(Doubly-) Charmed Baryon Lifetime Measurements at LHCb

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on behalf of LHCb

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Outline

- $\tau(\Omega_c^0,\ \Lambda_c^+,\ \Xi_c^+,\ \Xi_c^0)$
- Ξ_{cc}^{++} observation
- $\tau(\Xi_{cc}^{++})$

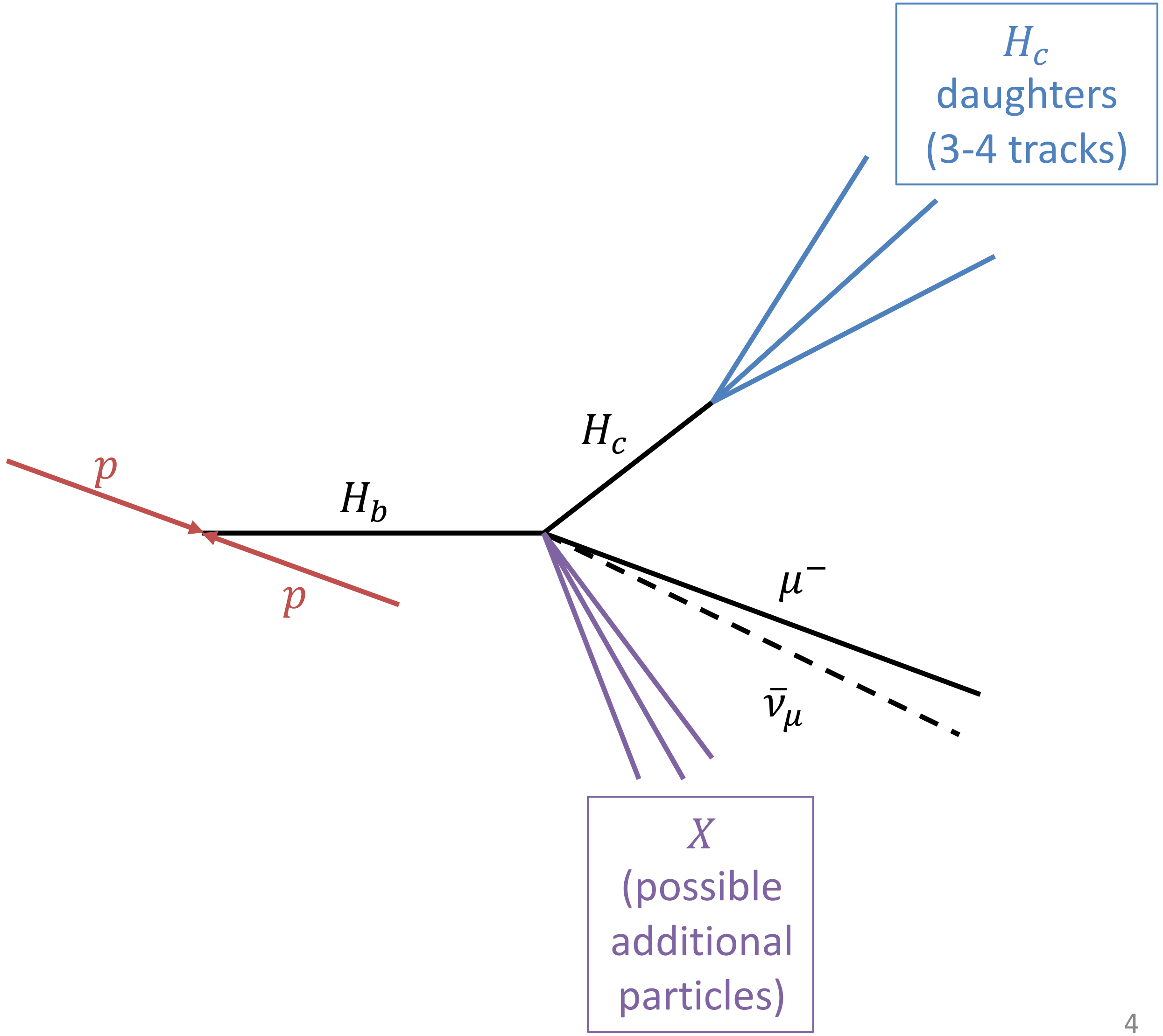
Measurement of the Ω_c^0 baryon lifetime, 31 August 2018, arXiv:1807.02024

Precision measurements of the Λ_c^+, Ξ_c^+ and Ξ_c^0 baryon lifetimes, 19 June 2019, arXiv:1906.08350

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

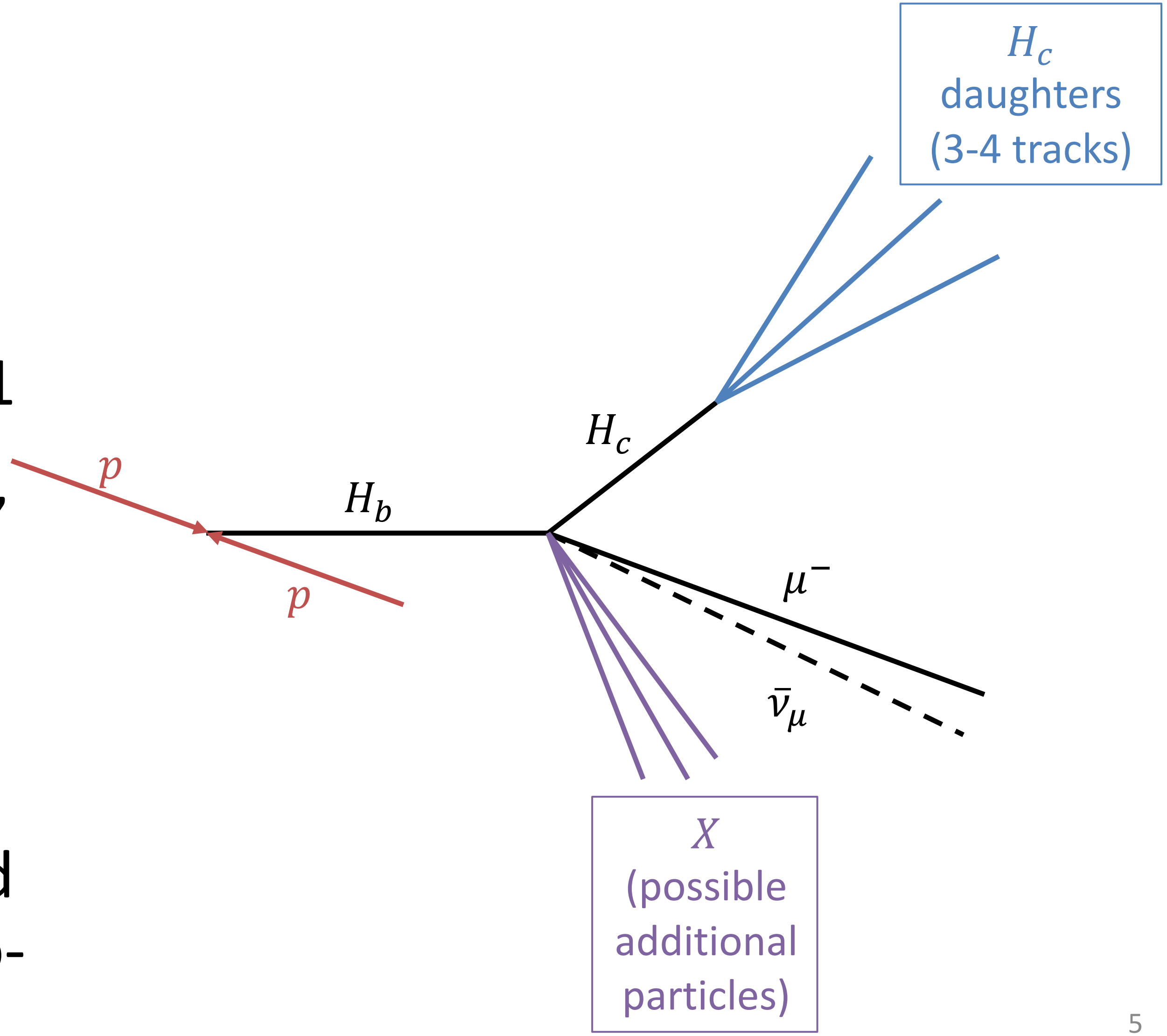
Decay Modes and Selections

- $\Omega_b^- \to \Omega_c^0 \mu^- \bar{\nu}_\mu X$
  - $\Omega_c^0 \to pK^-K^-\pi^+$
- $\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu X$
  - $\Lambda_c^+ \to pK^-\pi^+$
- $\Xi_b^0 \to \Xi_c^+ \mu^- \bar{\nu}_\mu X$
  - $\Xi_c^+ \to pK^-\pi^+$
- $\Xi_b^- \to \Xi_c^0 \mu^- \bar{\nu}_\mu X$
  - $\Xi_c^0 \to pK^-K^-\pi^+$
- Semileptonic decays
  - H_b reconstructed as $H_c\mu^-$
  - Separation of H_c from primary vertex reduces lifetime bias in selections



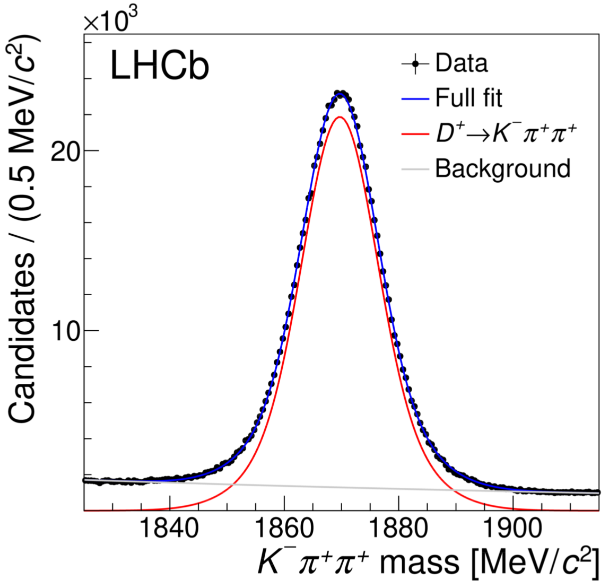
Decay Modes and Selections

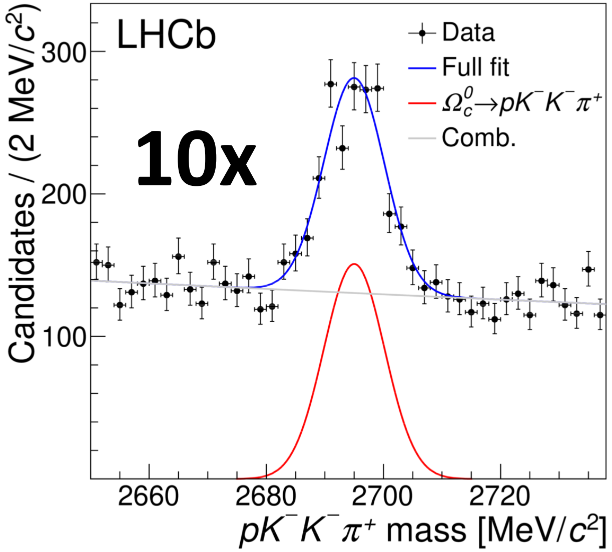
- $\frac{\tau_{H_c}}{\tau_{D^+}}$
  - Reduce systematics
  - $B \to D^+\mu^-\bar{\nu}_\mu X$
    - $D^+ \to K^-\pi^+\pi^+$
- $\int \mathcal{L} = 3.0\ \text{fb}^{-1}$ at 7 & 8 TeV in Run 1
- All modes require a set of kinematic, vertexing, and Particle IDentification (PID) selections to eliminate background
- Ω_c^0, Ξ_c^+ also use a Boosted Decision Tree (BDT) trained on simulation and mass sidebands to improve signal-to-background ratio

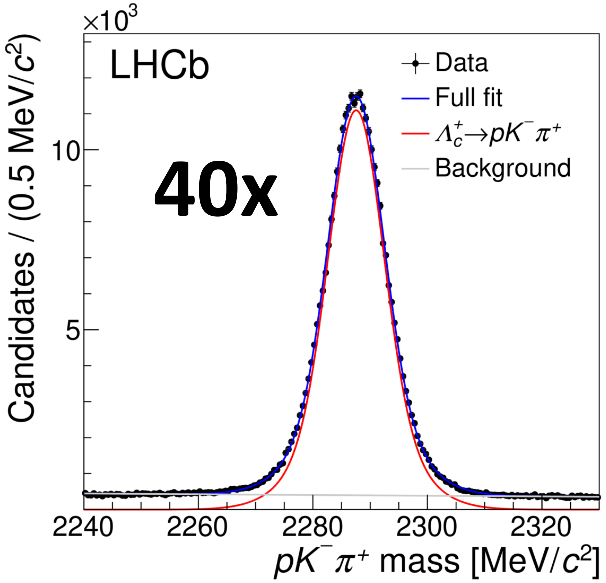


Fits to $m(H_c)$

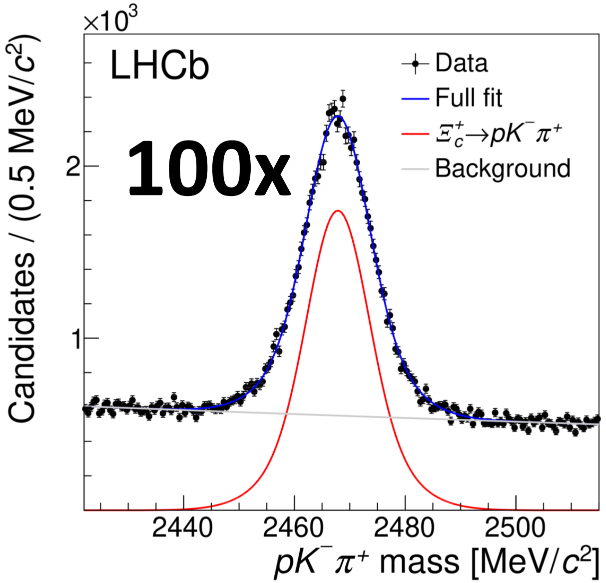
Fits to $m(H_c)$ using a sum of two Gaussians for the signal and an exponential function for the background (used for background subtraction of the decay time distributions)

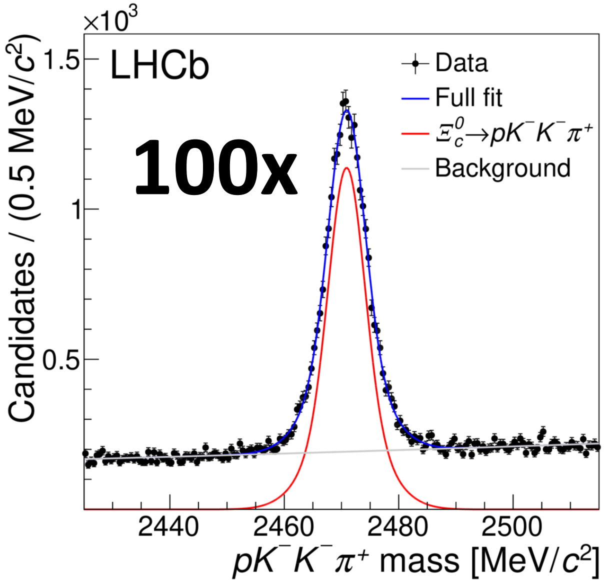




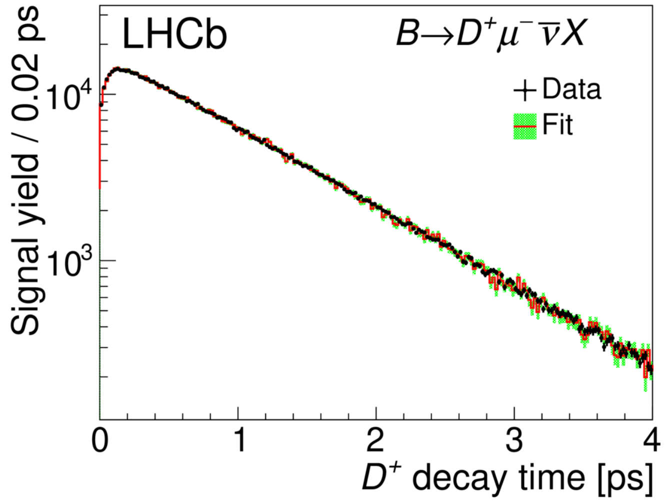


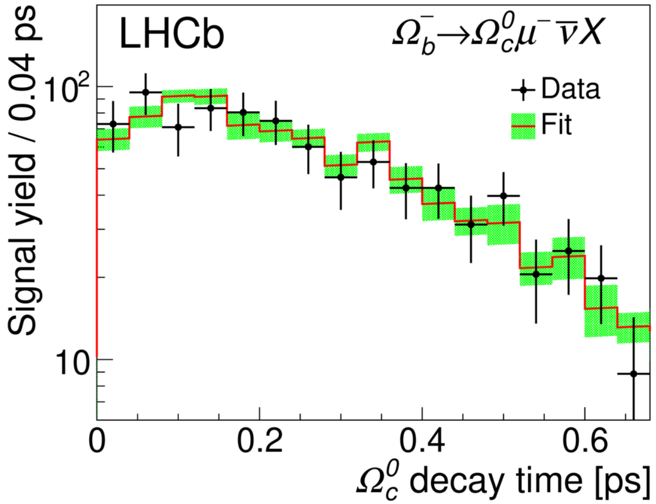
Larger signal yields than for any previous analysis

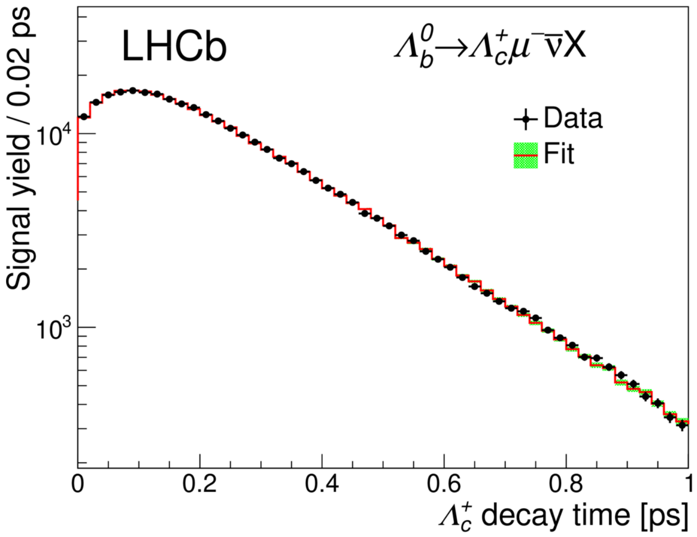




Fits to $\tau(H_c)$

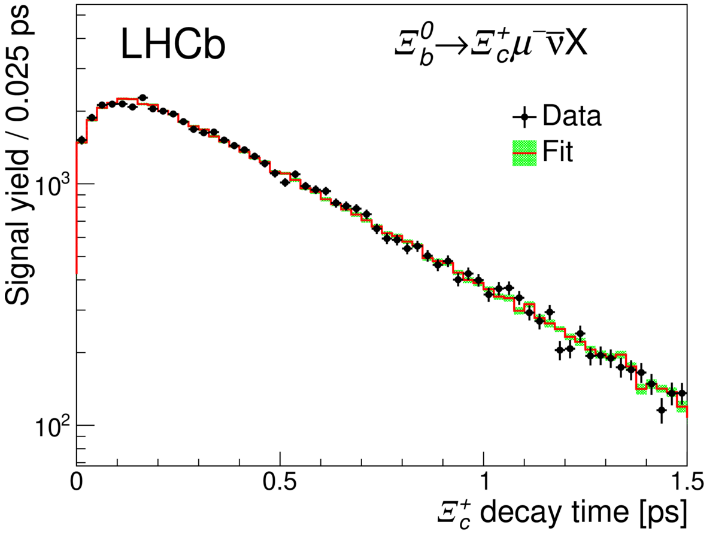


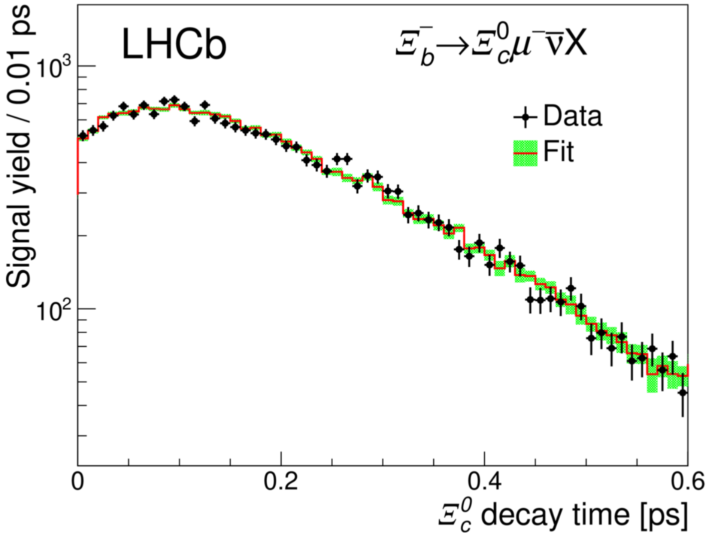




Fits to background-subtracted decay times

- signal templates taken from simulation
- linear correction for differences in efficiency between data and simulation
- floating weight for real vs. simulated lifetime



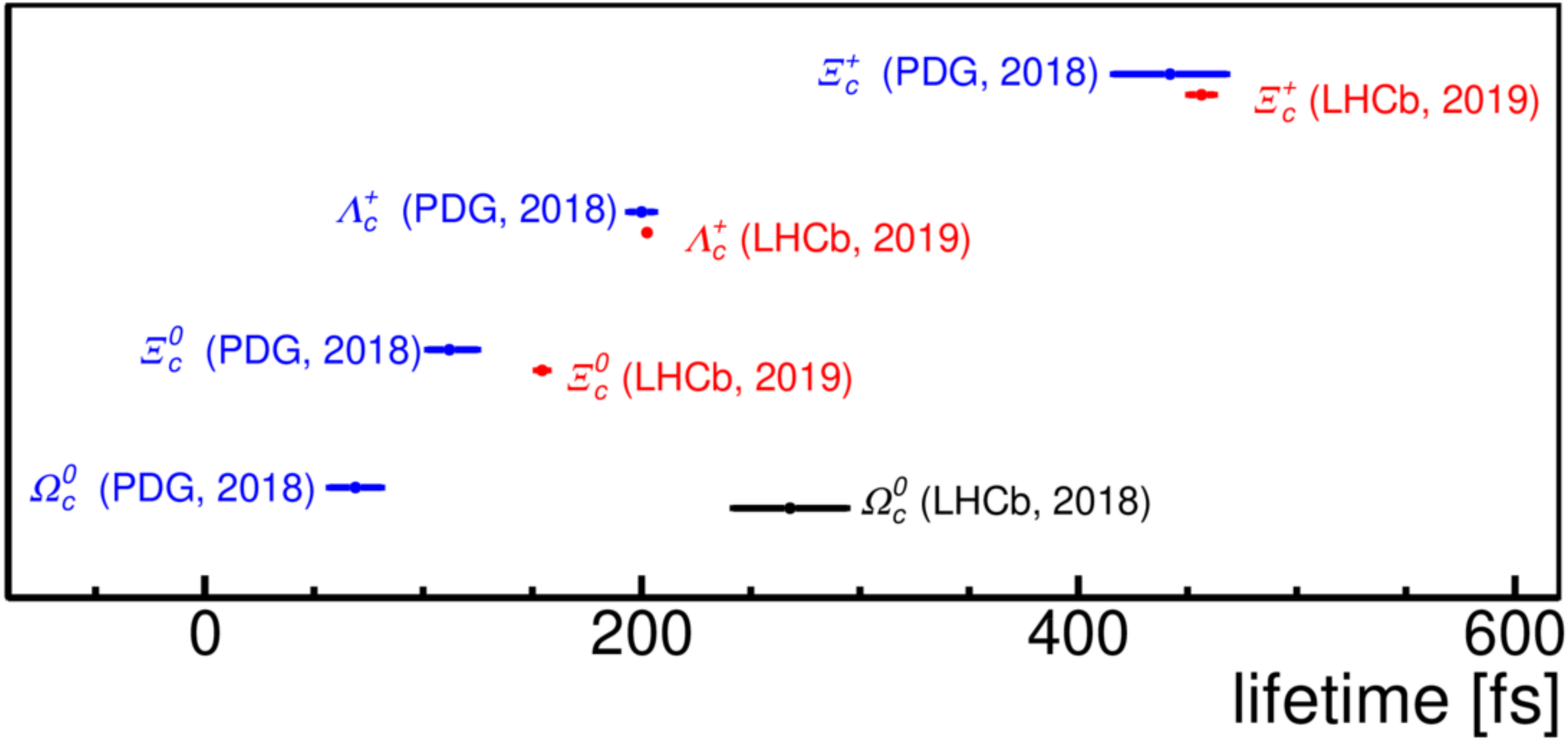


Results

$$\tau_{\Omega_c^0} = 268 \pm 24 \pm 10 \pm 2 \text{ fs}$$
$$\tau_{\Lambda_c^+} = 203.5 \pm 1.0 \pm 1.3 \pm 1.4 \text{ fs}$$
$$\tau_{\Xi_c^+} = 456.8 \pm 3.5 \pm 2.9 \pm 3.1 \text{ fs}$$
$$\tau_{\Xi_c^0} = 154.5 \pm 1.7 \pm 1.6 \pm 1.0 \text{ fs}$$

result ± statistical ± systematic ± due to uncertainty on τ_{D^+}

Results



Ξ_c^+ (PDG, 2018)
Ξ_c^+ (LHCb, 2019)
Λ_c^+ (PDG, 2018)
Λ_c^+ (LHCb, 2019)
Ξ_c^0 (PDG, 2018)
Ξ_c^0 (LHCb, 2019)
Ω_c^0 (PDG, 2018)
Ω_c^0 (LHCb, 2018)
0
200
400
600
lifetime [fs]

Results and Implications

$$\boldsymbol{\tau_{\Omega_c^0} = 268 \pm 24 \pm 10 \pm 2}\ \textbf{fs}$$
$$\boldsymbol{\tau_{\Lambda_c^+} = 203.5 \pm 1.0 \pm 1.3 \pm 1.4}\ \textbf{fs}$$
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result ± statistical ± systematic ± due to uncertainty on τ_{D^+}

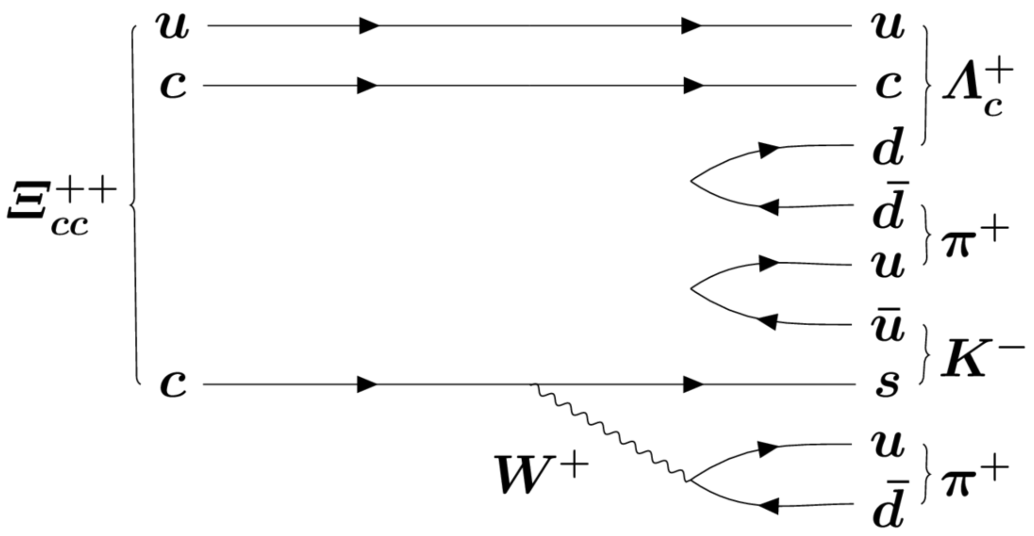
- $\tau_{\Lambda_c^+}$, $\tau_{\Xi_c^+}$, and $\tau_{\Xi_c^0}$ have 3-4x smaller uncertainties than previous world averages
- $\tau_{\Xi_c^0}$ 3.3σ larger than previous world average 112^{+13}_{-10} fs
- $\tau_{\Omega_c^0}$ 6.9σ larger than previous world average 69 ± 12 fs
  - Changes lifetime hierarchy
    - Previous world averages
      $\tau_{\Xi_c^+} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0} > \boldsymbol{\tau_{\Omega_c^0}}$
    - LHCb measurements
      $\tau_{\Xi_c^+} > \boldsymbol{\tau_{\Omega_c^0}} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0}$
  - Highlights theoretical uncertainties:
    - Higher-order terms in Heavy Quark Expansion (HQE)
    - Degree of interference between spectator *s*-quarks and that from $c \to sW^+$ transition ($\Omega_c^0 = css$)
    - Role of spectator *ss* system spin

Observation of the doubly charmed baryon Ξ_{cc}^{++}, 14 September 2017, arXiv:1707.01621

Ξ_{cc}^{++} OBSERVATION

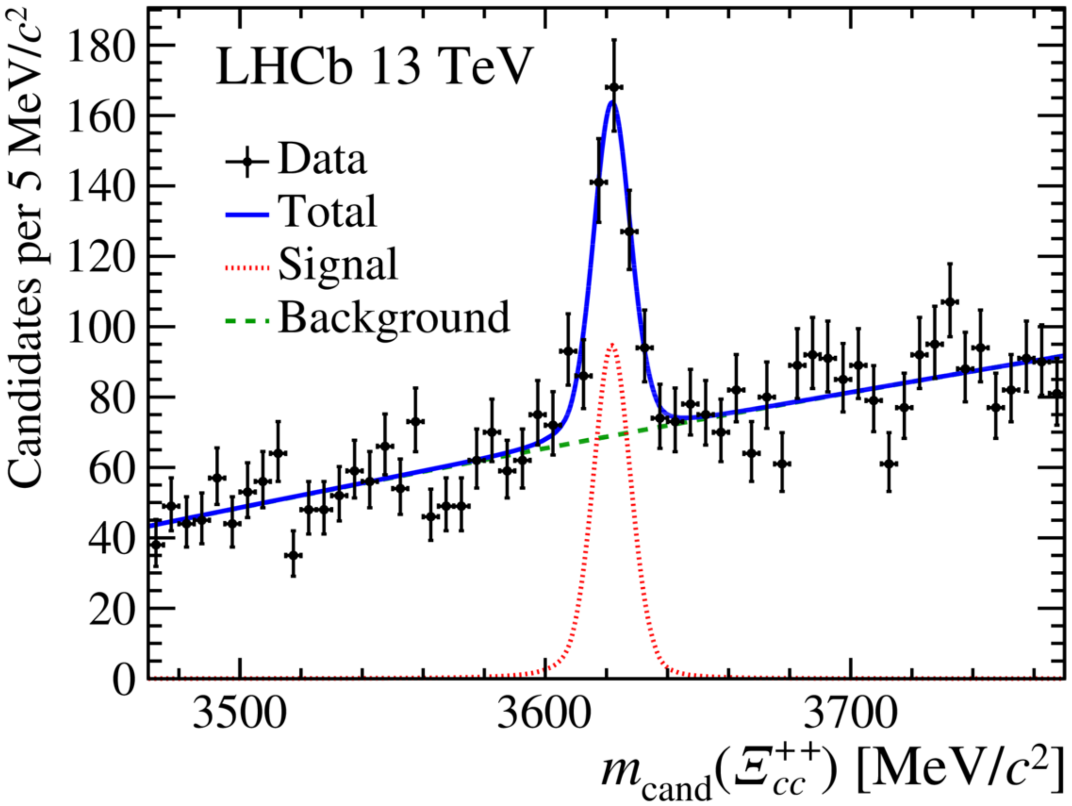
Decay Mode and Selections

- Look for $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$
  - $\Lambda_c^+ \to p K^- \pi^+$
- Measure $m_{\text{cand}}(\Xi_{cc}^{++}) \equiv m(\Lambda_c^+ K^- \pi^+ \pi^+) - m_{\text{cand}}(\Lambda_c^+) + m_{\text{PDG}}(\Lambda_c^+)$
- $\int \mathcal{L} = 1.7\ \text{fb}^{-1}$ at 13 TeV in Run 2
- Pass a set of kinematic, vertexing, and PID selections to eliminate background
- Neural network (MLP) trained on simulation and data control samples discriminates kinematic and vertexing parameters



Mass Fit

- Fit signal with the sum of a Gaussian and a double-sided Crystal Ball with the same means
  - Mass, yield, resolution float, other parameters fixed to simulation
- Fit background with 2nd order polynomial
- 313 ± 33 signal yield
  - $> 12\sigma$ local significance, verified with 8 TeV sample



Results and Implications

- $m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72 \pm 0.27 \pm 0.14\ \text{MeV}/c^2$
  - result ± statistical ± systematic ± due to uncertainty on $m(\Lambda_c^+)$
- Consistent with most theoretical expectations ($3.5\ \text{GeV} < m(\Xi_{cc}^{++}) < 3.7\ \text{GeV}$)
- 12σ significance even for candidates with decay time 5x > uncertainty
  - Indicates weak decay
- Mass splitting too large to be SELEX Ξ_{cc}^{+} isospin partner
  - SELEX observed a state identified as Ξ_{cc}^{+} in 2002 ($\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$, 6.3σ, arXiv:0208014) and 2004 ($\Xi_{cc}^{+} \to p D^+ K^-$, 4.8σ, arXiv:0406033).
    - FOCUS (Nucl. Phys. Proc. Suppl. 115 (2003) 33), BaBar (2006, arXiv:0605075), Belle (2006, arXiv:0606051), and LHCb (2013, arXiv:1310.2538) have null results when looking for this state…
      - …but SELEX used hyperon beam on fixed nuclear targets.
    - If SELEX measurement wrong, this is the 1st observation of a doubly-charmed baryon.
  - $m_{\text{LHCb}}(\Xi_{cc}^{++}) - m_{\text{SELEX}}(\Xi_{cc}^{+}) = 103 \pm 2\ \text{MeV}/c^2$

Measurement of the lifetime of the doubly charmed baryon Ξ_{cc}^{++}, 31 July 2018, arXiv:1806.02744

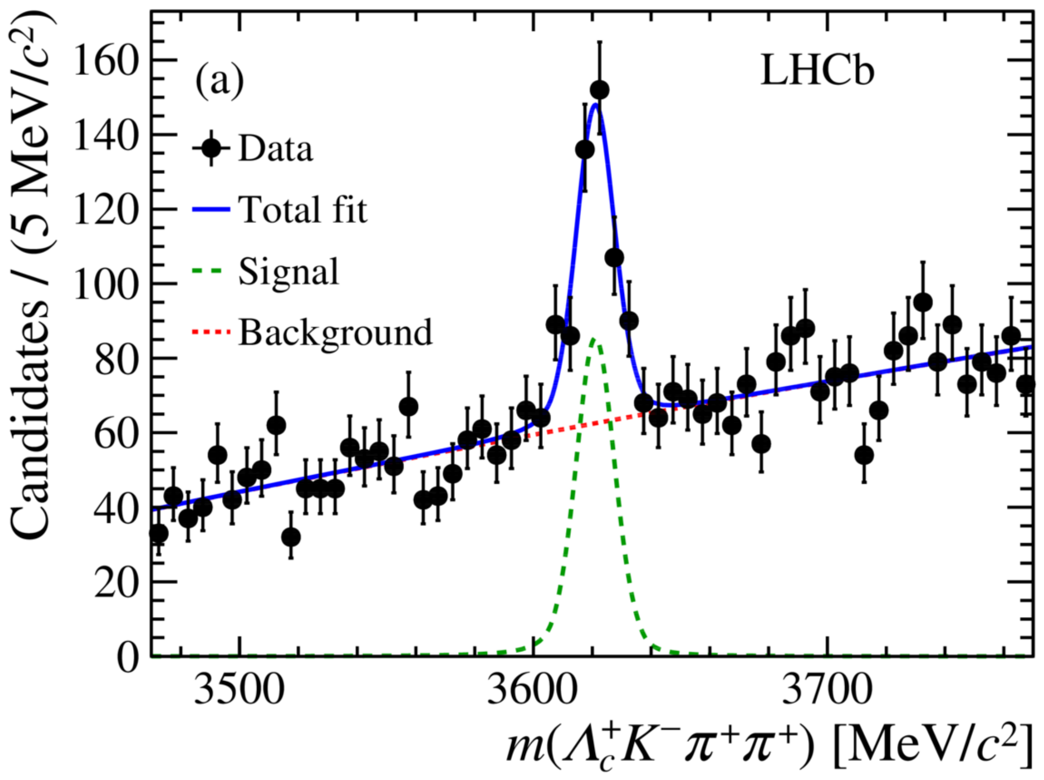
$\tau(\Xi_{cc}^{++})$

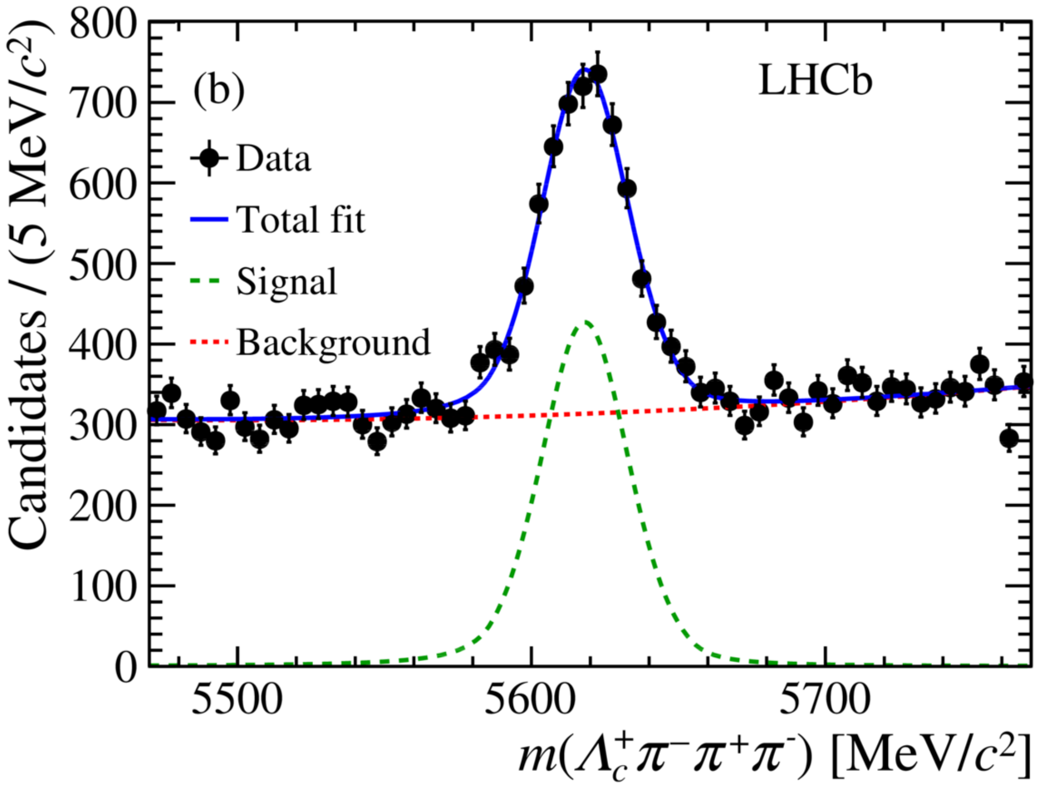
Decay Modes and Selections

- Look for $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$
  - $\Lambda_c^+ \to p K^- \pi^+$
- Measure $\frac{\tau_{\Xi_{cc}^{++}}}{\tau_{\Lambda_b^0}}$
  - $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$
- $m = M(\Lambda_c^+ h\pi\pi) - M\left([pK^-\pi^+]_{\Lambda_c^+}\right) + M_{\mathrm{PDG}}(\Lambda_c^+)$

- $\int \mathcal{L} = 1.7\ \mathrm{fb}^{-1}$ at 13 TeV in Run 2
- All modes require a set of kinematic, vertexing, and PID selections to eliminate background, as well as hardware triggers designed to minimize bias
- Neural network (MLP) trained on simulation and data control samples discriminates kinematic and vertexing parameters
- Largely mimics Ξ_{cc}^{++} observation analysis

Mass Fits

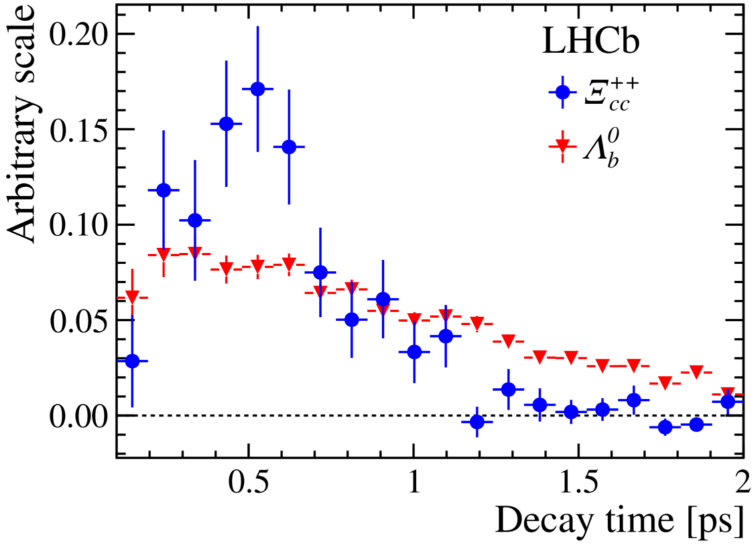


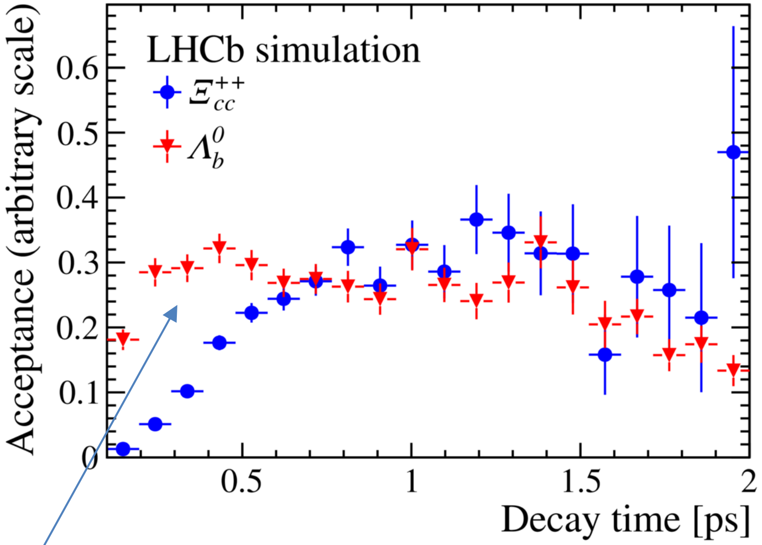


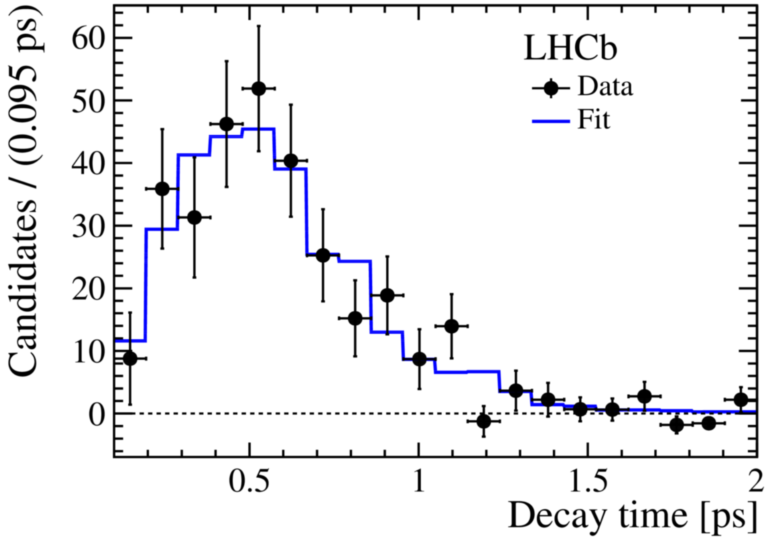
Fits to m using the sum of a Gaussian and a double-sided Crystal Ball for the signal and a 2nd order Chebychev polynomial for the background

304 ± 35 signal Ξ_{cc}^{++} and 3397 ± 119 normalization Λ_b^0 candidates

Lifetime Fit







After background-subtraction

Λ_b^0 has higher mass
⇒ higher momentum daughters, larger opening angle
⇒ higher acceptance

Acceptance is the ratio of reconstructed and generated decay times in simulation

Exponential fit to the background-subtracted, acceptance-corrected Λ_b^0 decay time as a cross check—consistent with world average

Fit to $f_{\Xi_{cc}^{++}}(t) =$

$$H_{\Lambda_b^0}(t)\,\frac{\epsilon_{\Xi_{cc}^{++}}(t)}{\epsilon_{\Lambda_b^0}(t)}\exp\left(\frac{t}{\tau_{\Lambda_b^0}} - \frac{t}{\tau_{\Xi_{cc}^{++}}}\right)$$

- $H_{\Lambda_b^0}$ is the background-subtracted Λ_b^0 decay time
- ϵ_i are the acceptances
- $\tau_{\Lambda_b^0}$ fixed to known value

Results and Implications

- $\tau_{\Xi_{cc}^{++}} = 256^{+24}_{-22} \pm 14\ \text{fs}$
  - result ± statistical ± systematic
- First measurement
  - Verifies weak decay
  - Favors the lower end of theoretical predictions
- From theoretical predictions,

$$\tau_{\Xi_{cc}^{++}} \simeq 3.5 \times \tau_{\Xi_{cc}^{+}} \Rightarrow \tau_{\Xi_{cc}^{+}} \simeq 60 - 90\ \text{fs}$$

  - Theoretically, $\tau_{\Xi_{cc}^{++}} > \tau_{\Xi_{cc}^{+}}$ because
    - Ξ_{cc}^{++} *u*-quark and decay products interfere destructively.
    - Ξ_{cc}^{+} *c*- and *d*-quarks contribute additional W-exchange.
  - Inconsistent, according to theoretical models, with SELEX result (90% CL, arXiv:0208014):

$$\tau_{\Xi_{cc}^{+}} < 33\ \text{fs}$$

CONCLUSIONS

Conclusions

- LHCb has recently advanced our knowledge of (doubly-) charmed baryon lifetimes.
  - Changed lifetime hierarchy:

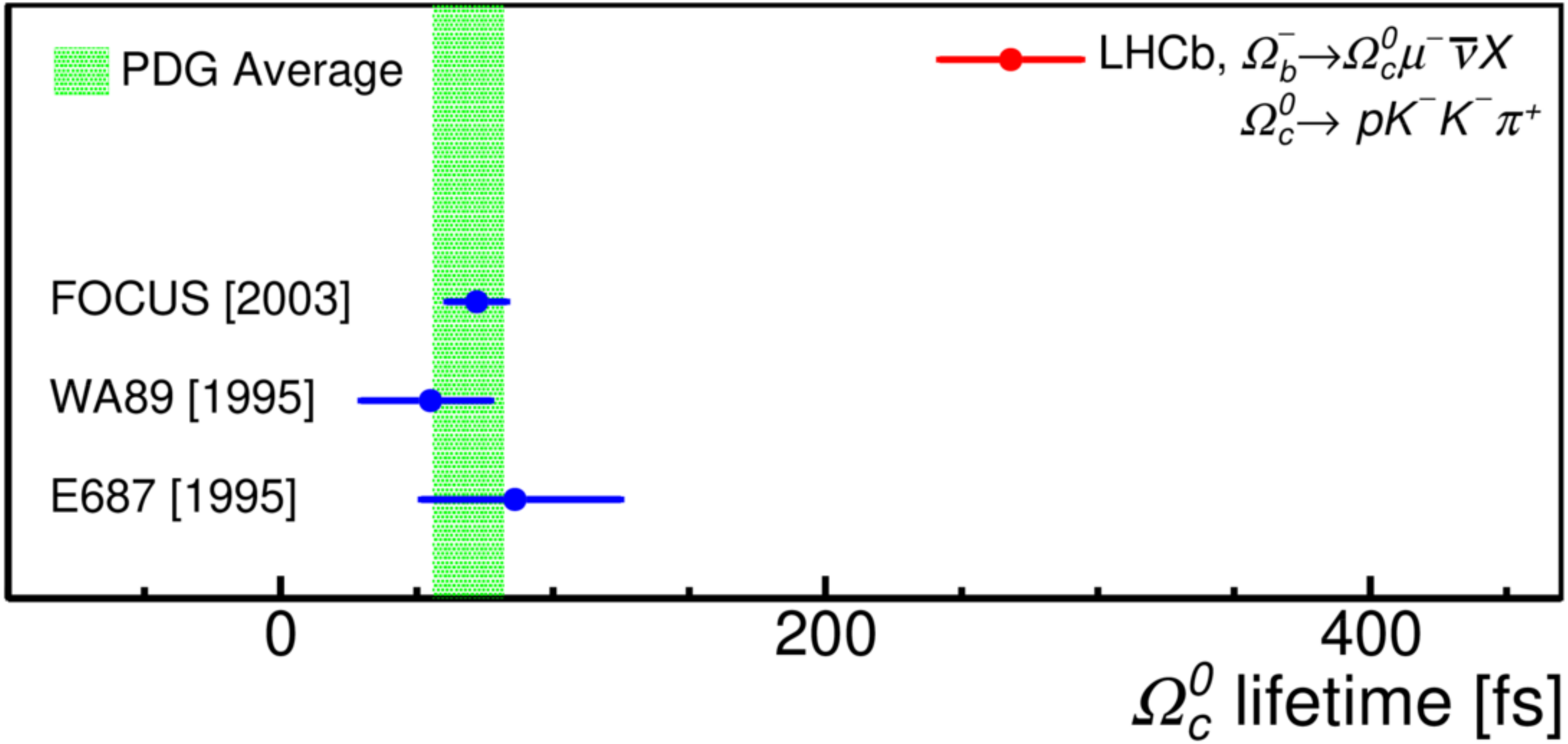
$$\tau_{\Xi_c^+} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0} > \boldsymbol{\tau_{\Omega_c^0}} \rightarrow \tau_{\Xi_c^+} > \boldsymbol{\tau_{\Omega_c^0}} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0}$$

  - $\tau_{\Xi_c^0} \sim 3.3\sigma$ greater than previous world average
  - Greater precision for $\tau_{\Lambda_c^+},\ \tau_{\Xi_c^+},\ \tau_{\Xi_c^0}$
  - First observation of Ξ_{cc}^{++}
  - First measurement of $\tau_{\Xi_{cc}^{++}}$

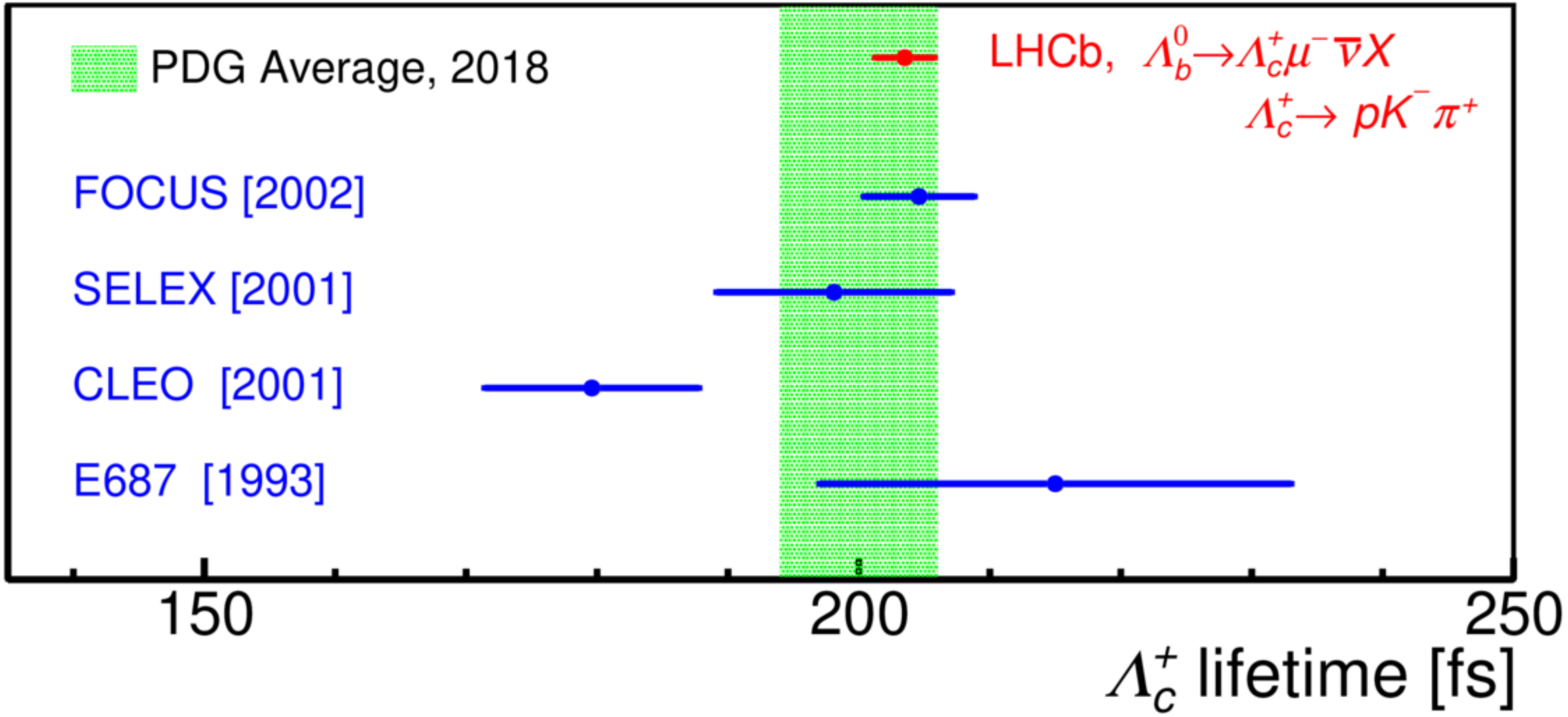
FIN

BACKUP

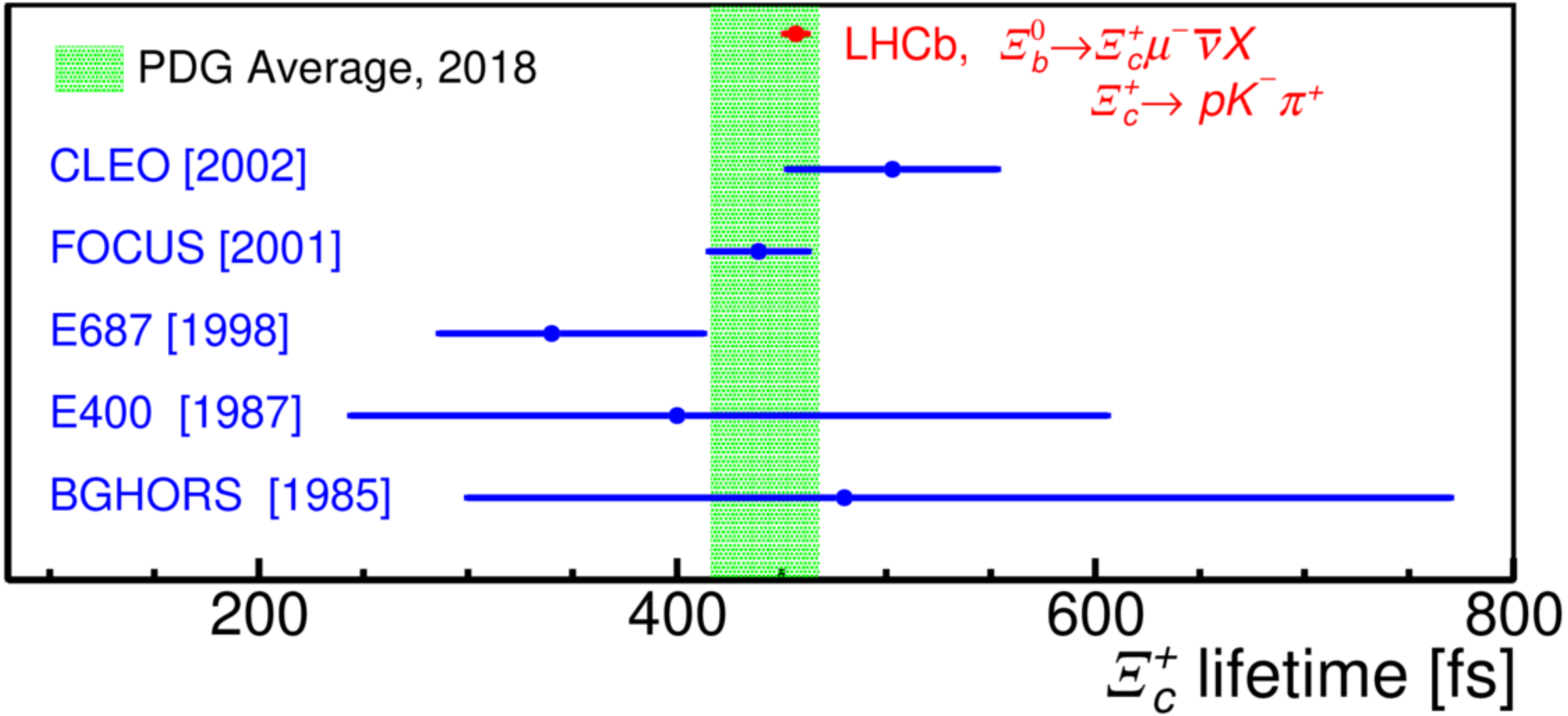
$\tau(\Omega_c^0)$


PDG Average
LHCb, $\Omega_b^- \to \Omega_c^0 \mu^- \overline{\nu} X$
$\Omega_c^0 \to pK^-K^-\pi^+$
FOCUS [2003]
WA89 [1995]
E687 [1995]
0
200
400
Ω_c^0 lifetime [fs]

$\tau(\Lambda_c^+)$

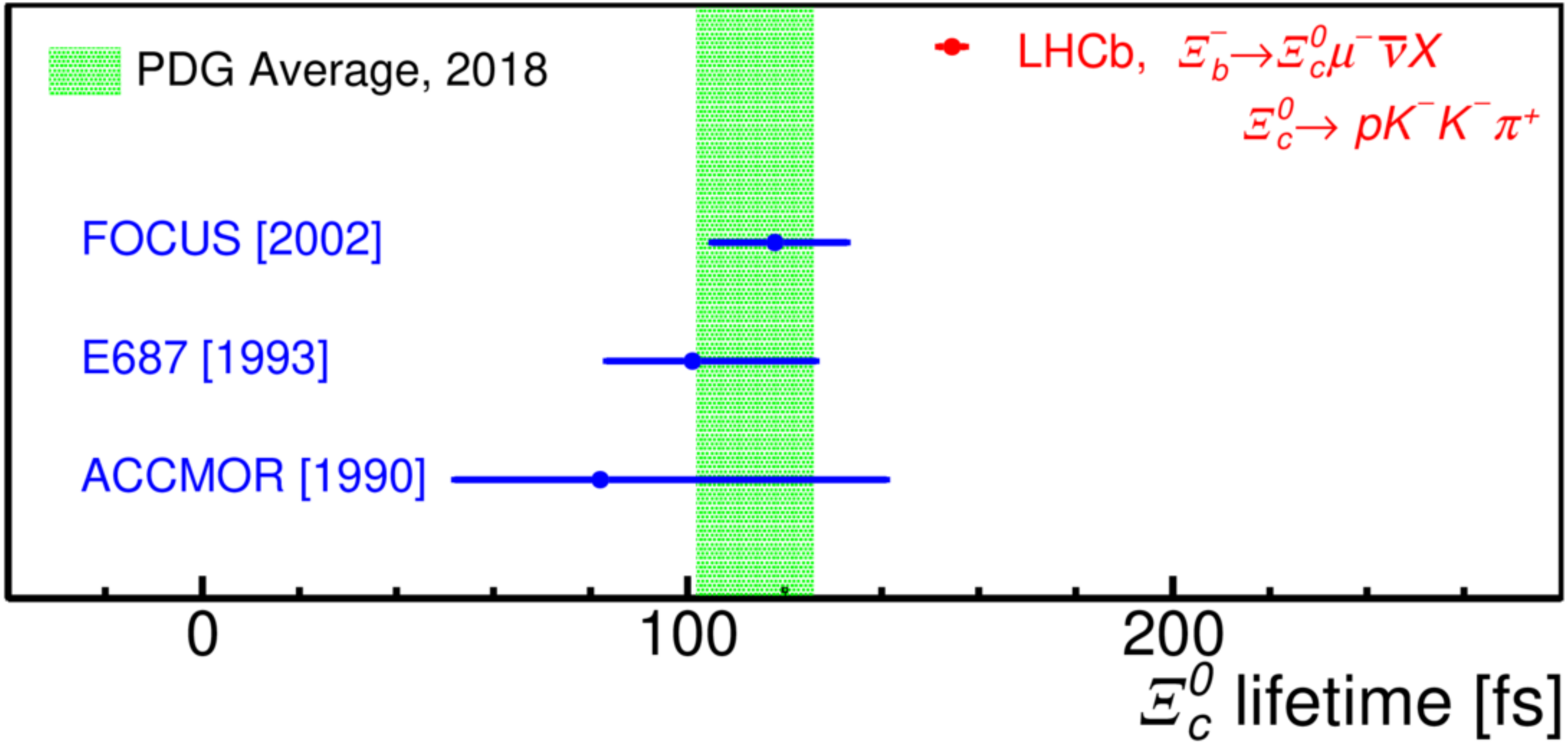

PDG Average, 2018
LHCb, $\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu} X$
$\Lambda_c^+ \to pK^- \pi^+$
FOCUS [2002]
SELEX [2001]
CLEO [2001]
E687 [1993]
150
200
250
Λ_c^+ lifetime [fs]

$\tau(\Xi_c^+)$

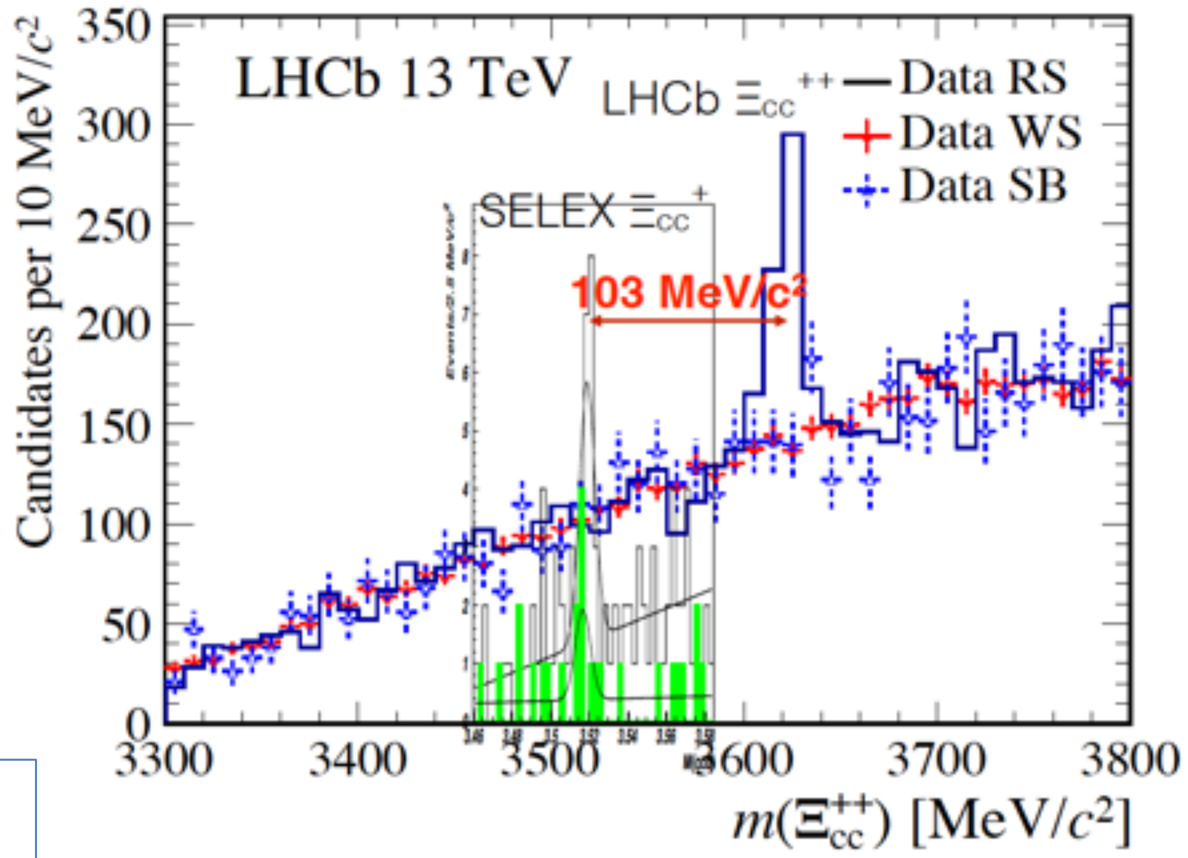


PDG Average, 2018
LHCb, $\Xi_b^0 \to \Xi_c^+ \mu^- \overline{\nu} X$
$\Xi_c^+ \to pK^- \pi^+$
CLEO [2002]
FOCUS [2001]
E687 [1998]
E400 [1987]
BGHORS [1985]
200
400
600
800
Ξ_c^+ lifetime [fs]

$\tau(\Xi_c^0)$


PDG Average, 2018
LHCb, $\Xi_b^- \to \Xi_c^0 \mu^- \overline{\nu} X$
$\Xi_c^0 \to pK^-K^-\pi^+$
FOCUS [2002]
E687 [1993]
ACCMOR [1990]
0
100
200
Ξ_c^0 lifetime [fs]

Results and Implications



SELEX (with fits):
$\Xi_{cc}^{+} \rightarrow \Lambda_c^+ K^- \pi^+$ empty
$\Xi_{cc}^{+} \rightarrow p D^+ K^-$ shaded

LHCb (no fits):
RS: $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$
WS: $\Lambda_c^+ K^- \pi^+ \pi^-$
SB: $m(\Lambda_c^+)$ sideband