Heavy flavor spectroscopy and exotic hadrons at LHCb

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on behalf of the LHCb collaboration

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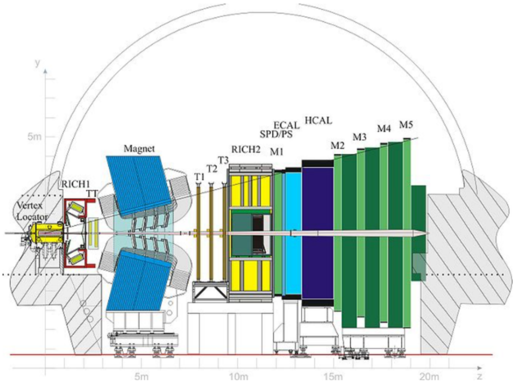
Introduction

- 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

The LHCb detector

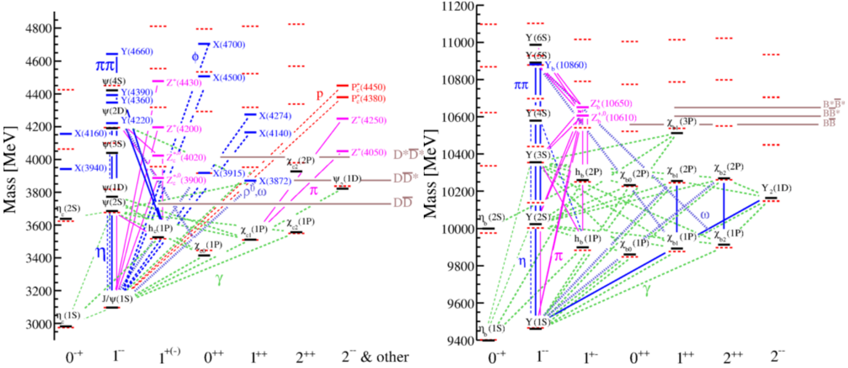
Designed to study CP-violating processes and rare b- and c-hadrons decays



Impact parameter:	$\boldsymbol{\sigma_{IP} = 20\ \mu m}$
Proper time:	$\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum:	$\Delta p/p = 0.4 \sim 0.6\%$ (5 – 100 GeV/c)
Mass :	$\boldsymbol{\sigma_m = 8}$ **MeV/c^2 for $B \to J/\psi X$ (constrained m$_{J/\psi}$)**
RICH $K-\pi$ separation:	**$\epsilon(K\to K) \sim 95\%$ mis-ID $\epsilon(\pi\to K) \sim 5\%$**
Muon ID:	**$\epsilon(\mu\to\mu) \sim 97\%$ mis-ID $\epsilon(\pi\to\mu) \sim 1-3\%$**
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E(\text{GeV})}$

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 starting from the discovery of the $X(3872)$ state
- Since then, a plethora of unexpected neutral (X, Y) and charged (Z^+, P_c^+) states have been discovered
- The nature and the internal structure of these states are still unclear (molecular/tightly bound): many efforts needed to uncover their nature



[Rev.Mod.Phys 90 (2018) 015003]

Exotic spectroscopy at LHCb: highlights

- LHCb made important contributions discovering new exotic states and measuring properties of known states
- X(3872): first exotic candidate discovered by Belle in 2003 [PRL 91 (2003) 262001]
  - Measurement of quantum numbers: $J^{PC} = 1^{++}$ [PRD92 (2015) 011102, PRL 110 (2013) 222001]
  - Search for new decay modes [EPJC 73 (2013) 2462, PRLB 769 (2017) 305]
  - direct production in pp collisions [EPJC 72 (2012) 1972]
  - studies of its nature [NPB 886 (2014) 665]
- Confirmation of the $Z_c(4430)^+$ charged charmonium-like state and determination of its $J^P = 1^+$ quantum numbers in $B^0 \to \psi(2S)K^+\pi^-$ decays [PRL 112 (2014) 222002, PRD92 (2015) 112009]
- Discovery of two pentaquark candidates in $\Lambda_b \to J/\psi p K^+$ decays [PRL 115 (2015) 072001, PRL 117 (2016) 082002] and evidence of pentaquark contributions in $\Lambda_b \to J/\psi p\pi^+$ decays [PRL 11 (2016) 082003]
- Neutral exotics in $B^+ \to J/\psi\phi K^+$ decays: confirmation of the $X(4140)$ and $X(4274)$ states and discovery of two higher mass states: $X(4400)$ and $X(4700)$ [PRL 118 (2016) 022003, PRD95 (2016) 012002]
- Search for weakly decaying b-flavoured pentaquarks [PRD 97 (2018) 032010]
- Search for $X_{b\bar{b}b\bar{b}} \to \Upsilon(1S)\mu^+\mu^-$ [JHEP 10 (2018) 086]

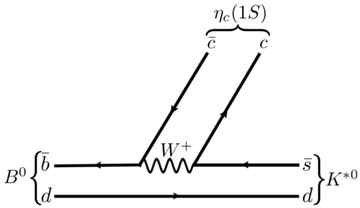
Evidence for an $\eta_c(1S)\pi^-$ resonance in $B^0 \to \eta_c(1S)K^+\pi^-$ decays

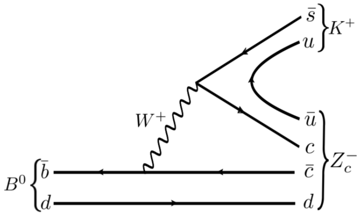
arXiv: 1809.07416, accepted by EPJC

$\eta_c\pi^-$ resonance in $B^0 \to \eta_c K^+\pi^-$: motivations

- Predictions of $\eta_c\pi^-$ states depending on the model used to describe the $Z_c(3900)^-$ discovered by BESIII [PRL 110 (2013) 252001]
  - hadrocharmonium state: charged charmonium-like state of mass $\sim 3800\,\mathrm{MeV}$ [PRD87 (2013) 091501]
  - quarkonium hybrids: prediction of states with quantum numbers allowing the decay into the $\eta_c\pi^-$ system
- Using the diquark model: a $J^P = 0^+$ exotic candidate below the open-charm threshold decaying to $\eta_c\pi^-$ [PRD71 (2005) 014028]

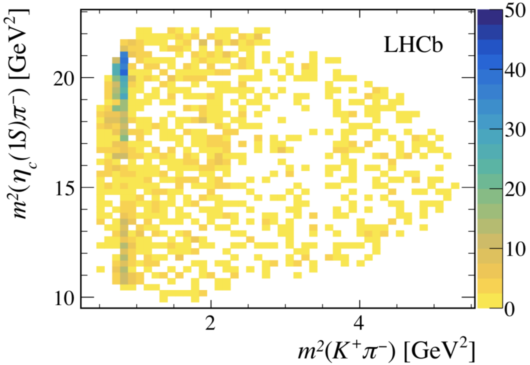
Search for possible exotic states in the $\eta_c\pi^-$ invariant mass using $B^0 \to \eta_c K^+\pi^-$ decays



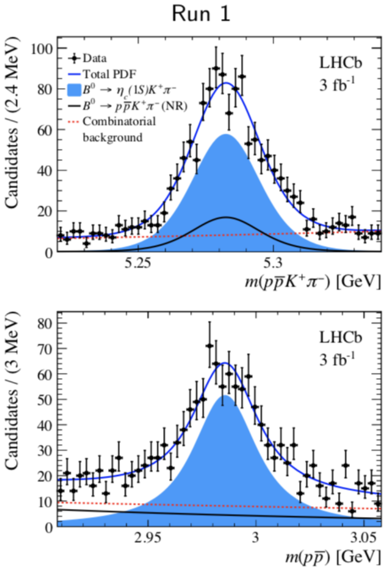


$B^0 \to \eta_c(1S)K^+\pi^-$: analysis strategy

- Using $L \sim 4.7\,\text{fb}^{-1}$, Run1+Run2 data (2011-2016)
- η_c reconstructed in $p\bar{p}$ final state
- isolate $B^0 \to \eta_c K^+\pi^-$ signal candidates from non-resonant $B^0 \to p\bar{p}K^+\pi^-$ and combinatorial background candidates
- Perform a Dalitz plot (DP) analysis to search for exotic hadrons: the $B^0 \to \eta_c(1S)K^+\pi^-$ decay involves only pseudo-scalar particles (fully described by only two independent kinematic quanties)
- Isobar model used to write the decay amplitude: $K^+\pi^-$ S-wave at low mass parametrised using the LASS PDF, Breit Wigner PDFs for the other $K^+\pi^-$ resonances



$B^0 \to \eta_c(1S)K^+\pi^-$: signal



- 2D fit to $m(p\bar{p}K^+\pi^-)$ and $m(p\bar{p})$ distributions
- to subtract non-resonant $B^0 \to p\bar{p}K^+\pi^-$ and combinatorial background candidates
- fitting separetely Run1 and Run2 data

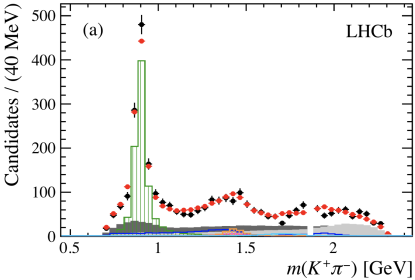
Component	Run 1	Run 2
$B^0 \to \eta_c K^+\pi^-$	805 ± 48	1065 ± 56
$B^0 \to p\bar{p}K^+\pi^-$ (NR)	234 ± 48	273 ± 56
Combinatorial background	409 ± 36	498 ± 41

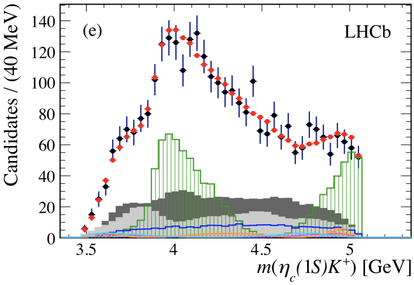
Dalitz plot analysis

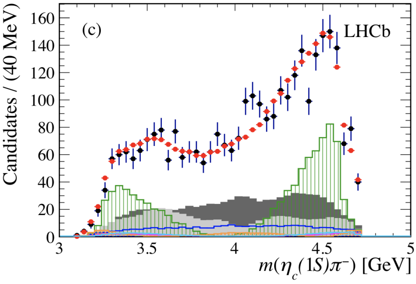
- Background: use sPlot technique to get the nonresonant and combinatorial background distributions (included in the amplitude fit)
- Efficiency:
  - variation caused by the detector acceptance and selection procedure
  - parametrisation using re-weighted simulated samples
- Baseline model includes 6 K^{*0} resonances + $K^+\pi^-$ NR (mass and width of each K^* resonance are fixed)

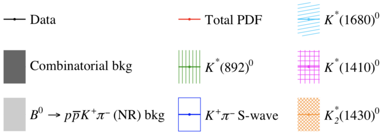
Resonance	Mass [MeV]	Width [MeV]	J^P	Model
$K^*(892)^0$	895.55 ± 0.20	47.3 ± 0.5	1^-	RBW
$K^*(1410)^0$	1414 ± 15	232 ± 21	1^-	RBW
$K_0^*(1430)^0$	1425 ± 50	270 ± 80	0^+	LASS
$K_2^*(1430)^0$	1432.4 ± 1.3	109 ± 5	2^+	RBW
$K^*(1680)^0$	1717 ± 27	322 ± 110	1^-	RBW
$K_0^*(1950)^0$	1945 ± 22	201 ± 90	0^+	RBW

Model with only $K^+\pi^-$ contributions



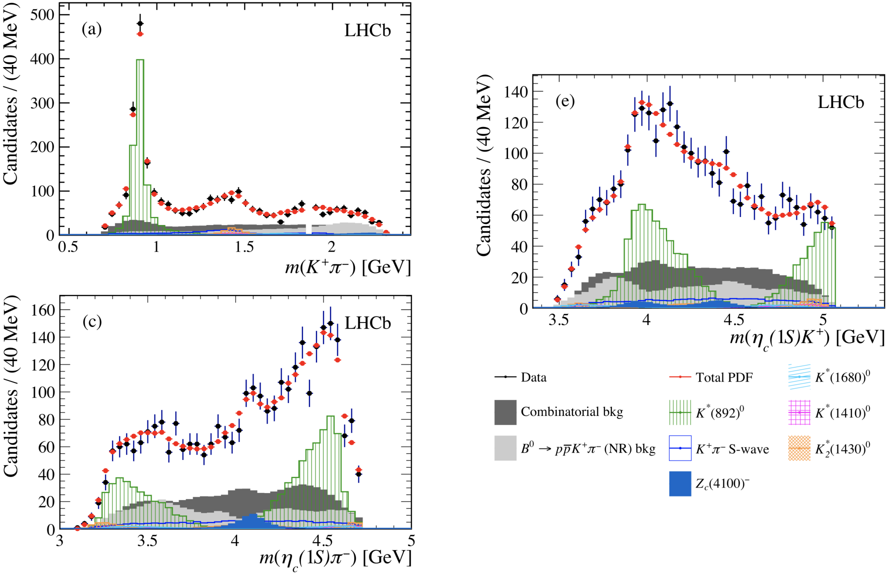






Discrepancy around $4100\,\mathrm{MeV}$ in the $m(\eta_c(1S)\pi^-)$ spectrum

Model with $K^+\pi^- + \eta_c(1S)\pi^-$ contributions



Evidence for an exotic $Z_c(4100)^-$

- Adding a Z_c^- resonance improves the fit of $\Delta(2ln\mathcal{L}) = 22.8$, 41.4 and 7.0 for $J^P = 0^+$, 1^- and 2^+.
- Resonance parameters:

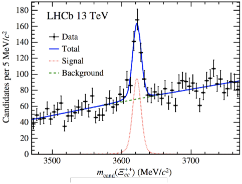
$$m_{Z_c^-} = 4096 \pm 20^{+18}_{-22}\,\mathrm{MeV}$$
$$\Gamma_{Z_c^-} 152 \pm 58^{+60}_{-35}\,\mathrm{MeV}$$

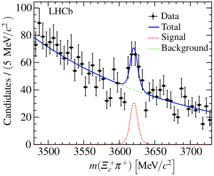
- Fit fraction of the Z_c^-: $3.3 \pm 1.1^{+1.2}_{-1.1}\%$
- $\mathcal{B}(B^0 \to Z_c(4100)^- K^+) = 1.89 \pm 0.64 \pm 0.04^{+0.69}_{-0.63} \pm 0.22$ (statistical, branching fraction systematic, fit fraction systematic, external branching fractions uncertainties)
- Significance is 3.2σ after considering systematic uncertainties
- Discrimination between $J^P = 0^+$ and $J^P = 1^-$ is not significant

Conventional spectroscopy in the bottom and charm sector at LHCb

Doubly-charmed baryons [PRL 119 (2017) 112001, PRL 121 (2018) 162002]

- Doubly charmed baryons: unique environment for testing models of QCD
- Observation of the Ξ_{cc}^{++} state using $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^-$ and $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ decays





$313 \pm 33,\ 12.9\sigma$ $\qquad$ $91 \pm 20,\ 5.9\sigma$

$$m(\Xi_c^{++}) = 3621.40 \pm 0.72(stat) \pm 0.31(syst)\,\mathrm{MeV/c^2}\ [\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^-]$$
$$m(\Xi_c^{++}) = 3620.6 \pm 1.5(stat) \pm 0.4(syst) \pm 0.3(\Xi_c^+)\,\mathrm{MeV/c^2}\ [\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+]$$
$$m(\Xi_c^{++}) = 3621.24 \pm 0.65(stat) \pm 0.31(syst)\,\mathrm{MeV/c^2}\ \text{[combined]}$$

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

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

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

Bottom spectroscopy

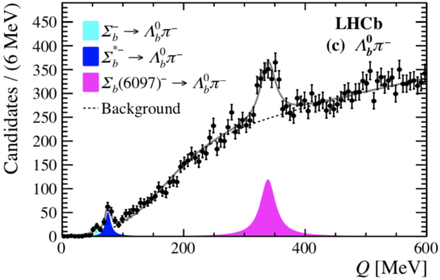
- LHCb has a unique capability to search for excited states of beauty hadrons
- Already a number have been discovered ($\Lambda_b(5912)^0$, $\Lambda_b(5920)^0$, $\Sigma_b^{*\pm}$, $\Xi_b^{'}(5935)^-$, $\Xi_b^*(5955)^-$ and $\Xi_b(5945)^0$)
- Recently LHCb observed a new Ξ_b^{**-} state, the $\Xi_b(6227)^-$ [PRL 121 (2018) 072002] in both fully hadronic ($\Lambda_b^0 \to \Lambda_c^+\pi^-$) and semileptonic ($\Lambda_b^0 \to \Lambda_c^+\mu^- X$, $\Xi_b^0 \to \Lambda_c^+\mu^- X$) decays measuring its mass, width and production ratios
- Consistent with expectations of either a $\Xi_b(1P)$ and $\Xi_b(2S)$ states
- J^P not yet measured to distinguish between the states

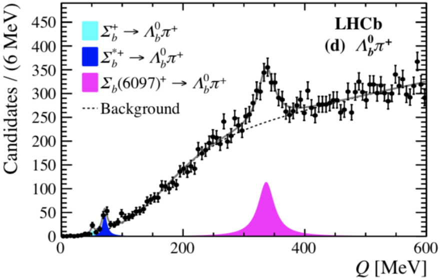
Observation of $\Sigma_b(6097)^{\pm}$ [arXiv:1809.07752, Submitted to PRL]

- $\Lambda_b^0 \to \Lambda_c^+\pi^-$ combined with $\pi^{\pm}$ from PV
- $p_T(\pi^{\pm}) > 1\,\mathrm{GeV}$ to suppress background
- Structures found in the $\Lambda_b^0\pi^{\pm}$ invariant mass spectra: $\Sigma_b(6097)^{\pm}$
- $\Sigma_b(6097)$ compatible with 1P state

Quantity	Value [MeV]
$m(\Sigma_b(6097)^-)$	$6098.0 \pm 1.7 \pm 0.5$
$m(\Sigma_b(6097)^+)$	$6095.8 \pm 1.7 \pm 0.4$
$\Gamma(\Sigma_b(6097)^-)$	$28.9 \pm 4.2 \pm 0.9$
$\Gamma(\Sigma_b(6097)^+)$	$31.0 \pm 5.5 \pm 0.7$

- Measured mass and width of the $\Sigma_b^{\pm}$ and $\Sigma_b^{*\pm}$ states: compatible and 5 times more precise than CDF measurement





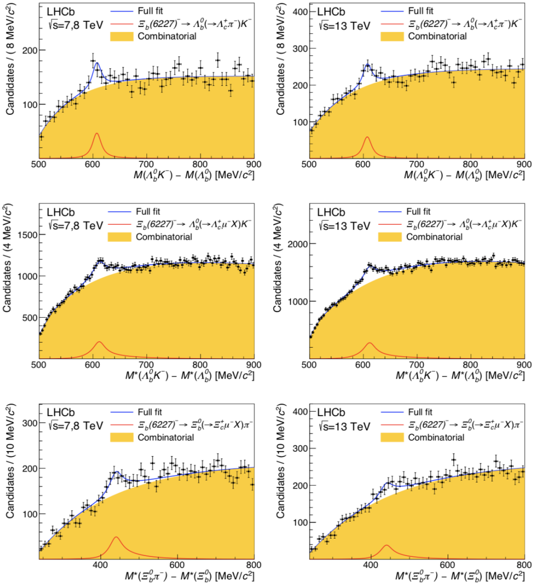
Conclusions

- 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
- The LHCb detector is going to be upgraded: collect a larger data sample with high efficiency!

Spare slides

A new Ξ_b^{**-} state! [PRL 121 (2018) 072002]

- 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! [PRL 121 (2018) 072002]

- With hadronic mode:

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

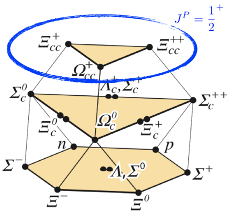
- Production ratios are also measured with SL modes

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

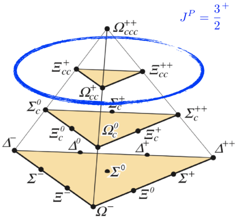
- Consistent with expectations of either a $\Xi_b(1P)$ and $\Xi_b(2S)$ states
- J^P not yet measured to distinguish between the states

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]



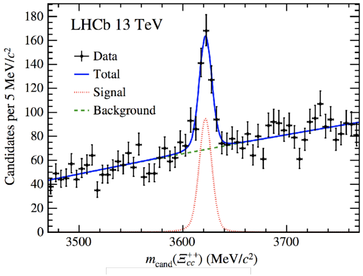
$J^P = 1/2^+$ baryons decay weakly to other flavours

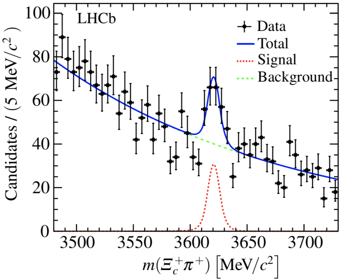


$J^P = 3/2^+$ baryons decay via strong interactions to $J^P = 1/2^+$

Observation of Ξ_{cc}^{++} [PRL 119 (2017) 112001, PRL 121 (2018) 162002]

- Search in LHCb using $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^-$ and $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$
- Data sample: $1.7\,\mathrm{fb}^{-1}$ at 13 TeV (2016) [Run2]





313 ± 33 $\quad$ 91 ± 20

12.9σ $\quad$ 5.9σ

- Mass measurements:

$$m(\Xi_c^{++}) = 3621.40 \pm 0.72(stat) \pm 0.31(syst)\,\mathrm{MeV/c^2}\ [\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^-]$$
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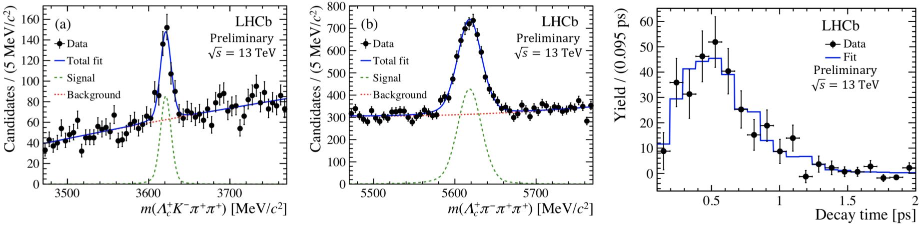
consistent with theoretical range of predictions, not consistent with Ξ_{cc}^+ SELEX measurement (100 MeV above SELEX Ξ_{cc}^+ peaks)

Lifetime measurement [PRL 121 (2018) 152002]

- 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

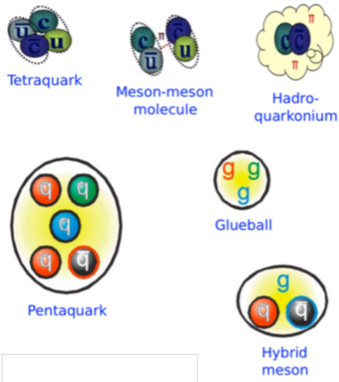


$$\tau_{\Xi_{cc}^{++}} = 0.256^{+0.224}_{-0.022}(stat) \pm 0.014(syst)\,\mathrm{ps}$$

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

Interpretations of exotic hadrons

- Different models have been proposed about the quark composition and binding mechanisms of these exotic hadrons



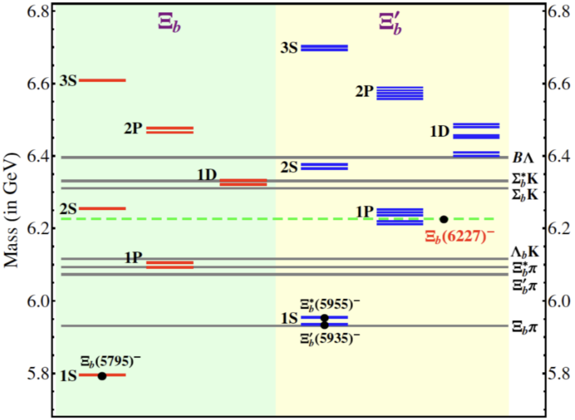
Predictions of a $\eta_c\pi^-$ exotic state

- $Z_c(3900)^-$ as hadrocharmonium state (where the compact heavy quark-antiquark pair interacts with the surrounding light quark mesonic excitation by a QCD analogue of the van der Waals force): predicts an as-yet-unobserved charged charmonium-like state with a mass of approximately $3800\,\mathrm{MeV}$ whose dominant decay mode is to the $\eta_c\pi^-$ system

- $Z_c(3900)^-$ as quarkonium hybrids where the excitation of the gluon field (the valence gluon) is replaced by an isospin-1 excitation of the gluon and light-quark fields
    - prediction of different multiplets of charmonium tetraquarks, comprising states with quantum numbers allowing the decay into the $\eta_c\pi^-$ system.
    - The $\eta_c\pi^-$ system carries isospin $I = 1$, G-parity $G = 1$, spin $J = L$ and parity $P = (-1)^L$, where L is the orbital angular momentum between the η_c and the π^- mesons. Lattice QCD calculations predict the mass and quantum numbers of these states, comprising a $I^G(J^P) = 1(0^+)$ state of mass $4025 \pm 49\,\mathrm{MeV}$, a $I^G(J^P) = 1^-(1^-)$ state of mass $3770 \pm 42\,\mathrm{MeV}$, and a $I^G(J^P) = 1^-(2^+)$ state of mass $4045 \pm 44\,\mathrm{MeV}$. The $Z_c(4430)$ resonance, discovered by the Belle collaboration and confirmed by LHCb, could also fit into this scenario.

- Diquark model: a $J^P = 0^+$ exotic candidate below the open-charm threshold decaying to $\eta_c\pi^-$

$\Sigma_b(6097)$ interpretation



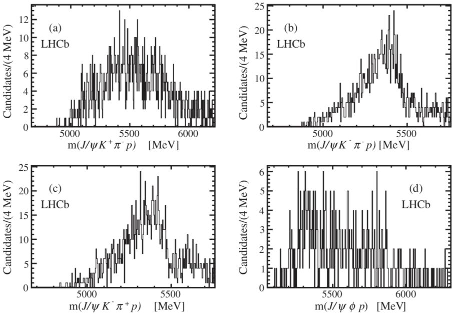
Bing Chen et. al. PRD 98 (2018) 031502(R)

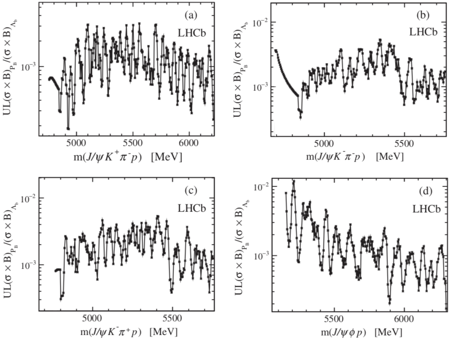
Search for weakly decaying b-flavoured pentaquarks

[PRD 97 (2018) 032010]

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

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



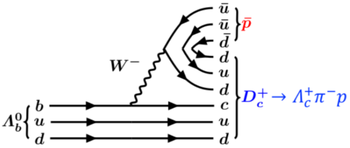


No evidence for signal, 90% CL limits on $R < 10^{-2}$-10^{-3}

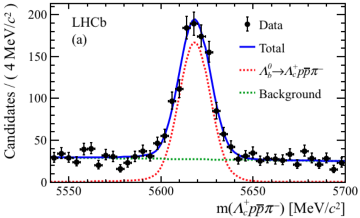
Search for dibaryon states

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

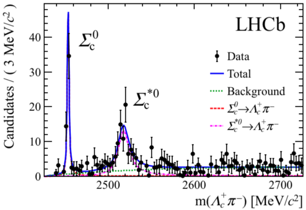
- Search for the lightest charmed dibaryon $D_c^+ = [cd][ud][ud]$ with a mass below 4682 MeV in $\Lambda_b^0 \to \bar{p} D_c^+$ decays
- The D_c^+ dibaryon decay could proceed via quark rearrangement to the final state $p\Sigma_c^0$ with $\Sigma_c^0 \to \Lambda_c^+ \pi^-$ or via a lighter pentaquark 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 $3\,\mathrm{fb}^{-1}$ 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]

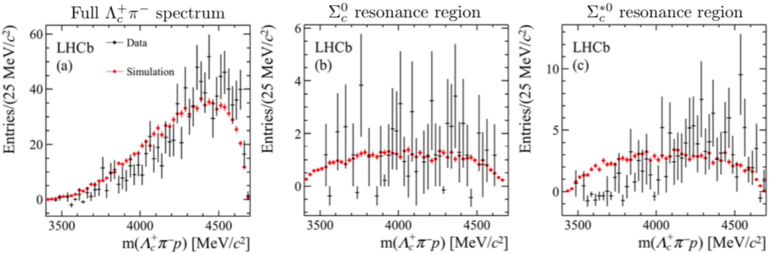
- Measurements of branching ratio:

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

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

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

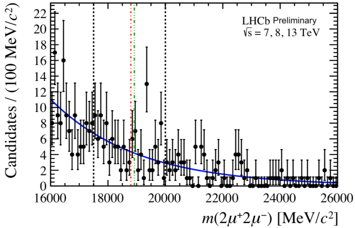
- No dibaryon peak in $m_{\Lambda_c^+\pi^-p}$ spectrum

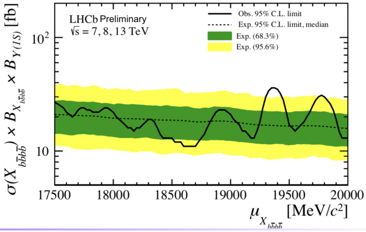


Search for beautiful tetraquarks in the $\Upsilon(1S)\mu^+\mu^-$ invariant mass spectrum

[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



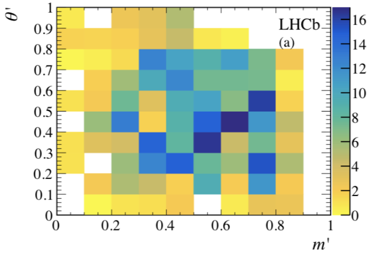


Parametrisation of the backgrounds

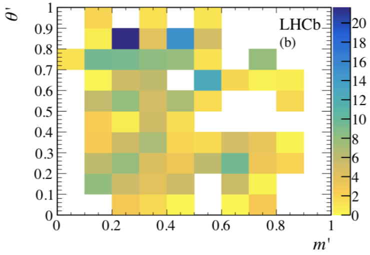
- sPlot technique from the joint 2D $m(p\bar{p}K^+\pi^-), m(p\bar{p})$ fit is used to extract combinatorial and NR background histograms
- Smoothing procedure using a 2D cubic spline interpolation
- Parametrised using the Square Dalitz plot (SDP) using the variables m' and θ' defined in the range 0 to 1 and given by

$$m' \equiv \frac{1}{\pi}\arccos\left(2\frac{m(K^+\pi^-)-m^{\min}_{K^+\pi^-}}{m^{\max}_{K^+\pi^-}-m^{\min}_{K^+\pi^-}}-1\right) \qquad \theta' \equiv \frac{1}{\pi}\theta(K^+\pi^-)$$

where $m^{\max}_{K^+\pi^-} = m_{B^0} - m_{\eta_c}$, $m^{\min}_{K^+\pi^-} = m_{K^+} + m_{\pi^-}$ and $\theta(K^+\pi^-)$ is the helicity angle of the $K^+\pi^-$ system (the angle between the K^+ and the η_c mesons in the $K^+\pi^-$ rest frame



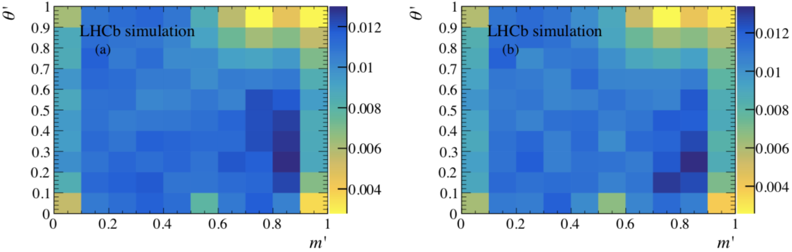
Combinatorial bkg



NR bkg

Efficiency

- Efficiency variation across the SDP caused by the detector acceptance and by the trigger and offline selection requirements
- Evaluated with simulated samples generated uniformly across the SDP.
- Corrections are applied for known differences between data and simulation
- Efficiency studied separately for the Run1 and Run2 subsamples
- Smoothing procedure using a 2D cubic spline interpolation



Cross-checks

- No significant improvement adding further high-mass K^{*0} states ($K_3^*(1780)^0$, $K_4^*(2045)^0$, the high mass $K_5^*(2380)^0$ which falls outside the phase space limits, the $K_2^*(1980)^0$ which has not been seen in the $K^+\pi^-$ final state thus far and the unestablished P-, D- and F-wave $K^+\pi^-$ states predicted by the GodfreyIsgur model)
- No significant additional amplitude decaying to $\eta_c\pi^-$
- No significant additional exotic amplitude decaying to $\eta_c K^+$
- Noegligible effect due to the variation of the η_c phase due to the sizeable natural width introducing interference effects with the NR $p\bar{p}$ contribution [data sample is divided in two, containing candidates with masses below and above the η_c meson peak]

Quasi-two-body branching fractions

Amplitude	Fit fraction (%)
$B^0 \to \eta_c K^*(892)^0$	$51.4 \pm 1.9\ ^{+1.7}_{-4.8}$
$B^0 \to \eta_c K^*(1410)^0$	$2.1 \pm 1.1\ ^{+1.1}_{-1.1}$
$B^0 \to \eta_c K^+\pi^-$ (NR)	$10.3 \pm 1.4\ ^{+1.0}_{-1.2}$
$B^0 \to \eta_c K_0^*(1430)^0$	$25.3 \pm 3.5\ ^{+3.5}_{-2.8}$
$B^0 \to \eta_c K_2^*(1430)^0$	$4.1 \pm 1.5\ ^{+1.0}_{-1.6}$
$B^0 \to \eta_c K^*(1680)^0$	$2.2 \pm 2.0\ ^{+1.5}_{-1.7}$
$B^0 \to \eta_c K_0^*(1950)^0$	$3.8 \pm 1.8\ ^{+1.4}_{-2.5}$
$B^0 \to Z_c(4100)^- K^+$	$3.3 \pm 1.1\ ^{+1.2}_{-1.1}$

Decay mode	Branching fraction (10^{-5})
$B^0 \to \eta_c K^*(892)^0$	$29.5 \pm 1.6 \pm 0.6\ ^{+1.0}_{-2.8} \pm 3.4$
$B^0 \to \eta_c K^*(1410)^0$	$1.20 \pm 0.63 \pm 0.02 \pm 0.63 \pm 0.14$
$B^0 \to \eta_c K^+\pi^-$ (NR)	$5.90 \pm 0.84 \pm 0.11\ ^{+0.57}_{-0.69} \pm 0.68$
$B^0 \to \eta_c K_0^*(1430)^0$	$14.50 \pm 2.10 \pm 0.28\ ^{+2.01}_{-1.60} \pm 1.67$
$B^0 \to \eta_c K_2^*(1430)^0$	$2.35 \pm 0.87 \pm 0.05\ ^{+0.57}_{-0.92} \pm 0.27$
$B^0 \to \eta_c K^*(1680)^0$	$1.26 \pm 1.15 \pm 0.02\ ^{+0.86}_{-0.97} \pm 0.15$
$B^0 \to \eta_c K_0^*(1950)^0$	$2.18 \pm 1.04 \pm 0.04\ ^{+0.80}_{-1.43} \pm 0.25$
$B^0 \to Z_c(4100)^- K^+$	$1.89 \pm 0.64 \pm 0.04\ ^{+0.69}_{-0.63} \pm 0.22$

Width of the $\eta_c(1S)$

- Necessary to take into account the sizeable natural width of the $\eta_c(1S)$ meson $(\Gamma \sim 32\,\mathrm{MeV})$:
  - Kinematic quantities such as $m^2(K^+\pi^-)$, $m^2(\eta_c\pi^-)$ and the helicity ancles are calculated using the invariant mass $m(p\bar{p})$ instead of the known value of the η_c mass
  - When computing the DP normalisation the width of the η_c meson is set to zero: the effect of this simplification is determined when assessing the systematic uncertainties
  - Amplitude fits are repeated computing the DP normalisations by using the $m_{\eta_c} + \Gamma_{\eta_c}$ and $m_{\eta_c} - \Gamma_{\eta_c}$

LASS model

- The amplitude parametrisations using RBW functions lead to unitarity violation within the isobar model if there are overlapping resonances or if there is a significant interference with a NR component, both in the same partial wave
- For the $K^+\pi$ S-wave at low $K^+\pi$ mass, where the $K_0(1430)^0$ resonance interferes strongly with a slowly varying NR S-wave component: LASS lineshape

$$T(m) = \frac{m}{|\vec{q}|\cot\delta_B - i|\vec{q}|} + e^{2i\delta_B}\frac{m_0\Gamma_0\frac{m_0}{q_0}}{m_0^2 - m^2 - im_0\Gamma_0\frac{|\vec{q}|}{m}\frac{m_0}{q_0}}$$

$$\cot\delta_B = \frac{1}{a|\vec{q}|} + \frac{1}{2}r|\vec{q}|$$

and where m_0 and Γ_0 are the pole mass and width of the $K_0(1430)^0$ state, and a and r are the scattering length and the effective range, respectively.

- The LASS model replaced with $K_0^*(1430)^0$ and $K_0^*(800)^0$ resonances parametrised with RBW functions, and a NR S-wave $K^+\pi^-$ component parametrised with a uniform amplitude within the DP.

Systematic uncertainties

- Experimental uncertainties
  - Fixed signal and background yields
  - background parametrisation
  - phase-space border veto applied on the parametrisation of the efficiencies
  - amplitude fit bias
- Model uncertainties
  - treatment of the $\eta_c(1S)$ natural width
  - $K^+\pi^-$ s-wave parametrisation
  - fixed parameters of the resonances
  - addition or removal of marginal components
- The systematic variations producing the largest deviations on the $Z_c(4100)$ parameters (mass, width and fit fraction) are used to evaluate the systematic effects on the significances
- $Z_c(4100)$ significance when including systematic uncertainties and correlations between them: 3.2σ

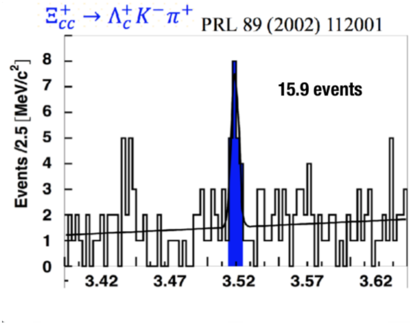
Source	$\Delta(-2\ln\mathcal{L})$	Significance
Nominal fit	41.4	4.8σ
Fixed yields	45.8	5.2σ
Phase-space border veto	44.6	5.1σ
η_c width	36.6	4.3σ
$K^+\pi^-$ S-wave	31.8	3.9σ
Background	27.4	3.4σ

Discrimination between $J^P = 0^+$ and $J^P = 1^-$

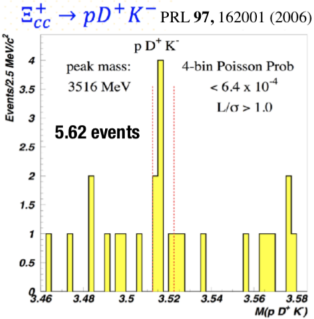
Source	$\Delta(-2\ln\mathcal{L})$	Significance
Default	18.6	4.3σ
Fixed yields	23.8	4.9σ
Phase-space border veto	24.4	4.9σ
η_c width	4.2	2.0σ
Background	3.4	1.8σ
$K^+\pi^-$ S-wave	1.4	1.2σ

SELEX Ξ_{cc}^{+}

Using collisions of a hyperon beam on fixed nuclear targets

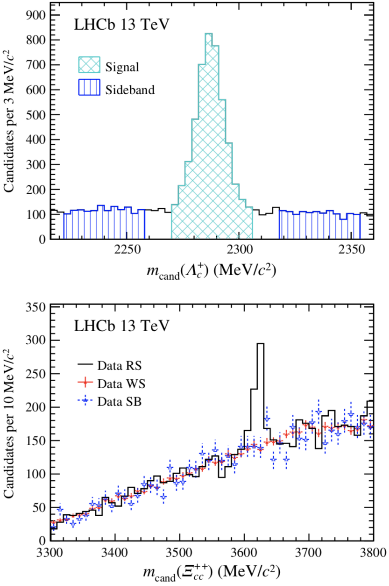


6.3σ



4.8σ

Ξ_{cc}^{+}

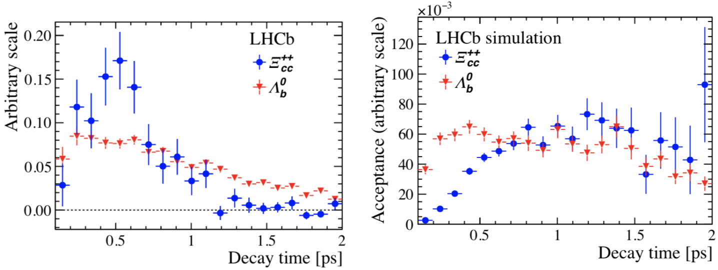

LHCb 13 TeV
Signal
Sideband
Candidates per 3 MeV/c^2
$m_{\rm cand}(\Lambda_c^+)$ (MeV/c^2)
900
800
700
600
500
400
300
200
100
0
2250
2300
2350
LHCb 13 TeV
Data RS
Data WS
Data SB
Candidates per 10 MeV/c^2
$m_{\rm cand}(\Xi_{cc}^{++})$ (MeV/c^2)
350
300
250
200
150
100
50
0
3300
3400
3500
3600
3700
3800

Future prospect for Ξ_{cc}^{++}

- Ξ_{cc}^{++}
  - Other decay modes
    - $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$
    - $\Xi_{cc}^{++} \to \Lambda_c^+ \pi^+$
    - $\Xi_{cc}^{++} \to p D^+ K^- \pi^+$
  - Production cross-section
- Other states
  - Ξ_{cc}^{+}
  - Ω_{cc}^{+}

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