# LHCb results in charm baryons

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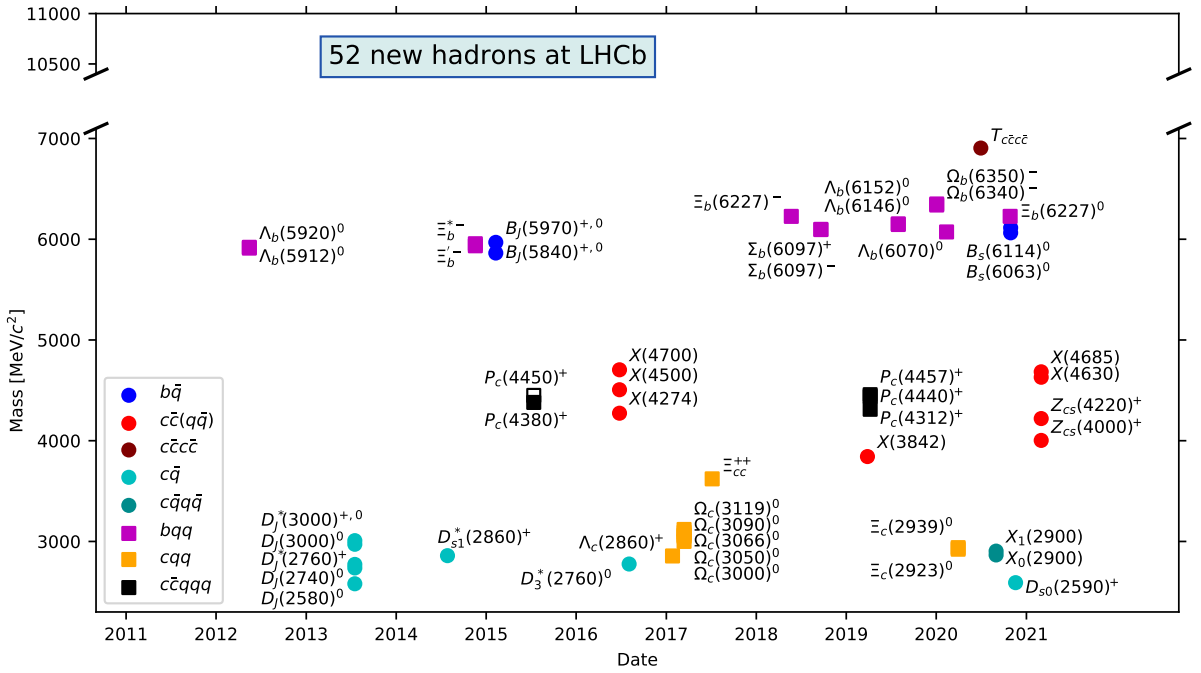
**on behalf of the LHCb Collaboration**

**QCD 2021**

**5 July 2021 – 9 July 2021**

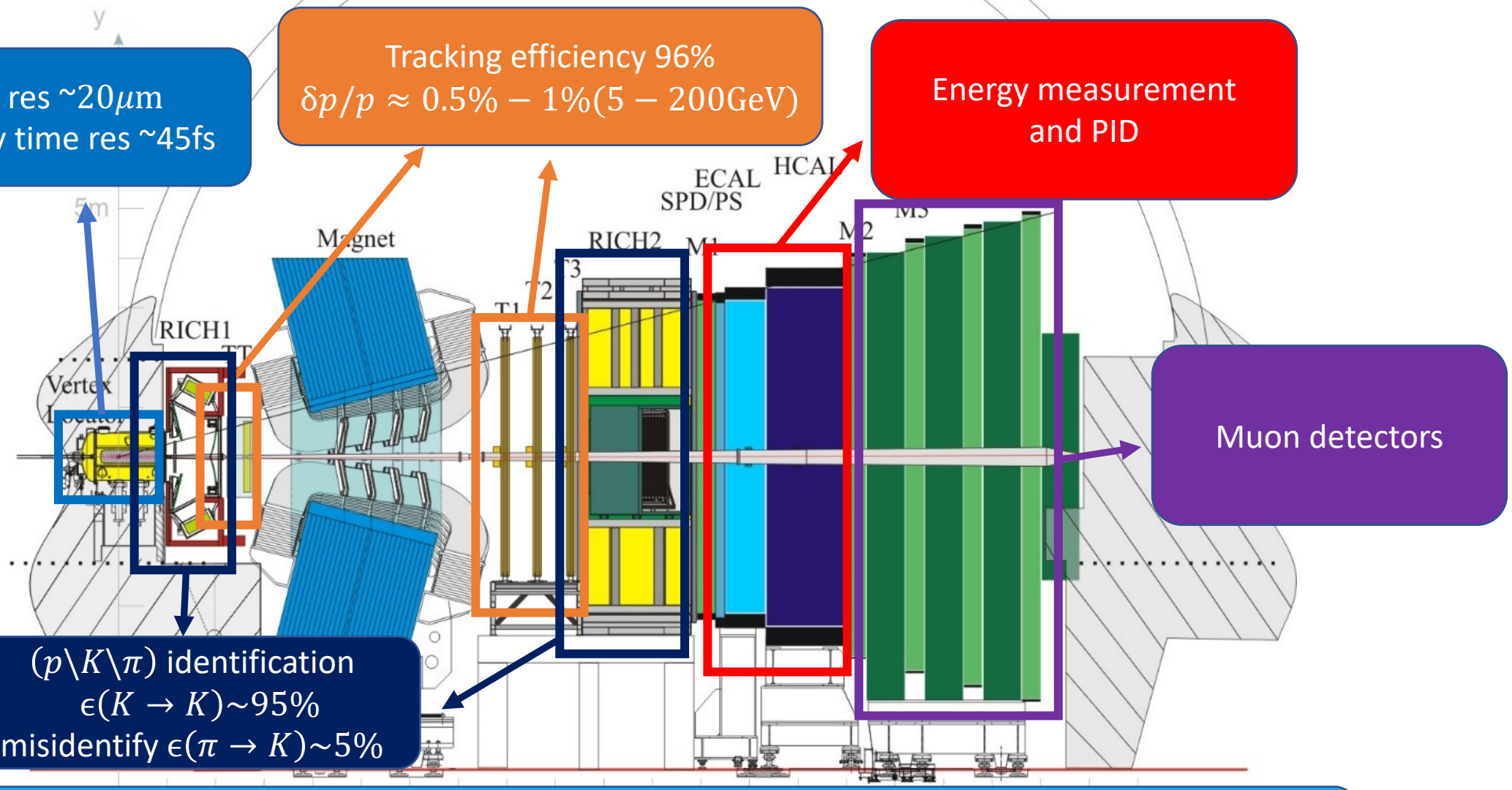
# Overview

- LHCb collected the world's **largest** sample of reconstructed charmed hadrons during LHC Run 1 and Run 2
- Providing the world's **most precise** measurements of properties and production of known charmed baryons
- Recent charm baryons results
  - Excited charms
  - Doubly charmed baryons
  - Charmed baryon lifetimes




LHCB-FIGURE-2021-001

# LHCb




Excellent for vertex reconstruction, tracking and PID
Good platform to study heavy flavour decays

# Excited charms

- Very rich spectroscopy of heavy baryons, many excited states found.
- In 2017, LHCb found 5 excited $\Omega_c^0$ in $\Xi_c^+ K^-$ final states (LHCb-PAPER-2017-002)
- Prediction issues:

  Bound state? Triquark or quark-diquark model?

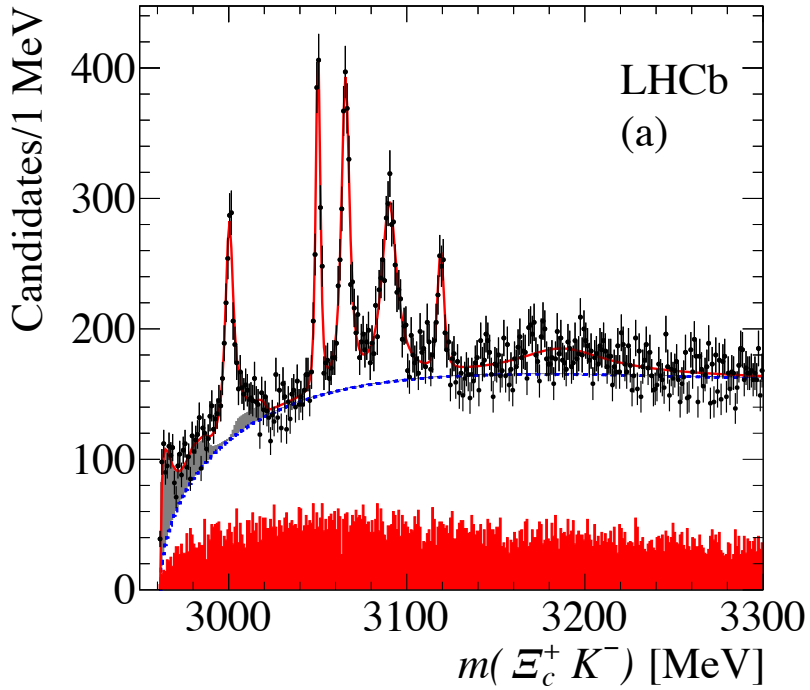
  Molecular state ?

- Different models lead to different quantum numbers

TABLE II. Spin-parity ($J^P$) numbers of the newly observed $\Omega_c$ states suggested in various works.

| State | [20] | [21] | [22] | [24] | [30] | [26] | [28] | [29] | [33] | [27] | This work |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\Omega_c(3000)$ | | $1/2^-$ | $1/2^-$ $(3/2^-)$ | $1/2^-$ | $1/2^-$ | $1/2^-$ | $1/2^-$ | $1/2^+$ or $3/2^+$ | $1/2^-$ | | $1/2^-$ |
| $\Omega_c(3050)$ | | $1/2^-$ | $1/2^-$ $(3/2^-)$ | $1/2^-$ | $5/2^-$ | $3/2^-$ | $1/2^-$ | $5/2^+$ or $7/2^+$ | $3/2^-$ | | $3/2^-$ |
| $\Omega_c(3066)$ | $1/2^+$ | $1/2^+$ or $1/2^-$ | $3/2^-$ $(5/2^-)$ | $3/2^-$ | $3/2^-$ | $5/2^-$ | $3/2^-$ | $3/2^-$ | $1/2^+$ | | $3/2^-$ |
| $\Omega_c(3090)$ | | | $3/2^-$ $(1/2^+)$ | $3/2^-$ | $1/2^-$ | $1/2^+$ | $3/2^-$ | $5/2^-$ | $1/2^+$ | | $5/2^-$ |
| $\Omega_c(3119)$ | $3/2^+$ | $3/2^+$ | $5/2^-$ $(3/2^+)$ | $5/2^-$ | $3/2^-$ | $3/2^+$ | $5/2^-$ | $5/2^+$ or $7/2^+$ | $3/2^+$ | $1/2^-$ | $1/2^+$ or $3/2^+$ |

PRD 95, 116010 (2017)



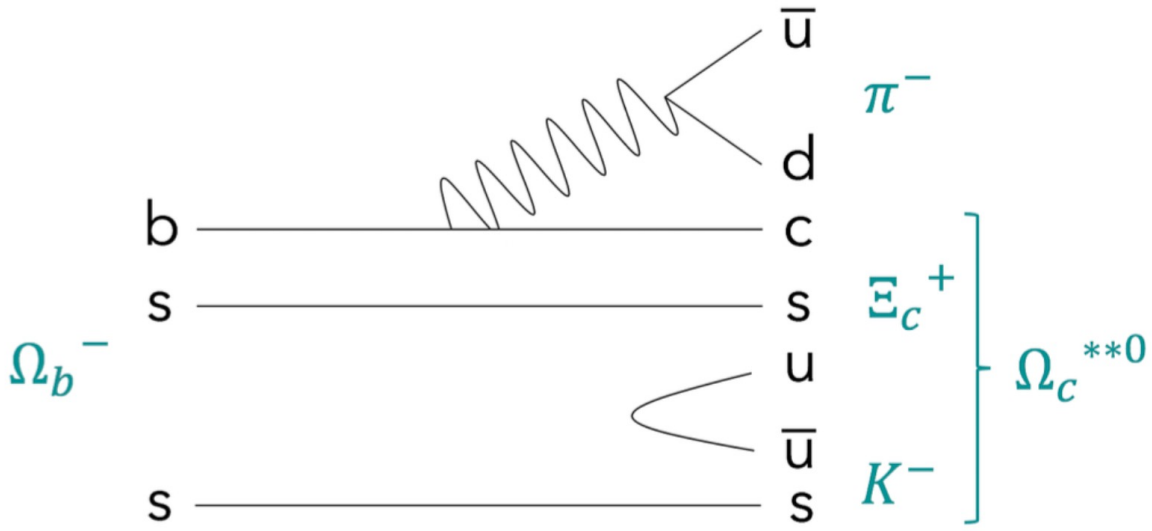

- Need more information to understand the nature

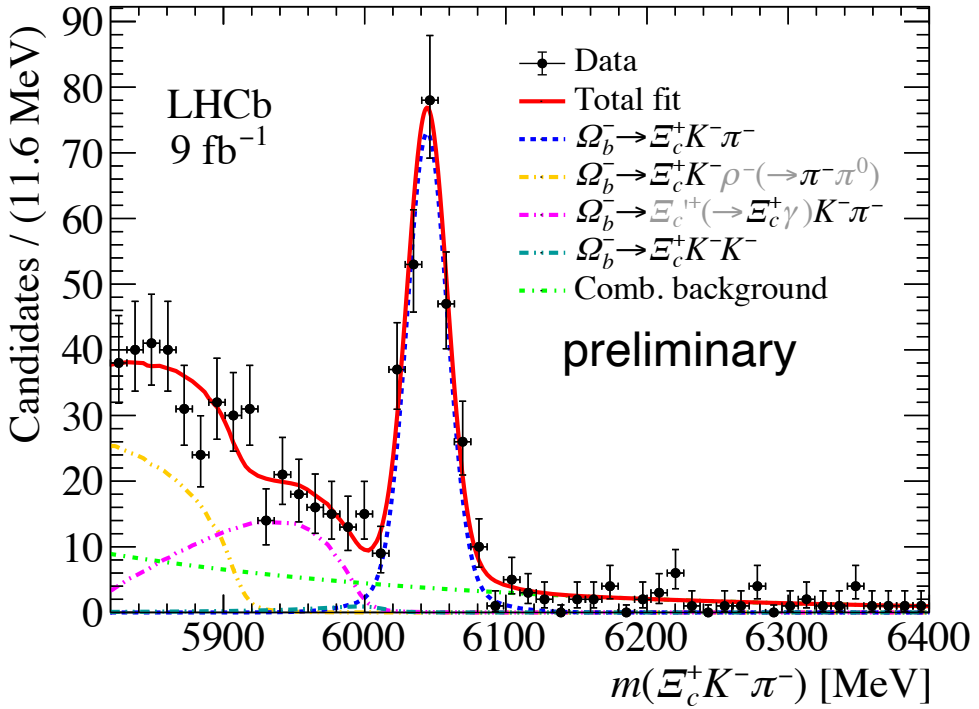
  More excited states

  More production modes (prompt or from b-decay)

# $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ LHCb-PAPER-2021-012 (in preparation)

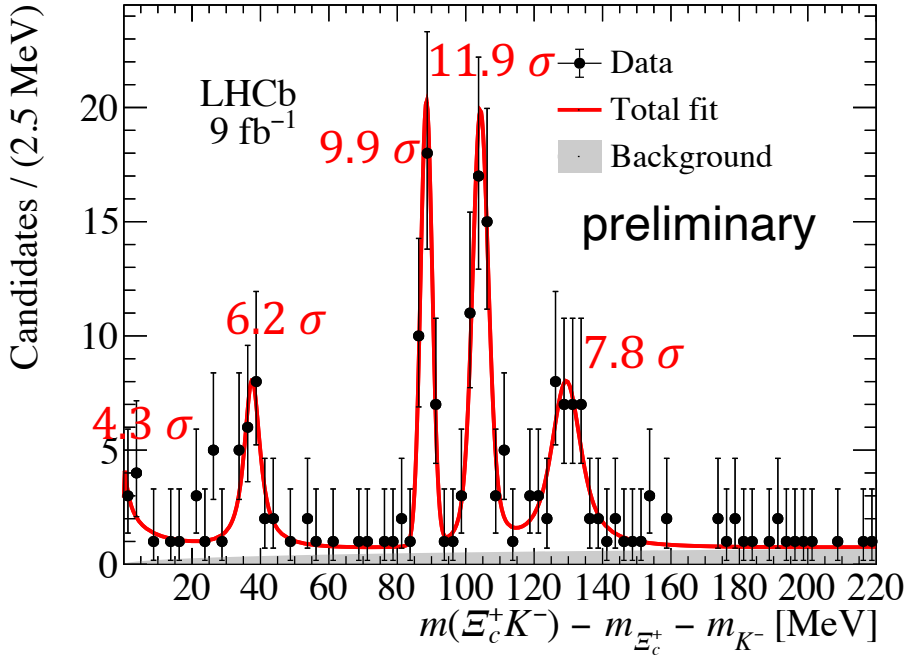
- First observation of a new decay mode $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ relative to $\Omega_b^- \to \Omega_c^- \pi^-$ with LHCb Run1 and Run2 data
- Structure observed in $\Xi_c^+ K^-$ resonance
- Observation of $\Omega_c^{**0}$ from $\boldsymbol{\Omega_b^-}$ **decays** (with known spin)
- Quantum numbers of $\Omega_c^{**0}$ could be determined

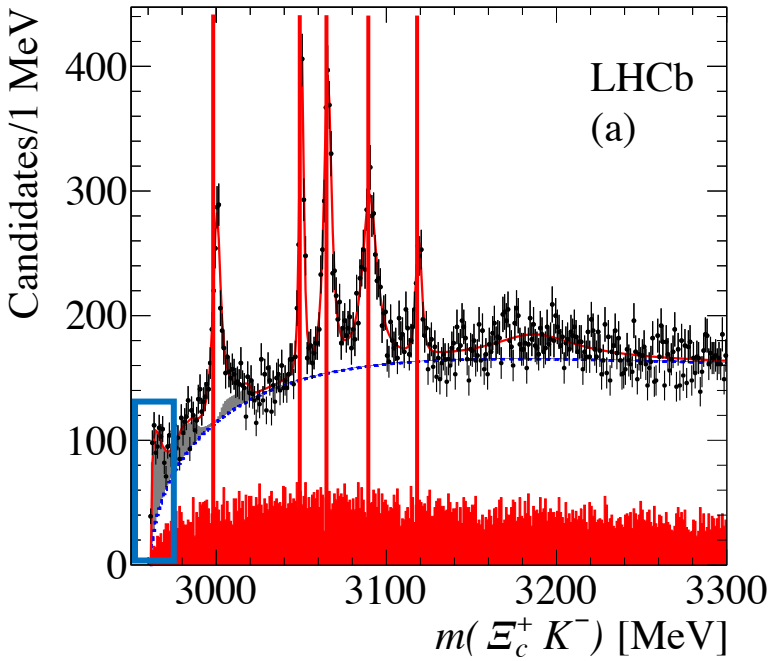


# $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ LHCb-PAPER-2021-012 (in preparation)

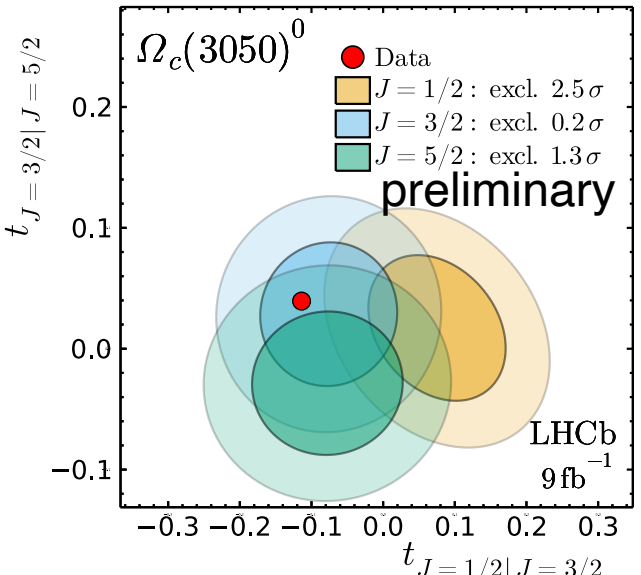
- Mass window: $\pm 2\sigma$ of the measured $\Omega_b^-$ mass
- Confirmed $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3065)^0$, $\Omega_c(3090)^0$, upper limits for $\Omega_c(3120)^0$ set up
- 4.3 $\sigma$ found for the threshold structure

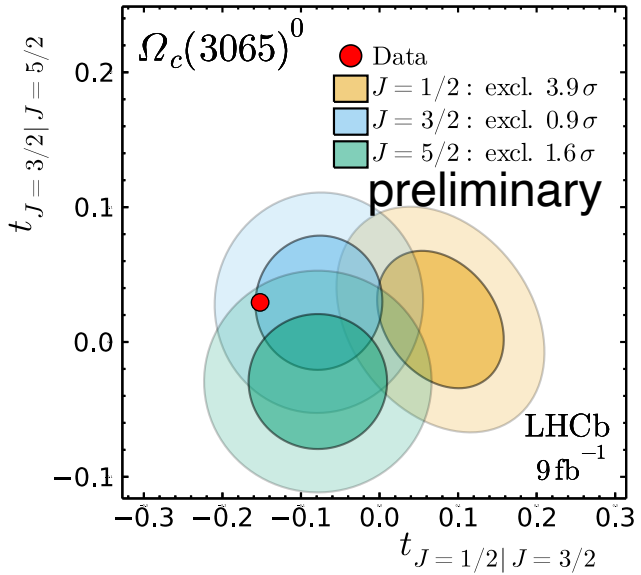


# $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ LHCb-PAPER-2021-012 (in preparation)

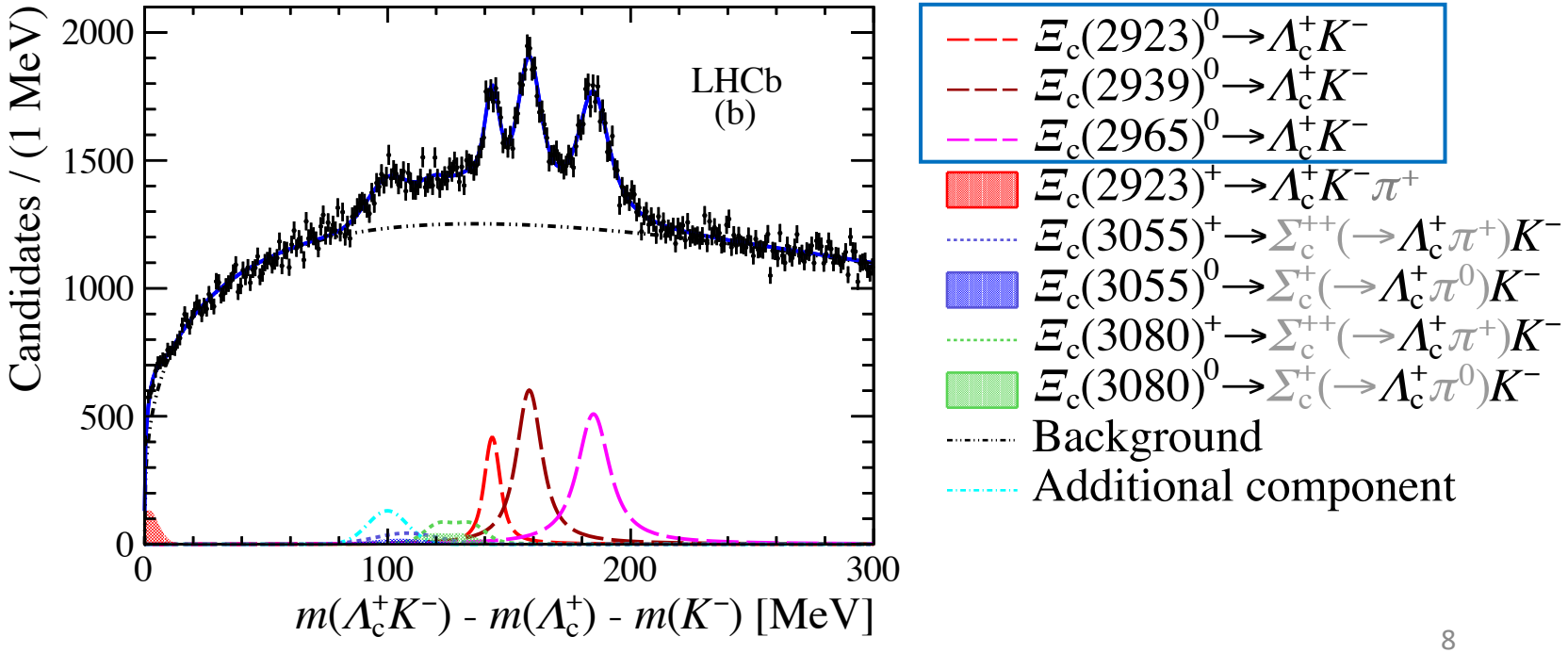
- Spin of $\Omega_b^-$ is 1/2, test the $\Omega_c^{**0}$
- 2.2 $\sigma$ rejection of J($\Omega_c\ (3050)^0$) = 1/2, 3.6 $\sigma$ rejection of J($\Omega_c\ (3065)^0$) = 1/2 (lowered by systematic uncertainty)
- Give one possible assignment, J = 1/2, 3/2, 3/2 and 5/2 for $\Omega_c\ (3000)^0$, $\Omega_c\ (3050)^0$, $\Omega_c\ (3065)^0$, $\Omega_c\ (3090)^0$ respectively



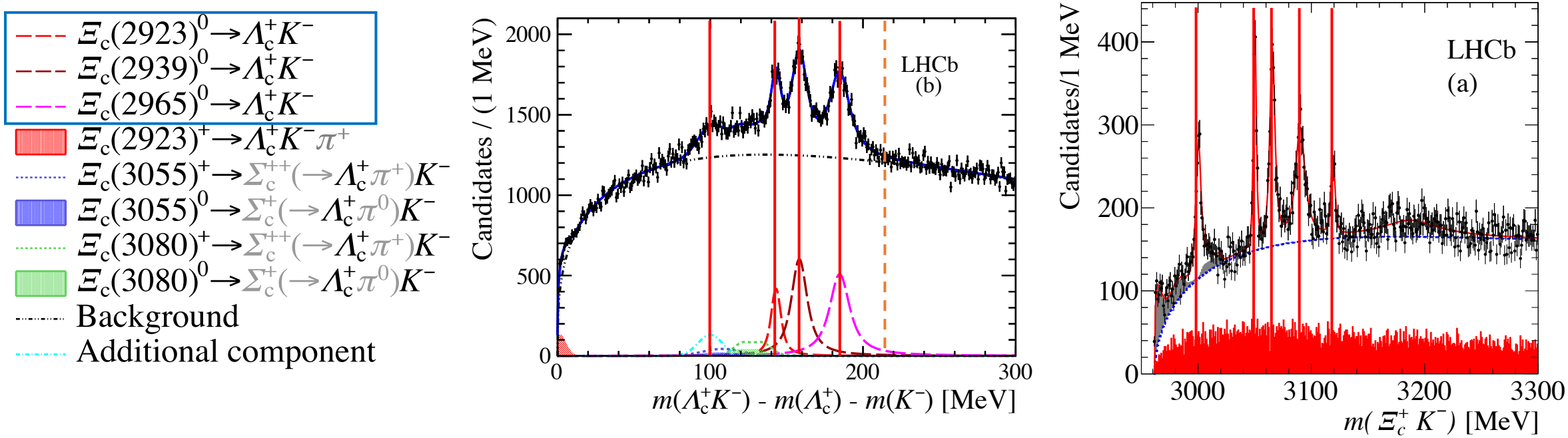
# $\Xi_c^{**0} \to \Lambda_c^+ K^-$ PRL 124, 222001 (2020)

- Has been previously searched by Belle EPJC (2018) 78:252 with no excited $\Xi_c^0$ found and Babar PRD 77, 012002 (2008) with $\Xi_c\,(2930)^0$found
- Motivated by $\Omega_c^{**0} \to \Xi_c^+ K^-$, look for $\Xi_c^{**0}$ in the $\Lambda_c^+ K^-$ mass spectrum with LHCb Run2 data (2016-2018)
- Three new states observed with large significance (local significance > 20 $\sigma$ for each state)

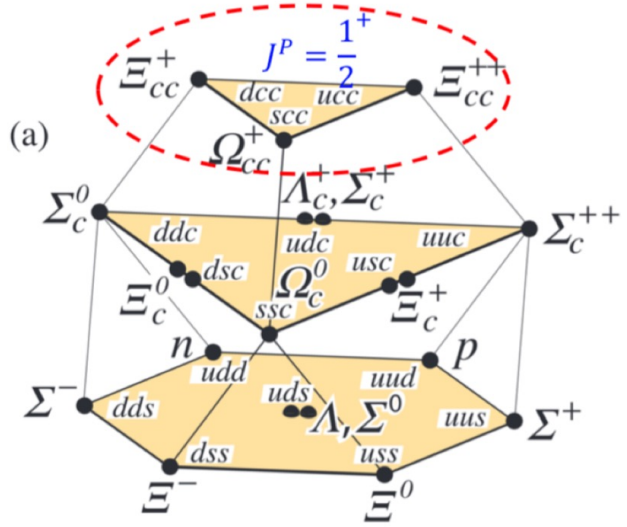
# $\Xi_c^{**0} \to \Lambda_c^+ K^-$ PRL 124, 222001 (2020)

- The known $\Xi_c\,(2930)^0$ might be the overlap of new $\Xi_c\,(2923)^0$ and $\Xi_c\,(2939)^0$
- $\Xi_c\,(2965)^0$ significantly different with the known $\Xi_c\,(2970)^0$ in width and mass, need further study
- Same peak spacing as for $\Omega_c^{**0}$

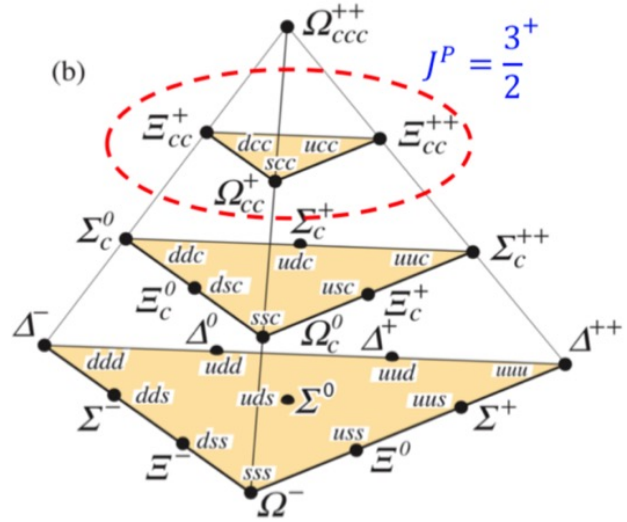


# Doubly charmed baryons

- Doubly charmed baryons predicted by SU(4) 20-plets
  $\Xi_{cc}^{++}(ccu),\ \Xi_{cc}^{+}(ccd),\ \Omega_{cc}^{+}(ccs)$




- Many studies done by LHCb
  First observation $\Xi_{cc}^{++}$ ($\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$) PRL 119 (2017) 112001
  Confirmation $\Xi_{cc}^{++}$ ($\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$) PRL 121 (2018) 162002
  Search for $\Xi_{cc}^{++} \to D^+ p K^- \pi^+$ decays JHEP 10 (2019) 124
  Lifetime measurement of $\Xi_{cc}^{++}$ PRL 121 (2018) 052002
  Production measurement of $\Xi_{cc}^{++}$ CPC44 (2020) 022001
  Precise mass measurement of $\Xi_{cc}^{++}$ JHEP 02 (2020) 049
  Search for $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$ decays SCPMA 63 (2020) 221062




- Recent studies
  Search for $\Xi_{cc}^{+} \to \Xi_c^+ \pi^- \pi^+$ and $\Omega_{cc}^{+} \to \Xi_c^+ K^- \pi^+$ decays

# Doubly charmed baryons

- Measurements and predictions
- $M(\Xi_{cc}^{++}) = 3621.55 \pm 0.23(stat) \pm 0.30(syst)$ MeV[1]
  $M(\Xi_{cc}^{+}) \approx M(\Xi_{cc}^{++})$, $M(\Omega_{cc}^{+}) \sim 3.6\text{-}3.9$ GeV[2]
- $\tau(\Xi_{cc}^{++}) = 0.256^{+0.024}_{-0.022}(stat) \pm 0.014(syst)$ ps[3]
- $\tau(\Xi_{cc}^{++}) > \tau(\Omega_{cc}^{+}) > \tau(\Xi_{cc}^{+})$[4]
- $\sigma(\Xi_{cc}^{++})/\sigma(\Lambda_c^{+}) = (2.22 \pm 0.27(stat) \pm 0.29(syst)) \times 10^{-4}$[5]
  $\sigma(\Xi_{cc}^{++}) = \sigma(\Xi_{cc}^{+}) = 3\sigma(\Omega_{cc}^{+})$[6]


[1] JHEP 02 (2020) 049

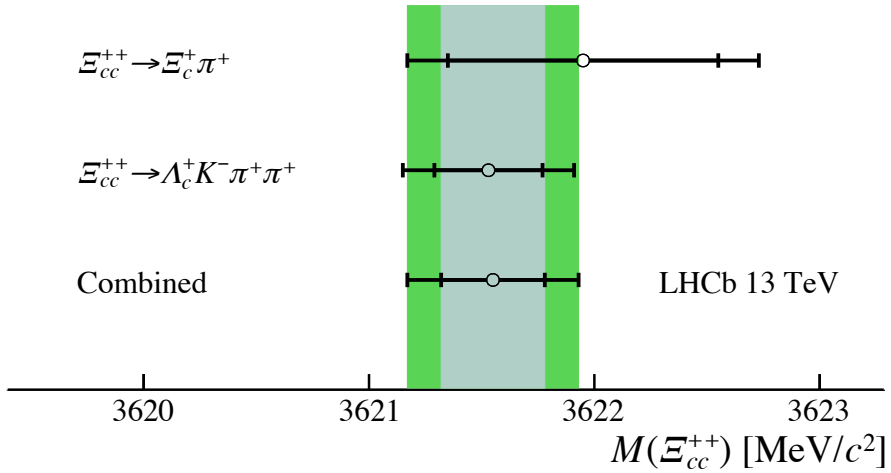
[2] PRD 66 (2002) 014008

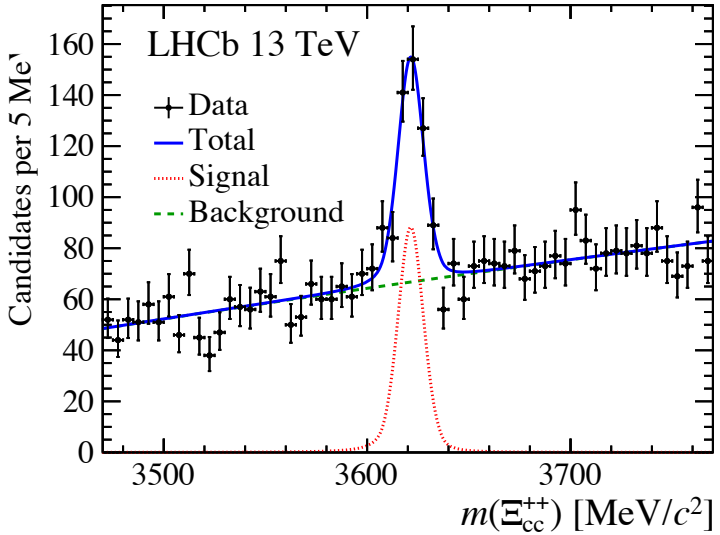
[3] PRL 121 (2018) 052002

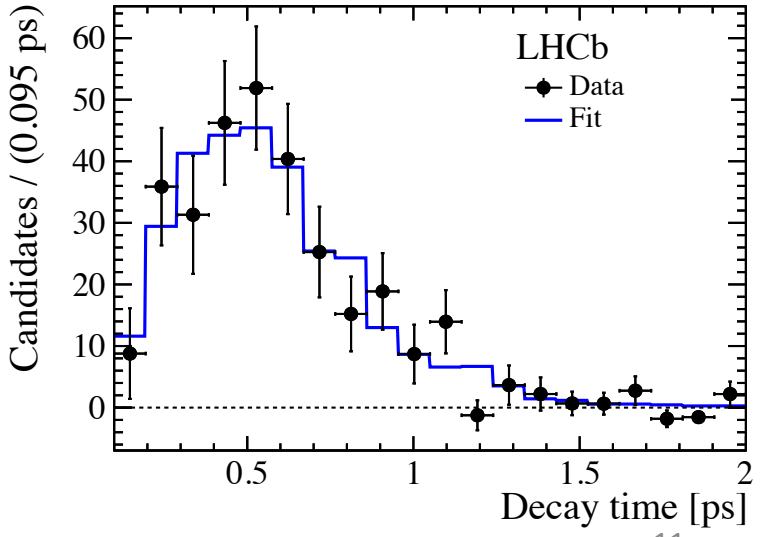
[4] PRD 98 (2018) 113005

[5] CPC44 (2020) 022001

[6] PRD 98 (2018) 113004

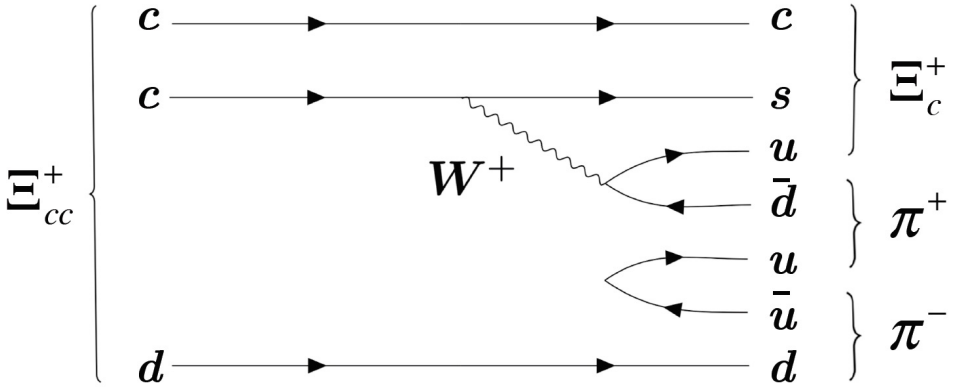



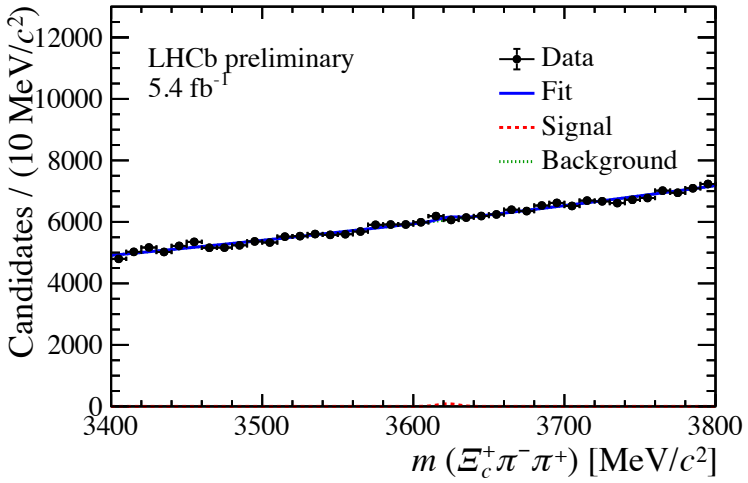



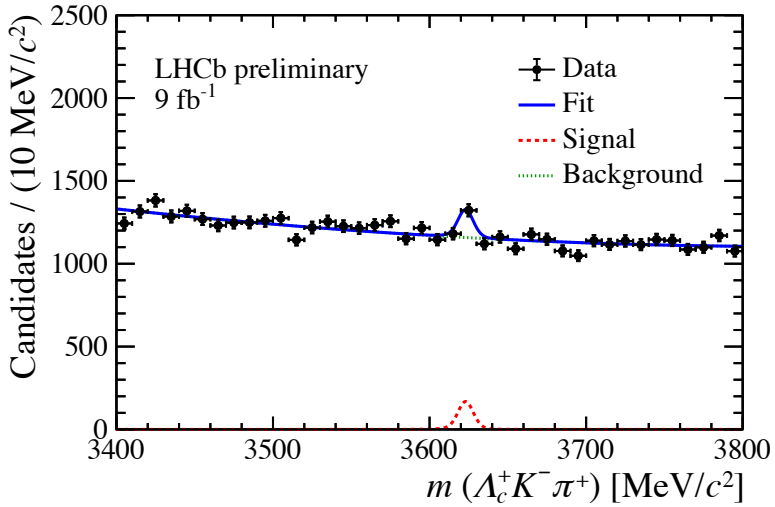



# $\Xi_{cc}^{+} \to \Xi_{c}^{+}\pi^{-}\pi^{+}$ LHCb-PAPER-2021-019 (in preparation)

- Search for $\Xi_{cc}^{+} \to \Xi_{c}^{+}\pi^{-}\pi^{+}$ decay with Run2 data (2016-2018), 3.3 GeV to 3.8 GeV blinded, $\Xi_{cc}^{+} \to \Xi_{c}^{+}\pi^{+}$ as normalisation mode
- No significant signal observed
- Combined fit with $\Xi_{cc}^{+} \to \Lambda_{c}^{+}K^{-}\pi^{+}$ final state, 3.1 $\sigma$ (1.7 $\sigma$) for local (global) significance using LHCb Run1 and Run2 data SCPMA 63 (2020) 221062



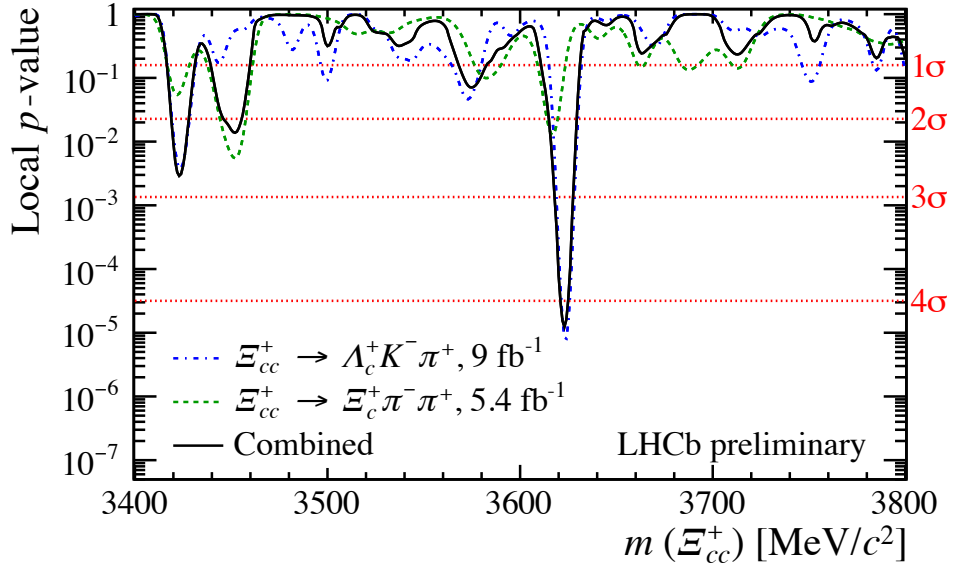



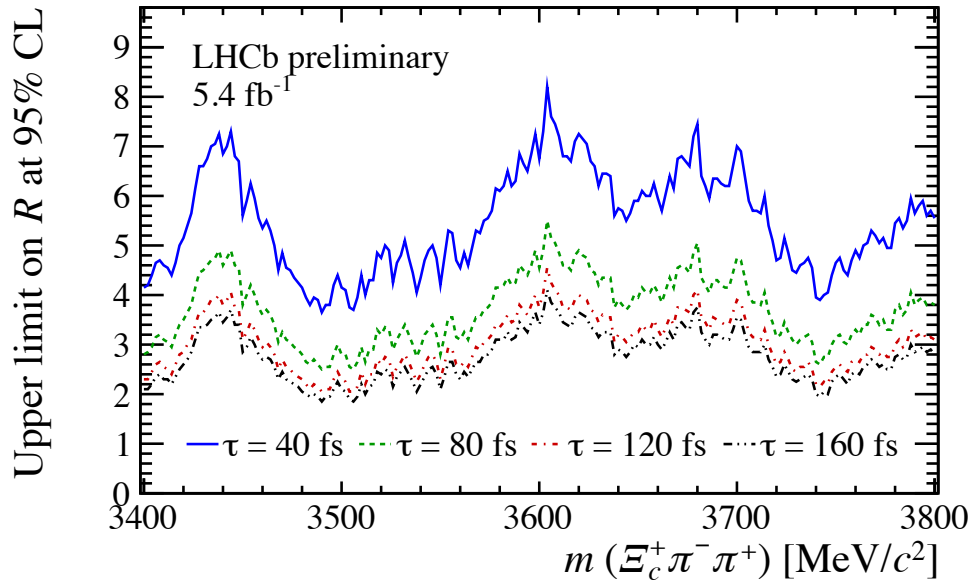



# $\Xi_{cc}^{+} \to \Xi_{c}^{+}\pi^{-}\pi^{+}$ LHCb-PAPER-2021-019 (in preparation)

- Combined local (global) significance 4.0 σ (2.9 σ)
- Best fit found around 3623.0 MeV
- Upper limit scan in mass region on $R$ for different lifetime hypotheses at 95%CL

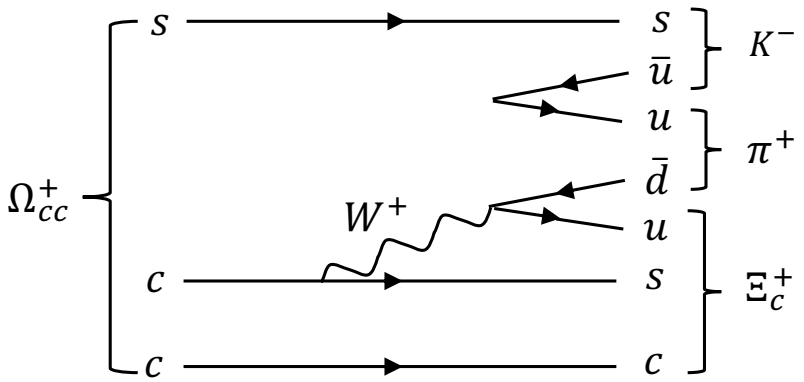
$$R = \frac{\sigma(\Xi_{cc}^{+}) \times \mathcal{B}(\Xi_{cc}^{+} \to \Xi_{c}^{+}\pi^{-}\pi^{+})}{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{+} \to \Xi_{c}^{+}\pi^{+})}$$

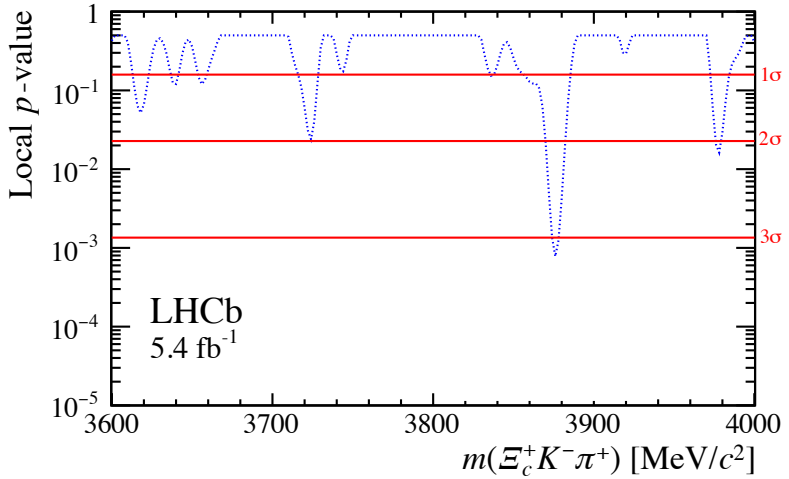


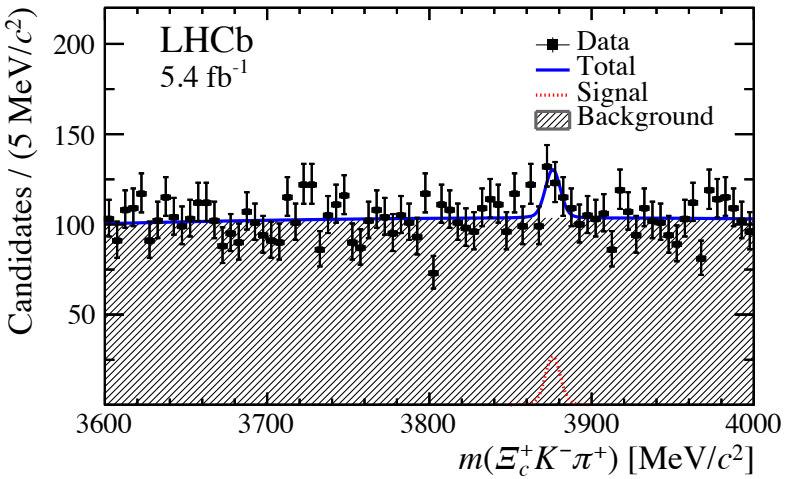



# $\Omega_{cc}^{+} \to \Xi_c^{+} K^{-} \pi^{+}$ arxiv: 2105. 06841

- First search for $\Omega_{cc}^{+}$ (ccs) at LHCb, 3.5 GeV to 4.0 GeV blinded
- $\Xi_c^{+} K^{-} \pi^{+}$ final states with LHCb Run2 data (2016-2018), $\Xi_{cc}^{++} \to \Lambda_c^{+} K^{-} \pi^{+} \pi^{+}$ as normalisation mode
- 3.2 $\sigma$ (1.8 $\sigma$) for local (global) significance, the largest local significance found around 3876.1 MeV



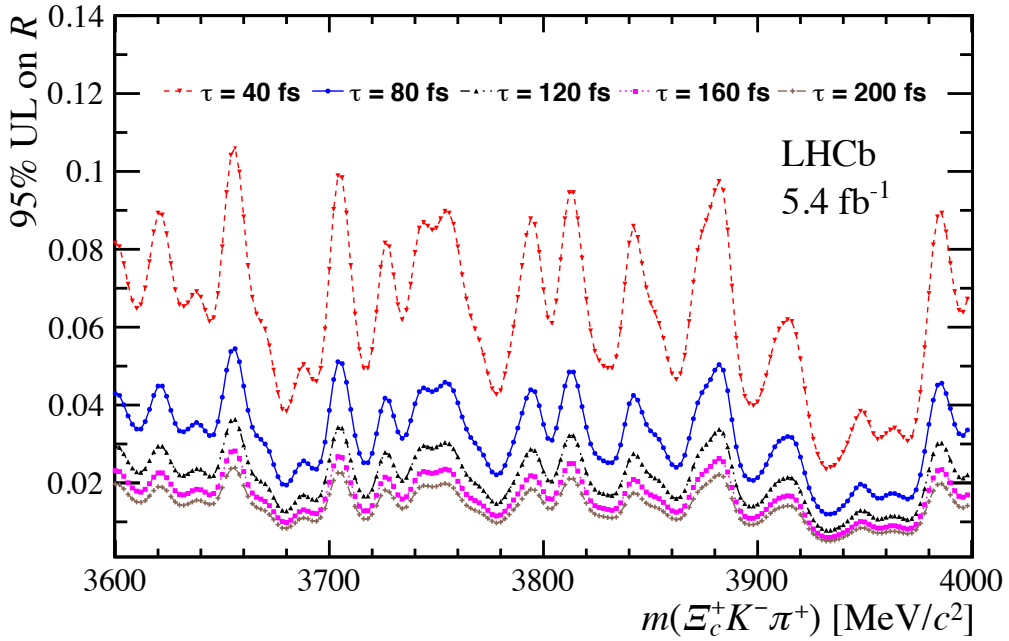



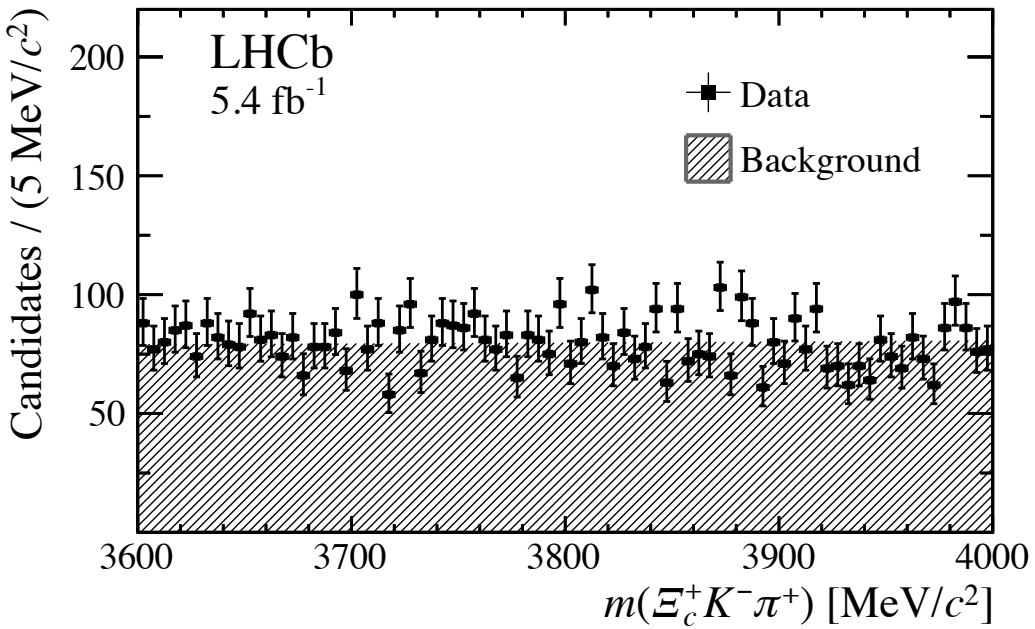



# $\Omega_{cc}^{+} \to \Xi_c^{+} K^{-} \pi^{+}$ arxiv: 2105. 06841

- Global significance <3σ, upper limit scan in mass region on $R$ for different lifetime hypotheses at 95%CL

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



# Charmed baryon lifetimes

- Heavy Quark Expansion (HQE) is the common approach for lifetime calculations of heavy flavour hadrons

$$\Gamma\left(H_Q \to f\right) = \frac{G_F^2 m_Q^5}{192\pi^3} V_{\mathrm{CKM}} \left(A_0 + \frac{A_2}{m_Q^2} + \frac{A_3}{m_Q^3} + \frac{A_4}{m_Q^4} + \mathcal{O}\left(\frac{1}{m_Q^5}\right)\right)$$

- $\mathrm{m_b} > \mathrm{m_c}$, HQE works well for expansions for $b$ quark, better description needed for $c$ quark

- Some prediction said lifetime pattern of charmed baryons was

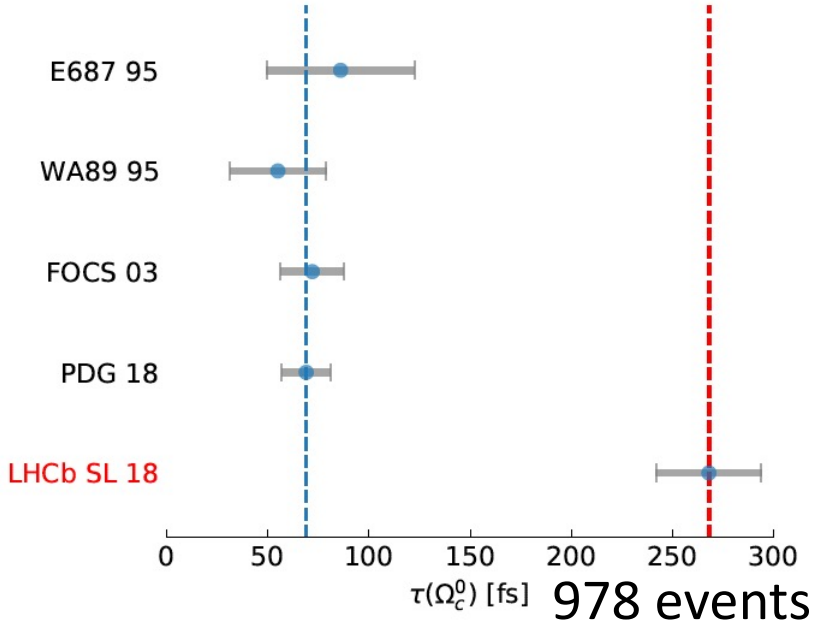
$$\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$$ FP 10(6), 101406 (2015)092003

- Shortest-lived $\Omega_c^0$ due to the constructive Pauli interference

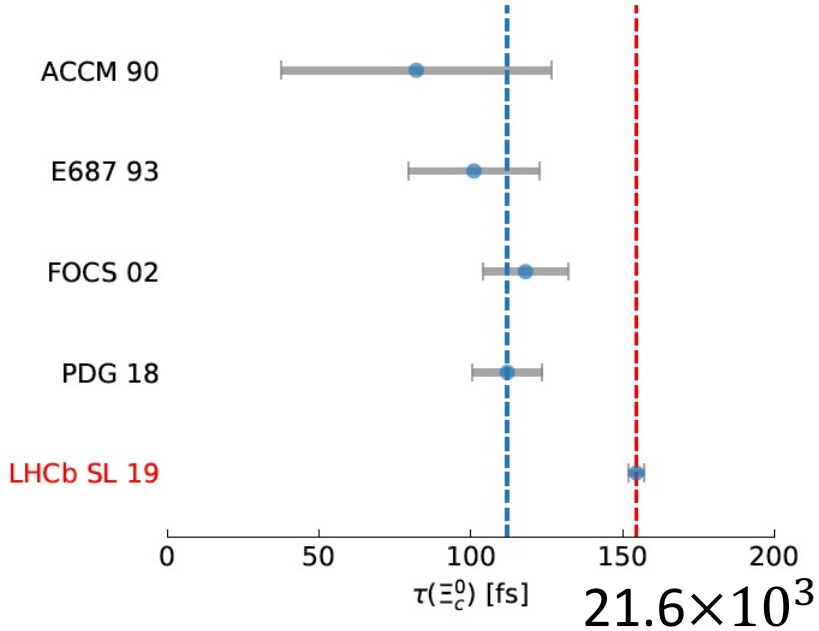
- $\tau(\Omega_c^0) = 86^{+27}_{-20}$ (stat)$\pm$28(syst) fs (25 events, E687) PLB 357 (1995) 678-684
  $\tau(\Omega_c^0) = 55^{+13}_{-11}$ (stat)$^{+18}_{-23}$(syst) fs (86 events, WA89) PLB 358 (1995) 151-161
  $\tau(\Omega_c^0) = 72 \pm 11$(stat)$\pm$11(syst) fs (64 events, FOCUS) PLB 561 (2003) 41-48

# $\Omega_c^0$ and $\Xi_c^0$ lifetimes

- LHCb performed measurements of lifetimes using Run 1 data and semileptonic b-hadron decays [PRL. 121 (2018) 9 092003, PRD.100 (2019) 032001]




978 events




$21.6\times10^3$ events

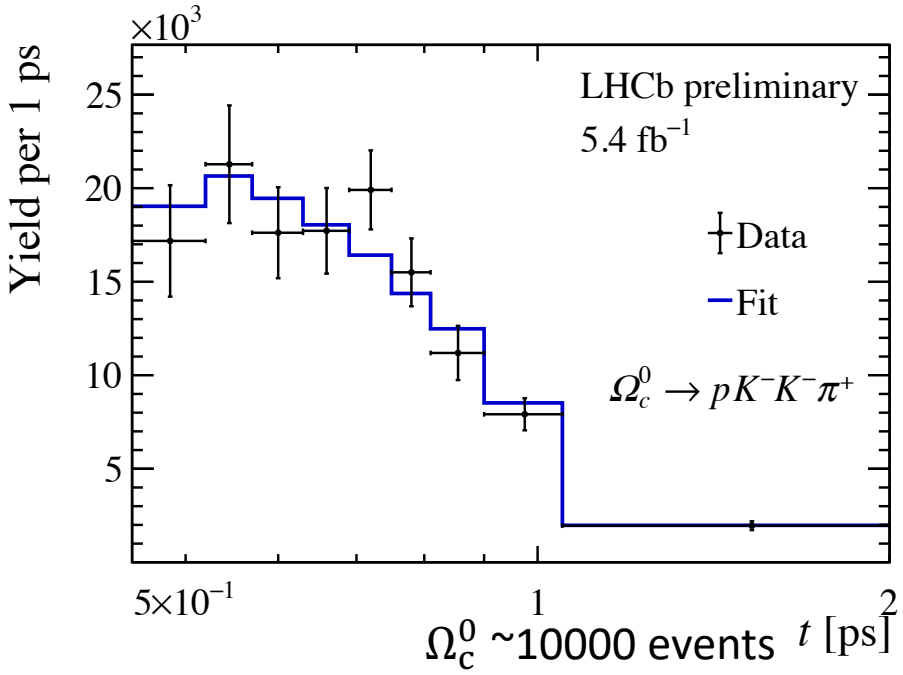
- Sizeable **inconsistency** with the previous PDG results

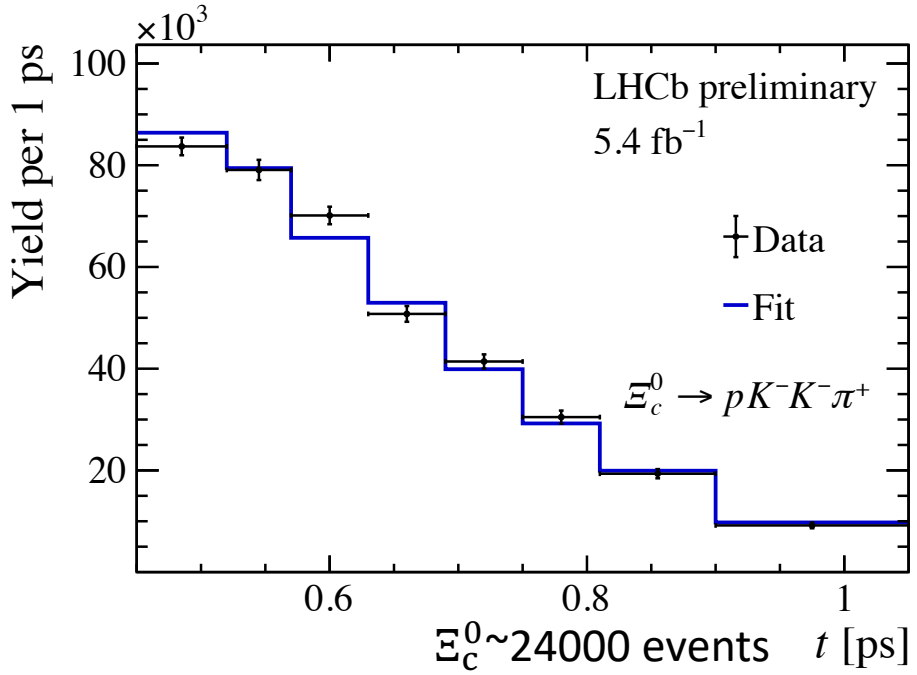
$$\tau(\Xi_c^+)>\tau(\Omega_c^0)>\tau(\Lambda_c^+)>\tau(\Xi_c^0)$$

# $\Omega_c^0$ and $\Xi_c^0$ lifetimes [LHCb-PAPER-2021-021 (in preparation)]

- Using promptly produced $\Omega_c^0$ and $\Xi_c^0$ using LHCb run2 data (2016-2018)
- Blinded analysis with $pK^-K^-\pi^+$ final states, relative to $D^0 \to K^+K^-\pi^+\pi^-$ statistically independent of the previous LHCb measurement

$$\tau(\Omega_c^0) = 276.5 \pm 13.4(\text{stat}) \pm 4.4(\text{syst}) \pm 0.7(\text{from } D^0)\text{fs}$$
$$\tau(\Xi_c^0) = 148.0 \pm 2.3(\text{stat}) \pm 2.2(\text{syst}) \pm 0.2(\text{from } D^0)\text{fs}$$



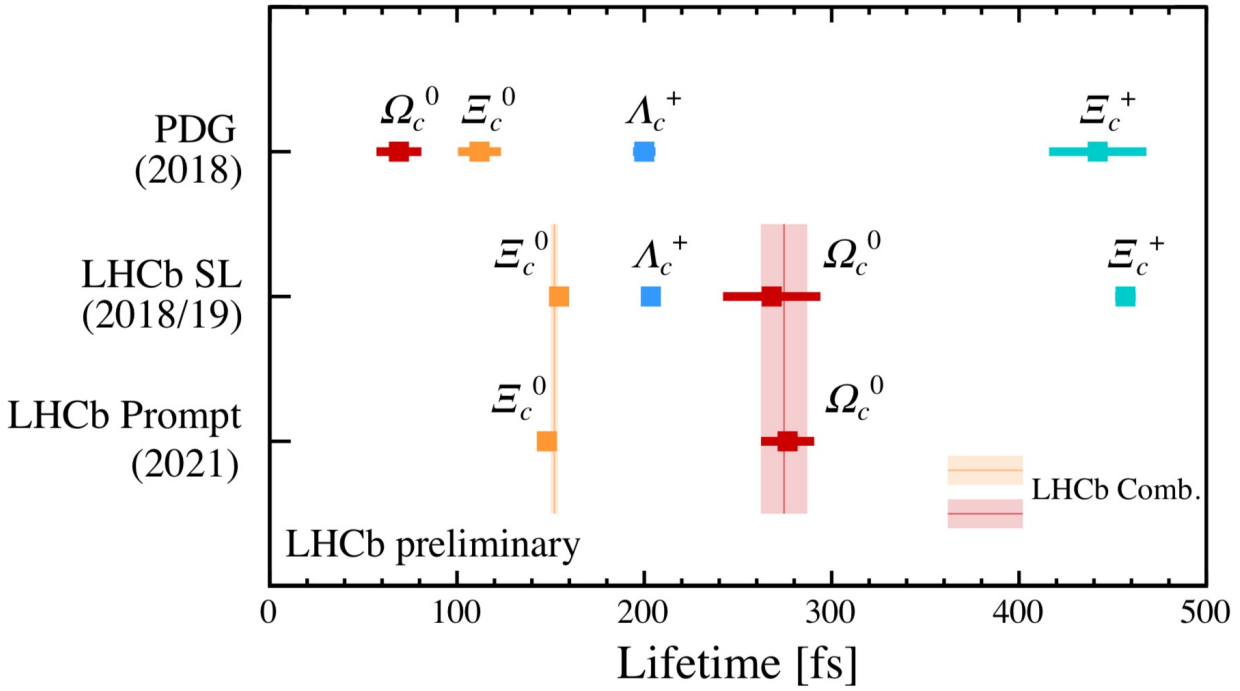



# $\Omega_c^0$ and $\Xi_c^0$ lifetimes [LHCb-PAPER-2021-021 (in preparation)]

- All new results are consistent with the previous LHCb semileptonic results

- The weighted average of LHCb measurements is

$$\tau(\Omega_c^0) = 274.5 \pm 12.4\text{fs}$$
$$\tau(\Xi_c^0) = 152.0 \pm 2.0\text{fs}$$



# Summary

- Reported recent LHCb results in charm baryons
- Excited charms
  - $\Omega_c^{**0} \to \Xi_c^+ K^-$ from $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ LHCb-PAPER-2021-012 (in preparation)
  - $\Xi_c^{**0} \to \Lambda_c^+ K^-$ PRL 124, 222001 (2020)
- Doubly charmed baryons
  - $\Xi_{cc}^+ \to \Xi_c^+ \pi^- \pi^+$ LHCb-PAPER-2021-019 (in preparation)
  - $\Omega_{cc}^+ \to \Xi_c^+ K^- \pi^+$ arxiv: 2105. 06841
- Charmed baryons lifetime for $\Omega_c^0$ and $\Xi_c^0$ LHCb-PAPER-2021-021 (in preparation)
- Upgraded LHCb experiment with **new detectors**, **improved trigger conditions** and **larger data samples** would be able to **improve** the study of charm baryons