Conventional hadron spectroscopy at LHCb

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on behalf of LHCb collaboration

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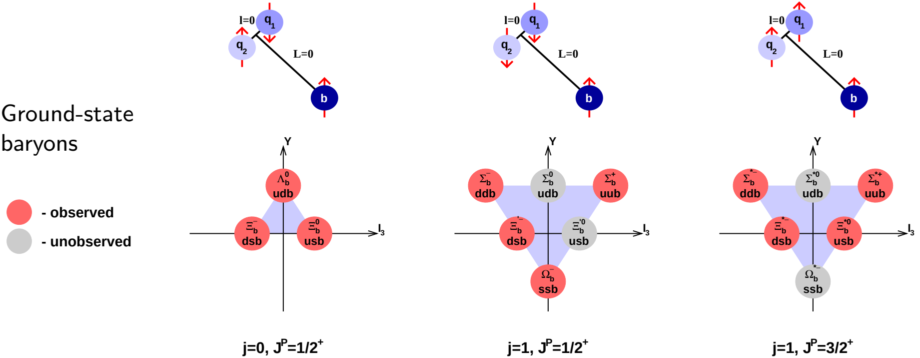
Outline

New results on conventional heavy flavour spectroscopy from LHCb

- Beauty baryon spectroscopy
  - Excited Λ_b^0 states
  - New measurements of $\Sigma_b^{\pm}$ baryons
- Observation of excited B_c^+ states
- Studies of doubly charmed baryons
  - New modes of Ξ_{cc}^{++} decays
  - Ξ_{cc}^{++} production in 13 TeV collisions
  - Search for Ξ_{cc}^{+}
- Charmonium in $D\overline{D}$ spectrum
- Open-charm spectroscopy in $B^+ \to D^{*-}\pi^+\pi^+$ amplitude analysis

Conventional states: b-baryons

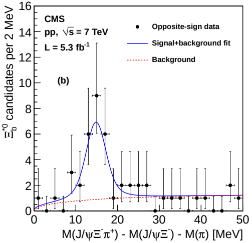
Ground-state baryons



Three of them discovered at LHC:

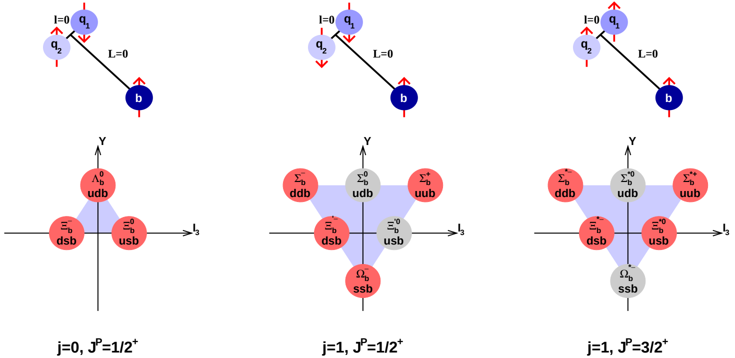
- Ξ_b^{*0}: CMS [PRL 108 (2012) 252002]
- $\Xi_b^{\prime -}$, Ξ_b^{*-}: LHCb [PRL 114 (2015) 062004]

Four still hiding (Σ_b^0, Σ_b^{*0}, $\Xi_b^{\prime 0}$, Ω_b^{*-})
(final state involves soft neutral particles)



Ground-state baryons

- observed
- unobserved



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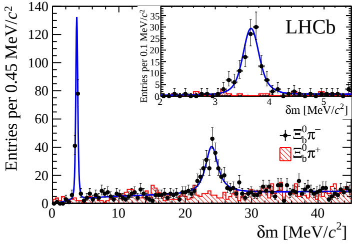


Excited Λ_b^0 and Σ_b states

Large number of excitations. Strong decays to $\Lambda_b^0\pi$, $\Lambda_b^0\gamma$, $\Lambda_b^0\pi^+\pi^-$

Baryon	State	J^P	Experiment [29]	Ref. [10]	Ref. [11]	Ref. [12]	Ref. [13]
Λ_b^0	1S	$1/2^+$	5619.60 ± 0.17	5619	5620	5612	5585
	1P	$1/2^-$	5912.20 ± 0.21	5911	5930	5939	5912
		$3/2^-$	5919.92 ± 0.19	5920	5942	5941	5920
	2S	$1/2^+$			6089	6107	6045
	1D	$3/2^+$		6147	6190	6181	6145
		$5/2^+$		6153	6196	6183	6165
	2P	$1/2^-$			6326	6180	6100
		$3/2^-$			6333	6191	6185
Σ_b^0	1S	$1/2^+$	$\sim 5810^\dagger$		5808	5833	5795
		$3/2^+$	$\sim 5830^\dagger$		5834	5858	5805
	1P	$1/2^-$			6101	6099	6070
		$3/2^-$			6096	6101	6070
		$5/2^-$			6084	6172	6090
	2S	$1/2^+$			6213	6294	6200
		$3/2^+$			6226	6308	6250
	1D	$1/2^+$			6311		
		$3/2^+$			6326		
		$3/2^+$			6285		
		$5/2^+$			6284	6325	6325
		$5/2^+$			6270	6328	

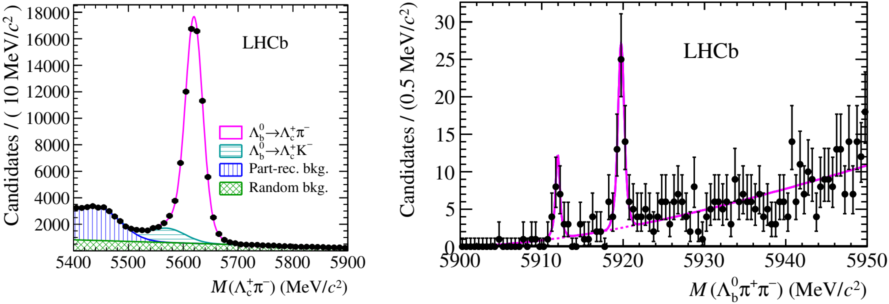
[10] B. Chen, K.-W. Wei, and A. Zhang, *Investigation of Λ_Q and Ξ_Q baryons in the heavy quark-light diquark picture*, Eur. Phys. J. **A51** (2015) 82, arXiv:1406.6561.

[11] D. Ebert, R. N. Faustov, and V. O. Galkin, *Spectroscopy and Regge trajectories of heavy baryons in the relativistic quark-diquark picture*, Phys. Rev. **D84** (2011) 014025, arXiv:1105.0583.

[12] W. Roberts and M. Pervin, *Heavy baryons in a quark model*, Int. J. Mod. Phys. **A23** (2008) 2817, arXiv:0711.2492.

[13] S. Capstick and N. Isgur, *Baryons in a relativized quark model with chromodynamics*, Phys. Rev. **D34** (1986) 2809.

$\Lambda_b^{*0} \to \Lambda_b^0 \pi^+ \pi^-$ near threshold ($\Lambda_b^0 \to \Lambda_c^+ \pi^-$, $\Lambda_c^+ \to pK^- \pi^+$). 1 fb^{-1} dataset.



$m(\Lambda_b(5912)^0) = 5911.97 \pm 0.12(\text{stat}) \pm 0.02(\text{syst}) \pm 0.66(\Lambda_b^0)\,\text{MeV}$

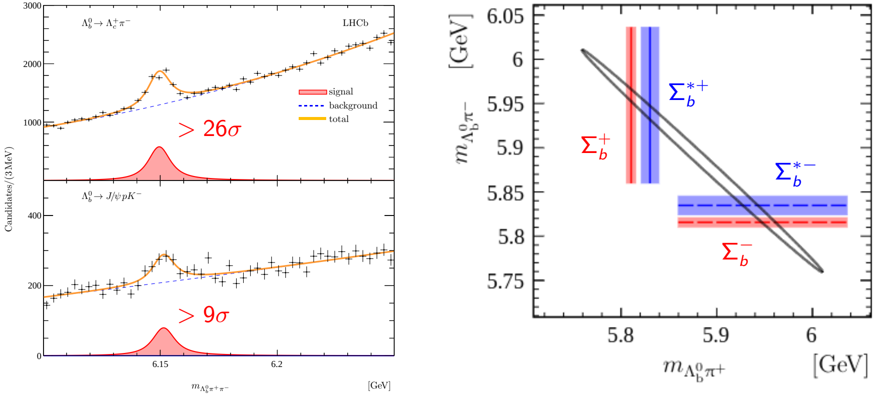
$\Gamma(\Lambda_b(5912)^0) < 0.66\,\text{MeV}$

$m(\Lambda_b(5920)^0) = 5919.77 \pm 0.08(\text{stat}) \pm 0.02(\text{syst}) \pm 0.66(\Lambda_b^0)\,\text{MeV}$

$\Gamma(\Lambda_b(5920)^0) < 0.63\,\text{MeV}$

Interpretation: doublet of orbitally excited $\Lambda_b^0(1P)$ states ($J^P = 1/2^-, 3/2^-$)

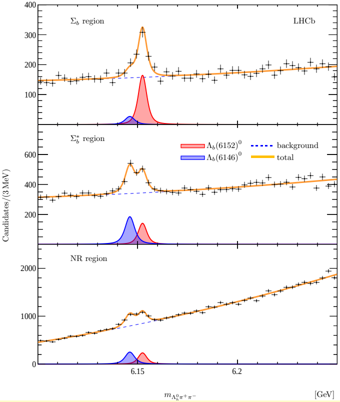
Spectrum of higher $\Lambda_b^0\pi^+\pi^-$ masses (above $\Sigma_b^\pm\pi^\mp$ threshold). Full Run I+II.

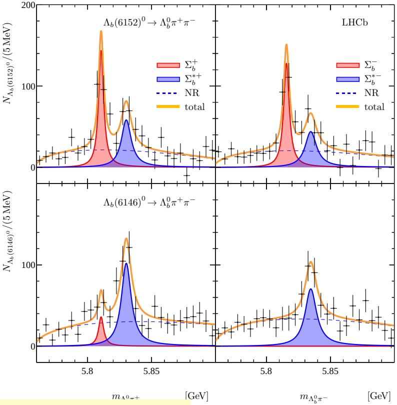


Relative rates with intermediate $\Sigma_b^\pm$ $(1/2^+)$ and $\Sigma_b^{*\pm}$ $(3/2^+)$ can constrain quantum numbers ⇒

Investigate $m(\Lambda_b^0\pi^+\pi^-)$ in 3 regions: $\Sigma_b^\pm\pi^\mp$, $\Sigma_b^{*\pm}\pi^\mp$ and "'non-resonant" (the rest)

Two peaks! ($> 7\sigma$ wrt one peak). Higher-mass $\rightarrow$ both $\Sigma_b^{(*)}$, lower $\rightarrow$ only to Σ_b^*





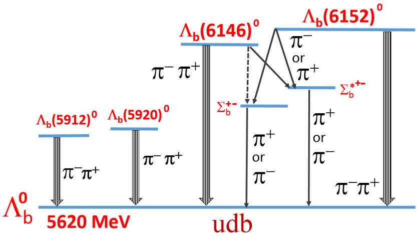
$$m(\Lambda_b(6146)^0) = 6146.17 \pm 0.33(\text{stat}) \pm 0.22(\text{syst}) \pm 0.16(\Lambda_b^0)\ \text{MeV}$$

$$\Gamma(\Lambda_b(6146)^0) = 2.9 \pm 1.3(\text{stat}) \pm 0.3(\text{syst})\ \text{MeV}$$

$$m(\Lambda_b(6152)^0) = 6152.51 \pm 0.26(\text{stat}) \pm 0.22(\text{syst}) \pm 0.16(\Lambda_b^0)\ \text{MeV}$$

$$\Gamma(\Lambda_b(6152)^0) = 2.1 \pm 0.8(\text{stat}) \pm 0.3(\text{syst})\ \text{MeV}$$

Possible interpretation: doublet of $\Lambda_b^0(1D)$ states with $J^P = 3/2^+, 5/2^+$.



$$3/2^+ \to 1/2^+ + 0^-: \; P\text{-wave.}$$
$$3/2^+ \to 3/2^+ + 0^-: \; P\text{-wave.}$$
$$5/2^+ \to 1/2^+ + 0^-: \; F\text{-wave.}$$
$$5/2^+ \to 3/2^+ + 0^-: \; P\text{-wave.}$$

In this interpretation, $m(\Lambda_b^0(3/2^+)) > m(\Lambda_b^0(5/2^+))$. Why?!

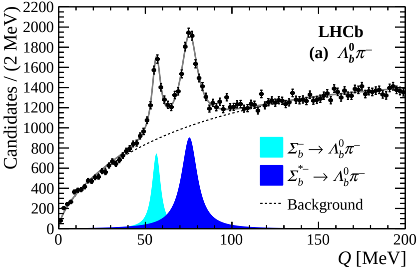
Other possible interpretations in the given mass range ($\Lambda_b(2S)$, $\Sigma_b(2S)$, $\Sigma_b(1P)$) are less likely.

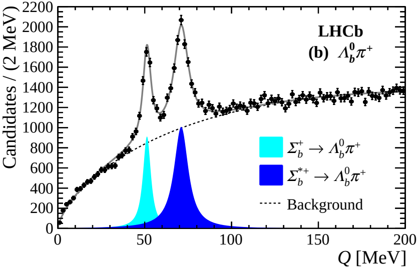
[W. Liang, Q.-F. Lu, X.-H. Zhong, PRD 100, 054013 (2019)]
[B. Chen, S.-Q. Luo, X. Liu, T. Matsuki, arXiv:1910.03318]

Ground-state Σ_b, Σ_b^* states near $\Lambda_b^0\pi$ threshold.

Discovered by CDF [PRL 99 (2007) 202001]

LHCb measurement: $\sim\times 5$ better precision ($3\,\mathrm{fb}^{-1}$, Run I)





$m(\Sigma_b^-) = 5815.64 \pm 0.14 \pm 0.24\,\mathrm{MeV}$

$\Gamma(\Sigma_b^-) = 5.33 \pm 0.42 \pm 0.37\,\mathrm{MeV}$

$m(\Sigma_b^{*-}) = 5834.73 \pm 0.17 \pm 0.25\,\mathrm{MeV}$

$\Gamma(\Sigma_b^{*-}) = 10.68 \pm 0.60 \pm 0.33\,\mathrm{MeV}$

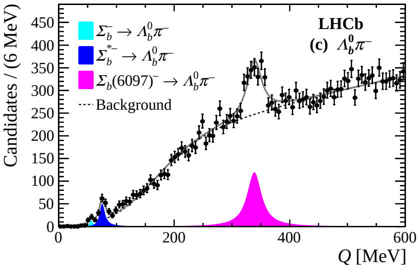
$m(\Sigma_b^+) = 5810.55 \pm 0.11 \pm 0.23\,\mathrm{MeV}$

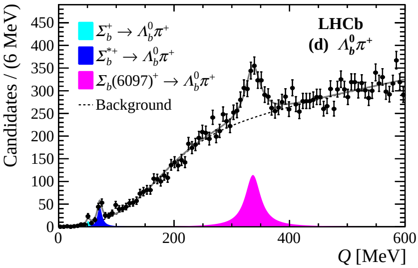
$\Gamma(\Sigma_b^+) = 4.83 \pm 0.31 \pm 0.37\,\mathrm{MeV}$

$m(\Sigma_b^{*+}) = 5830.28 \pm 0.14 \pm 0.24\,\mathrm{MeV}$

$\Gamma(\Sigma_b^{*+}) = 9.34 \pm 0.47 \pm 0.26\,\mathrm{MeV}$

Wider $m(\Lambda_b^0\pi)$ region:





$m(\Sigma_b(6097)^-) = 6098.0 \pm 1.7 \pm 0.5\,\mathrm{MeV}$

$\Gamma(\Sigma_b(6097)^-) = 28.9 \pm 4.2 \pm 0.9\,\mathrm{MeV}$

$m(\Sigma_b(6097)^+) = 6095.8 \pm 1.7 \pm 0.4\,\mathrm{MeV}$

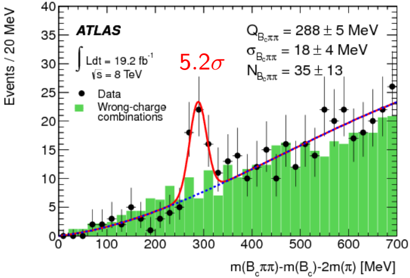
$\Gamma(\Sigma_b(6097)^+) = 31.0 \pm 5.5 \pm 0.7\,\mathrm{MeV}$

Several $\Sigma_b(1P)$ states ($J^P = 1/2^-, 3/2^-, 5/2^-$) are expected in 6100 MeV region. Could be one of them or a superposition.

Excitations in B_c^+ system: $B_c^+\gamma$, $B_c^+\pi^+\pi^-$, $B\bar{D}$

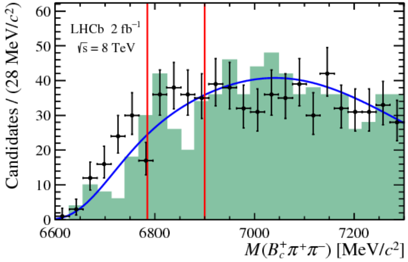
$B_c^{**} \to B_c^+\pi^+\pi^-$, $B_c^+ \to J/\psi\,\pi$, well suited for GPDs

[ATLAS, PRL 113 (2014) 212004]

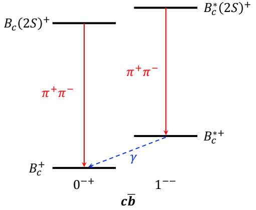


$m = 6842 \pm 4 \pm 5\,\mathrm{MeV}$

[LHCb, JHEP (2018) 2018:138]

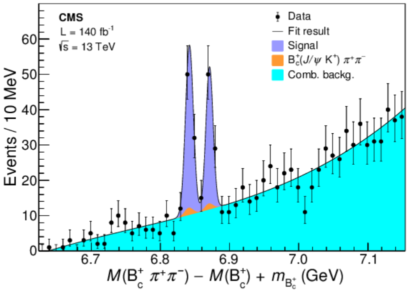


No evidence found



Both $B_c(1S)^+$ and $B_c(2S)^+$ have spin-excited vector partners, B_c^{*+}

$B_c^{*+} \to B_c^+\gamma$ with mass difference $20 - 50\,\mathrm{MeV}$

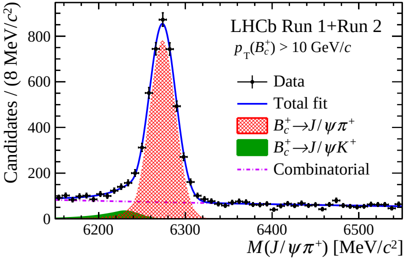


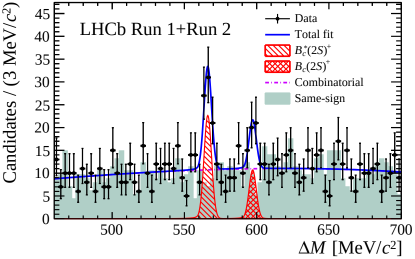
Two peaks, 6.5σ significance.

$$m(B_c(2S)^+) = 6871.0 \pm 1.2(\text{stat}) \pm 0.8(\text{syst}) \pm 0.8(B_c^+)\,\mathrm{MeV}$$

$$\Delta m = 29.1 \pm 1.5(\text{stat}) \pm 0.7(\text{syst})\,\mathrm{MeV}$$

$B_c^+\pi^+\pi^-$ spectrum, $B_c^+ \to J/\psi\,\pi^+$. Full Run I+II LHCb dataset.



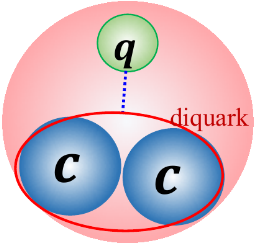


$m_1 = 6841.2 \pm 0.6(\text{stat}) \pm 0.1(\text{syst}) \pm 0.8(B_c^+)\,\text{MeV}$, 6.3σ global

$m_2 = 6872.1 \pm 1.3(\text{stat}) \pm 0.1(\text{syst}) \pm 0.8(B_c^+)\,\text{MeV}$, 2.2σ global

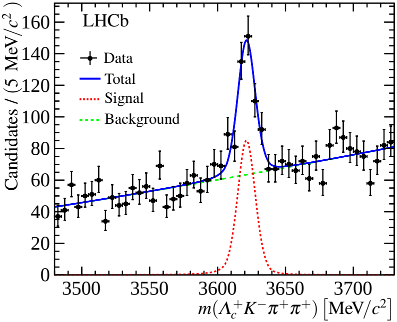
$\Delta m = 31.0 \pm 1.4(\text{stat}) \pm 0.0(\text{syst})\,\text{MeV}$

- Double heavy quarks have been seen for a long time in mesons: $\psi(c\bar{c})$, $\Upsilon(b\bar{b})$, $B_c^+(\bar{b}c)$.
- Expect three doubly-charmed baryons: Ξ_{cc}^+ (ccd), Ξ_{cc}^{++} (ccu) and Ω_{cc}^+ (ccs)
- A different system: cc as a heavy diquark; similar to heavy mesons Qq.
- Ξ_{cc}^+ and Ξ_{cc}^{++} expected to have small mass difference.



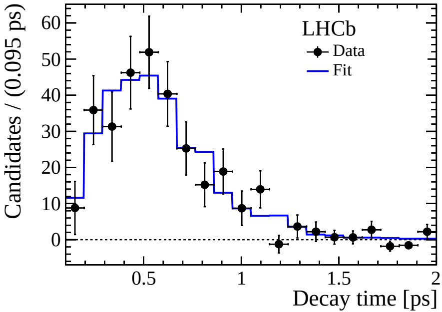
- Lifetime $\tau(\Xi_{cc}^{++}) > \tau(\Xi_{cc}^+)$ due to different interference pattern of spectator and exchange diagrams
- Ξ_{cc}^+ discovery claimed by SELEX $M(\Xi_{cc}^+) = 3518.7 \pm 1.7\,\mathrm{MeV}$
  Not confirmed by B-factories and LHCb (Run I)

[PRL 119 (2017) 112001]



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

[PRL 121 (2018) 052002]



Lifetime measurement

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

$\tau(\Xi_{cc}^{++}) = 0.256^{+0.024}_{-0.022}(\text{stat}) \pm 0.014(\text{syst})\,\text{ps}$

[LHCb-PAPER-2019-035, in preparation]

Measurement of the Ξ_{cc}^{++} production relative to Λ_c^+ at $\sqrt{s}$ =13 TeV.

Kinematic region: $4 < p_T < 15\,\mathrm{GeV}$, $2.0 < y < 4.5$

Production rate ratio:

$$\mathcal{R} = \frac{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}{\sigma(\Lambda_c^+)}$$

$\mathcal{R} = [2.22 \pm 0.27(\text{stat}) \pm 0.29(\text{syst})] \times 10^{-4}$ for $\tau(\Xi_{cc}^{++}) = 0.256\,\mathrm{ps}$

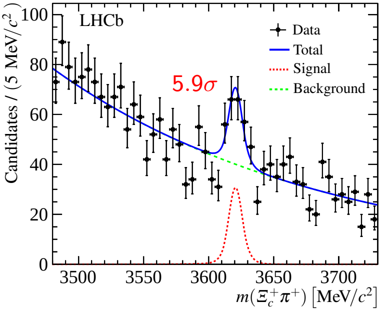
$[2.53 \pm 0.30(\text{stat}) \pm 0.33(\text{syst})] \times 10^{-4}$ $\tau(\Xi_{cc}^{++}) = 0.230\,\mathrm{ps}\ (-1\sigma)$

$[1.98 \pm 0.23(\text{stat}) \pm 0.26(\text{syst})] \times 10^{-4}$ $\tau(\Xi_{cc}^{++}) = 0.284\,\mathrm{ps}\ (+1\sigma)$

Preliminary!

[PRL 121 (2018) 162002]

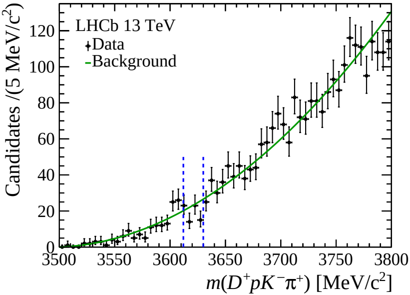
Observation in $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$



$$\mathcal{R} = \frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+)\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}$$
$$= 0.035 \pm 0.009 \pm 0.003$$

[arXiv:1905.02421]

No evidence in $\Xi_{cc}^{++} \to D^+ pK^- \pi^+$



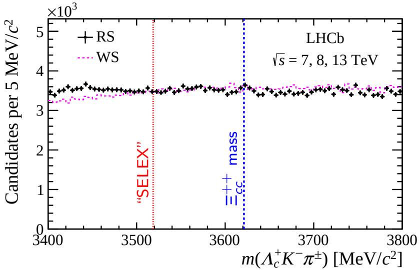
$$\mathcal{R} = \frac{\mathcal{B}(\Xi_{cc}^{++} \to D^+ pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}$$
$$< 1.7 \text{ (90\% CL)}$$

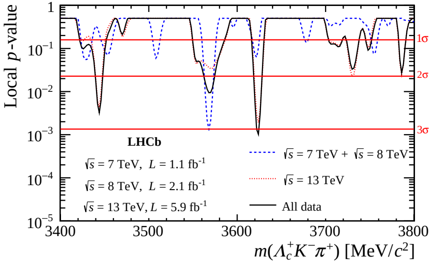
$$m(\Xi_{cc}^{++}) = 3620.6 \pm 1.5(\text{stat}) \pm 0.4(\text{syst}) \pm 0.3(\Xi_c^+)\,\text{MeV}$$

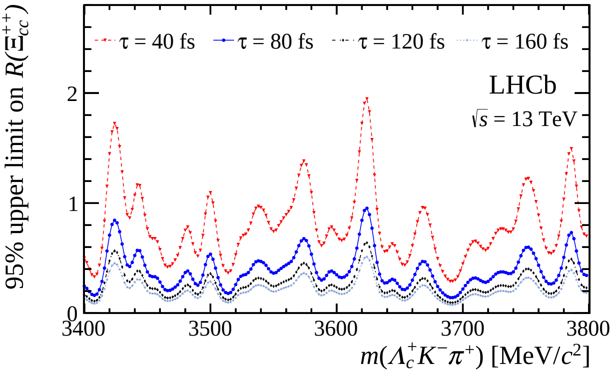
Search for decays of singly-charged $\Xi_{cc}^{+} \to \Lambda_c^{+}K^{-}\pi^{+}$.

Selection optimised for 5σ observation of a state with $\tau = 80\,\mathrm{fs}$

Largest local significance of 3.1σ (1.7σ global) at $3620\,\mathrm{MeV}$.



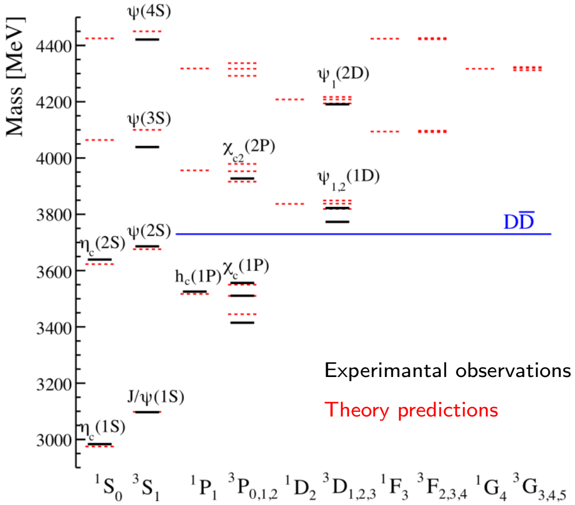




Upper limits on $\mathcal{R}(\Lambda_c^+) \equiv \frac{\sigma(\Xi_{cc}^{+})\mathcal{B}(\Xi_{cc}^{+}\to\Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)}$ and $\mathcal{R}(\Xi_{cc}^{++}) \equiv \frac{\sigma(\Xi_{cc}^{+})\mathcal{B}(\Xi_{cc}^{+}\to\Lambda_c^+ K^- \pi^+)}{\sigma(\Xi_{cc}^{++})\mathcal{B}(\Xi_{cc}^{++}\to\Lambda_c^+ K^- \pi^+\pi^+)}$ for four lifetime hypotheses

"Conventional" charmonium spectrum

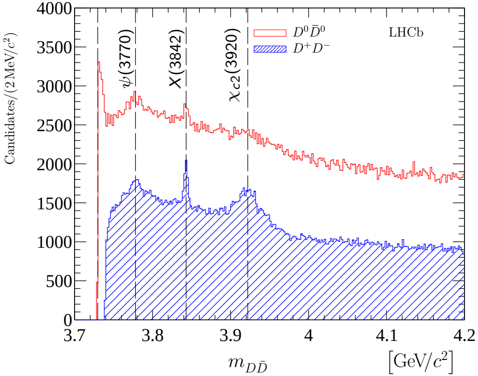
A few charmonium states over $D\bar{D}$ threshold are not yet observed:



Rev.Mod.Phys. 90 (2018) no.1, 015003

Study charmonium states above $\mathrm{D\bar{D}}$ threshold: prompt $\mathrm{D\bar{D}}$ spectrum

Full Run I+II



- Known $\psi(3770)$, $\chi_{c2}(3930)$
- New narrow peak at 3842 MeV
- Threshold enhancement in $\mathrm{D^0\bar{D}^0}$: partially reconstructed $X(3872) \to \mathrm{D^0\bar{D}^{*0}}$

$D\bar{D}$ spectrum

[JHEP 07 (2019) 035]

Measure parameters of the $X(3842)$ state

$$m(X(3842)) = 3842.71 \pm 0.16 \pm 0.12\,\mathrm{MeV}$$

$$\Gamma(X(3842)) = 2.79 \pm 0.51 \pm 0.35\,\mathrm{MeV}$$

Likely interpretation: $J^{PC} = 3^{--}$ charmonium state $\psi_3(1^3D_3)$

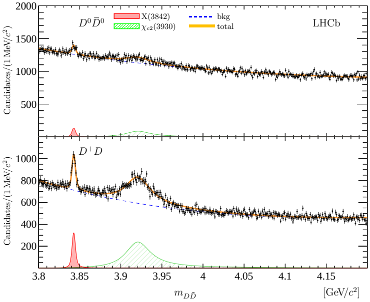
Parameters of the $\chi_{c2}(3930)$:

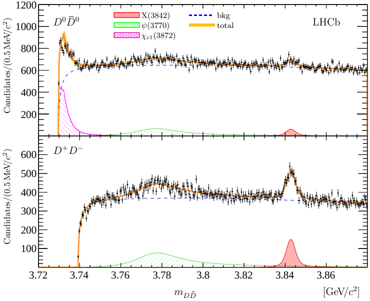
$$m(\chi_{c2}(3930)) = 3921.9 \pm 0.6 \pm 0.2\,\mathrm{MeV}$$

$$\Gamma(\chi_{c2}(3930)) = 36.6 \pm 1.9 \pm 0.9\,\mathrm{MeV}$$

Potential to measure $X(3872)$ lineshape?

- Excellent mass resolution at threshold
- But high background $\Rightarrow$ go for $D\bar{D}$ from B decays?





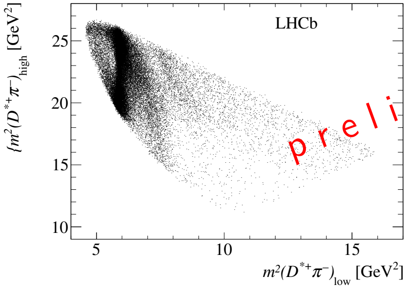
[LHCb-PAPER-2019-027, in preparation]

Study excited D^0 states in $D^{*+}\pi^-$ channel.

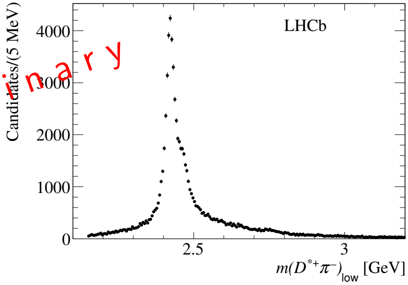
Large and pure dataset of $B^- \to D^{*+}\pi^-\pi^-$ ($\sim$ 80000 events, 90% purity)

Well-defined initial state, measure quantum numbers of $D^{*+}\pi^-$ resonances.

Amplitude analysis of 4D distribution: $m^2(D^*\pi)_{high,low}$, D^* angles θ, γ



Two identical pions, folded Dalitz plot



Low-mass $m(D^{*+}\pi^-)$ projection

Open-charm spectroscopy in $B^- \to D^{*+}\pi^-\pi^-$ Preliminary!

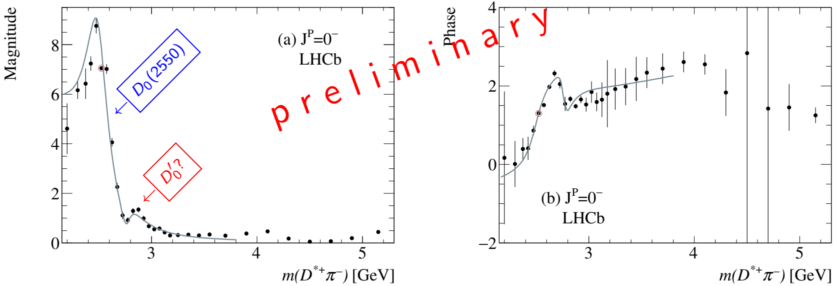
[LHCb-PAPER-2019-027, in preparation]

Established states:

$J^P = 1^+$: $D_1(2420)^0$
$J^P = 1^+$: $D_1(2430)^0$
$J^P = 2^+$: $D_2^*(2460)^0$

Quantum numbers for higher excitations:

$J^P = 0^-$: $D_0(2550)^0$
$J^P = 1^-$: $D_1^*(2600)^0$
$J^P = 2^-$: $D_2(2740)^0$
$J^P = 3^-$: $D_3^*(2750)^0$



Quasi-model-independent amplitude replacing each partial wave.

[LHCb-PAPER-2019-027, in preparation]

Established states:

$J^P = 1^+$: $D_1(2420)^0$
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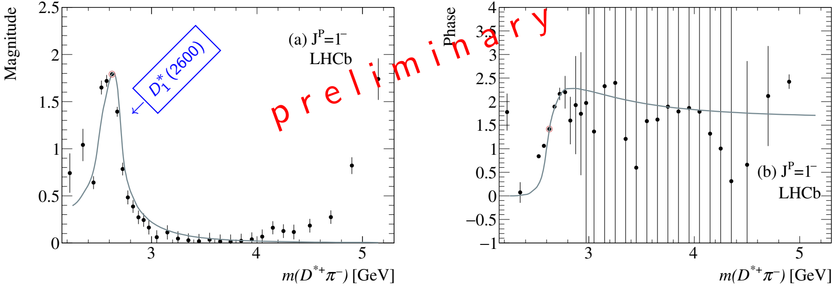

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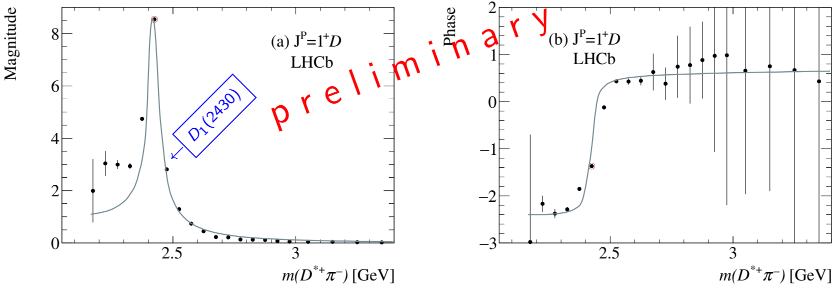

Quasi-model-independent amplitude replacing each partial wave.

[LHCb-PAPER-2019-027, in preparation]

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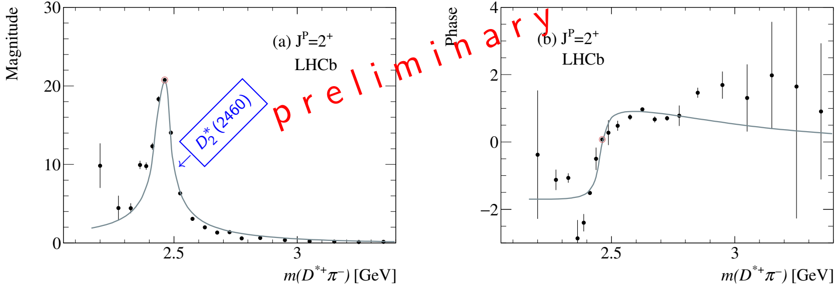
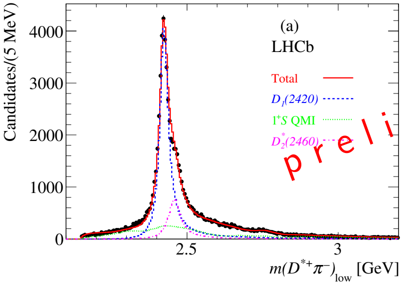
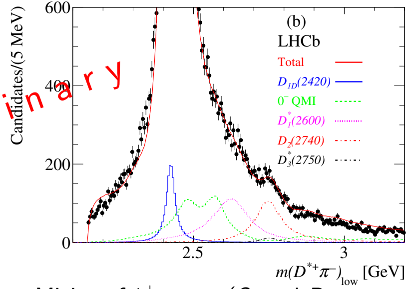


Quasi-model-independent amplitude replacing each partial wave.

Fit results with the final model: [LHCb-PAPER-2019-027, in preparation]

- Quasi-model-independent for $J^P = 0^-$ and 1^+ S-wave (> 1 state)
- Breit-Wigner amplitudes for the rest





State	J^P	M (MeV)	Γ (MeV)
$D_1(2420)$	1^+	$2424.8 \pm 0.1 \pm 0.6$	$33.6 \pm 0.3 \pm 2.8$
$D_1(2430)$	1^+	$2411 \pm 3 \pm 10$	$309 \pm 9 \pm 41$
$D_0(2550)$	0^-	$2518 \pm 2 \pm 10$	$199 \pm 5 \pm 20$
$D_1^*(2600)$	1^-	$2641.9 \pm 1.8 \pm 4.5$	$149 \pm 4 \pm 20$
$D_2(2740)$	2^-	$2751 \pm 3 \pm 12$	$102 \pm 6 \pm 27$
$D_3^*(2750)$	3^-	$2753 \pm 4 \pm 6$	$66 \pm 10 \pm 14$

Mixing of 1^+ states (S- and D-wave amplitudes):

$$A^{D_1'} = A^{1S}\cos\omega - A^{1D}\sin\omega e^{i\psi}$$
$$A^{D_1} = A^{1S}\sin\omega + A^{1D}\cos\omega e^{i\psi}$$

$\omega = -0.063 \pm 0.019 \pm 0.021$

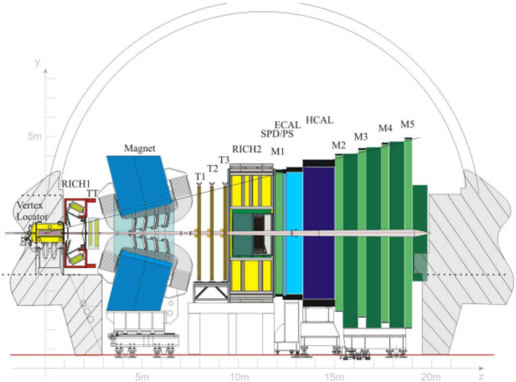
$\psi = -0.29 \pm 0.09 \pm 0.08$

Conclusion

- Experimental hadron spectroscopy is a very dynamic and exciting field now.
- In many areas, LHCb is a unique facility, *e.g.* heavy b-hadrons.
- A lot of new results during last year
  - Excited beauty baryons and mesons
  - Doubly charmed baryons
  - Charmonium and open charm
- Competitiion with B-factories, BES-III, but also ATLAS and CMS.
- Post-upgrade LHCb: expect enormous amounds of data.
  - Converted photons in radiative decays
  - Open-charm decays of charmonia
  - More amplitude analyses of B decays
  - bc, bb doubly heavy states
  - ...

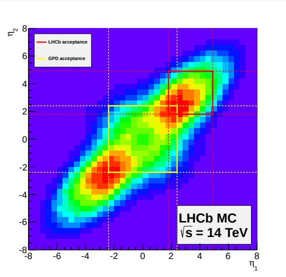
Backup

One-arm spectrometer optimised for studies of beauty and charm decays at LHC



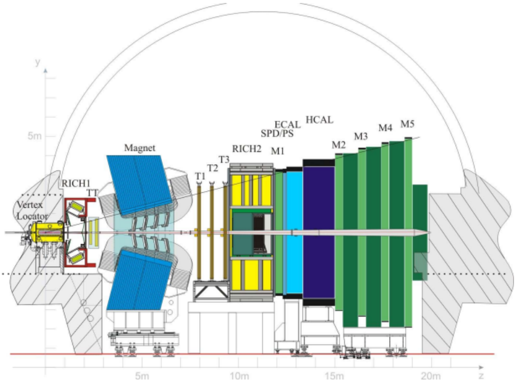
Rapidity coverage

$2 < \eta < 5$



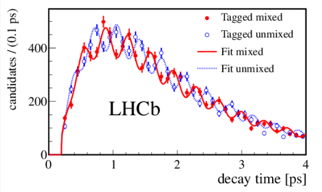
- Covers forward region (maximum of c and b production)

One-arm spectrometer optimised for studies of beauty and charm decays at LHC



Vertexing

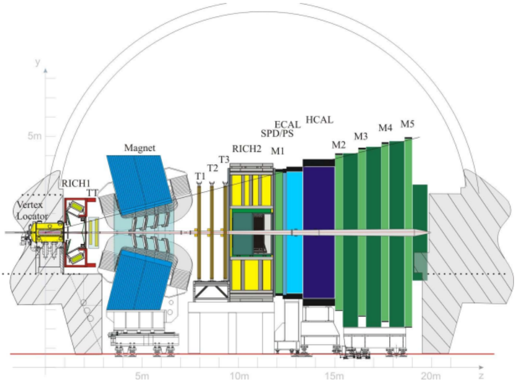
B_s^0 oscillations with $B_s^0 \to D_s\pi$



[New J. Phys. 15 (2013) 053021]

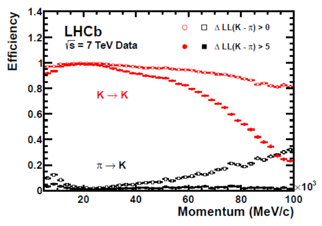
- Covers forward region (maximum of c and b production)
- Good vertexing: measure B^0 and B_s^0 oscillations, reject prompt background

One-arm spectrometer optimised for studies of beauty and charm decays at LHC



PID

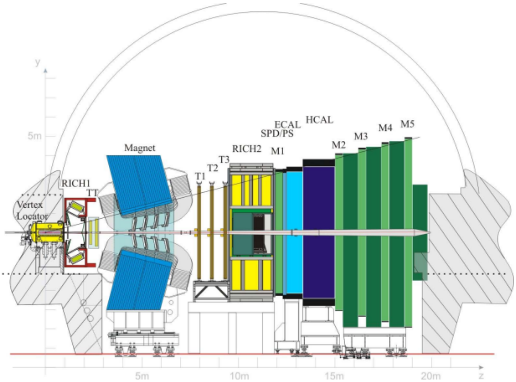
K/π ID efficiency and misID rate



[EPJ C73 (2013) 2431]

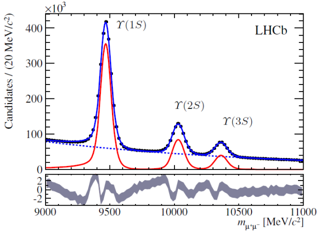
- Covers forward region (maximum of *c* and *b* production)
- Good vertexing: measure B^0 and B_s^0 oscillations, reject prompt background
- Particle identification: flavour tagging, misID background

One-arm spectrometer optimised for studies of beauty and charm decays at LHC



Tracking

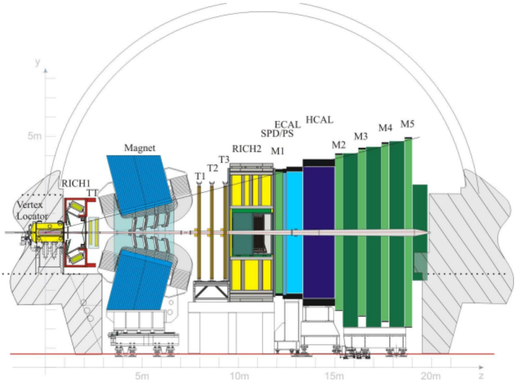
$\mu^+\mu^-$ mass spectrum



[PRL 111 (2013) 101805]

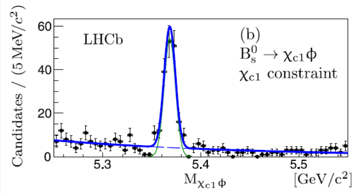
- Covers forward region (maximum of c and b production)
- Good vertexing: measure B^0 and B^0_s oscillations, reject prompt background
- Particle identification: flavour tagging, misID background
- High-resolution tracking

One-arm spectrometer optimised for studies of beauty and charm decays at LHC



Calorimetry

$B_s^0 \to \chi_{c1}\phi$, $\chi_{c1} \to J/\psi\gamma$



[Nucl. Phys. B874 (2013) 663]

- Covers forward region (maximum of c and b production)
- Good vertexing: measure B^0 and B_s^0 oscillations, reject prompt background
- Particle identification: flavour tagging, misID background
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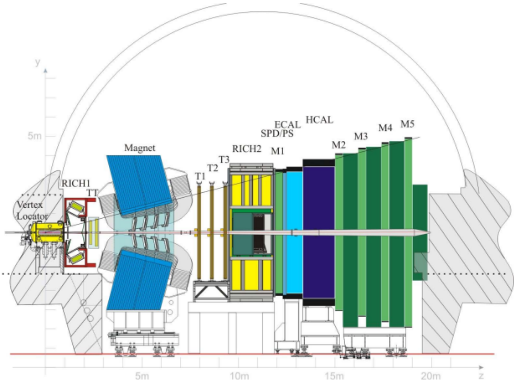
- Calorimetry: reconstruct neutrals (π^0, γ) in the final state

One-arm spectrometer optimised for studies of beauty and charm decays at LHC



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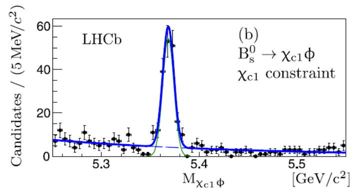
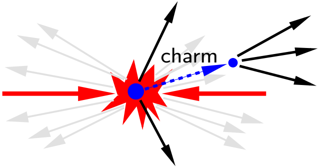


[Nucl. Phys. B874 (2013) 663]

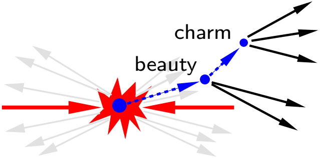
- Covers forward region (maximum of c and b production)
- Good vertexing: measure B^0 and B_s^0 oscillations, reject prompt background
- Particle identification: flavour tagging, misID background
- High-resolution tracking
- Calorimetry: reconstruct neutrals (π^0, γ) in the final state
- Efficient trigger, including fully hadronic modes

Conventional and exotic charm states are studied at LHCb in two production regimes:

- **Prompt production** in pp collisions
  - High statistics
  - High combinatorial background



- **Weak decays** of beauty hadrons (fully or partially reconstructed)
  - Low background
  - Well-defined initial state, determination of quantum numbers
  - Kinematic constraints



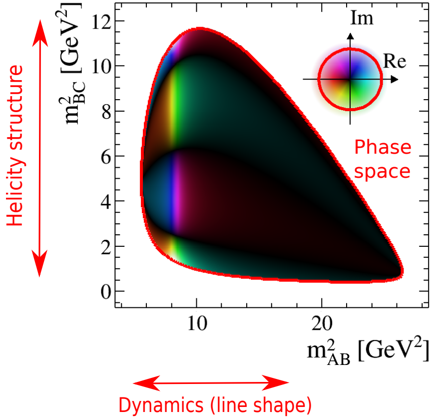
Properties of exotic states which can be determined and tested against theory models

- Mass and width
- Production and decay channels, branching ratios
- Quantum numbers: spin, parity
- Line shape

Many of LHCb exotic measurements use amplitude analysis technique.

Perform fits of the amplitude as a function of phase space variables

- Three-body decays $D \to ABC$: two kinematic variables M^2_{AB}, M^2_{BC} (Dalitz plot)
- Add angular variables if initial/final state not scalar



- Both lineshape parameters and spin can be extracted.
- Complex phases of components can be accessed though interference with other structures.

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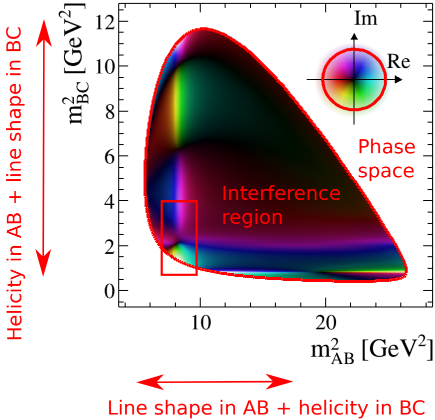
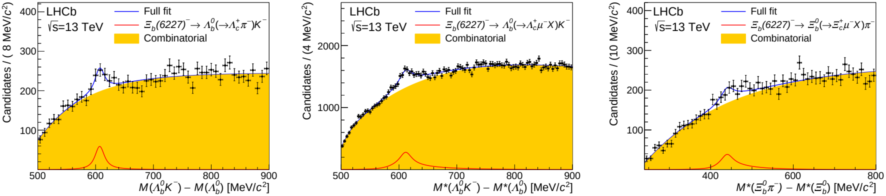


- Both lineshape parameters and spin can be extracted.
- Complex phases of components can be accessed though interference with other structures.

Discovery of a new Ξ_b state

[PRL 121 (2018) 072002]

Orbitally or radially excited state, decaying to $\Xi_b^0\pi^-$ and $\Lambda_b^0 K^-$



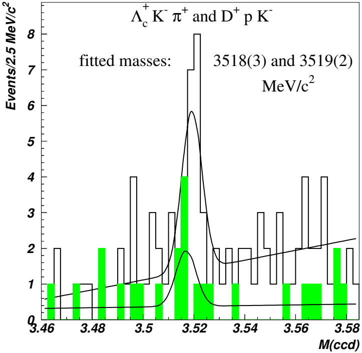
Partially reconstructed $\Lambda_b^0 \to \Lambda_c^+ \mu^- \nu_\mu$, $\Xi_b^0 \to \Xi_c^+ \mu^- \nu_\mu$ decays;
reasonable resolution in mass difference

$$m(\Xi_b(6227)^-) = 6226.9 \pm 2.0 \pm 0.3(\text{syst}) \pm 0.2(\Lambda_b^0)\,\mathrm{MeV}$$

$$\Gamma(\Xi_b(6227)^-) = 18.1 \pm 5.4 \pm 1.8\,\mathrm{MeV}$$

Interpretation: $\Xi_b(1P)$ or $\Xi_b(2S)$ state (or a superposition of several states).

SELEX collaboration (Fermilab E781) seen a peak in $\Lambda_c^+ K^- \pi^+$ and $D^+ p K^-$ spectra



[PRL 89 (2002) 112001, PLB 628 (2005) 18]

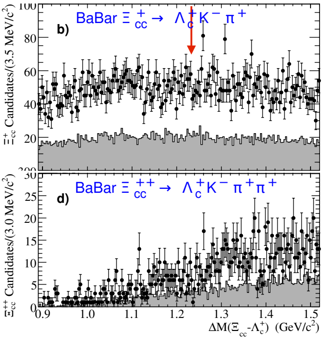
Combined mass:

$M(\Xi_{cc}^+) = 3518.7 \pm 1.7\,\mathrm{MeV}$

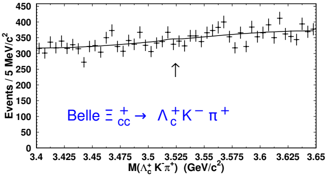
Questions:

- Weakly decaying, but very short lifetime ($\tau(\Xi_{cc}^+) < 33$ fs 90% CL)
- Large production ratio (20% of Λ_c^+ rate through Ξ_{cc}^+)

Not confirmed by B-factories and LHCb:

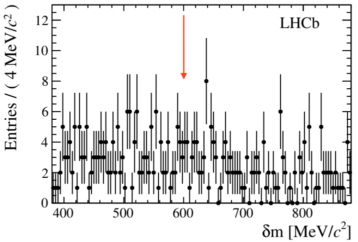


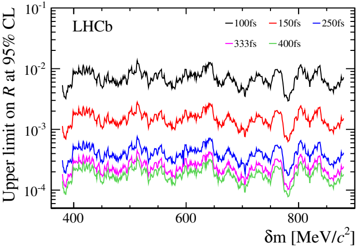
BaBar: Phys.Rev. D74 (2006) 011103



Belle: Phys.Rev.Lett. 97 (2006) 162001

$\delta m \equiv m(\Lambda_c^+ K \pi) - m(\Lambda_c^+) - m(K) - m(\pi)$





[LHCb, JHEP 12 (2013) 090] (0.65 fb^{-1})