Spectroscopy highlights from Run I and II at LHCb and outlook for the upgrade

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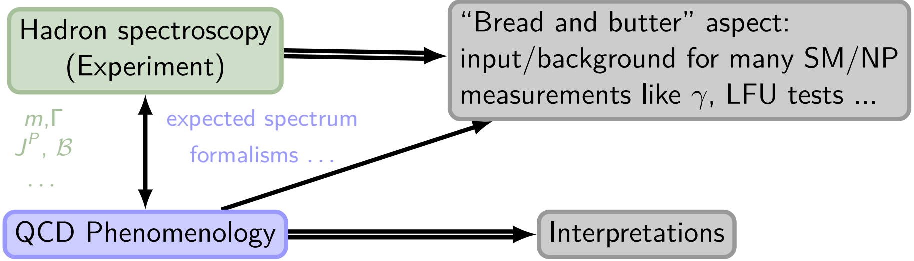
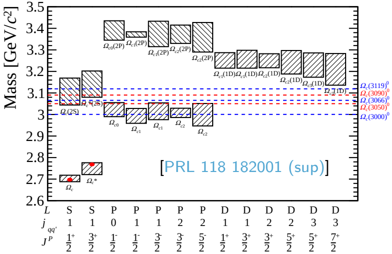
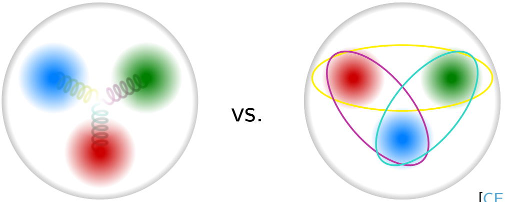
Implications of LHCb measurements and future prospects
October 16th, 2018





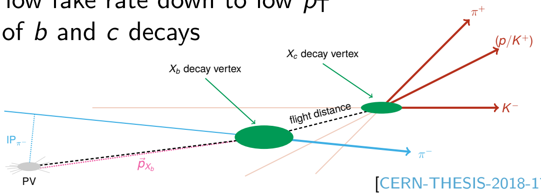
[PRL 118 182001 (sup)]



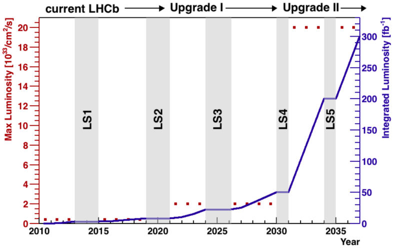
[CERN-THESIS-2018-176]

- Greater challenge: link QCD's pure Yang-Mills sector to observations
- Hadronic spectrum is the prime observable of QCD

- ✓ Excellent mass-, momentum-, vertex- and decay time resolution
  - Highly efficient track reconstruction at low fake rate down to low p_{T}
  - Fast and efficient topological selection of b and c decays
- ✓ Excellent particle identification
  - High purity hadronic final states
- ✓ Flexible, offline quality software trigger
- ✓ Huge samples of b and c hadrons
  - All types of hadrons are produced, incl. b baryons and excited states
  - LHCb is a b baryon factory! $\approx$ 2M (180k) reco'd and selected $\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu$ ($\Lambda_b^0 \to \Lambda_c^+ \pi^-$) per fb^{-1} @ 13 TeV
  - Large samples of exclusive decays for amplitude analyses
- ✓ Upgrade: no hardware trigger, resolutions improve, instantaneous luminosity increases



[CERN-THESIS-2018-176]

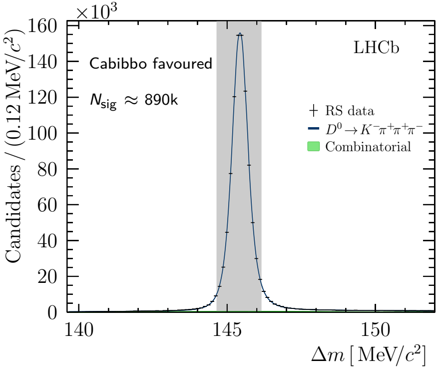


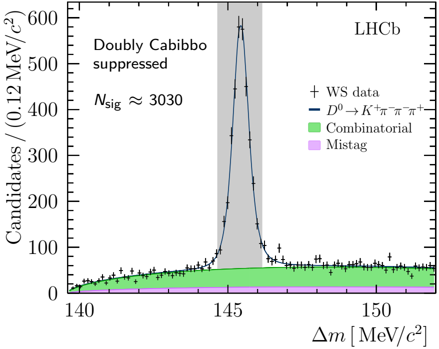
[LHCb-PUB-2018-009]

- LHCb has unique potential for spectroscopy

[EPJC 78 (2018) 443]

- $D^0 \to K^\mp\pi^\pm\pi^\pm\pi^\mp$ amplitudes input to γ and charm mixing measurements
- Spectroscopy: light hadronic spectrum crucial for modelling non-perturbative QCD
- Challenges: broad states, interference, threshold effects, model complexity
- Double tag method: $\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu$ with $D^{*+} \to D^0\pi^+$. *Still a huge sample!*

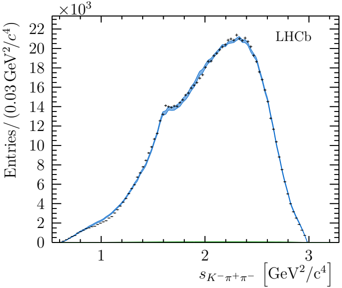




[EPJC 78 (2018) 443]

- Resonance structure dominated by axial resonances; fit fraction of $D^0 \to K_0(1460)^-\pi^+ \approx 4\,\%$ with $K_0(1460)^- \to K^-\pi^+\pi^-$
- Spectroscopic highlight: quasi model independent partial wave analysis (QMIPWA) of the kaons first radial excitation $K_0(1460)^-$

$K(1460)^-$ $\quad m_0 = 1482.40 \pm 3.58 \pm 15.22\,\mathrm{MeV}/c^2$; $\Gamma_0 = 335.60 \pm 6.20 \pm 8.65\,\mathrm{MeV}/c^2$



Citation: M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018)

$K(1460)$ $\quad I(J^P) = \frac{1}{2}(0^-)$

OMITTED FROM SUMMARY TABLE
Observed in $K\pi\pi$ partial-wave analysis.

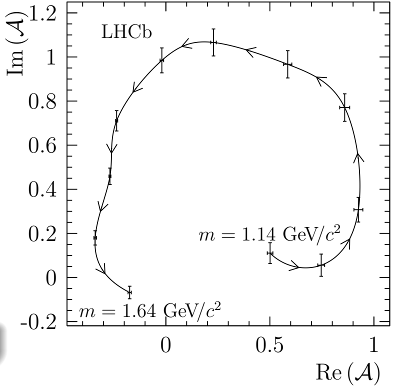
$K(1460)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1460	DAUM	81C	CNTR	–	63 $K^- p \to K^- 2\pi p$
~ 1400	[1] BRANDENB...	76B	ASPK	±	13 $K^\pm p \to K^\pm 2\pi p$

[1] Coupled mainly to $K f_0(1370)$. Decay into $K^*(892)\pi$ seen.

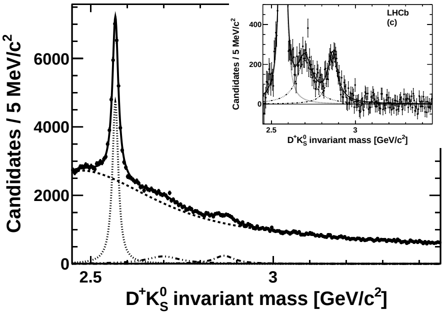
$K(1460)$ WIDTH

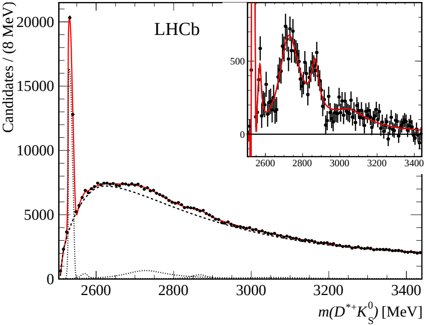
VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 260	DAUM	81C	CNTR	–	63 $K^- p \to K^- 2\pi p$
~ 250	[2] BRANDENB...	76B	ASPK	±	13 $K^\pm p \to K^\pm 2\pi p$



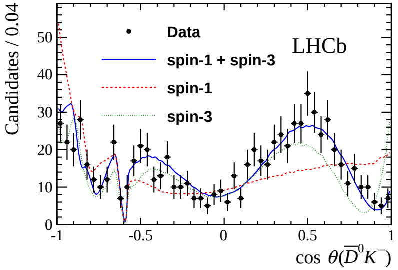
- Great potential to study light spectrum at LHCb

- Open charm spectroscopy probes perturbative – non-perturbative transition region; static heavy quarks (HQET) vs. dynamical resonance generation
- Much discussed example: $D_{sJ}^*(2860)$
  - Observed in inclusive reactions in the DK and D^*K channels at BaBar [PRL 97 222001],[PRD 80 092003] and LHCb [JHEP10(2012)151],[JHEP02(2016)133] respectively
  - Assignment as 1^3D_3 state preferred, but large D^*K rate measured at BaBar is puzzling [Rept.Prog.Phys. 80 076201]





- $D^*_{sJ}(2860)^-$ puzzle (momentarily) solved by $B^0_s \to \overline{D}^0 K^- \pi^+$ amplitude analysis
  - Resolved $D^*_{sJ}(2860)^-$ into $D^*_{s1}(2860)^-$ ($J^P = 1^-$) and $D^*_{s3}(2860)^-$ ($J^P = 3^-$)



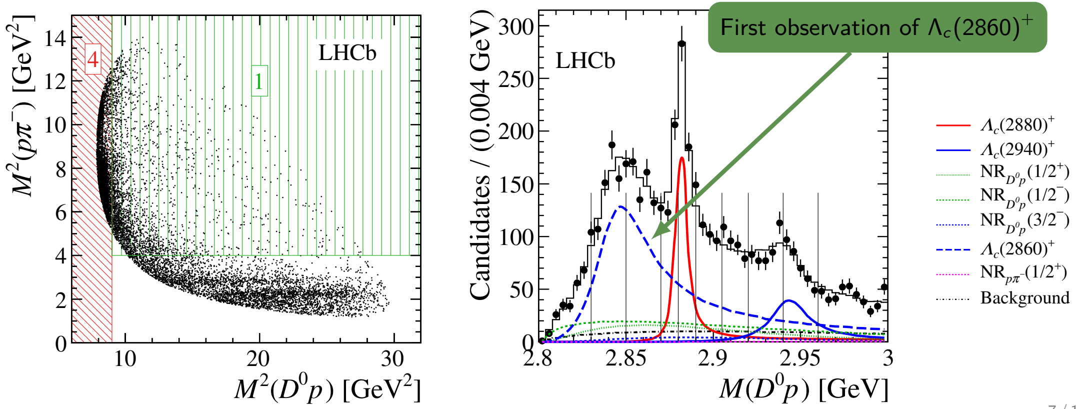
$$m(D^*_{s1}(2860)^-) = 2859 \pm 12 \pm 6 \pm 23\ \mathrm{MeV}/c^2,$$
$$\Gamma(D^*_{s1}(2860)^-) = 159 \pm 23 \pm 27 \pm 72\ \mathrm{MeV}/c^2,$$
$$m(D^*_{s3}(2860)^-) = 2860.5 \pm 2.6 \pm 2.5 \pm 6.0\ \mathrm{MeV}/c^2,$$
$$\Gamma(D^*_{s3}(2860)^-) = 53 \pm 7 \pm 4 \pm 6\ \mathrm{MeV}/c^2,$$

  - Favoured assignments $D_s(1^3D_1)$ and $D_s(1^3D_3)$
  - Do $D_s(1^3D_1)$ and $D_s(2^3S_1)$ states mix to form $D^*_{s1}(2860)^-$ and $D^*_{s1}(2700)^-$?
  - Amplitude analysis in D^*K channel (e.g. $B^0_s \to D^{*-} K^0_S \pi^+$) and measurement of decay rates relative to DK sensitive to mixing parameters

- Reached precision era of single open charm spectroscopy

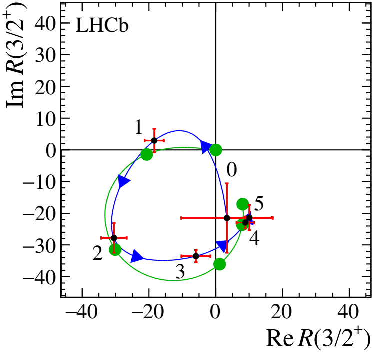
[JHEP05(2017)030]

- First amplitude analysis involving open charm baryons
- Is the $\Lambda_c(2940)^+$ a $D^* N$ molecule? $\Rightarrow$ Measure J^P
- Kinematic separation of $p\pi^-$ and $D^0 p$ resonances $\Rightarrow$ analyse only $D^0 p$ amplitudes
- Near threshold region can only be described by adding new $\Lambda_c(2860)^+$ resonance



[JHEP05(2017)030]

- Phase motion of $\Lambda_c(2860)^+$ $[(J^P)_{\text{preferred}} = 3/2^+]$ resembles Breit-Wigner
- $\Lambda_c(2860)^+$ and $\Lambda_c(2880)^+$ $[(J^P)_{\text{preferred}} = 5/2^+]$ consistent with D-wave doublet
- $\Lambda_c(2940)^+$ $[(J^P)_{\text{preferred}} = 3/2^-]$ radial $2P$ excitation or S-wave $D^* N$ molecule?
- Need to study $\Sigma_c^{(*)}\pi$ channel [arXiv:1803.00364 [hep-ph]][RevModPhys 90 015004]



$$m(\Lambda_c(2860)^+) = 2856.1^{+2.0}_{-1.7}(\text{stat}) \pm 0.5(\text{syst})^{+1.1}_{-5.6}(\text{model})\ \text{MeV},$$
$$\Gamma(\Lambda_c(2860)^+) = 67.6^{+10.1}_{-8.1}(\text{stat}) \pm 1.4(\text{syst})^{+5.9}_{-20.0}(\text{model})\ \text{MeV}$$

$$m(\Lambda_c(2880)^+) = 2881.75 \pm 0.29(\text{stat}) \pm 0.07(\text{syst})^{+0.14}_{-0.20}(\text{model})\ \text{MeV},$$
$$\Gamma(\Lambda_c(2880)^+) = 5.43^{+0.77}_{-0.71}(\text{stat}) \pm 0.29(\text{syst})^{+0.75}_{-0.00}(\text{model})\ \text{MeV}.$$

$$m(\Lambda_c(2940)^+) = 2944.8^{+3.5}_{-2.5}(\text{stat}) \pm 0.4(\text{syst})^{+0.1}_{-4.6}(\text{model})\ \text{MeV},$$
$$\Gamma(\Lambda_c(2940)^+) = 27.7^{+8.2}_{-6.0}(\text{stat}) \pm 0.9(\text{syst})^{+5.2}_{-10.4}(\text{model})\ \text{MeV}.$$

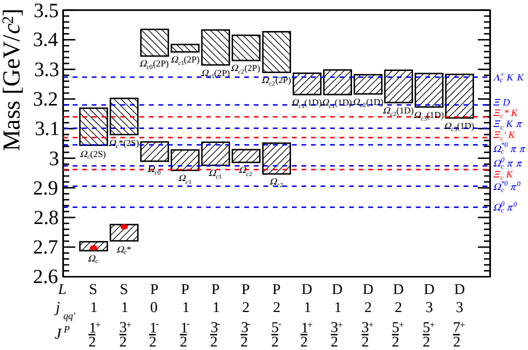
$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c(2860)^+\pi^-) \times \mathcal{B}(\Lambda_c(2860)^+ \to D^0 p)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c(2880)^+\pi^-) \times \mathcal{B}(\Lambda_c(2880)^+ \to D^0 p)} = 4.54^{+0.51}_{-0.39}(\text{stat}) \pm 0.12(\text{syst})^{+0.17}_{-0.58}(\text{model}),$$
$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c(2940)^+\pi^-) \times \mathcal{B}(\Lambda_c(2940)^+ \to D^0 p)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c(2880)^+\pi^-) \times \mathcal{B}(\Lambda_c(2880)^+ \to D^0 p)} = 0.83^{+0.31}_{-0.10}(\text{stat}) \pm 0.06(\text{syst})^{+0.17}_{-0.43}(\text{model}),$$

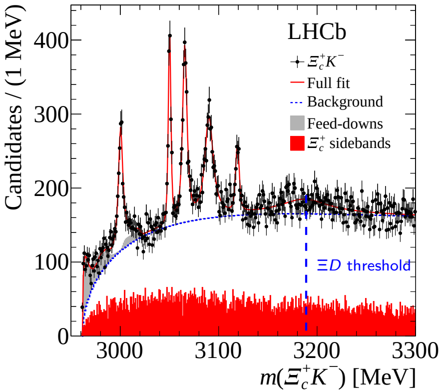
- Precision spectroscopy of charm baryons just begun. Many possibilities ahead

[PRL 118 182001]

- Before: Only ground state $\overset{(css)}{\Omega_c}$ and $\Omega_c(2770)^0$ known. More Ω_c^*s expected
- Observed 5 new narrow states + 1 broad (?) in inclusive $\overset{(cus)(s\bar{u})}{\Xi_c^+ K^-}$ spectrum
- Why so many? Why so narrow? Expected only narrow Ω_{c2} D-wave decays in $\Xi_c^+ K^-$
- Narrowness: ss diquark hard to separate? No decays to ΞD (kinematics)[PRD 95 114012]

$(uss)(c\bar{u})$ or $(dss)(c\bar{d})$





Ω_c^{**0} states (inclusive $\Xi_c^+ K^-$)

- Several interpretations, many implications...
- Study further incl. channels (*e.g.* $\Omega_c^0\gamma/\pi^+\pi^-$, $\Xi_c^0 K_S^0$)
- Measure J^P (incl. or excl., *e.g.* $\Xi_b \to \Omega_c^{**0}\overline{D}$, $\Xi_b^-/\Omega_b^- \to \Omega_c^{**0}\pi^-$)

[PRL 118 182001]

Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		$< 1.2\,\text{MeV}, 95\%$ CL		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$	10.4
		$< 2.6\,\text{MeV}, 95\%$ CL		
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	

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

[PRD 95 11610]

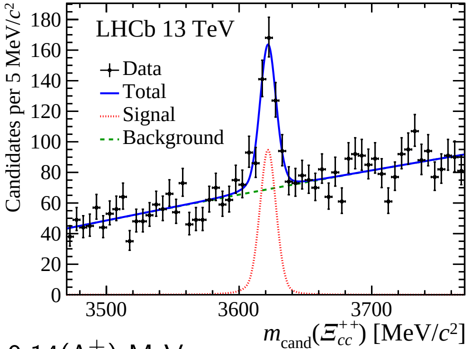
State	[20]	[21]	[22]	[24]	[30]	[26]	[28]	[29]	[33]	[27]	This work
$\Omega_c(3000)$		$1/2^-$	$1/2^-$ $(3/2^-)$	$1/2^-$	$1/2^-$	$1/2^-$	$1/2^-$	$1/2^+$ or $3/2^+$	$1/2^-$		$1/2^-$
$\Omega_c(3050)$		$1/2^-$	$1/2^-$ $(3/2^-)$	$1/2^-$	$5/2^-$	$3/2^-$	$1/2^-$	$5/2^+$ or $7/2^+$	$3/2^-$		$3/2^-$
$\Omega_c(3066)$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

- Anticipate rich Ω_b^{**-} spectrum
- Are some Ω_c^{**0}s molecules/multiquarks?

[PRL 121 052002]

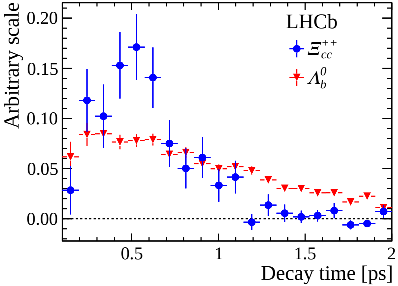
- The quark model predicts three $J^P = 1/2^+$ doubly charmed ground state baryons: $\Xi_{cc}^{+}\,(ccd)$ $\Xi_{cc}^{++}\,(ccu)$ and $\Omega_{cc}^{+}\,(ccs)$ [PRL 89 112001][PLB 628 18]
  - Experimental evidence for Ξ_{cc}^{+} in $\Lambda_c^+ K^- \pi^+$ and pD^+K^- @ ≈ 3520 MeV from SELEX, measuring an short lifetime and large production rate ($<$ 33 fs @ 90 % CL, $\approx$ 20 % of Λ_c^+ come from Ξ_{cc}^{+})
  - Null results from FOCUS, BaBar, Belle and LHCb (2011 $1\,\text{fb}^{-1}$ at $\sqrt{s} = 7$ TeV) [Nucl. Phys. B Proc. Suppl. 115 33][PRD 74 011103][PRL 97 162001][JHEP 12(2013)090]

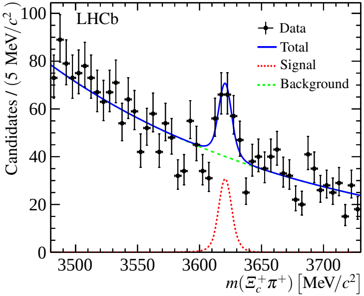
- LHCb observed Ξ_{cc}^{++} in $\Lambda_c^+ K^- \pi^+ \pi^+$ using 2016 data ($1.7\,\text{fb}^{-1}$ at $\sqrt{s} = 13$ TeV)
  - Expected 3–4 times longer lifetime w.r.t. Ξ_{cc}^{+} $\rightsquigarrow$ higher sensitivity
  - Full event reconstruction in software trigger
  - Confirmed with 2012 data ($2\,\text{fb}^{-1}$ at $\sqrt{s} = 8$ TeV)



$$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72(\text{stat}) \pm 0.27(\text{syst}) \pm 0.14(\Lambda_c^+)\ \text{MeV}$$

- Lifetime of Ξ_{cc}^{++} expected to be enhanced by destructive Pauli interference (valence u with u from weak c decay), and Ξ_{cc}^{+} shortened by W capture
- $\tau(\Xi_{cc}^{++}) = 0.256^{+0.024}_{-0.022}(\text{stat}) \pm 0.014(\text{syst})$ ps somewhat lower than expectations
- Interfering c decay amplitudes can change dynamics of weak decay
  $\Rightarrow$ study further decay channels like $\Xi_{cc}^{++} \to \Xi_{cc}^{+}\pi^{+}$



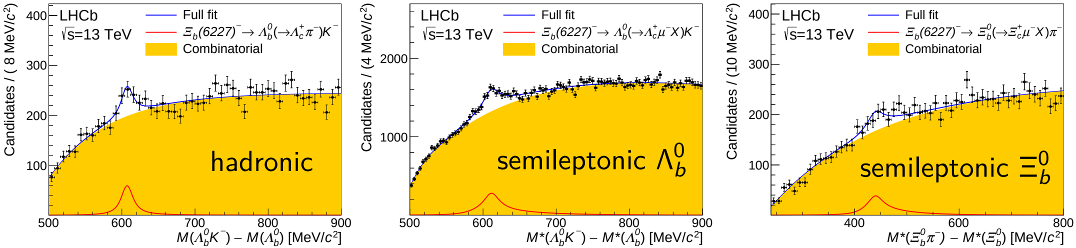


- Renewed interest in doubly heavy exotics (talks by Anthony Francis and Ahmed Ali)
- Search for doubly heavy ground state and excited baryons

$\Xi_b(6227)^-$ observation

[PRL 121 072002]

- Observed new $\Xi_b(6227)^-$ resonance in $\Lambda_b^0 K^-$ and $\Xi_b^0 \pi^-$ decays
- Measured m and Γ in excl. hadronic $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ decays; exploited high statistics semileptonic (SL) $\Lambda_b^0/\Xi_b^0 \to \Lambda_c^+/\Xi_c^+ \mu^- \bar{\nu}_\mu$ decays for production ratio measurements
- SL: Infer $\bar{\nu}_\mu$ momentum from Λ_b^0/Ξ_b^0 mass constraint $\rightsquigarrow \approx 20$ MeV FWHM resolution

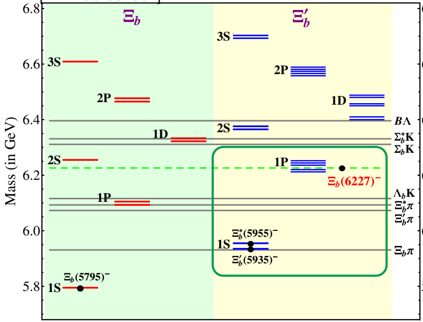


$m(\Xi_b(6227)^-) = 6226.9 \pm 2.0(\text{stat}) \pm 0.3(\text{syst}) \pm 0.2(\Lambda_b^0)$ MeV
$\Gamma(\Xi_b(6227)^-) = 18.1 \pm 5.4(\text{stat}) \pm 1.8(\text{syst})$ MeV

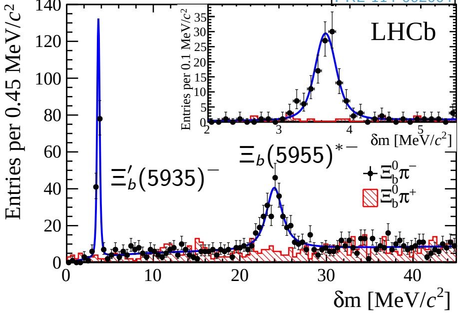
- Measured production ratios imply that $\mathcal{B}(\Xi_b(6227)^- \to \Lambda_b^0 K^-) \approx \mathcal{B}(\Xi_b(6227)^- \to \Xi_b^0 \pi^-)$

- Interpretation of $\Xi_b(6227)^-$ as $1P$ orbital excitation of $\Xi_b(5955)^-$ ($J^P = 3/2^-$ or $5/2^-$) preferred over $2S$ state
- Future: Search isospin partner; decays via Ξ_b' and Ξ_b^* could help to determine J^P

[PRD 98 031502]



[PRL 114 062004]



- Sensitivity boost from adding high statistics semileptonic channels

- Pattern in (non-exotic) spectroscopy: Search for 1. ground state and 2. excited states in inclusive decays. 3. Precision spectroscopy of excited states in amplitude analyses
- Prospects and challenges in light hadron spectroscopy
  - Large statistics; large dynamical/non-perturbative effects $\rightsquigarrow$ challenging parametrisation of amplitude models
- Prospects and challenges in (single) open charm spectroscopy
  - Entering and laying foundation for precision charm spectroscopy
- Prospects and challenges in beauty and double charm spectroscopy
  - We are at steps 1. and 2.; Step 3. requires much more data
  - Anticipate rich excited doubly charmed and Ω_b spectrum

Bright future for spectroscopy at LHCb