Charmed Baryons at LHCb

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Introduction

PDG2022
Chin. J. Phys. 78 (2022) 324

Charmed baryon spectroscopy and properties are very important to probe low-energy non-perturbative QCD dynamics

Charmed baryon properties:

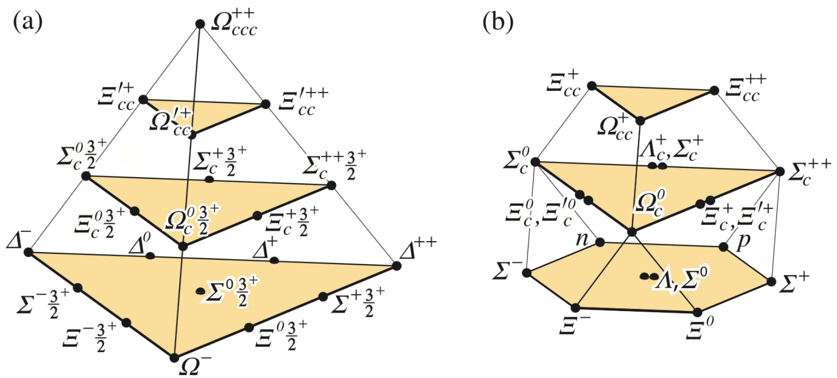
Mass, width (lifetime)

Production

Branching fraction

Quantum numbers (I^G, J^{PC})

Decay parameters ...



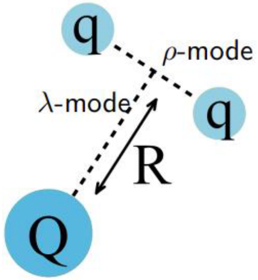
Searching for new charmed baryons:

Missing particles in charmed sector:

- Ground ccq, ccc states
- Excited cqq states

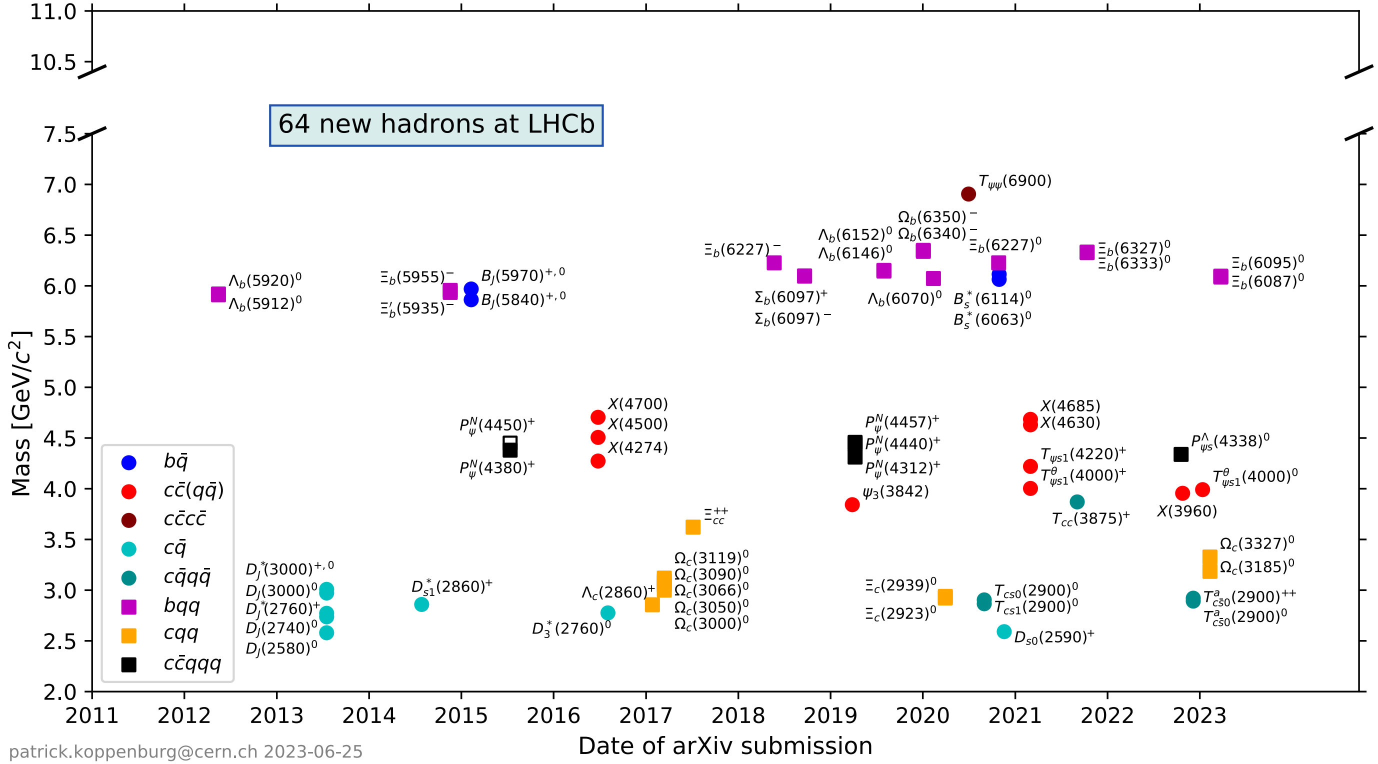
Inner structure of excited states:

- Pentaquark (hidden $q\bar{q}$)? Molecular?
- Radially mode? Orbital mode?



Charmed spectroscopy at LHCb

The world's largest samples of reconstructed charmed baryons are collected with LHCb during LHC Run1 and Run2

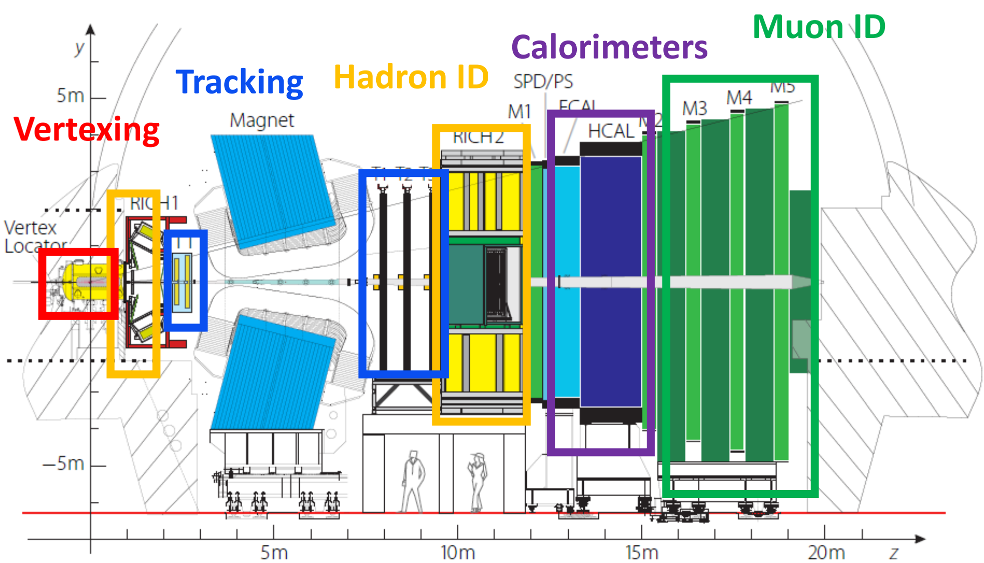


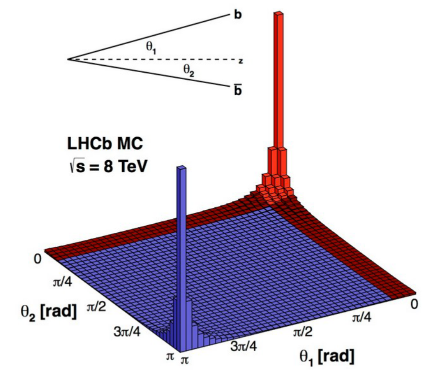
[*LHCb collaboration, P. Koppenburg, List of hadrons observed at the LHC*, [*LHCb-FIGURE-2021-001*](), *2021, and* [*2023 updates*]()]

11 new charmed baryons discovered at LHCb (1 doubly-charmed and 10 singly-charmed)

The LHCb experiment

JINST 3 (2008) S08005, IJMPA 30 (2015) 1530022



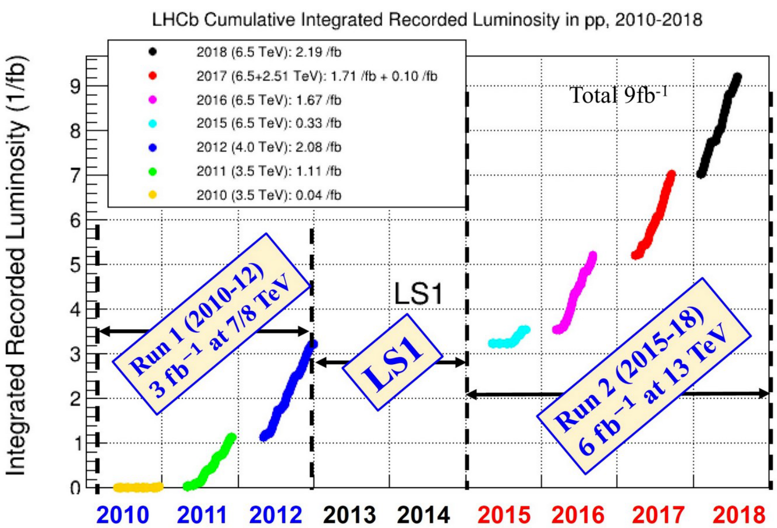


Single arm spectrometer, 25% of $b\bar{b}$ pairs produced in the acceptance

Designed to study heavy hadron decays

Unique kinematic region: high rapidity ($2 < \eta < 5$) and low p_{T}

Excellent vertexing, tracking, momentum resolution and particle identification



Overview of selected results

Singly charmed baryon:

Observation of Cabibbo-suppressed two-body decays of Ω_c^0 ~New

Precise mass measurement of Ω_c^0 ~New

LHCb-PAPER-2023-011 in preparation

Lifetime measurements of Ω_c^0 and Ξ_c^0

Sci. Bull. 67 (2022) 479

Charmed baryon excited states:

Observation of new excited Ω_c^0 states

PHYS. REV. LETT. 118 (2017) 182001
PHYS. REV. D 97 (2018) 5, 051102
PHYS. REV. D 104 (2021) L091102
arXiv: 2302.04733

Search for new excited Ξ_c^0

PHYS. REV. LETT. 124 (2020) 222001
arXiv: 2211.00812

Doubly charmed baryon:

Observation of $\Xi_{cc}^{++} \to \Xi_c^{\prime +}\pi^+$ decay

JHEP 05 (2022) 038

Searches for Ξ_{cc}^+ and Ω_{cc}^+

Sci. China Phys. Mech. Astron. (2020) 63: 221062
Sci. China Phys. Mech. Astron. (2021) 64: 101062

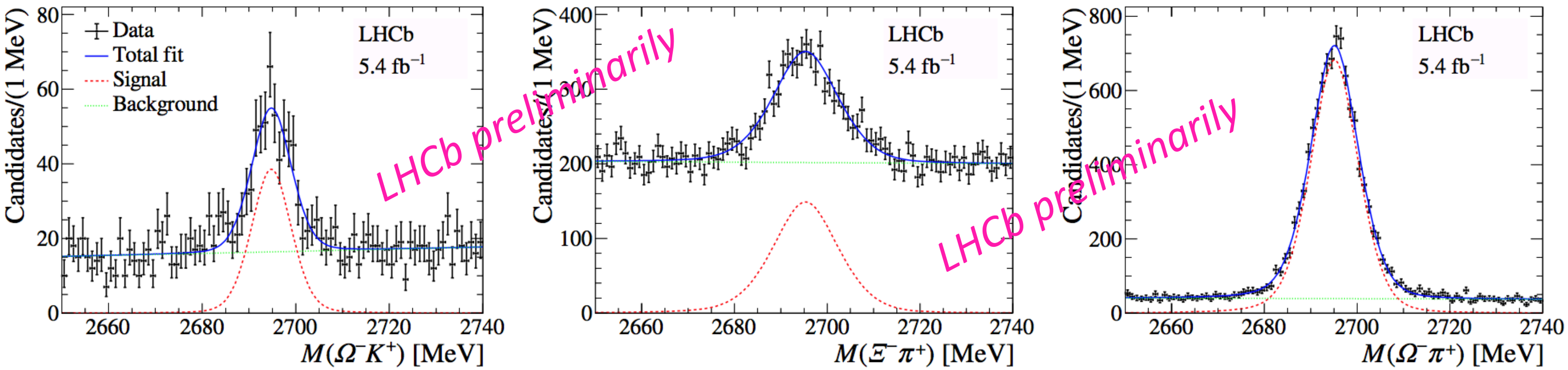
New

Observation of $\Omega_c^0 \to \Omega^- K^+$ and $\Omega_c^0 \to \Xi^- \pi^+$

LHCb-PAPER-2023-011 in preparation

Using LHCb 2016-2018 dataset, at 13 TeV and 5.4 fb^{-1}

Signal candidates: ~400 for $\Omega_c^0 \to \Omega^- K^+$ and ~2800 for $\Omega_c^0 \to \Xi^- \pi^+$ (both >10σ)

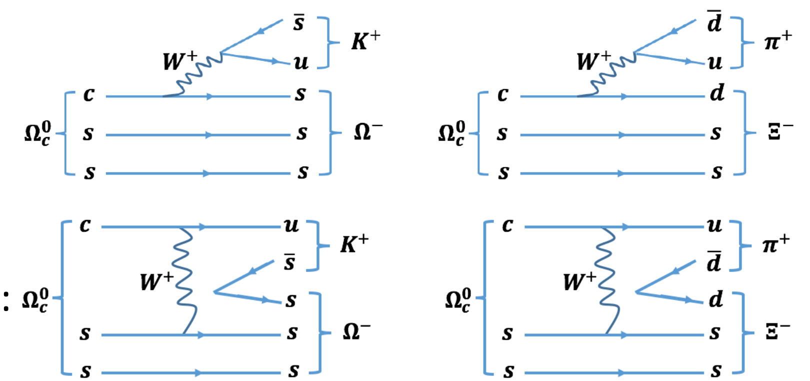


The branching fraction ratios are measured to be:

$$\frac{\mathcal{B}(\Omega_c^0 \to \Omega^- K^+)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)} = 0.0608 \pm 0.0051\,(\text{stat}) \pm 0.0040\,(\text{syst}),$$

$$\frac{\mathcal{B}(\Omega_c^0 \to \Xi^- \pi^+)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)} = 0.1581 \pm 0.0087\,(\text{stat}) \pm 0.0043\,(\text{syst}) \pm 0.0016\,(\text{ext})$$

Non-factorizable contribution from *W*-exchange:



Our results are larger than the predictions from current algebra or light-front quark model

The non-factorizable contributions are crucial to accurately calculate the BFs

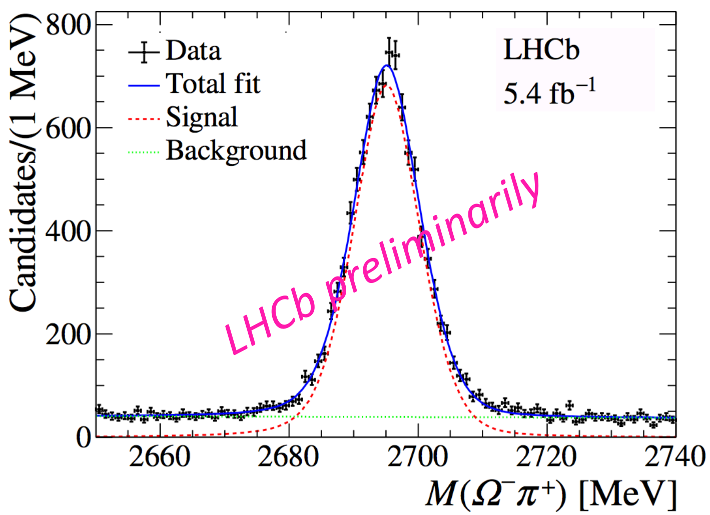
New

Precise mass measurement of Ω_c^0

LHCb-PAPER-2023-011 in preparation

Using LHCb 2016-2018 dataset, at 13 TeV and 5.4 fb^{-1}

The fit result of Cabibbo-favoured decay $\Omega_c^0 \rightarrow \Omega^- \pi^+$, signal candidates ~9300



PDG2022

Λ_c^+ MASS	2286.46 ± 0.14 MeV
Ξ_c^+ MASS	2467.71 ± 0.23 MeV (S = 1.3)
Ξ_c^0 MASS	2470.44 ± 0.28 MeV (S = 1.2)
Ω_c^0 MASS	2695.2 ± 1.7 MeV (S = 1.3)

Systematic uncertainty:

Source	δM [MeV]
Momentum scale calibration	0.27
Energy loss correction	0.03
Fit model	0.01
Total	0.27
External input mass	0.30

$$M(\Omega_c^0) = 2695.28 \pm 0.07\,(\mathrm{stat}) \pm 0.27\,(\mathrm{syst}) \pm 0.30\,(\mathrm{ext})\,\mathrm{MeV}.$$

Improving the precision of the previous world-average by **a factor of four**

Lifetime measurement of Ω_c^0 and Ξ_c^0

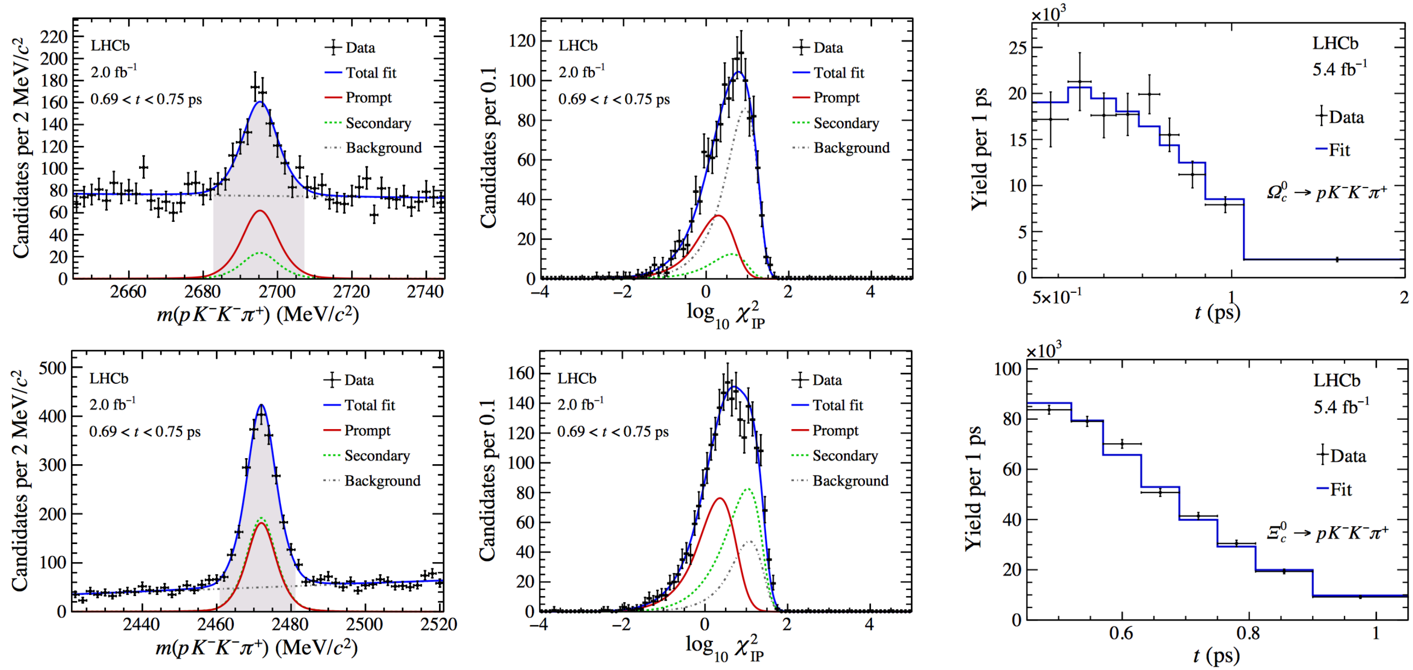
Sci. Bull. 67 (2022) 479

Using LHCb 2016-2018 dataset, at 13 TeV and 5.4 fb^{-1} (Prompt production)

Two-dimensional unbinned extended maximum likelihood fits are performed to the invariant-mass and $\log_{10}\chi^2_{\text{IP}}$ distributions

Ω_c^0:

Ξ_c^0:



$$\tau_{\Omega_c^0} = 276.5 \pm 13.4 \pm 4.4 \pm 0.7\,\text{fs},$$
$$\tau_{\Xi_c^0} = 148.0 \pm 2.3 \pm 2.2 \pm 0.2\,\text{fs}$$

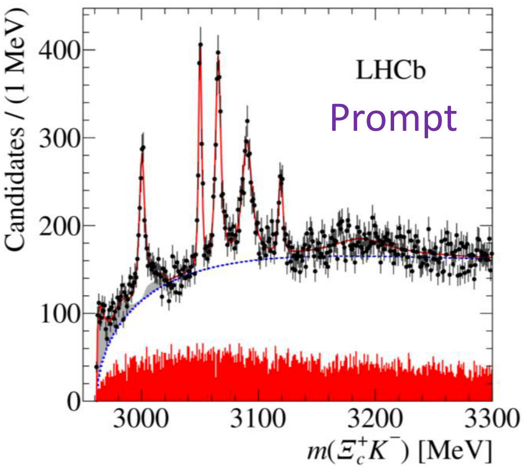
$$\tau_{\Xi_c^+} > \tau_{\Omega_c^0} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0}.$$

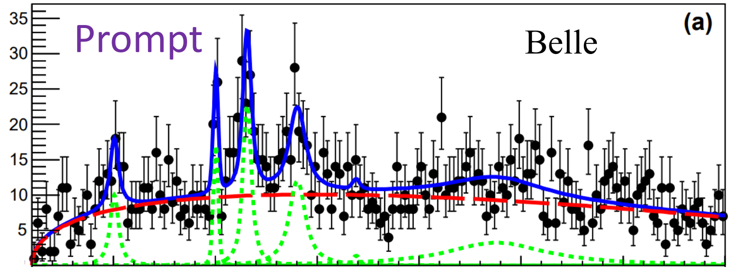
Our results confirm the charmed-hadron lifetime hierarchy from the secondary studies, improve the precision of the previous Ω_c^0 lifetime by a factor of two

Excited Ω_c^0 states

PHYS. REV. LETT. 118 (2017) 182001
PHYS. REV. D 97 (2018) 5, 051102
PHYS. REV. D 104 (2021) L091102

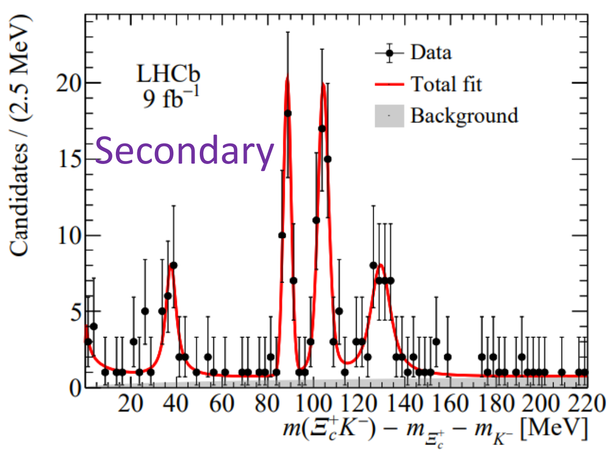
In 2017, five new excited Ω_c^0 are observed by LHCb, **four** of them confirmed by Belle





In 2021, observed **four** of them from $\Omega_b^- \to \Omega_c^{(**)0}\pi^-$

Spin test performed, but no strong conclusion.



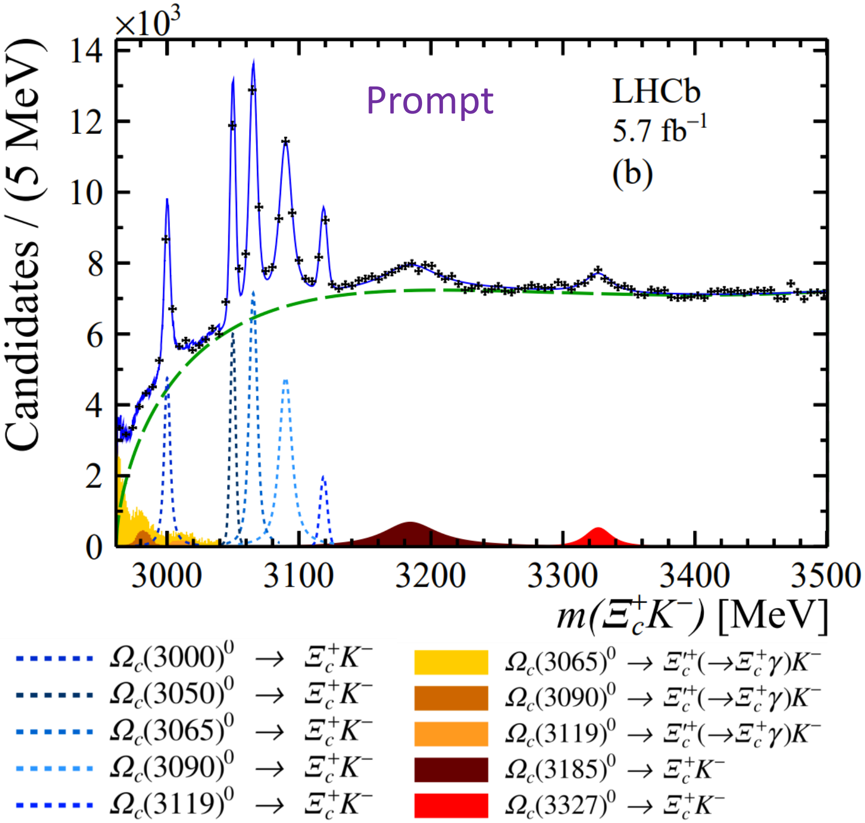
State	Observable	Measurement
Ω_b^-	m	$6044.3 \pm 1.2 \pm 1.1^{+0.19}_{-0.22}$ MeV
	$\mathcal{R}$	$1.35 \pm 0.11 \pm 0.05$
Threshold structure	Significance	$4.3\,\sigma$
$\Omega_c(3000)^0$	Significance	$6.2\,\sigma$
	ΔM	$37.6 \pm 0.9 \pm 0.9$ MeV
	m	$2999.2 \pm 0.9 \pm 0.9^{+0.19}_{-0.22}$ MeV
	Γ	$4.8 \pm 2.1 \pm 2.5$ MeV
	$\mathcal{P}$	$0.11 \pm 0.02 \pm 0.04$
	J rejection	$0.5\,\sigma\,(J=1/2), 0.8\,\sigma\,(J=3/2), 0.4\,\sigma\,(J=5/2)$
$\Omega_c(3050)^0$	Significance	$9.9\,\sigma$
	ΔM	$88.5 \pm 0.3 \pm 0.2$ MeV
	m	$3050.1 \pm 0.3 \pm 0.2^{+0.19}_{-0.22}$ MeV
	Γ	< 1.6 MeV, 95% CL
	$\mathcal{P}$	$0.15 \pm 0.02 \pm 0.02$
	J rejection	$2.2\,\sigma\,(J=1/2), 0.1\,\sigma\,(J=3/2), 1.2\,\sigma\,(J=5/2)$
$\Omega_c(3065)^0$	Significance	$11.9\,\sigma$
	ΔM	$104.3 \pm 0.4 \pm 0.4$ MeV
	m	$3065.9 \pm 0.4 \pm 0.4^{+0.19}_{-0.22}$ MeV
	Γ	$1.7 \pm 1.0 \pm 0.5$ MeV
	$\mathcal{P}$	$0.23 \pm 0.02 \pm 0.02$
	J rejection	$3.6\,\sigma\,(J=1/2), 0.6\,\sigma\,(J=3/2), 1.2\,\sigma\,(J=5/2)$
$\Omega_c(3090)^0$	Significance	$7.8\,\sigma$
	ΔM	$129.4 \pm 1.1 \pm 1.0$ MeV
	m	$3091.0 \pm 1.1 \pm 1.0^{+0.19}_{-0.22}$ MeV
	Γ	$7.4 \pm 3.1 \pm 2.8$ MeV
	$\mathcal{P}$	$0.19 \pm 0.02 \pm 0.04$
	J rejection	$0.3\,\sigma\,(J=1/2), 0.8\,\sigma\,(J=3/2), 0.5\,\sigma\,(J=5/2)$
$\Omega_c(3120)^0$	$\mathcal{P}$	< 0.03, 95% CL

New excited Ω_c^0 states

arXiv: 2302.04733

New excited states observed: $\Omega_c(3185)^0$ and $\Omega_c(3327)^0$

All previous states confirmed, and masses and widths improved with the highest precision



Resonance	m (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.44 \pm 0.07\ ^{+0.07}_{-0.13} \pm 0.23$	$3.83 \pm 0.23\ ^{+1.59}_{-0.29}$
$\Omega_c(3050)^0$	$3050.18 \pm 0.04\ ^{+0.06}_{-0.07} \pm 0.23$	$0.67 \pm 0.17\ ^{+0.64}_{-0.72}$
		< 1.8 MeV, 95% C.L.
$\Omega_c(3065)^0$	$3065.63 \pm 0.06\ ^{+0.06}_{-0.06} \pm 0.23$	$3.79 \pm 0.20\ ^{+0.38}_{-0.47}$
$\Omega_c(3090)^0$	$3090.16 \pm 0.11\ ^{+0.06}_{-0.10} \pm 0.23$	$8.48 \pm 0.44\ ^{+0.61}_{-1.62}$
$\Omega_c(3119)^0$	$3118.98 \pm 0.12\ ^{+0.09}_{-0.23} \pm 0.23$	$0.60 \pm 0.63\ ^{+0.90}_{-1.05}$
		< 2.5 MeV, 95% C.L.
$\Omega_c(3185)^0$	$3185.1 \pm 1.7\ ^{+7.4}_{-0.9} \pm 0.2$	$50 \pm 7\ ^{+10}_{-20}$
$\Omega_c(3327)^0$	$3327.1 \pm 1.2\ ^{+0.1}_{-1.3} \pm 0.2$	$20 \pm 5\ ^{+13}_{-1}$

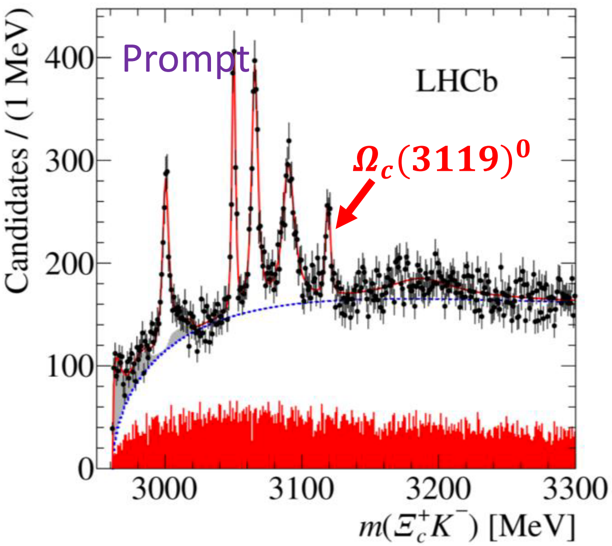
Detail study of the threshold enhancement
Study of the $\Omega_c(3185)^0$ with alternative model

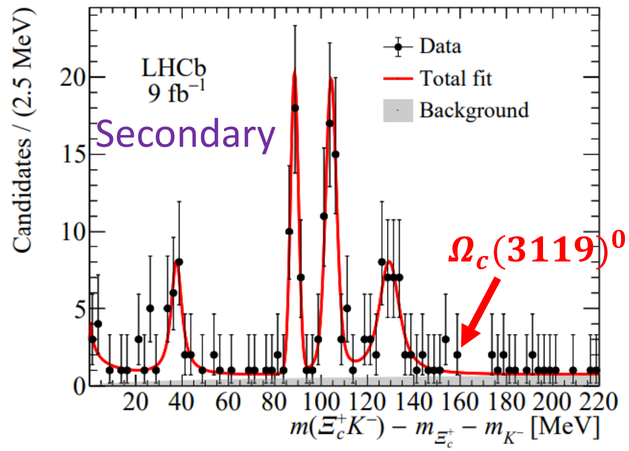
→ As systematic uncertainty

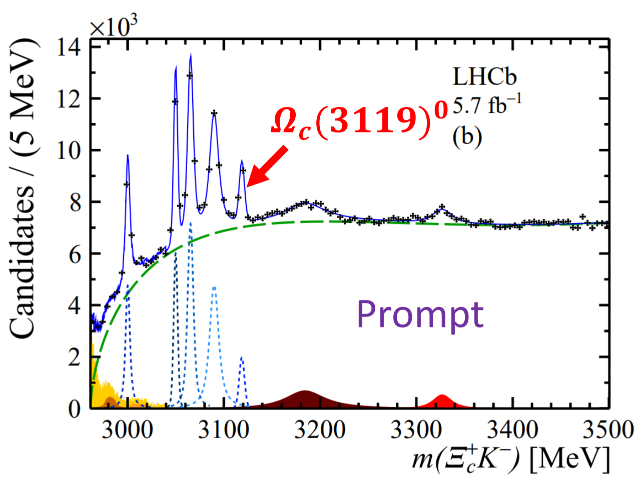
Comparison of excited Ω_c^0 results

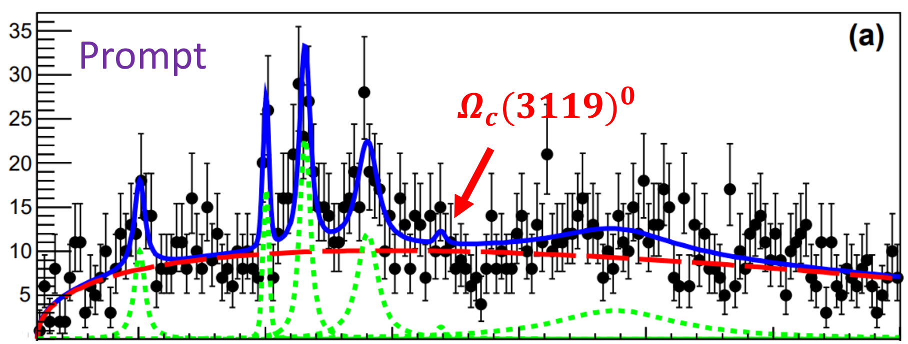
Three $m(\Xi_c^+ K^-)$ studies from LHCb, and one $m(\Xi_c^+ K^-)$ study from Belle

PHYS. REV. LETT. 118 (2017) 182001
PHYS. REV. D 97 (2018) 5, 051102
PHYS. REV. D 104 (2021) L091102
arXiv: 2302.04733









What is wrong with $\boldsymbol{\Omega_c(3119)^0}$?

What happens on the threshold?

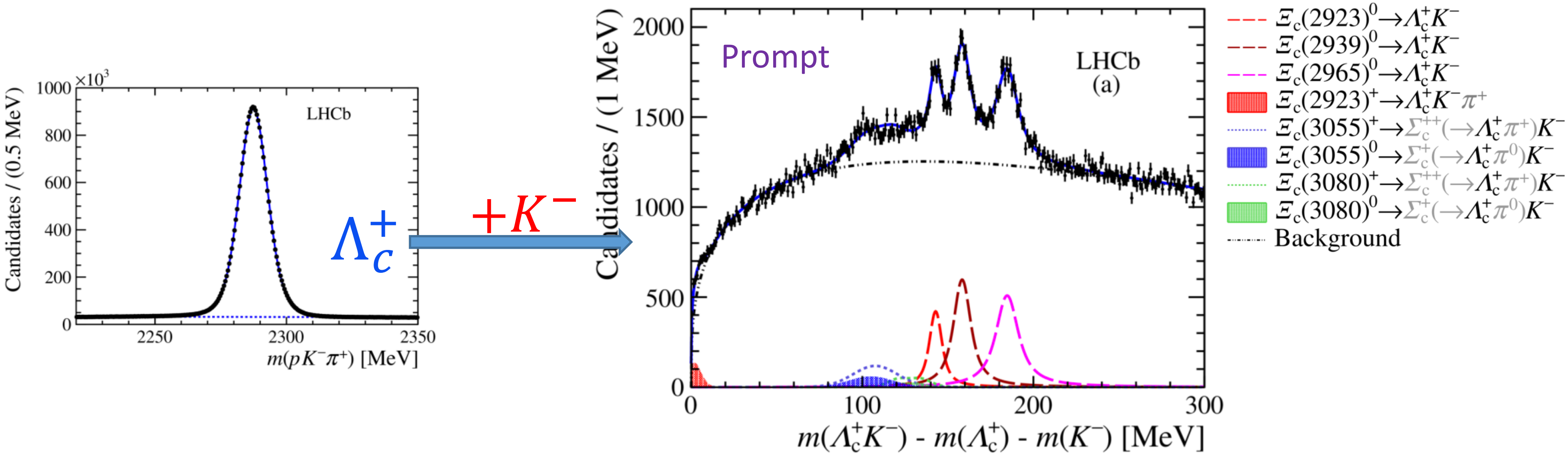
Excited Ξ_c^0 states

PHYS. REV. LETT. 124 (2020) 222001

Using LHCb 2016-2018 dataset, at 13 TeV and 5.4 fb^{-1}

Three excited Ξ_c^0 were observed in prompt $m(\Lambda_c^+ K^-)$

The significances of these excited Ξ_c^0 are >>5σ



Resonance	Peak of ΔM [MeV]	Mass [MeV]	Γ [MeV]
$\Xi_c(2923)^0$	$142.91 \pm 0.25 \pm 0.20$	$2923.04 \pm 0.25 \pm 0.20 \pm 0.14$	$7.1 \pm 0.8 \pm 1.8$
$\Xi_c(2939)^0$	$158.45 \pm 0.21 \pm 0.17$	$2938.55 \pm 0.21 \pm 0.17 \pm 0.14$	$10.2 \pm 0.8 \pm 1.1$
$\Xi_c(2965)^0$	$184.75 \pm 0.26 \pm 0.14$	$2964.88 \pm 0.26 \pm 0.14 \pm 0.14$	$14.1 \pm 0.9 \pm 1.3$

Stat. Sys. input

New excited Ξ_c^0 states?

arXiv: 2211.00812

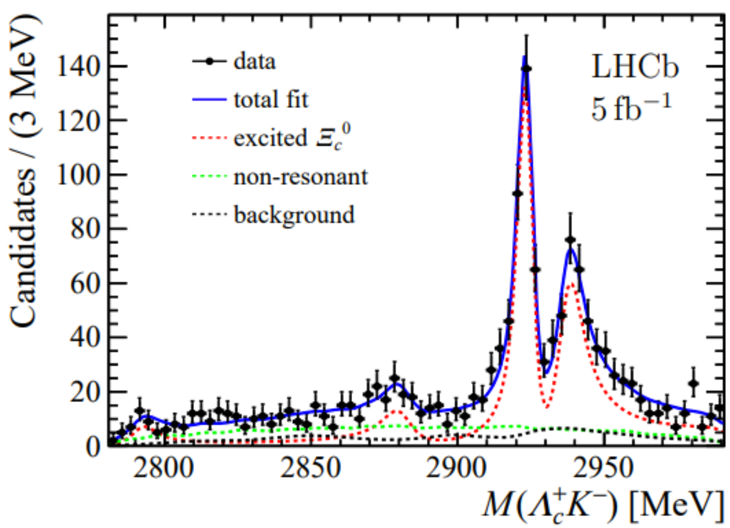
$m(\Lambda_c^+ K^-)$ is studied using $B^- \to \Lambda_c^+ \Lambda_c^- K^-$ decay

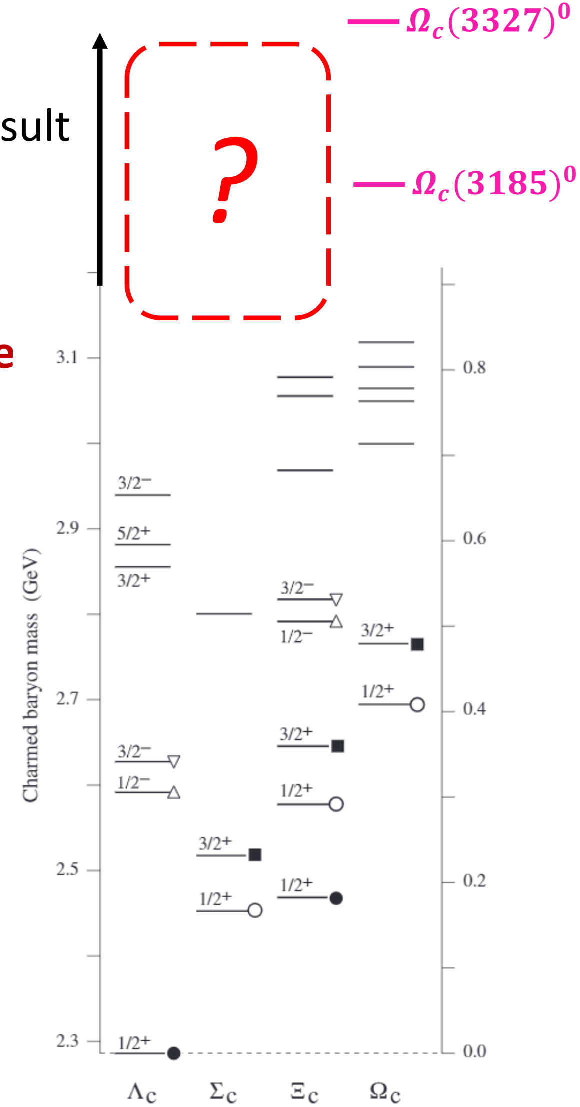
$\Xi_c(2923)^0$ and $\Xi_c(2939)^0$ confirmed, consistent with prompt result

Evidence of $\Xi_c(2880)^0 \to \Lambda_c^+ K^-$ observed (3.8σ)

No structure on $m(\Lambda_c^- K^-)$ and $m(\Lambda_c^+ \Lambda_c^-)$

Search for high mass excited Ξ_c or Σ_c states with other final state





State	Mass (MeV)	Width (MeV)
$\Xi_c(2880)^0$	$2881.8 \pm 3.1 \pm 8.5$	$12.4 \pm 5.2 \pm 5.8$
$\Xi_c(2923)^0$	$2924.5 \pm 0.4 \pm 1.1$	$4.8 \pm 0.9 \pm 1.5$
$\Xi_c(2939)^0$	$2938.5 \pm 0.9 \pm 2.3$	$11.0 \pm 1.9 \pm 7.5$

$$\frac{\mathcal{B}(B^- \to \Lambda_c^+ \Lambda_c^- K^-)}{\mathcal{B}(B^- \to D^+ D^- K^-)} = 2.36 \pm 0.11 \pm 0.22 \pm 0.25$$

Observation of $\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^{+}$

JHEP 05 (2022) 038

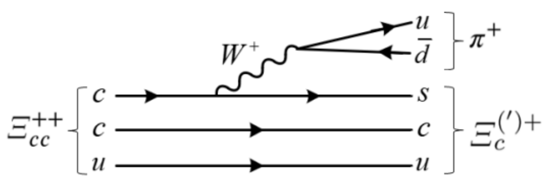
In 2017, Ξ_{cc}^{++} was first observed via $\Xi_{cc}^{++} \to \Lambda_c^{+}K^{-}\pi^{+}\pi^{+}$ at LHCb (Phys. Rev. Lett. 119 (2017) 112001)

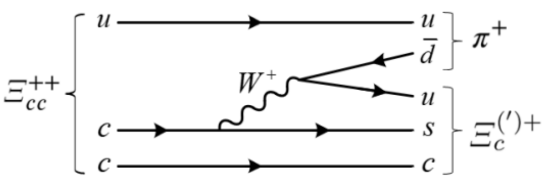
$\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^{+}$ is reconstructed partially using LHCb 2016-2018 dataset

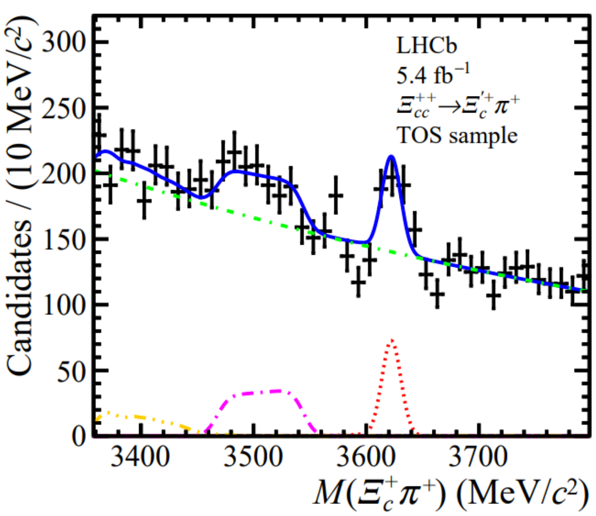
The result is not consistent with current theoretical predictions

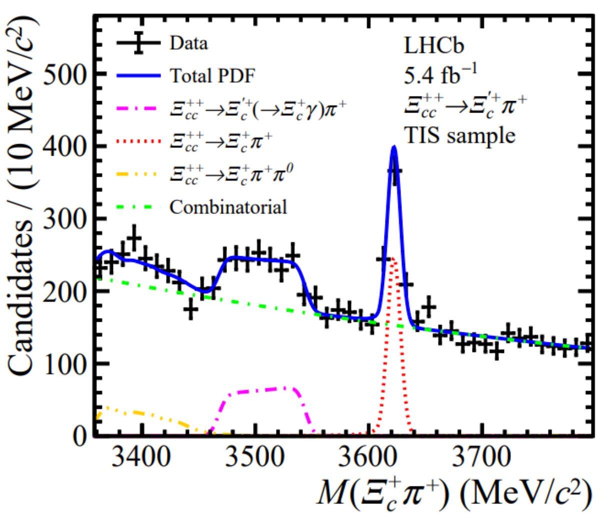
Prediction regions of BF ratio are $(0.30, 0.83)$ or $(4.33, 6.74)$

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^{+})}{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{+}\pi^{+})} = 1.41 \pm 0.17 \pm 0.10$$









Search for $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$

Sci. China Phys. Mech. Astron. (2020) 63: 221062

Using LHCb Run1+Run2 data, at 7, 8, 13 TeV and 9 fb^{-1}

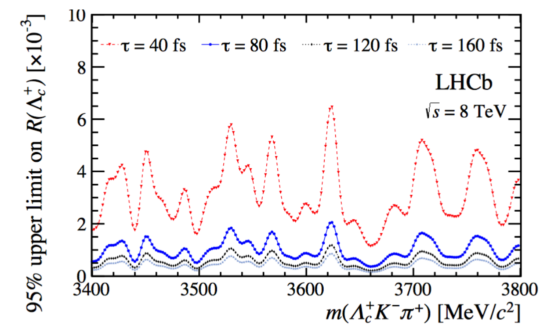
No significant signal is observed in the mass range from 3.4 to 3.8 GeV/c^2

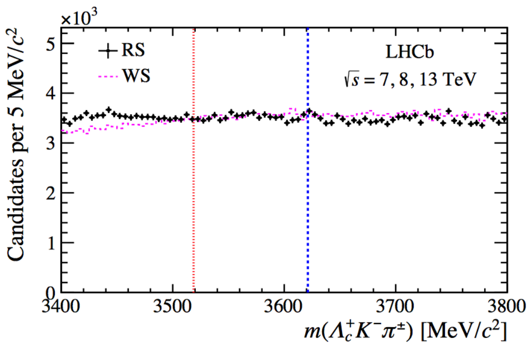
Upper limits are set at 95% credibility level on the ratio of $\sigma \times \mathcal{B}$

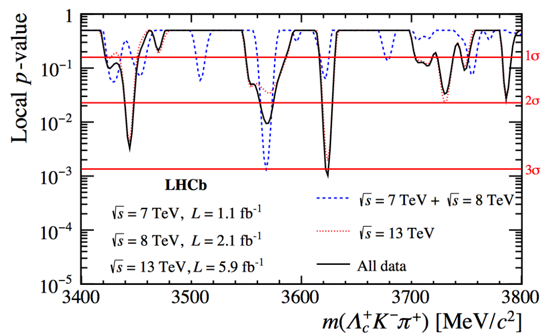
The UL depends strongly on the mass and lifetime of Ξ_{cc}^{+}

0.45×10^{-3} (2.0) for 40 fs to 0.12×10^{-3} (0.5) for 160 fs

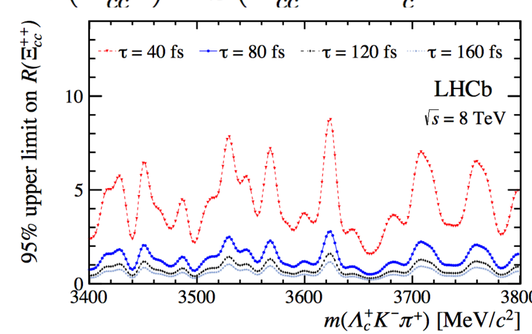
$$\mathcal{R}(\Lambda_c^+) \equiv \frac{\sigma(\Xi_{cc}^+) \times \mathcal{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)}$$







$$\mathcal{R}(\Xi_{cc}^{++}) \equiv \frac{\sigma(\Xi_{cc}^+) \times \mathcal{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}$$



The largest upper limits on production ratios:

Lifetime	$\sqrt{s} = 8$ TeV		$\sqrt{s} = 13$ TeV	
	$\mathcal{R}(\Lambda_c^+)$ [$\times 10^{-3}$]	$\mathcal{R}(\Xi_{cc}^{++})$	$\mathcal{R}(\Lambda_c^+)$ [$\times 10^{-3}$]	$\mathcal{R}(\Xi_{cc}^{++})$
40 fs	6.5	8.8	0.45	2.0
80 fs	2.1	2.8	0.22	1.0
120 fs	1.2	1.6	0.15	0.6
160 fs	0.9	1.2	0.12	0.5

Search for $\Omega_{cc}^{+} \to \Xi_c^{+} K^{-} \pi^{+}$

Sci. China Phys. Mech. Astron. (2021) 64: 101062

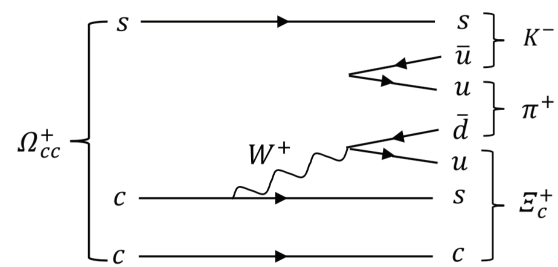
Using LHCb 2016-2018 dataset, at 13 TeV and 5.4 fb^{-1}

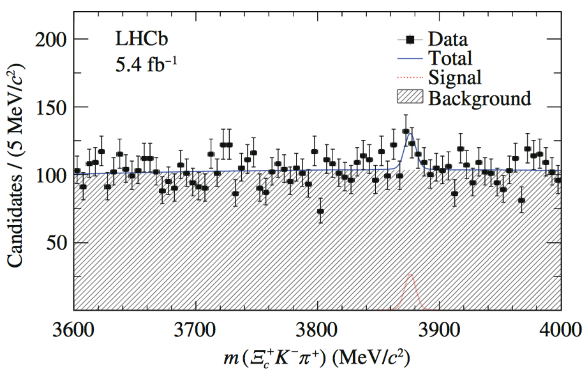
No significant signal is observed within the mass range from 3.6 to 4.0 GeV/c^2

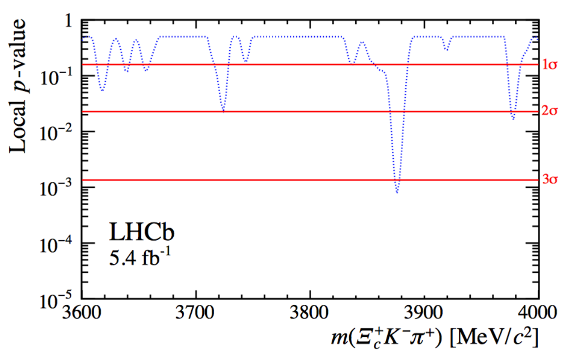
Upper limits are set at 95% credibility level on the ratio of $\sigma \times \mathcal{B}$

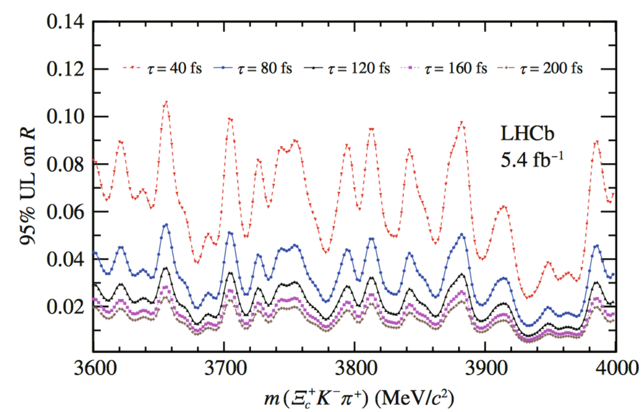
The highest UL is 0.11 (40 fs) and the lowest is 0.005 (200 fs)

$$R \equiv \frac{\sigma(\Omega_{cc}^{+}) \times \mathcal{B}(\Omega_{cc}^{+} \to \Xi_c^{+} K^{-}\pi^{+}) \times \mathcal{B}(\Xi_c^{+} \to pK^{-}\pi^{+})}{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^{+} K^{-}\pi^{+}\pi^{+}) \times \mathcal{B}(\Lambda_c^{+} \to pK^{-}\pi^{+})}$$









Trigger by one of the Ξ_c^{+} (Λ_c^{+}):

Year	α (10^{-2})				
	τ = 40 fs	τ = 80 fs	τ = 120 fs	τ = 160 fs	τ = 200 fs
2016	0.86 ± 0.17	0.46 ± 0.09	0.32 ± 0.06	0.25 ± 0.05	0.22 ± 0.04
2017	1.29 ± 0.20	0.69 ± 0.11	0.48 ± 0.07	0.38 ± 0.06	0.33 ± 0.05
2018	1.26 ± 0.18	0.67 ± 0.10	0.47 ± 0.07	0.37 ± 0.05	0.32 ± 0.05

Conclusions

Presented a selection of the latest LHCb results on charmed baryons

- ✓ Observation of Cabibbo-suppressed two-body decays of Ω_c^0
- ✓ Confirmed the lifetime hierarchy of Ω_c^0 and Ξ_c^0
- ✓ Observation of new excited Ω_c^0 and new excited Ξ_c^0
- ✓ Observation of $\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^+$ and searches for Ξ_{cc}^+ and Ω_{cc}^+

Provides a wealth of information for theory community

More data is need to confirm and better investigate these results

Thank you for your attention!