 3h$ are seen on LHCb previously

  [Phys. Rev. Lett. 108, 251802] [Phys. Rev. Lett. 113, 152003] [JHEP11(2013)094]

- 4 decay modes of $B_c^+ \to \psi 3h$ are first observed

$B_c^+ \to J/\psi K^+\pi^-\pi^+$ $B_c^+ \to \psi(2S)\pi^+\pi^-\pi^+$ $B_c^+ \to J/\psi K^+K^-K^+$ $B_c^+ \to \psi(2S)K^+K^-\pi^+$



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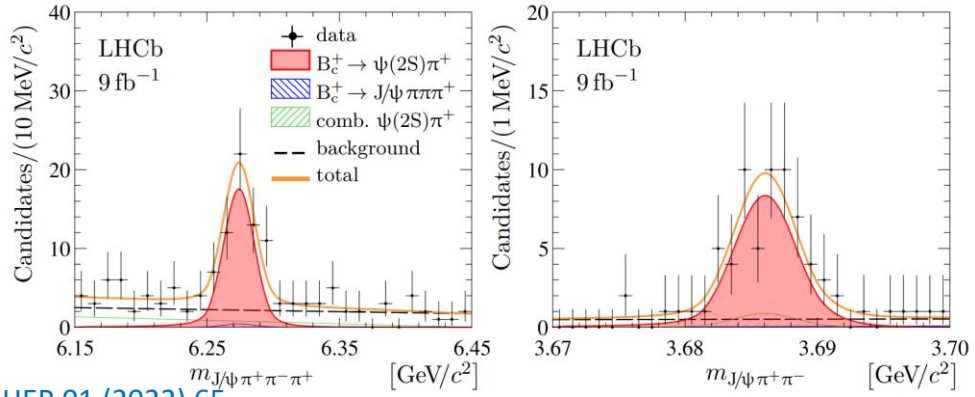
- $B_c^+ \to \psi(2S)(\to J/\psi\pi^+\pi^-)\pi^+$ first observed through $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$



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Decay	Yield	$\mathcal{S}$ [σ]
$B_c^+ \to J/\psi\pi^+\pi^-\pi^+$	2750 ± 69	
$B_c^+ \to J/\psi K^+K^-\pi^+$	686 ± 48	
$B_c^+ \to J/\psi K^+K^-K^+$	43 ± 10	5.2
$B_c^+ \to J/\psi K^+\pi^-\pi^+$	148 ± 22	7.8
$B_c^+ \to \psi(2S)\pi^+\pi^-\pi^+$	49 ± 11	5.8
$B_c^+ \to \psi(2S)K^+K^-\pi^+$	19 ± 6	3.7
$B_c^+ \to (\psi(2S) \to J/\psi\pi^+\pi^-)\pi^+$	54 ± 9	11.8
Parameter	**Value**	
$m_{B_c^+}$ [MeV/c^2]	6274.14 ± 0.26	
$m_{\psi(2S)}$ [MeV/c^2]	3686.05 ± 0.01	

Study of the $B_c^+ \to \psi 3h$

- Resonance structures in $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$

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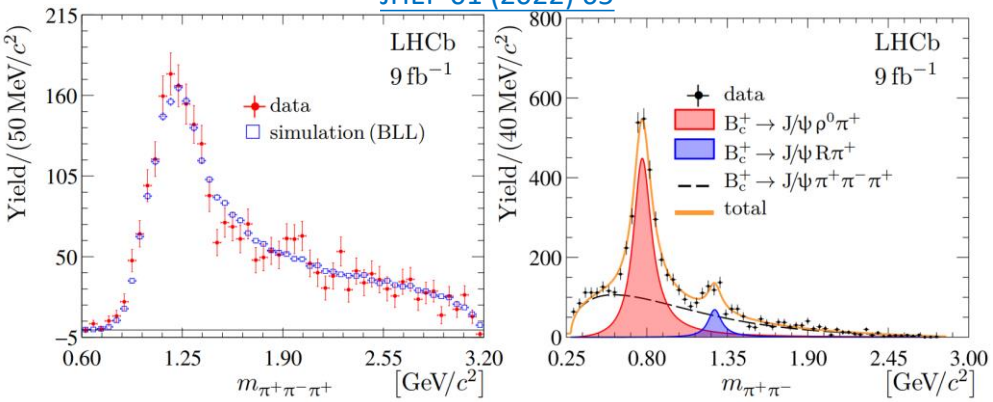

Parameter		Value
$f_{\rho^0}^{B_c^+\to J/\psi\pi^+\pi^-\pi^+}$	[%]	88.1 ± 3.0
$f_R^{B_c^+\to J/\psi\pi^+\pi^-\pi^+}$	[%]	10.4 ± 1.4
m_R	[MeV/c^2]	1265 ± 10
Γ_R	[MeV]	110 ± 21
$\mathcal{S}_R$	[σ]	8

- Structure near $m_{\pi^+\pi^-} \sim 1.3$ GeV/c^2: referred to as R
- The obtained mass, width and fraction of R is consistent with those for $a_1(1260)^+ \to f_0(1370)(\to \pi^+\pi^-)\pi^+$ obtained by CLEO Phys. Rev. D 61 (2000) 012002
- Resonance structures in $B_c^+ \to J/\psi K^+K^-\pi^+$

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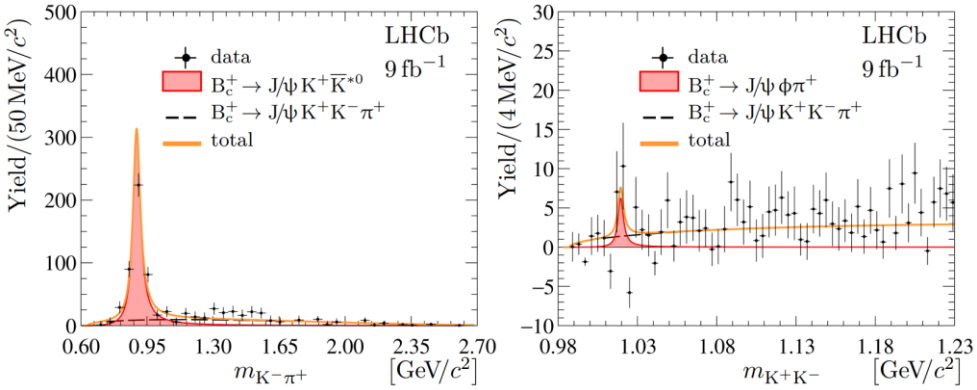


$$f_{\overline{K}^{*0}}^{B_c^+\to J/\psi K^+K^-\pi^+} = \left(64.5 \pm 4.7^{+3.9}_{-4.8}\right)\%$$

$$f_{\phi}^{B_c^+\to J/\psi K^+K^-\pi^+} < 4.2\,(4.8)\%$$

Gaussian constraints to the PDG values for the width and mass of $\overline{K}^{*0}$ and ϕ are used

Study of the $B_c^+ \to \psi 3h$

- Ratios of branching fractions from this measurement are compared with theory and previous experiments

Ratio	Value	Prediction, measurement
$\mathcal{R}^{\psi(2S)K^+K^-\pi^+}_{\psi(2S)\pi^+\pi^-\pi^+}$	$0.37 \pm 0.15 \pm 0.01$	0.16
$\mathcal{R}^{J/\psi K^+\pi^-\pi^+}_{J/\psi K^+K^-\pi^+}$	$0.35 \pm 0.06 \pm 0.01$	0.37
$\mathcal{R}^{J/\psi K^+\pi^-\pi^+}_{J/\psi \pi^+\pi^-\pi^+}$	$(6.4 \pm 1.0 \pm 0.2) \times 10^{-2}$	7.7×10^{-2}
$\mathcal{R}^{J/\psi K^+K^-\pi^+}_{J/\psi \pi^+\pi^-\pi^+}$	$0.185 \pm 0.013 \pm 0.006$	0.21
$\mathcal{R}^{\psi(2S)\pi^+}_{J/\psi K^+K^-\pi^+}$	$0.19 \pm 0.03 \pm 0.01$	0.18 ± 0.04
$\mathcal{R}^{\psi(2S)\pi^+}_{J/\psi \pi^+\pi^-\pi^+}$	$(3.5 \pm 0.6 \pm 0.2) \times 10^{-2}$	$(3.9 \pm 0.9) \times 10^{-2}$
$\mathcal{R}^{J/\psi K^+K^-\pi^+}_{J/\psi \pi^+\pi^-\pi^+}$	$0.185 \pm 0.013 \pm 0.006$	0.22 ± 0.06

	Value $[10^{-2}]$
$\mathcal{R}^{J/\psi K^+K^-K^+}_{J/\psi K^+K^-\pi^+}$	$7.0 \pm 1.8 \pm 0.2$
$\mathcal{R}^{J/\psi K^+\pi^-\pi^+}_{J/\psi \pi^+\pi^-\pi^+}$	$6.4 \pm 1.0 \pm 0.2$
$\frac{\mathcal{B}(B_c^+ \to J/\psi K^+)}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)}$	7.9 ± 0.8
$\frac{\mathcal{B}(B^+ \to \overline{D}^0 K^+\pi^-\pi^+)}{\mathcal{B}(B^+ \to \overline{D}^0 \pi^+\pi^-\pi^+)}$	9.3 ± 5.1
$\frac{\mathcal{B}(B^0 \to D^- K^+\pi^-\pi^+)}{\mathcal{B}(B^0 \to D^- \pi^+\pi^-\pi^+)}$	5.8 ± 1.5
$\frac{\mathcal{B}(B^0 \to D^{*-} K^+\pi^-\pi^+)}{\mathcal{B}(B^0 \to D^{*-} \pi^+\pi^-\pi^+)}$	6.5 ± 0.6
$\frac{\mathcal{B}(B_s^0 \to D_s^- K^+\pi^-\pi^+)}{\mathcal{B}(B_s^0 \to D_s^- \pi^+\pi^-\pi^+)}$	5.2 ± 1.3

- The ratios of branching fractions agree well with theory and previous experiments

Study of B_c^+ decays to charmonia and multihadron final states

LHCb-PAPER-2022-025

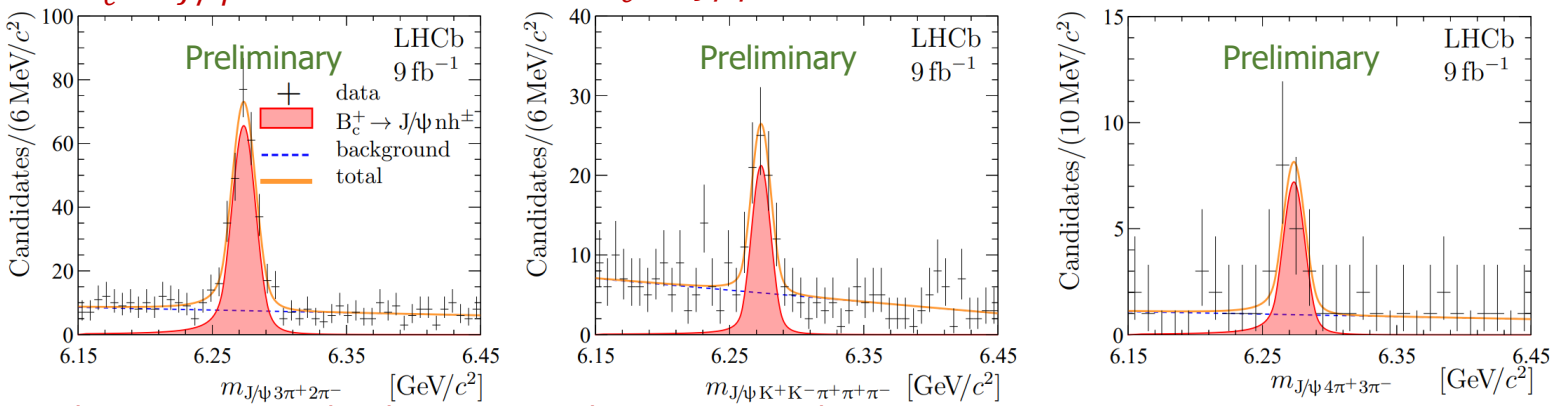
in preparation

Study of the $B_c^+ \to \psi 5h$

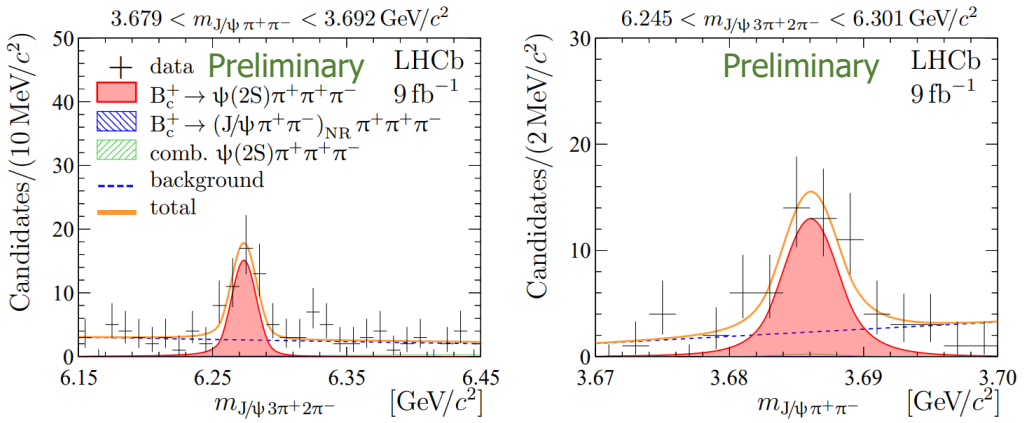
LHCb-PAPER-2022-025 in preparation

- $B_c^+ \to J/\psi K^+K^-\pi^+\pi^+\pi^-$ is first observed
- First evidence of $B_c^+ \to J/\psi 4\pi^+3\pi^-$ is obtained with significance of 4.7σ

$B_c^+ \to J/\psi 3\pi^+2\pi^-$ $B_c^+ \to J/\psi K^+K^-\pi^+\pi^+\pi^-$ $B_c^+ \to J/\psi 4\pi^+3\pi^-$



- $B_c^+ \to \psi(2S)\pi^+\pi^+\pi^-$ and $B_c^+ \to J/\psi 3\pi^+2\pi^-$ comfirmed



Decay	Yield	$\mathcal{S}$ [σ]
$B_c^+ \to J/\psi 3\pi^+2\pi^-$	268 ± 20	21.
$B_c^+ \to J/\psi K^+K^-\pi^+\pi^+\pi^-$	69 ± 11	9.1
$B_c^+ \to J/\psi 4\pi^+3\pi^-$	16 ± 5	4.9
$B_c^+ \to (\psi(2S) \to J/\psi\pi^+\pi^-)\pi^+\pi^+\pi^-$	40 ± 8	6.4

$$\mathcal{R}^{J/\psi K^+K^-\pi^+\pi^+\pi^-}_{J/\psi 3\pi^+2\pi^-} = (33.7 \pm 5.7 \pm 1.6) \times 10^{-2}$$

$$\mathcal{R}^{J/\psi 4\pi^+3\pi^-}_{J/\psi 3\pi^+2\pi^-} = (28.5 \pm 8.7 \pm 2.0) \times 10^{-2}$$

$$\mathcal{R}^{\psi(2S)\pi^+\pi^+\pi^-}_{J/\psi 3\pi^+2\pi^-} = (17.6 \pm 3.6 \pm 0.8) \times 10^{-2}$$

Summary

- Lots of new particles and excited states have been discovered at LHCb!
- Observation of the decay $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$
  - $\mathcal{R}(\Lambda_c^+) \equiv \mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)/\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)$ is determined and agree with SM prediction
- Observation of two new excited Ξ_b^0 states decaying to $\Lambda_b^0 K^- \pi^+$
  - New excited Ξ_b^0 states $\Xi_b(6327)^0$ and $\Xi_b(6333)^0$ are consistent with the theoretical predictions of 1D Ξ_b^0 states with $J^P = 3/2^+$ and $5/2^+$
- Study of the B_c^+ decays into charmonia and three light hadrons
  - Serval decay modes of $B_c^\pm \to \psi 3h$ are first observed
- Study of the $B_c^+ \to \psi 5h$
  - $B_c^+ \to J/\psi K^+ K^- \pi^+ \pi^+ \pi^-$ is first observed

Thanks for listening