HADRON 2021

19th International Conference on
Hadron Spectroscopy and Structure

LHCb results in charmed baryons

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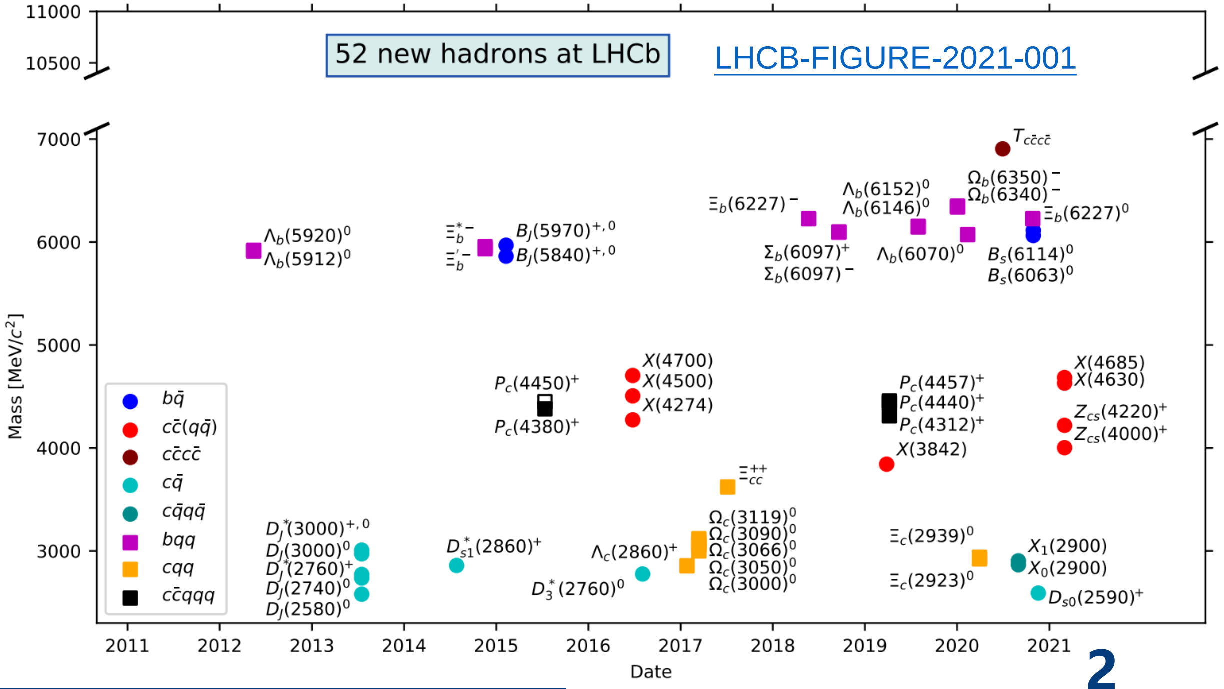
LHCb

Introduction

- LHCb collected the **largest samples** of reconstructed charmed hadrons during LHC Run 1 and Run 2.

- Providing the **most precise measurements** of properties and production of known charmed baryons.

- Recent result：
  - ➢**Excited charmed baryons**
    - ➢$\Omega_c^{**0}, \Xi_c^{**0}$
  - ➢**Double charmed baryons**
    - ➢$\Xi_{cc}^{+}, \Omega_{cc}^{+}$
  - ➢**Properties**
    - ➢**Lifetime**
    - ➢**Branching fraction**

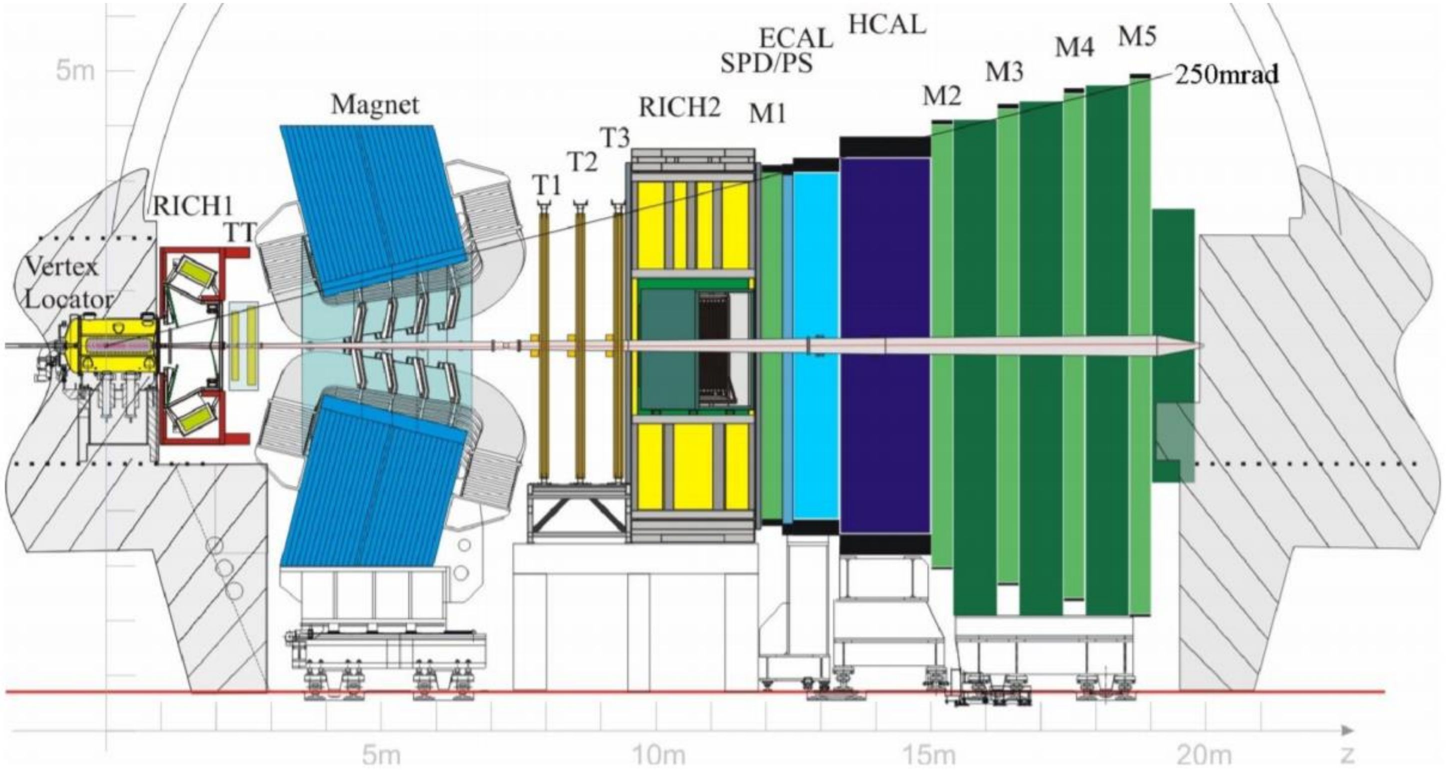


LHCb experiment

$\sigma_{\mathrm{IP}} = 20\ \mu\mathrm{m}$
$\sigma_{\tau} = 45\ \mathrm{fs}$

$\sigma_p/p \sim 0.5\% - 1\%$
$\sigma_E/E = \frac{10\%}{\sqrt{E}} \pm 1\%$

$\epsilon(K \to K) \sim 95\%$
Mis-ID $\epsilon(\pi \to K) \sim 5\%$



- LHCb designed for study charmed and bottom hadron.
- Excellent vertex, tracking and PID performance.

Excited Ω_c^0

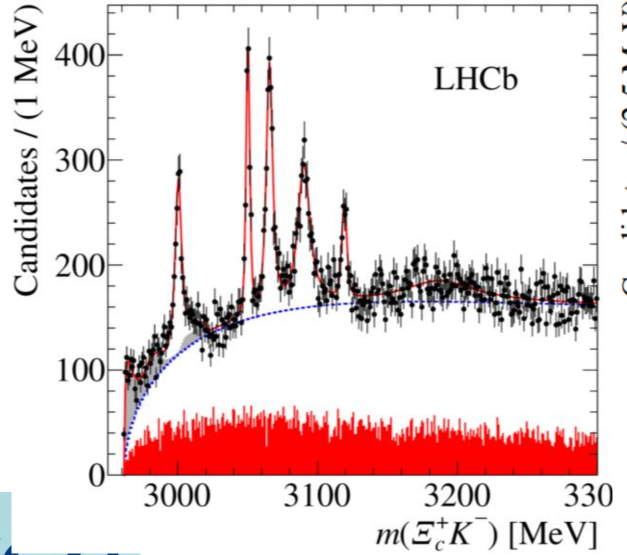
- In 2017, LHCb observed five new excited Ω_c^0 in $m(\Xi_c^+ K^-)$.

  PHYS. REV. LETT. 118 (2017) 182001

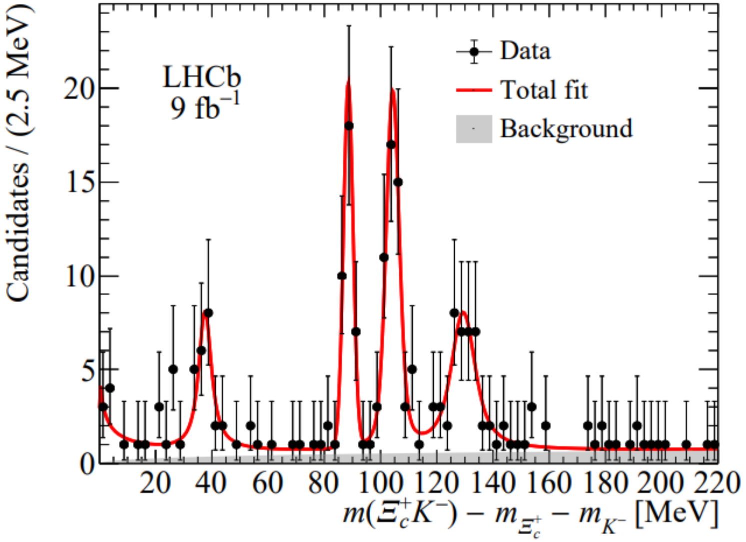
- In 2021, LHCb observed 4 of them from $\Omega_b \to \Omega_c \pi$.

  ARXIV:2107.03419.

  FIND MORE DETAILS IN SARA ELIZABETH MITCHELL'S TALK.



2017 result



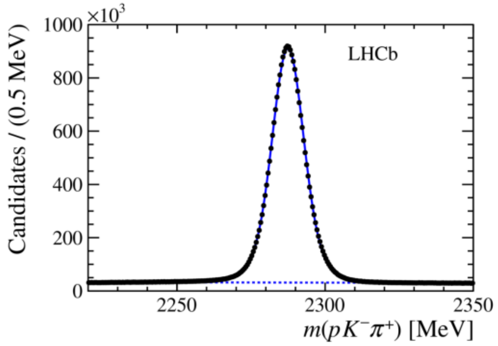
2021 result

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	Stat. Sys. $4.3\,\sigma$
$\Omega_c(3000)^0$	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

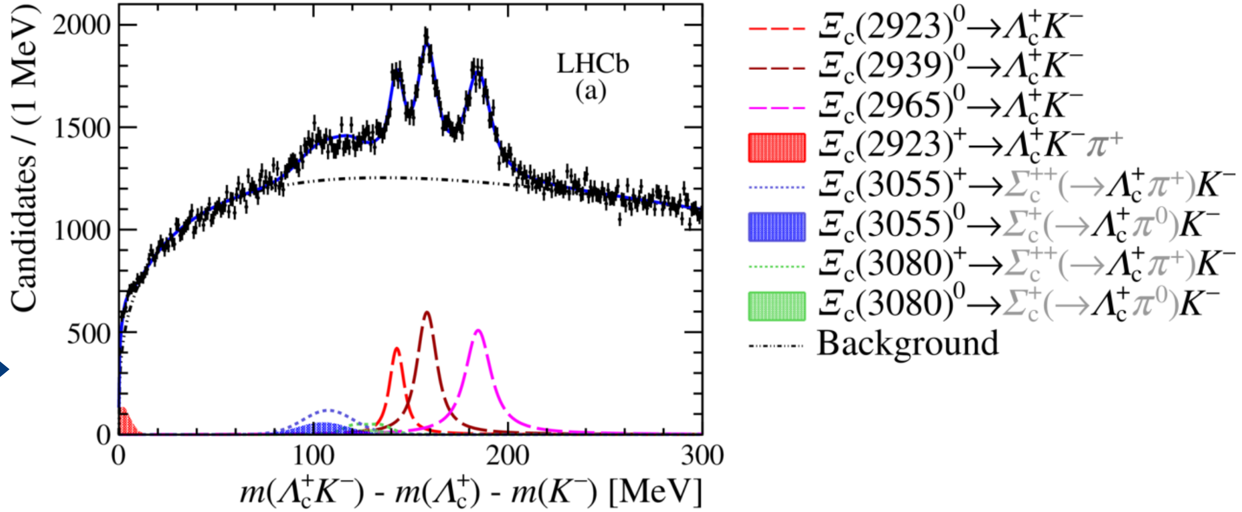
$\Xi_c^{**0} \to \Lambda_c^+ K^-$

PHYS. REV. LETT. 124 (2020) 222001

- Three excited Ξ_c^0 were observed in $m(\Lambda_c^+ K^-)$.
- Using LHCb 2016-2018 data, at 13 TeV and 5.4 fb^{-1}.
- Multivariate method was used in the selection of Λ_c^+.



$+K^- \rightarrow$



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

$\Xi_c^{**0} \to \Lambda_c^+ K^-$

[PHYS. REV. LETT. 124 (2020) 222001]

- Gell-Mann-Okubo formula for charmed baryons:

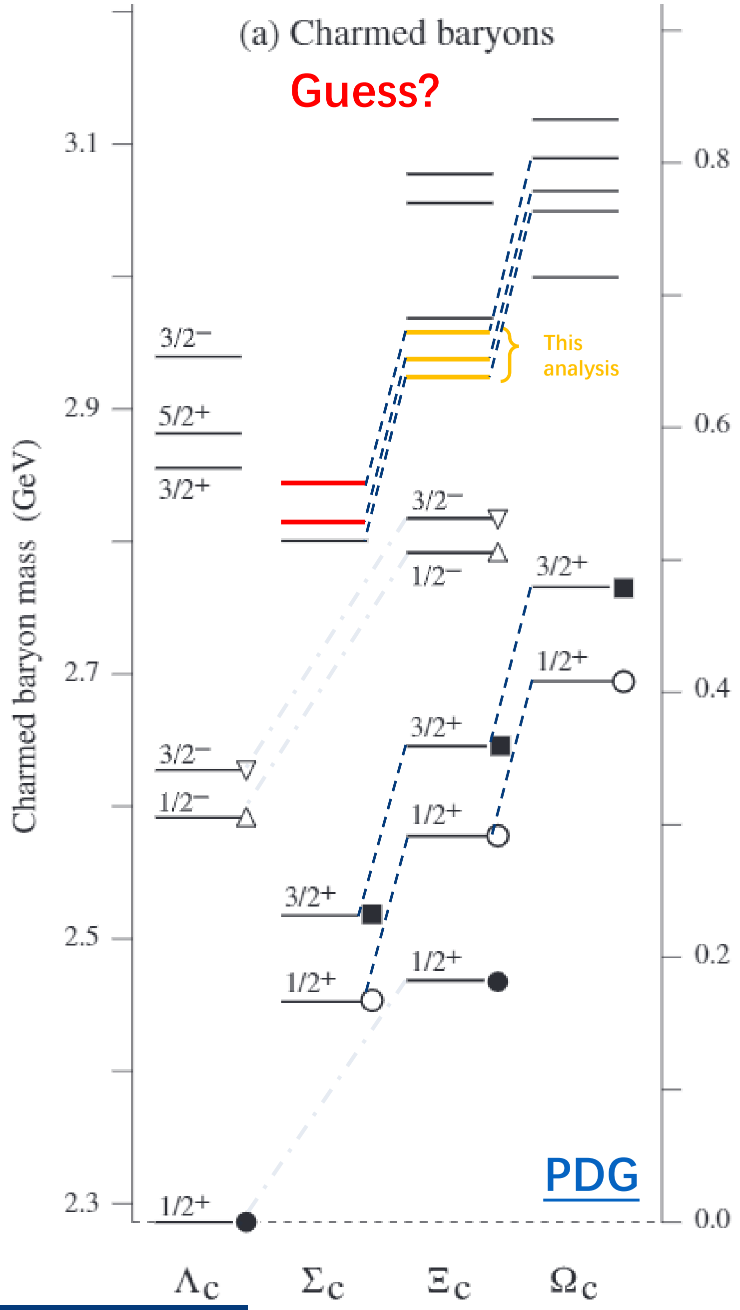
$$m(\Omega_c^{**}) - m(\Xi_c^{**}) = m(\Xi_c^{**}) - m(\Sigma_c^{**})$$

- After this analysis, we have:

$$m(\Omega_c^0(3050)) - m(\Xi_c^0(2923))$$
$$\approx m(\Xi_c^0(2923)) - m(\Sigma_c^0(2800)) \approx 125\text{ MeV}$$
$$m(\Omega_c^0(3065)) - m(\Xi_c^0(2939)) \approx 125\text{ MeV}$$
$$m(\Omega_c^0(3090)) - m(\Xi_c^0(2965)) \approx 125\text{ MeV}$$

- They should belong to the same flavour multiplets?
  - If so, their quantum number should be the same.
  - Spin-parities test should be done to confirm that.

- More topic…
  - Dominant decay ($\Xi_c^+\pi^-, \Xi_c'^+\pi^-$).
  - Inner structure (molecular states?).

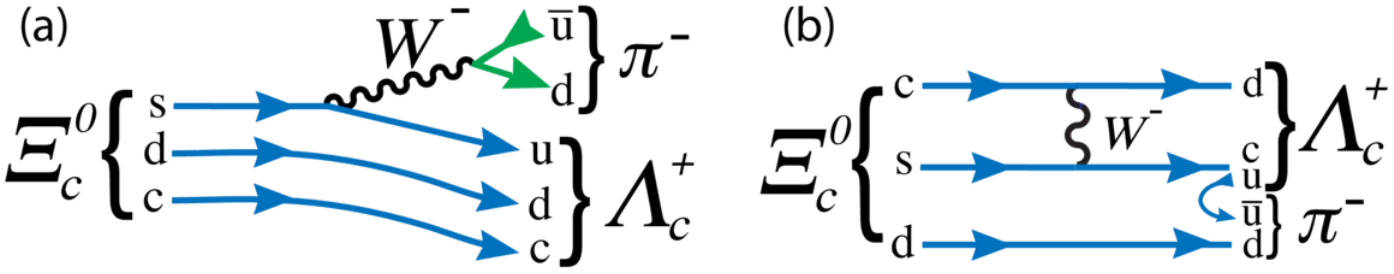


$\mathcal{B}(\Xi_c^0 \to \Lambda_c^+ \pi^-)$

PHYS. REV. D102 (2020) 071101(R)

- Usually, Ξ_c^0 decay into the charmless final states by the $c \to s$ transition. It also can decay in to $\Lambda_c^+\pi^-$ by $cs \to dc$ weak scattering.

- For this decay, there are two amplitudes (SUUD and WS), and their interference can be positive or negative.



SUUD WS

$\mathcal{B}(\Xi_c^0 \to \Lambda_c^+\pi^-)$

PHYS. REV. D102 (2020) 071101(R)

- Firstly measured the $\mathcal{B}(\Xi_c^0 \to \Lambda_c^+\pi^-)$ in 2017-2018 LHCb data.
- This branching fraction was determined by two observables:

$$\mathcal{R}_1 \equiv \frac{N(\Xi_c^0)}{N(\Lambda_c^+)} = \frac{f_{\Xi_c^0}}{f_{\Lambda_c^+}} \mathcal{B}(\Xi_c^0 \to \Lambda_c^+\pi^-)$$

And [derivation]

$$\mathcal{R}_2 \equiv \frac{N(\Xi_c^0)}{N(\Xi_c^+)} = \frac{f_{\Xi_c^0}}{f_{\Xi_c^+}} \cdot \frac{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)} \cdot \mathcal{B}(\Xi_c^0 \to \Lambda_c^+\pi^-)$$

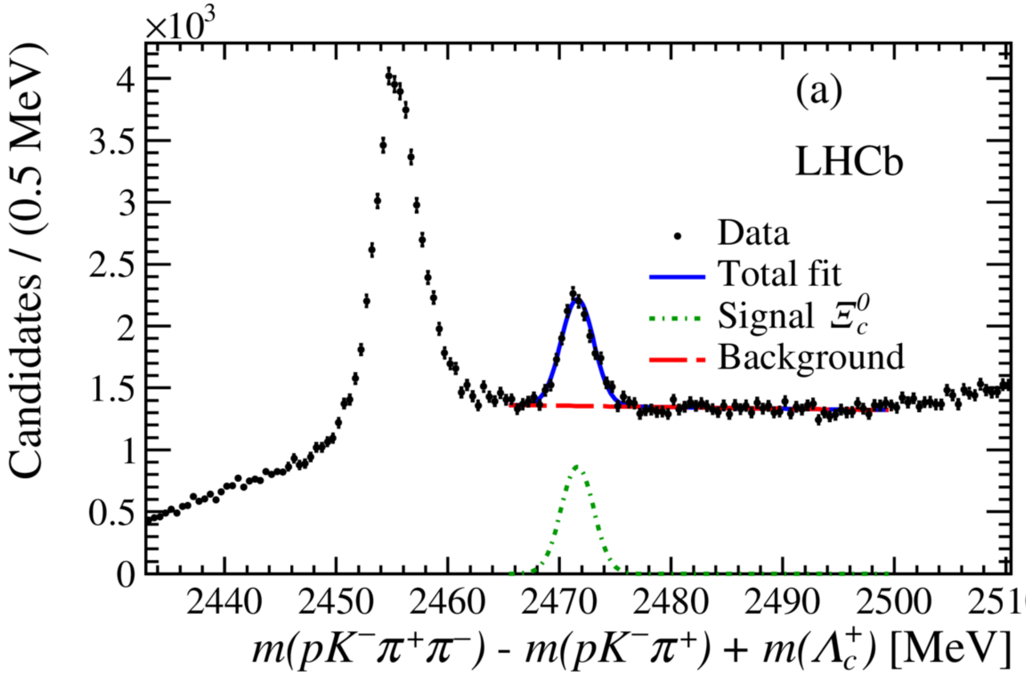
- The result of these observables:

$$\mathcal{R}_1 = (0.095 \pm 0.003 \pm 0.012)\%$$
$$\mathcal{R}_2 = (5.70 \pm 0.19 \pm 0.07)\%$$

- Then the branching fraction can be calculate:

$$\boldsymbol{\mathcal{B}(\Xi_c^0 \to \Lambda_c^+\pi^-) = (0.55 \pm 0.02 \pm 0.18)\%}$$

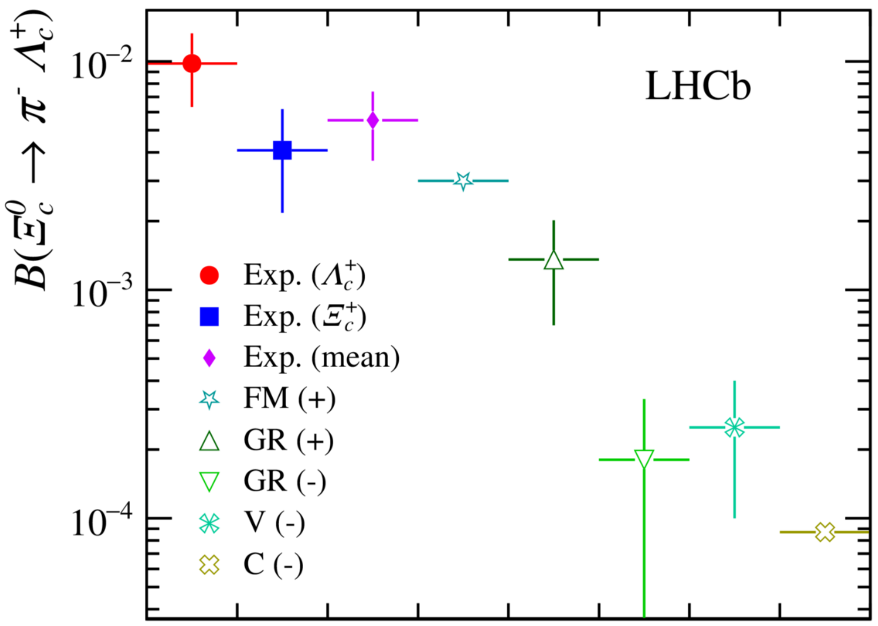
Stat. Sys.

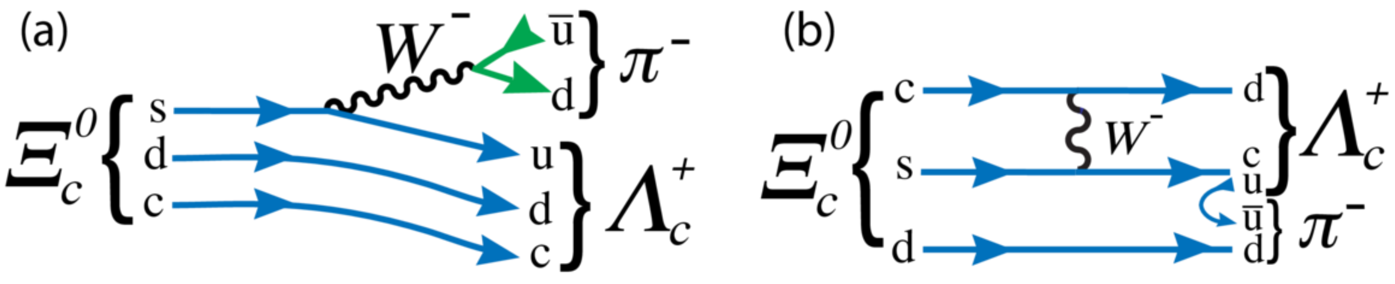


$\mathcal{B}(\Xi_c^0 \to \Lambda_c^+ \pi^-)$

PHYS. REV. D102 (2020) 071101(R)

- Interference between SUUD and WS can be obtained from this measurement.
- This result is in agreement with the positive assuming.





Lifetimes of charmed baryons

- The expected lifetime of single charmed baryons hierarchy should be:

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

Frontiers of Physics 10.6 (2015): 101406.
International Journal of Modern Physics A 30.10 (2015): 1543005.

Or

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

JHEP 11(2018)014

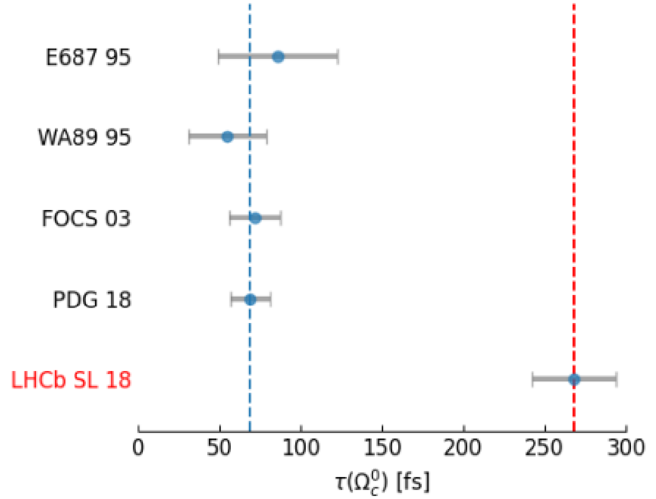
- Measurement results before 2018:

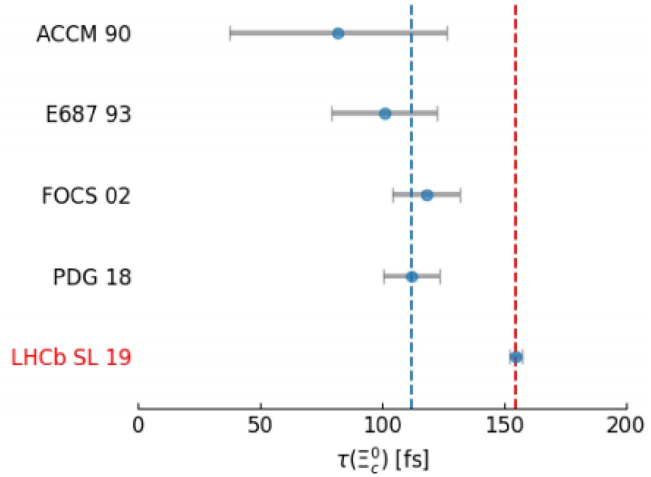
$$\tau_{\Xi_c^+} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0} > \tau_{\Omega_c^0}$$

- LHCb Run-1 result with signals from semi-leptonic beauty-hadron decays:

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

PHYS. REV. LETT. 121 (2018) 092003
PHYS. REV. D100 (2019) 032001



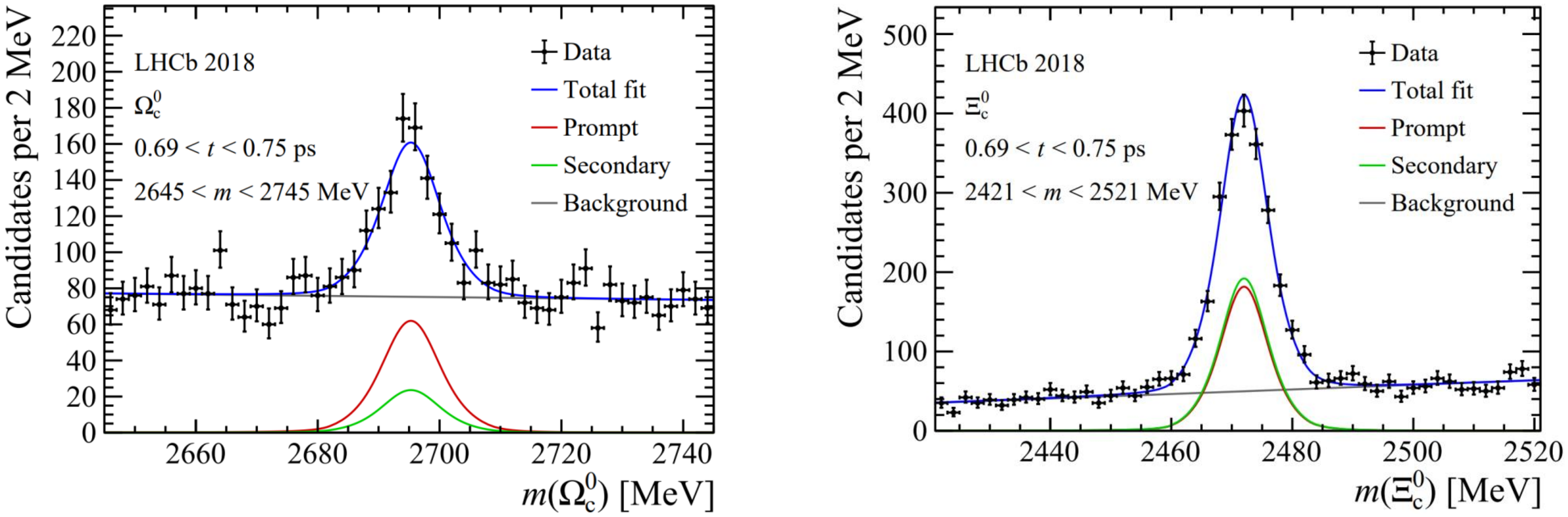


Lifetimes of Ω_c^0 and Ξ_c^0

New

PAPER-2021-021 (IN PREPARATION)

- The lifetimes of Ω_c^0 and Ξ_c^0 baryons is measured in 2016-2018 data.
- Both Ω_c^0 and Ξ_c^0 were reconstructed in the $pK^-K^-\pi^+$ final states.

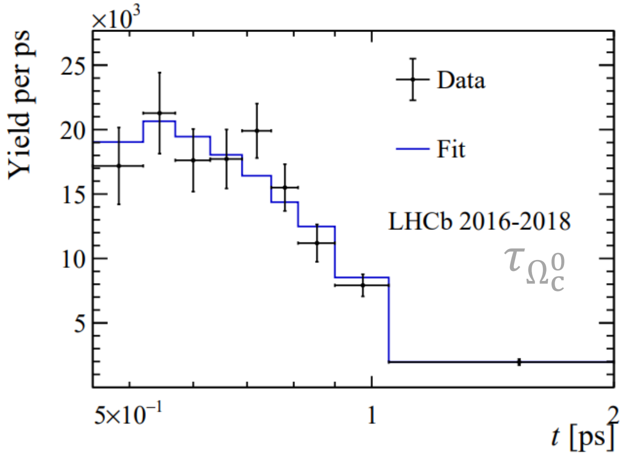


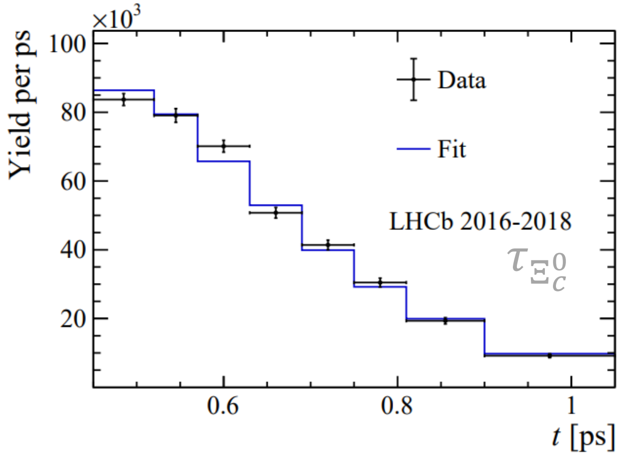
Prompt: candidates from pp interaction point.
Secondary: candidates from b-hadron decay.

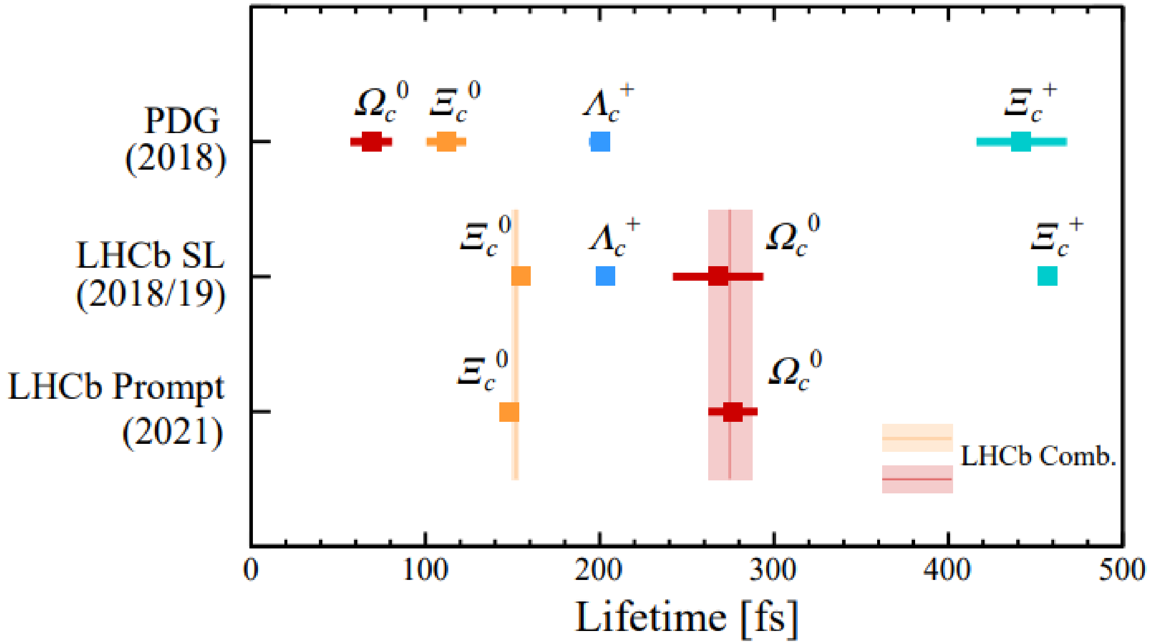
New

Lifetimes of Ω_c^0 and Ξ_c^0

PAPER-2021-021 (IN PREPARATION)







- Results from this analysis:

$$\tau_{\Omega_c^0} = (276.5 \pm \overset{\text{Stat.}}{13.4} \pm \overset{\text{Sys.}}{4.3} \pm \overset{\text{input}}{0.7})\ \text{fs}$$
$$\tau_{\Xi_c^0} = (148.0 \pm 2.3 \pm 2.2 \pm 0.2)\ \text{fs}$$

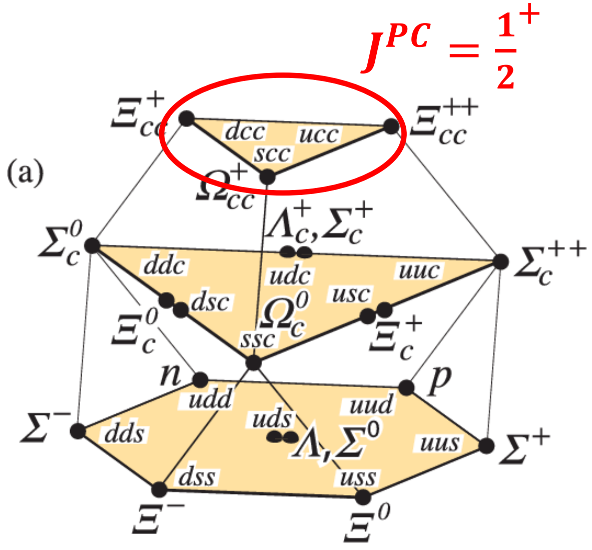
- Combine with previous results:

PHYS. REV. LETT. 121 (2018) 092003
PHYS. REV. D100 (2019) 032001

$$\tau_{\Omega_c^0} = (274.6 \pm 12.4)\ \text{fs}$$
$$\tau_{\Xi_c^0} = (152.0 \pm 2.0)\ \text{fs}$$

Doubly charmed baryons

- Doubly charmed baryons were predicted by $SU(4)$ multiplet. $\Xi_{cc}^{++}(ucc), \Xi_{cc}^{+}(dcc), \Omega_{cc}^{+}(scc)$.



- A lot of Ξ_{cc}^{++} study done by LHCb:
  - Mass

    Stat. Sys.

    $$m(\Xi_{cc}^{++}) = 3621.55 \pm 0.23 \pm 0.30\ \mathrm{MeV}/c^2$$

    JHEP 02 (2020) 049
  - Lifetime

    $$\tau(\Xi_{cc}^{++}) = 0.256^{+0.024}_{-0.022} \pm 0.014\ \mathrm{ps}$$

    PRL 121 (2018) 052002
  - Production

    $$\frac{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}{\sigma(\Lambda_c^+)} = 2.22 \pm 0.27 \pm 0.29$$

    CPC44 (2020) 022001
  - Branching fraction

$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$

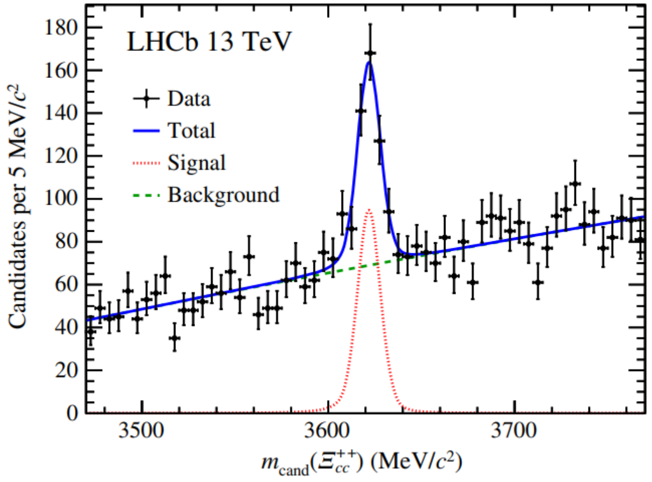
$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) \times \mathcal{B}(\Xi_c^+ \to p K^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+) \times \mathcal{B}(\Lambda_c^+ \to p K^- \pi^+)} = 0.035 \pm 0.009 \pm 0.003$$

PRL 121 (2018) 162002

$\Xi_{cc}^{++} \to D^+ p K^- \pi^+$

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to D^+ p K^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)} < 1.7$$

JHEP 10 (2019) 124



First observation in $m(\Lambda_c^+ K^- \pi^+ \pi^+)$

PRL 119 (2017) 112001

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

SCPMA 63 (2020) 221062

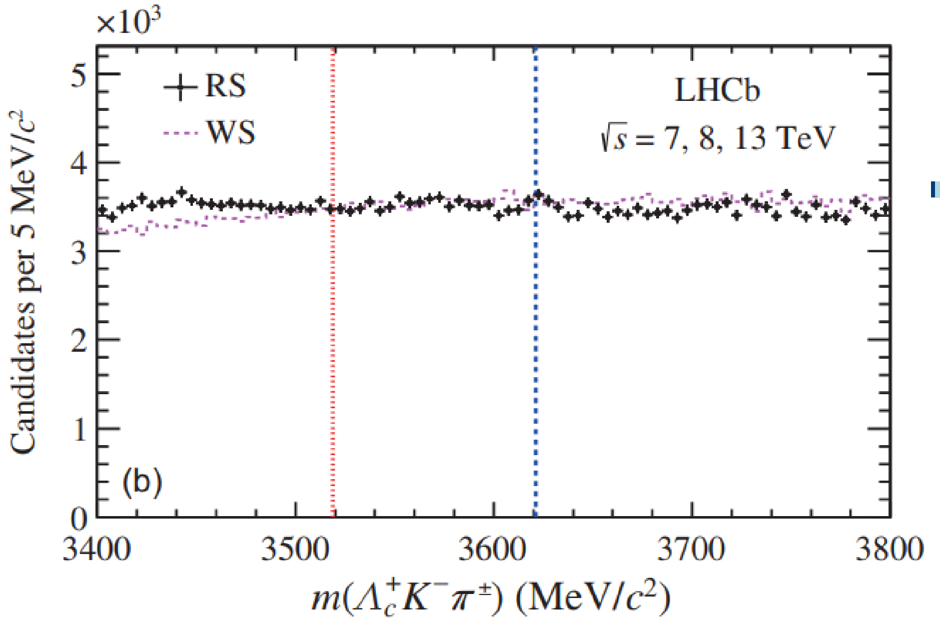
- Search for Ξ_{cc}^{+} in $\Lambda_c^{+} K^{-} \pi^{+}$ final states.
- Using all LHCb data, $9\ \text{fb}^{-1}$.

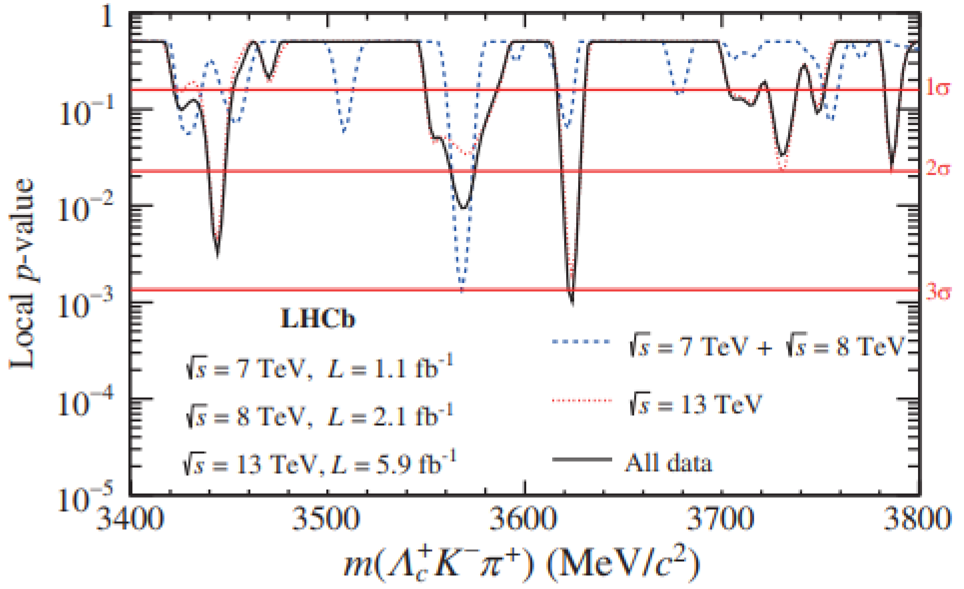
- No significant signal was observed.
- Local (global) significance is 2.7σ (1.7σ)

- Upper limit of $\mathcal{R}(\Lambda_c^{+}/\Xi_{cc}^{++})$ were set at 95% CL.

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

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

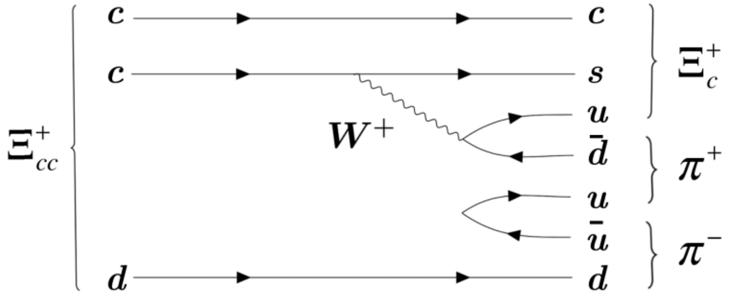


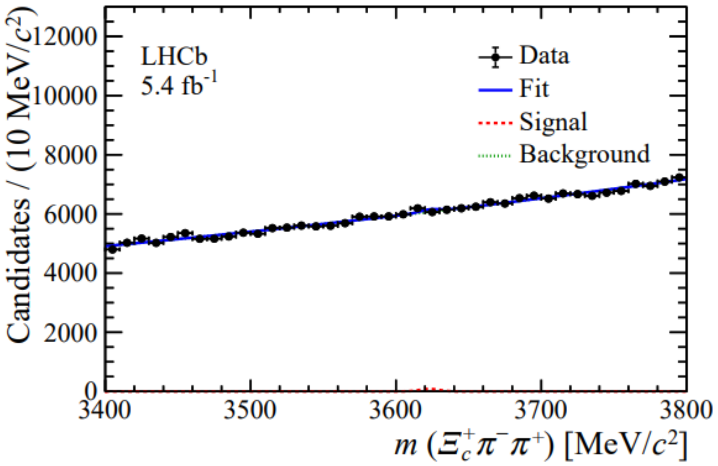


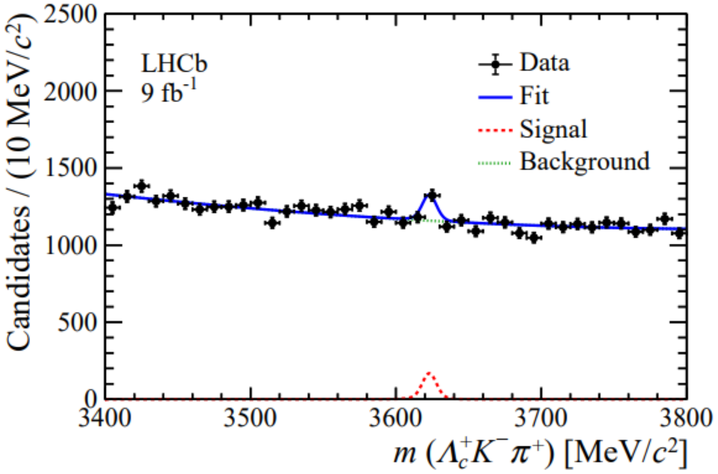
Search for Ξ_{cc}^{+} in $\Xi_{c}^{+}\pi^{-}\pi^{+}$

PAPER-2021-019 (IN PREPARATION)

- Search for Ξ_{cc}^{+} in $\Xi_{c}^{+}\pi^{-}\pi^{+}$ final states.
- Using LHCb 2016-2018 data, at 13 TeV and 5.4 fb^{-1}.
- No significant signal. Local significance is 2.3σ
- Combine with $\Xi_{cc}^{+} \to \Lambda_{c}^{+}K^{-}\pi^{+}$ result. SCPMA 63 (2020) 221062







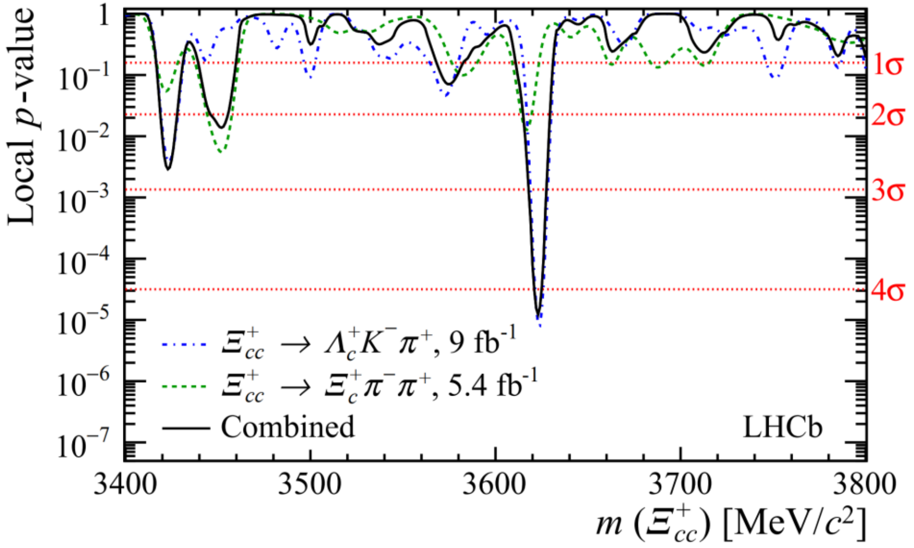
New

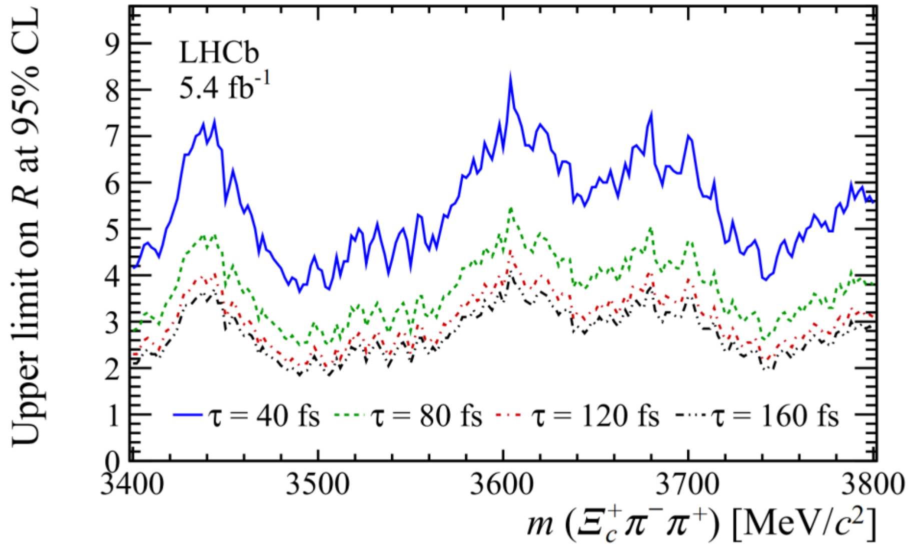
Search for Ξ_{cc}^{+} in $\Xi_c^{+}\pi^{-}\pi^{+}$

PAPER-2021-019 (IN PREPARATION)

- Combined local (global) significance 4.0 σ (2.9 σ). Best fit found around 3623.0 MeV.
- Upper limit scan done in $3.4 - 3.8\ \mathrm{GeV}$ on R for different lifetime hypotheses at 95% CL.

$$\boldsymbol{R} = \frac{\sigma(\Xi_{cc}^{+}) \times \mathcal{B}(\Xi_{cc}^{+} \to \Xi_c^{+}\pi^{-}\pi^{+})}{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{+}\pi^{+})}$$



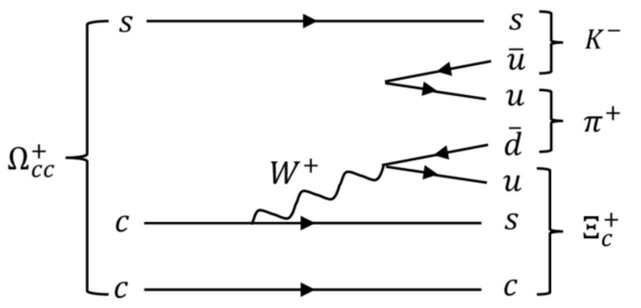


Search for Ω_{cc}^{+} in $\Xi_c^{+} K^{-} \pi^{+}$

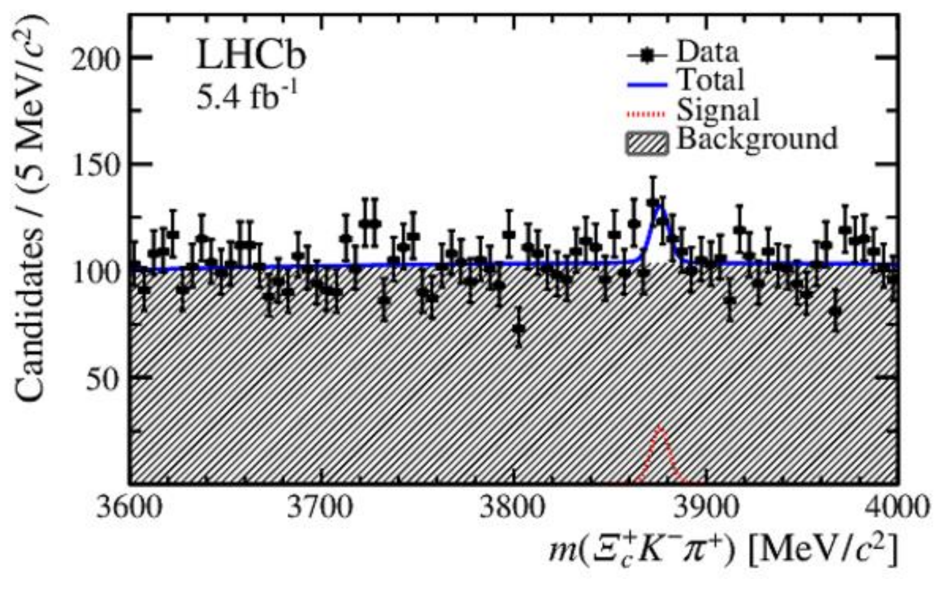
New

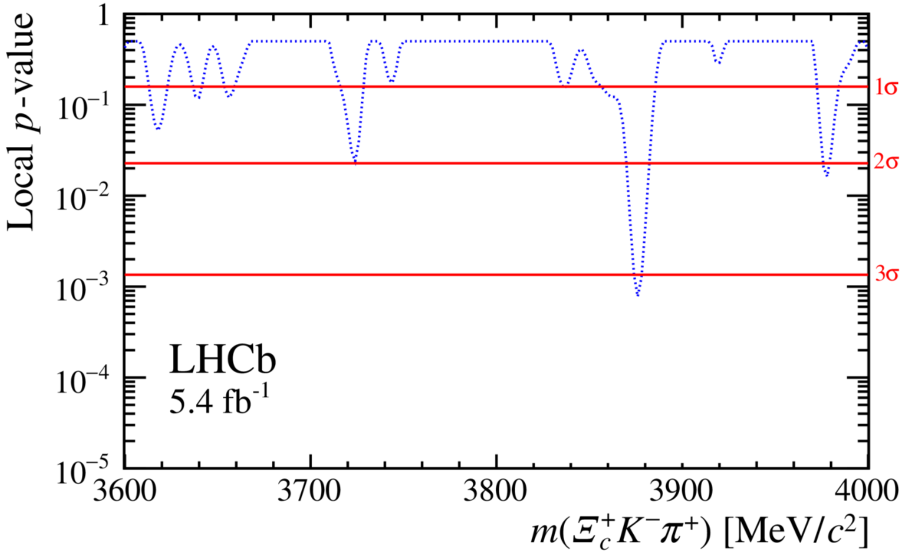
[ARXIV:2105.06841]

- First searching for Ω_{cc}^{+} in $\Xi_c^{+} K^{-} \pi^{+}$ final states.
- Using LHCb 2016-2018 data, at 13 TeV and 5.4 fb^{-1}.



- 3.2σ (1.8σ) for local (global) significance, the largest local significance found around 3876.1 MeV.





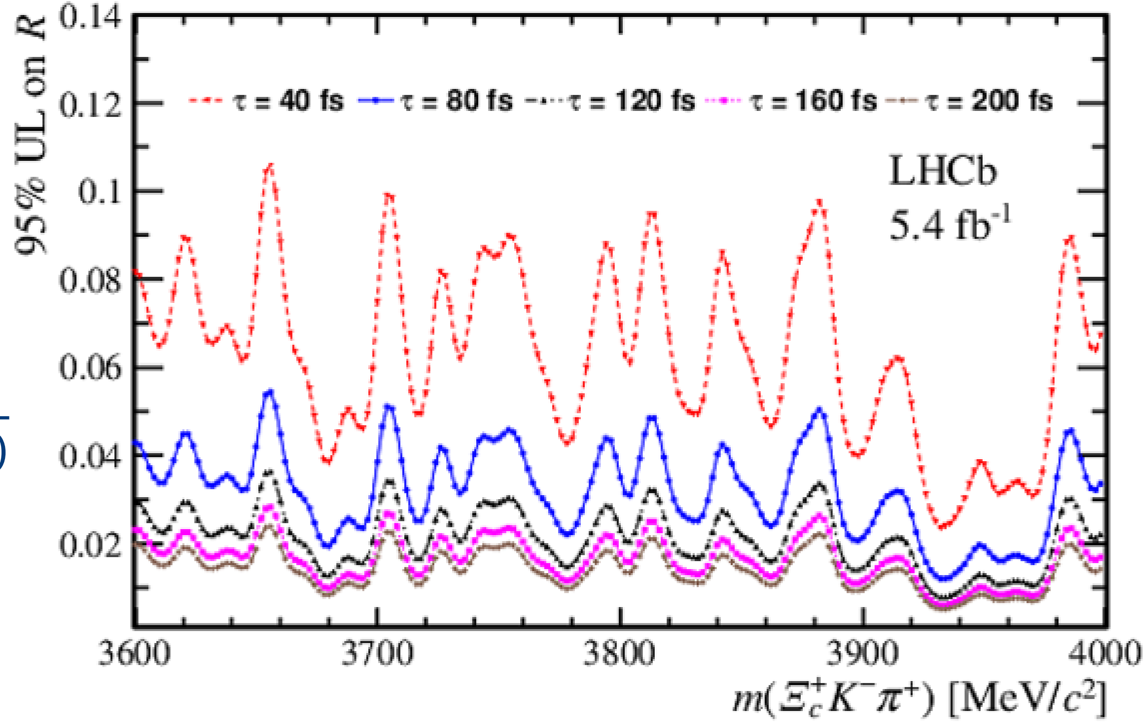
New

Search for Ω_{cc}^{+} in $\Xi_c^+ K^- \pi^+$

ARXIV:2105.06841

- Global significance $< 3\sigma$
- Upper limit scan done in $3.6-4.0\ \mathrm{GeV}$ on R for different lifetime hypotheses at 95% CL.

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



Summary

- Charmed baryons
  - Observation of excited Ω_c^0 baryons
  - Observation of excited Ξ_c^0 baryons
  - First branching fraction measurement of the $\Xi_c^0 \to \Lambda_c^+ \pi^-$
  - Lifetime measurement of Ω_c^0 and Ξ_c^0 baryons

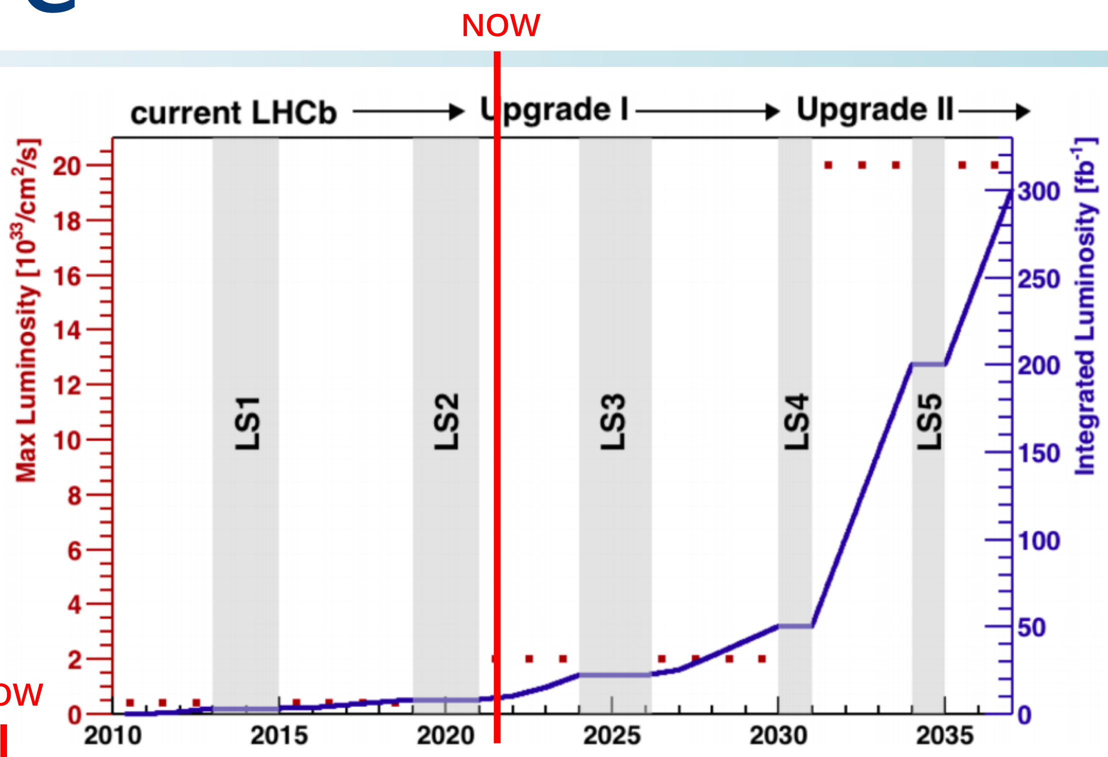
More states to be found...

More precise measurement to be done...

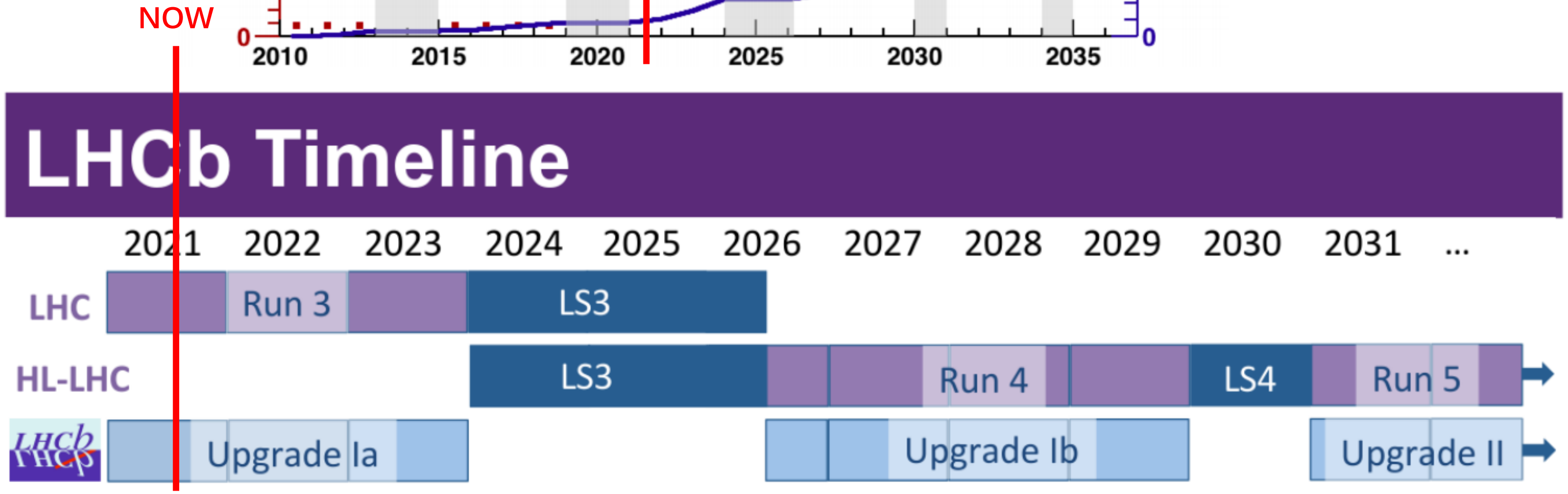
- Double charmed baryons
  - Search for the doubly charmed baryon Ω_{cc}^+
  - Search for the doubly charmed baryon Ξ_{cc}^+

More events to be accumulate···

Future



- More and more charmed baryons will be found.
- Properties will be measured more precisely.



Thanks!

Lifetime of Ω_c^0 and Ξ_c^0 New

PAPER-2021-021 (IN PREPARATION)

- The lifetimes of the Ω_c^0 and Ξ_c^0 baryons are determined from a binned χ^2 fit to the data collected in 2016–2018, which is constructed as:

$$\chi^2(\tau,\vec{C}) = \sum_{\text{year}}\sum_{i} \frac{\left(N^{\text{sig}}_{i,\text{year}} - C_{\text{year}} \times F_i(\tau) \times \frac{N^{\text{con}}_{i,\text{year}}}{M^{\text{con}}_{i,\text{year}}} \times M^{\text{sig}}_{i,\text{year}}\right)^2}{\sigma^2_{N^{\text{sig}}_{i,\text{year}}} + C^2_{\text{year}} \times F_i^2(\tau) \times \sigma^2_{\left(\frac{N^{\text{con}}_{i,\text{year}}}{M^{\text{con}}_{i,\text{year}}} \times M^{\text{sig}}_{i,\text{year}}\right)}},$$

$$F_i(\tau) = \frac{\int_i \exp(-t/\tau)\mathrm{d}t}{\int_i \exp(-t/\tau_{\text{sim}})\mathrm{d}t} \Big/ \frac{\int_i \exp(-t/\tau^{\text{con}})\mathrm{d}t}{\int_i \exp(-t/\tau^{\text{con}}_{\text{sim}})\mathrm{d}t}$$

where $N^{sig}_{i,year}$ ($N^{con}_{i,year}$) is the signal yield in data for the signal (control) mode in decay-time bin i and for each year, M is the effective yield predicted from simulation. $F_i(\tau)$ aim to account for the difference in lifetime between the data and the simulated samples and C is a normalisation factor for this term. σ is the uncertainty of the relevant quantity.

$\Xi_c^{**0} \to \Lambda_c^+ K^-$

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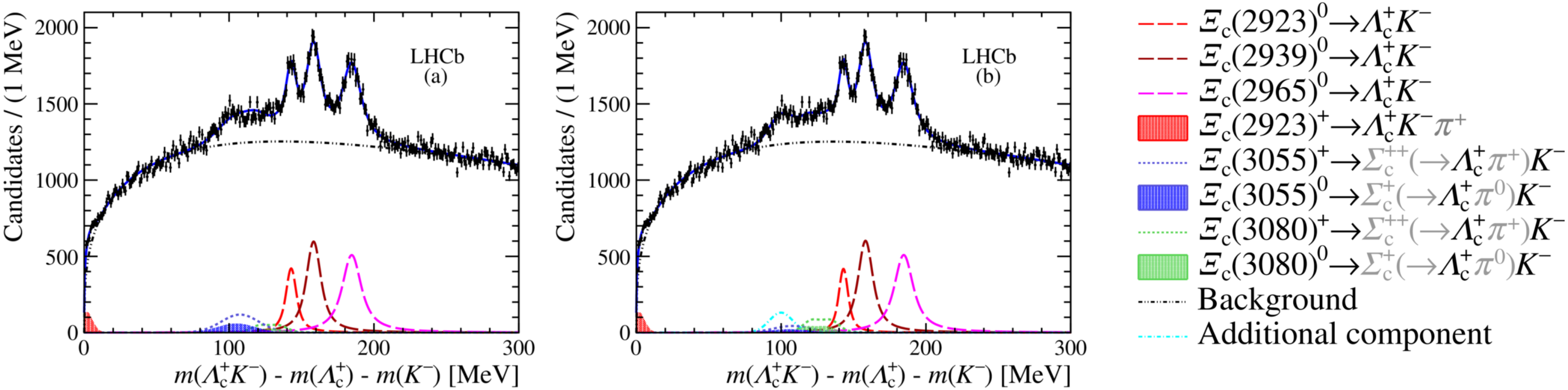
- Alternative fit with one additional components which need to be explain.



- More data are required to understanding this structure.

Derivation of $\mathcal{R}_1$

$$\mathcal{B}(\Xi_c^0 \to \pi^- \Lambda_c^+) = N(\Xi_c^0 \to \pi^- \Lambda_c^+)/N(\Xi_c^0)$$

$$N(\Xi_c^0) = \frac{f_{\Xi_c^0}}{f_{\Lambda_c^+}} \cdot N(\Lambda_c^+).$$

$$\frac{f_{\Xi_c^0}}{f_{\Lambda_c^+}} = \mathcal{C} \cdot \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}},$$

$$\mathcal{B}(\Xi_c^0 \to \pi^- \Lambda_c^+) = \underbrace{\frac{N(\Xi_c^0 \to \pi^- (\Lambda_c^+ \to pK^-\pi^+))}{N(\Lambda_c^+ \to pK^-\pi^+)}}_{\mathcal{R}_1:} \cdot \underbrace{\frac{1}{\mathcal{C}} \cdot \frac{f_{\Lambda_b^0}}{f_{\Xi_b^-}}}_{\text{Known}}.$$

$\mathcal{R}_1$: Known

Derivation of $\mathcal{R}_2$

$$\mathcal{B}(\Xi_c^0 \to \pi^- \Lambda_c^+) = N(\Xi_c^0 \to \pi^- \Lambda_c^+)/N(\Xi_c^0)$$

$$N(\Xi_c^0) = \frac{f_{\Xi_c^0}}{f_{\Xi_c^+}} \cdot N(\Xi_c^+)$$

$$\frac{f_{\Xi_c^0}}{f_{\Xi_c^+}} \approx 1$$

$$\mathcal{B}(\Xi_c^0 \to \pi^- \Lambda_c^+) = N(\Xi_c^0 \to \pi^- \Lambda_c^+)/N(\Xi_c^+).$$

$$\mathcal{B}(\Xi_c^+ \to pK^-\pi^+) = \underbrace{\frac{N(\Xi_c^+ \to pK^-\pi^+)}{N(\Lambda_c^+ \to pK^-\pi^+)}}_{\text{Can be measured}} \cdot \underbrace{\frac{1}{\mathcal{C}} \cdot \frac{f_{\Lambda_b^0}}{f_{\Xi_b^-}} \cdot \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}_{\text{Known}},$$

$$\mathcal{B}(\Xi_c^0 \to \pi^- \Lambda_c^+) = \underbrace{\frac{N(\Xi_c^0 \to \pi^- (\Lambda_c^+ \to pK^-\pi^+))}{N(\Xi_c^+ \to pK^-\pi^+)}}_{\mathcal{R}_2} \cdot \frac{\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}.$$

$\mathcal{R}_2$: