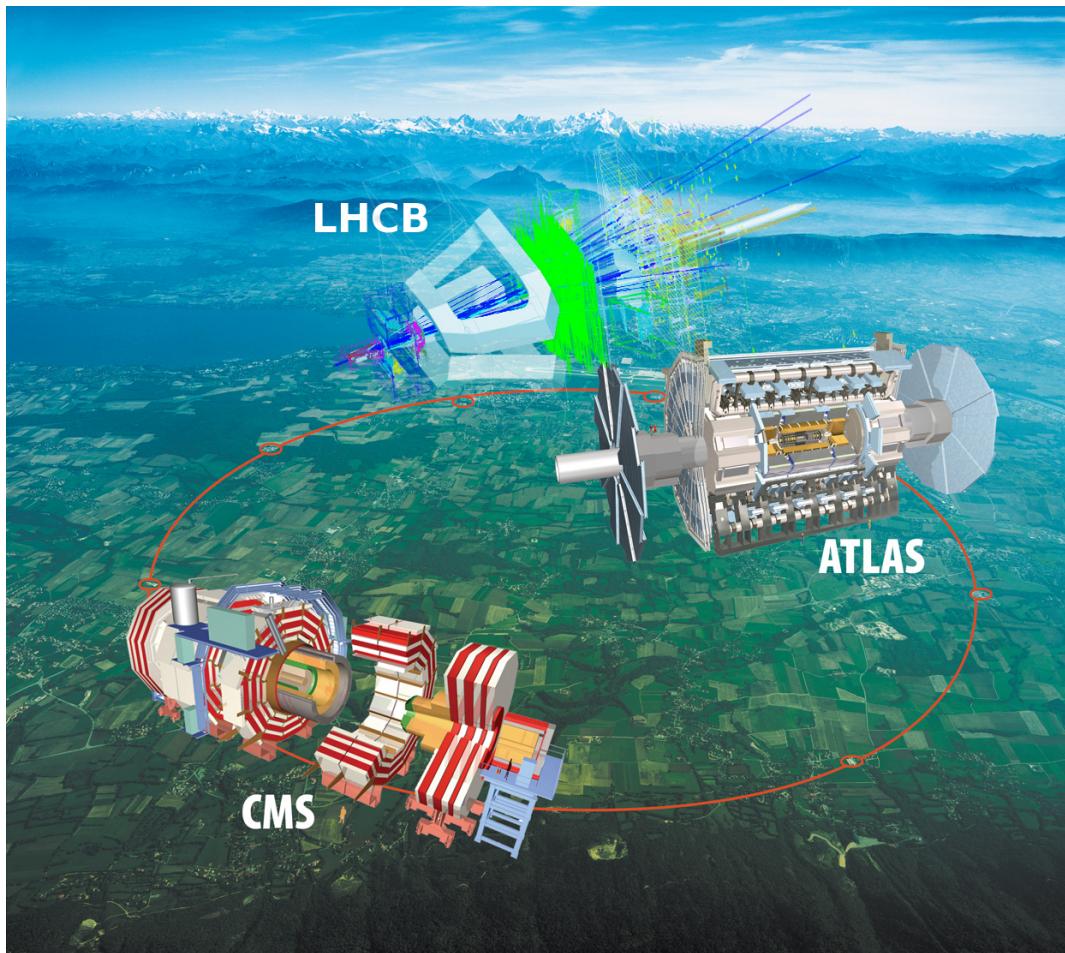


# Spectroscopy of open Heavy Flavour states with emphasis on $B_c$ and $b$ -baryons



Giacomo Graziani (INFN Firenze)

on behalf of the LHCb Collaboration  
including results from ATLAS and CMS

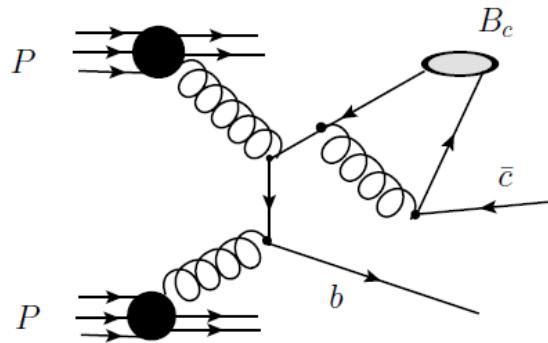


Rencontres du Vietnam 2014  
Physics at LHC and beyond  
Quy-Nhon, Vietnam  
August 13, 2014

Produced hadrons within LHCb acceptance  
during Run I ( $3.0 \text{ fb}^{-1}$ ):

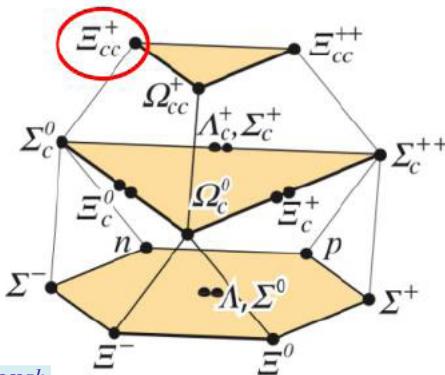
$D^0/\bar{D}^0$	$\sim 4500 \times 10^9$
$B^0/\bar{B}^0$	$\sim 150 \times 10^9$
$\Lambda_b/\bar{\Lambda}_b$	$\sim 90 \times 10^9$
$B_c^\pm$	$\approx 0.9 \times 10^9$

# Outline



## B baryons

- Lifetime, and mass, for  $\Lambda_b$ ,  $\Xi_b^0$ ,  $\Xi_b^-$ ,  $\Omega_b^-$
- Decay modes and CPV

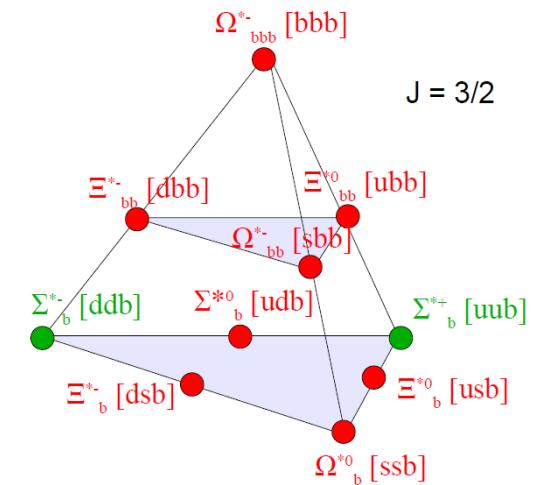
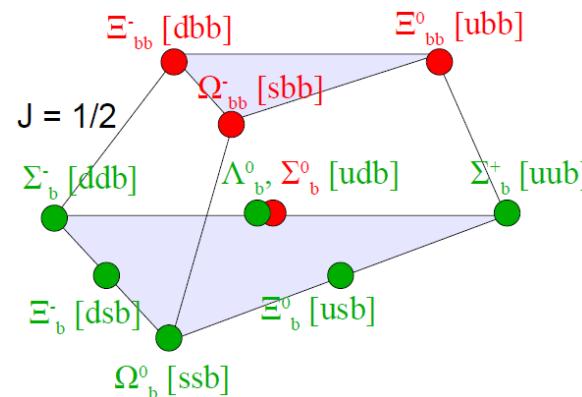


## B and D meson spectroscopy

- New  $D_s^{*-}$  states

## $B_c$ meson

- Mass and lifetime
- Decay modes
- Excited  $B_c$



## Double Heavy baryons

- search for  $\Xi_{cc}$

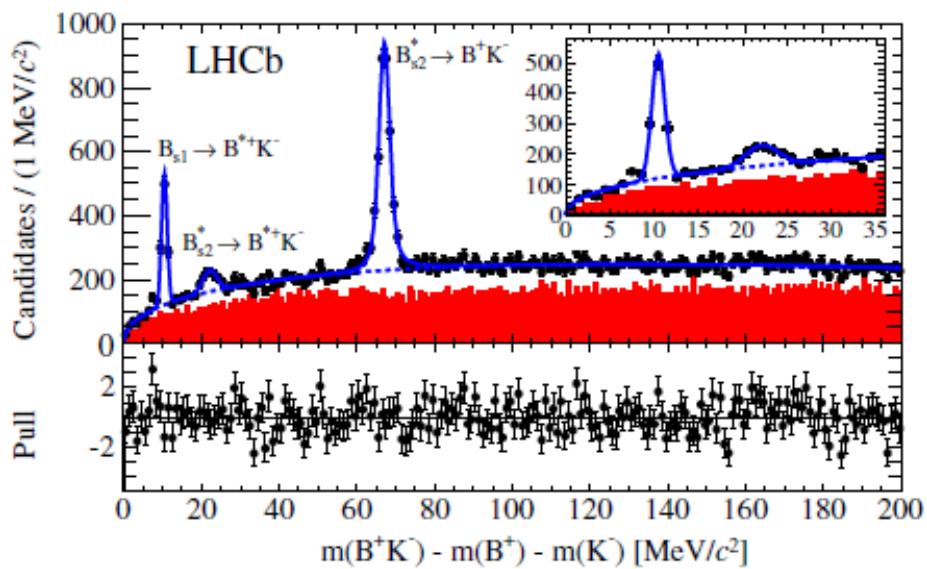
# What to learn from these states

- The theoretical tools developed/used to study production and decays of B mesons and quarkonia (NRQCD, HQET, QCD sum rules, light front quark model, HQE...) can be tested in novel context
- double heavy states offer unique laboratory to study interplay of strong and weak interactions
- spin of baryon allows to probe the helicity structure in  $b$  decays
- Theoretical literature more limited wrt B meson decays
  - some accurate predictions from Heavy Quark Expansion exist for lifetime ratios of  $b$  hadrons
  - for many processes results from different approaches differ
    - measurements needed to probe and tune models
- Some prospects for measuring weak phases and CP violation in  $B_c$  and  $b$ -baryon decays

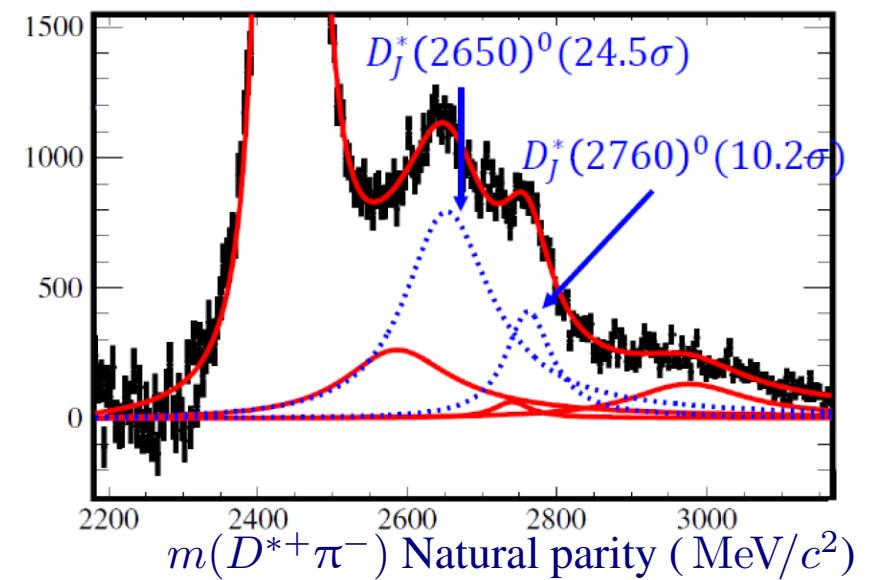
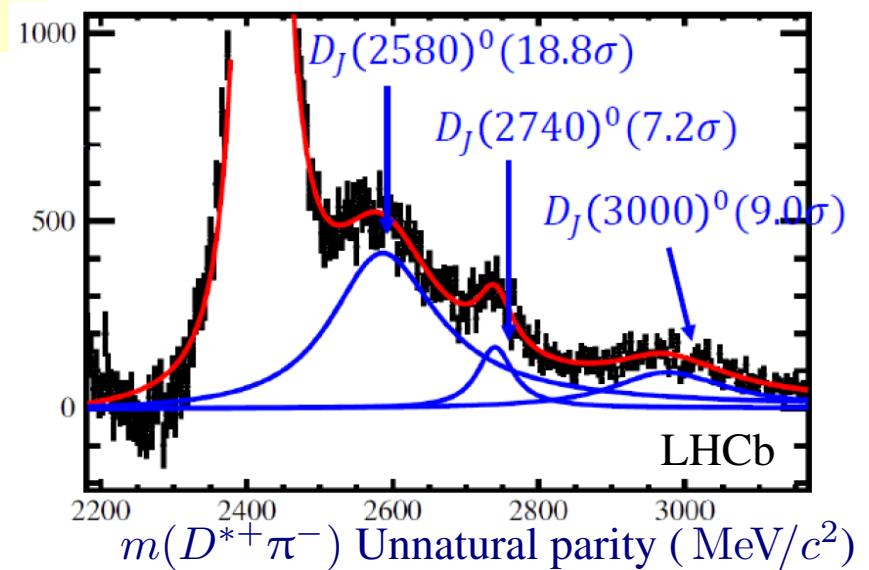
# B and D meson spectroscopy

Though  $B_{(s)}$  and  $D_{(s)}$  meson spectra were already extensively studied before LHC, there's still to learn from Run I data. New excited states and decay modes reported by LHCb.

First observation of the  $B_{s2}^* \rightarrow B^{*+}K^-$  decays and world's best measurement of the  $B_{s1}, B_{s2}^*$  and  $B^*$  masses



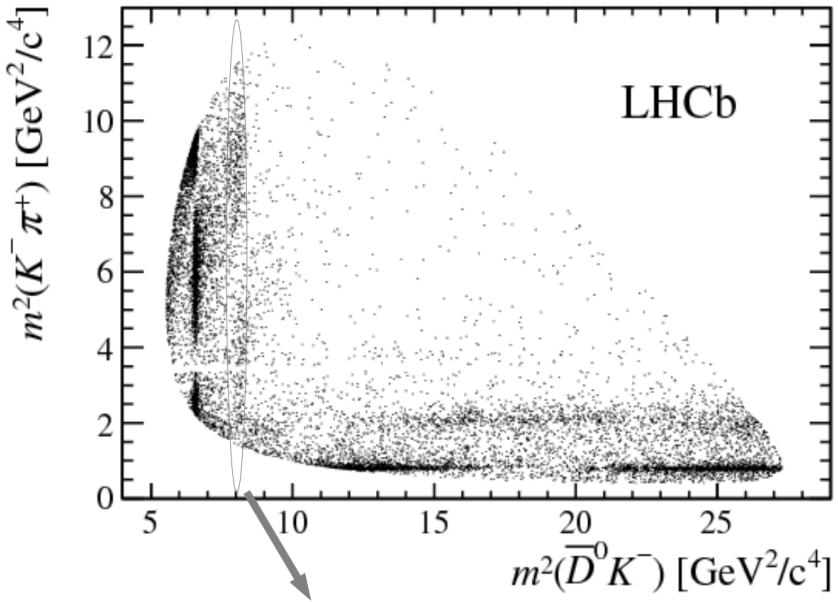
LHCb 1.0 fb<sup>-1</sup> PRL 110 (2013) 151803



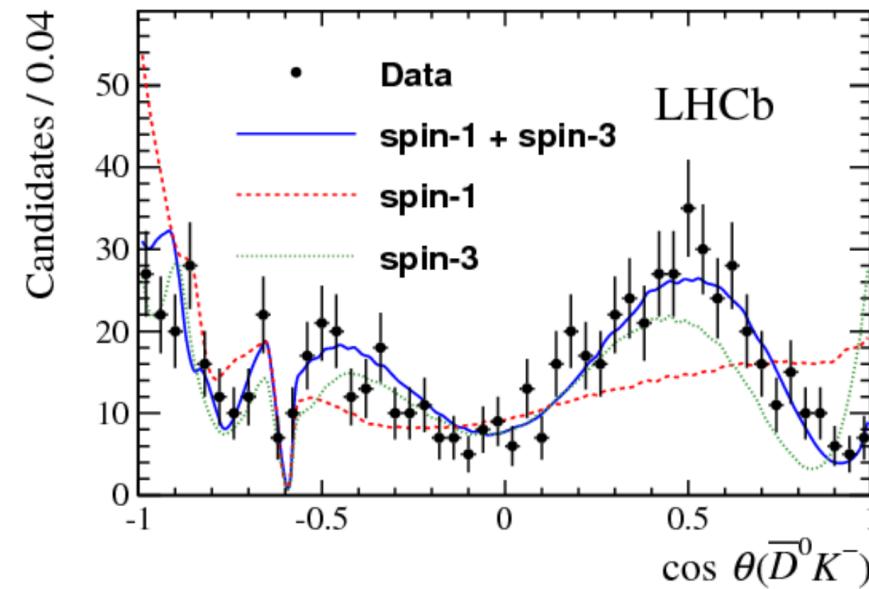
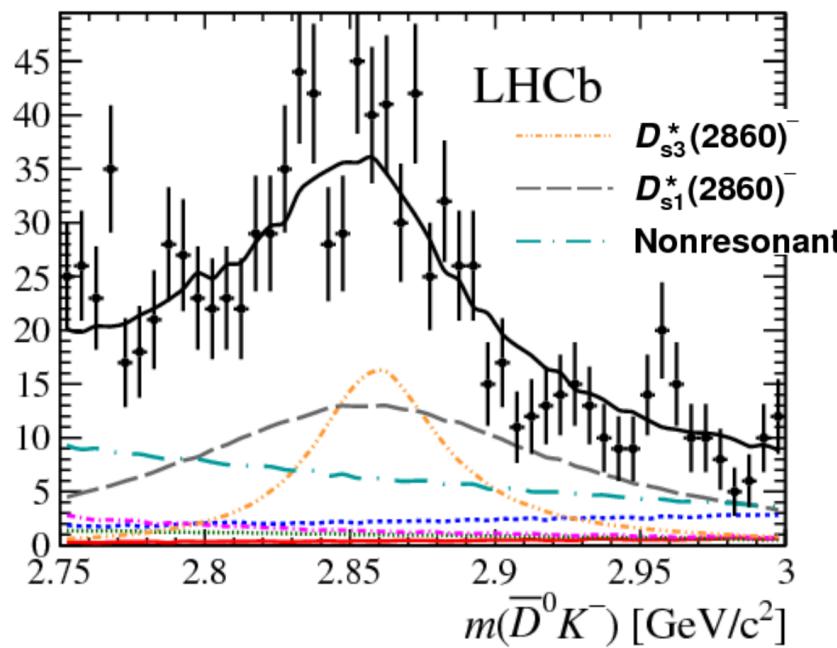
Four D excited states (probably 2S and 1D states) identified, and some structures around 3 GeV (likely 1F states)

LHCb 1.0 fb<sup>-1</sup> JHEP 09 (2013) 145

# $D_s$ meson spectroscopy



- Study of  $\bar{D}^0 K^-$  structures in  $B_s^0 \rightarrow \bar{D}^0 K^- \pi^+$  decays
- Structure at 2860 MeV/ $c^2$  interpreted through angular analysis as superposition of  $J^P = 1^-$  and  $3^-$  states (likely 1D)  
both with significance  $> 10\sigma$
- First observation of a spin 3 heavy hadron!



NEW

LHCb

3.0 fb $^{-1}$

arXiv:1407.7574

arXiv:1407.7712

# The $B_c$ meson

## A unique system in the standard model

- only meson made of two heavy quarks with open flavour
- peculiar production mechanism
- non relativistic system: spectroscopy similar to quarkonium
- decays only through weak interactions

A great "laboratory" for testing QCD-inspired potential models and weak decay mechanism of heavy-quark bound states.

## Pre-LHC knowledge

- discovered at Tevatron (1998) in semileptonic modes significance  $> 5 \sigma$  only with Tevatron Run II (2008)

- only two decay modes observed:

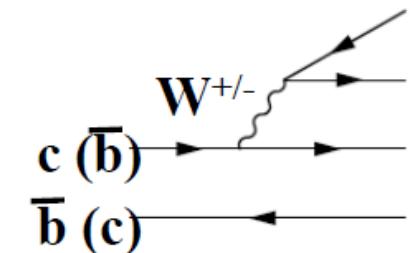
$$B_c^+ \rightarrow J/\psi \ell^+ \nu_\ell$$

$$B_c^+ \rightarrow J/\psi \pi^+$$

- Mass and lifetime measurements (CDF/D0):

6 MeV/ $c^2$  mass uncertainty ( $< 0.3$  MeV/ $c^2$  for other B mesons)

7% uncertainty on the lifetime ( $< 0.7\%$  for other B mesons)



Citation: J. Beringer et al. (Particle Data Group), PR D86, 010001 (2012) (URL: <http://pdg.lbl.gov>)

BOTTOM, CHARMED MESONS ( $B = C = \pm 1$ )			
$B_c^\pm$	$I(J^P) = 0(0^-)$ $I, J, P$ need confirmation.	Quantum numbers shown are quark-model predictions.	
$B_c^+$	$m = 6.277 \pm 0.006$ GeV   ( $S = 1.6$ )		
	Mean life $\tau = (0.453 \pm 0.041) \times 10^{-12}$ s		
$B_c^-$	$B_c^-$ modes are charge conjugates of the modes below.		
$B_c^+$ DECAY MODES $\times B(\bar{b} \rightarrow B_c)$	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$p$ (MeV/c)
The following quantities are not pure branching ratios; rather the fraction $\Gamma_i/\Gamma \times B(\bar{b} \rightarrow B_c)$ .			
$J/\psi(1S) e^+ \nu_\ell$ anything	$(5.2^{+2.4}_{-2.1}) \times 10^{-5}$	–	
$J/\psi(1S) \pi^+$	$< 8.2 \times 10^{-5}$	90%	2372
$J/\psi(1S) \pi^+ \pi^-$	$< 5.7 \times 10^{-4}$	90%	2352
$J/\psi(1S) \eta_1(1260)$	$< 1.2 \times 10^{-3}$	90%	2171
$D^*(2010)^+ \overline{D}^0$	$< 6.2 \times 10^{-3}$	90%	2468

PDG2012

$$\sigma(B_c)_{\text{LHC}} / \sigma(B_c)_{\text{Tevatron}} \sim 10$$

The era of precision  $B_c$  studies started at LHC!

# Measurements using the “easiest” fully reconstructed mode $B_c^+ \rightarrow J/\psi \pi^+$

**$B_c$  mass**



$$M(B_c) = 6273.7 \pm 1.3 \text{ (stat)} \pm 1.6 \text{ (syst)} \text{ MeV}/c^2$$

$0.37 \text{ fb}^{-1}$  PRL 109 (2012) 232001



$$M(B_c) = 6282 \pm 7 \text{ (stat)} \text{ MeV}/c^2$$

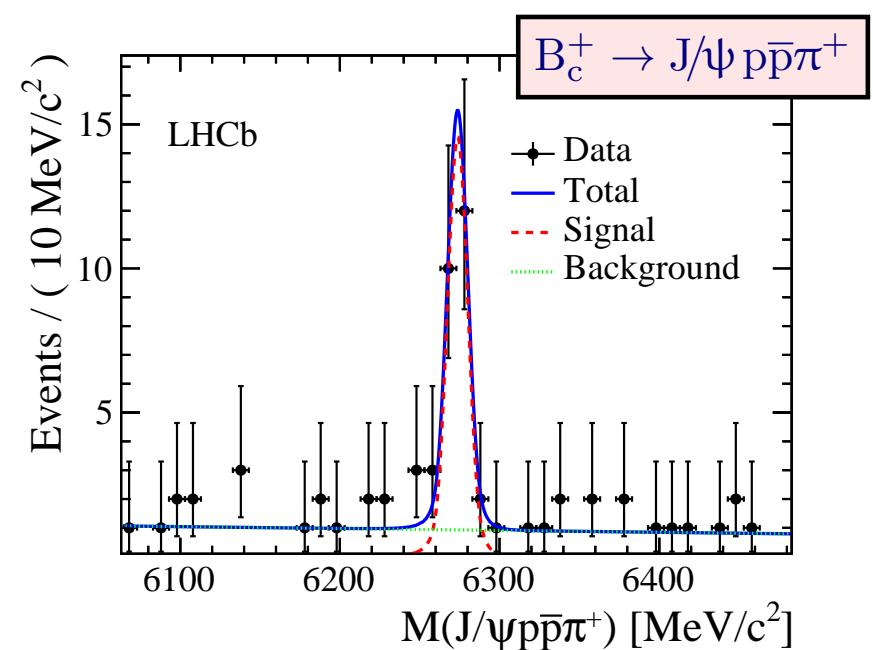
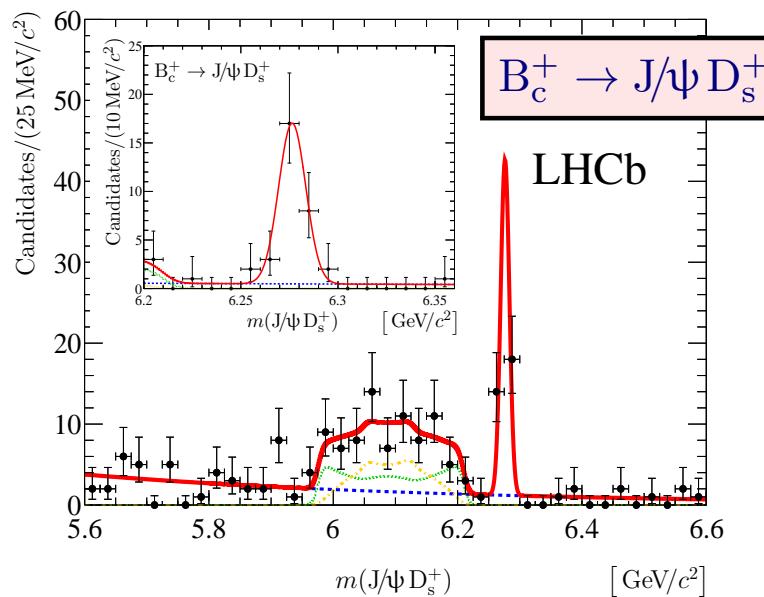
$4.3 \text{ fb}^{-1}$  preliminary ATLAS-CONF-2012-028



$$M(B_c) = 6272 \pm 3 \text{ (stat)} \text{ MeV}/c^2$$

$4.7 \text{ fb}^{-1}$  preliminary CMS-PAS-BPH-11-003

LHCb result limited by systematic uncertainty on momentum scale ( $\pm 3 \times 10^{-4}$ ). Can be improved exploiting decays with lower Q-value:



$$M(B_c) = 6273.28 \pm 1.44 \text{ (stat)} \pm 0.36 \text{ (syst)} \text{ MeV}/c^2$$



$3.0 \text{ fb}^{-1}$  PRD 87 (2013) 112012

✓ syst. uncertainty from momentum scale reduced to 0.30 and 0.40 MeV/ $c^2$  in the two cases



$3.0 \text{ fb}^{-1}$  arXiv:1408.0971

New LHCb average  $M(B_c) = 6274.7 \pm 1.2 \text{ MeV}/c^2$

Measured at LHCb using partially reconstructed semileptonic decays

$$B_c^+ \rightarrow J/\psi (\mu^+ \mu^-) \mu^+ \nu_\mu X$$

- ✓ High rate: BR is  $\sim 20 \times$  BR( $J/\psi \pi^+$ )
- ✓ Clean  $3 - \mu$  signature: trigger/selection possible without bias on decay time

Need to account for uncertainties from

- ✗ signal decay model and feed-downs (missing kinematics)
- ✗ backgrounds from  $B$  decays with particle misidentification

$\sim 9000$  candidates selected with moderate background. Statistics allow to constrain the main uncertainties using data.

Lifetime obtained from fit to 2D distribution decay time vs  $M(J/\psi \mu)$

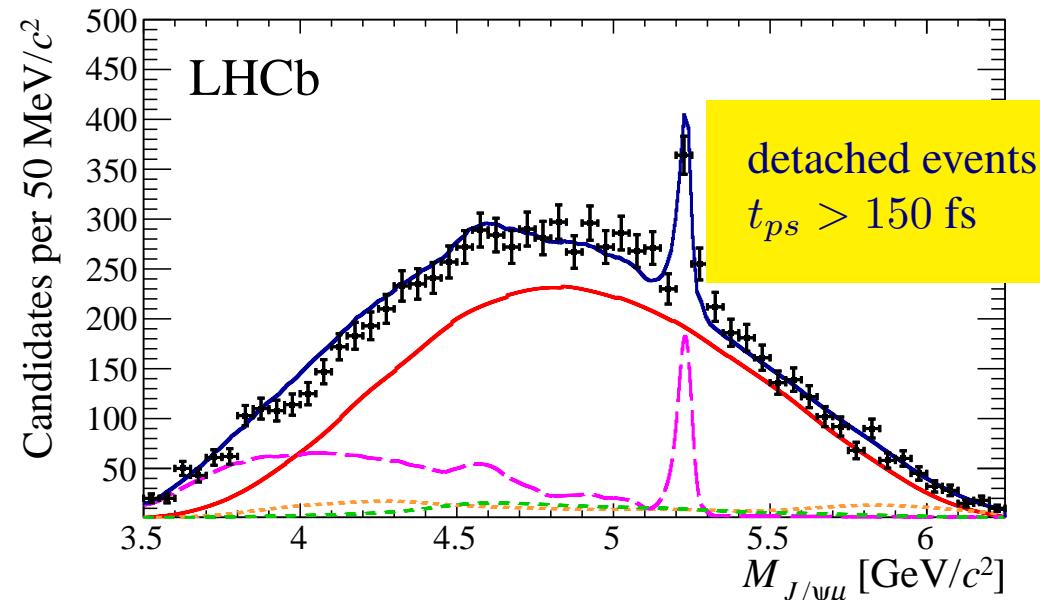
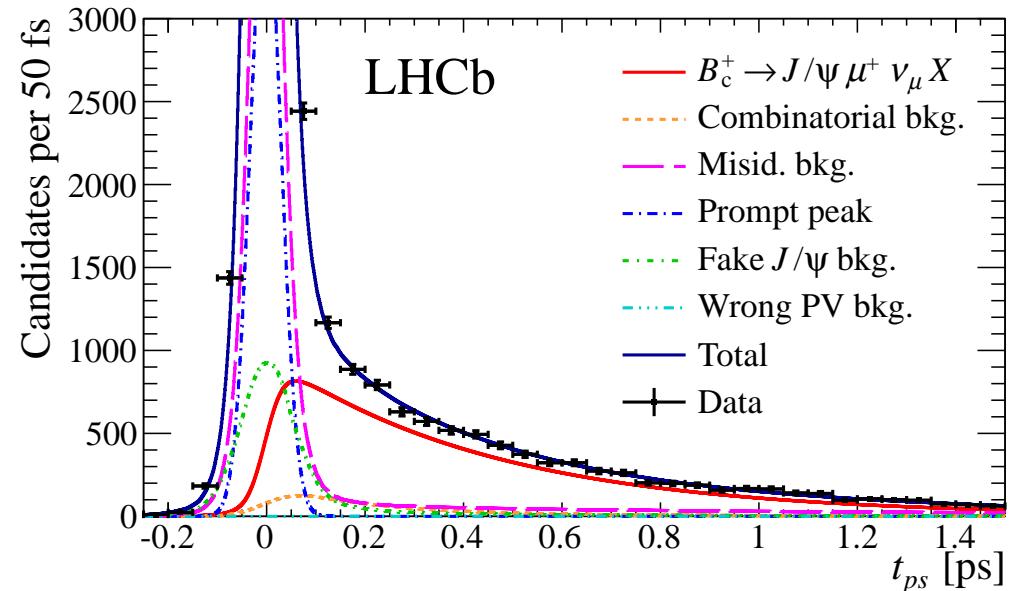
$$\tau(B_c) = 509 \pm 8 \text{ (stat)} \pm 12 \text{ (syst)} \text{ fs}$$

  $2 \text{ fb}^{-1}$  EPJC 74 (2014) 2839

Prediction range: 300 - 700 fs

< half uncertainty wrt previous world average  
Expect further improvements from analysis on  $J/\psi \pi^+$  mode

## B<sub>c</sub> lifetime



# B<sub>c</sub> decay modes

Many new decay modes discovered at LHC,  
mostly J/ $\psi$  + hadrons modes ( $b \rightarrow cW$ ):

$$B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$$

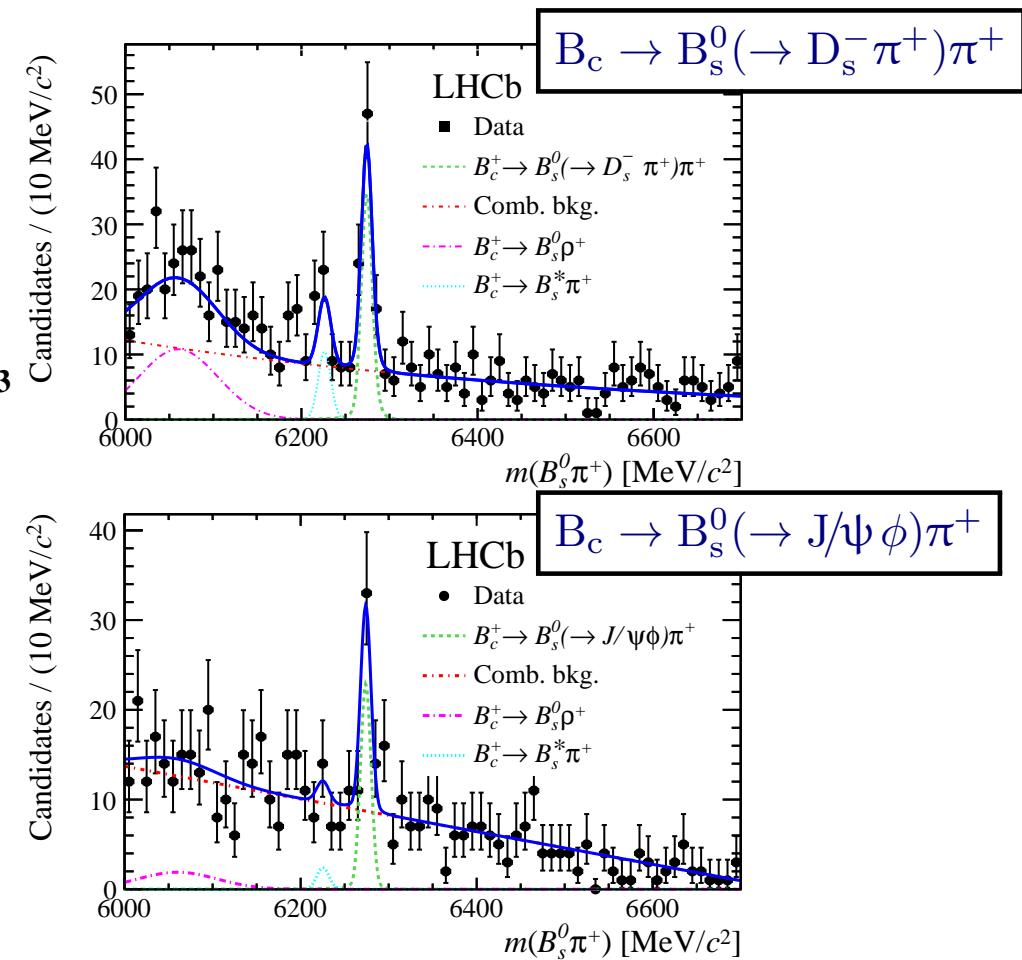
LHCb 0.8 fb<sup>-1</sup> PRL 108 (2012) 251802  
 CMS 4.7 fb<sup>-1</sup> prelim. CMS-PAS-BPH-11-003

$$\begin{aligned} B_c^+ &\rightarrow \psi(2S)\pi^+ \\ B_c^+ &\rightarrow J/\psi D_s^{+(*)} \\ B_c^+ &\rightarrow J/\psi K^+ \\ B_c^+ &\rightarrow J/\psi K^+ K^- \pi^+ \\ B_c^+ &\rightarrow J/\psi 3\pi^+ 2\pi^- \\ B_c^+ &\rightarrow J/\psi p\bar{p}\pi^+ \end{aligned}$$

LHCb 1.0 fb<sup>-1</sup> PRD87 (2013) 071103  
 LHCb 3.0 fb<sup>-1</sup> PRD87 (2013) 112012  
 LHCb 1.0 fb<sup>-1</sup> JHEP 09 (2013) 075  
 LHCb 3.0 fb<sup>-1</sup> JHEP 11 (2013) 094  
 LHCb 3.0 fb<sup>-1</sup> JHEP 05 (2014) 148  
 LHCb 3.0 fb<sup>-1</sup> arXiv:1408.0971 NEW

but also first observation of a  $c \rightarrow sW$  transition  
(expected to account for  $\sim 70\%$  of width, but  
experimentally more difficult):

$$B_c^+ \rightarrow B_s^0 \pi^+ \quad \text{LHCb } 3.0 \text{ fb}^{-1} \text{ PRL 111 (2013) 181801}$$



$B_s^0$  reconstructed in  $D_s^- \pi^+$  and  $J/\psi \phi$   
( $> 5\sigma$  significance for each final state)

Knowledge of some reference absolute BR still missing to determine absolute  $B_c$  production.  
Production  $\times$  BR measurements in  $J/\psi \pi^+$  and  $B_s^0 \pi^+$  modes, combined with theoretical estimates  
for the BRs, indicate that  $\frac{\sigma(B_c^+)}{\sigma(B_s^0)} \sim 2\%$ , at the upper edge of expectations.  
More measurements and theoretical work needed!!

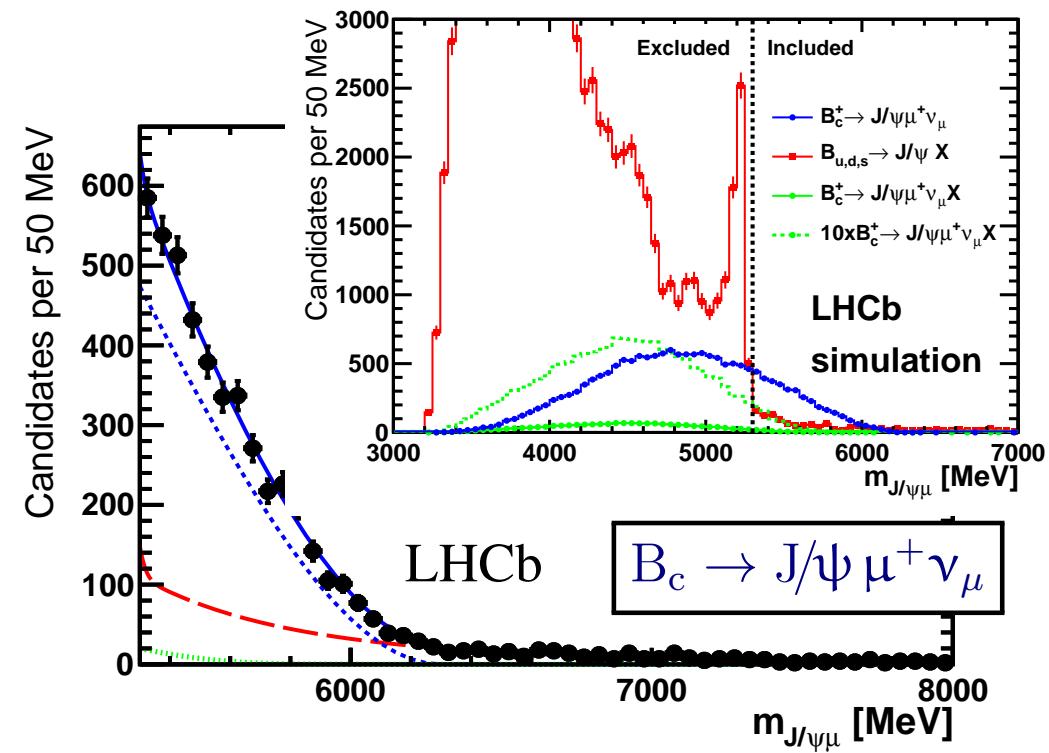
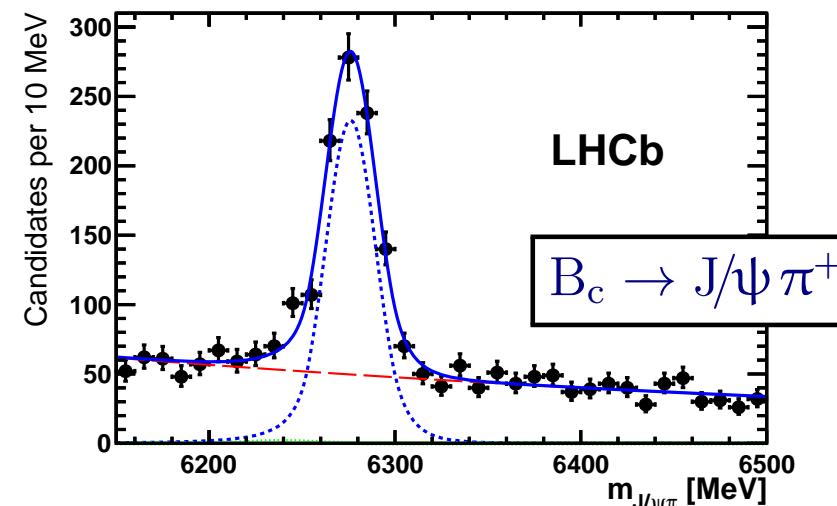
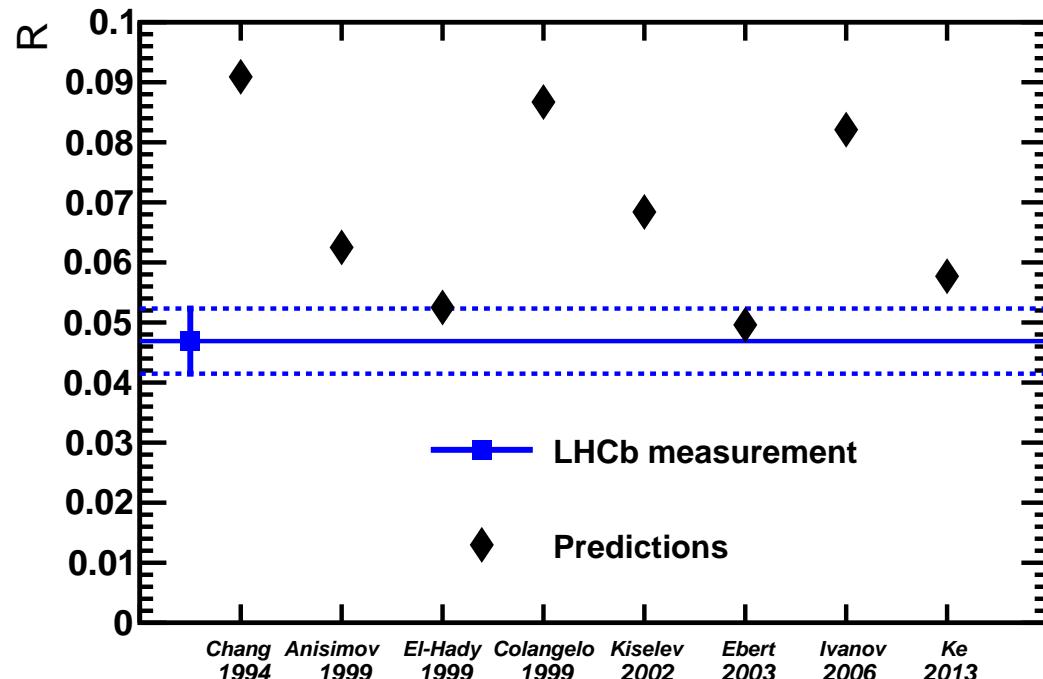
$$\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)/\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)$$

- Wide spread in predictions:  $0.05 - 0.09$
- Use semileptonic decays with  $J/\psi \mu$  above  $B^+$  meson mass (low background)
- Main syst. uncertainty from model-dependence in extrapolation to full phase space

$$R = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)} = 0.0469 \pm 0.0028 \pm 0.0046$$

**NEW**   $1.0 \text{ fb}^{-1}$  arXiv:1407.2126

at the lower end of range of expectations



# Excited $B_c$ !

First observation by ATLAS of an excited  $B_c$  state decaying to  $B_c^+ \pi^+ \pi^-$ , compatible with expected 2S state  
 $58 \pm 14$  candidates, significance is  $5.2\sigma$   
(3.7 $\sigma$  in 7 TeV and 4.5 $\sigma$  in 8 TeV data alone). Mass and width consistent in the two datasets. Width compatible with experimental resolution.

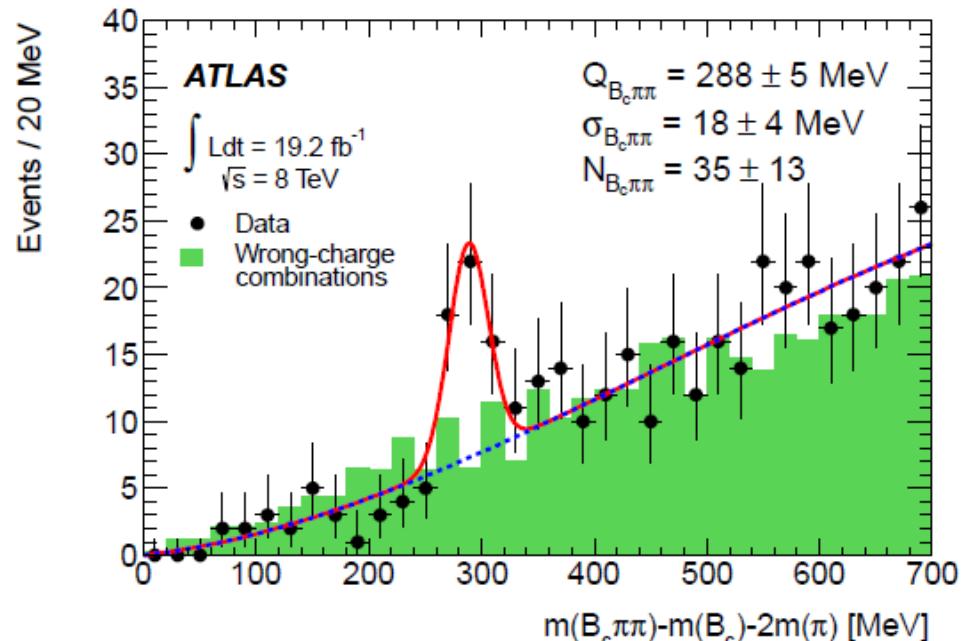
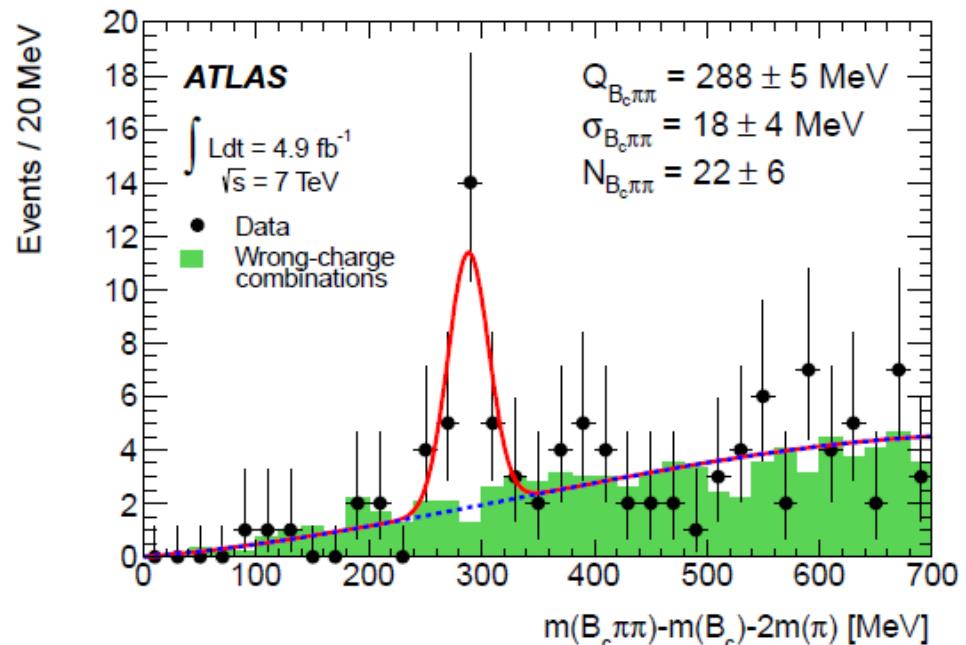


$$M(B_c^+(2S)) = 6842 \pm 4 \pm 5 \text{ MeV}$$

$4.9 \text{ fb}^{-1}$  @ 7 TeV +  $19.2 \text{ fb}^{-1}$  @ 8 TeV arXiv:1407.1032

Prediction range 6835–6917 MeV

Likely to be  ${}^32S_1 \rightarrow {}^31S_1 (\rightarrow {}^11S_0 \gamma_{\text{soft}}) \pi^+ \pi^-$  decay, with undetected soft ( $\sim 50$  MeV) photon (production of vector state expected to be favoured).



(Trigger/selection efficiency different for the two samples)

# B baryons

- limited knowledge on  $b$ -baryons before LHC:
- lifetime measured to better than 10% only for  $\Lambda_b$ : result from LEP ( $\tau(\Lambda_b)/\tau(B^0) \sim 0.8$ ) significantly below predictions, puzzling to explain
- most other states unobserved or  $J^P$  not confirmed
- only one  $\Lambda_b$  excited state observed

Citation: J. Beringer et al. (Particle Data Group), PR D86, 010001 (2012) [URL: <http://pdg.lbl.gov>]

BOTTOM BARYONS ( $B = -1$ )		
$A_b^0 = udb, \Xi_b^0 = usb, \Xi_b^- = us\bar{b}, \Omega_b^- = ss\bar{b}$		

$$i(J^P) = 0(\frac{1}{2}^+)$$

$i(J^P)$  not yet measured;  $0(\frac{1}{2}^+)$  is the quark model prediction.

Mass  $m = 5619.4 \pm 0.7$  MeV

$m_{\Lambda_b^0} = m_{\Xi_b^0} = 5626.2 \pm 0.7$  MeV

$m_{\Xi_b^-} = m_{\Xi_b^-} = 5397.1 \pm 0.7$  MeV

Mean life  $\tau_{\Lambda_b^0} = (1.425 \pm 0.022) \times 10^{-12}$  s

$c\tau = 427$   $\mu$ m

$A_{CP}(A_b^0 \rightarrow \ell^+ \nu_\ell X) = 0.03 \pm 0.18$

$A_{CP}(A_b^0 \rightarrow \ell^- \bar{\nu}_\ell) = 0.37 \pm 0.17$

The branching fractions  $B(b\text{-baryon} \rightarrow A^0 \ell^+ \nu_\ell \text{anything})$  and  $B(A_b^0 \rightarrow A_b^0 \ell^+ \nu_\ell \text{anything})$  are not pure measurements because the underlying measured products of these with  $B(b \rightarrow b\text{-baryon})$  were used to determine  $B(b \rightarrow b\text{-baryon})$ , as described in the note "Production and Decay of  $b$ -Flavored Hadrons".

For inclusive branching fractions, e.g.,  $A_b \rightarrow A^-$ , anything, the values usually are multiplicities, not branching fractions. They can be greater than one.

Λ <sub>b</sub> DECAY MODES		
	Fraction ( $F_J/\Gamma$ )	Scale factor / $\mu$ (MeV/c)
$J/\psi(1S) \times B(b \rightarrow A_b^0)$	$(5.8 \pm 0.2) \times 10^{-5}$	1740
$A_b^0 \pi^+$	$(5.7 \pm 4.0) \times 10^{-3}$	2342
$A_b^0 \pi_1(1260)^-$	seen	2152
$A_b^0 \pi^+ \pi^- \pi^-$	$(0 \pm 1.5) \times 10^{-3}$	2232
$A_b(2995)^+ \pi^-$	$(3.7 \pm 2.5) \times 10^{-4}$	2210
$A_b(2995)^0 \pi^+$	$(3.6 \pm 2.1) \times 10^{-4}$	2193
$A_b(2625)^+ \pi^-$	$(0 \pm 1.5) \times 10^{-3}$	2112
$\Lambda_b(2625)^0 \pi^+ \pi^-$	$(0 \pm 1.5) \times 10^{-4}$	2195
$\Sigma_b(2485)^0 \pi^+ \pi^-$	$(0 \pm 1.5) \times 10^{-4}$	2285
$A_b^0 \pi^+$		

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HTTP://PDG.LBL.GOV Page 3 Created: 6/18/2012 15:06

Citation: J. Beringer et al. (Particle Data Group), PR D86, 010001 (2012) [URL: <http://pdg.lbl.gov>]

$\Sigma_c(2455)^{++} \pi^- \pi^- \Sigma_c^{*-}$	$(3.5 \pm 2.5) \times 10^{-4}$	2205
$A_c^+ \ell^+ \nu_\ell \text{anything}$	[a] $(9.8 \pm 2.5) \%$	-
$A_c^+ \pi^+ \pi^- \ell^+ \nu_\ell$	$(0.5 \pm 2.2) \%$	2345
$A_c^+ \pi^+ \pi^- \ell^+ \nu_\ell$	$(5.6 \pm 3.1) \%$	2350
$A_c(2985)^+ \ell^+ \nu_\ell$	$(0 \pm 1.5) \times 10^{-3}$	2212
$A_c(2625)^+ \ell^+ \nu_\ell$	$(1.4 \pm 0.5) \times 10^{-3}$	2195
$\rho^0 \pi^-$	[b] $< 2.3 \times 10^{-6}$	2720
$\rho^0 \pi^-$	[b] $(3.8 \pm 1.0) \times 10^{-6}$	2730
$\rho^0 K^-$	$(5.5 \pm 1.0) \times 10^{-6}$	2708
$\rho^0 \eta'$	$(1.7 \pm 0.7) \times 10^{-6}$	2095
$A\mu^+ \mu^-$	$< 1.3 \times 10^{-6}$	2099
$A\gamma$		

$$i(J^P) = 0(\frac{1}{2}^+)$$

$i(J^P)$  not yet measured. See note at head of  $A_b^0$  Decay Modes.

$\rho^0 \pi^-$  means  $\pi^- \pi^+$  or  $K^- \bar{K}^0$ .

Σ <sub>b</sub> DECAY MODES		
	Fraction ( $F_J/\Gamma$ )	$\mu$ (MeV/c)
$A_b^0 \pi^+$	dominant	134

$$i(J^P) = 0(\frac{1}{2}^+)$$

$i(J^P)$  not yet measured. See note at head of  $A_b^0$  Decay Modes.

$\Xi_b^- \pi^+$  means  $\pi^+ \pi^-$  or  $K^+ \bar{K}^-$ .

Σ <sub>b</sub> <sup>0</sup> DECAY MODES		
	Fraction ( $F_J/\Gamma$ )	$\mu$ (MeV/c)
$A_b^0 \pi^+$	dominant	134

$$i(J^P) = 0(\frac{1}{2}^+)$$

$i(J^P)$  not yet measured. See note at head of  $A_b^0$  Decay Modes.

$\Xi_b^- \pi^+$  means  $\pi^+ \pi^-$  or  $K^+ \bar{K}^-$ .

Citation: J. Beringer et al. (Particle Data Group), PR D86, 010001 (2012) [URL: <http://pdg.lbl.gov>]

Ξ <sub>b</sub> <sup>0</sup> DECAY MODES		
	Fraction ( $F_J/\Gamma$ )	$\mu$ (MeV/c)
$\Xi_b^0 \pi^+$	$i(J^P) = 0(\frac{1}{2}^+)$ $i(J^P)$ not yet measured. See note at head of $A_b^0$ Decay Modes.	-

$m(\Xi_b^0) = 5791.3 \pm 2.2$  MeV

$m(\Xi_b^0) = 5789 \pm 5$  MeV

$m_{\Xi_b^0} = m_{\Xi_b^0} = 3 \pm 6$  MeV

Mean life  $\tau_{\Xi_b^0} = (1.56 \pm 0.26) \times 10^{-12}$  s

Mean life  $\tau_{\Xi_b^0} = (1.49^{+0.19}_{-0.16}) \times 10^{-12}$  s

Ξ <sub>b</sub> <sup>-</sup> DECAY MODES		
	Fraction ( $F_J/\Gamma$ )	Scale factor
$\Xi_b^- \pi^+$	$(3.9 \pm 1.2) \times 10^{-4}$	1.4
$\Xi_b^- \Xi_b^0$	$(1.0 \pm 1.2) \times 10^{-5}$	-

$i(J^P) = 0(\frac{1}{2}^+)$   
 $i(J^P)$  not yet measured. See note at head of  $A_b^0$  Decay Modes.

$Mass m = 6071 \pm 40$  MeV ( $S = 6.2$ )

Mean life  $\tau = (1.3^{+0.4}_{-0.4}) \times 10^{-12}$  s

Ξ <sub>b</sub> <sup>-</sup> DECAY MODES		
	Fraction ( $F_J/\Gamma$ )	$\mu$ (MeV/c)
$J/\psi(1S) \times B(b \rightarrow \Xi_b^-)$	$(2.8^{+1.1}_{-0.9}) \times 10^{-6}$	103

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Citation: J. Beringer et al. (Particle Data Group), PR D86, 010001 (2012) [URL: <http://pdg.lbl.gov>]

Mean life  $\tau = (1.382 \pm 0.029) \times 10^{-12}$  s

These branching fractions are actually as average over all decay b-hadrons weighted by their production rates at the LHC, Tevatron, branching ratios, and detection efficiencies. They scale with the b-hadron production rates.

The branching fractions  $B(b\text{-baryon} \rightarrow A^0 \text{anything})$  and  $B(A_b^0 \rightarrow A_b^0 \text{anything})$  are not pure measurements because the underlying measured products of these with  $B(b \rightarrow b\text{-baryon})$  were used to determine  $B(b \rightarrow b\text{-baryon})$ , described in the note "Production and Decay of  $b$ -Flavored Hadrons".

For inclusive branching fractions, e.g.,  $B \rightarrow D^3\text{anything}$ , the values are multiplicities, not branching fractions. They can be greater than one.

$b$ -baryon ADMIXTURE DECAY MODES		
	Fraction ( $F_J/\Gamma$ )	$\mu$ (MeV/c)
$\rho^0 \pi^- \nu_\ell \text{anything}$	$(5.3^{+2.0}_{-1.9}) \%$	-
$\rho^0 \ell^+ \bar{\nu}_\ell \text{anything}$	$(5.1^{+1.2}_{-1.1}) \%$	-
$\rho^0 \eta' \text{anything}$	$(0.9^{+0.2}_{-0.1}) \%$	-
$A^0 \pi^- \nu_\ell \text{anything}$	$(3.4^{+0.6}_{-0.5}) \%$	-
$A^0 \ell^+ \bar{\nu}_\ell \text{anything}$	$(3.0^{+0.8}_{-0.7}) \%$	-
$\Xi^0 \ell^+ \bar{\nu}_\ell \text{anything}$	$(5.9^{+1.6}_{-1.5}) \%$	-

[a] Not a pure measurement. See note at head of  $A_b^0$  Decay Modes.

[b] Here  $h^-$  means  $\pi^-$  or  $K^-$ .

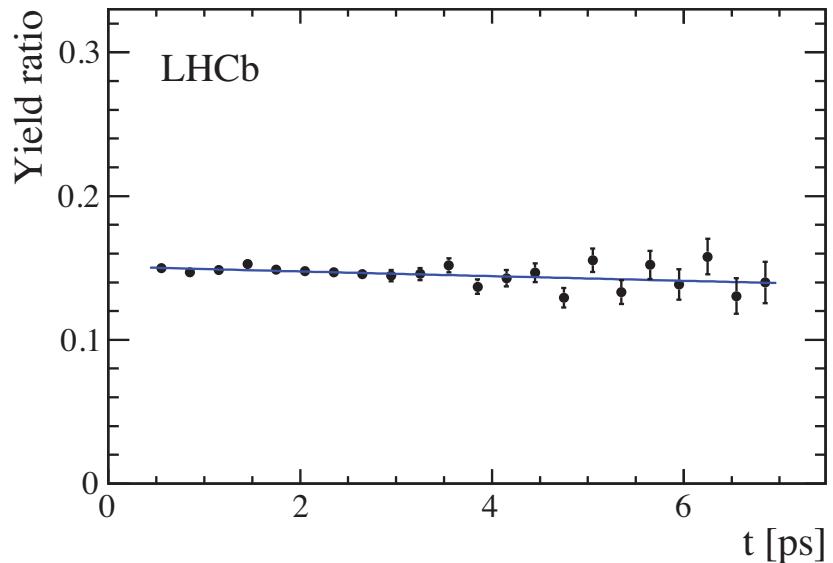
PDG2012

# $\Lambda_b$ lifetime

Measured relatively to  $B^0$  using similar final states:

$$\Lambda_b \rightarrow J/\psi \ p \ K^- \quad \bar{B}^0 \rightarrow J/\psi \ \bar{K}^{*0} (\rightarrow K^- \ \pi^+)$$

- ✓ most systematics cancel, small correction to acceptance ratio vs time evaluated from simulation



$\tau(\Lambda_b)/\tau(\bar{B}^0) = 0.974 \pm 0.006 \pm 0.004$

in agreement with HQE predictions and ATLAS/CMS:

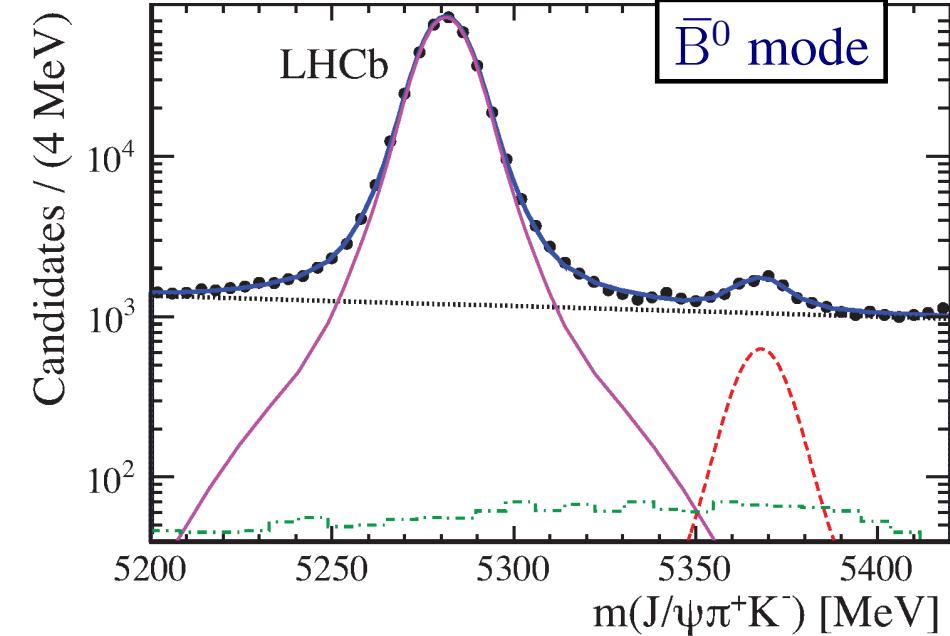
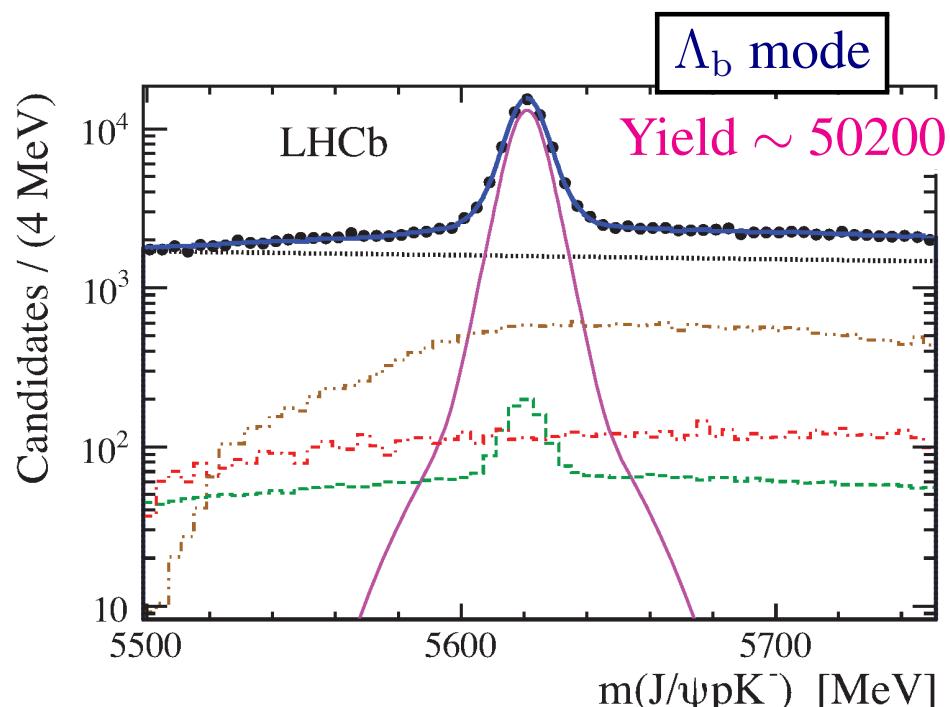
$\tau(\Lambda_b)/\tau(\bar{B}^0) = 0.960 \pm 0.025 \pm 0.016$

PRD87 (2013) 3, 032002

$\tau(\Lambda_b)/\tau(\bar{B}^0) = 0.989 \pm 0.034 \pm 0.020$

JHEP 07 (2013) 163

Long-standing puzzle seems to be solved !



$3.0 \text{ fb}^{-1}$  PLB 734 (2014) 122

Rencontres du Vietnam 2014

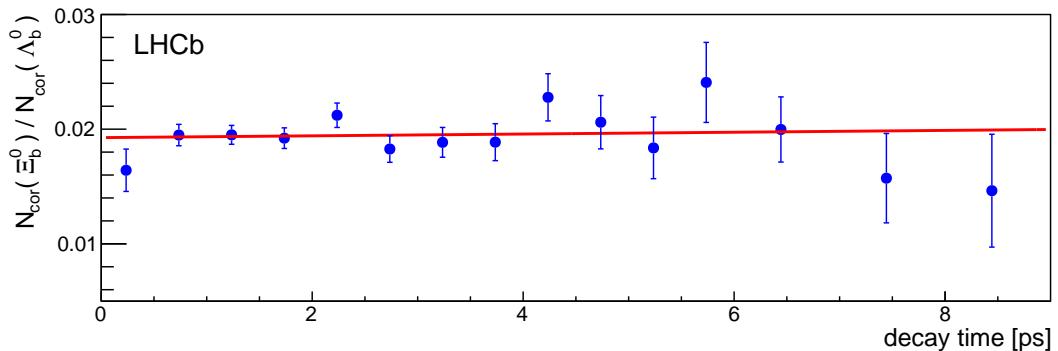
# $\Xi_b^0$ mass and lifetime

Using  $\Xi_b^0 \rightarrow \Xi_c^+ (\rightarrow pK^- \pi^+) \pi^-$

- ✗  $\Xi_c^+$  decay Cabibbo-suppressed, lose factor 3 in BR wrt  $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$ ,  $\Xi^- \rightarrow \Lambda (\rightarrow p\pi^-) \pi^-$
- ✓ but big gain in efficiency since no hyperons in final state!
- ✓ ideal normalization available:  $\Lambda_b \rightarrow \Lambda_c (\rightarrow pK^-\pi^+)\pi^-$  (identical final state)

$$M(\Xi_b^0) = 5791.80 \pm 0.39 \pm 0.17 \pm 0.26_{\Lambda_b} \text{ MeV}/c^2$$

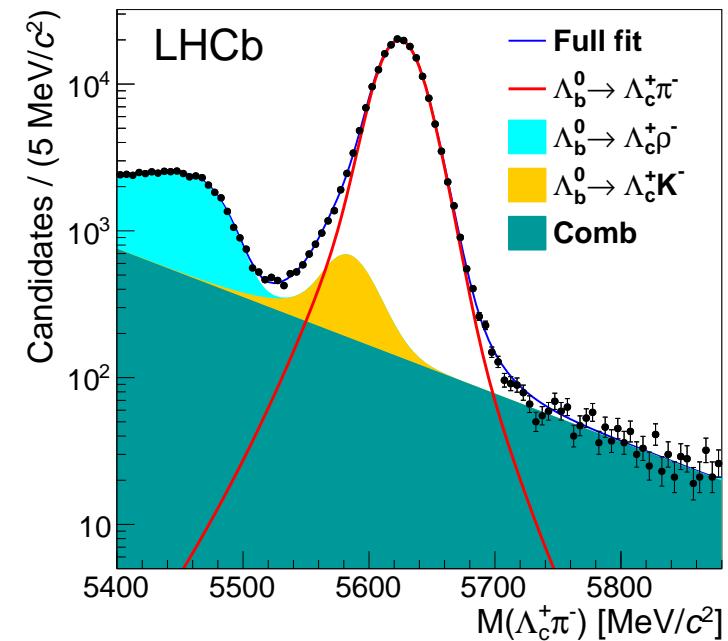
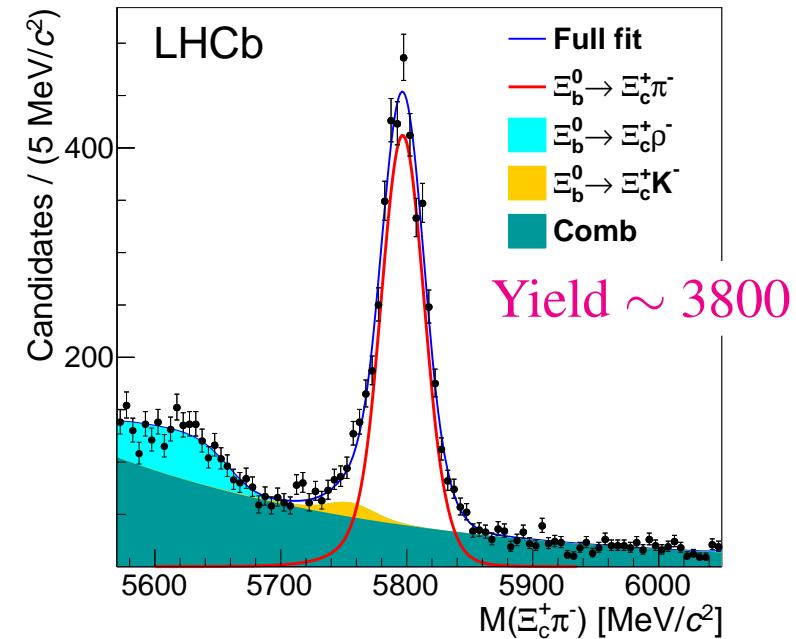
First  $\Xi_b^0$  lifetime measurement, relative to  $\Lambda_b$



$$\tau(\Xi_b^0)/\tau(\Lambda_b) = 1.006 \pm 0.018 \pm 0.010$$

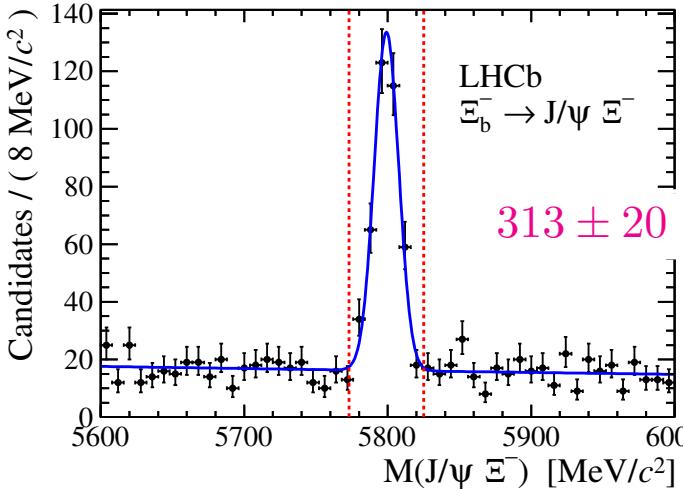
Lifetime agree within 2%, as expected from HQE predictions

Also improving  $\Xi_c^+$  mass measurement by factor  $\sim 4$  wrt WA!

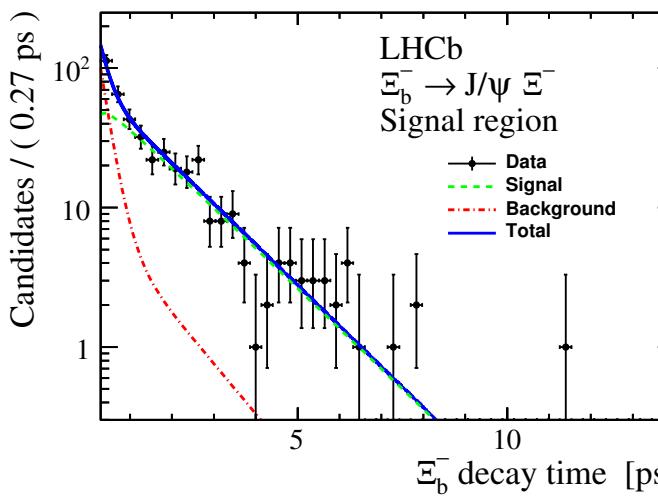
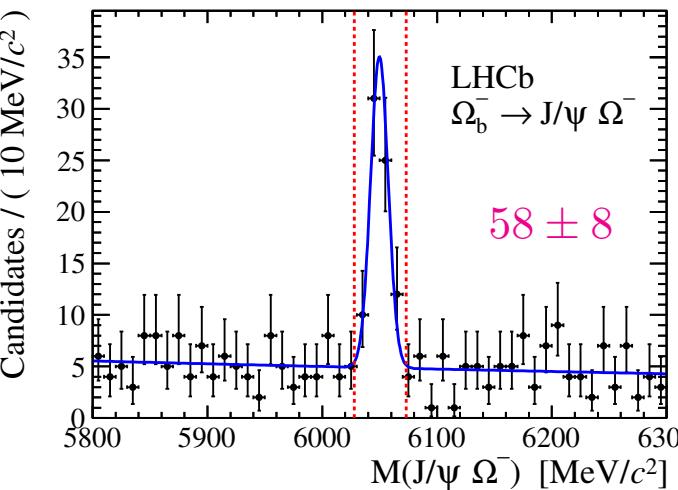


# $\Xi_b^-/\Omega_b^-$ lifetime

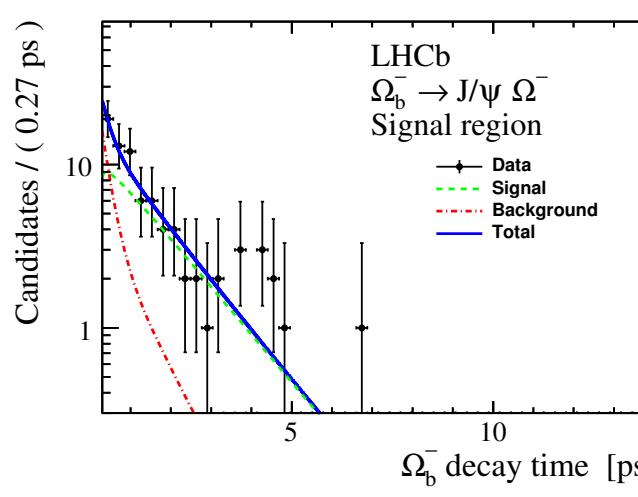
$\Xi_b^- \rightarrow J/\psi \Xi^-$



$\Omega_b^- \rightarrow J/\psi \Omega^-$



$$\tau(\Xi_b^-) = 1.55^{+0.10}_{-0.09} \pm 0.03 \text{ ps}$$



$$\tau(\Omega_b^-) = 1.54^{+0.26}_{-0.21} \pm 0.05 \text{ ps}$$

Absolute lifetime measurement using  $J/\psi$ -hyperon modes

- ✓ clean signature from  $J/\psi$  and detached hyperon decays
- ✗ low efficiency for hyperon reconstruction
- ✗ systematic limited by knowledge of absolute efficiency (evaluated from MC and validated with  $B^0 \rightarrow J/\psi K_s^0$  and other data-driven checks)

World's best measurements!

Consistent with previous (Tevatron) results, and HQE predictions.

For  $\Xi_b^-$ , expect further improvement from  $\tau(\Xi_b^-)/\tau(\Lambda_b)$  analysis similar to the  $\Xi_b^0$  case.

Several recent first observations and precision measurements  
of  $\Lambda_b$  decay channels

## $\Lambda_b$ decay modes

- First observation of a  $b$ -baryon decay to double-charm  $\Lambda_b \rightarrow \Lambda_c D_{(s)}^-$  provides best measurement of  $\Lambda_b$  mass  $m(\Lambda_b) = 5619.30 \pm 0.24 \pm 0.18 \text{ MeV}/c^2$

LHCb  
 $\Gamma_{\text{HCP}}$

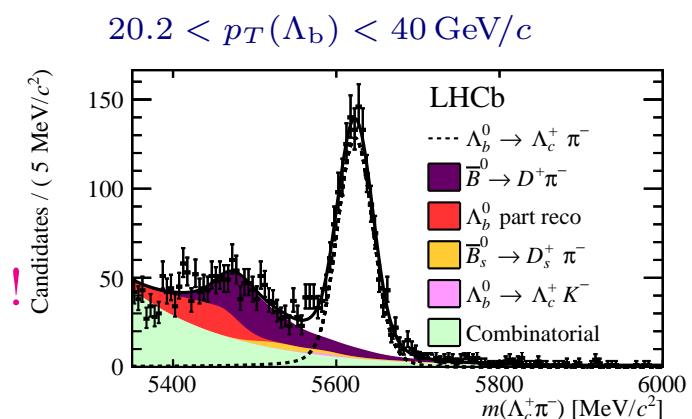
$3.0 \text{ fb}^{-1}$  PRL 112 (2014) 202001

- $\mathcal{B}(\Lambda_b \rightarrow \Lambda_c \pi^-) = (4.30 \pm 0.03^{+0.12}_{-0.11} \pm 0.26_{f_{\Lambda_b}/f_d} \pm 0.21_{\text{norm}}) \times 10^{-3}$

measured from  $\sim 45000$   $\Lambda_b \rightarrow \Lambda_c (\rightarrow J/\psi p K^-) \pi^-$  decays using  $B^0 \rightarrow D^- \pi^+$  as normalization mode, and the ratio of fragmentation fraction  $f_{\Lambda_b}/f_d$  measured in semileptonic mode (PRD 85, 032008 (2012)).

LHCb  
 $\Gamma_{\text{HCP}}$   $1.0 \text{ fb}^{-1}$  arXiv:1405.6842

Precision improved from 70% to 8% !



- Observation of  $\Lambda_b/\Xi_b^0$  decays to  $D^0 p K^-$

Can be used to measure CKM angle  $\gamma$  using decays common to  $D^0$  and  $\bar{D}^0$  (à la  $B^0 \rightarrow D^0 K^{*0}$ ).

Observed so far with CF  $D^0 \rightarrow K^- \pi^+$  mode.

LHCb  
 $\Gamma_{\text{HCP}}$   $1.0 \text{ fb}^{-1}$

PRD 89 (2014) 032001

- Measurement of the P-violating asymmetry  $\alpha_b$  in  $\Lambda_b \rightarrow J/\psi \Lambda$

$$\frac{dN_{\Lambda_b}}{d \cos \theta} \propto \frac{1}{2} (1 + \alpha_b P \cos \theta)$$

( $P$  is  $\Lambda_b$  polarization)

Test of non-perturbative QCD predictions

LHCb  
 $\Gamma_{\text{HCP}}$



$$\alpha_b = 0.05 \pm 0.17 \pm 0.07$$

$1.0 \text{ fb}^{-1}$  PLB 724 (2013) 27

$$\alpha_b = 0.30 \pm 0.16 \pm 0.06$$

$4.6 \text{ fb}^{-1}$  PRD 89 092009 (2014)

# CPV in $\Lambda_b$ decays

- first observation of the CS  $\Lambda_b \rightarrow J/\psi p\pi^-$  decay, proceeding through 2 amplitudes with different weak phase: can exhibit direct CPV, sensitive to new physics  
BR and CP asymmetry measured wrt CF mode  $\Lambda_b \rightarrow J/\psi pK^-$

$$\frac{\mathcal{B}(J/\psi p\pi^-)}{\mathcal{B}(J/\psi pK^-)} = (8.24 \pm 0.25 \pm 0.42)\%$$

$$\Delta A_{CP} = A_{CP}(J/\psi p\pi^-) - A_{CP}(J/\psi pK^-) = (5.7 \pm 2.3 \pm 1.2)\%$$

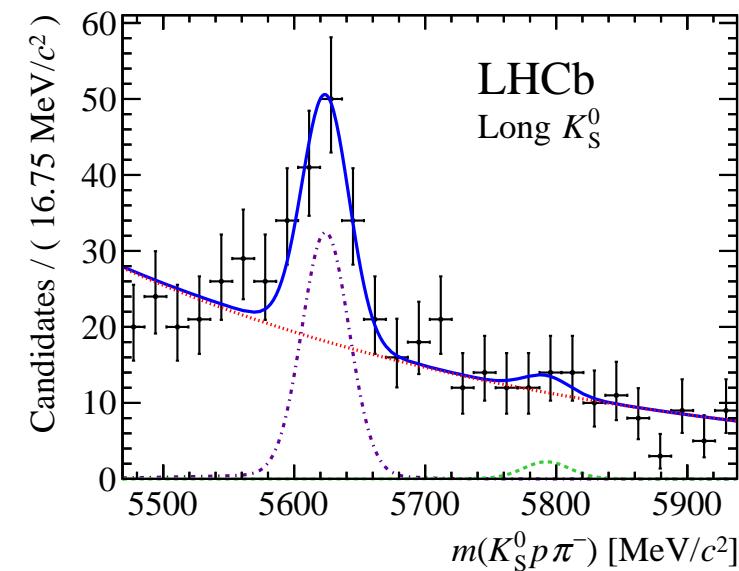
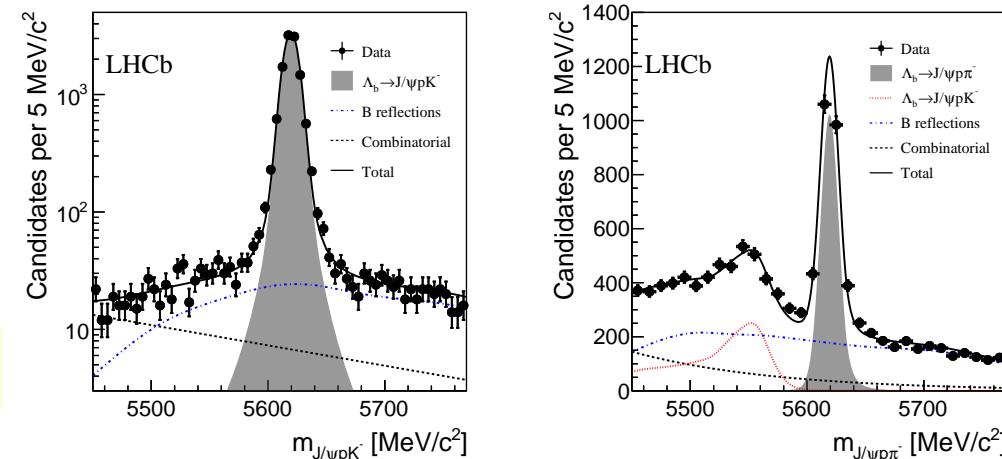
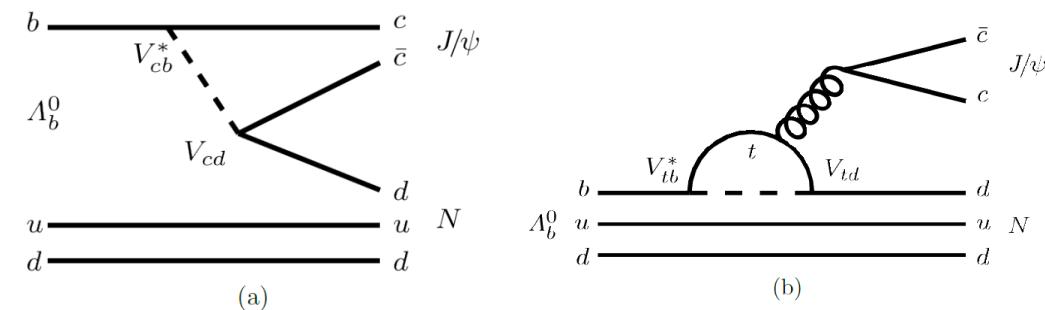
LHCb 3.0 fb<sup>-1</sup> arXiv:1406.0755

- Similar case for  $\Lambda_b \rightarrow K_s^0 p\pi^-$ , the first observed 3-body charmless  $b$ -baryon decay

$$\Delta A_{CP} = A_{CP}(K_s^0 p\pi^-) - A_{CP}(\Lambda_c \rightarrow K_s^0 p)\pi^- = (22 \pm 13 \pm 3)\%$$

Limits set on many other similar modes

LHCb 1.0 fb<sup>-1</sup> JHEP 04 (2014) 087

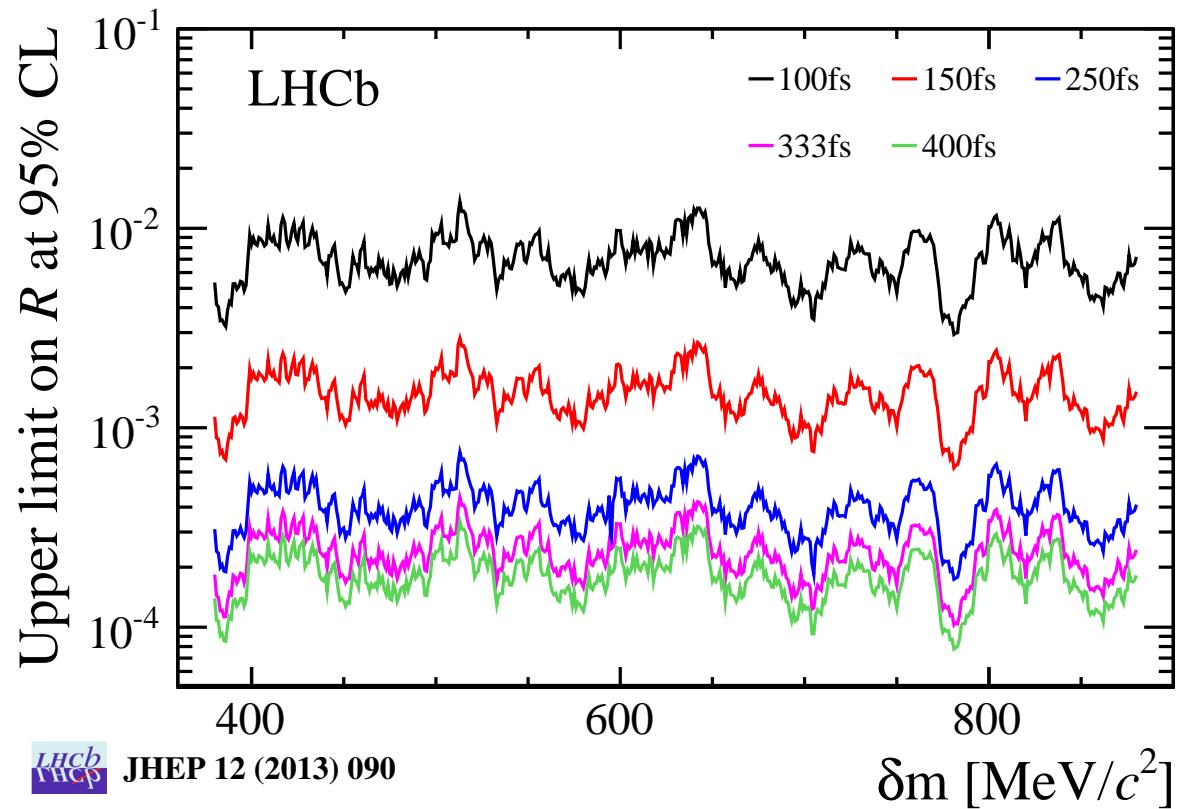


# Double heavy baryons

- Only one of such states reported so far by SELEX (PLB 628 18, PRL 89 112001):  $\Xi_{cc}$  candidate with anomalous lifetime and prod. cross section.  
Not confirmed at B factories and Tevatron
- LHCb sensitivity not far from predicted yield  
Search performed on  $0.65 \text{ fb}^{-1}$ . Negative result: 95% CL upper limits set on  $R \equiv \sigma(\Xi_{cc}) \frac{\mathcal{B}(\Xi_{cc} \rightarrow \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)}$  as a function of  $\Xi_{cc}$  lifetime and mass

95% CL upper limits range from  $1.4 \times 10^{-2}$  ( $\tau = 100 \text{ fs}$ ) to  $3.4 \times 10^{-4}$  ( $400 \text{ fs}$ )  
(predictions  $\sim 10^{-5} - 10^{-4}$ )

Does not exclude SELEX results ( $\tau < 33 \text{ fs}$ )



# Conclusions and Prospects

- The era of precision physics with  $B_c$  and  $b$ -baryon states has started at LHC!
- Mass and lifetime measurements provide accurate tests of effective models

	HQE2014	pre-LHC	LHCb
e.g. $b$ -baryon lifetimes	Lenz arXiv:1405.3601		
$\tau(\Lambda_b)/\tau(B^0)$	$0.935 \pm 0.054$	$0.912 \pm 0.025$	$0.974 \pm 0.007$
$\tau(\Xi_b^0)/\tau(\Xi_b^-)$	$0.95 \pm 0.06$	unmeasured	$0.95 \pm 0.07$

- experiments often ahead of prediction accuracy... theoretical progress on  $b$ -baryon and double heavy states would be very useful!
- Bright future for such physics at LHC with Run II data, and LHCb upgrade phase (from 2019):
  - spectroscopy of  $B_c$  and  $b$ -baryons has just started, still some time to make predictions!
  - first CPV measurements with  $\Lambda_b$  decays, many other interesting modes accessible in the near future, e.g.  $\Lambda_b/\Xi_b \rightarrow D^0 p K^-$ ,  $B_c^+ \rightarrow D_s^+ D^0$  can contribute to CKM angle  $\gamma$  determination
  - the quest for double heavy baryons  $\Xi_{QQ}$  ( $Q = b, c$ ) started

# Backup Material

# $D_s^*$ new states

Results for mass and width of the  $J^P = 1^-$  and  $3^-$  states at  $2860 \text{ MeV}/c^2$ .

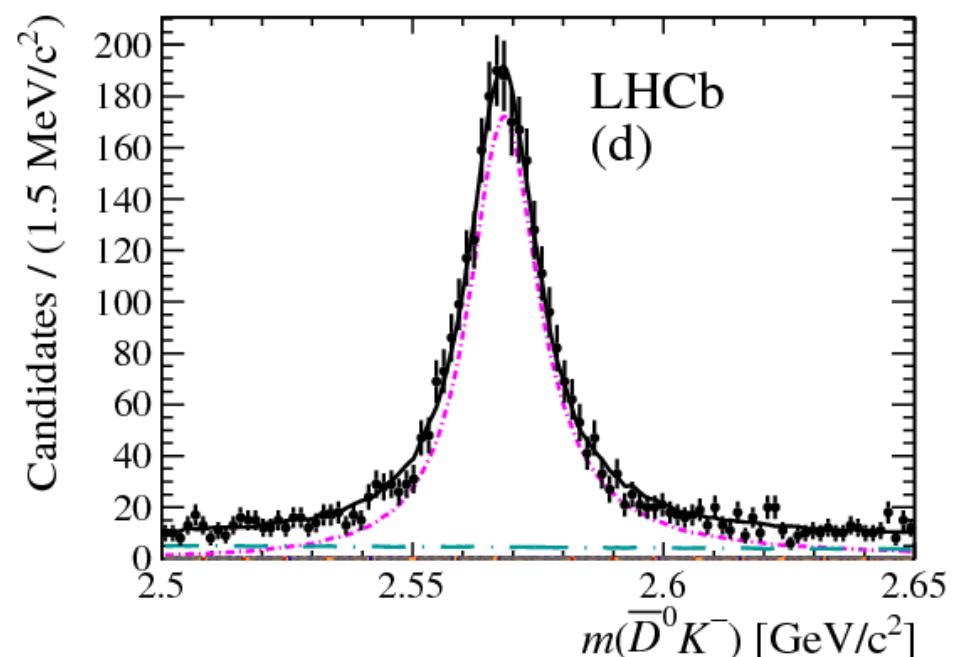
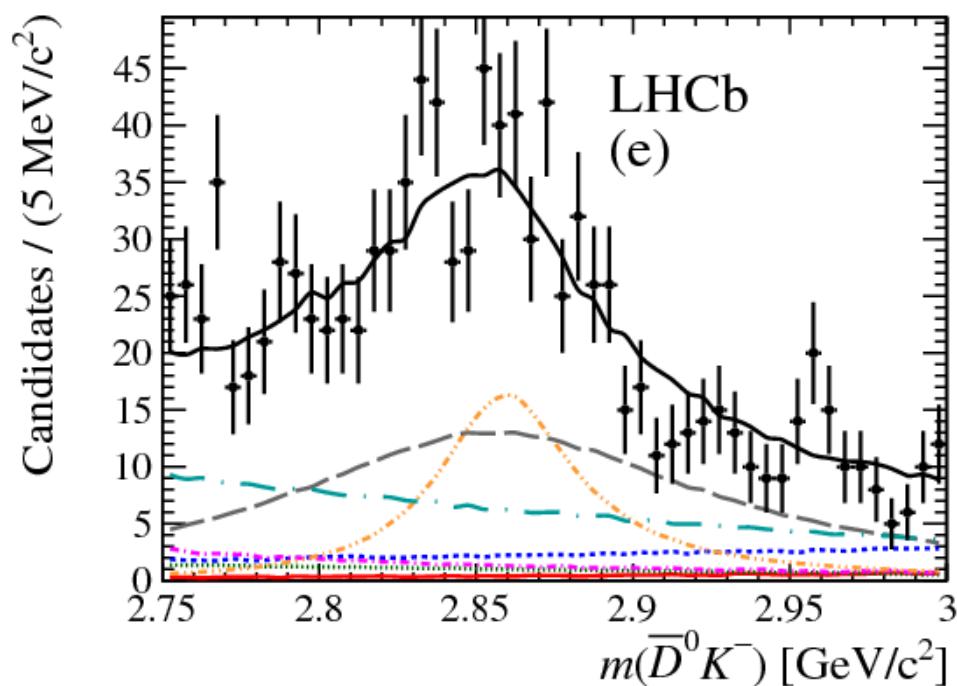
Also best measurements for the already known  $D_{s2}^*(2573)^-$  state.

	Mass ( MeV/ $c^2$ )
$D_{s1}^*(2860)^-$	$2859 \pm 12 \pm 6 \pm 23$
$D_{s3}^*(2860)^-$	$2860.5 \pm 2.6 \pm 2.5 \pm 6.0$

	Width ( MeV/ $c^2$ )
$D_{s2}^*(2573)^-$	$159 \pm 23 \pm 27 \pm 72$
$D_{s2}^*(2573)^-$	$53 \pm 7 \pm 4 \pm 6$

$D_{s2}^*(2573)^-$      $2568.39 \pm 0.29 \pm 0.19 \pm 0.18$      $16.9 \pm 0.5 \pm 0.4 \pm 0.4$

(uncertainties are due to statistical, experimental systematic, model dependence effects)



LHCb  
3.0  $\text{fb}^{-1}$  arXiv:1407.7574  
arXiv:1407.7712

# $B_c^+ \rightarrow J/\psi p\bar{p}\pi^+$

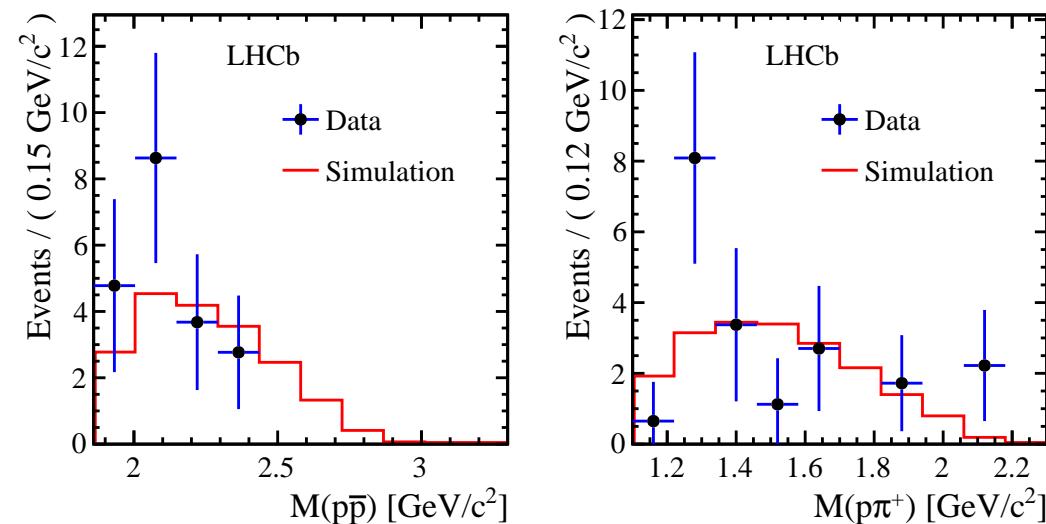
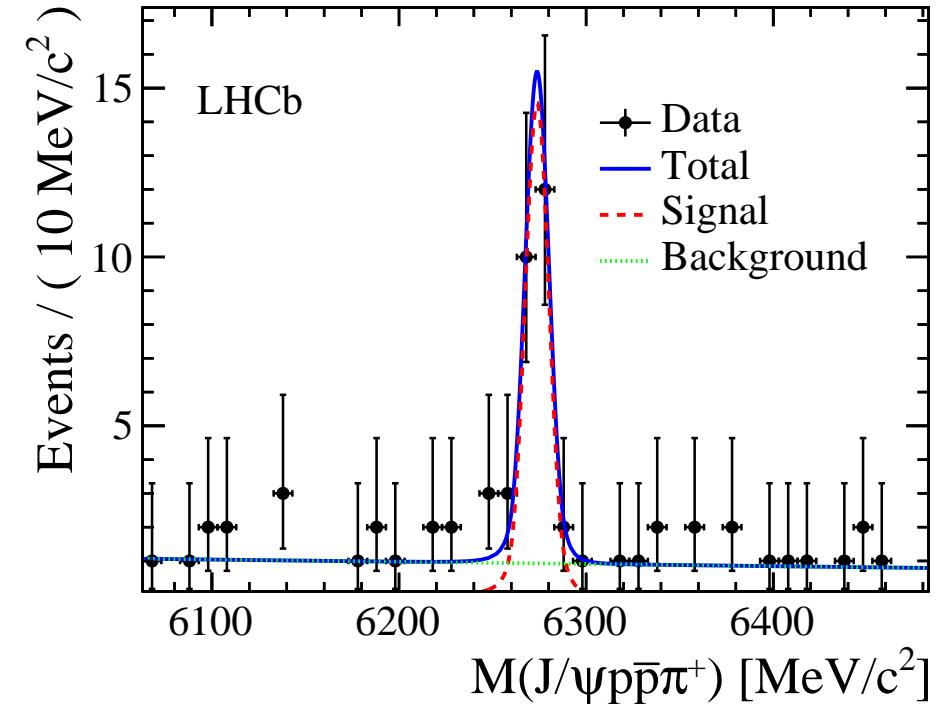
- first baryonic  $B_c^+$  decay !
- adds input to baryon production studies in b decays, after observing enhancement at low  $M(p\bar{p})$  in B meson decays
- provides another precise  $B_c$  mass measurements
- larger statistics will allow search for p excited states

Decay observed with  $7.3\sigma$  significance

$$\frac{\mathcal{B}(B_c^+ \rightarrow J/\psi p\bar{p}\pi^+)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)} = 0.143^{+0.039}_{-0.034} \pm 0.013$$

consistent with expectation from spectator decay model + factorization

$$\frac{\mathcal{B}(B_c^+ \rightarrow J/\psi p\bar{p}\pi^+)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)} \sim \frac{\mathcal{B}(B^0 \rightarrow D^{*-} p\bar{p}\pi^+)}{\mathcal{B}(B^0 \rightarrow D^{*-} \pi^+)} = 0.17 \pm 0.02$$



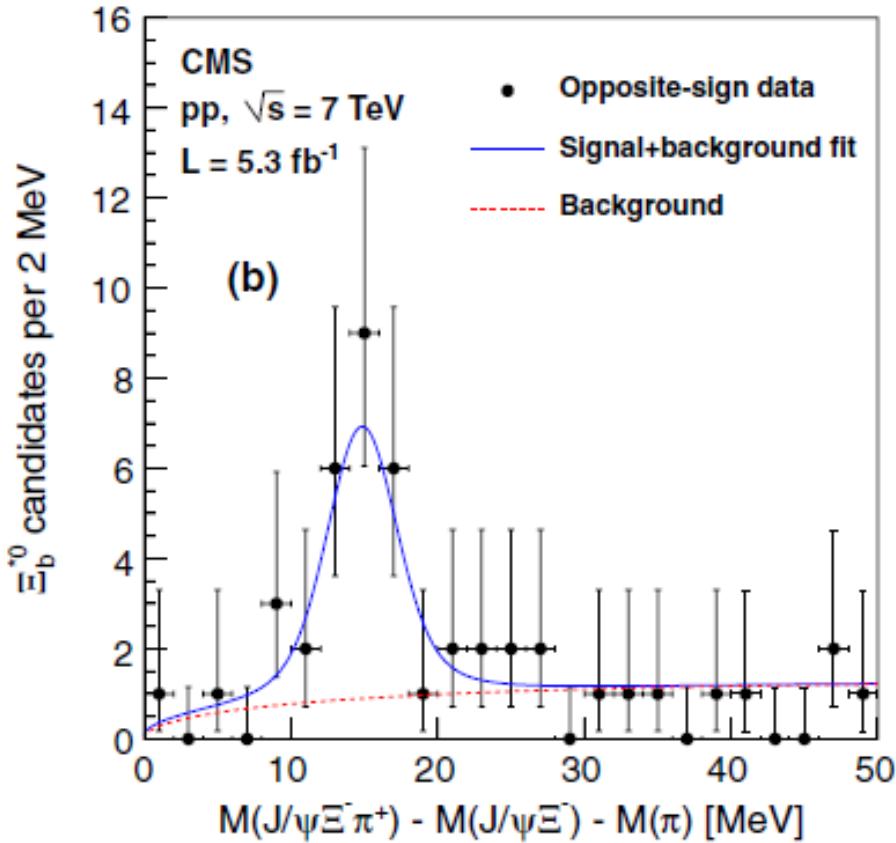
(simulation uses uniform phase space model)



$3.0 \text{ fb}^{-1}$  arXiv:1408.0971

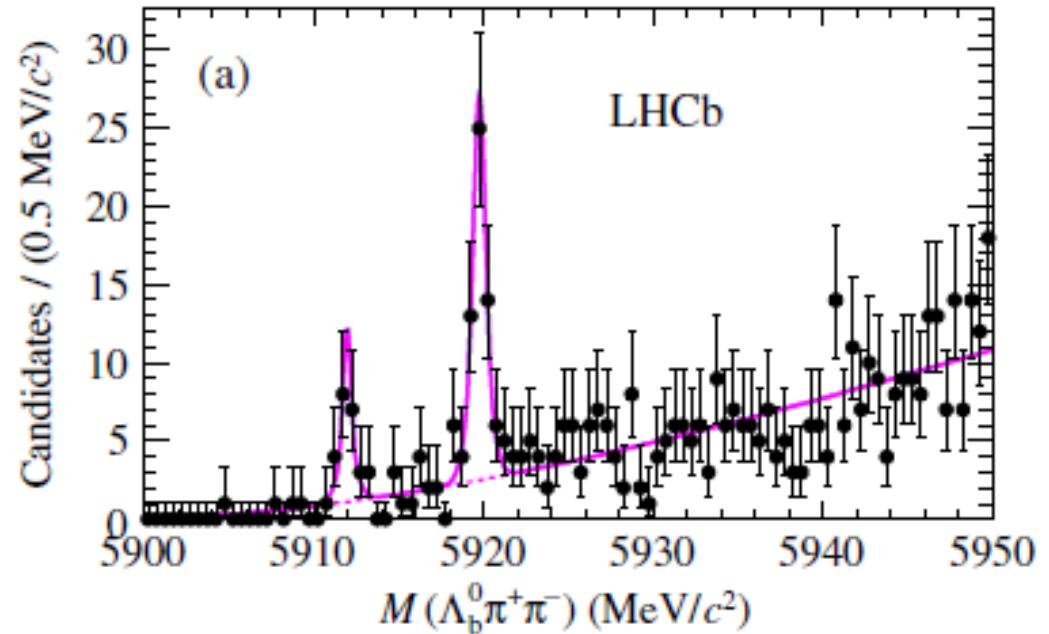
# New excited $b$ -baryon states

Two spectroscopy results from the first LHC data



New neutral  $\Xi_b^*$  observed by CMS, decaying to  $\Xi_b^- \pi^+$ , likely to be a  $J^P = 3/2^+$  state

$5.3 \text{ fb}^{-1}$  PRL 108, 252002 (2012)



Two new states  $\Lambda_b^{*0}(5912)$  and  $\Lambda_b^{*0}(5920)$  observed by LHCb in  $\Lambda_b \pi^+ \pi^-$  spectrum, compatible with orbitally excited  $\Lambda_b$

$1.0 \text{ fb}^{-1}$  PRL 109, 172003 (2012)

$\Lambda_b^{*0}(5920)$  confirmed by CDF ([arXiv:1309.6269](https://arxiv.org/abs/1309.6269))

$$\Lambda_b \rightarrow \Lambda_c D_{(s)}^-$$

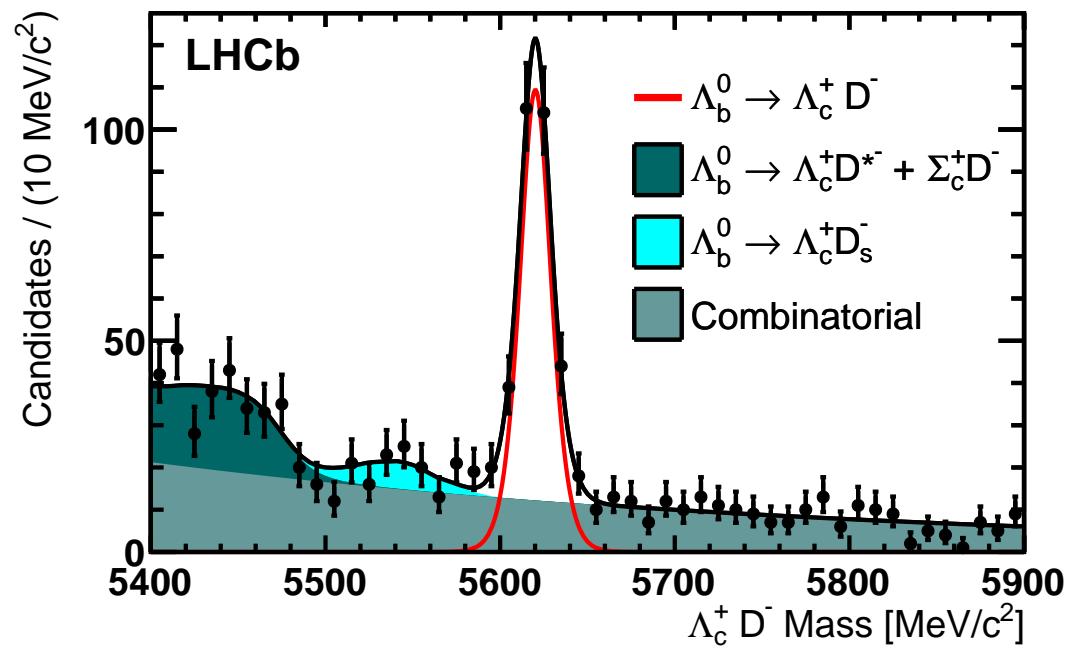
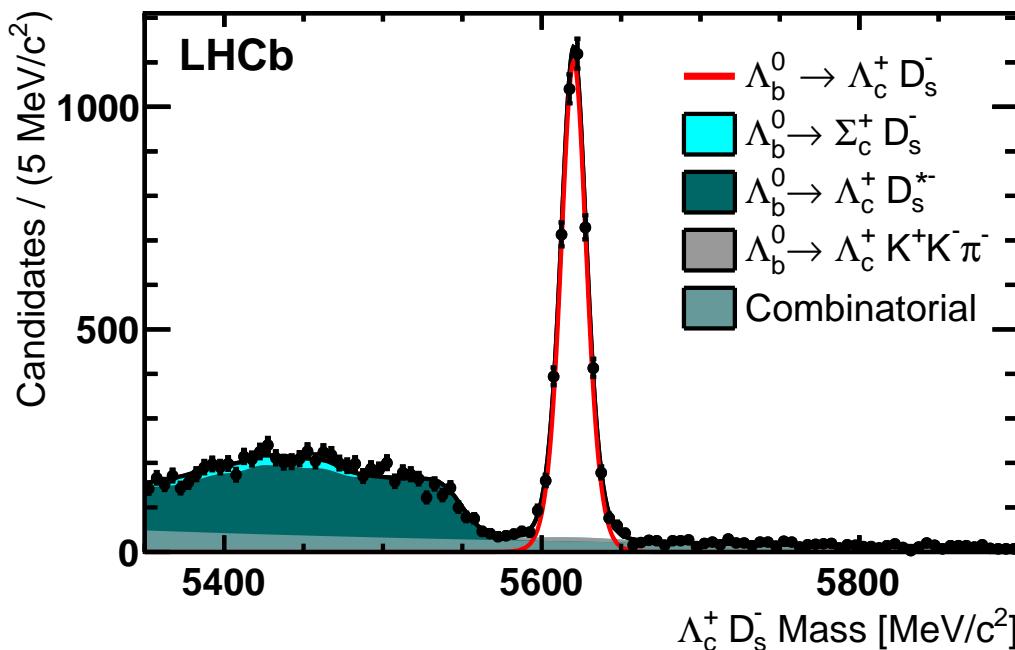
First observation of a  $b$ -baryon decay to double-charm provides best measurement of  $\Lambda_b$  mass

$$m(\Lambda_b) = 5619.30 \pm 0.24 \pm 0.18 \text{ MeV}/c^2$$

main systematic uncertainty from  $\Lambda_c, D^-$  lifetime values

$$\mathcal{B}(\Lambda_b \rightarrow \Lambda_c D_s^-) = (1.1 \pm 0.1) \times 10^{-2}$$

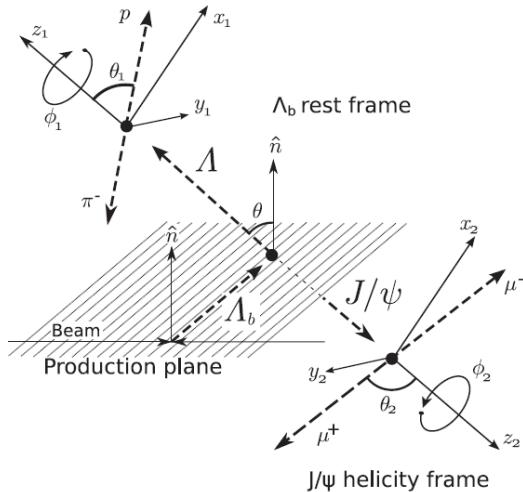
$$\mathcal{B}(\Lambda_b \rightarrow \Lambda_c D^-) = (4.7 \pm 0.6) \times 10^{-4}$$



# $\Lambda_b$ polarization and P-violating asymmetry

$$\frac{dN_{\Lambda_b}}{d\cos\theta} \propto \frac{1}{2}(1 + \alpha_b \mathbf{P} \cdot \mathbf{\hat{P}} \cos\theta)$$

$\Lambda$  helicity frame



Angular analysis of  $\Lambda_b \rightarrow J/\psi (\mu^+ \mu^-) \Lambda (\pi^-)$

- P-violating asymmetry  $\alpha_b$  related to helicity amplitudes  

$$\alpha_b = |\mathcal{M}_{+1/2,0}|^2 - |\mathcal{M}_{-1/2,0}|^2 + |\mathcal{M}_{-1/2,-1}|^2 - |\mathcal{M}_{+1/2,+1}|^2$$
can be determined from angular fit (even with null average  $\Lambda_b$  polarization  $\mathbf{P}$ ).
- Average  $\mathbf{P} = 0$  for ATLAS, using a symmetric rapidity interval around 0 ( $P(p_T, \eta) = -P(p_T, -\eta)$ );  $\mathbf{P}$  measured in LHCb
- No CPV assumed in  $\Lambda_b$  and  $\Lambda$  decays.



$1.0 \text{ fb}^{-1}$  PLB 724 (2013) 27



$4.6 \text{ fb}^{-1}$  PRD 89 092009 (2014)

$\mathbf{P}$	$0.06 \pm 0.07 \pm 0.02$	$0 \text{ (fixed)}$
$\alpha_b$	$0.05 \pm 0.17 \pm 0.07$	$0.30 \pm 0.16 \pm 0.06$
$ \mathcal{M}_{+1/2,0} ^2$	$0.01 \pm 0.04 \pm 0.03$	$0.17^{+0.12}_{-0.17} \pm 0.09$
$ \mathcal{M}_{-1/2,0} ^2$	$0.57 \pm 0.06 \pm 0.03$	$0.59^{+0.06}_{-0.07} \pm 0.03$
$ \mathcal{M}_{-1/2,-1} ^2$	$0.51 \pm 0.05 \pm 0.02$	$0.79^{+0.04}_{-0.05} \pm 0.02$
$ \mathcal{M}_{+1/2,+1} ^2$	$-0.10 \pm 0.04 \pm 0.03$	$0.08^{+0.13}_{-0.08} \pm 0.06$

- $\alpha_b$  values from ATLAS and LHCb in agreement, above range -0.2 to -0.1 indicated by most predictions
- polarization measured at LHCb below predicted values of 10-20 % (PLB 649 (2007) 152, PLB 614 (2005) 165) while consistent with vanishing polarization at small  $x$ , observed for  $\Lambda$  baryons in fixed-target experiments