

# Physics with $b$ -baryons at LHCb

J. McCarthy on behalf of the LHCb collaboration

University of Birmingham

06/05/2015

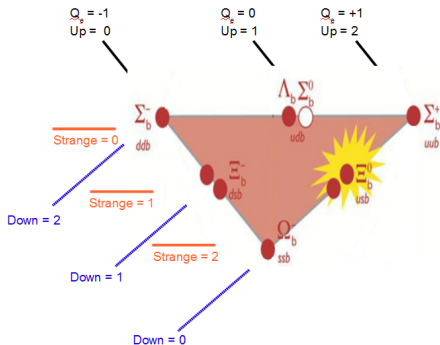
UNIVERSITY OF  
BIRMINGHAM



The 2014 Phenomenology Symposium  
University of Pittsburgh, 5-7 May 2014

# Introduction

- Physics with  $b$ -baryons relatively unexplored.
- Baryons have non-zero spin
  - Probe helicity structure of HQE Hamiltonian
- Need precision measurements of mass, lifetime and branching fractions.
- $CP$  measurements interesting.
  - Due interference between tree and loop diagrams.
  - Self tagging decays.
  - No  $CP$  asymmetries observed.
- Focus on results of baryon decays and  $\Xi_b^0$  measurements.



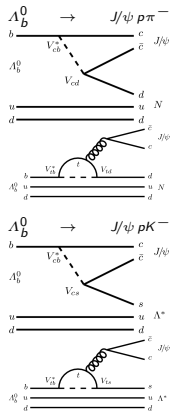
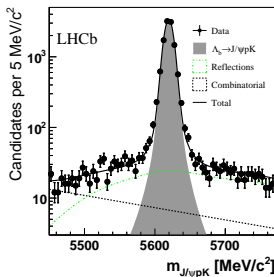
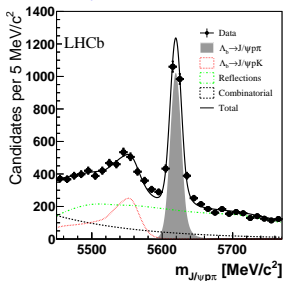
# Contents

- 1 Observation of the  $\Lambda_b^0 \rightarrow J/\psi p \pi^-$  decay.
- 2  $\Lambda_b^0 \rightarrow \Lambda_c^+ D^-$  and  $\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^-$  decays.
- 3  $\Lambda_b^0(\Xi_b^0) \rightarrow D^0 p h^-$  and  $\Lambda_b^0(\Xi_b^0) \rightarrow \Lambda_c^+ h^-$  decays.
- 4 Mass and lifetime measurements of  $\Xi_b^0$
- 5  $\Lambda_b^0$  production and  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  branching fraction measurements.

# $\Lambda_b^0 \rightarrow J/\psi p \pi^-$ observation. LHCb-PAPER-2014-020

- Search for  $\Lambda_b^0 \rightarrow J/\psi p \pi^-$  in  $3 \text{ fb}^{-1}$  data.
- $\Lambda_b^0 \rightarrow J/\psi p K^-$  decay as control channel.
- Loose selection followed by PID and Neural Network.

$\Lambda_b^0 \rightarrow J/\psi p \pi^-$  Preliminary  $\Lambda_b^0 \rightarrow J/\psi p K^-$



$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi p \pi^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi p K^-)} = \frac{N(\Lambda_b^0 \rightarrow J/\psi p \pi^-)}{N(\Lambda_b^0 \rightarrow J/\psi p K^-)} \times \frac{\eta(\Lambda_b^0 \rightarrow J/\psi p K^-)}{\eta(\Lambda_b^0 \rightarrow J/\psi p \pi^-)}$$

$$= 0.0824 \pm 0.0025 \text{ (stat)} \pm 0.0042 \text{ (syst)}$$

$\mathcal{A}^{CP}$  measurements. LHCb-PAPER-2014-020

- Measure raw asymmetries,  $\mathcal{A}^{\text{raw}} = \frac{N(\Lambda_b^0) - N(\bar{\Lambda}_b^0)}{N(\Lambda_b^0) + N(\bar{\Lambda}_b^0)}$

$$\mathcal{A}^{\text{raw}}(\Lambda_b^0 \rightarrow J/\psi p \pi^-) = (+7.9 \pm 2.2)\%$$

$$\mathcal{A}^{\text{raw}}(\Lambda_b^0 \rightarrow J/\psi p K^-) = (+1.1 \pm 0.7)\%$$

- Related to  $CP$  asymmetry:  $\mathcal{A}^{\text{raw}} = \mathcal{A}^{CP} + \mathcal{A}^{\text{prod}}(\Lambda_b^0) - \mathcal{A}^{\text{det}}(\pi/K) + \mathcal{A}^{\text{det}}(p)$
- Calculate difference in decay modes:

$$\begin{aligned} \Delta \mathcal{A}^{CP} &= \mathcal{A}^{CP}(J/\psi p \pi^-) - \mathcal{A}^{CP}(J/\psi p K^-) \\ &= \mathcal{A}^{\text{raw}}(J/\psi p \pi^-) - \mathcal{A}^{\text{raw}}(J/\psi p K^-) + \mathcal{A}^{\text{det}}(\pi) - \mathcal{A}^{\text{det}}(K) \end{aligned}$$

- Find  $\mathcal{A}^{\text{det}}(\pi) - \mathcal{A}^{\text{det}}(K)$  from  $\bar{B}^0 \rightarrow J/\psi \bar{K}^{*0}$  decay.

$$\begin{aligned} \mathcal{A}^{\text{raw}}(\bar{B}^0 \rightarrow J/\psi \bar{K}^{*0}) &= \mathcal{A}^{CP}(\bar{B}^0 \rightarrow J/\psi \bar{K}^{*0}) + \mathcal{A}^{\text{prod}}(B^0) + \mathcal{A}^{\text{det}}(\pi) - \mathcal{A}^{\text{det}}(K) \\ &\approx \mathcal{A}^{\text{det}}(\pi) - \mathcal{A}^{\text{det}}(K) \end{aligned}$$

Preliminary  $\Delta \mathcal{A}^{CP} = (+5.7 \pm 2.3 \text{ (stat)} \pm 1.2 \text{ (syst)})\%$

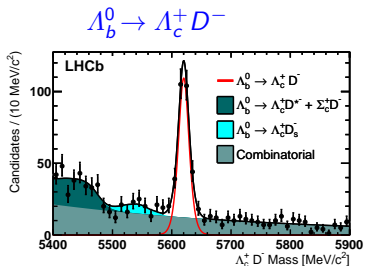
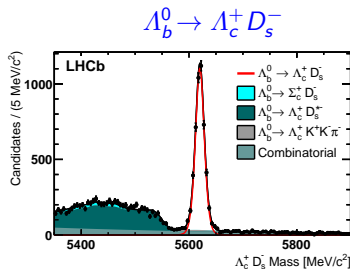
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# Beauty hadron decays into pairs of charm hadrons

arXiv:1403.3606

- Search for  $\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^-$  and  $\Lambda_b^0 \rightarrow \Lambda_c^+ D^-$  decays.
- Reconstruct resonances:  $D^+ \rightarrow K^- \pi^+ \pi^+$ ,  $D_s^+ \rightarrow K^- K^+ \pi^+$ ,  $\Lambda_c^+ \rightarrow p K^- \pi^+$
- First observation of these decays:



$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^-)} = 0.042 \pm 0.003 \text{ (stat)} \pm 0.003 \text{ (syst)}$$

# Mass measurement arXiv:1403.3606

- Measure relative to high statistics channel  $\bar{B}^0 \rightarrow D^+ D_s^-$
- Double ratio removes any dependence on production fractions.

$$\left[ \frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^-)}{\mathcal{B}(\bar{B}^0 \rightarrow D^+ D_s^-)} \right] / \left[ \frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)}{\mathcal{B}(\bar{B}^0 \rightarrow D^+ \pi^-)} \right] = 0.96 \pm 0.02 \text{ (stat)} \pm 0.06 \text{ (syst)}$$

$$\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^-) = (1.1 \pm 0.1) \times 10^{-2}$$

$$\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D^-) = (4.7 \pm 0.6) \times 10^{-4}$$

- Kinematics similar enough to measure mass difference
  - $[m(\Lambda_b^0) - m(\Lambda_c^+) - m(D_s^-)] - [m(B^0) - m(D^+) - m(D_s^-)]$  is small.
  - Small uncertainty on momentum scale ( $\approx 0.03\%$ ).

$$m(\Lambda_b^0) - m(B^0) = 339.72 \pm 0.24 \text{ (stat)} \pm 0.18 \text{ (syst)} \text{ MeV}/c^2$$

$$m(\Lambda_b^0) = 5619.36 \pm 0.26 \text{ MeV}/c^2$$

- Averaged with LHCb  $\Lambda_b^0 \rightarrow J/\psi \Lambda$  result Phys. Rev. Lett. 110 (2013) 182001

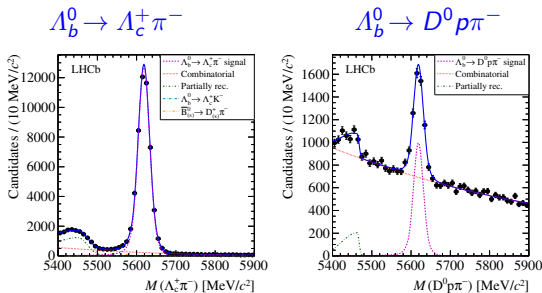


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# Measurement of $\Lambda_b^0 \rightarrow D^0 p \pi^-$ Phys. Rev. D89 (2014) 032001

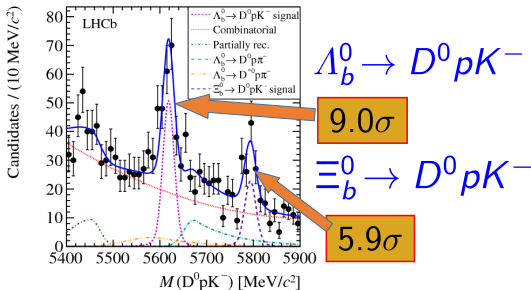
- Dalitz analysis would allow extraction of  $\gamma$
- Reconstruct  $D^0 \rightarrow K^- \pi^+$  decay.
- Normalize to  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  with  $\Lambda_c^+ \rightarrow p K^- \pi^+$ .
- Search in  $1 \text{ fb}^{-1}$  2011 data
- Measure Cabibbo favoured  $\Lambda_b^0 \rightarrow D^0 p \pi^-$  with loose selection only.



$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow D^0 p \pi^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)} \times \frac{\mathcal{B}(D^0 \rightarrow K^- \pi^+)}{\mathcal{B}(\Lambda_c^+ \rightarrow p K^- \pi^+)} = 0.0806 \pm 0.0023 \pm 0.0035$$

# Observation of $\Lambda_b^0(\Xi_b^0) \rightarrow D^0 p K^-$ Phys. Rev. D89 (2014) 032001

- Search also for Cabibbo suppressed  $\Lambda_b^0$  and  $\Xi_b^0$  decays.
- Apply BDT selection to separate signal and background.

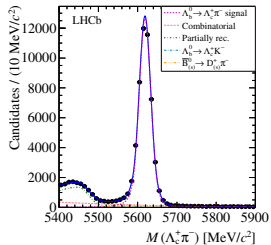


$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow D^0 p K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow D^0 p \pi^-)} = 0.073 \pm 0.008^{+0.005}_{-0.006}$$

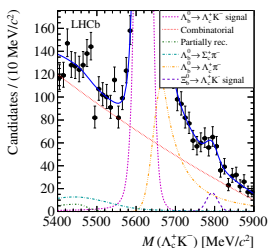
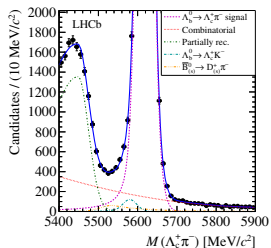
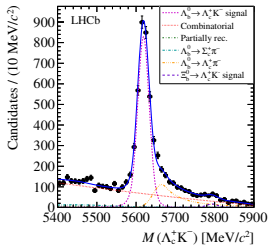
$$\frac{f_{\Xi_b^0} \times \mathcal{B}(\Xi_b^0 \rightarrow D^0 p K^-)}{f_{\Lambda_b^0} \times \mathcal{B}(\Lambda_b^0 \rightarrow D^0 p K^-)} = 0.44 \pm 0.09 \pm 0.06$$

# Search for $\Lambda_b^0(\Xi_b^0) \rightarrow \Lambda_c^+ h^-$ Phys. Rev. D89 (2014) 032001

$$\Lambda_b^0(\Xi_b^0) \rightarrow \Lambda_c^+ \pi^-$$



$$\Lambda_b^0(\Xi_b^0) \rightarrow \Lambda_c^+ K^-$$



- First observation of  $\Lambda_b^0 \rightarrow \Lambda_c^+ K^- > 10\sigma$

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)} = 0.0731 \pm 0.0016 \pm 0.0016$$

- Evidence for  $\Xi_b^0 \rightarrow \Lambda_c^+ K^-$  at  $3.3\sigma$

ZOOMED

# Contents

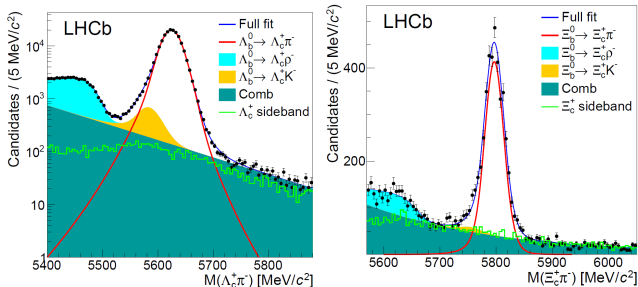
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# Mass of $\Xi_b^0$ LHCb-PAPER-2014-021

- CDF measured  $m(\Xi_b^0) = 5787.8 \pm 5.0 \pm 1.3 \text{ MeV}/c^2$
- Measured using full  $3 \text{ fb}^{-1}$  data.
- Using  $\Xi_b^0 \rightarrow \Xi_c^+ \pi^-$  with  $\Xi_c^+ \rightarrow p K^- \pi^+$
- Normalise with  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  with  $\Lambda_c^+ \rightarrow p K^- \pi^+$

Phys. Rev. Lett. 107 (2011) 102001

$\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  Preliminary  $\Xi_b^0 \rightarrow \Xi_c^+ \pi^-$

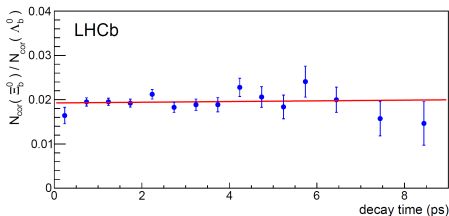


$$m(\Xi_b^0) - m(\Lambda_b^0) = 172.44 \pm 0.39 \text{ (stat)} \pm 0.17 \text{ (syst)} \text{ MeV}/c^2$$

**Preliminary**  $m(\Xi_b^0) = 5791.80 \pm 0.39 \text{ (stat)} \pm 0.17 \text{ (syst)} \pm 0.26 \text{ MeV}/c^2$

Lifetime of  $\Xi_b^0$  LHCb-PAPER-2014-021

- First measurement of  $\Xi_b^0$  lifetime.
- Fit to ratio of yields and function of decay time.



Preliminary

- Exponential function,  $e^{\beta t}$ , where  $\beta = \frac{1}{\tau(\Xi_b^0)} - \frac{1}{\tau(\Lambda_b^0)}$

$$\begin{aligned} \frac{\tau(\Xi_b^0)}{\tau(\Lambda_b^0)} &= \frac{1}{1 - \beta\tau(\Lambda_b^0)} \\ &= 1.006 \pm 0.018 \text{ (stat)} \pm 0.010 \text{ (syst)} \end{aligned}$$

*Preliminary*  $\tau(\Xi_b^0) = 1.477 \pm 0.026 \text{ (stat)} \pm 0.014 \text{ (syst)} \pm 0.013(\Lambda_b^0) \text{ ps}$

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# $\Lambda_b^0$ production fractions

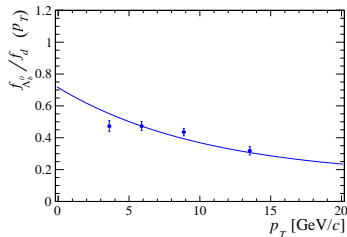
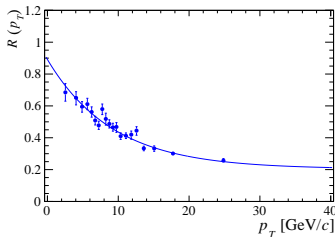
LHCb-PAPER-2014-004

- $f_{\Lambda_b^0}$  varies as a function of  $p_T$  and  $\eta$
- Measured by LHCb in semi-leptonic decays [Phys. Rev. D85 \(2012\) 032008](#)
- Updated measurement using  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  and  $\bar{B}^0 \rightarrow D^+ \pi^-$  decays.
- Fit exponential for  $p_T$  dependence, and linear  $\eta$  dependence.

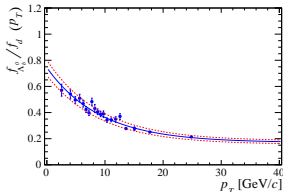
$$\frac{f_{\Lambda_b^0}}{f_d}(X) = \frac{\mathcal{B}(B^0 \rightarrow D^+ \pi^-) \mathcal{B}(D^+ \rightarrow K^- \pi^+ \pi^+)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-) \mathcal{B}(\Lambda_c^+ \rightarrow p K^- \pi^+)} \times \frac{N_{\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-}(X) \epsilon_{B^0 \rightarrow D^+ \pi^-}(X)}{N_{B^0 \rightarrow D^+ \pi^-}(X) \epsilon_{\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-}(X)}$$

$$\equiv S \times R(X)$$

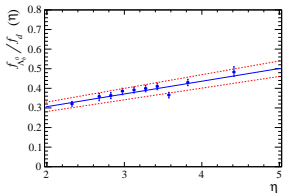
Preliminary



## Preliminary



← 40 - 50%



$$\frac{f_{\Lambda_b^0}}{f_d}(p_T) = a + \exp(b + c \times p_T [\text{GeV}/c])$$

$$a = 0.151 \pm 0.016_{-0.025}^{+0.024}$$

$$b = -0.573 \pm 0.040_{-0.097}^{+0.101}$$

$$c = -0.095 \pm 0.007 \pm 0.014$$

$$\frac{f_{\Lambda_b^0}}{f_d}(\eta) = a + b \times (\eta - 3.198)$$

$$a = 0.387 \pm 0.013_{-0.030}^{+0.028}$$

$$b = 0.067 \pm 0.005_{-0.009}^{+0.012}$$

- From scale factor,  $S$ , extract absolute branching fraction:

$$\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-) = (4.46 \pm 0.36) \times 10^{-3}$$

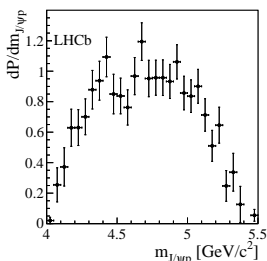
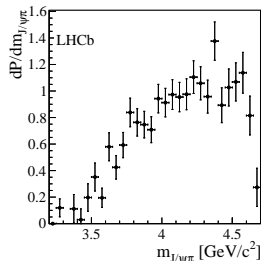
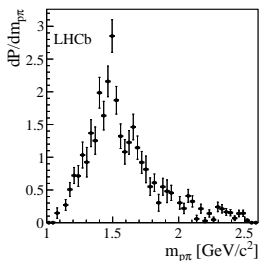
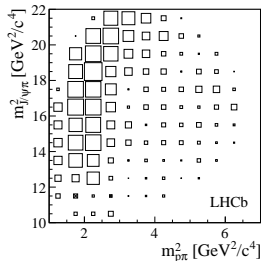
- Most precise measurement of a  $\Lambda_b^0$  branching fraction.

# Summary

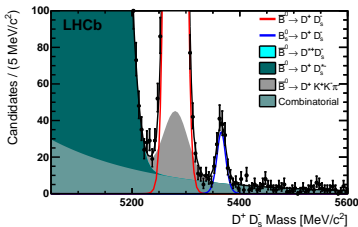
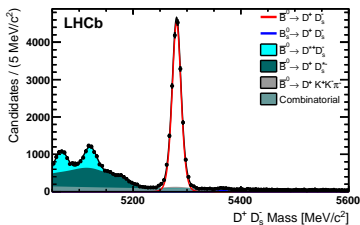
- First observation of  $\Lambda_b^0 \rightarrow J/\psi p \pi^-$
- $\Delta \mathcal{A}^{CP} = \mathcal{A}^{CP}(J/\psi p \pi^-) - \mathcal{A}^{CP}(J/\psi p K^-) = (+5.7 \pm 2.3 \text{ (stat)} \pm 1.2 \text{ (syst)})\%$
- First observation of  $\Lambda_b^0 \rightarrow \Lambda_c^+ D^-$  and  $\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^-$  decays.
- Used to measure  $m(\Lambda_b^0) = 5619.36 \pm 0.26 \text{ MeV}/c^2$
- First observation of  $\Lambda_b^0 \rightarrow \Lambda_c^+ K^-$  and evidence for  $\Xi_b^0 \rightarrow \Lambda_c^+ K^-$
- Most precise measurements of  $\Xi_b^0$  baryon.
  - $m(\Xi_b^0) = 5791.80 \pm 0.39 \text{ (stat)} \pm 0.17 \text{ (syst)} \pm 0.26 \text{ MeV}/c^2$
  - $\tau(\Xi_b^0) = 1.477 \pm 0.026 \text{ (stat)} \pm 0.014 \text{ (syst)} \pm 0.013(\Lambda_b^0)ps$
- Measured  $\Lambda_b^0$  production fractions as a function of  $p_T$  and  $\eta$
  
- Many new observations of baryonic decays shown.
- Expect many more in the years to come!

## Back-Up Slides

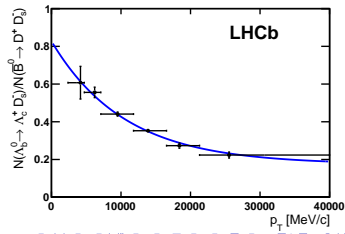
# $\Lambda_b^0 \rightarrow J/\psi p \pi^-$ Dalitz distributions



# $\bar{B}^0 \rightarrow D^+ D_s^-$ and $B_s^0 \rightarrow D^+ D_s^-$ invariant mass distributions



Efficiency corrected ratio of yields as a function of  $p_T$



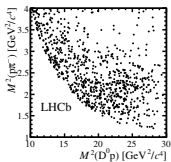
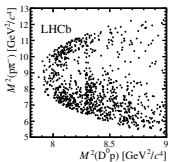
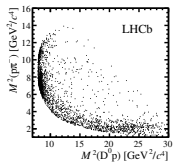
$$\frac{\mathcal{B}(B_s^0 \rightarrow D^+ D_s^-)}{\mathcal{B}(\bar{B}^0 \rightarrow D^+ D_s^-)} = 0.038 \pm 0.004 \pm 0.003$$

$$\frac{\mathcal{B}(\bar{B}^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-)}{\mathcal{B}(\bar{B}^0 \rightarrow D^+ D_s^-)} < 0.0022 \text{ at } 95\% \text{ C.L.}$$

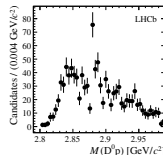
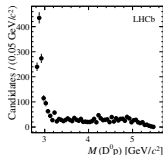
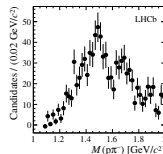
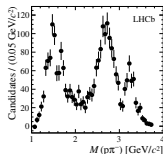
$$\frac{\mathcal{B}(B_s^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-)}{\mathcal{B}(B_s^0 \rightarrow D^+ D_s^-)} < 0.30 \text{ at } 95\% \text{ C.L.}$$

# $\Lambda_b^0 \rightarrow D^0 p \pi^-$ Dalitz distributions

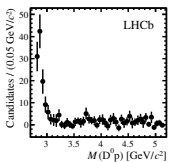
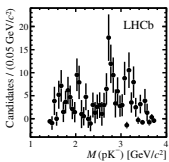
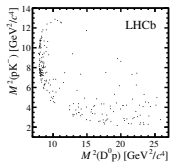
$$\Lambda_b^0 \rightarrow D^0 p \pi^-$$



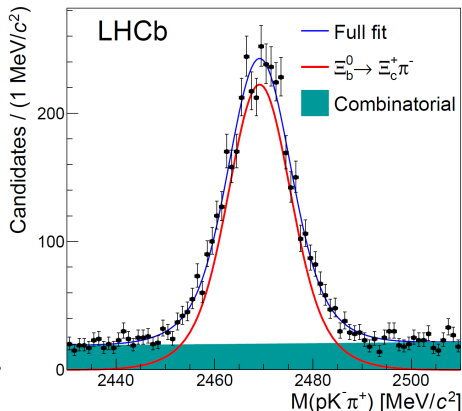
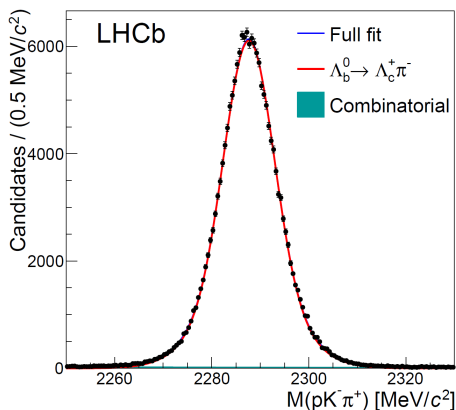
$$\Lambda_b^0 \rightarrow D^0 p \pi^-$$



$$\Lambda_b^0 \rightarrow D^0 p K^-$$



# $\Xi_c^+$ mass.



$$m(\Xi_c^+) - m(\Lambda_c^+) = 181.51 \pm 0.14 (\text{stat}) \pm 0.17 (\text{syst}) \text{ MeV}/c^2$$

*Preliminary*  $m(\Xi_c^+) = 2467.97 \pm 0.14 (\text{stat}) \pm 0.09 (\text{syst}) \pm 0.14 \text{ MeV}/c^2$