Heavy Quark Baryons

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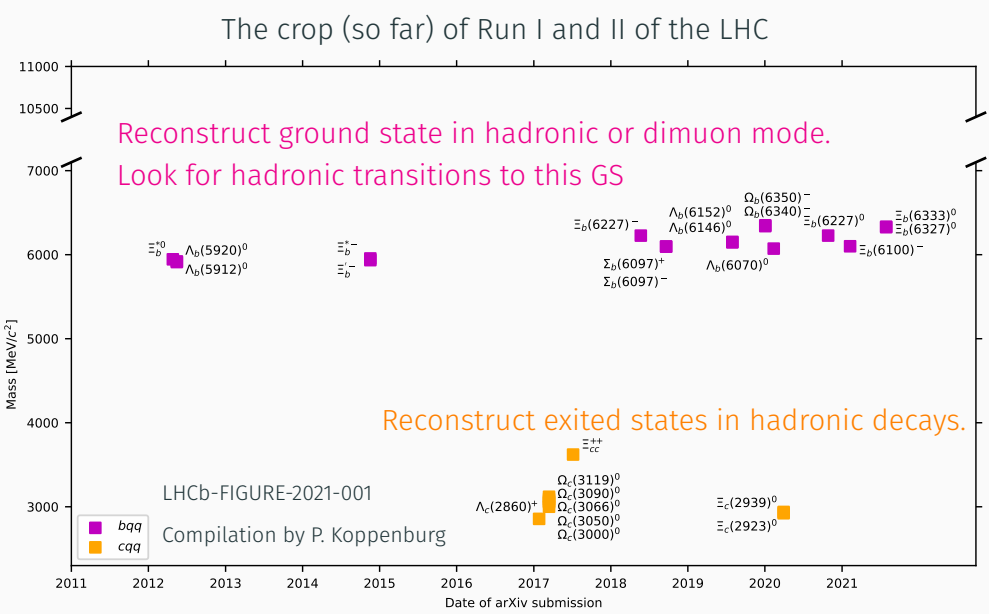
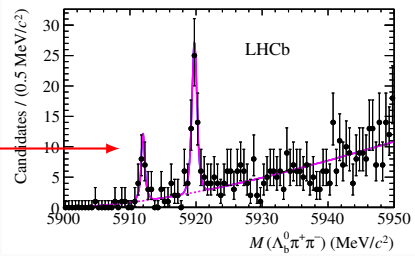
STRONG2020 Online Workshop, September 16th, 2021

Heavy Quark Baryons at the LHC

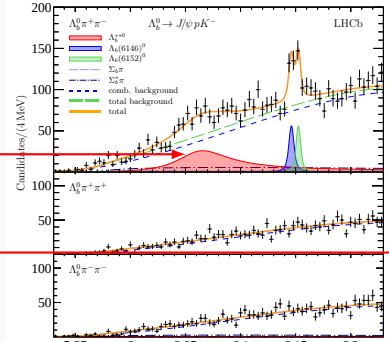


A good example of how collecting more data leads to further discoveries

2012
[PRL109 172003]

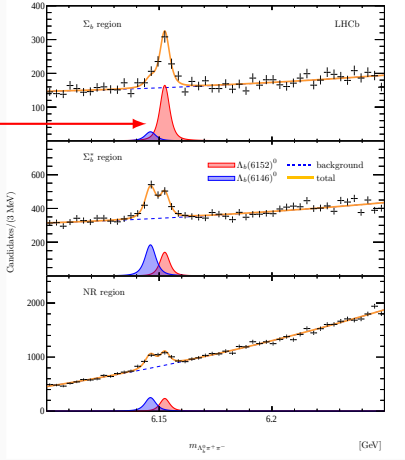


- $\Lambda_b(5620)^0$
- $\Lambda_b(5912)^0$
- $\Lambda_b(5920)^0$
- $\Lambda_b(5670)^0$
- $\Lambda_b(6146)^0$
- $\Lambda_b(6152)^0$



2020
[JHEP2006 136]

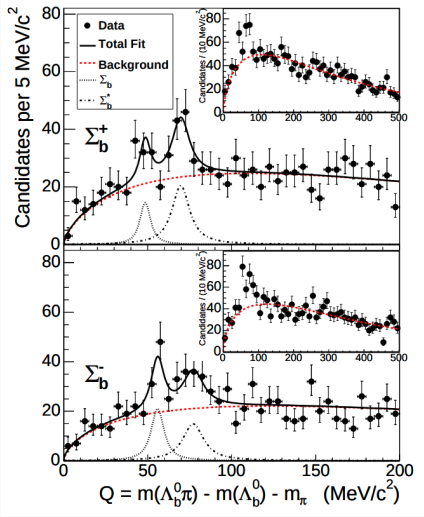
2019 [PRL123,15]



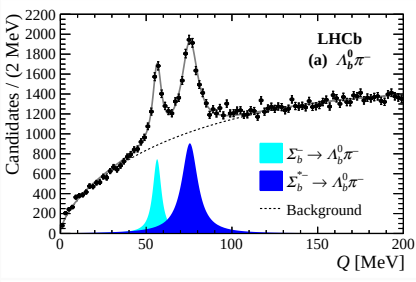
Σ_b and Σ_b^* in $\Lambda_b^0\pi^\pm$

$|udb\rangle, I = 1, S = 0$

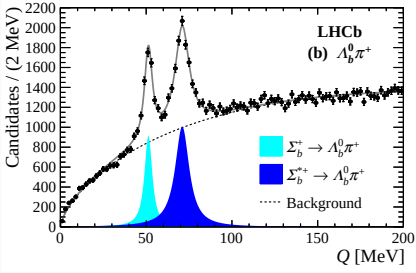
CDF discovery [PRL99(2007)202001]



LHCb [PRL122(2019)012001]



$\Lambda_b\pi^-$



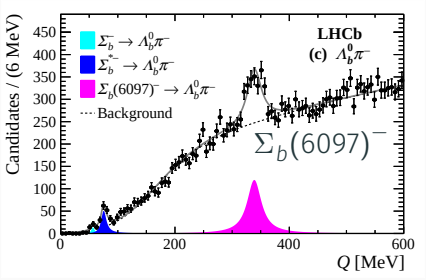
$\Lambda_b\pi^+$

Triplet incomplete. Neutral state still missing. $\Lambda_b^0\pi^0$ experimentally challenging.

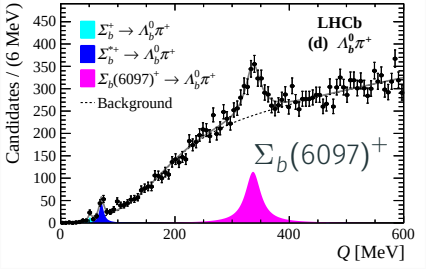
A new Σ_b excitation

$|udb\rangle, I = 1, S = 0$

[PRL122(2019)012001]



$\Lambda_b\pi^-$



$\Lambda_b\pi^+$

Quantity	Value [MeV]
$m(\Sigma_b(6097)^-)$	$6098.0 \pm 1.7 \pm 0.5$
$m(\Sigma_b(6097)^+)$	$6095.8 \pm 1.7 \pm 0.4$
$\Gamma(\Sigma_b(6097)^-)$	$28.9 \pm 4.2 \pm 0.9$
$\Gamma(\Sigma_b(6097)^+)$	$31.0 \pm 5.5 \pm 0.7$
$\Sigma_b^{(*)}$ masses and widths in agreement with CDF	
$m(\Sigma_b^{*-}) - m(\Sigma_b^-)$	$19.09 \pm 0.22 \pm 0.02$
$m(\Sigma_b^{*+}) - m(\Sigma_b^+)$	$19.73 \pm 0.18 \pm 0.01$
$\Delta(\Sigma_b(6097)^\pm)$	$-2.2 \pm 2.4 \pm 0.3$
$\Delta(\Sigma_b^\pm)$	$-5.09 \pm 0.18 \pm 0.01$
$\Delta(\Sigma_b^{*\pm})$	$-4.45 \pm 0.22 \pm 0.01$

- 5 $\Sigma_b(1P)$ states expected in heavy-quark limit

  e. g. [Nucl. Phys. A965(2017)57]

- **$\Sigma_b(6097)$ might be a superposition of several resonances**

A doublet of strangely beautiful baryons: Ξ_b $S = -1, I = 1/2$

Groundstate parameters (PDG)

State	M [MeV/c^2]	Mean life [10^{-12} s]
Ξ_b^-	5797.0 ± 0.9	1.572 ± 0.040
Ξ_b^0	5791.9 ± 0.5	1.477 ± 0.030

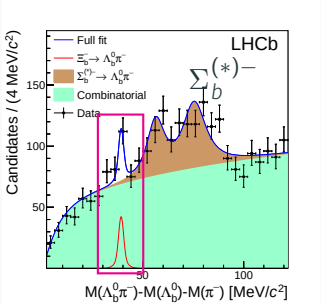
New mass measurement from LHCb:

$$m(\Xi_b^-) = 5796.70 \pm 0.39 \pm 0.15 \pm 0.17\,\text{MeV}/c^2$$

[PRD99(2019)052006]
in agreement with previous results

- Lifetimes benchmark for HQET
- Good agreement with HQE prediction
  [Int.J.Mod.Phys.A30(2015)1543005]

Evidence for a strangeness changing decay $\Xi_b^- \to \Lambda_b \pi^-$ [PRL115(2015)241801]



$$\mathcal{B}(\Xi_b^- \to \Lambda_b{}^0 \pi^-) = 0.2 \cdots 0.6\%$$

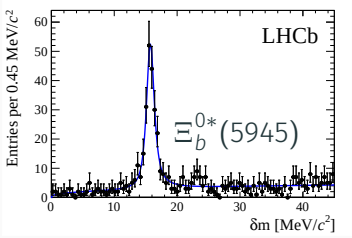
in agreement with [PLB750(2015)653]

Ξ_b excitation spectrum overview

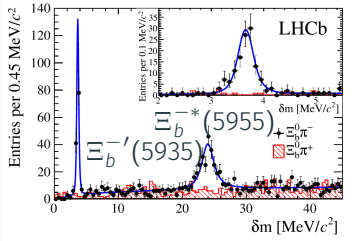
- 5 excited states known
- Isospin partner of the $1/2^+$ excitation missing
  - probably below $\Xi_b^0\pi^0$ threshold

J^P	$I_3 = -\frac{1}{2}$	$I_3 = +\frac{1}{2}$
$\frac{1}{2}^+$	$\Xi_b^-(5935)$	missing
$\frac{3}{2}^+$	$\Xi_b^-(5955)$	$\Xi_b^0(5945)$
?	$\Xi_b^-(6100)$ NEW	
?	$\Xi_b^-(6227)$	

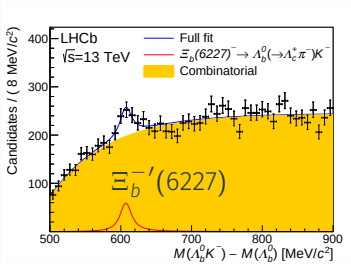
[JHEP05(2016)161]



[PRL114(2015)062004]

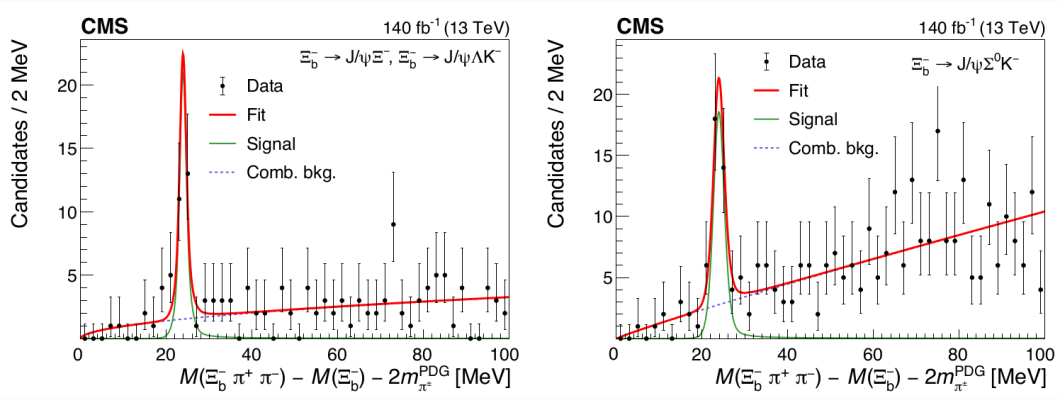


[PRL121(2018)072002]



The new $\Xi_b(6100)^-$ at CMS

$\Xi_b\pi^+\pi^-$ with Xi_b reconstructed at CMS in two modes [PRL126(2021)252003]



$m = 6100.3 \pm 0.2 \pm 0.1 \pm 0.6\,\text{MeV}$ $\quad$ $\Gamma < 1.9\,\text{MeV}\,(95\%CL)$

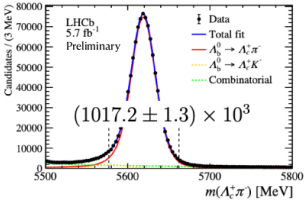
Possible assignment: P-wave excitation $J^P = 3/2^-$ (analog to $\Xi_c(2815)$)

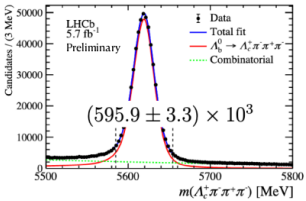
News: two new Ξ_b excitations from LHCb (shown at PWA/ATHOS)

- Example of a resent search (arXiv this August)
- Use the very abundant samples of Λ_b saved on disk
- Use both:
  - $\Lambda_b \to \Lambda_c \pi$
  - $\Lambda_b \to \Lambda_c \pi \pi^+ \pi$

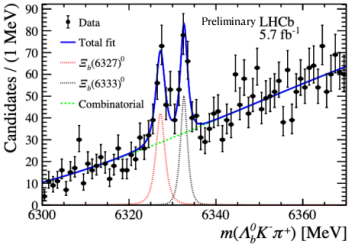
Paper in Preparation
LHCb-PAPER-2021-025

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





- Two narrow peaks in the Λ_b K- π+ mass spectrum are observed



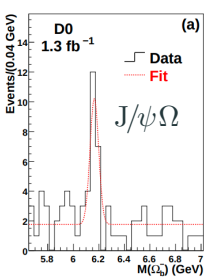
$$m_{\Xi_b(6327)^0} = 6327.28^{+0.23}_{-0.21} \pm 0.08 \pm 0.24\,\text{MeV},$$
$$m_{\Xi_b(6333)^0} = 6332.69^{+0.17}_{-0.18} \pm 0.03 \pm 0.22\,\text{MeV},$$
$$\Gamma_{\Xi_b(6327)^0} < 2.20\ (2.56)\,\text{MeV at 90\% (95\%) CL},$$
$$\Gamma_{\Xi_b(6333)^0} < 1.55\ (1.85)\,\text{MeV at 90\% (95\%) CL},$$

- Discovered at D0 and CDS
- $\Omega_b \to J/\psi\Omega$
- For a long time only ground state known
- Only two decay modes established

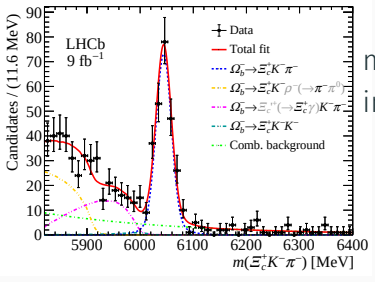
LHCb is reconstructing Ω_b in several final states

[arXiv:2107.03419]

[PRL99(2007)202001]

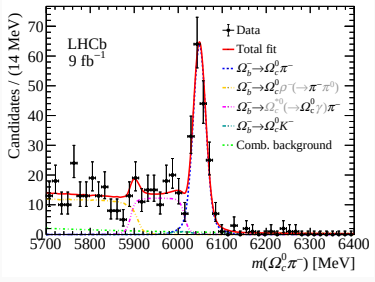


$\Xi_c^+ K^- \pi^-$



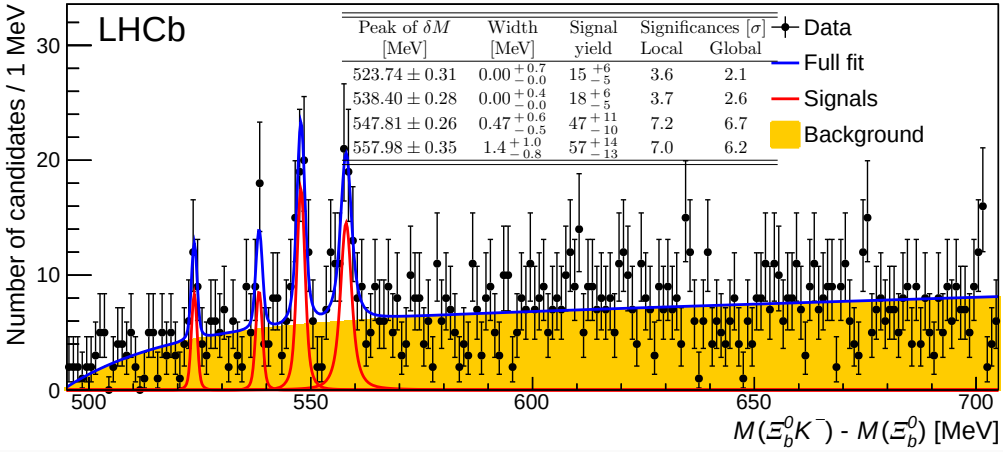
more on this in the next talk

$\Omega_c^0 \pi^-$



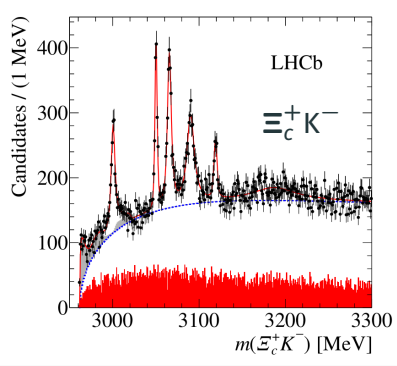
$\Xi_b^0 K^-$ produced in pp collisions at the LHC. Full dataset corresponding to $9\,\text{fb}^{-1}$

[PRL124(2020)082002]

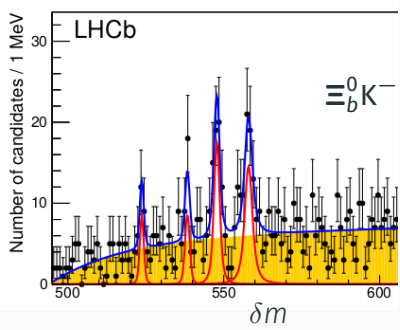


Double strange heavy baryons - comparison

[PRL118(2017)182001]



[PRL124(2020)082002]



- Most natural J^P assignment would be $1/2^-, 1/2^-, 3/2^-, 3/2^-, 5/2^-$
- Quark di-quark model predicts 5 P-wave excitations, 5/2 Ω_b state not seen? [PRD102(2020)014027]
- Molecular model can explain 3 Ω_c and 4 Ω_b states $\Xi_Q' \bar{K}, \Xi_Q^* \bar{K}, \Xi \bar{B}/\bar{D}, \Xi \bar{B}^*$ [PRD101(2020)054033] J^P assignment would be $1/2^-, 3/2^-, 1/2^-, 3/2^-$ for Ω_b

Charmed Baryons

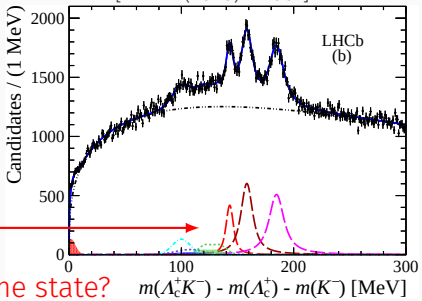
Ξ_c states

$|cqs\rangle, S = -1, I = 1/2$

Ξ_c
Ξ_c'
$\Xi_c(2645)$
$\Xi_c(2790)$
$\Xi_c(2815)$
$\Xi_c(2923)$
$\Xi_c(2930)$
$\Xi_c(2965)$
$\Xi_c(2970)$
$\Xi_c(3055)$
$\Xi_c(3080)$
$\Xi_c(3123)$

5 P-wave states?

[PRL124(2020)222001]

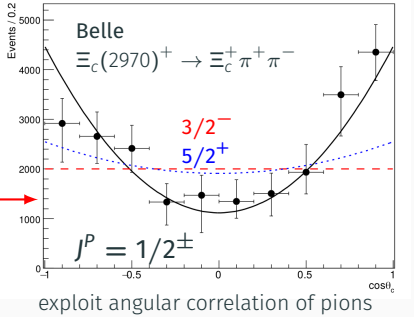


same state?

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

Belle: $\Gamma(\Xi_c(2970))^+ = 30.3 \pm 2.3^{+1.0}_{-1.8}$

[PRD103(2021)111101]



exploit angular correlation of pions

Belle: comprehensive study in hadronic transitions to Ξ_c [PRD94(2016)052011]

Ω_c lifetime

- HQE: lifetime hierarchy

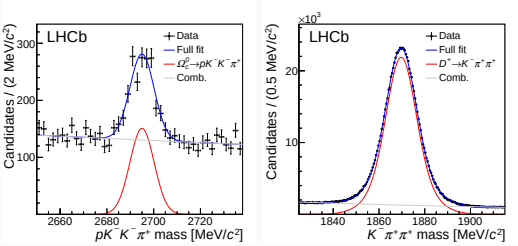
$$\tau_{\Xi_c^+} > \tau_{\Lambda_c^0} > \tau_{\Xi_c^0} > \tau_{\Omega_c^0}$$

- $\tau_{\Omega_c^0}$ considered smallest due to constructive interference between s-quark in $c \to s$ transition and spectator s
- HQE allows inverted hierarchy depending on treatment of higher orders [hep-ph/9311331]
- $\tau_{\Omega_c^0} = 69 \pm 12\,fs$ from small statistics, fixed target experiments, consistent with hierarchy

- Measure lifetime ratio

$$r_{\Omega_c^0} = \frac{\tau_{\Omega_c^0}}{\tau_{\mathrm{D}^+}}$$

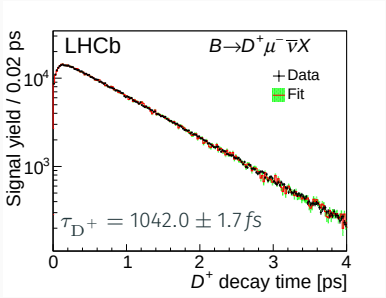
- Using semileptonic decays $\Omega_b^- \to \Omega_c^0 \mu^- \bar{\nu}_\mu X$ and $\mathrm{B}^0 \to \mathrm{D}^+ \mu^- \bar{\nu}_\mu X$

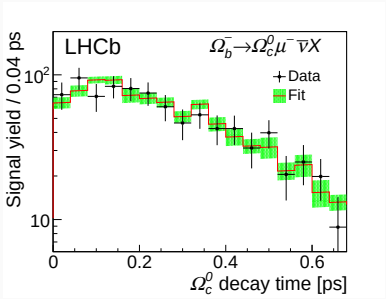


[PRL121(2018)092003]

Ω_c lifetime in semileptonic decays at LHCb

[PRL121(2018)092003]

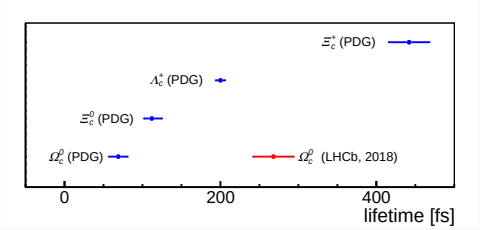




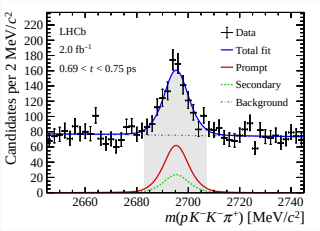
- Calibrated on $\mathrm{B}^0 \to \mathrm{D}^+ \mu^- \bar{\nu}_\mu X$

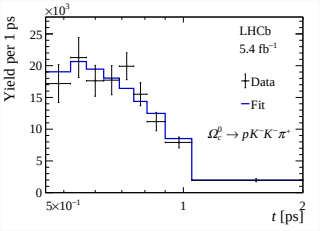
$$r_{\Omega_c^0} = \frac{\tau_{\Omega_c^0}}{\tau_{\mathrm{D}^+}} = 0.258 \pm 0.023 \pm 0.010$$
$$\tau_{\Omega_c^0} = 268 \pm 24 \pm 10 \pm 2\, fs$$

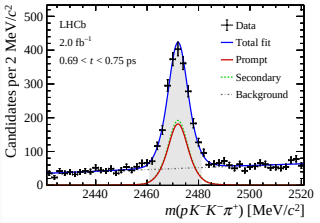
- ~ 4 times larger than world average
- new hierarchy:

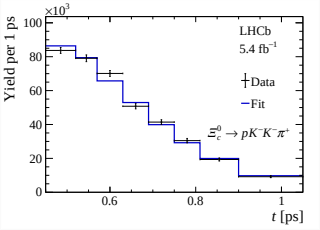


Both states reconstructed in $\mathrm{pK^-K^-\pi^+}$. Prompt contributions unfolded by simultaneous fit of mass and separation between collision point and decay vertex. $\mathrm{D^0 \to K^+K^-\pi^+\pi^-}$ as control.



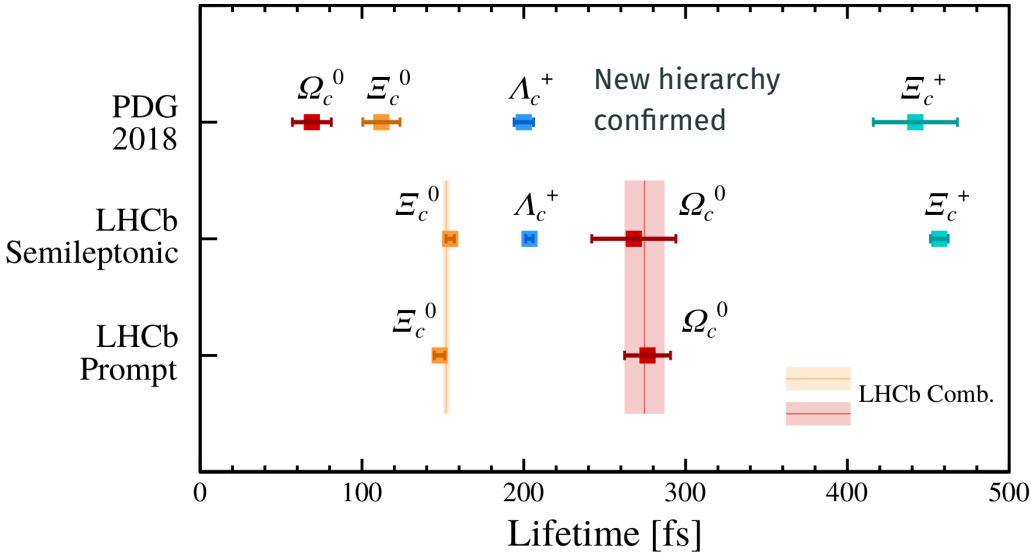






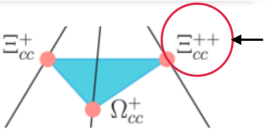
$\mathbf{\Omega_c^0}$ $\tau_{\Omega_c^0} =$
$276.5 \pm 13.4 \pm 4.4 \pm 0.7$ fs

$\mathbf{\Sigma_c^0}$ $\tau_{\Sigma_c^0} =$
$148.0 \pm 2.3 \pm 2.2 \pm 0.2$ fs


PDG 2018
LHCb Semileptonic
LHCb Prompt
Ω_c^0
Ξ_c^0
Λ_c^+
New hierarchy confirmed
Ξ_c^+
Ξ_c^0
Λ_c^+
Ω_c^0
Ξ_c^+
Ξ_c^0
Ω_c^0
LHCb Comb.
0
100
200
300
400
500
Lifetime [fs]

• Ξ_{cc}^{++}

- Well established in 2 different modes (as required by PDG)
- Lifetime measured as well



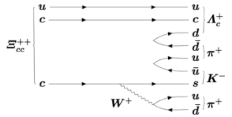
3621.6 ± 0.4 MeV

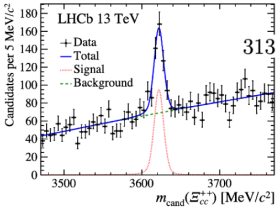
$(2.56 \pm 0.27) \times 10^{-13}$ s

	Mode
Γ_1	$\Lambda_c^+ K^- \pi^+ \pi^+$
Γ_2	$\Xi_c^+ \pi^+$, $\Xi_c^+ \to pK^- \pi^+$
Γ_3	$D^+ pK^- \pi^+$

Phys. Rev. Lett. 119, 112001 **(2017)**

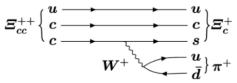
$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

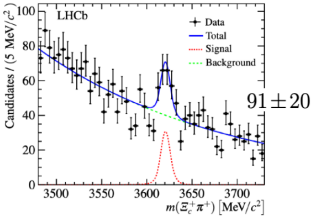




Phys. Rev. Lett. 121, 162002 (2018)

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





JHEP10(2019)124

$\Xi_{cc}^{++} \to D^+ pK^- \pi^+$ decays

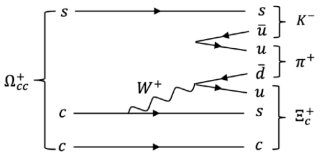
No significant signal is observed
Upper limit set

Searches for double-heavy baryons

Search for the doubly charmed baryon Ω_{cc}^+

arXiv:2105.06841

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



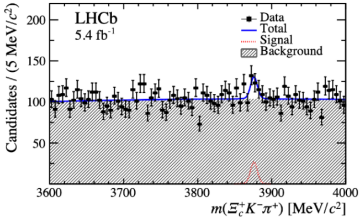
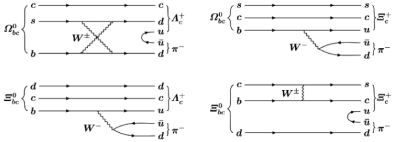
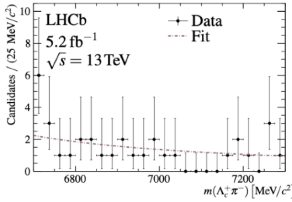


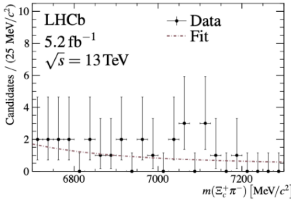
Figure 2: Invariant mass $m(\Xi_c^+ K^- \pi^+)$ distribution of selected Ω_{cc}^+ candidates from (black points) selection A, with (blue solid line) the fit with the largest local significance at the mass of 3876 MeV/c^2 superimposed.

Search for the doubly heavy baryons Ω_{bc}^0 and Ξ_{bc}^0 decaying to $\Lambda_c^+ \pi^-$ and $\Xi_c^+ \pi^-$

arXiv:2104.04759







Summary - Heavy Baryons

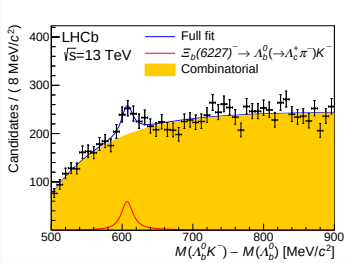
- Rich crop from the LHC Run I and II, especially in beauty sector.
- Rare modes need more statistics
  $\Rightarrow$ LHC Run 3 starts next year.
- In particular for spin-parity measurements.
- Belle data very valuable in Charm sector
  – looking forward to Belle II.
- Searches for double-heavy baryons picking up speed.

Backup

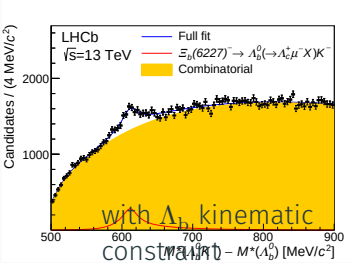
The (formerly) heaviest Baryon

[PRL121(2018)072002]

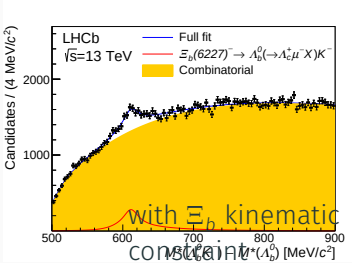
Exclusive $\Lambda_b K$ with $\Lambda_b \to \Lambda_c^+ \pi$



Semileptonic $\Lambda_b K$ with $\Lambda_b \to \Lambda_c^+ \mu X$



Semileptonic $\Xi_b \pi$ with $\Xi_b \to \Xi_c \mu X$



- Mass: $m(\Xi_b(6227)^-) = 6226.9 \pm 2.0 \pm 0.3 \pm 0.2\,\mathrm{MeV}/c^2$
- Width: $\Gamma(\Xi_b(6227)^-) = 18.1 \pm 5.4 \pm 1.8\,\mathrm{MeV}/c^2$