Spectroscopy results from LHCb

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on behalf of the LHCb collaboration

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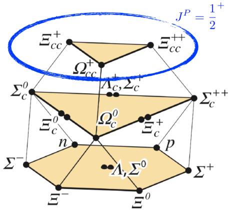
Introduction

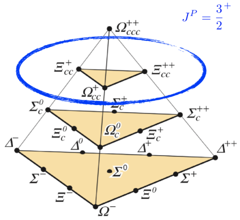
- Spectroscopy provides opportunities to study QCD predictions for models
- QCD predictions are quite reliable for standard hadrons (mesons and baryons)
- Many observed states still lack of interpretation: exotic states which are not fitting the standard picture
- LHCb physics program is devoted not only to precision measurements in b, c sectors but also to spectroscopy
- LHCb has produced striking results in the spectroscopy sector

Ξ_{cc} system

- Doubly charmed baryons predicted by quark model
- Theoretical predictions of Ξ_{cc}^{++} mass are between $3.5\text{-}3.7\,\mathrm{GeV}/c^2$ [PRD70 (2004) 094004, PRD73 (2006) 094022, PRD78 (2008) 094007, EPJA37 (2008) 217, E2PJA45 (2010) 267,...] close to Ξ_{cc}^{+}
- Different theoretical predictions are available also for the lifetime showing a large ambiguity: 150 - 1550 fs [PRD60 (1999) 014007, EPJC9(1999) 213, PRD66(2002) 014007, PRD90 (2014) 094007, ...]
- Ξ_{cc}^{+} state observed by SELEX experiment [PRL 89 (2002) 112001, PRL97 (2006) 162001]:
  - $M = 3518.7 \pm 1.7\,\mathrm{MeV}$
  - Unexpected short lifetime: $\tau < 33\,\mathrm{fs}$ @ 90% CL
- Not confirmed by Focus [Nucl.Phys.Proc.Suppl 115 (2003)33], BaBar [PRD 74 (2006) 011103], Belle [PRL 97(2006) 162001] nor LHCb [JHEP 12 (2013) 090]



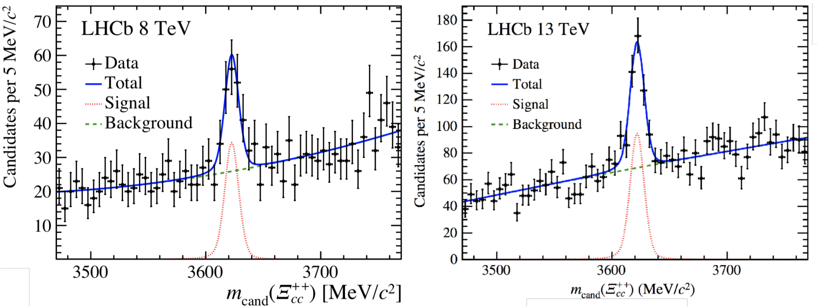
$J^P = 1/2^+$ baryons decay weakly to other flavours



$J^P = 3/2^+$ baryons decay via strong interactions to $J^P = 1/2^+$

Observation of Ξ_{cc}^{++} [PRL 119 (2017) 112001]

- Search in LHCb using $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^-$
- Data sample: $2.0\,\text{fb}^{-1}$ at 8 TeV (2012) + $1.7\,\text{fb}^{-1}$ at 13 TeV (2016)



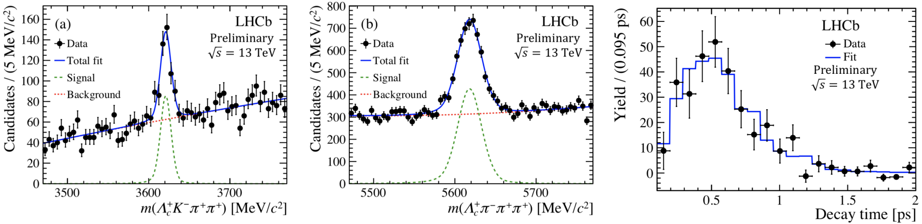
- Highly significant peaks: 7.6σ (2012), 12.9σ (2016)
  Yields: 313 ± 33 (2016) and 113 ± 21 (2012)
- Mass measured with the 2016 sample:

$$m(\Xi_c^{++}) = 3621.40 \pm 0.72(stat) \pm 0.31(syst)\,\text{MeV}/\text{c}^2$$

consistent with theoretical range of predictions, not consistent with Ξ_{cc}^+ SELEX measurement (100 MeV above SELEX Ξ_{cc}^+ peaks)

Lifetime measurement [LHCB-PAPER-2018-19, PRELIMINARY]

- Measuring its lifetime is crucial to establish the weak nature of its decay and for comparison with theoretical predictions
- Using the $\Xi_c^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ decay relative to the control channel $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$ ($\sim 1.7\,\mathrm{fb}^{-1}$ - $13\,\mathrm{TeV}$)
- Unbinned maximum likelihood fit of the background-subtracted Ξ_{cc}^{++} decay time distribution

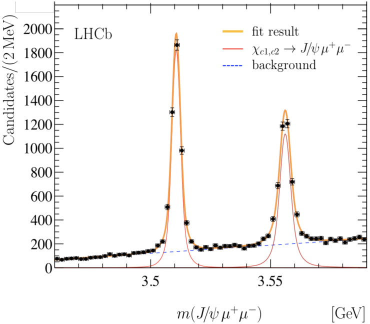


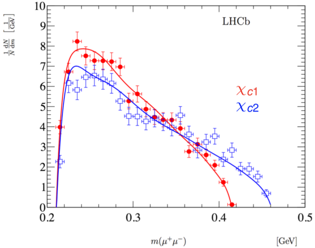
$$\tau_{\Xi_{cc}^{++}} = 0.256^{+0.224}_{-0.022}(stat) \pm 0.014(syst)\,\mathrm{ps}$$

- Many studies of other Ξ_{cc}^{++} decay modes and properties (production mechanism, ...) and search for other doubly-charmed baryon states

Studies of χ_c Dalitz decays [PRL 119 (2017) 22, 221801]

- Study of quarkonia to test QCD mechanism
- $\chi_{c(1,2)}$ states studied using radiative $\chi_{c(1,2)} \to J/\psi\gamma$ decays
- First observation of $\chi_{c1,2} \to J/\psi\mu^+\mu^-$ with $J/\psi \to \mu^+\mu^-$ using Run1 ($1+2\,\mathrm{fb}^{-1}$ at 7 and $8\,\mathrm{TeV}$) + Run 2 ($1.9\,\mathrm{fb}^{-1}$ at $13\,\mathrm{TeV}$)
- Event topology with 4 muons: clean signature!





Background subtracted dimuon mass distributions agree well with the theoretical expectation of photon-mediated amplitudes

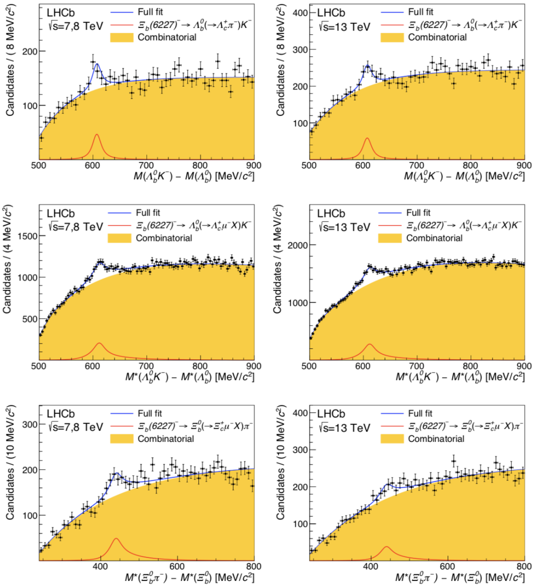
- Measurements of χ_{c1} and χ_{c2} parameters are consistent with and have similar precision to current world averages

$$m(\chi_{c1}) = 3510.71 \pm 0.04 \pm 0.09\,\mathrm{MeV}$$
$$m(\chi_{c2}) = 3556.10 \pm 0.06 \pm 0.11\,\mathrm{MeV}$$
$$m(\chi_{c2}) - m(\chi_{c1}) = 45.39 \pm 0.07 \pm 0.03\,\mathrm{MeV}$$

$$\Gamma(\chi_{c2}) = 2.10 \pm 0.20\,(\mathrm{stat}) \pm 0.02\,(\mathrm{syst})\,\mathrm{MeV}$$

A new Ξ_b^{**-} state! [PAPER-2018-013 arXiv:1805.09418]

- LHCb has a unique capability to search for excited states of beauty hadrons
- Already a number have been discovered ($\Lambda_b(5912)^0$, $\Lambda_b(5920)^0$, $\Sigma_b^{*\pm}$, $\Xi_b^{'}(5935)^-$, $\Xi_b^*(5955)^-$ and $\Xi_b(5945)^0$)
- Dataset: $1.0\,\mathrm{fb}^{-1}$ at $7\,\mathrm{TeV}$ + $2.0\,\mathrm{fb}^{-1}$ at $8\,\mathrm{TeV}$ + $1.5\,\mathrm{fb}^{-1}$ at $13\,\mathrm{TeV}$
- A new Ξ_b^{**-} state seen in both fully hadronic and semileptonic (SL) decays
  - Hadronic $\Lambda_b^0 \to \Lambda_c^+\pi^-$ with resolution $2\,\mathrm{MeV}$, 7.9σ
  - SL $\Lambda_b^0 \to \Lambda_c^+\mu^- X$ with resolution $18\,\mathrm{MeV}$, $\times 15$ yield, 25σ
  - SL $\Xi_b^0 \to \Lambda_c^+\mu^- X$, 9.2σ



A new Ξ_b^{**-} state! [PAPER-2018-013 arXiv:1805.09418]

- With hadronic mode:

$$m_{\Xi_b(6227)^-} - m_{\Lambda_b^0} = 607.3 \pm 2.0\,(\text{stat}) \pm 0.3\,(\text{syst})\,\text{MeV}/c^2,$$
$$\Gamma_{\Xi_b(6227)^-} = 18.1 \pm 5.4\,(\text{stat}) \pm 1.8\,(\text{syst})\,\text{MeV}/c^2,$$
$$m_{\Xi_b(6227)^-} = 6226.9 \pm 2.0\,(\text{stat}) \pm 0.3\,(\text{syst}) \pm 0.2(\Lambda_b^0)\,\text{MeV}/c^2$$

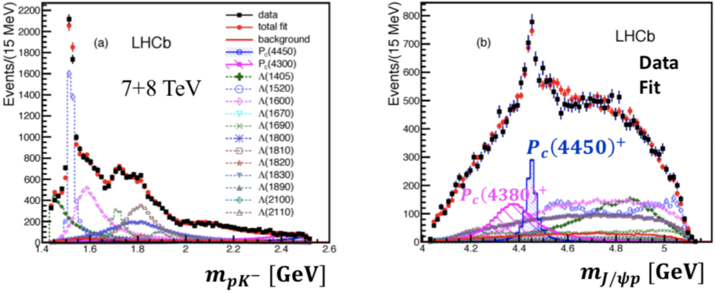
- Production ratios are also measured with SL modes

Quantity $[10^{-3}]$	$7+8\,\text{TeV}$	$13\,\text{TeV}$
$(\sigma_{\Xi_b^{**-}}/\sigma_{\Lambda_b^0})\mathcal{B}(\Xi_b^{**-} \to \Lambda_b^0 K^-)$	$3.0 \pm 0.3 \pm 0.4$	$3.4 \pm 0.3 \pm 0.4$
$(\sigma_{\Xi_b^{**-}}/\sigma_{\Xi_b^0})\mathcal{B}(\Xi_b^{**-} \to \Xi_b^0 \pi^-)$	$47 \pm 10 \pm 7$	$22 \pm 6 \pm 3$

- Consistent with expectations of either a $\Xi_b(1P)$ and $\Xi_b(2S)$ states
- J^P not yet measured to distinguish between the states

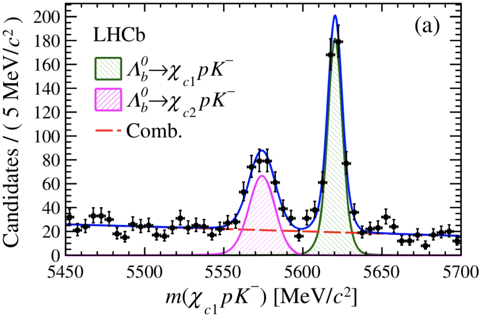
Exotic spectroscopy

- The observation of states with properties inconsistent with pure $c\bar{c}$ and $b\bar{b}$ states raised the interest of the so-called exotic (non-standard) quarkonium states from both the theoretical and experimental point of view
- The nature and the internal structure of these states are still unclear (molecular/tightly bound)
- The observation of charmonium pentaquark states ($c\bar{c}uud$) by LHCb in $\Lambda_b \to J/\psi p K^-$ [PRL 115 (2015) 072001, PRL 117 (2016) 082002] and $\Lambda_b \to J/\psi p \pi^-$ [PRL 117 (2016) 082003] decay channels raises the interest of searches of other pentaquark states



Observation of $\Lambda_b \to \chi_{c(1,2)} p K^-$ [PRL 119 (2017) 062001]

- The pentaquark $P_c(4450)^+$ state has mass close to $\chi_{c1}p$ threshold
- Test of the hypothesis of $P_c(4450)^+$ as a kinematic effect of the rescattering $\chi_{c1}p$ to $J/\psi p$
- If a kinematic effect, it should be absent in $\Lambda_b \to \chi_{c(1,2)} p K^-$ [PLB 751 (2015) 59, PRD 91 (2015) 071502 (R)]
- $3\,\text{fb}^{-1}$ at 7 and 8 TeV (Run 1)
- Reconstruct as $\chi_{c(1,2)} \to J/\psi\gamma$ with the $m(J/\psi\gamma)$ constrained to the $m(\chi_{c1})$: $\Lambda_b \to \chi_{c2} p K^-$ is displaced
- Observed: $\Lambda_b^0 \to \chi_{c1} p K$ (453 ± 25 candidates, 29σ) and $\Lambda_b^0 \to \chi_{c2} p K$ (285 ± 23 candidates, 17σ)
- Measurement of the branching fractions



$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.242 \pm 0.014 \pm 0.013 \pm 0.009$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.248 \pm 0.020 \pm 0.014 \pm 0.009$$

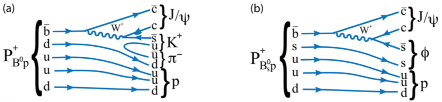
$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)} = 1.02 \pm 0.10 \pm 0.02 \pm 0.05$$

- Amplitude analysis will be performed after adding Run2 data!

Search for weakly decaying b-flavoured pentaquarks

[PRD 97 (2018) 032010]

- Search for pentaquark states containing a b (anti)quark, long-lived with a lifetime of the same order of other B-hadrons, decaying weakly
- Skyrme model: heavy quarks give tightly bound pentaquarks [PLB 590(2004) 185; PLB 586(2004)337; PLB 331(1994)362]
- Using modes involving a J/ψ in the final state due to large efficiencies and reduced backgrounds



- Search for mass peaks below the corresponding strong decay threshold mass

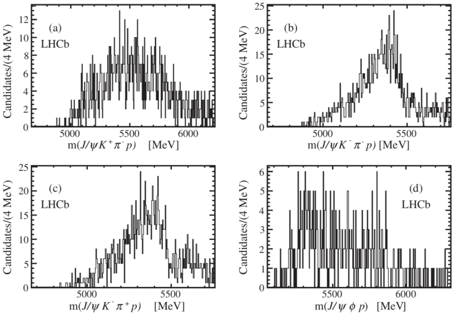
Quark content	Decay mode	Search window
$\bar{b}duud$	$P^+_{B^0 p} \to J/\psi K^+ \pi^- p$	4668–6220 MeV
$b\bar{u}udd$	$P^-_{\Lambda^0_b \pi^-} \to J/\psi K^- \pi^- p$	4668–5760 MeV
$b\bar{d}uud$	$P^+_{\Lambda^0_b \pi^+} \to J/\psi K^- \pi^+ p$	4668–5760 MeV
$\bar{b}suud$	$P^+_{B^0_s p} \to J/\psi \phi p$	5055–6305 MeV

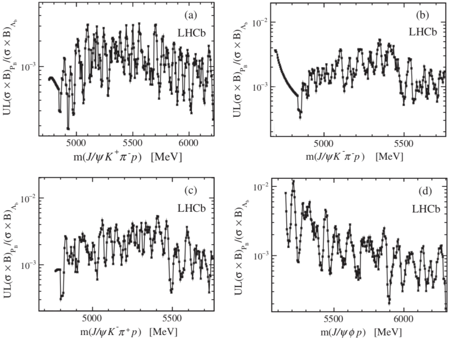
Search for weakly decaying b-flavoured pentaquarks

[PRD 97 (2018) 032010]

- Measurement of the production ratio with respect to $\Lambda_b^0 \to J/\psi p K^-$ measured by LHCb

$$R = \frac{\sigma(pp \to P_B X) \cdot \mathcal{B}(P_B \to J/\psi X)}{\sigma(pp \to \Lambda_b^0 X) \cdot \mathcal{B}(\Lambda_b^0 \to J/\psi K^- p)}$$





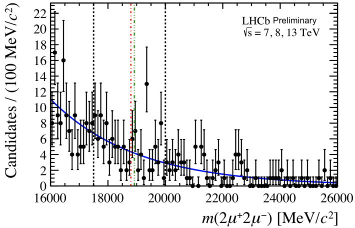
No evidence for signal, 90% CL limits on $R < 10^{-2}$-10^{-3}

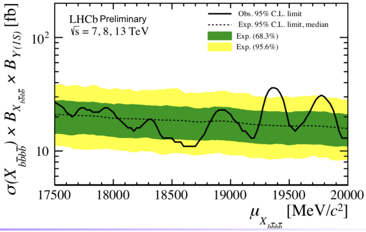
Search for beautiful tetraquarks in the $\Upsilon(1S)\mu^+\mu^-$ invariant mass spectrum

[LHCb-PAPER-2018-027, preliminary]

- Search for a possible exotic meson state composed of two b and two $\bar{b}$ quarks: $X_{bb\bar{b}\bar{b}}$

- Several predictions for the mass and width of an exotic $X_{bb\bar{b}\bar{b}}$ state [PRD86 (2012) 034004, PLB773 (2017) 247, PRD95 (2017) 034011, EPJC77 (2017) 432, ...]
- It should have mass around 18.4-$18.8\,\mathrm{GeV/c^2}$, below the $2m_{\eta_b}$ threshold, meaning that it can decay to $\Upsilon\ell^+\ell^-$
- Data sample: $6.0\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 7$, 8 and $13\,\mathrm{TeV}$
- No significant excess is seen for any mass hypothesis in the range $[17.5, 20.0]\,\mathrm{GeV/c^2}$
- Set upper limits on $\sigma(pp \to X_{b\bar{b}b\bar{b}}) \times \mathcal{B}(X_{b\bar{b}b\bar{b}} \to \Upsilon(1S)\mu^+\mu^-) \times \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)$ normalising to $\Upsilon(1S) \to \mu^+\mu^-$ decay channel



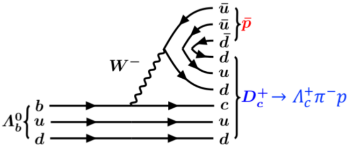


Search for dibaryon states

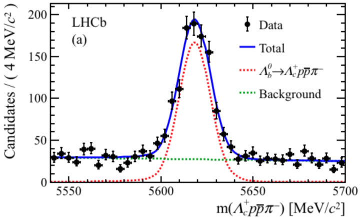
[LHCb-PAPER-2018-005, arXiv:1804.09617, submitted to PLB]

- Search for the lightest charmed dibaryon $D_c^+ = [cd][ud][ud]$ with a mass below 4682 MeV in $\Lambda_b^0 \to \bar{p} D_c^+$ decays

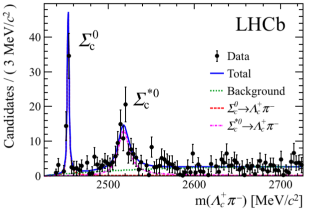
- The D_c^+ dibaryon decay could proceed via quark rearrangement to the final state $p\Sigma_c^0$ with $\Sigma_c^0 \to \Lambda_c^+\pi^-$ or via a lighter pentaquark state $P_c(\bar{u}[cd][ud])p$



- LHCb observed for the first time the $\Lambda_b \to \Lambda_c^+ p\bar{p}\pi^-$ decay using $3\,\text{fb}^{-1}$ of data



Resonance contributions in $\Lambda_c^+\pi^-$



$$N_{\Lambda_b^0 \to \Lambda_c^+ p\bar{p}\pi^-} = 926 \pm 43$$

$$N_{\Lambda_b^0 \to \Sigma_c^0 p\bar{p}} = 59 \pm 10 \quad N_{\Lambda_b^0 \to \Sigma_c^{*0} p\bar{p}} = 104 \pm 17$$

Search for dibaryon states

[LHCb-PAPER-2018-005, arXiv:1804.09617, submitted to PLB]

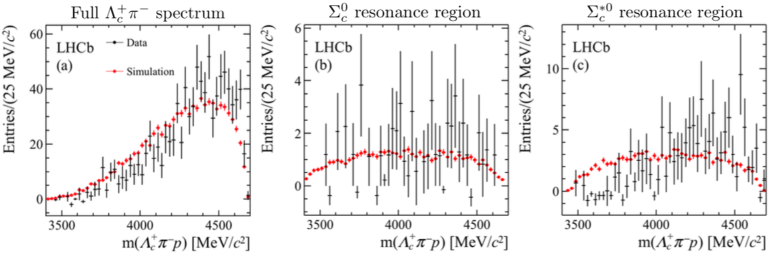
- Measurements of branching ratio:

$$\frac{\mathcal{B}(\Lambda_b \to \Lambda_c^+ p\bar{p}\pi^-)}{\mathcal{B}(\Lambda_b \to \Lambda_c^+ \pi^-)} = 0.0540 \pm 0.0023 \pm 0.0032$$

$$\frac{\mathcal{B}(\Lambda_b \to \Sigma_c^0(\to \Lambda_c^+ \pi^-) p\bar{p}\pi^-)}{\mathcal{B}(\Lambda_b \to \Lambda_c^+ p\bar{p}\pi^-)} = 0.089 \pm 0.015 \pm 0.006$$

$$\frac{\mathcal{B}(\Lambda_b \to \Sigma_c^{*0}(\to \Lambda_c^+ \pi^-) p\bar{p}\pi^-)}{\mathcal{B}(\Lambda_b \to \Lambda_c^+ p\bar{p}\pi^-)} = 0.119 \pm 0.020 \pm 0.014$$

- No dibaryon peak in $m_{\Lambda_c^+\pi^- p}$ spectrum



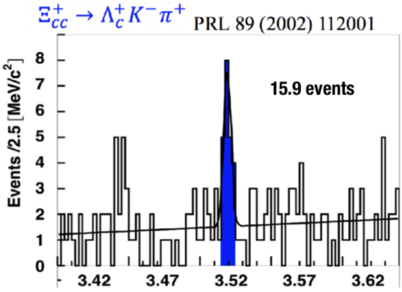
Conclusions

- Spectroscopy is an essential part of the LHCb physics programme
  - Study of exotic states
  - Observation of doubly charmed baryons
  - Study of excited b hadrons
- Continuing to exploit LHCb potential adding Run2 data
  - Updates of present analyses with higher stats, precision measurements
  - More amplitude analysis
  - Exotic states searches in other decay channels

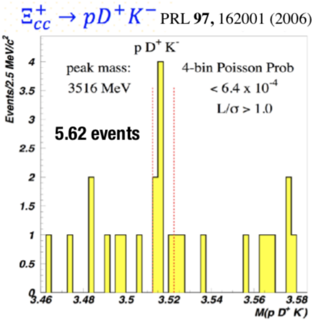
Spare slides

SELEX Ξ_{cc}^{+}

Using collisions of a hyperon beam on fixed nuclear targets

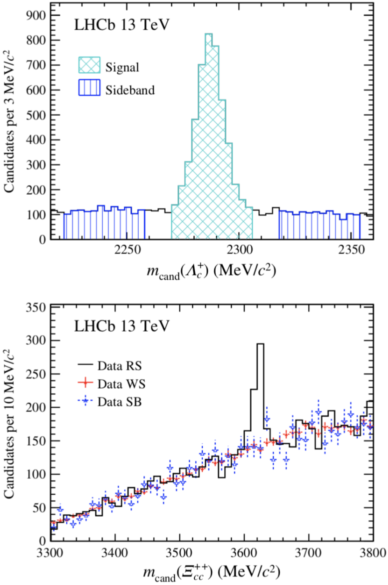


6.3σ



4.8σ

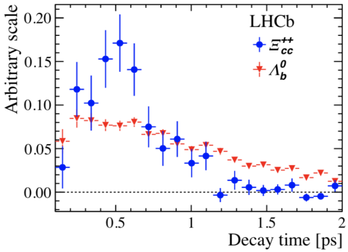
Ξ_{cc}^{+}

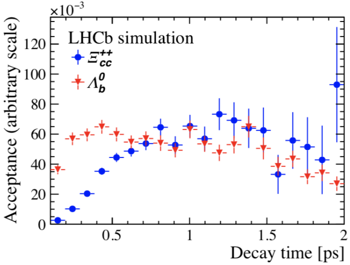


LHCb 13 TeV
Signal
Sideband
Candidates per 3 MeV/c^2
900
800
700
600
500
400
300
200
100
0
2250
2300
2350
$m_{\text{cand}}(\Lambda_c^+)$ (MeV/c^2)
LHCb 13 TeV
Data RS
Data WS
Data SB
Candidates per 10 MeV/c^2
350
300
250
200
150
100
50
0
3300
3400
3500
3600
3700
3800
$m_{\text{cand}}(\Xi_{cc}^{++})$ (MeV/c^2)

Ξ_{cc}^{++} lifetime

$$f_{\Xi_{cc}^{++}}(t) = H_{\Lambda_b^0}(t) \times \frac{\epsilon_{\Xi_{cc}^{++}}}{\epsilon_{\Lambda_b^0}} \times exp(\frac{t}{\tau(\Lambda_b^0)} - \frac{t}{\tau(\Xi_{cc}^{++})})$$





Ξ_{cc}^{++} lifetime: systematic uncertainties

Source	Uncertainty (ps)
Signal and background mass models	0.005
Correlation of mass and decay-time	0.004
Binning	0.001
Data-simulation differences	0.004
Resonant structure of decays	0.011
Hardware trigger threshold	0.002
Simulated Ξ_{cc}^{++} lifetime	0.002
Λ_b^0 lifetime uncertainty	0.001
Sum in quadrature	0.014

Studies of χ_c Dalitz decays

Source of uncertainty	$m(\chi_{c1})$	$m(\chi_{c2})$	$m(\chi_{c2}) - m(\chi_{c1})$
Momentum scale	88	102	18
Energy loss correction	20	20	...
Final-state radiation	7	10	12
Resonance shape	15	24	25
Background model	<2	<2	<2
Resolution model	7	2	6
Sum in quadrature	92	107	34

- Systematic uncertainties on the χ_{c2} width
  - Knowledge of the detector resolution (in statistical uncertainty)
  - Breit-Wigner parameters
  - Resolution model
  - Background model: negligible