



Observation of new excited heavy flavour hadrons at LHCb

牟宏杰 (Hongjie Mu)
Tsinghua University

中国物理学会高能物理分会第十三届全国粒子物理学学术会议 2021,
August 16, 2021

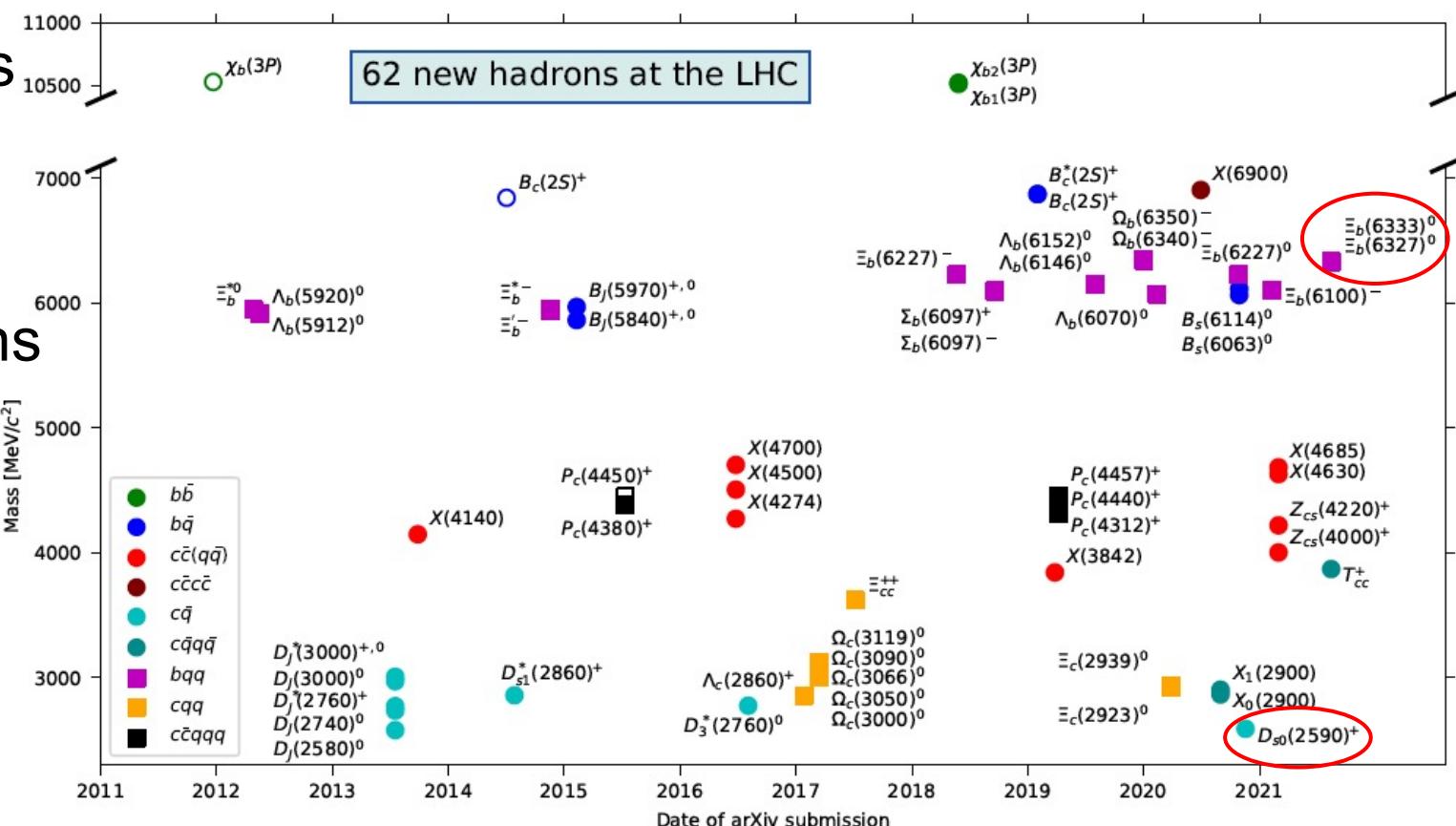
Introduction

➤ Study of heavy-hadron spectroscopy

helps to understand the hadronic
structure and how QCD works

➤ LHC observed 62 new hadrons

- 55 new hadrons at LHCb



[LHCb-FIGURE-2021-001]

[LHCb-PAPER-2021-025, in preparation]

[LHCb-PAPER-2021-031, in preparation]

Recent results of new heavy hadrons

➤ Observation of a new excited D_s^+ meson in $B^0 \rightarrow D^- D^+ K^+ \pi^-$

[PRL 126 (2021) 122002]

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

[LHCb-PAPER-2021-025, in preparation]

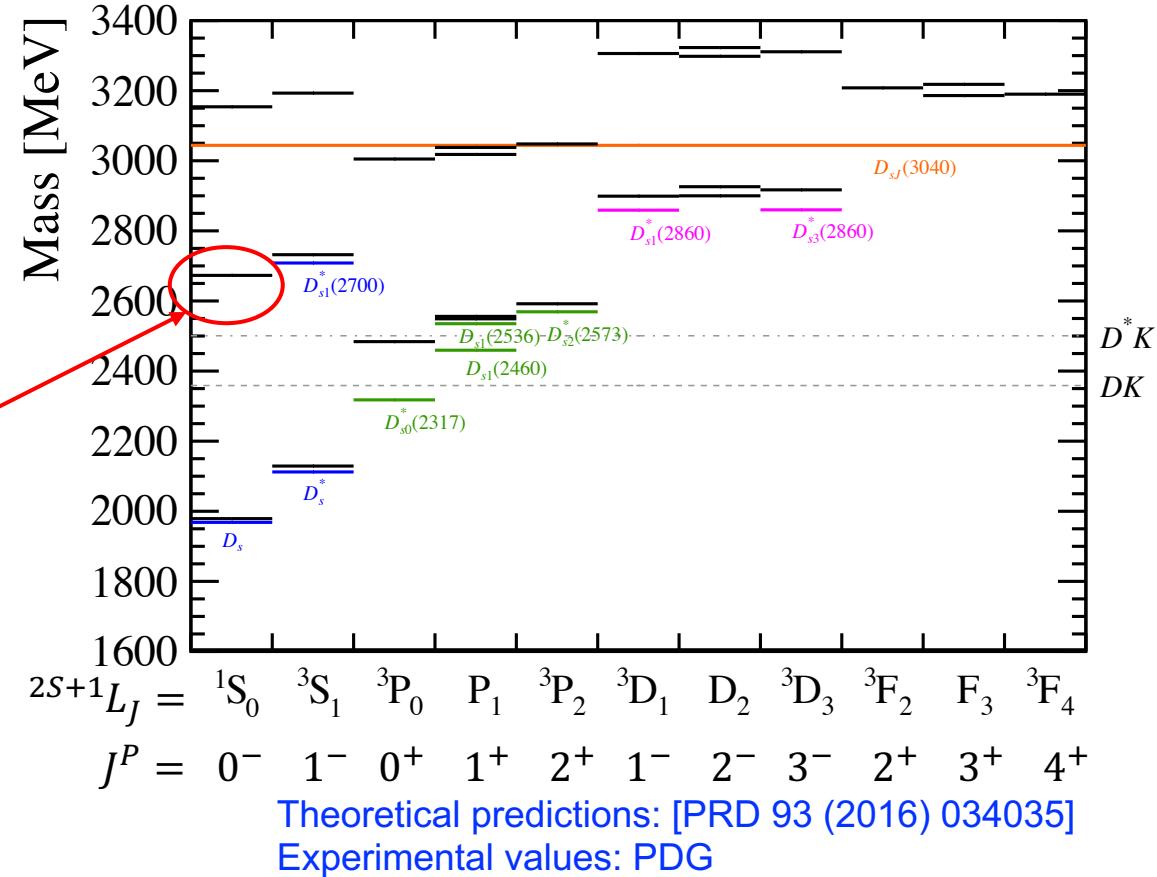
Observation of a new excited D_s^+ meson in $B^0 \rightarrow D^- D^+ K^+ \pi^-$

[PRL 126 (2021) 122002]

Motivation

➤ D_s^+ spectroscopy

- Nine states with spin-parity determined
- $D_{sJ}(3040)^+$ with unknown spin-parity
- Masses of $D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$ are much smaller than predictions
- Six states missing below 3.1 GeV
 - 2^1S_0 is expected to be the lightest

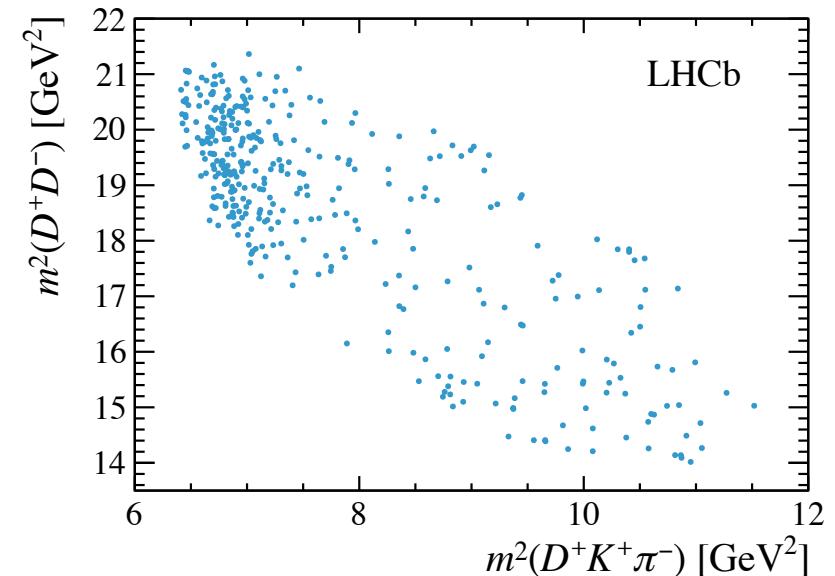
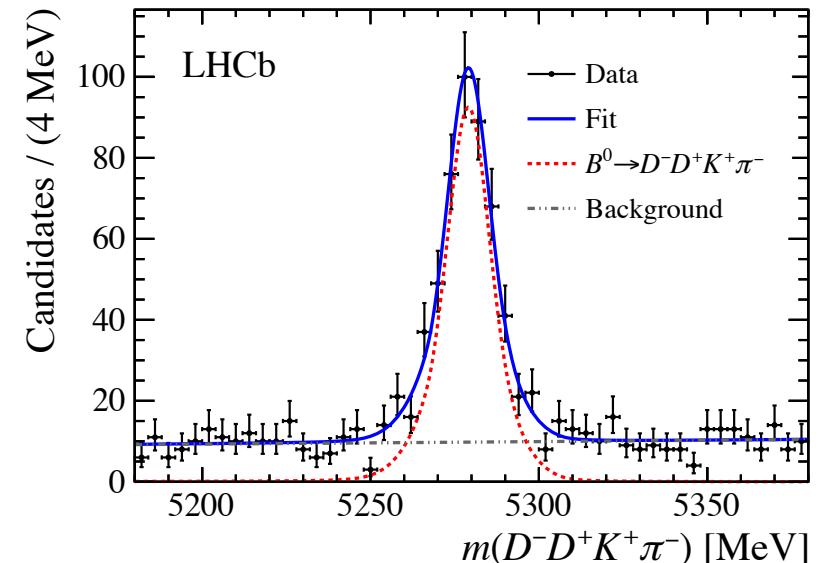


➤ Why $B^0 \rightarrow D^- D^+ K^+ \pi^-$?

- B -decays provide excellent potential for new D_s states search
 - $D_{s1}^*(2700)$, $D_{s1}^*(2860)$, $D_{s3}^*(2860)$ observed in DK system with natural spin-parity ($J^P = 0^+, 1^-, 2^+$, ...)
- Can access the unnatural spin-parity in $D^+ K^+ \pi^-$
 - When $m_{K^+ \pi^-}$ is restricted below $K^*(892)$, only D_s^+ with unnatural spin-parity can decay to $D^+ K^+ \pi^-$
 $K^+ \pi^-$ system can be assumed to be in S wave ($J^P = 0^+$)

Dataset

- Collected by LHCb experiment in 2016-2018
- $B^0 \rightarrow D^- D^+ K^+ \pi^-$ with $D^+ \rightarrow K^- \pi^+ \pi^+$
 - $m(K^+ \pi^-) < 0.75 \text{ GeV}$
- Cut-based selection
- Fit model
 - Signal: sum of two Crystal Ball functions
 - Background: an exponential function
- Signal yield: 444 ± 27



Amplitude analysis

➤ Amplitude constructed using helicity formalism

$$\mathcal{M} = \sum_k \mathcal{H}^{D_{sk}} d_{0,0}^{J_{D_{sk}}}(\theta_{D_s}) p^{L_{B^0}} F_{L_{B^0}}(pa) q^{L_{D_{sk}}} F_{L_{D_{sk}}}(qa) \text{BW}(m_{K^+\pi^-}) \text{BW}_{D_{sk}}(m_{D^+K^+\pi^-})$$

➤ Three components in $D^+K^+\pi^-$ system

- New D_s^+ state around 2.6 GeV: Relativistic Breit-Wigner (RBW) amplitude
- $J^P = 1^+$ $D_{s1}(2536)^+$ state: RBW amplitude
- $J^P = 0^-$ non-resonant component: constant line shape

➤ Line shape of $K^+\pi^-$ system modelled by $J^P = 0^+ K_0^*(700)^0$: RBW amplitude

➤ Width parameterization

- $K_0^*(700)^0$: Two-body mass-dependent width
- $D_{s1}(2536)^+$: constant width
- New D_s^+ state: $\Gamma^{D_{sJ}^+}(m_{D^+K^+\pi^-}) = \boxed{\Gamma^{D_{sJ}^+ \rightarrow D^*K}(m_{D^+K^+\pi^-})} + \boxed{\Gamma^{D_{sJ}^+ \rightarrow DK\pi}(m_{D^+K^+\pi^-})}$

Two-body mass-dependent width

Constant width

➤ Combinatorial background subtracted by sPlot method

[Nucl. Instrum. Meth. A 555 (2005) 356]

Fit results with $J^P = 0^-$

➤ Mass projections

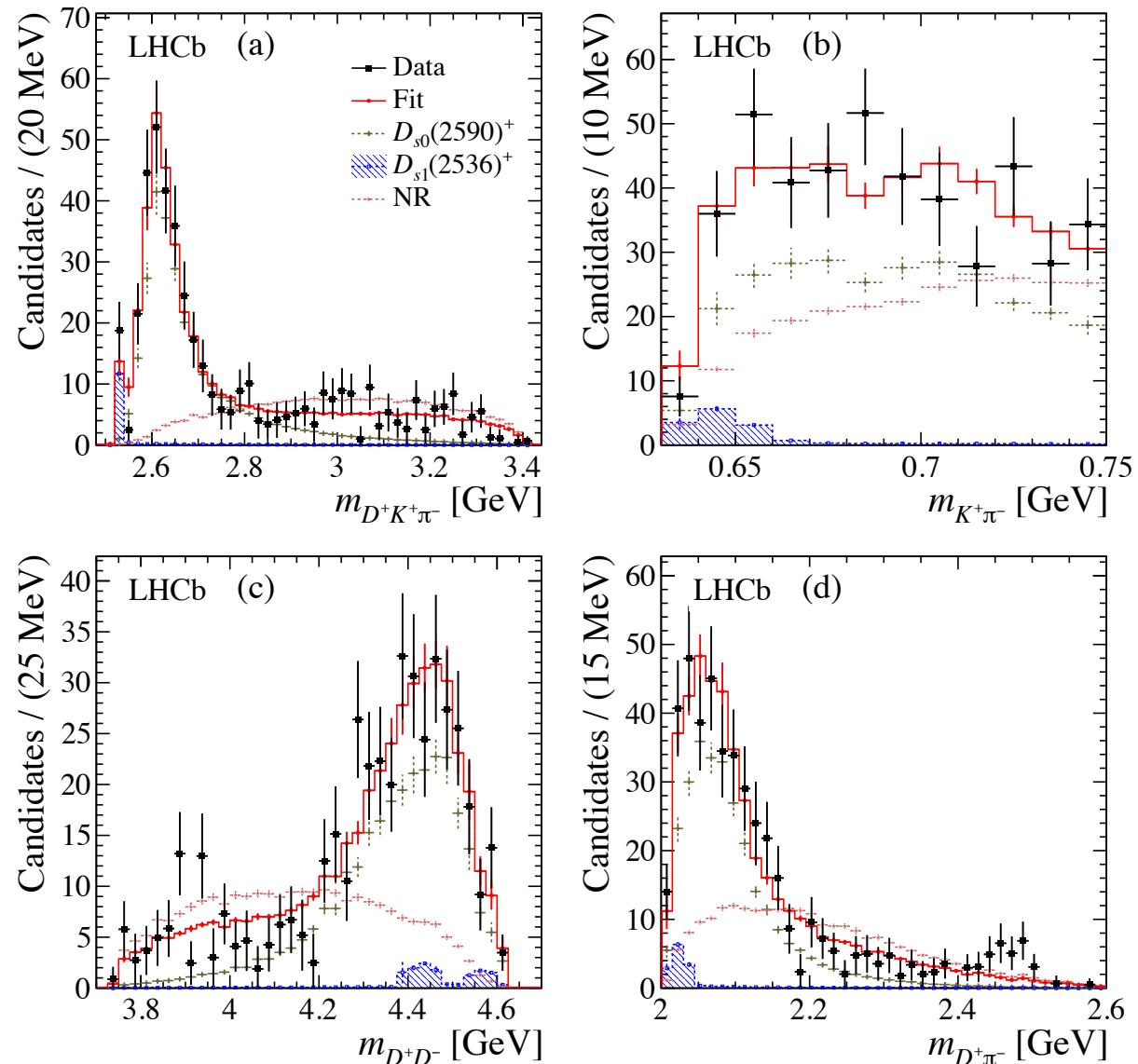
- No significant D^+D^- contribution

➤ Pole mass and width

- $m_R = 2591 \pm 6 \pm 7 \text{ MeV}$
- $\Gamma_R = 89 \pm 16 \pm 12 \text{ MeV}$

	Fit fraction ($\times 10^{-2}$)
$D_{s0}(2590)^+$	$63 \pm 9(\text{stat}) \pm 9(\text{syst})$
$D_{s1}(2536)^+$	$3.9 \pm 1.4(\text{stat}) \pm 0.8(\text{syst})$
NR	$51 \pm 11(\text{stat}) \pm 19(\text{syst})$
$D_{s0}^+ - \text{NR}$	$-18 \pm 18(\text{stat}) \pm 24(\text{syst})$
D_{s1}^+ / D_{s0}^+	$6.1 \pm 2.4(\text{stat}) \pm 1.4(\text{syst})$

➤ Null hypothesis is rejected by $> 10\sigma$



J^P measurement of new D_s^+ state

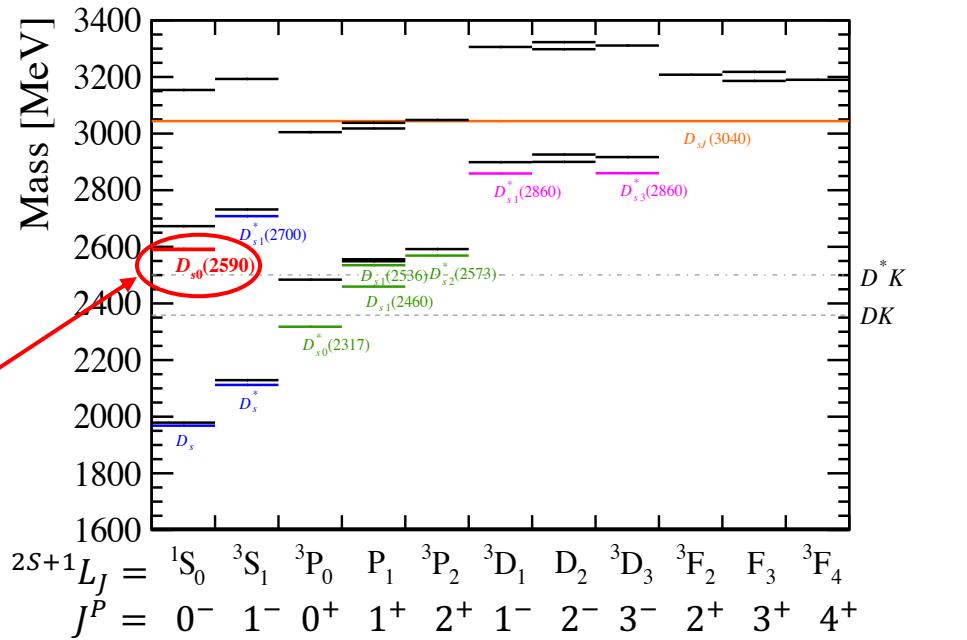
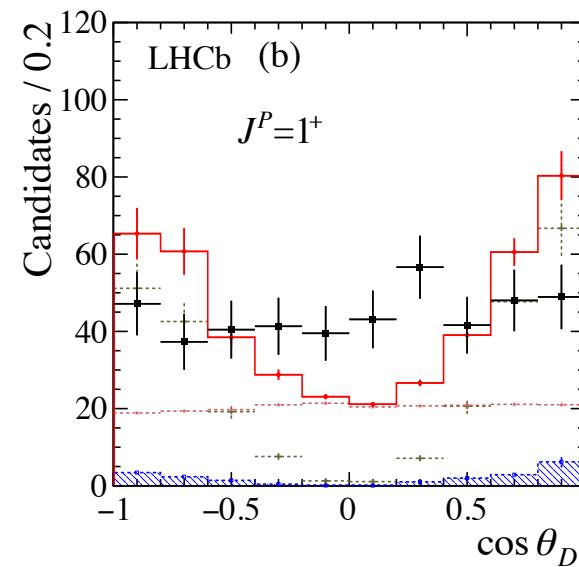
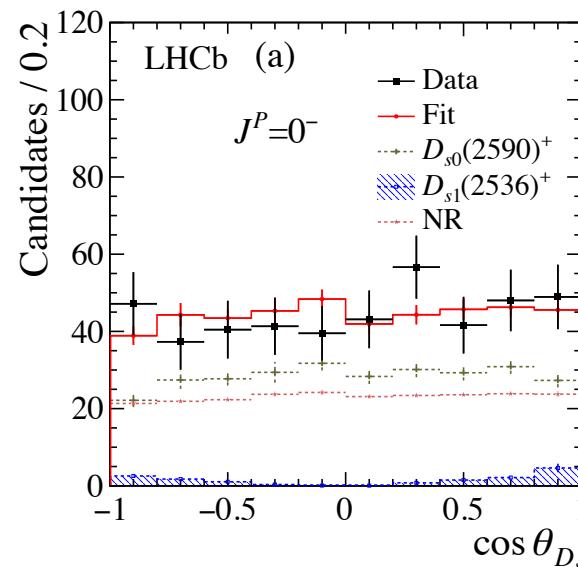
➤ Angular distributions ($\cos \theta_{D_s}$) with different J^P hypothesis

- $J^P = 0^-$: a constant function
- $J^P = 1^+$: $\sim \cos^2 \theta_{D_s}$
- $J^P = 2^-$: $\sim (3\cos^2 \theta_{D_s} - 1)^2$

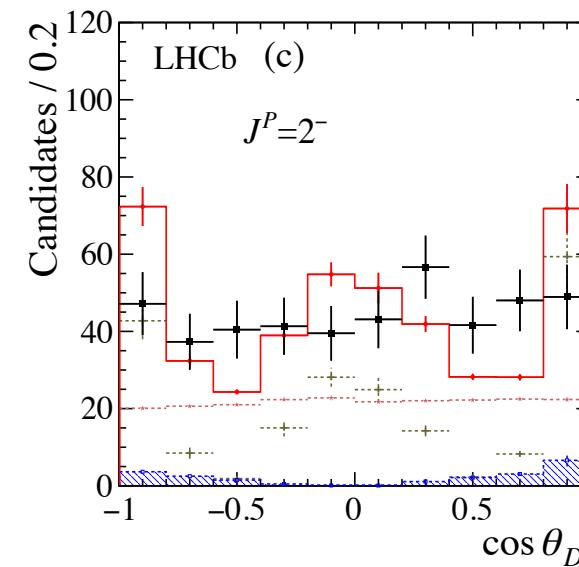
➤ $J^P = 0^-$ is most consistent with data

- $J^P = 1^+$ and 2^- are rejected by $>10\sigma$

➤ A strong candidate to be the $D_s(2^1S_0)^+$ state



Theoretical predictions: [PRD 93 (2016) 034035]
Experimental values: PDG



Systematic uncertainties

➤ Primary source: $D_{s0}(2590)^+$ width model

Source	m_R [MeV]	Γ_R [MeV]	Fit fraction ($\times 10^{-2}$)				
			D_{s0}^+	D_{s1}^+	NR	$D_{s0}^+ - \text{NR}$	D_{s1}^+ / D_{s0}^+
$D_{s0}(2590)^+$ width model	6.1	8.0	4.7	0.0	15.0	19.6	0.5
$D_{s1}(2536)^+$ mass shape	0.3	4.3	2.3	0.6	3.5	5.3	1.1
$K^+\pi^-$ mass shape	2.7	2.6	3.0	0.2	1.2	4.4	0.1
Blatt-Weisskopf factor	0.7	3.4	2.8	0.3	1.3	3.0	0.2
Including $c\bar{c}$ resonances	1.1	5.4	2.7	0.1	6.3	10.0	0.4
$D^+\pi^-$ resonance veto	2.4	2.1	4.6	0.3	9.4	4.6	0.2
Simulation correction	0.2	1.1	0.3	0.1	0.7	0.8	0.2
Momentum calibration	0.5	0.4	1.3	0.0	1.4	2.5	0.2
Total	7.2	11.7	8.6	0.8	19.3	23.9	1.4

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

[LHCb-PAPER-2021-025, in preparation]

Single heavy baryon

➤ The single heavy baryon can be modeled by Diquark-quark system

- Determined by 7 quantities

- \vec{l}_ρ : angular momentum between the two light quarks (q_1, q_2)
- \vec{l}_λ : angular momentum between the heavy quark (Q_3) and the diquark system
- \vec{L} : total angular momentum, $\vec{L} = \vec{l}_\rho + \vec{l}_\lambda$
- \vec{s}_{qq} : diquark spin, $\vec{s}_{qq} = \vec{s}_{q_1} + \vec{s}_{q_2}$ (0 or 1)
- \vec{s}_Q : spin of heavy quark (1/2), $Q = b, c$
- \vec{j}_{qq} : total angular momentum of the diquark system, $\vec{j}_{qq} = \vec{L} + \vec{s}_{qq}$
- \vec{j} : total angular momentum of the heavy baryon, $\vec{j} = \vec{j}_{qq} + \vec{s}_Q$

- λ -model: system with $l_\rho = 0$ and different l_λ

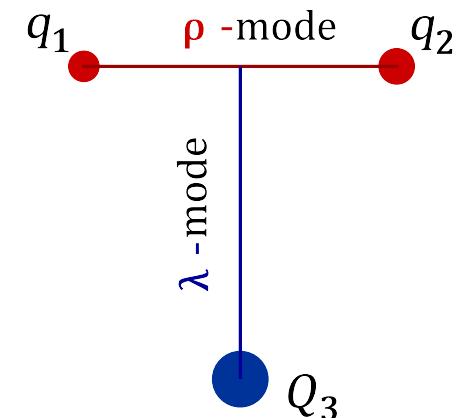
- Almost all observed states can be explained as λ -model excited states

- Beauty baryon contains one s quark (bsq)

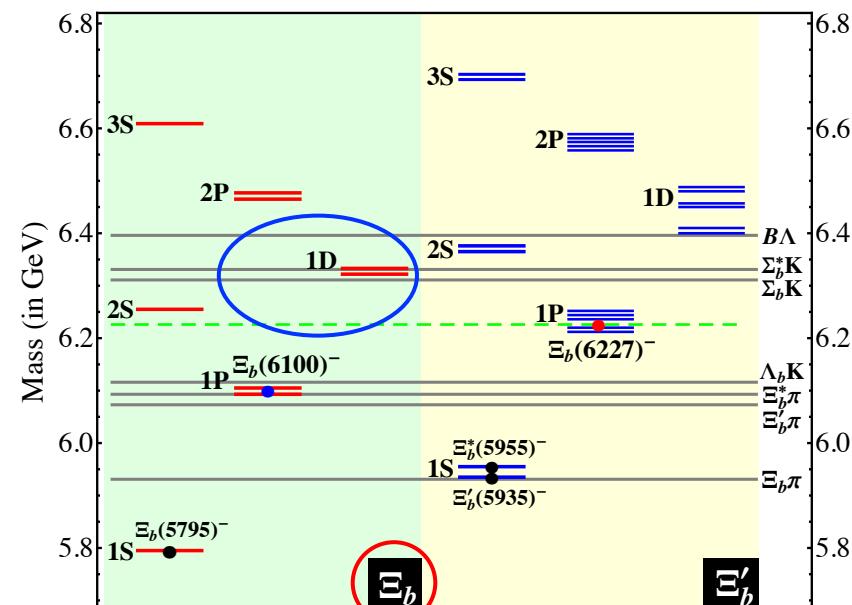
- Ξ_b family: $s_{qq} = 0$
- Ξ'_b family: $s_{qq} = 1$

➤ 1D Ξ_b^0 (bsu)

- $l_\rho = 0, l_\lambda = 2$ (D wave), $s_{qq} = 0, s_Q = \frac{1}{2}$
- Spin: $J = \frac{3}{2}, \frac{5}{2}$



[Bing Chen et. al. PRD 100 (2019) 094032]



[Bing Chen et. al. PRD 98 (2018) 031502]

[PRL 126 (2021) 252003]

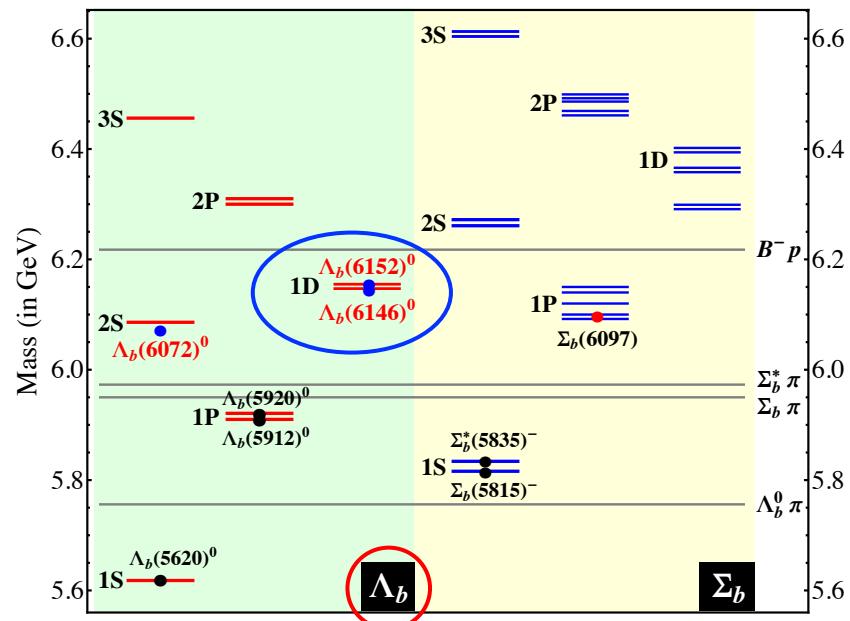
Motivation

➤ LHCb observed two Λ_b^0 states in $\Lambda_b^0\pi^+\pi^-$

- Consistent with 1D Λ_b^0 ($L = 2$)

➤ Two 1D Ξ_b^0 states are predicted

- Search for 1D Ξ_b^0 states in $\Lambda_b^0 K^- \pi^+$

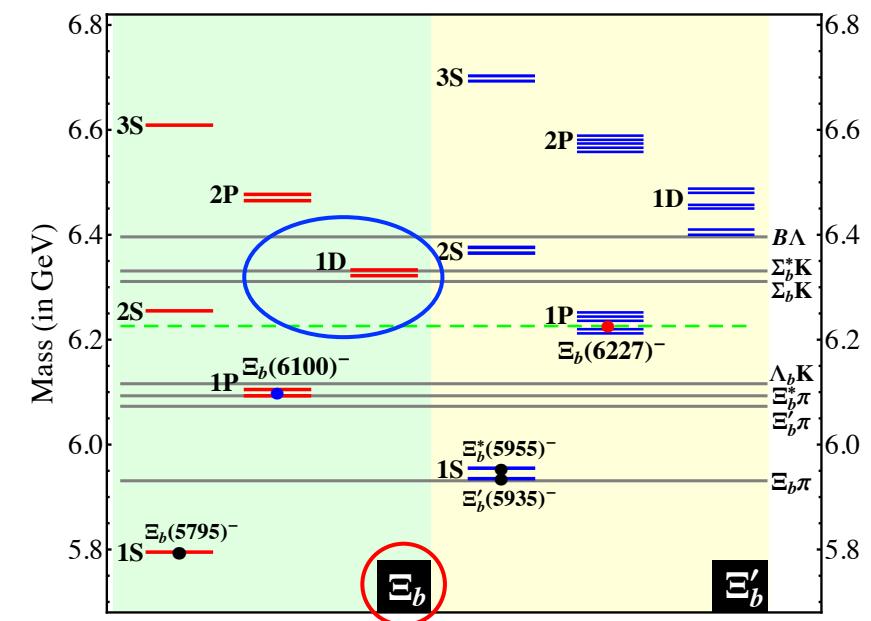


[Bing Chen et. al. PRD 98 (2018) 074032]

[JHEP 06 (2020) 136]

Decay mode	$\Xi_b(6327)$ [3/2 ⁺ (1D)]	$\Xi_b(6330)^0$ [5/2 ⁺ (1D)]
$\Xi'_b(5935)\pi$	0.39 ^p	0.09 ^f
$\Sigma_b(5815)K$	1.73 ^p	0.00 ^f
$\Xi_b^*(5955)\pi$	0.09 ^p , 0.15 ^f	0.51 ^p , 0.07 ^f
$\Sigma_b^*(5835)K$	0.02 ^p , 0.00 ^f	0.09 ^p , 0.00 ^f
Total width	2.38	0.76

[Bing Chen et. al. PRD 100 (2019) 094032]



[Bing Chen et. al. PRD 98 (2018) 031502]

[PRL 126 (2021) 252003]

Dataset of Λ_b^0 candidates

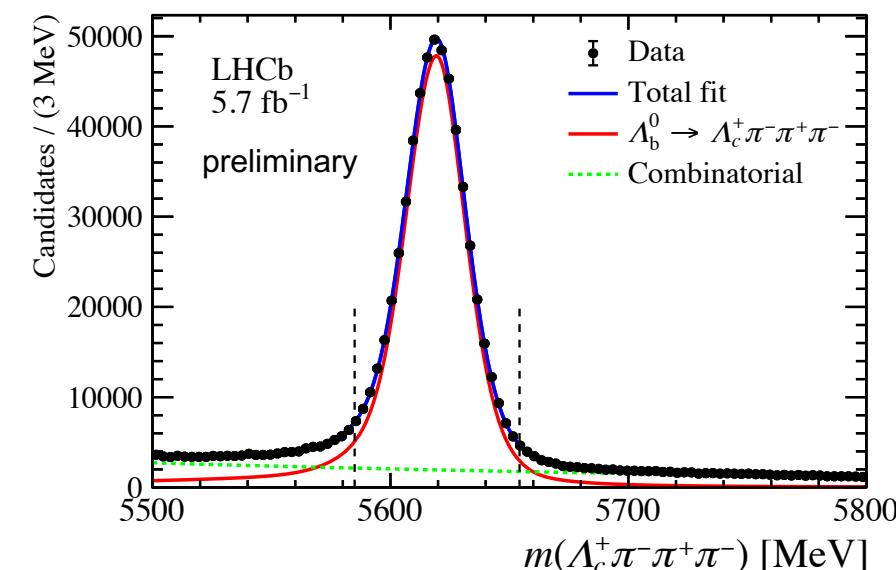
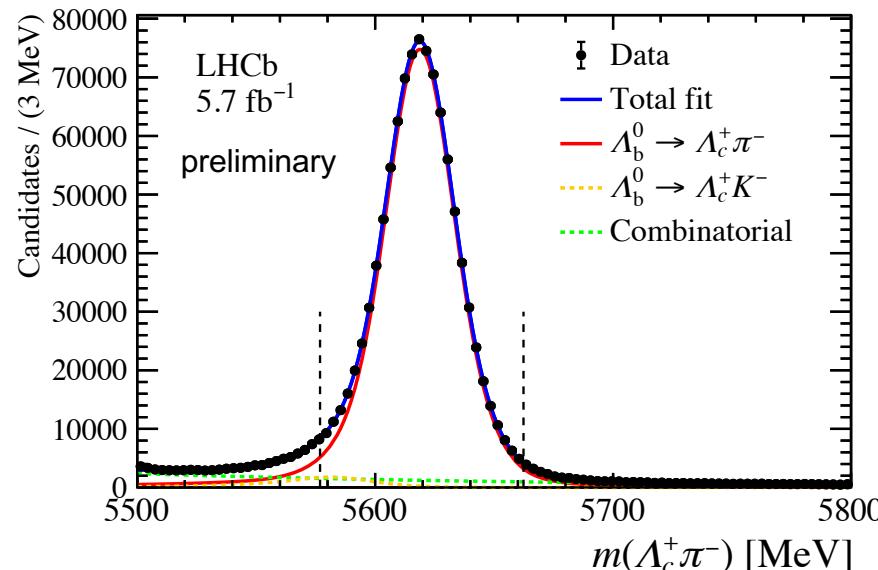
➤ Collected by LHCb experiment in 2015-2018

➤ Decay modes

- $\Lambda_b^0 \rightarrow \Lambda_c^+ (\rightarrow p K^- \pi^+) \pi^-$
- $\Lambda_b^0 \rightarrow \Lambda_c^+ (\rightarrow p K^- \pi^+) \pi^- \pi^+ \pi^-$

➤ Cut-based preselection + BDT

➤ Signals within mass window: 966k ($\Lambda_c^+ \pi^-$) + 533k ($\Lambda_c^+ \pi^- \pi^+ \pi^-$)



$\Lambda_b^0 K\pi$ mass spectrum

➤ Λ_b^0 combined with kaon and pion

- Right-sign (RS)

- $\Lambda_b^0 K^- \pi^+$
- Search for excited Ξ_b^0 states

- Wrong-sign (WS)

- $\Lambda_b^0 K^+ \pi^-$
- Background study

- Cut-based selection

- Especially optimize p_T and PID cuts of prompt kaons and pions

- Redefine mass for better resolution

- $m(\Lambda_b^0 K\pi) \equiv m_{\Lambda_b^0 K\pi} - m_{\Lambda_b^0} + 5619.62 \text{ MeV}$

Λ_b^0 mass [PRL 119 (2017) 062001]

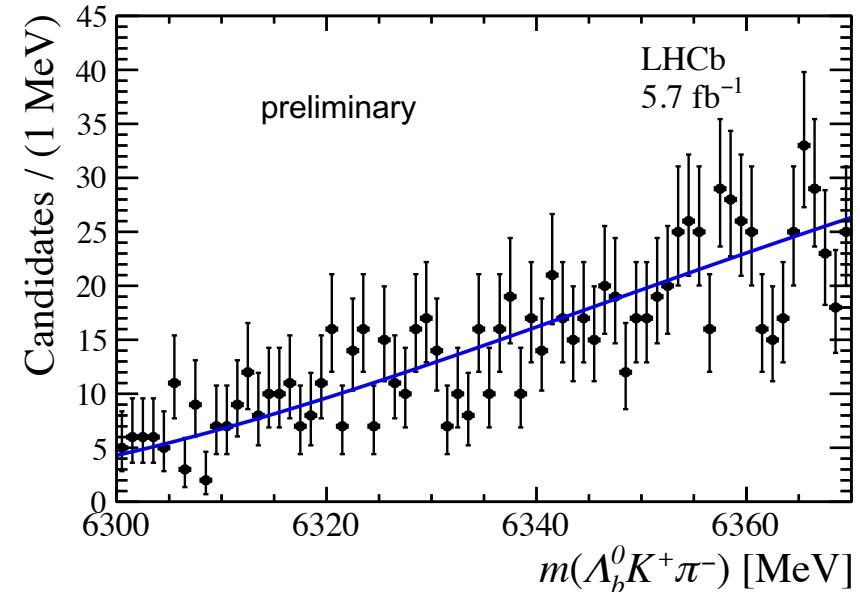
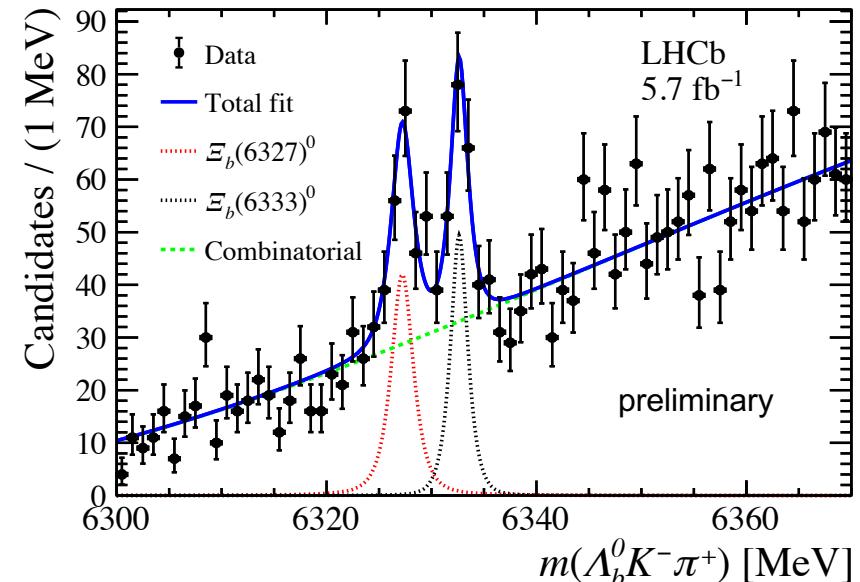
➤ Simultaneous fit (RS+WS)

- Signal

- RBW with constant width
- Detector resolution determined from simulation

- Background

- A threshold function
- RS and WS samples share the same background parameters



Results

➤ Masses and widths

$$m_{\Xi_b(6327)^0} = 6327.28^{+0.23}_{-0.21}(\text{stat}) \pm 0.08(\text{syst}) \pm 0.24(m_{\Lambda_b^0}) \text{ MeV}$$

$$m_{\Xi_b(6333)^0} = 6332.69^{+0.17}_{-0.18}(\text{stat}) \pm 0.03(\text{syst}) \pm 0.22(m_{\Lambda_b^0}) \text{ MeV}$$

$$\Delta m \equiv m_{\Xi_b(6333)^0} - m_{\Xi_b(6327)^0} = 5.41^{+0.26}_{-0.27}(\text{stat}) \pm 0.06(\text{syst}) \text{ MeV}$$

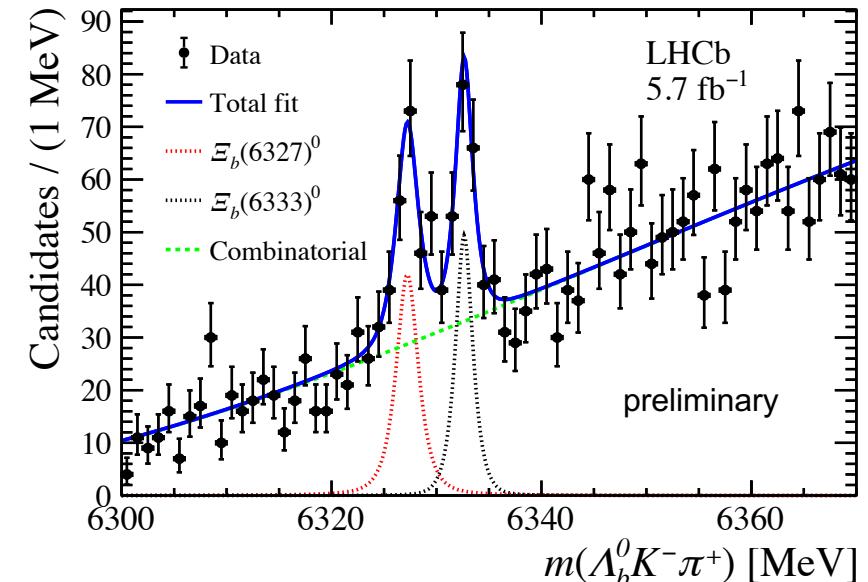
$$\Gamma_{\Xi_b(6327)^0} < 2.20 \text{ (2.56) MeV at 90% (95%) CL}$$

$$\Gamma_{\Xi_b(6333)^0} < 1.55 \text{ (1.85) MeV at 90% (95%) CL}$$

- Masses are consistent with 1D Ξ_b^0

➤ Significance considering systematic uncertainty

- 9.9σ for two-peak vs background-only hypothesis
- 5.8σ for two-peak vs one-peak hypothesis

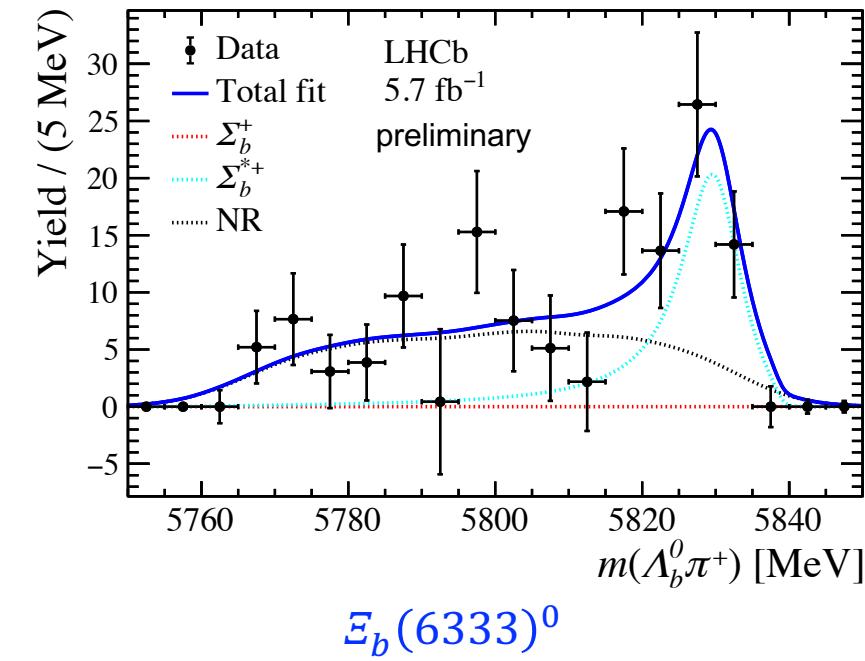
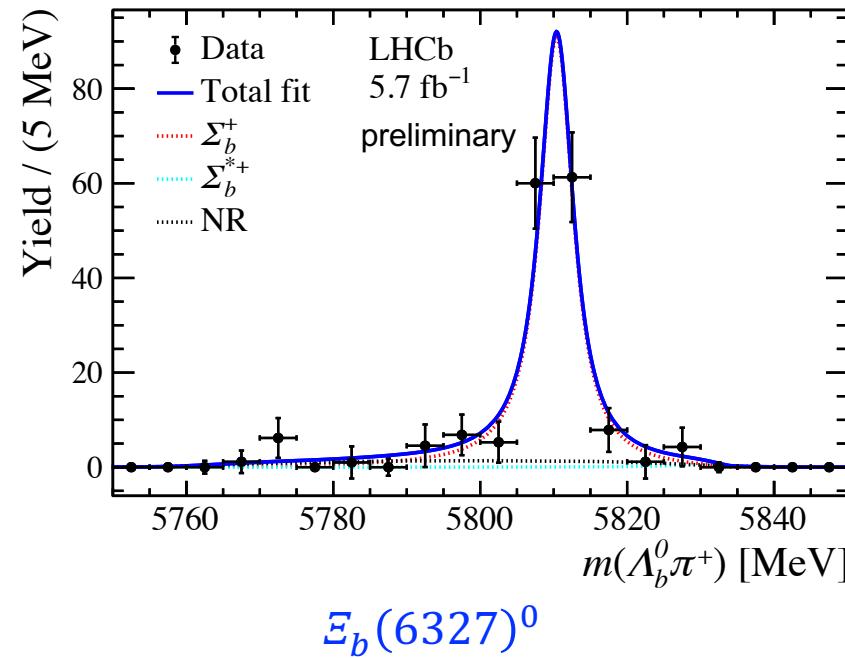


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$\Sigma_b^*(5835) K$	$0.02^p, 0.00^f$	$0.09^p, 0.00^f$
Total width	2.38	0.76

[Bing Chen et. al. PRD 100 (2019) 094032]

Resonant structure in $\Lambda_b^0\pi^+$ mass spectrum

- $\Xi_b(6327)^0$ predominantly decays to $\Sigma_b^+ K^-$
- About half of $\Xi_b(6333)^0$ decays to $\Sigma_b^{*+} K^-$, the rest decays without $\Lambda_b^0\pi^+$ resonances
- Consistent with 1D Ξ_b^0 doublets [Bing Chen et. al. PRD 100 (2019) 094032]



Systematic uncertainties

- Systematic uncertainties are smaller than statistical uncertainties

Statistical uncertainties

State	Mass [MeV]	Width [MeV]
$\Xi_b(6327)^0$	$6327.28^{+0.23}_{-0.21}$	$0.93^{+0.74}_{-0.60}$
$\Xi_b(6333)^0$	$6332.69^{+0.17}_{-0.18}$	$0.25^{+0.58}_{-0.25}$

Systematic uncertainties on mass (MeV) and width (MeV)

Source	$\Xi_b(6327)^0$		$\Xi_b(6333)^0$		
	m	Γ	m	Γ	Δm
Momentum scale	0.06	0.06	0.03	0.04	0.03
Signal shape	0.01	0.12	0.00	0.25	0.01
Background shape	0.01	0.17	0.01	0.15	0.00
Resolution model	0.05	0.20	0.01	0.25	0.05
Total systematic uncertainty	0.08	0.29	0.03	0.39	0.06
Λ_b^0 mass (syst, momentum scale)	0.12	-	0.12	-	-
Λ_b^0 mass (syst, excl. momentum scale)	0.05	-	0.05	-	-
Λ_b^0 mass (stat)	0.16	-	0.16	-	-
Total uncertainty from $m_{\Lambda_b^0}$	0.24	-	0.22	-	-

Summary

➤ New heavy hadrons observed at LHCb

- Observation of a new excited D_s^+ meson in $B^0 \rightarrow D^- D^+ K^+ \pi^-$

$$m_R = 2591 \pm 6 \pm 7 \text{ MeV}$$

$$\Gamma_R = 89 \pm 16 \pm 12 \text{ MeV}$$

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

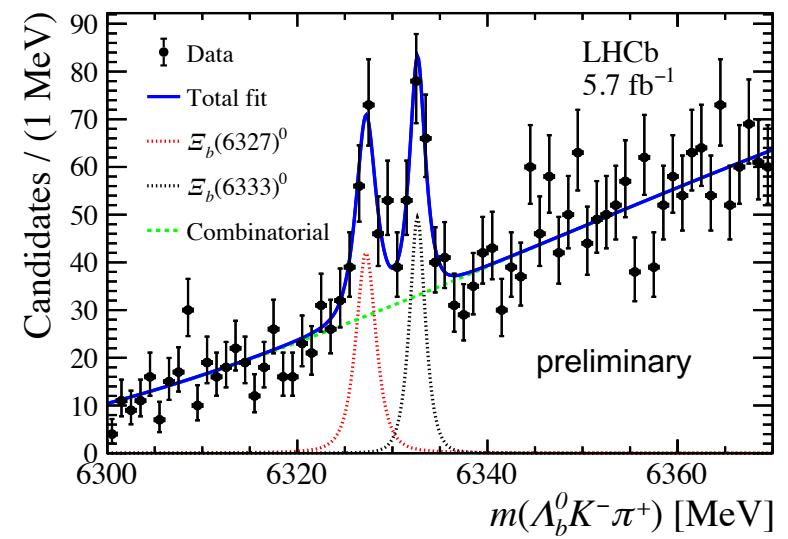
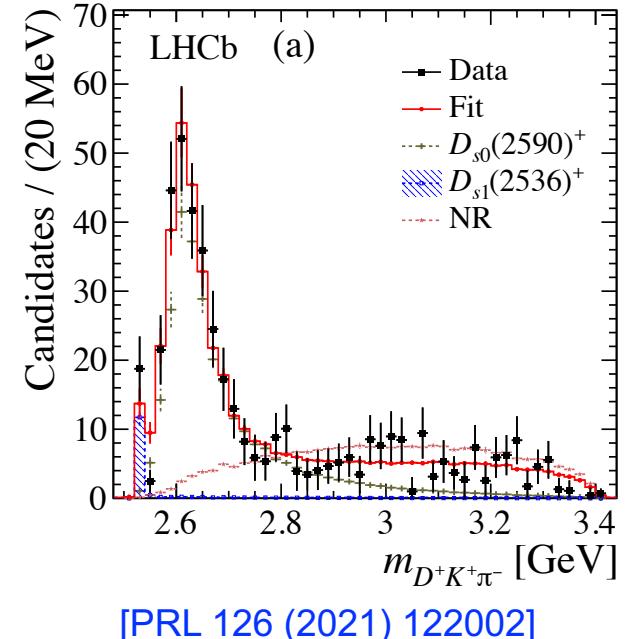
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$$\Delta m \equiv m_{\Xi_b(6333)^0} - m_{\Xi_b(6327)^0} = 5.41^{+0.26}_{-0.27}(\text{stat}) \pm 0.06(\text{syst}) \text{ MeV}$$

$$\Gamma_{\Xi_b(6327)^0} < 2.20 \text{ (2.56) MeV at 90% (95%) CL}$$

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Thank you!