



華中師範大學



# $B_c$ physics at LHCb

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On behalf of the LHCb Collaboration

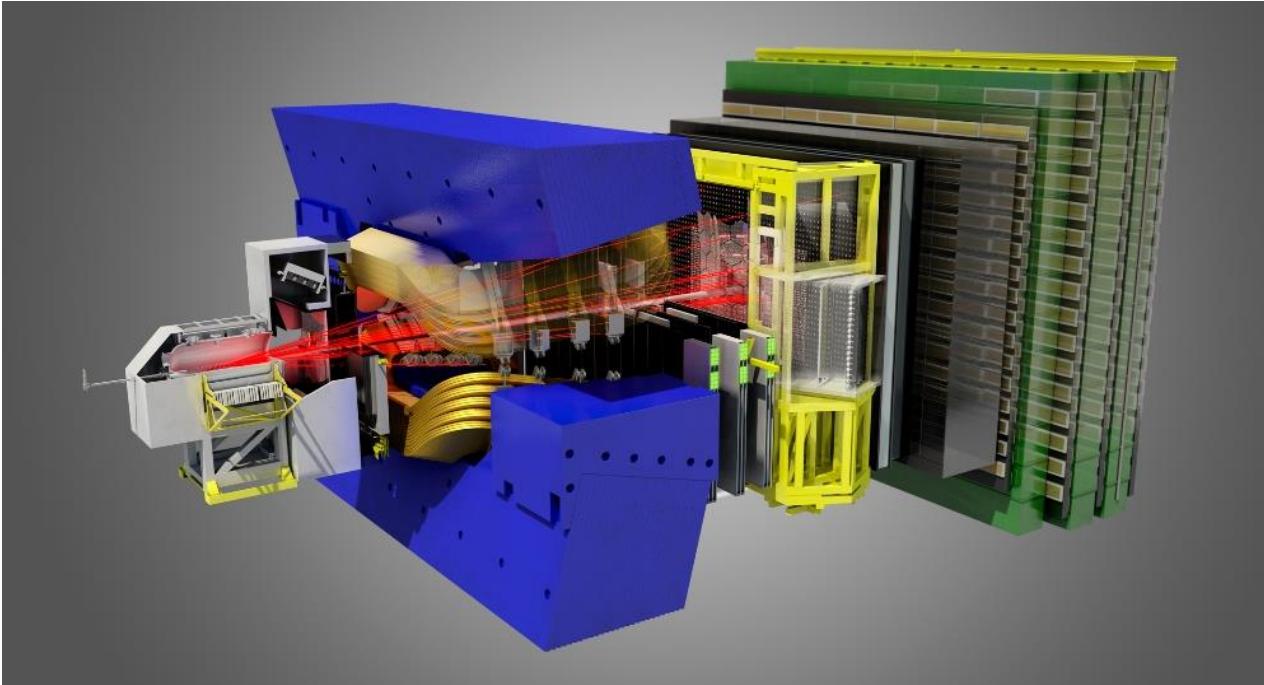
Central China Normal University

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DIS 2016 conference

# Introduction

- $B_c^+$  meson discovered by CDF in 1998
  - Only  $\sim 10$  decay channels are currently known
  - The measured mass has larger uncertainty compared with that of other B meson:  $6275.1 \pm 1.0$  MeV [PDG 2015](#)
- $B_c^+$  meson is the ground state of the ( $\bar{b}c$ ) bound state
- $B_c^+$  has a much **shorter lifetime** than other B mesons
- Heavy quark-antiquark pair of different flavours: unique state in the Standard Model
- Great potential for the LHC, especially the **LHCb** experiment

# LHCb detector and $B_c^+$ production



Unique geometrical acceptance:  $2 < \eta < 5$   
Excellent Vertex Locator (VELO):  $\sigma_{PV_{xy}} \sim 10\mu m$ ,  
 $\sigma_{PV_z} \sim 60\mu m$

Tracking system:  $\Delta p/p \sim 0.5 - 1\%$

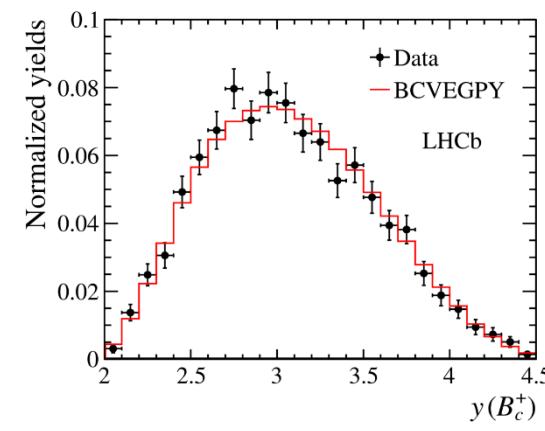
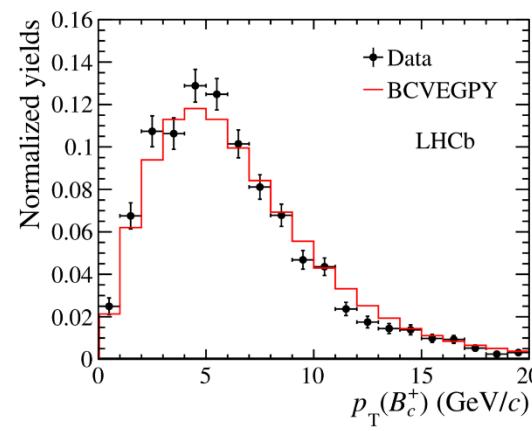
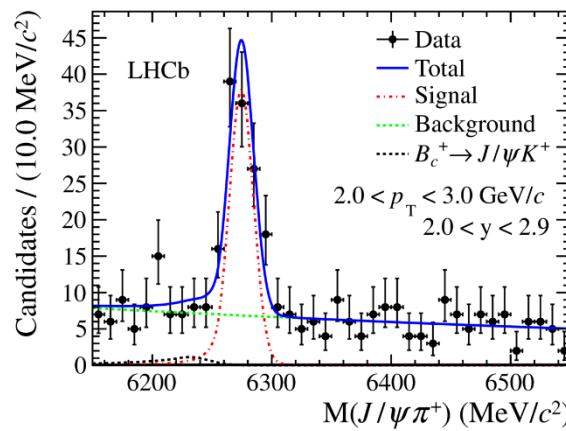
Muon system:  $\varepsilon \sim 99\%$ , MisID ( $h \rightarrow \mu$ )  $\sim 1\%$

- $B_c^+$  is produced mainly through **gluon-gluon fusion** at hadron colliders: high energy hadron colliders with high luminosity
- Production cross section increases fast with higher central of energy
  - $0.47 \mu b$  @ 8 TeV,  $0.9 \mu b$  @ 14 TeV

# $B_c^+$ production measurement

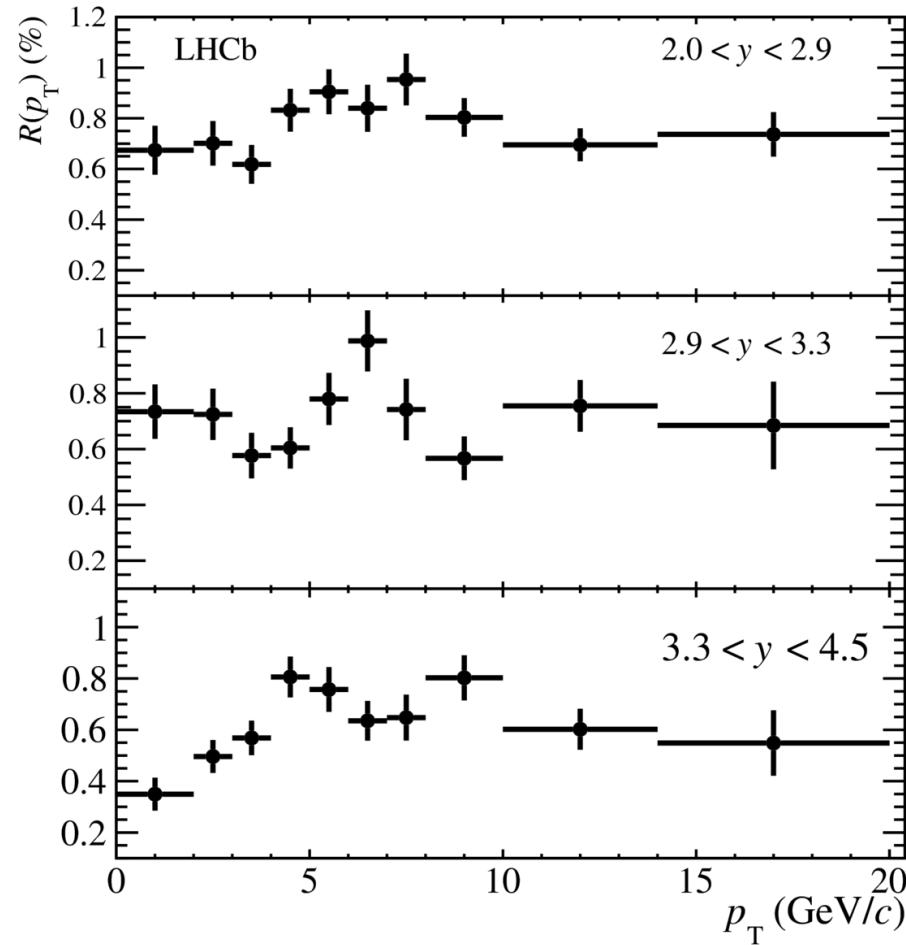
- Proton-Proton collisions at 8 TeV,  $2 \text{ fb}^{-1}$  of data collected in 2012
- Measured in  $B_c^+ \rightarrow J/\psi \pi^+$  decay, relative to  $B^+ \rightarrow J/\psi K^+$
- Selection:  $J/\psi$  + charged particle; trained BDT:  $\chi_{IP}^2, p_T$  of  $\mu, J/\Psi, \pi^+$ , decay length/time,  $\chi_{Vtx}^2$
- First double-differential cross section measurement of  $B_c^+$ 
  - Range:  $0 < p_T < 20 \text{ GeV}/c$ ,  $2 < y < 4.5$
- $R = (0.683 \pm 0.018 \pm 0.009)\%$ 
  - Consistent with 7 TeV results
  - Lower than CMS results ( $p_T > 15 \text{ GeV}/c$ ,  $|y| < 1.6$ ) as expected:  $B_c^+$   $p_T$  softer than  $B^+$

$$R = \frac{\sigma(B_c^+) \mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)}{\sigma(B^+) \mathcal{B}(B^+ \rightarrow J/\psi K^+)}$$



PRL 114, 132001 (2015)

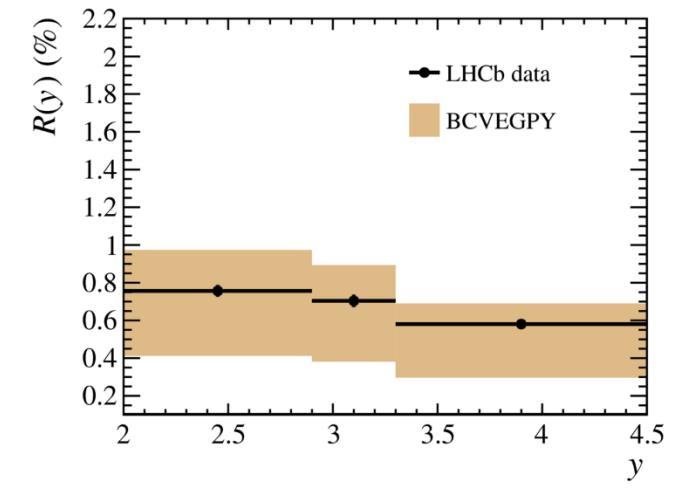
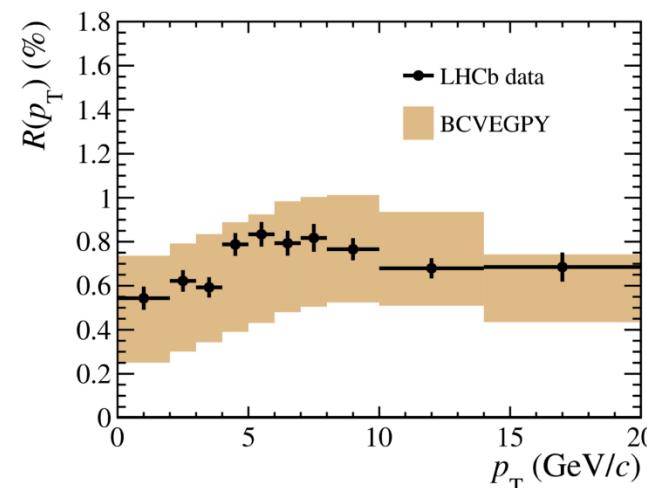
# $B_c^+$ production measurement



- $R$  as function of  $p_T$  and  $y$  agrees with theoretical prediction
  - FNOLL for  $B^+$ , BCVEGPY for  $B_c^+$

[JHEP 10 \(2012\) 137](#)

[Comput. Phys. Commun. 174 \(2006\) 241](#)



[PRL 114, 132001 \(2015\)](#)

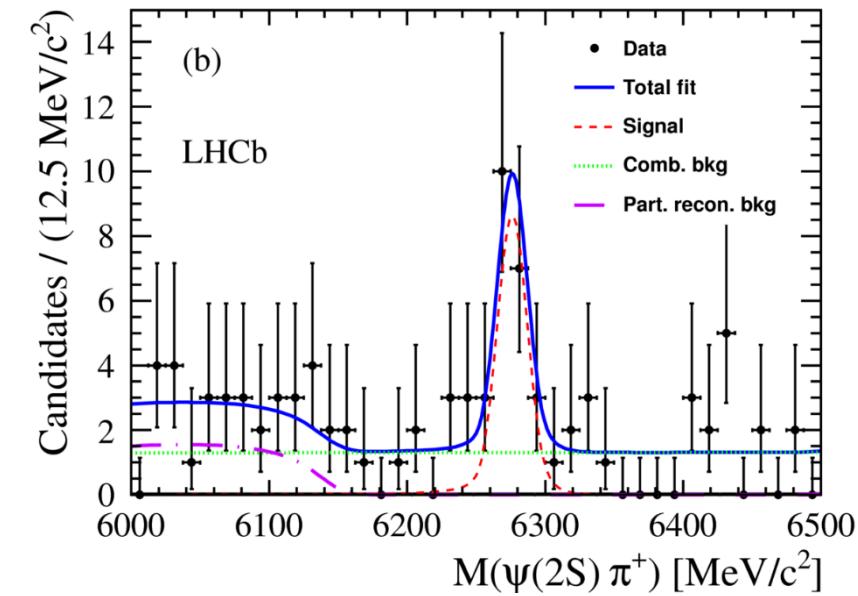
# $B_c^+ \rightarrow \Psi(2S)\pi^+$ relative BF

- First observed by LHCb with 2011 1 fb<sup>-1</sup> data
- Update with full Run-I data set, 3 fb<sup>-1</sup>
  - Standard  $\Psi(2S) + J/\Psi$  selection + a charged pion
  - BDT: With 2 independently trained BDT, to avoid bias
    - $\chi_{IP}^2$ , kinematic, decay length/time,  $\chi_{Vtx}^2$ , angles

$$R_B = 0.026 \pm 0.032 \text{ (stat)} \pm 0.007 \text{ (syst)} \pm 0.006 \text{ (BF)}$$

- Consistent with 7 TeV results
- The results can distinguish the differences between theoretical calculations of  $R_B$ 
  - Nonrelativistic QCD at NLO, perturbative QCD based on  $k_T$  factorization, the relativistic quark model, the quark potential model, the relativistic constituent quark model, the QCD relativistic potential model

$$R_B = \frac{\mathcal{B}(B_c^+ \rightarrow \psi(2S)\pi^+)}{\mathcal{B}(B_c^+ \rightarrow J/\psi\pi^+)}$$

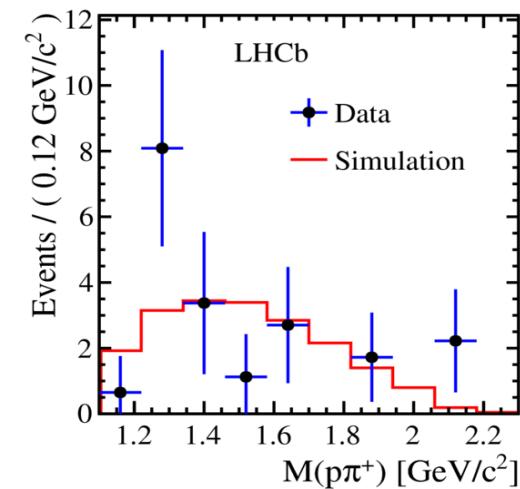
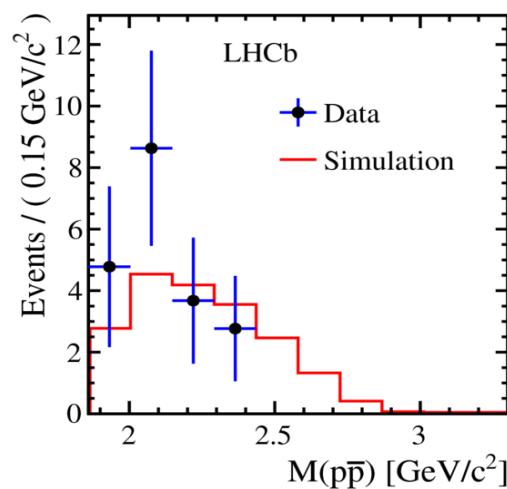
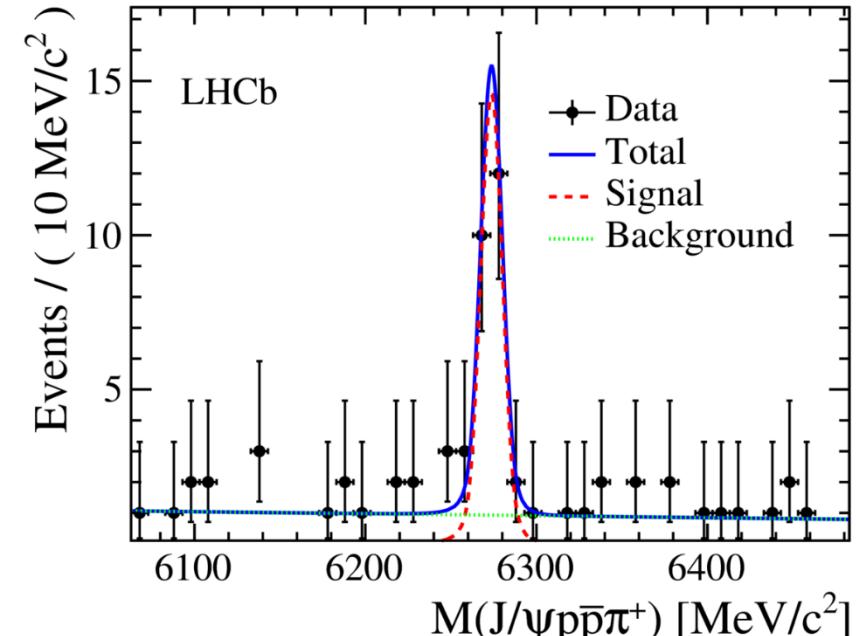


# First baryonic decay

- Proton-proton collisions at 7/8 TeV,  
3 fb<sup>-1</sup> full Run-I data
- Search in  $B_c^+ \rightarrow J/\psi p\bar{p}\pi^+$ 
  - $N = 23.9 \pm 5.3$  ( $7.3\sigma$ )

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

- $M(p\bar{p})$  and  $M(p\pi^+)$  consistent with simulation



[PRL 113, 152003 \(2014\)](#)

# Mass measurement

- LHCb average:  
 $6274.7 \pm 1.2$  MeV

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

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

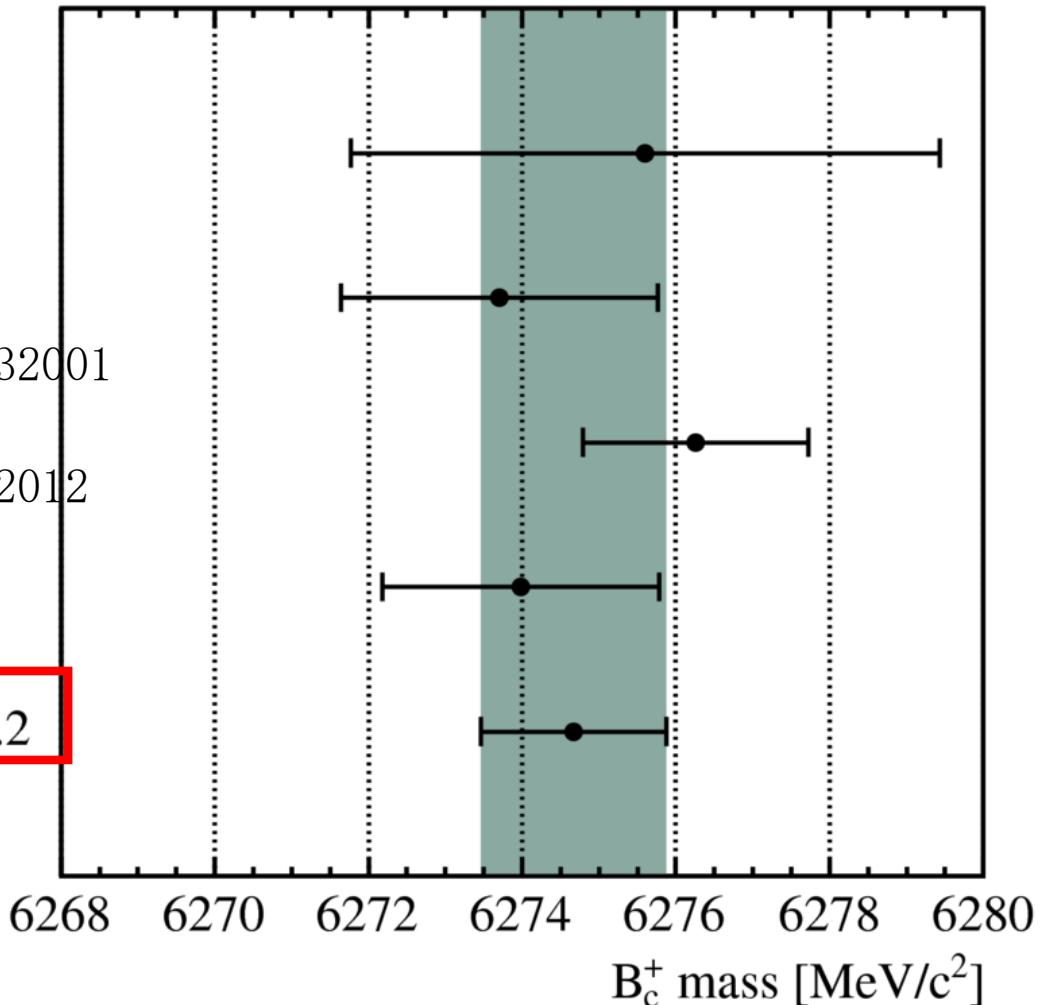
PRL 109 (2012) 232001

LHCb  $B_c^+ \rightarrow J/\psi D^\pm$

PRD 87 (2013) 112012

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

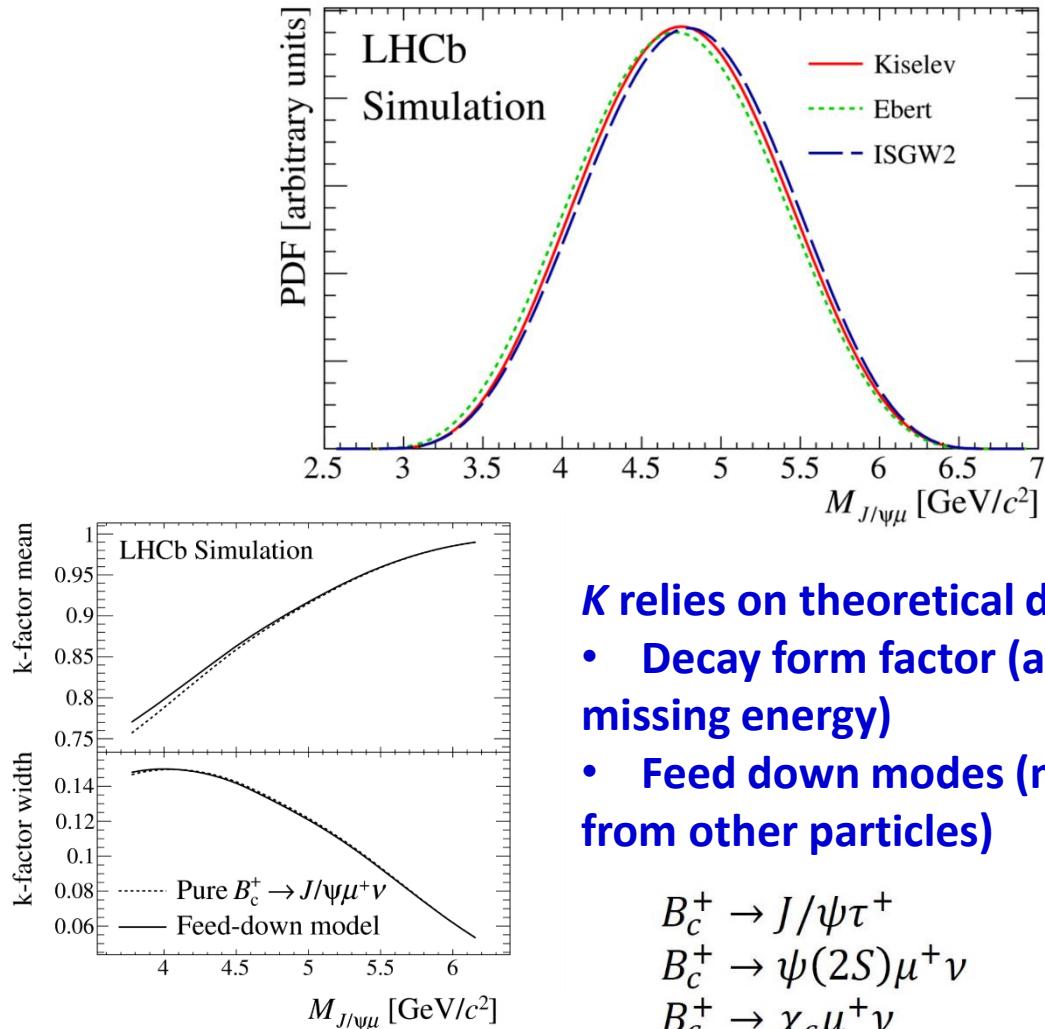
LHCb average:  $6274.7 \pm 1.2$



# Lifetime measurement with $B_c^+ \rightarrow J/\Psi \mu^+ \nu X$

- Proton-proton collisions at 8 TeV, 2 fb<sup>-1</sup> Run-I data
- Signal: di-muon ( $J/\Psi$ ) + bachelor muon track
- Pseudo-proper time:  $t_{ps} = p \cdot (\nu - x) \frac{M_{3\mu}}{|p|^2}$ 
  - $M_{3\mu}, p$ : Mass, three momentum of  $J/\Psi \mu$  system in the lab frame
  - $\nu, x$ : measured position of B decay and production vertex
- K-factor method: infer B decay time and pseudo-proper time
- 2D maximum likelihood unbinned fit:  $t_{ps}$  and  $M_{3\mu}$  (3.5-6.3 GeV/c<sup>2</sup>)

# Lifetime measurement with $B_c^+ \rightarrow J/\Psi \mu^+ \nu X$



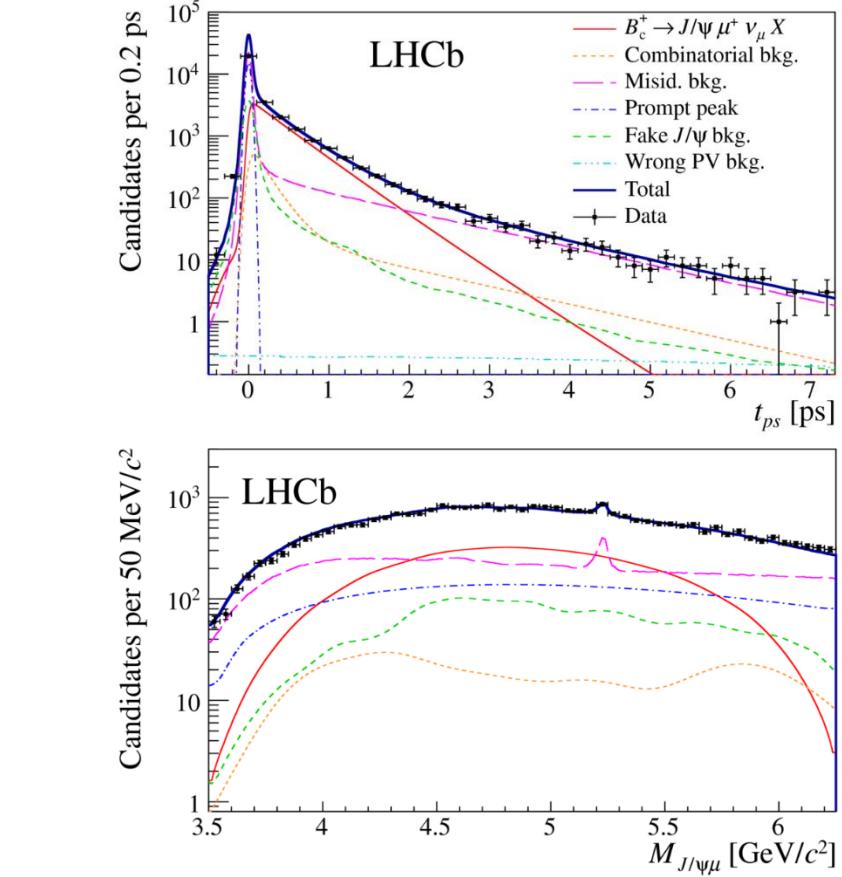
2016/4/12

- K relies on theoretical decay modes**
  - Decay form factor (accounting for  $\nu$  missing energy)**
  - Feed down modes (missing energy from other particles)**

$$\begin{aligned} B_c^+ &\rightarrow J/\psi \tau^+ \\ B_c^+ &\rightarrow \psi(2S) \mu^+ \nu \\ B_c^+ &\rightarrow \chi_c \mu^+ \nu \end{aligned}$$

...

Bc physics at LHCb



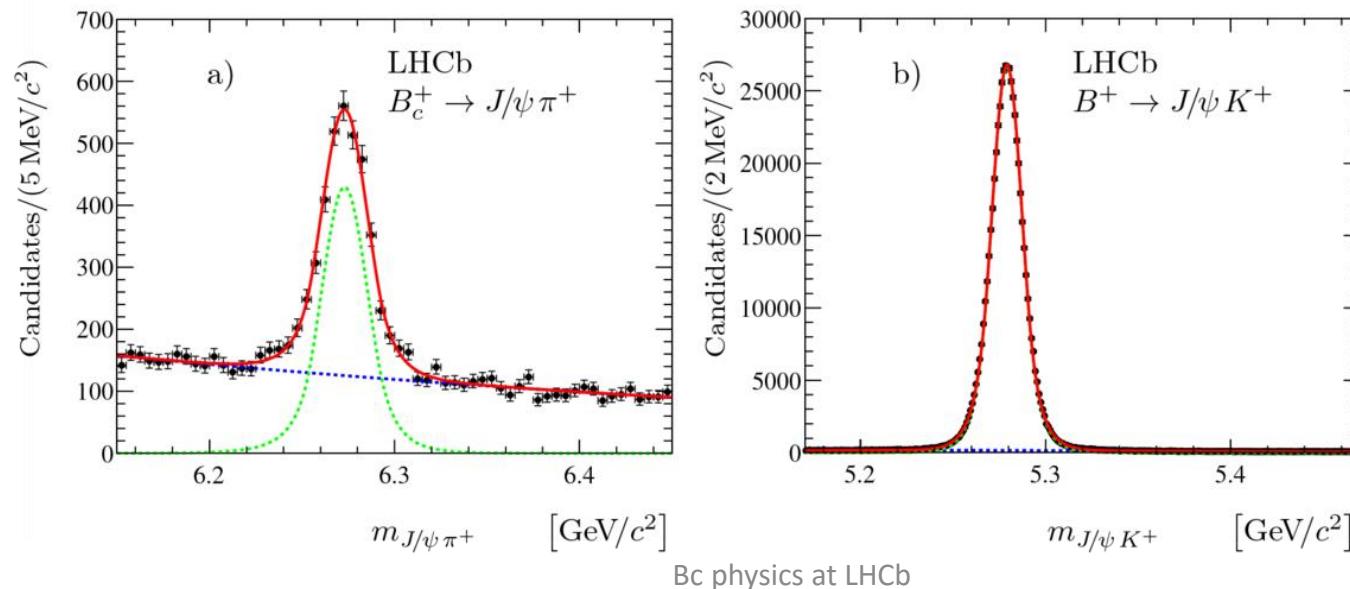
$$\tau = 509 \pm 8 \text{ (stat)} \pm 12 \text{ (syst)} \text{ fs}$$

EPJC 74 (2014) 5, 2839

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# Lifetime measurement with $B_c^+ \rightarrow J/\Psi\pi^+$

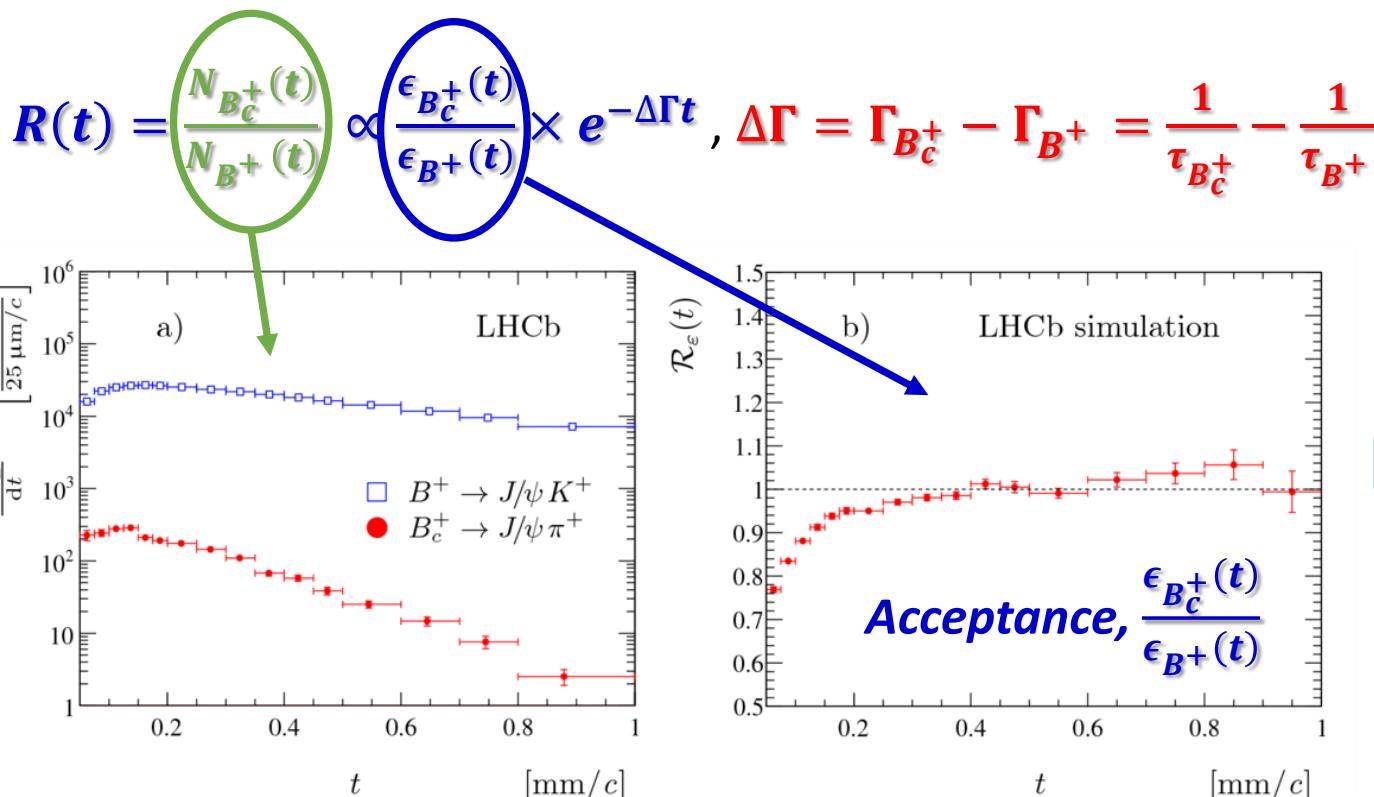
- Proton-proton collisions at 7/8 TeV,  $3 \text{ fb}^{-1}$  full Run-I data
- With  $B_c^+ \rightarrow J/\Psi\pi^+$  and  $B^+ \rightarrow J/\Psi K^+$
- Measure the time evolution of  $B_c^+$  and  $B^+$
- Better signal and background separation with hadronic channel



[PLB 742 \(2015\) 29](#)

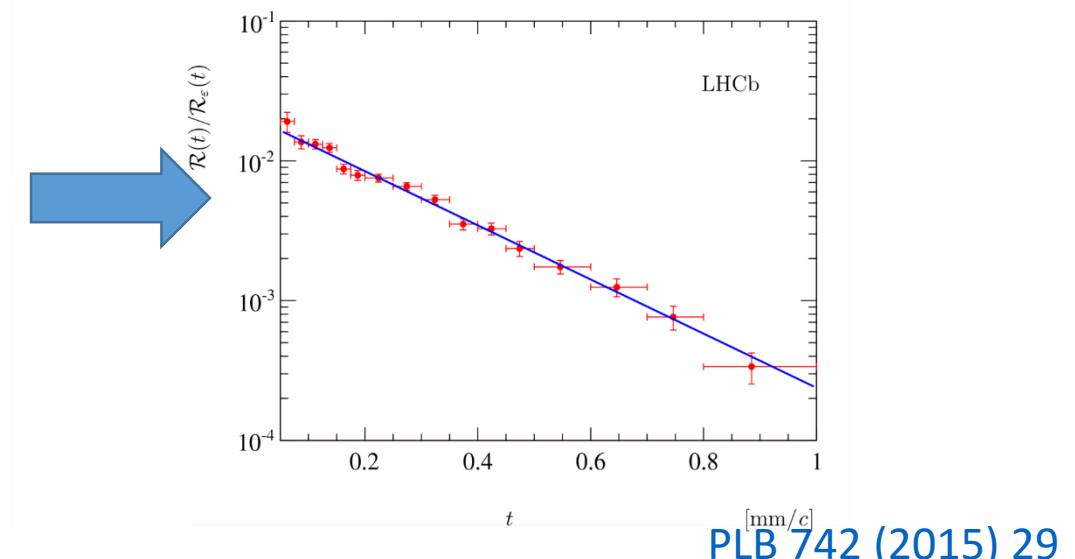
# Lifetime measurement with $B_c^+ \rightarrow J/\Psi\pi^+$

**Decay time distribution:**  $N_B(t) \propto \epsilon_B(t) \times e^{-t/\tau_B}$ ,  $\epsilon_B(t)$  is acceptance function



Decay time distribution

$$\begin{aligned} \Delta\Gamma &= 4.46 \pm 0.14 \pm 0.07 \text{ mm}^{-1}c, \\ \tau_{B^+} \text{ from PDG} \\ \tau_{B_c^+} &= 513.4 \pm 11.0 \pm 5.7 \text{ fs} \end{aligned}$$



# Conclusion

- For  $B_c^+$  measurement, LHCb achieved the world best measurements of
  - Production cross section
  - Mass
  - Lifetime
- In the LHC Run-II, with increasing luminosity, enhanced production cross section
  - Precision measurement of  $B_c^+$  meson
  - Yielding to new exciting results: excited states

# Conclusion

<b>Production</b>		<b>New decay and BF (<math>B_c^+ \rightarrow \dots</math>)</b>	
$\frac{\sigma(B_c^+)B(B_c^+ \rightarrow J/\psi\pi^+)}{\sigma(B^+)B(B^+ \rightarrow J/\psi K^+)}$	PRL 109 (2012) 232001	$J/\psi\pi^+\pi^-\pi^+$	PRL 108 (2012) 251802
$\frac{\sigma(B_c^+)}{\sigma(B_s^0)}B(B_c^+ \rightarrow B_s^0\pi^+)$	PRL 111 (2013) 181801	$\psi(2S)\pi^+$	PRD 87 (2013) 071103 (R)
$\frac{\sigma(B_c^+)B(B_c^+ \rightarrow J/\psi\pi^+)}{\sigma(B^+)B(B^+ \rightarrow J/\psi K^+)}$ vs. $dp_T dy$	PRL 114 (2015) 132001		PRD 92 (2015) 072007
<b>Mass</b>		$J/\psi K^+$	JHEP 09 (2013) 075
$M(B_c^+ \rightarrow J/\psi\pi^+)$	PRL 109 (2012) 232001	$J/\psi D_s^{(*)+}$	PRD 87 (2013) 112012
$M(B_c^+ \rightarrow J/\psi D_s^+)$	PRD 87 (2013) 112012	$J/\psi K^+K^-\pi^+$	JHEP 1311 (2013) 094
$M(B_c^+ \rightarrow J/\psi p\bar{p}\pi^+)$	PRL 113 (2014) 152003	$J/\psi 3\pi^+2\pi^-$	JHEP 1405 (2014) 148
<b>Lifetime</b>		$J/\psi p\bar{p}\pi^+$	PRL 113 (2014) 152003
$\tau(B_c^+ \rightarrow J/\psi\mu\nu)$	EPJC 74 (2014) 2839	$\mathcal{B}(J/\psi\pi^+)/\mathcal{B}(J/\psi\mu\nu)$	PRD 90 (2014) 032009
$\tau(B_c^+ \rightarrow J/\psi\pi^+)$	PLB 742 (2015) 39	$B_s^0\pi^+$	PRL 111 (2013) 181801

# *Backup*

# Lifetime measurement with $B_c^+ \rightarrow J/\Psi \mu^+ \nu X$

- Proton-proton collisions at 8 TeV, 2 fb<sup>-1</sup> Run-I data
- Signal: di-muon ( $J/\Psi$ ) + bachelor muon track
- Pseudo-proper time:  $t_{ps} = p \cdot (\nu - x) \frac{M_{3\mu}}{|p|^2}$ 
  - $p$ : three momentum of  $J/\Psi \mu$  system in the lab frame
  - $\nu/x$ : measured position of B decay and production vertex
- K-factor method: infer B decay time and pseudo-proper time
  - $k' \equiv \frac{t_{ps}}{t^*} = \frac{t_{ps}}{t_{ps}^*} \times \frac{t_{ps}^*}{t^*} \equiv \frac{t_{ps}}{t_{ps}^*} \times k$
  - $t_{ps}^*$ : pseudo-proper time truth value
  - $k \equiv \frac{t_{ps}}{t^*}$ : only kinematic effects from unobserved final state particle
- 2D maximum likelihood unbinned fit:  $t_{ps}$  and  $M_{3\mu}$  (3.5-6.3 GeV/c<sup>2</sup>)