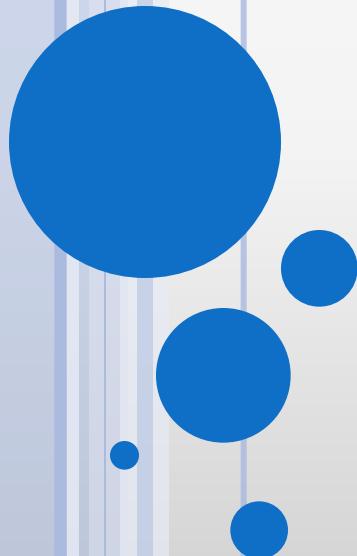


HEAVY BARYONS AND MULTIPLE-FLAVORED EXOTICS AT LHCb

Marco Pappagallo
University of Edinburgh



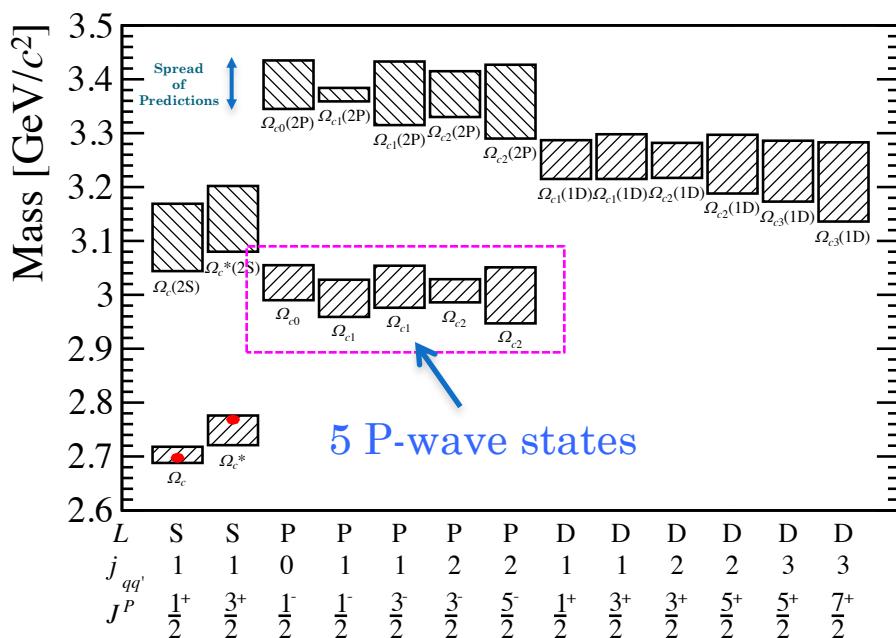
Exotic Hadron and Flavor Physics
28 May-1 June 2018, Stony Brook, New York

OUTLINE

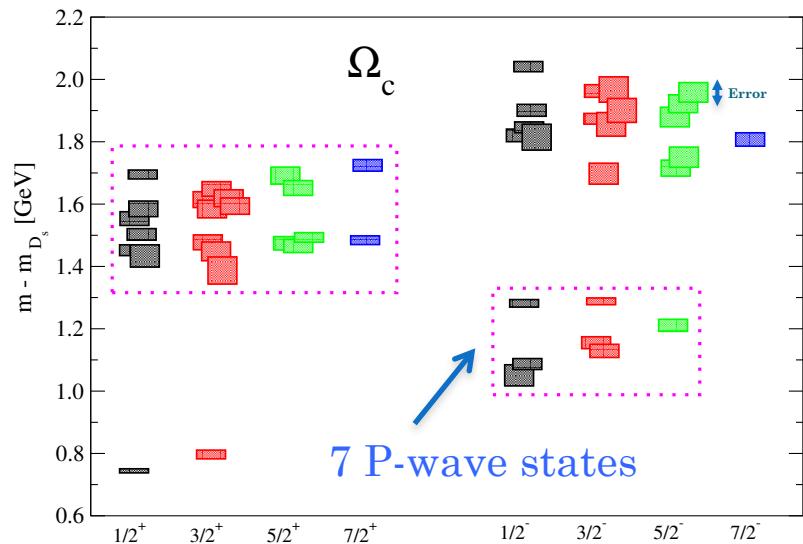
- Observation of 5 new narrow Ω_c^0 states [PRL 118 (2017) 182001]
- Observation of doubly heavy baryon Ξ_{cc}^{++} [PRL 119 (2017) 112001]
- Measurement of Ξ_{cc}^{++} lifetime [LHCb-PAPER-2018-019] 
- Observation of a new Ξ_b^- resonance [arXiv:1805.09418] 
- Search for tetraquarks in $Y(1S)\mu^+\mu^-$ [LHCb-PAPER-2018-027] 
- Plans & Prospects

Excited Ω_c^0 States

Only the ground states Ω_c^0 ($J^P=1/2^+$) and Ω_c^{*0} ($J^P=3/2^+$) are known so far

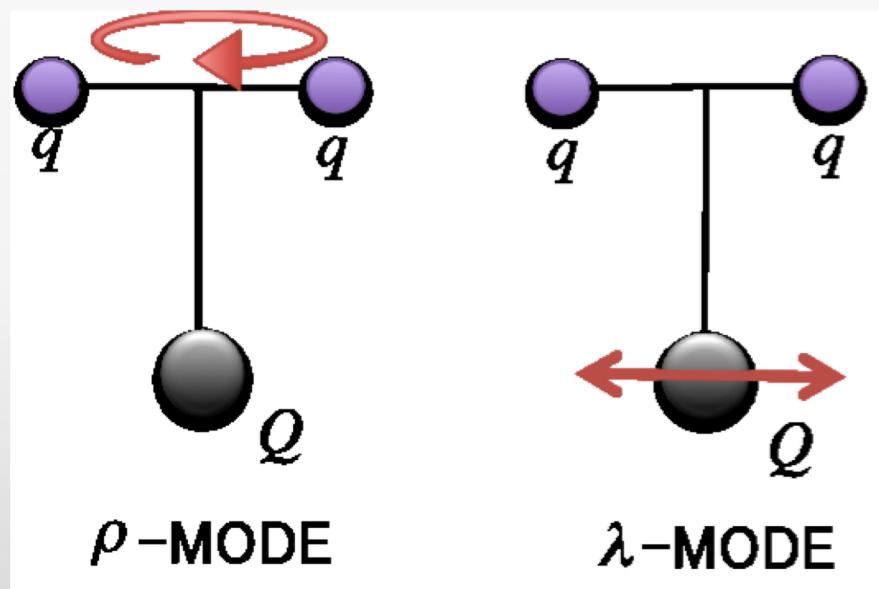


Lattice QCD:
[M. Padmanath *et al.* arXiv:1311.4806]

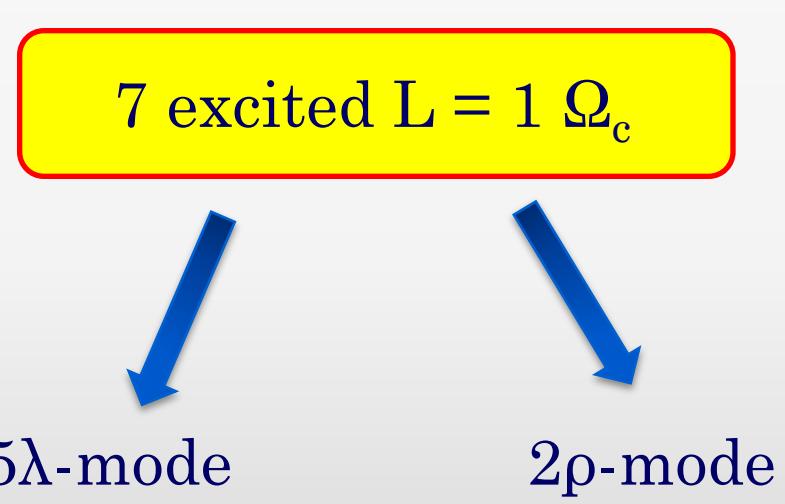


ORBITALLY EXCITED BARYONS

The ρ - and λ -mode excitations of the single-heavy baryon

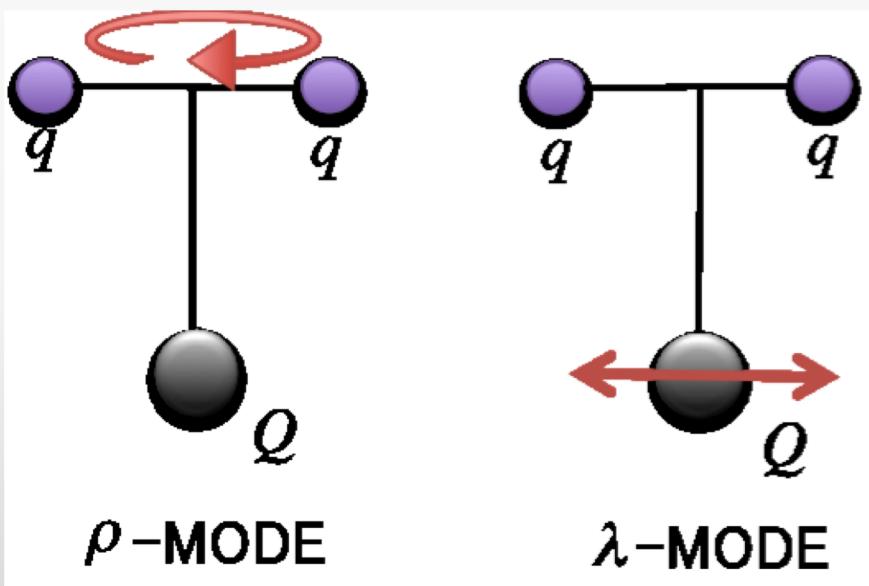


[Phys.Rev. D92 (2015) 114029]

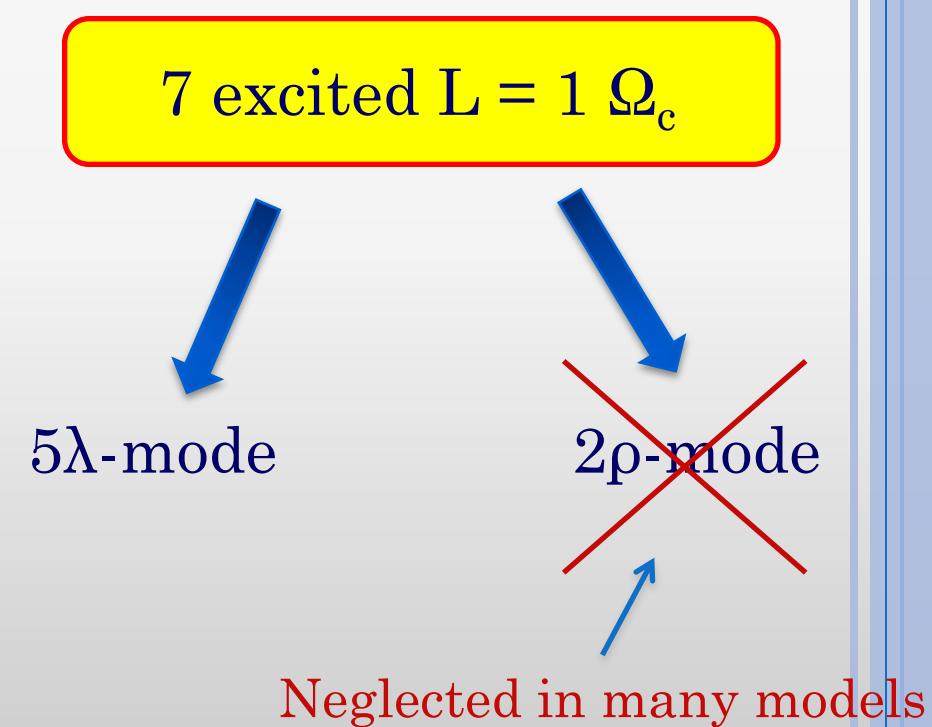


ORBITALLY EXCITED BARYONS

The ρ - and λ -mode excitations of the single-heavy baryon



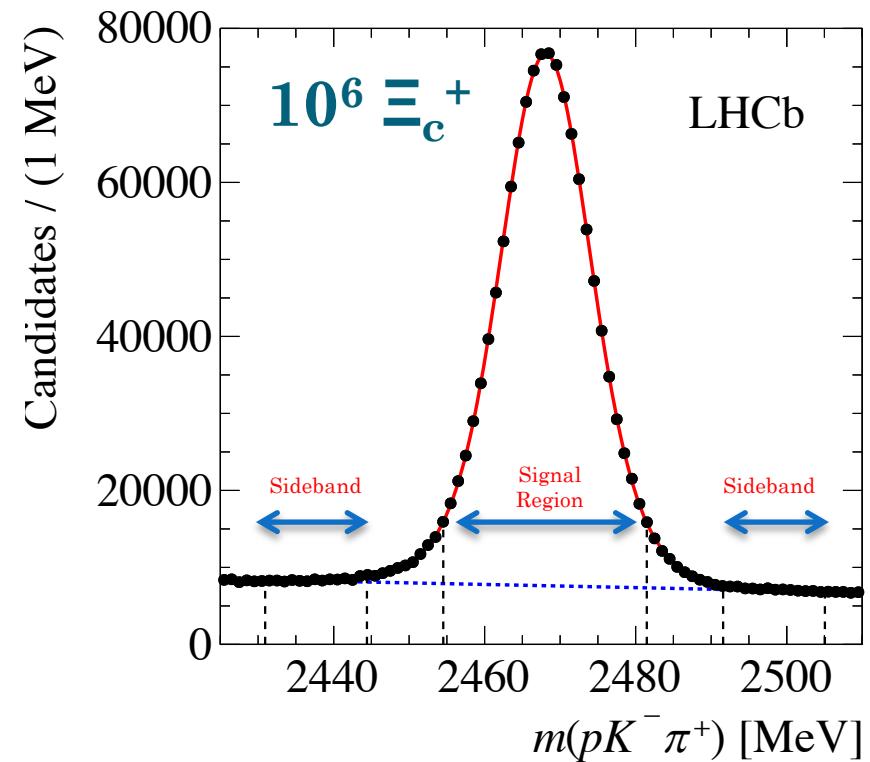
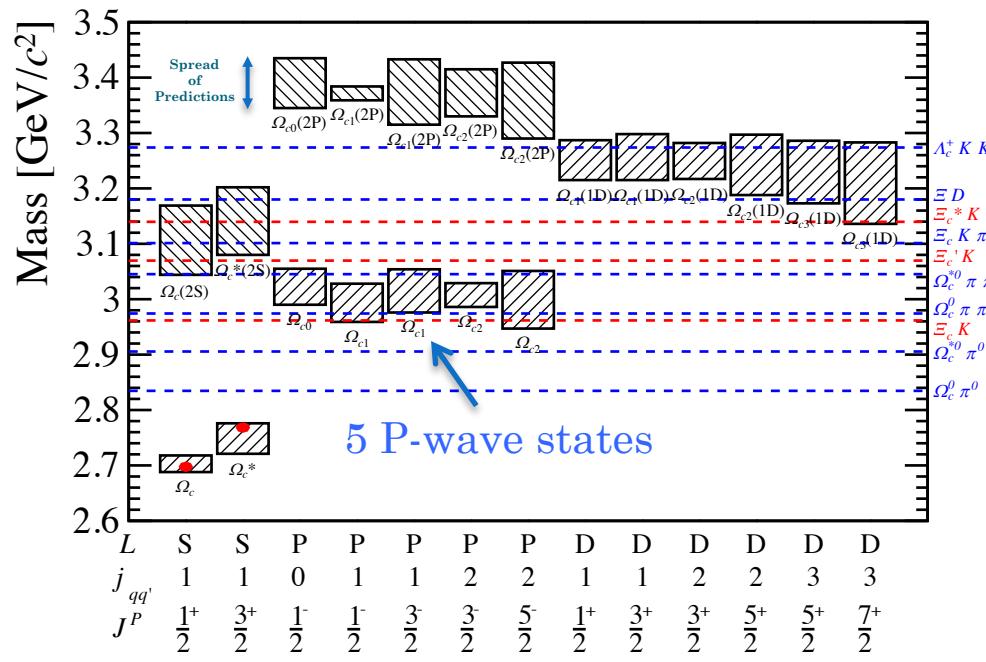
[Phys.Rev. D92 (2015) 114029]



EXCITED Ω_c^0 STATES DECAYING TO $\Xi_c^+ K^-$

[PRL 118 (2017) 182001]

- Reconstruction of Cabibbo suppressed $\Xi_c^+ \rightarrow p K^- \pi^+$ decays
- Data sample: 1.0 fb^{-1} (7 TeV) + 2.0 fb^{-1} (8 TeV) + 0.3 fb^{-1} (13 TeV) = 3.3 fb^{-1}
- A dedicated trigger (and the larger collision energy) boosted the number of the reconstructed Ξ_c^+ in the 13 TeV sample (x 3)

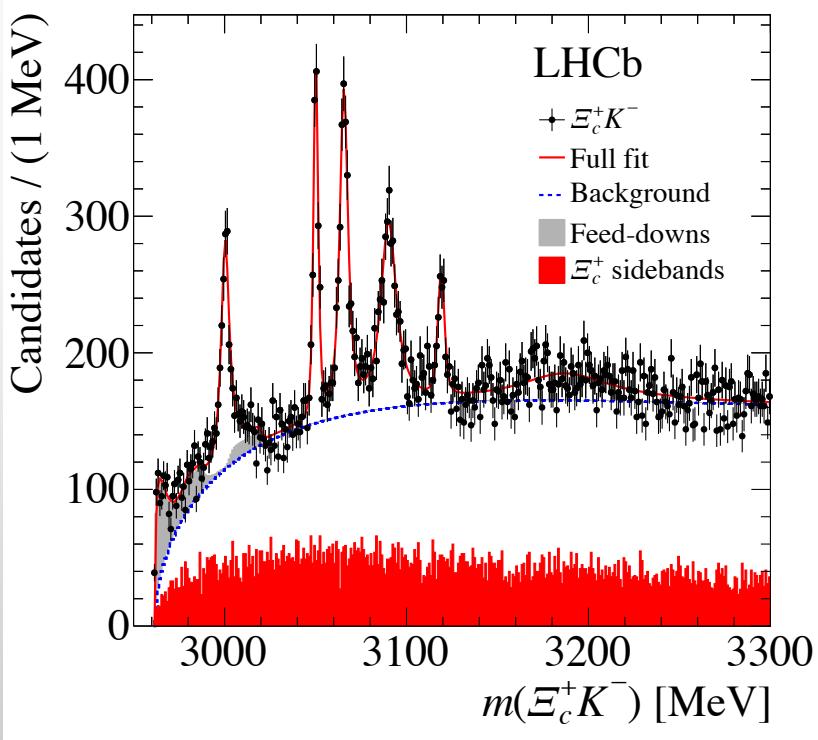


FIVE NEW EXCITED Ω_c^0 STATES!

LHCb
LHCb

[PRL 118 (2017) 182001]

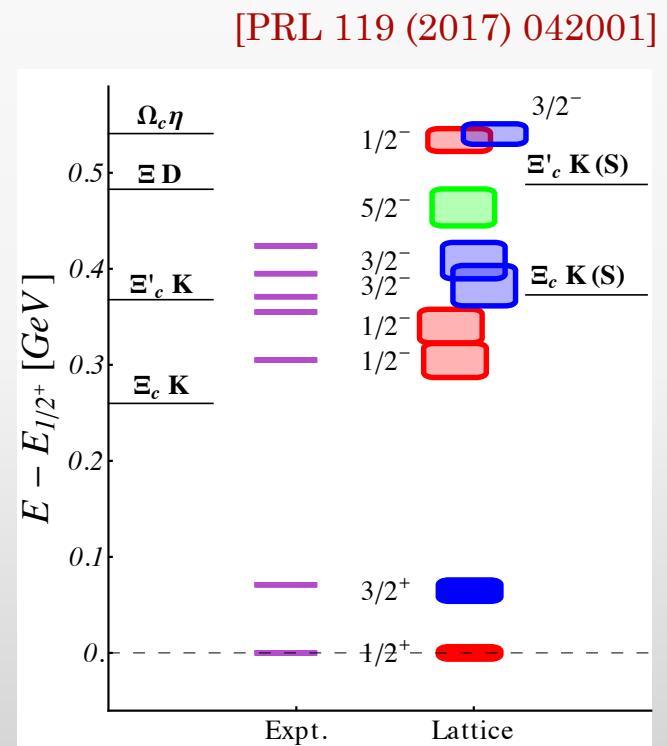
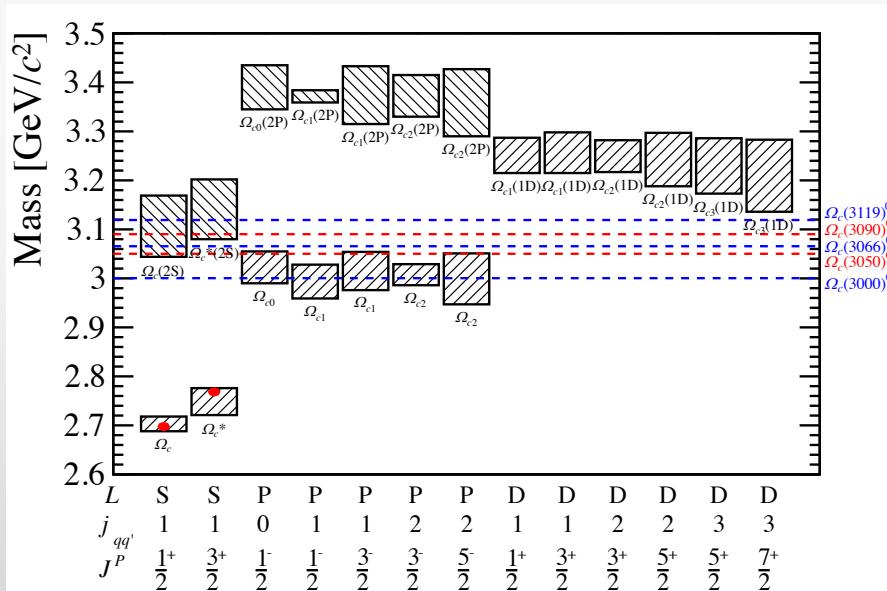
- Observation of **5** new excited Ω_c states! Two of them extremely narrow
- Many interpretations proposed (including pentaquarks)
- The broad state could be a superposition of several states
- Threshold enhancement consistent with being due to the partially reconstructed decay $\Omega_c(3066)^0 \rightarrow \Xi_c^+ K^-$



Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
		$< 1.2 \text{ MeV, 95\% CL}$
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$
		$< 2.6 \text{ MeV, 95\% CL}$
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$

WHAT ARE THEY? WHY ARE THEY SO NARROW?

Most of the authors identified these states as the orbitally or radially excitations of the Ω_c^0 baryon



WHAT ARE THEY? WHY ARE THEY SO NARROW?

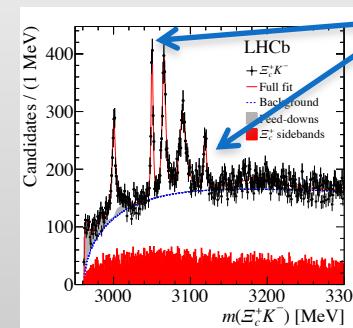
Are they orbitally excited ($L=1$) states? Or radiatally excitations? Or...

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

State	[19]	[20]	[21]	[23]	[29]	[25]	[27]	[28]	[32]	[26]	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 ⁺

[K.-L. Wang, L.-Y. Xiao, X.-H. Zhong, Q. Zhao, Phys. Rev. D95 (2017) 116010]

...or are they pentaquarks?

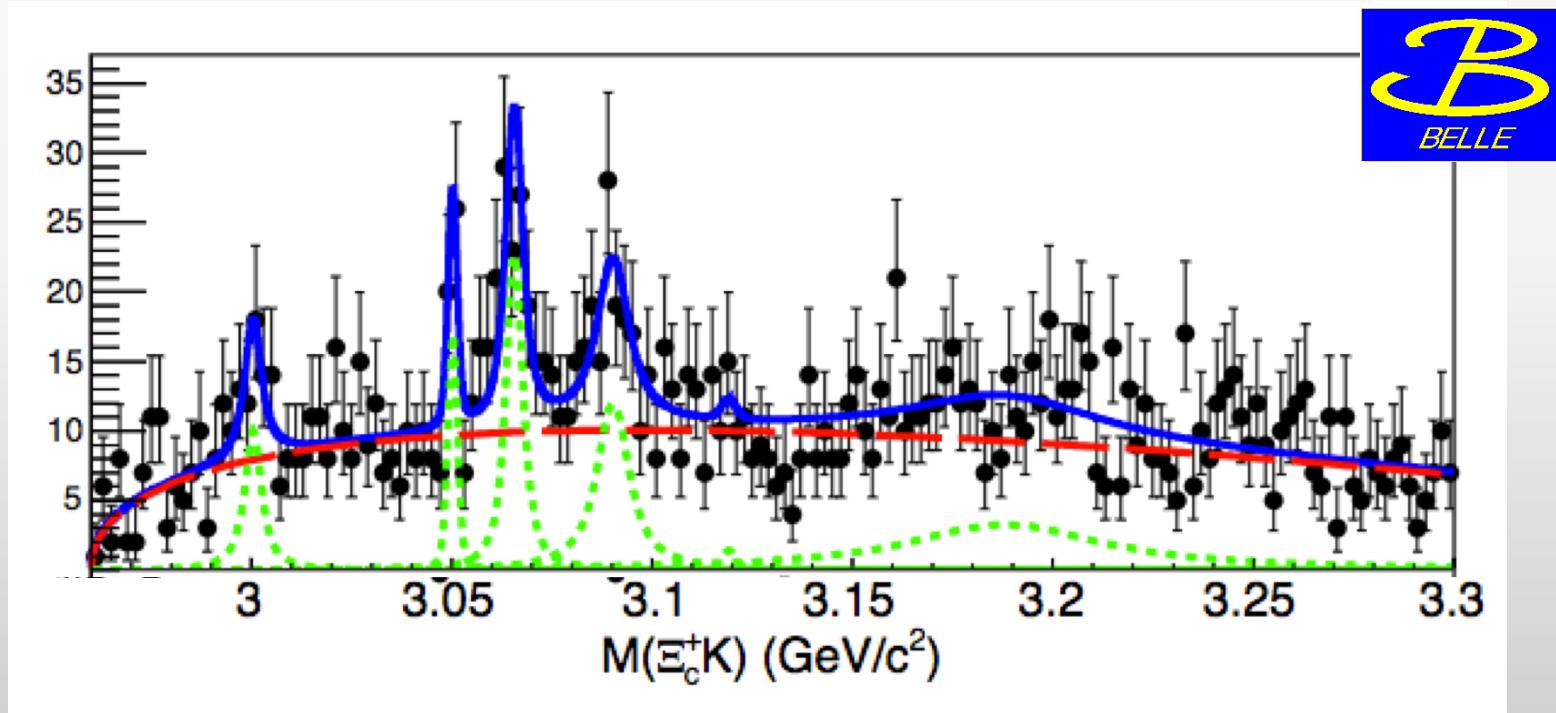


Pentaquarks?

CONFIRMATION OF EXCITED Ω^0_c AT BELLE

[PRD 97 (2018) 051102]

- 4 out of 5 states confirmed
- The narrow state at high mass is missing (not in disagreement with the LHCb observation)
- If the 5th state is a pentaquark, suppression expected in the e^+e^- production

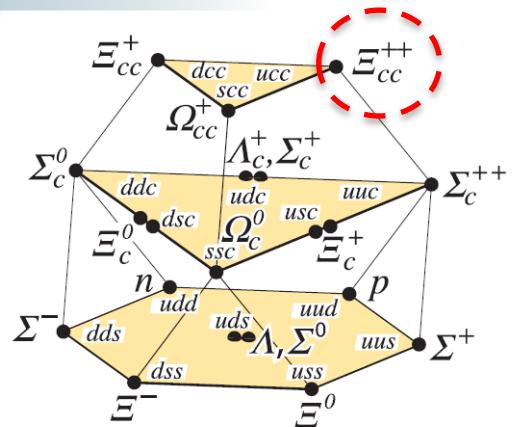


OBSERVATION OF THE DOUBLY CHARMED BARYON Ξ_{cc}^{++}

[PRL 119 (2017) 112001]



- All of the ground states with C=0 or C=1 have been observed
- Three weakly decaying C=2 states expected: Ξ_{cc} isodoublet and Ω_{cc} isosinglet
- SELEX reported signals of $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$, pD⁺K⁻ [PRL 89 (2002) 112001, PLB 628 (2005) 18]
- Not confirmed by BaBar [PRD 74 (2006) 011103], Belle [PRL 97 (2006) 162001] nor LHCb [JHEP 12 (2013) 090]

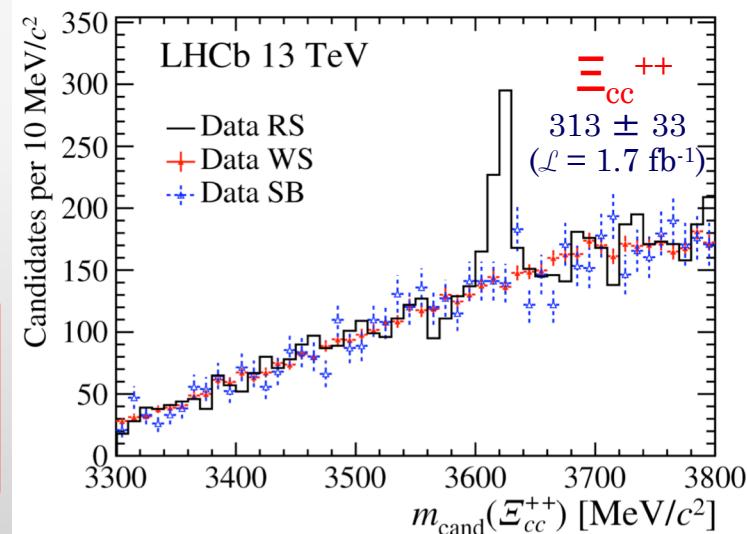


Search for Ξ_{cc}^{++} in the decay chain (2016 data):

$$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+, \quad \Lambda_c^+ \rightarrow p K^- \pi^+$$

Highly significant signal observed ($>12\sigma$) consistent with a state decaying weakly

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



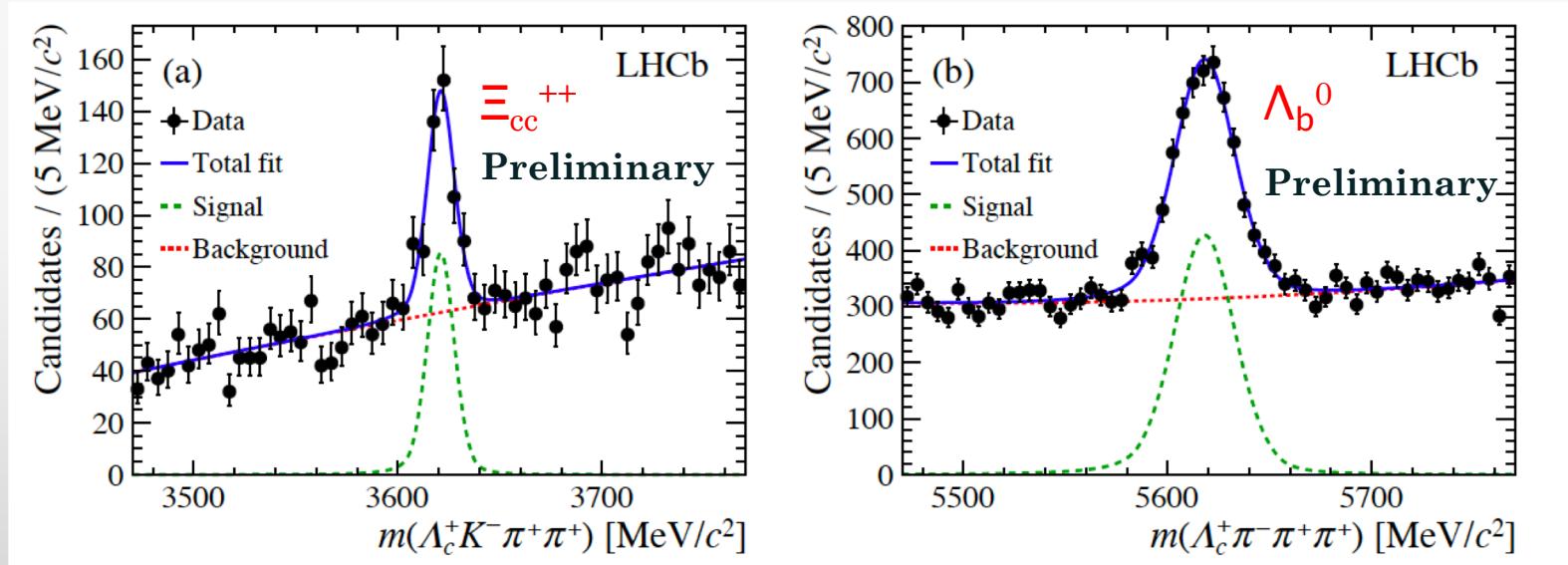
Inconsistent with being isospin partner of the SELEX state: $m(\Xi_{cc}^{++}) - m(\Xi_{cc}^+) = 103 \pm 2 \text{ MeV}$

FIRST MEASUREMENT OF THE LIFETIME OF Ξ_{cc}^{++}

[LHCb-PAPER-2018-019]

LHCb
~~THCP~~

- Dataset: 1.7 fb^{-1} (2016 @ 13 TeV)
- Lifetime measurement of $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ relative to $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^+$ (similar topology)
- Similar selection as for the discovery paper



$$N_{\Xi_{cc}^{++}} = 304 \pm 35$$

$$N_{\Lambda_b^0} = 3397 \pm 119$$

FIRST MEASUREMENT OF THE LIFETIME OF Ξ_{cc}^{++}

[LHCb-PAPER-2018-019]

LHCb
~~FNAL~~

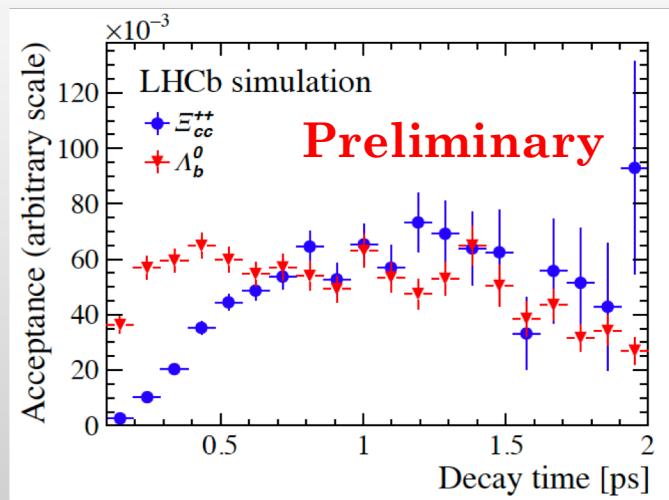
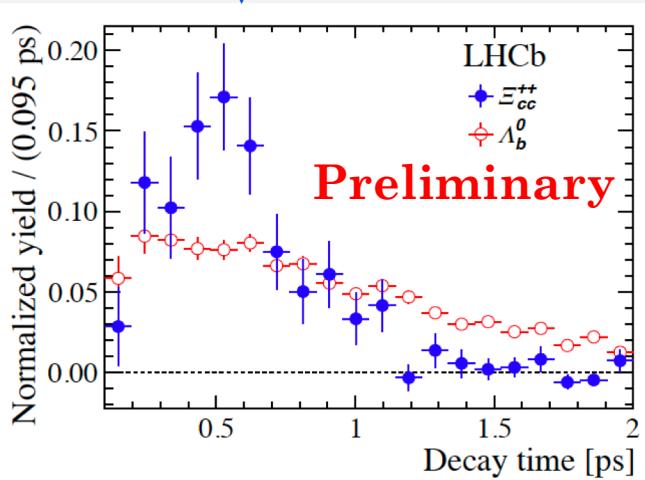
- Lifetime measurement of $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ relative to $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^+$
- Many uncertainties cancel out in the ratio

$$R(t) = \frac{f_{\Xi_{cc}^{++}}}{f_{\Lambda_b^0}} \times \frac{\epsilon_{\Lambda_b^0}}{\epsilon_{\Xi_{cc}^{++}}} = R(0)e^{-\left(\frac{1}{\tau_{\Xi_{cc}^{++}}} - \frac{1}{\tau_{\Lambda_b^0}}\right)t} \quad \text{where } t \in [0.1 - 2.0] \text{ ps}$$

S-weighted data
to subtract
background

$$\epsilon(t) = \frac{N_{\text{Rec}}(t)}{N_{\text{Gen}}(t)}$$

Resolutions (~60 fs) negligible



FIRST MEASUREMENT OF THE LIFETIME OF Ξ_{cc}^{++}

[LHCb-PAPER-2018-019]

LHCb
~~FNAL~~

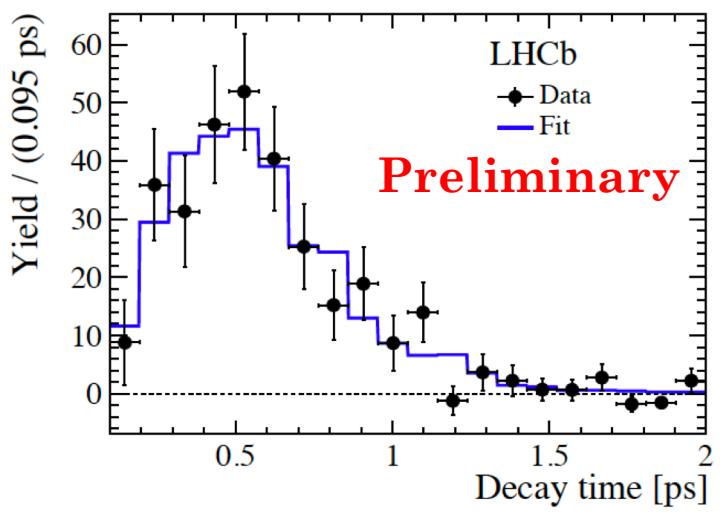
$$f_{\Xi_{cc}^{++}} = h_{\Lambda_b^0} \times \frac{\epsilon_{\Xi_{cc}^{++}}}{\epsilon_{\Lambda_b^0}} \times e^{-\left(\frac{1}{\tau_{\Xi_{cc}^{++}}} - \frac{1}{\tau_{\Lambda_b^0}}\right)t}$$

Data

MC

$\tau_{\Lambda_b^0} = 1.470 \pm 0.010$ ps (PDG)

Free parameter

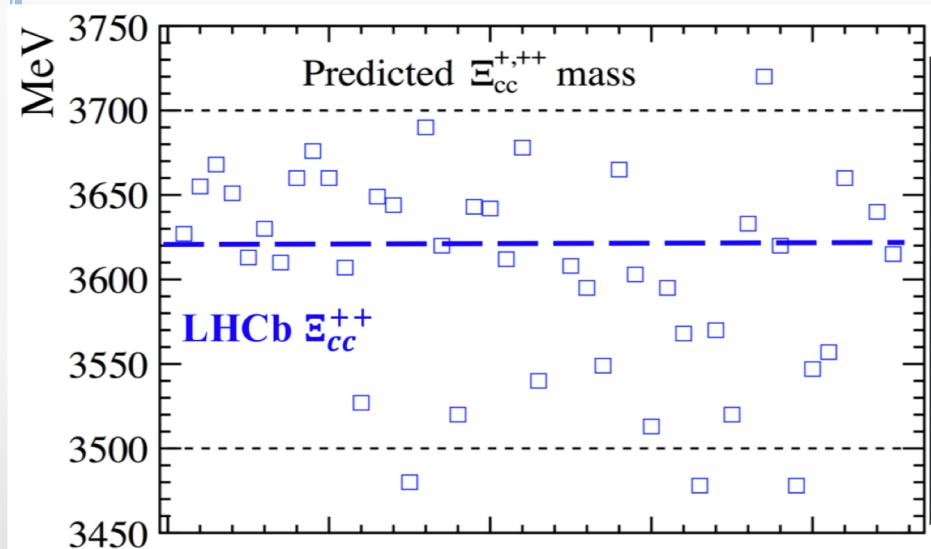


$$\tau_{\Xi_{cc}^{++}} = 0.256 \pm^{0.024}_{0.022} \pm 0.014 \text{ ps}$$

FIRST MEASUREMENT OF THE LIFETIME OF Ξ_{cc}^{++}

[LHCb-PAPER-2018-019]

LHCb
~~FNAL~~

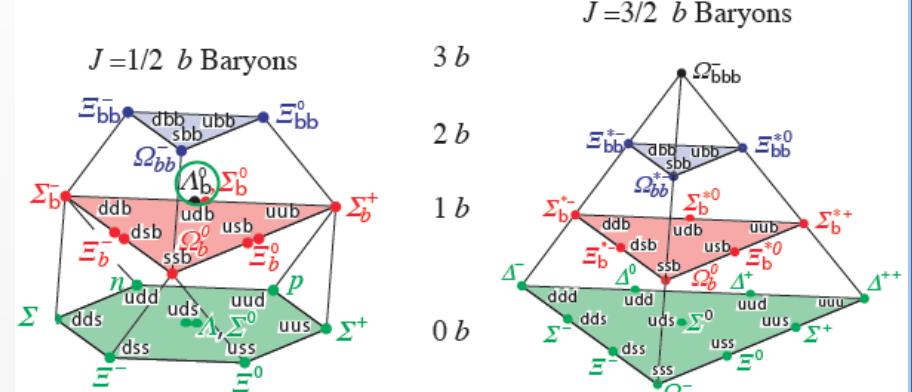


Reference	Ξ_{cc}^{++} (ps)	Ξ_{cc}^+ (ps)	Ω_{cc}^+ (ps)
Karliner, Rosner, 2014	0.185	0.053	
Kiselev, Likhoded, Onishchenko, 1998	0.430 +/- 0.100	0.110 +/- 0.010	
Kiselev, Likhoded, 2002	0.460 +/- 0.050	0.160 +/- 0.050	0.270 +/- 0.060
Guberina, Melic, Stefancic, 1998	1.050	0.200	0.300
Chang, Li, Li, Wang, 2007	0.670	0.250	0.210

$$\tau_{\Xi_{cc}^{++}} = 0.256 \pm^{0.024}_{0.022} \pm^{0.014}_{0.014} \text{ ps}$$

THE bqq ($q=u,d,s$) BARYONS (B=1, C=0)

Notation	Quark content	J^P	SU(3)	(I, I_3)	S	B
Λ_b	$b[ud]$	$1/2^+$	3^*	$(0, 0)$	0	1
Ξ_b^0	$b[su]$	$1/2^+$	3^*	$(1/2, 1/2)$	-1	1
Ξ_b^-	$b[sd]$	$1/2^+$	3^*	$(1/2, -1/2)$	-1	1
Σ_b^+	buu	$1/2^+$	6	$(1, 1)$	0	1
Σ_b^0	$b\{ud\}$	$1/2^+$	6	$(1, 0)$	0	1
Σ_b^-	bdd	$1/2^+$	6	$(1, -1)$	0	1
$\Xi_b^{0'}$	$b\{su\}$	$1/2^+$	6	$(1/2, 1/2)$	-1	1
$\Xi_b^{-'}$	$b\{sd\}$	$1/2^+$	6	$(1/2, -1/2)$	-1	1
Ω_b^-	bss	$1/2^+$	6	$(0, 0)$	-2	1
Σ_b^{*+}	buu	$3/2^+$	6	$(1, 1)$	0	1
Σ_b^{*0}	bud	$3/2^+$	6	$(1, 0)$	0	1
Σ_b^{*-}	bdd	$3/2^+$	6	$(1, -1)$	0	1
Ξ_b^{*0}	bus	$3/2^+$	6	$(1/2, 1/2)$	-1	1
Ξ_b^{*-}	bds	$3/2^+$	6	$(1/2, -1/2)$	-1	1
Ω_b^{*-}	bss	$3/2^+$	6	$(0, 0)$	-2	1

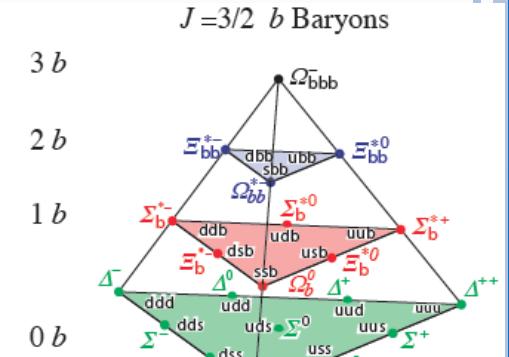
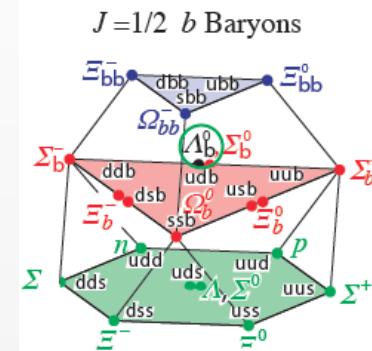


Missing states before LHC era

“Spin excited states”

THE bqq ($q=u,d,s$) BARYONS (B=1, C=0)

Notation	Quark content	J^P	SU(3)	(I, I_3)	S	B
Λ_b	$b[ud]$	$1/2^+$	3^*	$(0, 0)$	0	1
Ξ_b^0	$b[su]$	$1/2^+$	3^*	$(1/2, 1/2)$	-1	1
Ξ_b^-	$b[sd]$	$1/2^+$	3^*	$(1/2, -1/2)$	-1	1
Σ_b^+	buu	$1/2^+$	6	$(1, 1)$	0	1
Σ_b^0	$b\{ud\}$	$1/2^+$	6	$(1, 0)$	0	1
Σ_b^-	bdd	$1/2^+$	6	$(1, -1)$	0	1
$\Xi_b^{0'}$	$b\{su\}$	$1/2^+$	6	$(1/2, 1/2)$	-1	1
$\Xi_b^{-'}$	$b\{sd\}$	$1/2^+$	6	$(1/2, -1/2)$	-1	1
Ω_b^-	bss	$1/2^+$	6	$(0, 0)$	-2	1
Σ_b^{*+}	buu	$3/2^+$	6	$(1, 1)$	0	1
Σ_b^{*0}	bud	$3/2^+$	6	$(1, 0)$	0	1
Σ_b^{*-}	bdd	$3/2^+$	6	$(1, -1)$	0	1
Ξ_b^{*0}	bus	$3/2^+$	6	$(1/2, 1/2)$	-1	1
Ξ_b^{*-}	bds	$3/2^+$	6	$(1/2, -1/2)$	-1	1
Ω_b^{*-}	bss	$3/2^+$	6	$(0, 0)$	-2	1



Still missing states
because soft gamma/pi0
involving in the decays

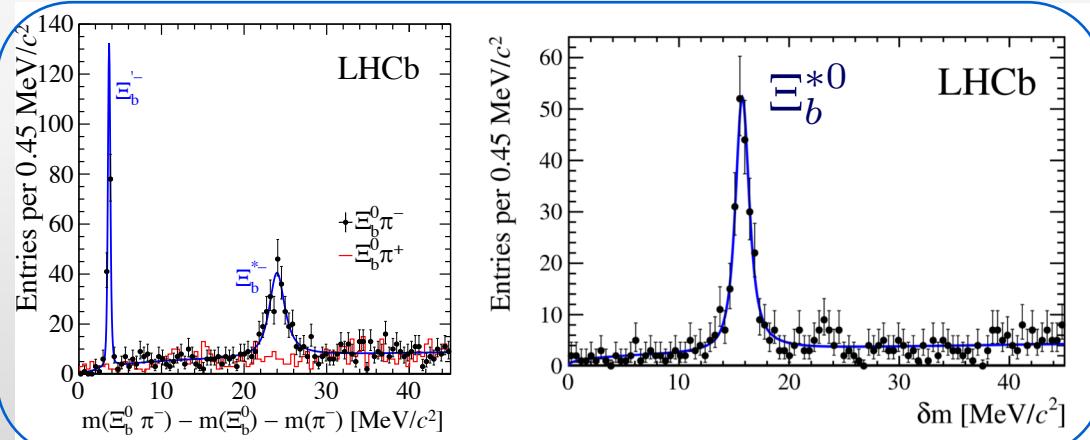
“Spin excited states”

BEAUTY BARYON SPECTROSCOPY

- ✓ Filling the gaps of the missing ground states
- ✓ First observation of excited beauty baryons

[PRL 114 (2015) 062004, JHEP 05 (2016) 161]

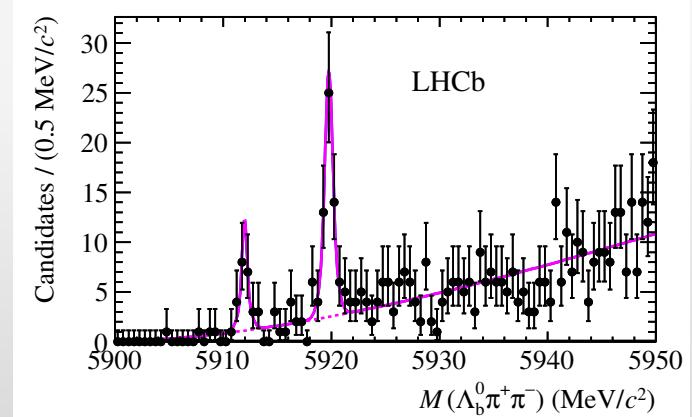
$$\Xi_b^{**} \rightarrow \Xi_b \Pi, \text{ where } \Xi_b \rightarrow \Xi_c \Pi$$



Three narrow peaks interpreted as Ξ_b^{*-} ($J^P = 1/2^+$),
 Ξ_b^{*+} ($J^P = 3/2^+$), Ξ_b^{*0} ($J^P = 3/2^+$)

[PRL 109 (2012) 172003]

$$\Lambda_b^{**0} \rightarrow \Lambda_b^0 \Pi^+ \Pi^-, \text{ where } \Lambda_b^0 \rightarrow \Lambda_c^+ \Pi^-$$



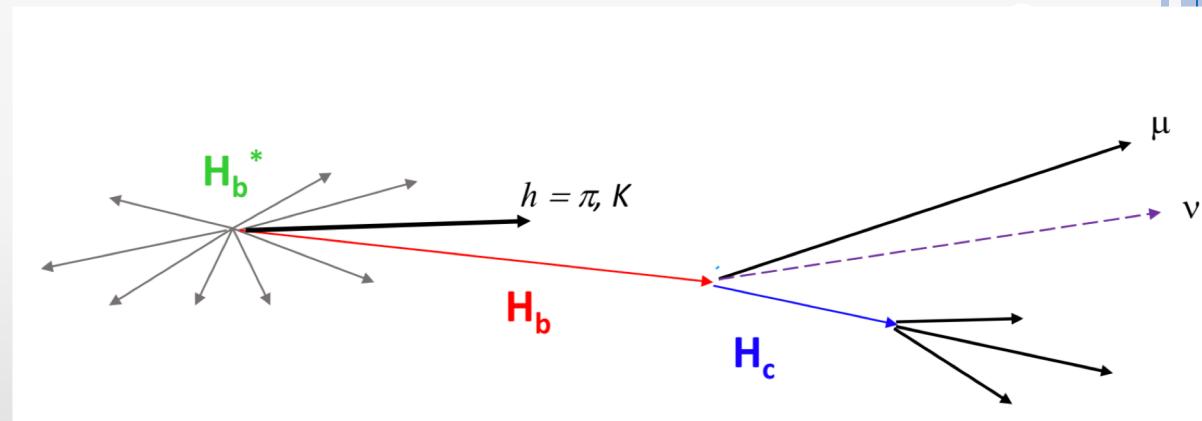
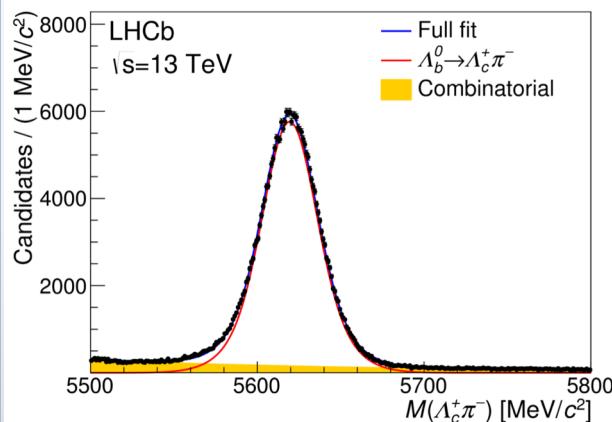
Two new peaks are interpreted as the
orbitally L=1 excited Λ_b^0 states

OBSERVATION OF A NEW Ξ_B^- RESONANCE

LHCb
THCP

[arXiv:1805.09418]

- Dataset: 1.0 fb^{-1} (7 TeV) + 2.0 fb^{-1} (8 TeV) 1.5 fb^{-1} (13 TeV)
- Mass Spectra:
- ✓ $\Lambda_b^0 K^-$, where $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ (Fully reconstructed)
- ✓ $\Lambda_b^0 K^-$, where $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \nu$ (Semileptonic)
- ✓ $\Xi_b^0 \pi^-$, where $\Xi_b^0 \rightarrow \Xi_c^+ \mu^- \nu$ (Semileptonic)
- ✓ Semileptonic decays featured by BR's 10-20 times larger



\mathbf{p}_ν estimated by assuming it is carried by a zero-mass particle that balances the momentum transverse to the direction of Λ_b^0/Ξ_b^0 state and constraining the invariant mass of the system to the nominal Λ_b^0/Ξ_b^0 mass

OBSERVATION OF A NEW Ξ_b^- RESONANCE

LHCb
THCP

[arXiv:1805.09418]

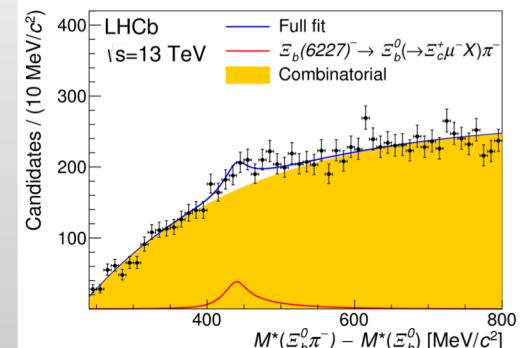
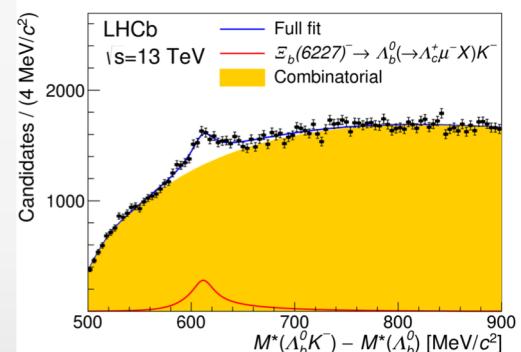
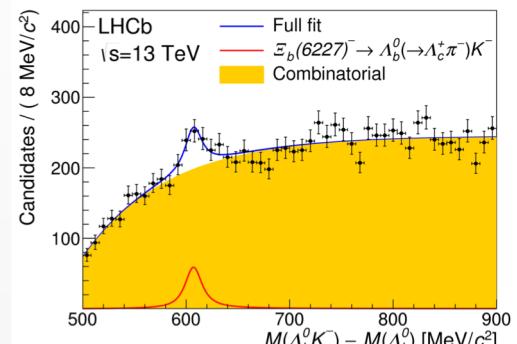
$$m_{\Xi_b(6227)^-} = 6226.9 \pm 2.0_{\text{stat}} \pm 0.3_{\text{syst}} \pm 0.2(\Lambda_b^0) \text{ MeV}/c^2$$

$$\Gamma_{\Xi_b(6227)^-} = 18.1 \pm 5.4_{\text{stat}} \pm 1.8_{\text{syst}} \text{ MeV}/c^2$$

Production rates of two decay modes relative to Λ_b^0/Ξ_b^0

Quantity [10 ⁻³]	7, 8 TeV	13 TeV
$R(\Lambda_b^0 K^-)$	$3.0 \pm 0.3 \pm 0.4$	$3.4 \pm 0.3 \pm 0.4$
$R(\Xi_b^0 \pi^-)$	$47 \pm 10 \pm 7$	$22 \pm 6 \pm 3$

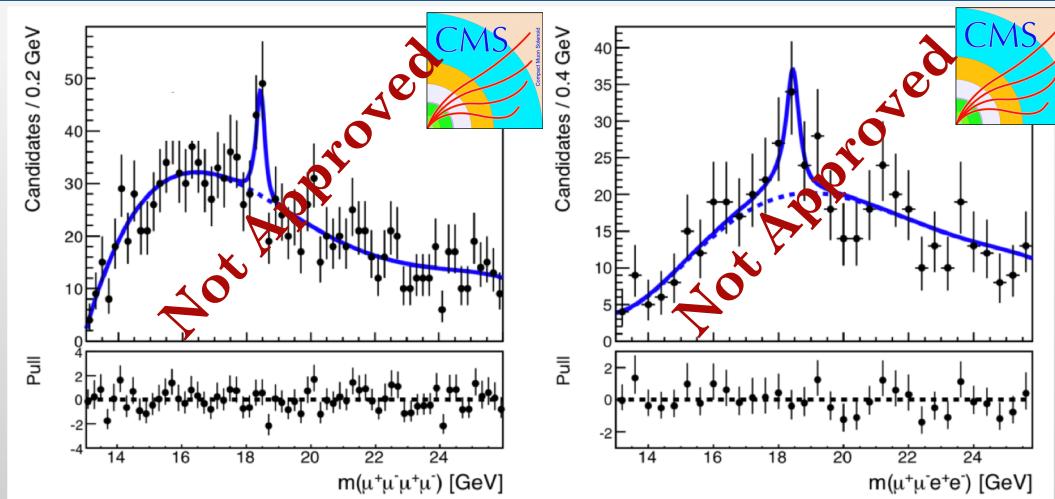
- Branching ratio ~ 1 assuming $f_{\Xi_b 0} \sim 0.1 f_{\Lambda_b 0}$
- New state could be $\Xi_b(1P)^-$ or $\Xi_b(2S)^-$



SEARCH FOR X_{bbbb}

[LHCb-PAPER-2018-027]

- Recently several predictions for an exotic state with quark composition bbbb with a mass below, the $2^*m(\eta_b)$ threshold, which implies that it can decay to $\Upsilon(1S)\mu^+\mu^-$
- Rumours about the observation of a peak at ~ 18 GeV at ATLAS/CMS
- However lattice QCD calculations do not find evidence for such a state in the hadron spectrum [PRD 97 (2018) 054505]
- Given the presence of four muons in the final state, LHCb has a large sensitivity into observing the first exotic state composed of more than two heavy quarks

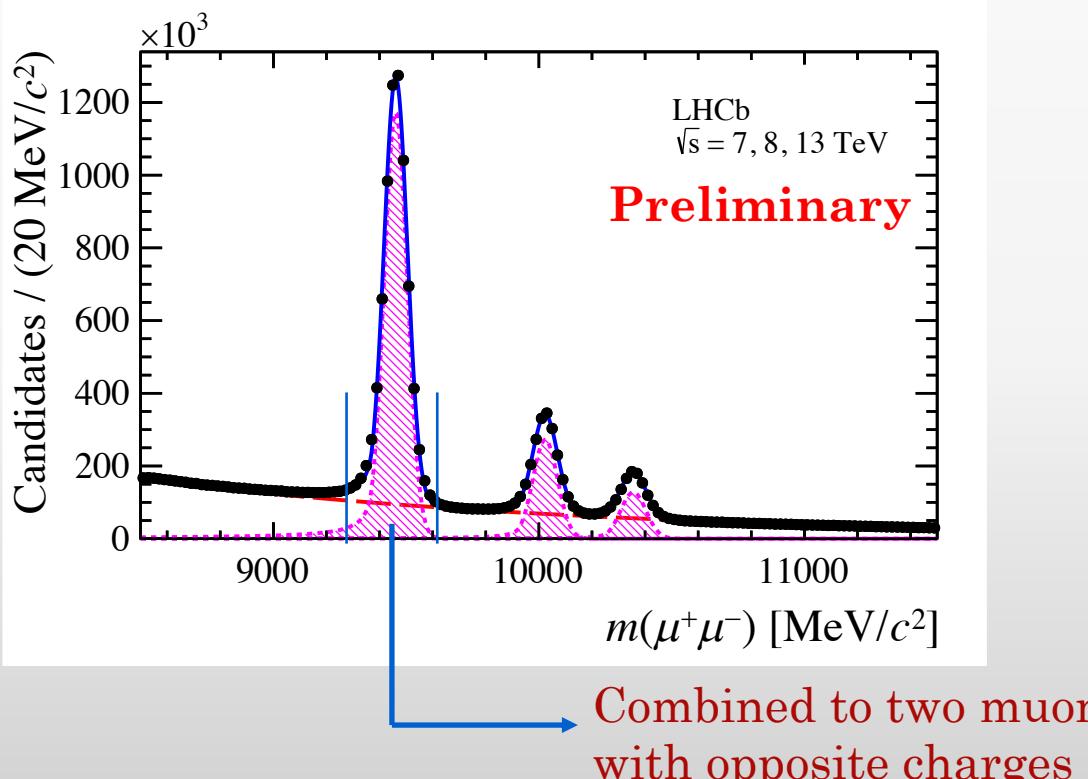


https://absuploads.aps.org/presentation/upload/APR18/U09/APR18-2018-001130/presentation14072_oenvhvnehnzhz.pdf

SEARCH FOR X_{bbbb}

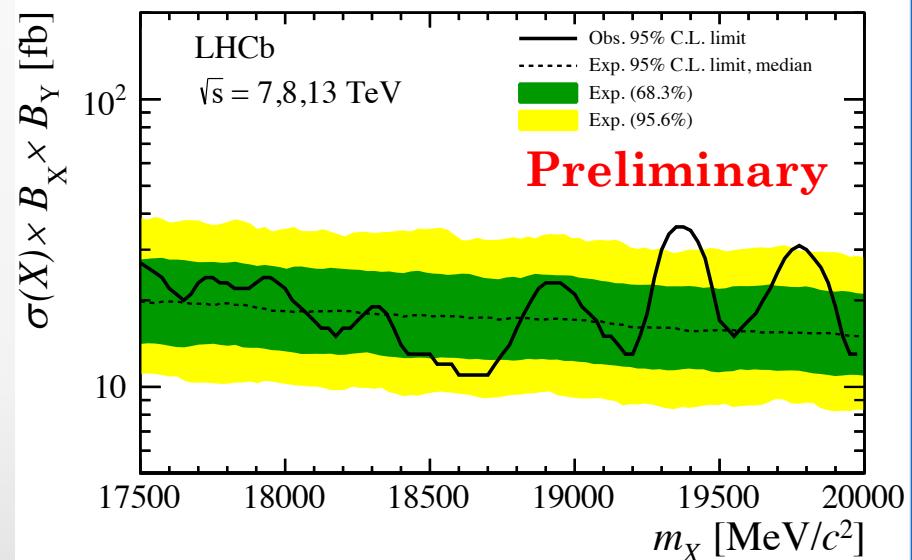
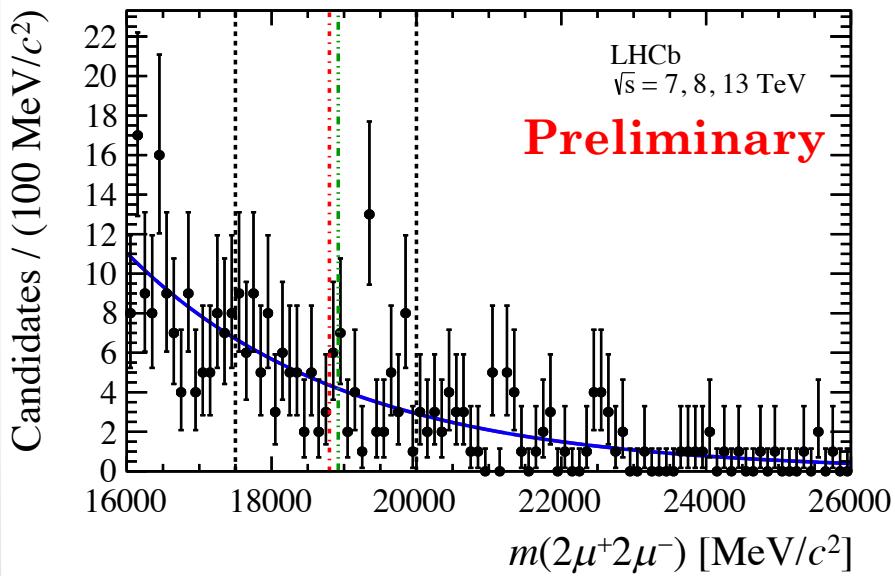
[LHCb-PAPER-2018-027]

- Dataset: 6.0 fb^{-1} (2011 → 2017!)



SEARCH FOR X_{bbbb}

[LHCb-PAPER-2018-027]



No significant excess is seen at any mass hypothesis $\in [16-26] \text{ GeV}$

PLANS & PROSPECTS

LHCb GOING TO UPGRADE

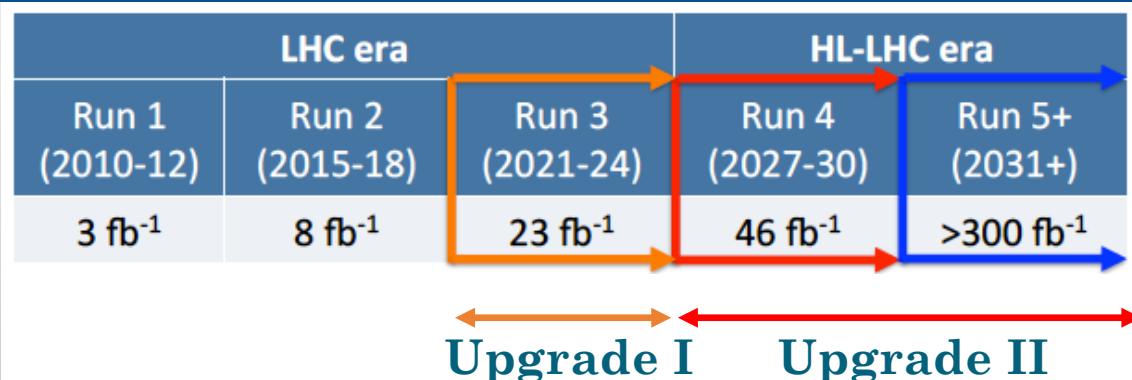
Upgrade I

- Main limitation that prevents exploiting higher luminosity with the present detector is the Level-0 (hardware) trigger
 - ✓ – Level-0 output rate < 1 MHz (readout rate) requires raising thresholds
- This is particularly problematic for hadronic final states
- Running at $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ with full software trigger, running at 40 MHz

Upgrade II

To be installed in Long Shutdown 4 of the LHC:

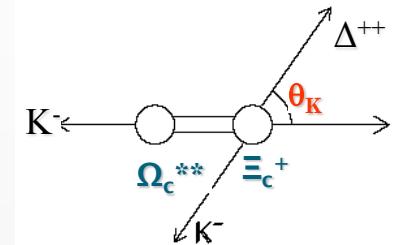
- Subsystems redesigned to operate at a luminosity of $1\text{-}2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- Integrated luminosity of $> 300 \text{ fb}^{-1}$
- Extension of the experiment's capabilities into selecting π^0 , η and low-momentum tracks



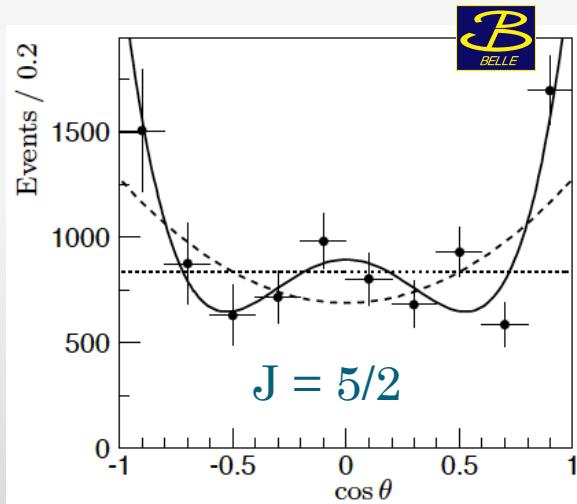
EXCITED Ω_c^0 : DETERMINATION OF SPIN J

(E.g.) Decay chain $\Omega_c^{**} \rightarrow \Xi_c (\rightarrow \Delta^{++} K^- \text{ or } pK^*) K$

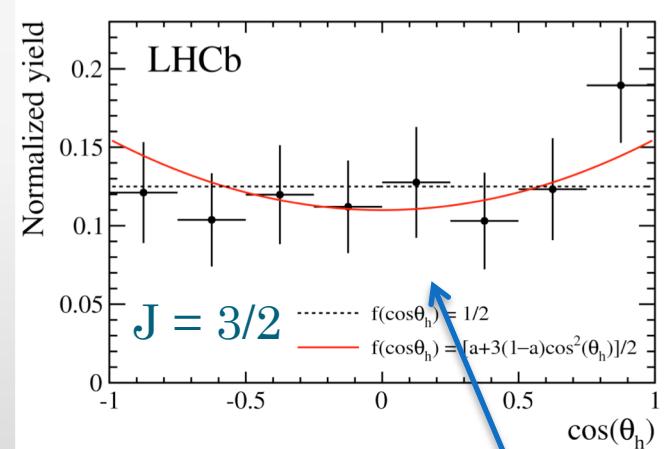
Helicity angle θ_K distributions may be used to distinguish between spin hypotheses for resonances.



$\Lambda_c(2880)^+ \rightarrow \Sigma_c(2455) (\rightarrow \Lambda_c \pi) \pi$
[Belle:Phys. Rev. Lett. 98 (2007) 262001]



$\Xi_b^{*-} \rightarrow \Xi_b^0 (\rightarrow \Xi_c^+ \pi^-) \pi^-$
[LHCb:Phys. Rev. Lett. 114 (2015) 062004]

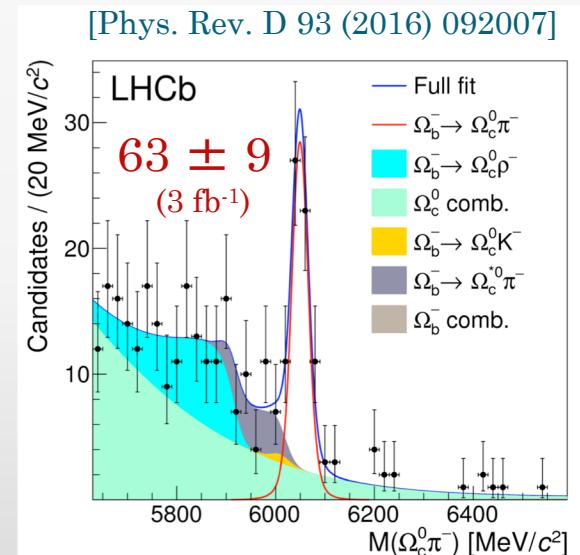
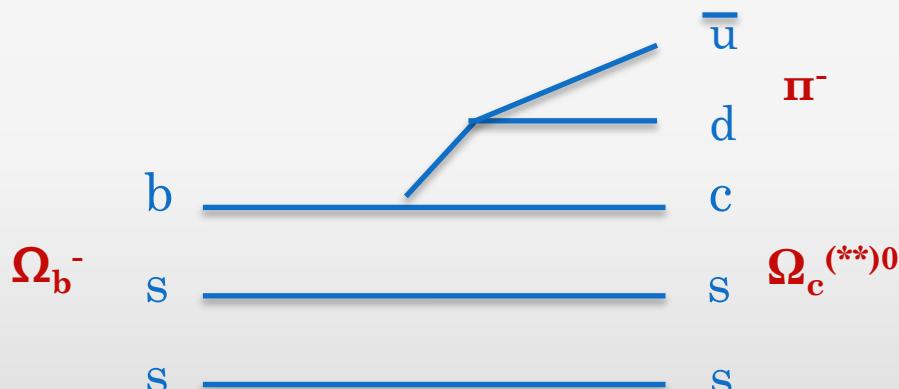


The method is not sensitive to the parity
(neither to the spin if the resonances are produced unpolarized)

EXCITED Ω_c^0 : DETERMINATION OF SPIN-(PARITY?) J^P

Study of Ω_c^{**} in fully reconstructed decays: (e.g.) $\Omega_b^- \rightarrow \Xi_c^+ K^- \pi^-$

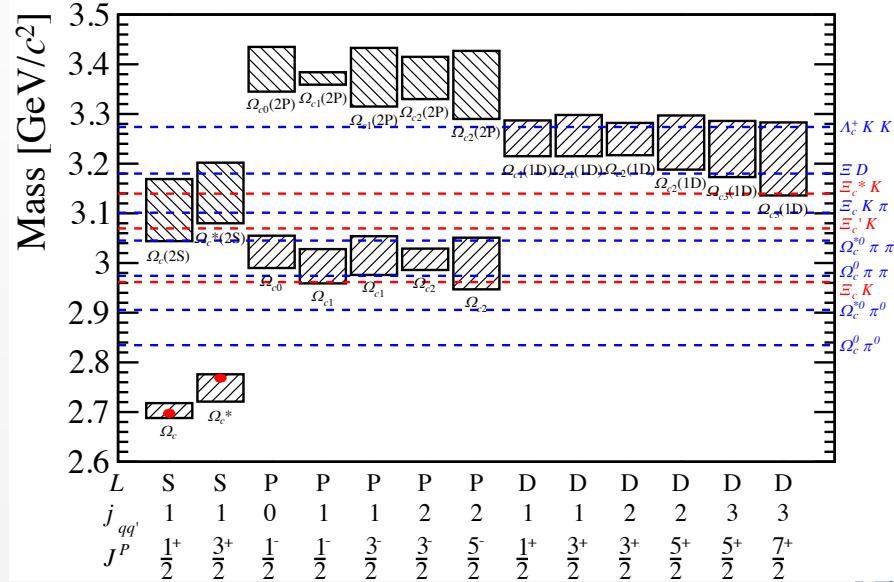
The decays $\Omega_b^- \rightarrow \Omega_c^0 (\rightarrow p K K \pi) \pi^-$ already observed.
Same number and type of tracks in the final state



- ✓ Angular distributions might slightly affected by $\Xi_c^{**0} \rightarrow \Xi_c^+ \pi^-$
- ✓ No resonances expected in the $K^- \pi^-$ system

EXCITED Ω_c^0 : PROBING THEIR NATURE

The nature of Ω_c^{**0} states can be probed by looking for new decay modes which can constrain the quantum numbers as well



✓ $\Omega_c^0 \pi^+ \pi^-$ and $\Omega_c^0 \gamma$

Cabibbo suppressed decays $\Omega_c^0 \rightarrow p K K \pi$ are suitable to these searches. Low efficiency due to the large number of tracks or presence of a photon

✓ Search for isospin-partner pentaquarks

- Search for exotic $\Omega_c^{**-} \rightarrow \Xi_c^0 K^-$ by $\Xi_c^0 \rightarrow p K K \pi$
- Similar selection to $\Omega_c^{**0} \rightarrow \Xi_c^+ K^-$

DOUBLY HEAVY BARYONS

- Observations of two missing weakly decaying Ξ_{cc}^+ and Ω_{cc} expected with RUN II data or during the upcoming Upgrade I
- The Phase II upgrade will be useful into studying their differential production and excited spectra: Ξ_{cc}^{**} and Ω_{cc}^{**}

	LHCb Upgrade II (300 fb ⁻¹)	Belle II (50 ab ⁻¹)
$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$	90k	< 6k

WHAT ABOUT Ξ_{bc} ?

- The B_c meson was discovered almost two decades ago
In LHCb, $\sim 5000 B_c \rightarrow J/\psi \pi$ in Run I

So, why have we not yet seen bcq baryons (Ξ_{bc})?

Lower production rates, guess $\sigma(X_{bc}) \sim (0.1 - 0.5) \times \sigma(B_c^+)$

In J/ψ modes, (usually) get a charm baryon: yield reduced by $BF(X_c) \times \epsilon_{\text{sel}}(X_c)$
Shorter lifetime ($\sim 0.15 - 0.4$ ps range, compared to ~ 0.5 ps for B_c)

$$\begin{aligned} (\text{e.g.}) N(\Xi_{bc}^0 \rightarrow J/\psi \Lambda_c^+ K^-; \text{Run1}) &= N(B_c^+ \rightarrow J/\psi D_s^{(*)+}; \text{Run1}) \\ &\times \frac{\sigma(pp \rightarrow \Xi_{bc} X)}{\sigma(pp \rightarrow B_c^+ X)} \times f_{\Xi_{bc} \rightarrow \Xi_{bc}^0} \\ &\times \frac{Br(\Xi_{bc}^0 \rightarrow J/\psi \Lambda_c^+ K^-)}{Br(B_c^+ \rightarrow J/\psi D_s^{(*)+})} \\ &\times \epsilon_{K^-} \\ &\simeq 3 \text{ candidates} \end{aligned}$$

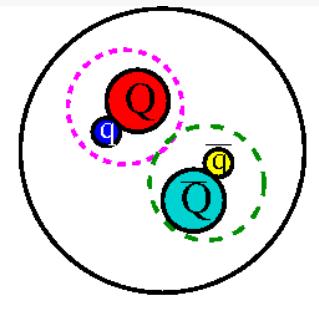
$$N(\Xi_{bc}^0 \rightarrow J/\psi \Lambda_c^+ K^-; \text{Run 5}) \simeq 6 \times 10^2$$

DOUBLY CHARMED TETRAQUARK: $cc\bar{q}\bar{q}$

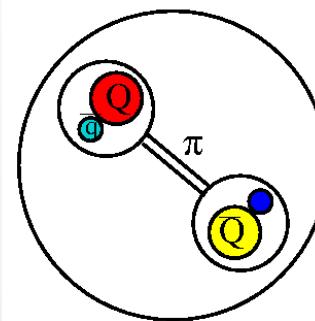
[A. Esposito et al.: PRD 88 (2013) 054029]

- Observation of several hadronic resonances with hidden charm or beauty (so called X, Y, Z states) in the last decade at LHC and B-factories
- They barely fit into the standard quarkonium scenarios and “exotic” interpretations have been proposed

Tetraquark



Loosely bound molecules



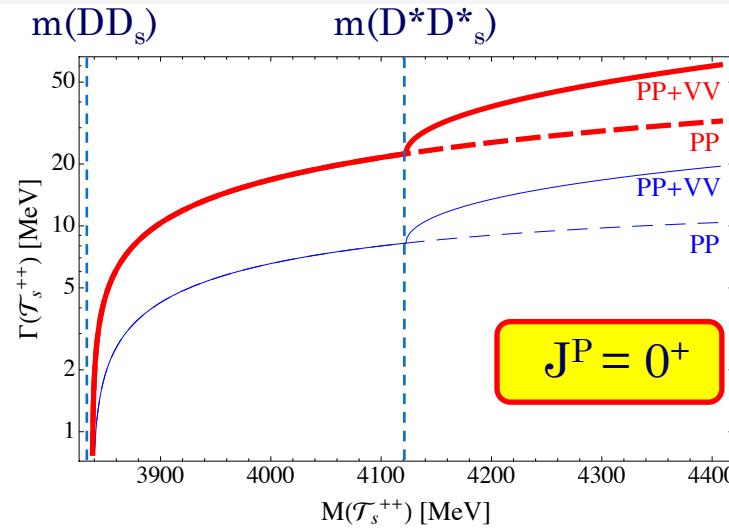
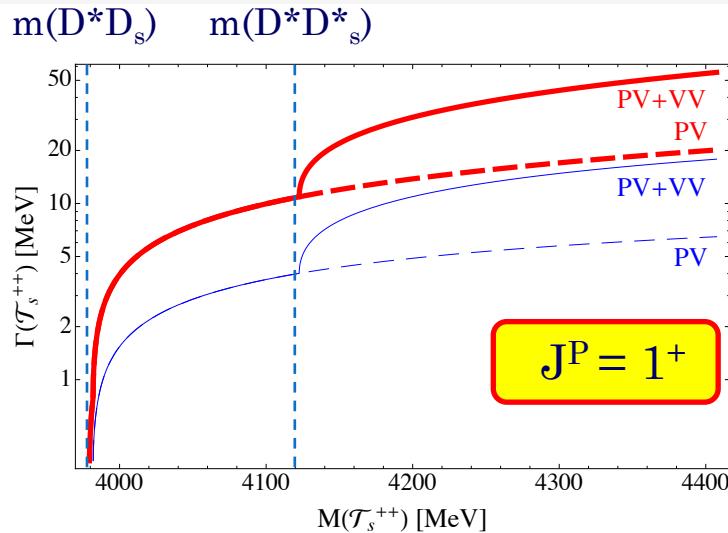
- Doubly charmed particles are a straightforward consequence
- If discovered, they would be almost full-proof states made of 4 quarks

- Observation of doubly charged states would be even more important to understand their nature: indeed in a loosely bound molecule, Coulomb repulsion would induce a fall-apart decay on very short time scales

DOUBLY CHARMED TETRAQUARK: $cc\bar{q}\bar{q}$

[A. Esposito et al.: PRD 88 (2013) 054029]

- If the masses of such states are below the DD thresholds \rightarrow strong decays are forbidden and weak decay pattern would be complicated
- If the masses are above the DD thresholds, pure tetraquark models predict (narrow) states with quantum numbers $J^P = 0^+, 1^+$ and 2^+
- 0^+ and 1^+ states expected to be the lighter and more likely to be formed (and observed)

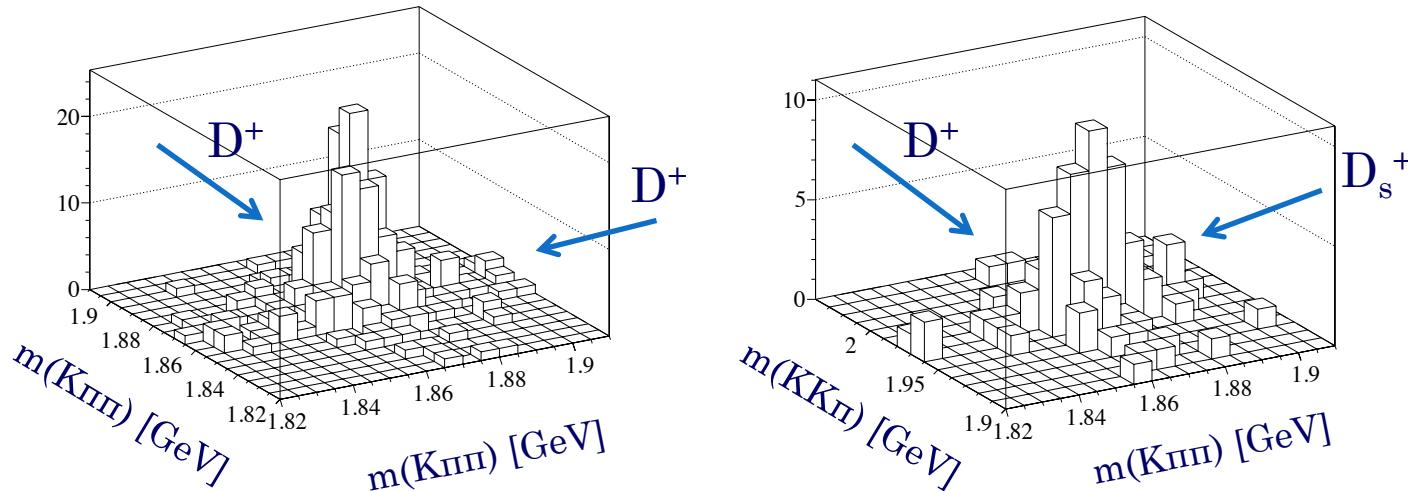


Natural widths as predicted by a pure tetraquark model

DOUBLY CHARMED TETRAQUARK IN PROMPT PRODUCTION

Narrow states could be easily spotted in the prompt production

Associated production of D^+D^+ and $D^+D_s^+$ (0.3 fb^{-1})



[LHCb: JHEP 06 (2012) 141]

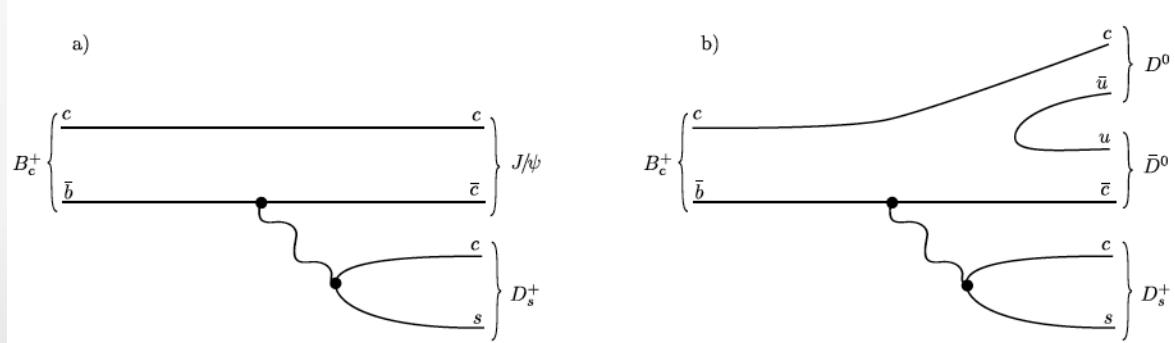
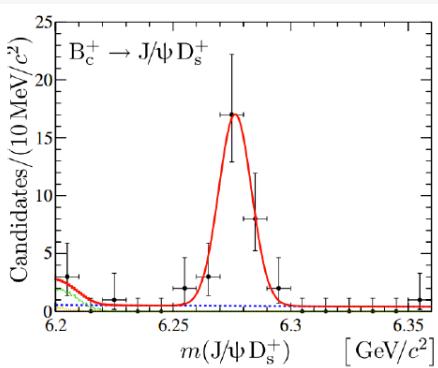
$$N(D^+D^+; \text{Run5}) \simeq 750\text{k candidates}$$

$$N(D^+D_s^+; \text{Run5}) \simeq 150\text{k candidates}$$

DOUBLY CHARMED TETRAQUARK IN B_c DECAYS

- If the states are broad-ish → Search for them in B_c decays where the quantum numbers can be also measured
- The B_c meson is the lightest state in the standard model that can decay to two same-flavour charmed hadrons.
- Search for tetraquark: $\mathcal{T}_s^+(cc\bar{u}\bar{s}) \rightarrow D^0 D_s^+$

[LHCb: PRD 87 (2013) 112012]



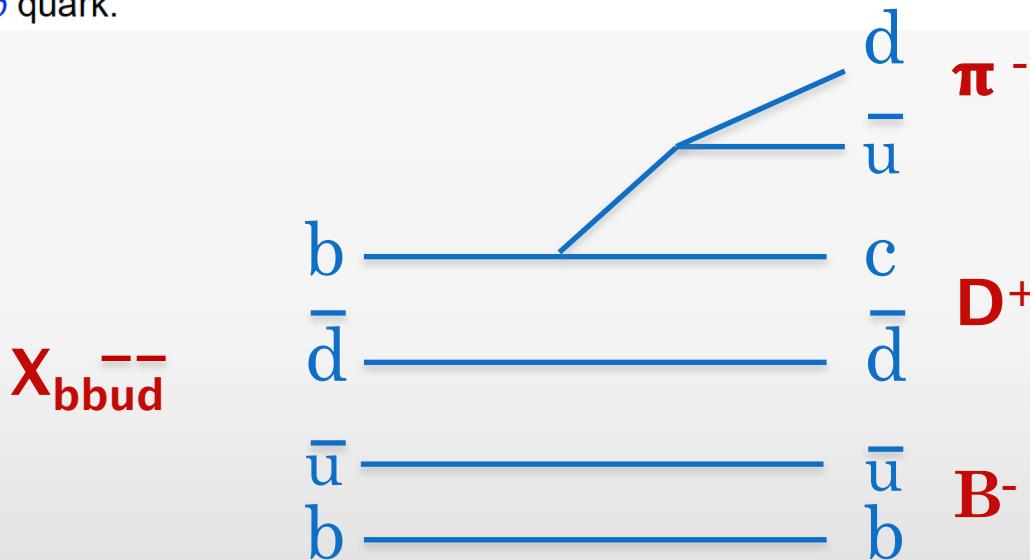
$$N = 28.9 \pm 5.6 \text{ (3 fb}^{-1}\text{)}$$

$$N(B_c^+ \rightarrow D^0 \bar{D}^0 D_s^+; \text{Run5}) \simeq 10^2 \text{ candidates}$$

Clear signature. Expected to be background free.
Three pseudoscalars in the final state

SEARCH A STABLE 1^{++} $b\bar{b}ud$ TETRAQUARK

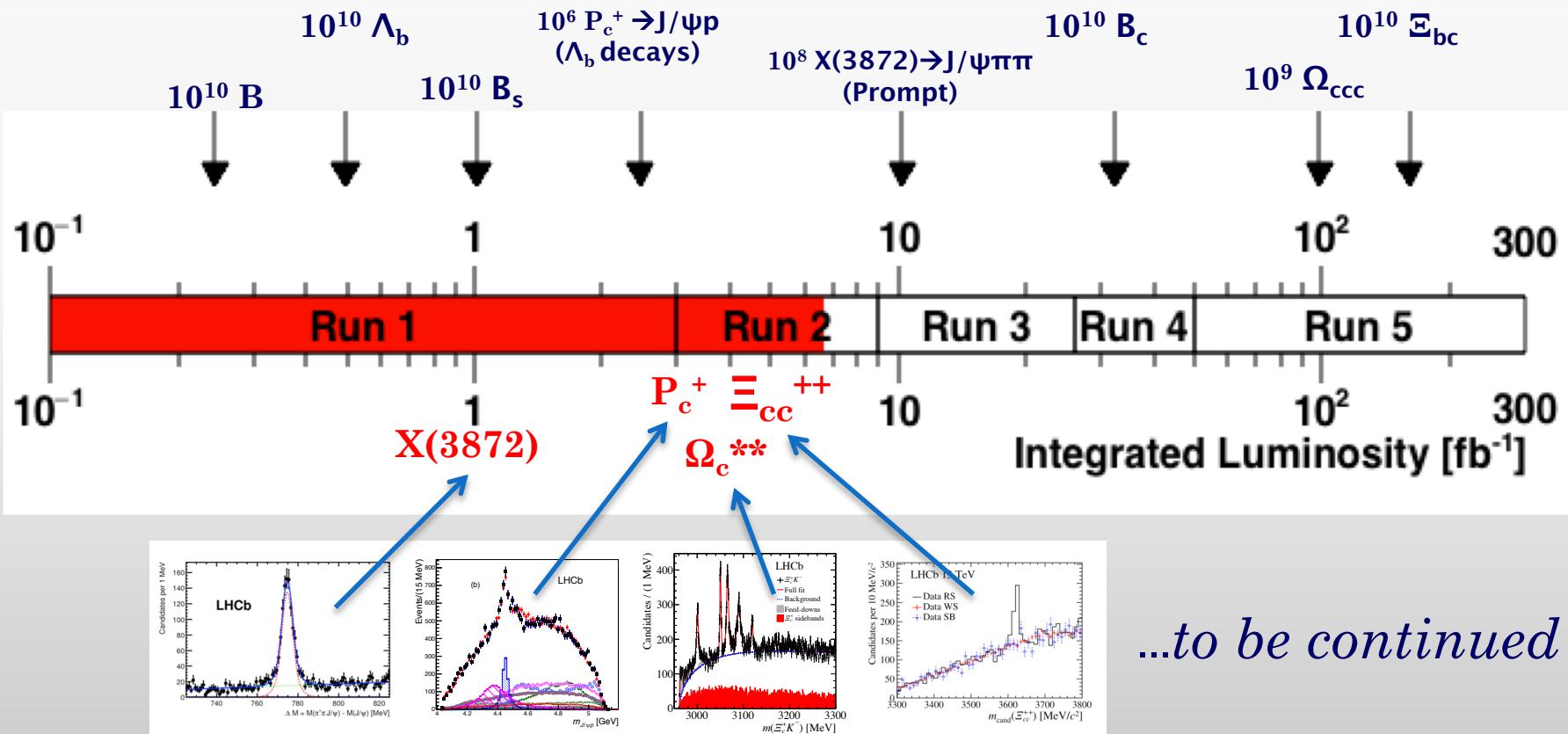
- It would have observable lifetime, thus combinatorial background would be under control
- CMS claimed observation of 38 ± 7 ($\gamma \rightarrow \mu^+ \mu^-$) $(\gamma \rightarrow \mu^+ \mu^-)$ events ($b\bar{b} + b\bar{b}$) in 21 fb^{-1} of 8 TeV data JHEP 1705, 013 (2017).
- Unfortunately bbq baryons have not been detected yet, reflecting low prompt production rates expected for both b quarks to end up in the same hadron, and difficulty in reconstruction of two subsequent weak decays of b quark.



- Inclusive reconstructive efficiencies for B mesons are low at LHCb due to low branching fractions into low multiplicity final states
- Not promising even for Upgrade II!

SUMMARY

- Excited Ω_c^{**0} : Opportunity of studying the fine and hyperfine structure of the heavy baryons
- Observation of the first doubly heavy baryon Ξ_{cc}^{++} !
- The large data set collected, together with an upgraded detector, will boost sensitivity in searches for heavy states with small production cross sections and/or small decay rates

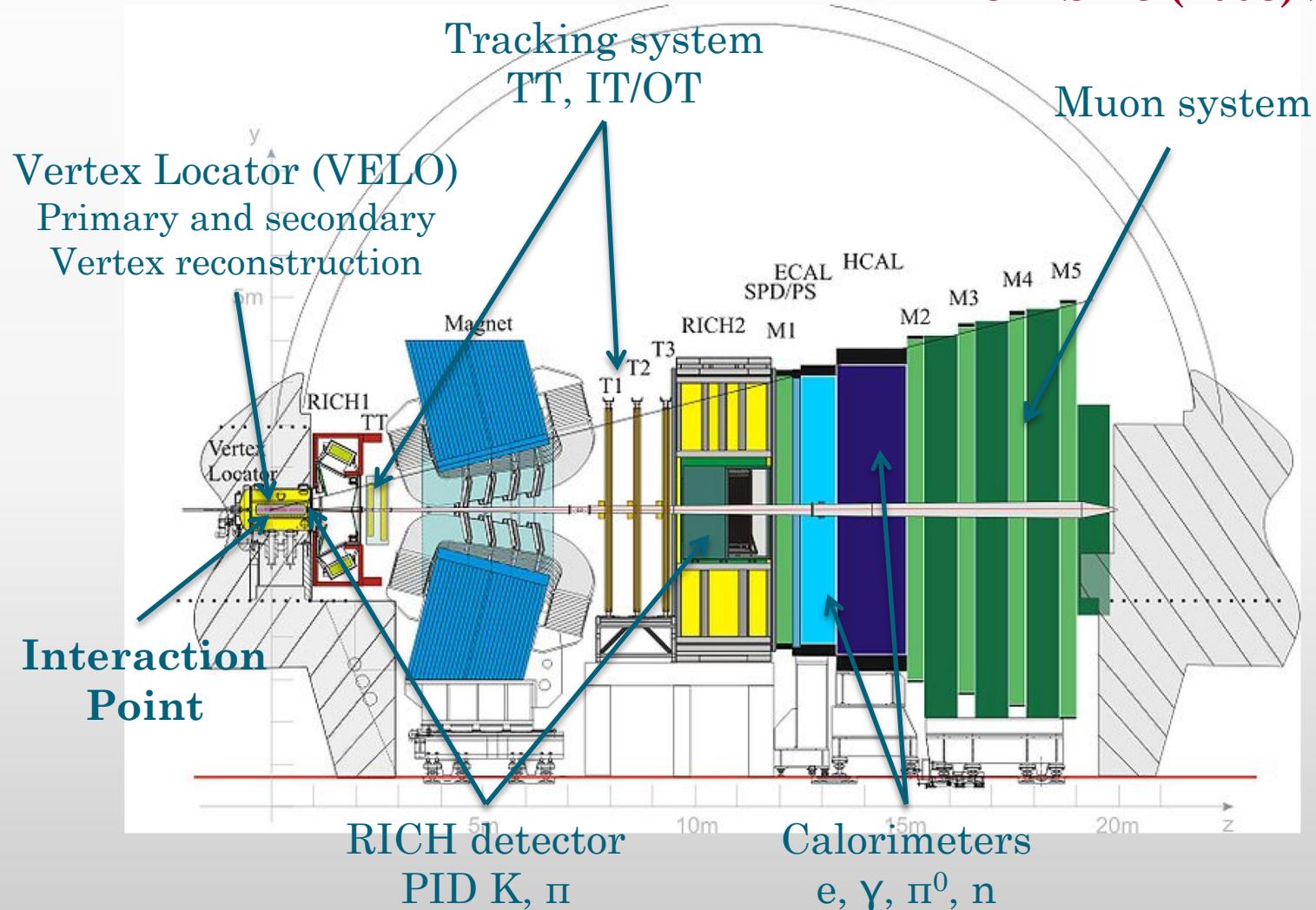




BACK UP

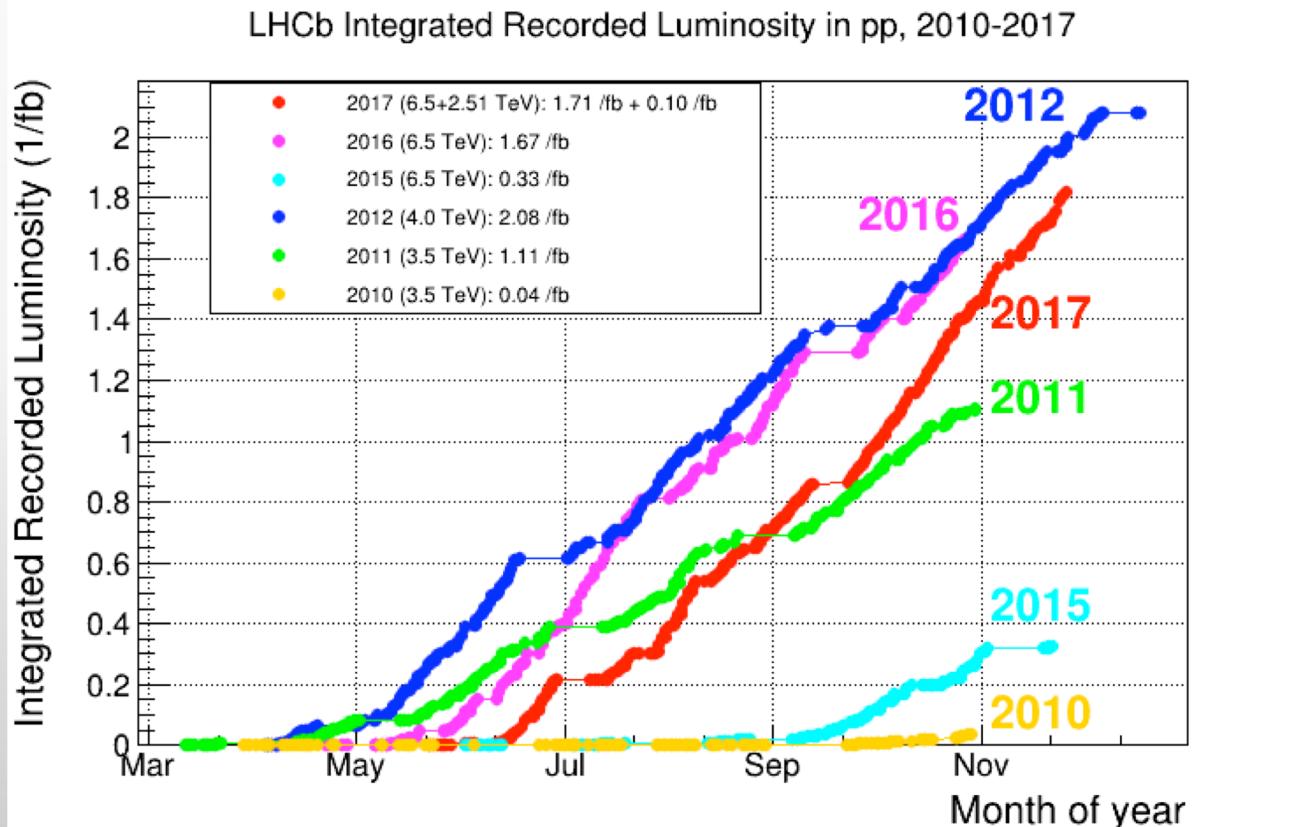
THE LHCb DETECTOR

JINST 3 (2008) S08005



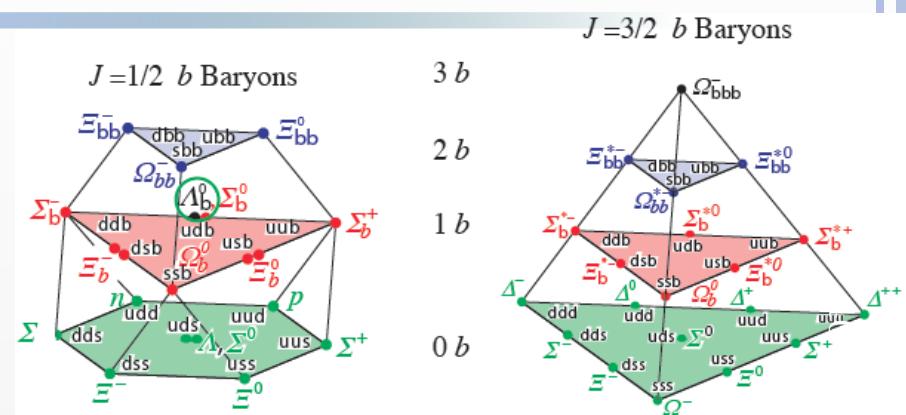
DATASETS

LHCb has just doubled the RUN I (2010-2012) dataset.
So far 1 fb^{-1} at 7 TeV + 2 fb^{-1} at 8 TeV + 3.7 fb^{-1} at 13 TeV



THE bqq ($q=u,d,s$) BARYONS (B=1, C=0)

Notation	Quark content	J^P	SU(3)	(I, I_3)	S	B
Λ_b	$b[ud]$	$1/2^+$	3^*	$(0, 0)$	0	1
Ξ_b^0	$b[su]$	$1/2^+$	3^*	$(1/2, 1/2)$	-1	1
Ξ_b^-	$b[sd]$	$1/2^+$	3^*	$(1/2, -1/2)$	-1	1
Σ_b^+	buu	$1/2^+$	6	$(1, 1)$	0	1
Σ_b^0	$b\{ud\}$	$1/2^+$	6	$(1, 0)$	0	1
Σ_b^-	bdd	$1/2^+$	6	$(1, -1)$	0	1
$\Xi_b^{0'}$	$b\{su\}$	$1/2^+$	6	$(1/2, 1/2)$	-1	1
$\Xi_b^{-'}$	$b\{sd\}$	$1/2^+$	6	$(1/2, -1/2)$	-1	1
Ω_b^-	bss	$1/2^+$	6	$(0, 0)$	-2	1
Σ_b^{*+}	buu	$3/2^+$	6	$(1, 1)$	0	1
Σ_b^{*0}	bud	$3/2^+$	6	$(1, 0)$	0	1
Σ_b^{*-}	bdd	$3/2^+$	6	$(1, -1)$	0	1
Ξ_b^{*0}	bus	$3/2^+$	6	$(1/2, 1/2)$	-1	1
Ξ_b^{*-}	bds	$3/2^+$	6	$(1/2, -1/2)$	-1	1
Ω_b^{*-}	bss	$3/2^+$	6	$(0, 0)$	-2	1



The system of baryons containing a b quark remains largely unexplored, despite recent progress made at the experiments at the Tevatron

Missing states

“Spin excited states”

SEARCH FOR $\Sigma_b^{(*)0} \rightarrow \Lambda_b^0 \pi^0$

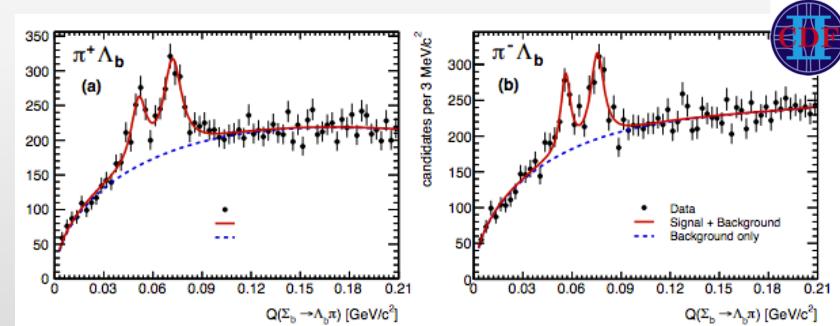


Notation	Quark content	J^P	SU(3)	(I, I_3)	S	B
Λ_b	$b[ud]$	$1/2^+$	3^*	$(0, 0)$	0	1
Ξ_b^0	$b[su]$	$1/2^+$	3^*	$(1/2, 1/2)$	-1	1
Ξ_b^-	$b[sd]$	$1/2^+$	3^*	$(1/2, -1/2)$	-1	1
Σ_b^+	buu	$1/2^+$	6	$(1, 1)$	0	1
Σ_b^0	$b\{ud\}$	$1/2^+$	6	$(1, 0)$	0	1
Σ_b^-	bdd	$1/2^+$	6	$(1, -1)$	0	1
$\Xi_b^{0'}$	$b\{su\}$	$1/2^+$	6	$(1/2, 1/2)$	-1	1
$\Xi_b^{-'}$	$b\{sd\}$	$1/2^+$	6	$(1/2, -1/2)$	-1	1
Ω_b^-	bss	$1/2^+$	6	$(0, 0)$	-2	1
Σ_b^{*+}	buu	$3/2^+$	6	$(1, 1)$	0	1
Σ_b^{*0}	bud	$3/2^+$	6	$(1, 0)$	0	1
Σ_b^{*-}	bdd	$3/2^+$	6	$(1, -1)$	0	1
Ξ_b^{*0}	bus	$3/2^+$	6	$(1/2, 1/2)$	-1	1
Ξ_b^{*-}	bds	$3/2^+$	6	$(1/2, -1/2)$	-1	1
Ω_b^{*-}	bss	$3/2^+$	6	$(0, 0)$	-2	1

$$m(\Sigma_b^0) \sim 5813 \text{ MeV}$$

$$m(\Sigma_b^{*0}) \sim 5833 \text{ MeV}$$

- Large Λ_b sample available
- Suppression of background is challenging, even more than $\Sigma_b^{(*)\pm}$



[PRD85 (2012) 092011]



SEARCH FOR Ξ_b' AND Ω_b^*

42

Notation	Quark content	J^P	SU(3)	(I, I_3)	S	B
Λ_b	$b[ud]$	$1/2^+$	3^*	$(0, 0)$	0	1
Ξ_b^0	$b[su]$	$1/2^+$	3^*	$(1/2, 1/2)$	-1	1
Ξ_b^-	$b[sd]$	$1/2^+$	3^*	$(1/2, -1/2)$	-1	1
Σ_b^+	buu	$1/2^+$	6	$(1, 1)$	0	1
Σ_b^0	$b\{ud\}$	$1/2^+$	6	$(1, 0)$	0	1
Σ_b^-	bdd	$1/2^+$	6	$(1, -1)$	0	1
$\Xi_b^{0'}$	$b\{su\}$	$1/2^+$	6	$(1/2, 1/2)$	-1	1
$\Xi_b^{-'}$	$b\{sd\}$	$1/2^+$	6	$(1/2, -1/2)$	-1	1
Ω_b^-	bss	$1/2^+$	6	$(0, 0)$	-2	1
Σ_b^{*+}	buu	$3/2^+$	6	$(1, 1)$	0	1
Σ_b^{*0}	bud	$3/2^+$	6	$(1, 0)$	0	1
Σ_b^{*-}	bdd	$3/2^+$	6	$(1, -1)$	0	1
Ξ_b^{*0}	bus	$3/2^+$	6	$(1/2, 1/2)$	-1	1
Ξ_b^{*-}	bds	$3/2^+$	6	$(1/2, -1/2)$	-1	1
Ω_b^{*-}	bss	$3/2^+$	6	$(0, 0)$	-2	1

$$\Xi_b' - \Xi_b \sim 120 \text{ MeV}$$



$$\mathcal{B}(\Xi_b' \rightarrow \Xi_b \gamma) \sim 100\%$$

$$\Omega_b^* - \Omega_b \sim 20 \text{ MeV}$$



$$\mathcal{B}(\Omega_b^* \rightarrow \Omega_b \gamma) \sim 100\%$$

- Soft photon → Low efficiency
- Small Ω_b sample

LIGHT BARYON SPECTROSCOPY

- The poor knowledge of the light sector (Λ^* , N^* , etc...) has had a large impact on the amplitude analyses aiming to the search for the pentaquarks
- LHCb can contribute to study the spectroscopy of the light sector as well

