



# Physics with the $B_c^+$ meson

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on behalf of the LHCb collaboration

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# Contents

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- A large, Gothic-style stone building, likely the Cathedral of Learning at the University of Pittsburgh, stands prominently against a clear blue sky. In the foreground, a grassy lawn is dotted with people sitting or walking, and a few trees are visible.
- 1.  $B_c^+$  Motivation
  - 2. Why at LHCb?
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  - 4. Mass measurement
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# Pre-LHC: Status of $B_c^+$ meson <sup>1</sup>

## BOTTOM, CHARMED MESONS ( $B = C = \pm 1$ )

$$B_c^+ = c\bar{b}, B_c^- = \bar{c}b, \text{ similarly for } B_c^* \text{'s}$$

$B_c^\pm$

$$I(J^P) = 0(0^-)$$

$I, J, P$  need confirmation.

Quantum numbers shown are quark-model predictions.

Mass  $m = 6.277 \pm 0.006$  GeV ( $S = 1.6$ )

Mean life  $\tau = (0.453 \pm 0.041) \times 10^{-12}$  s

$B_c^-$  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)
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The following quantities are not pure branching ratios; rather the fraction

$\Gamma_i/\Gamma \times B(\bar{b} \rightarrow B_c)$ .

$J/\psi(1S)\ell^+\nu_\ell$ anything	$(5.2^{+2.4}_{-2.1}) \times 10^{-5}$	–	–
$J/\psi(1S)\pi^+$	$< 8.2 \times 10^{-5}$	90%	2372
$J/\psi(1S)\pi^+\pi^-\pi^-$	$< 5.7 \times 10^{-4}$	90%	2352
$J/\psi(1S)a_1(1260)$	$< 1.2 \times 10^{-3}$	90%	2171
$D^*(2010)^+\overline{D}^0$	$< 6.2 \times 10^{-3}$	90%	2468

- Discovered by CDF in 1998<sup>2</sup> using  $B_c^+ \rightarrow J/\psi l^+ \nu_l X$  ( $l = e, \mu$ )
- Mass and lifetime measured at Tevatron<sup>3,4</sup>
  - 6 MeV mass uncertainty
  - 10% uncertainty on lifetime
- Only 1 ( $\sigma \times BF$ ) measured

<sup>1</sup>PR D86, 010001 (2012)

<sup>2</sup>PRL 81 2432 (1998)

<sup>3</sup>PRL 100 182002

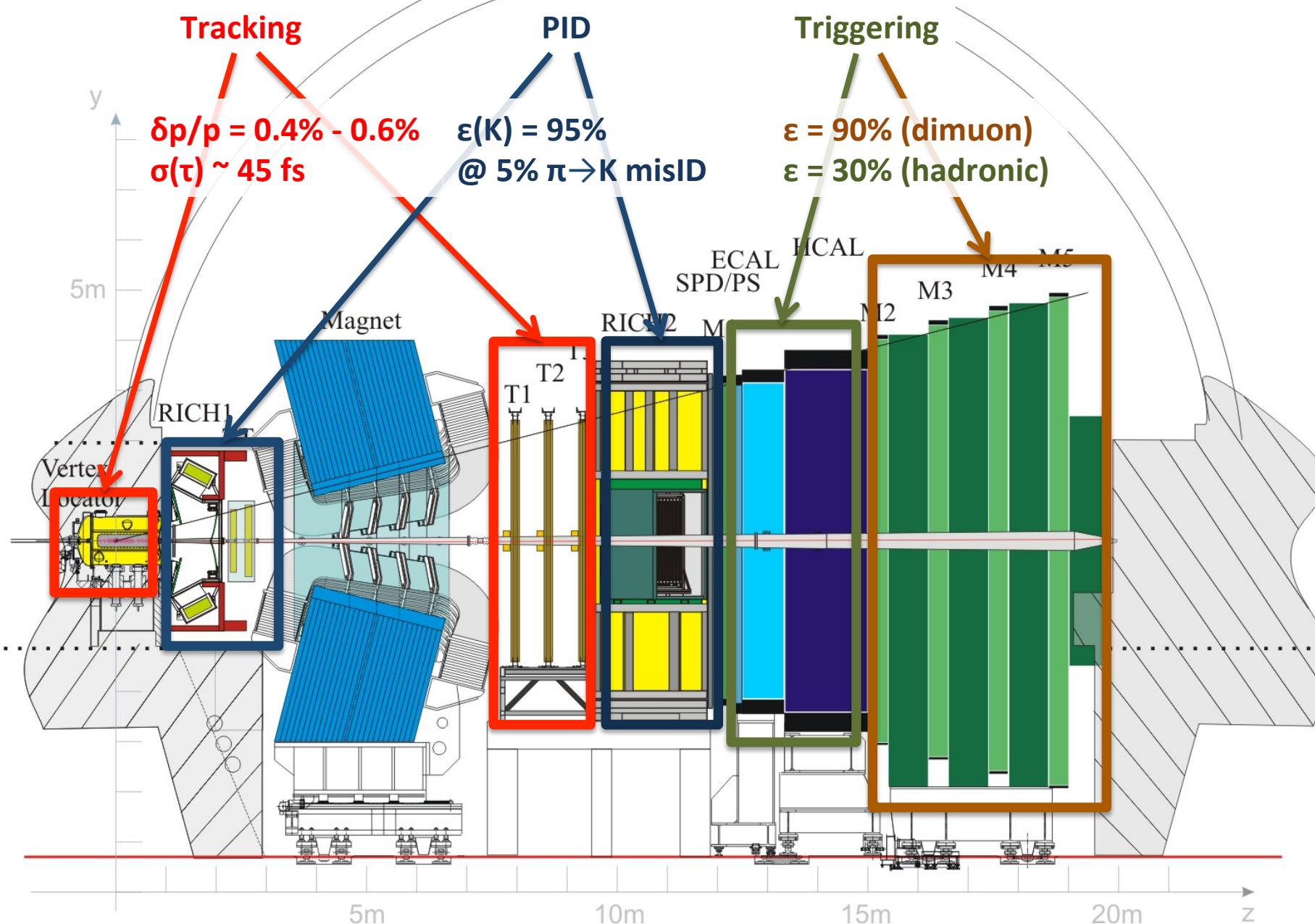
<sup>4</sup>PRL 101 012001

# Motivation

- $B_c^+$  is the heaviest flavored meson
- Production, lifetime, mass affected by **2** heavy quarks:
  - $\sigma(B_c^+)/\sigma(B_s^0) \sim 2\% \text{ (@ LHCb)}$
  - Lifetime  $\sim 1/3$  of  $B_{(s)}$  lifetime
  - Mass:  $\sim 6275 \text{ MeV}$

→ Interesting system to test QCD models

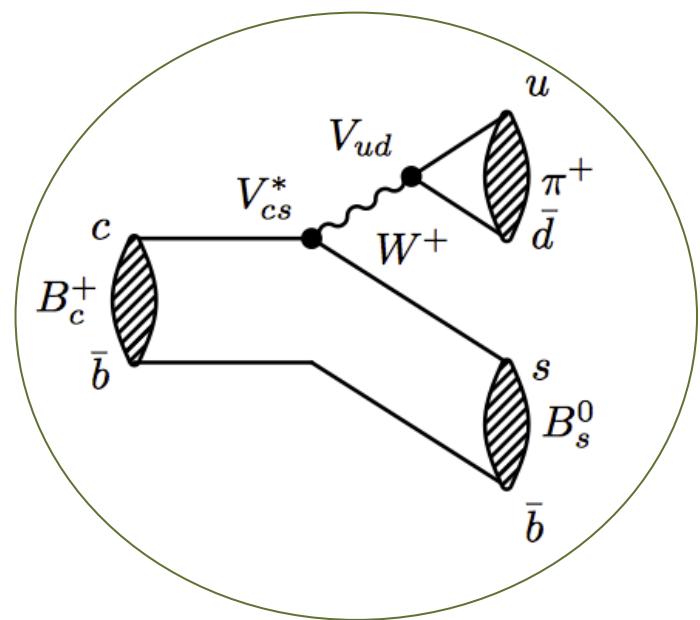
- Very little known, all knowledge in PDG from Tevatron
- LHCb vs Tevatron, already now:
$$\sigma(b\bar{b}) \times \int L = 100 \times 1/10 \rightarrow 10x \text{ more } b\bar{b}$$



$$B_c^+ \rightarrow B_s^0 \pi^+$$

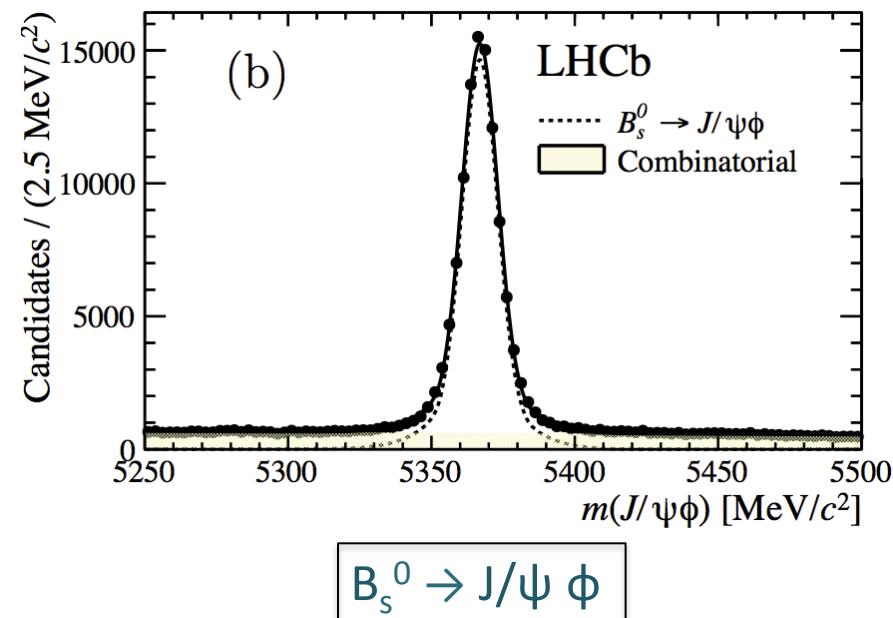
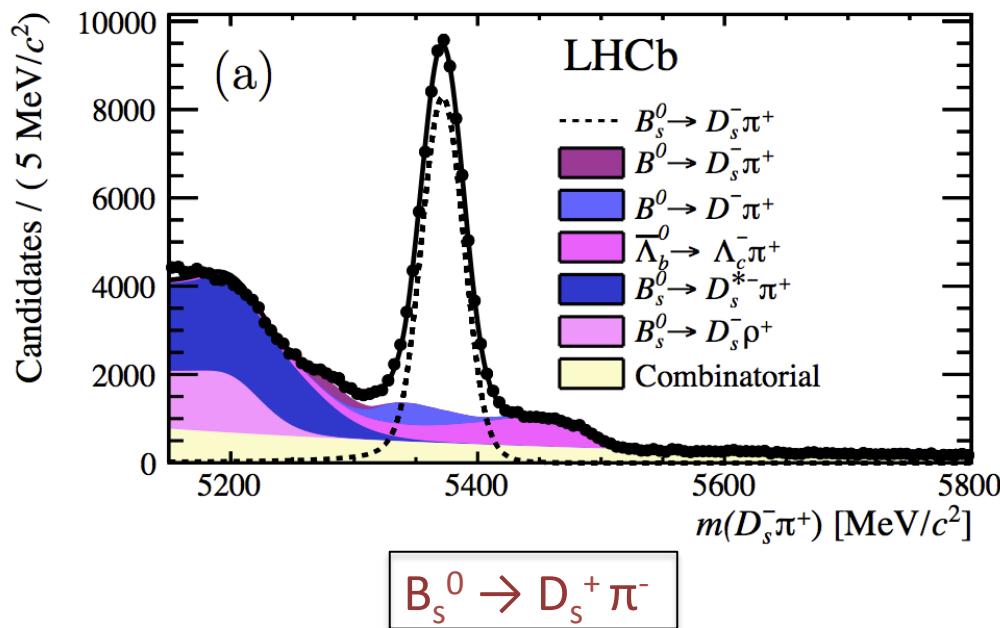
(PRL 111 (2013) 181801)

- Theoretical motivation:
  - First decay with b as spectator:
    - $M(B_c^+) - M(B_s^0) \sim 910$  MeV
    - $M(D_s^0) - M(D^+) \sim 98.9$  MeV;  $M(B_s^0) - M(B^+) \sim 87$  MeV
  - $B_c^+ \rightarrow B_s^0$ : largest branching ratio of  $B_c^+$  ( $V_{cs}$  vs  $V_{cb}$ ).  
(Same diagram as abundant  $D^0 \rightarrow K^+\pi^-$ )
- Experimental interest:
  - Possible source of  $B_s^0$  mesons
  - Possible tagging of  $B_s^0$  decays
- Use 2  $B_s^0$  decay modes:
  - $B_s^0 \rightarrow [D_s^+ \rightarrow K^+K^-\pi^+] \pi^-$
  - $B_s^0 \rightarrow [J/\psi \rightarrow \mu^+\mu^-] [\phi \rightarrow K^+K^-]$



$$B_c^+ \rightarrow B_s^0 \pi^+$$

First select the  $B_s^0$ ...

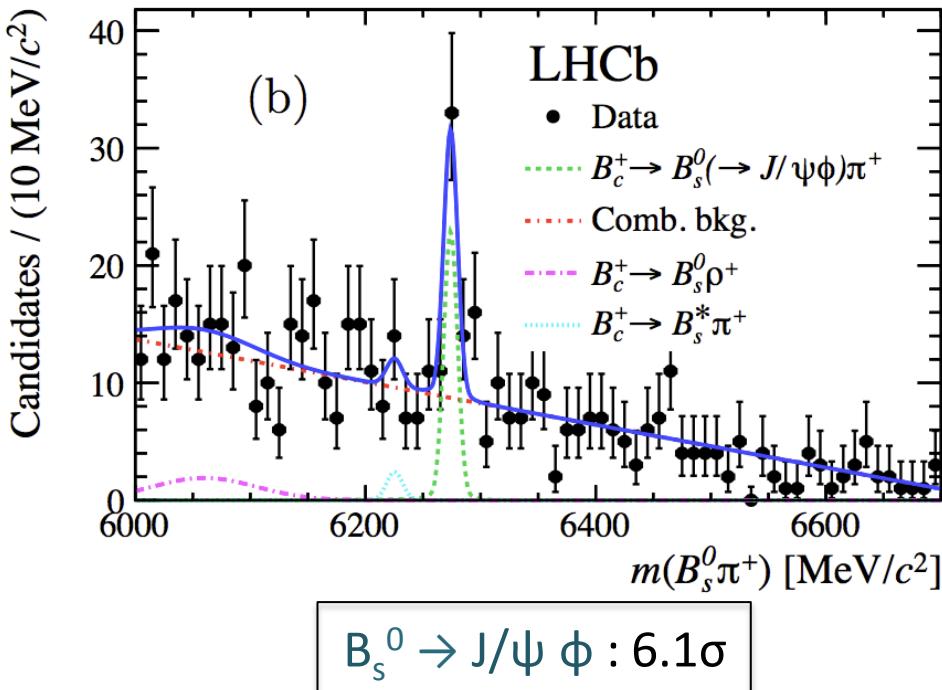
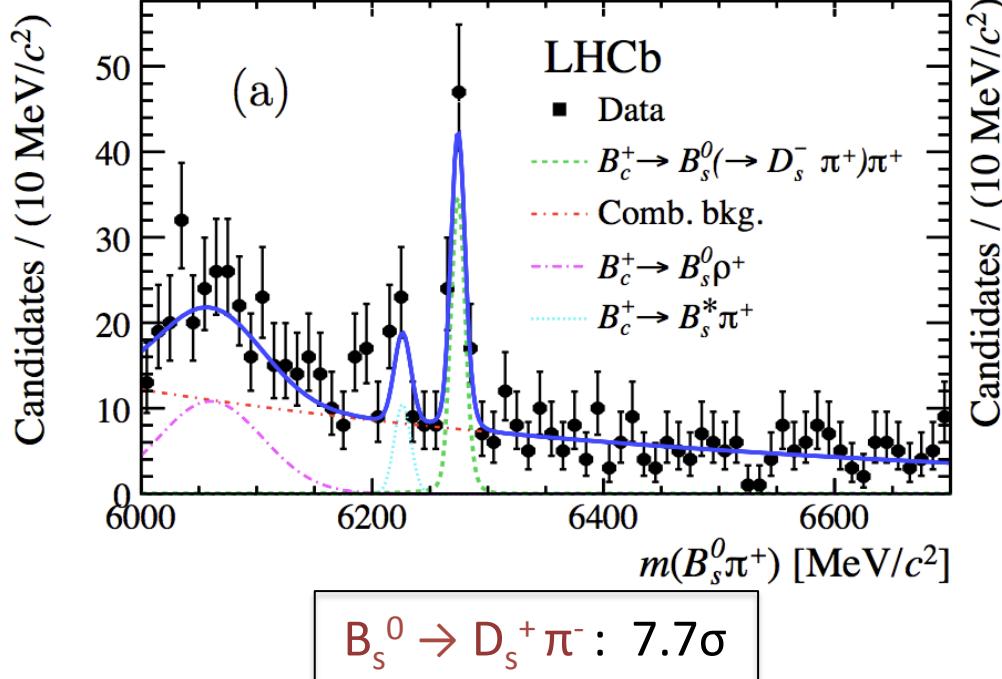


- Partially reconstructed bkg
- Misidentified bkg

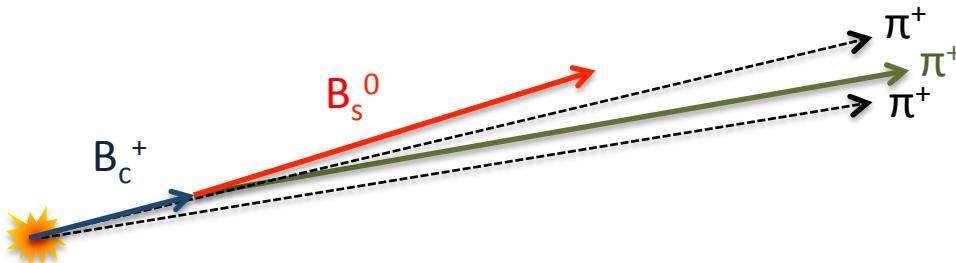
- 2 muons in final state
- narrow  $\phi$  mass peak

$$B_c^+ \rightarrow B_s^0 \pi^+$$

... Then add a pion.



Largest background:  
real  $B_s^+$  + prompt pions



$$B_c^+ \rightarrow B_s^0 \pi^+$$

Result:

$$\frac{\sigma(B_c^+)}{\sigma(B_s^0)} \times \mathcal{B}(B_c^+ \rightarrow B_s^0 \pi^+) = (2.37 \pm 0.31 \text{ (stat)} \pm 0.11 \text{ (syst)} {}^{+0.17}_{-0.13} (\tau_{B_c^+})) \times 10^{-3}$$

→ 1/400  $B_s^0$  originate from  $B_c^+ \rightarrow B_s^0 \pi^+$  decays (@ LHCb)

- Largest systematic due to  $B_c^+$  lifetime
- Combined with other measurements<sup>1,2,3</sup>
  - $\text{BR}(B_c^+ \rightarrow B_s^0 \pi^+)/\text{BR}(B_c^+ \rightarrow J/\psi \pi^+) = 88 \pm 21$
- Assuming  $\text{BR}(B_c^+ \rightarrow J/\psi \pi^+) = 0.15\%$ <sup>4</sup>
  - $\text{BR}(B_c^+ \rightarrow B_s^0 \pi^+) \sim 10\%$  (typical hadronic B BR < 1%)
  - $\sigma(B_c^+)/\sigma(B_s^0) \sim 2\%$

<sup>1</sup>LHCb: PRL **109** (2012) 232001

<sup>2</sup>LHCb: JHEP **04** (2013) 1

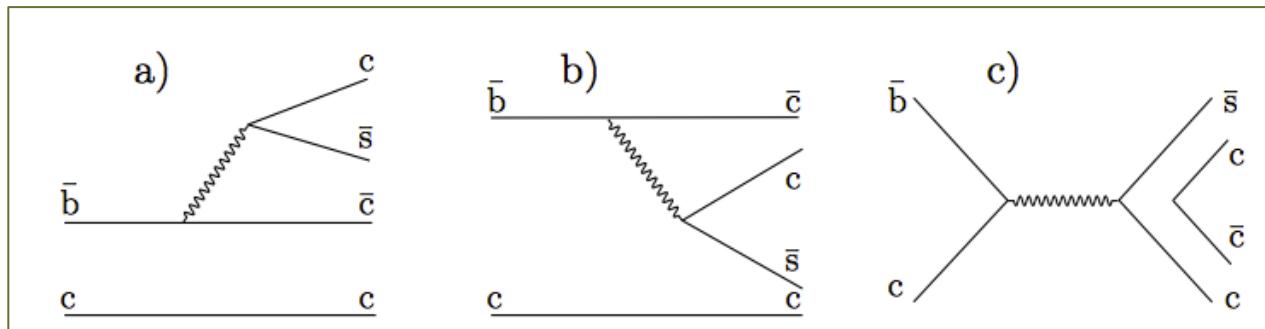
<sup>3</sup>PDG: PR **D86** (2012) 010001

<sup>4</sup>PR **D73** (2006) 054024

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

(PR D87 (2013) 112012)

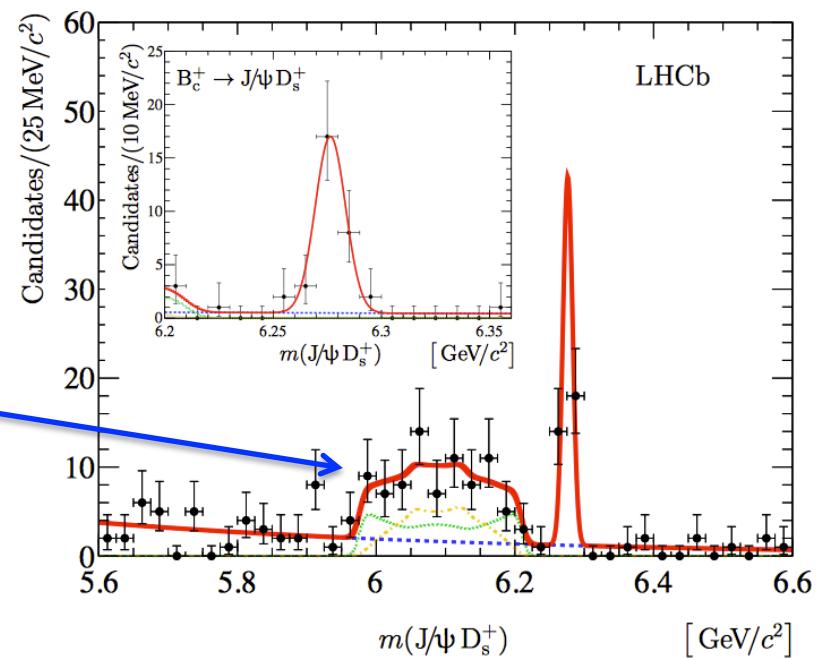
- $B_c^+ \rightarrow J/\psi D_s^+$ : weak annihilation topology not CKM suppressed



- Narrow peak: Q-value  $\sim 1300$  MeV
- $D_s^{+*}$  contribution:
  - Pseudoscalar  $\rightarrow$  vector vector, missing p
  - $\rightarrow$  helicity components

### Results:

- First observation of  $B_c^+ \rightarrow J/\psi D_s^{+(*)}$
- $M(B_c^+) = 6276.28 \pm 1.48$  MeV

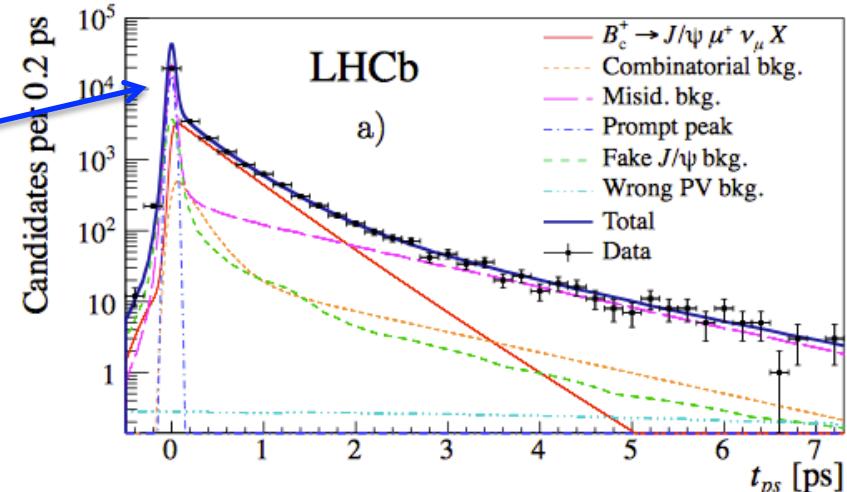


# $B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu X$ ( $B_c^+$ lifetime)

- Large spread of predictions in various QCD models: 0.300 – 0.700 ps <sup>4</sup>
- Large systematic uncertainty in  $B_c^+$  branching fraction measurements
- Complicated analysis ( misID, missing momentum, feed-down, 2D fit, ...)
- Avoid lifetime bias → prompt backgr.

CDF <sup>1</sup>	$B_c^+ \rightarrow J/\psi e^+ \nu$	$0.448 \pm 0.049$ ps
D0 <sup>2</sup>	$B_c^+ \rightarrow J/\psi \mu^+ X$	$0.463 \pm 0.079$ ps
LHCb <sup>3</sup>	$B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu X$	<b><math>0.509 \pm 0.014</math> ps</b>

→ best measurement of  $B_c^+$  lifetime



<sup>1</sup>PRL **97** (2006) 012002

<sup>2</sup>PRL **102** (2009) 092001

<sup>3</sup>arXiv:1401.6932, submitted to EPJC

<sup>4</sup>PAN **67** (2004) 1559; PR **D53** (1996) 4991; PL **B452** (1999) 129 ; NP **B585** (2000) 353; PR **D64** (2001) 014003

# $B_c^+$ branching ratios by LHCb

(Normalized to  $\text{BR}(B_c^+ \rightarrow J/\psi \pi^+)$  )

$\text{BR}(B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+)$	$2.14 \pm 0.45$	$>5\sigma$	19 Jun 2012	PRL <b>108</b> (2012) 251802
$\text{BR}(B_c^+ \rightarrow \psi(2S)\pi^+)$	$0.250 \pm 0.070$	$5.2\sigma$	26 Apr 2013	PR D <b>87</b> (2013) 071103
<b><math>\text{BR}(B_c^+ \rightarrow J/\psi D_s^+)</math></b>	$2.90 \pm 0.62$	$>9\sigma$	28 Jun 2013	PR D <b>87</b> (2013) 112012
<b><math>\text{BR}(B_c^+ \rightarrow J/\psi D_s^{*+})</math></b>	$6.9 \pm 2.2$	$>9\sigma$ *	"	"
$\text{BR}(B_c^+ \rightarrow J/\psi K^+)$	$0.069 \pm 0.020$	$5.0\sigma$	13 Sep 2013	JHEP <b>09</b> (2013) 075
<b><math>\text{BR}(B_c^+ \rightarrow B_s^0 \pi^+)</math></b>	$88 \pm 21$	$7.7\sigma$ **	1 Nov 2013	PRL <b>111</b> (2013) 181801
$\text{BR}(B_c^+ \rightarrow J/\psi K^+ K^- \pi^+)$	$0.53 \pm 0.11$	$6.2\sigma$	Subm.	arXiv: 1309.0587 (submitted to JHEP)
$\text{BR}(B_c^+ \rightarrow J/\psi 3\pi^+ 2\pi^-)$	$1.74 \pm 0.50$	$4.5\sigma$	Subm.	arXiv: 1404.0287 (submitted to JHEP)
$\frac{f_c}{f_u} \times \frac{\text{BR}(B_c^+ \rightarrow K_s^0 K^+)}{\text{BR}(B_c^+ \rightarrow K_s^0 \pi^+)}$	$< 5.8 \times 10^{-2}$	90% CL ***	Subm.	arXiv: 1308.1277 (submitted to PLB)

\* originally normalized to  $\text{BR}(B_c^+ \rightarrow J/\psi D_s^+)$ , to be **2.37 +/- 0.57**

\*\* calculated using the same references as on slide 9

\*\*\* NOT normalized to  $\text{BR}(B_c^+ \rightarrow J/\psi \pi^+)$  )

# Experiment and Theory

	LHCb	RQM & fac.	NRQCD/HQET	QCD rel. pot.	NLO & nonf	Other
$\text{BR}(\text{B}_c^+ \rightarrow \text{J}/\psi \pi^+)$	-	0.034-0.17	0.13	0.13	0.291	0.13-0.2
$\text{BR}(\text{B}_c^+ \rightarrow \text{J}/\psi \pi^+ \pi^- \pi^+) / \text{BR}$	$2.14 \pm 0.45$	-			2.85	1.5-4.5
$\text{BR}(\text{B}_c^+ \rightarrow \psi(2S)\pi^+) / \text{BR}$	$0.250 \pm 0.070$	0.18		0.15	0.26	
<b><math>\text{BR}(\text{B}_c^+ \rightarrow \text{J}/\psi D_s^+) / \text{BR}</math></b>	$2.90 \pm 0.62$	2.0-3.4	1.31	2.62		1.6-2.9
<b><math>\text{BR}(\text{B}_c^+ \rightarrow \text{J}/\psi D_s^{+*}) / \text{BR}</math></b>	$6.9 \pm 2.2$	5.7	15.2	4.5		3.4-6.4
$\text{BR}(\text{B}_c^+ \rightarrow \text{J}/\psi K^+) / \text{BR}$	$0.069 \pm 0.020$	0.076-0.089	0.085	0.052	0.076	
<b><math>\text{BR}(\text{B}_c^+ \rightarrow B_s^0 \pi^+) / \text{BR}</math></b>	$88 \pm 21$	23-353	127-135	31		
$\text{BR}(\text{B}_c^+ \rightarrow \text{J}/\psi K^+ K^- \pi^+) / \text{BR}$	$0.53 \pm 0.11$					0.47-0.49
$\text{BR}(\text{B}_c^+ \rightarrow \text{J}/\psi 3\pi^+ 2\pi^-) / \text{BR}$	$1.74 \pm 0.50$					0.95-1.1

(all modes relative to  $\text{BR}(\text{B}_c^+ \rightarrow \text{J}/\psi \pi^+)$ )

RQM & fact.: <sup>1</sup>S. Naimuddin et al., Phys. Rev. **D86** (2012) 094028

<sup>2</sup>M.A. Ivanov et al., Phys. Rev. **D73** (2006) 054024

<sup>3</sup>D. Ebert et al., Phys. Rev. D **68** (2003) 094020 and D.Ebert et al., Eur. Phys. J. **C32** (2003) 29

NRQCD/HQET: <sup>4</sup>V. Kiselev et al., Nucl. Phys. **B585** (2000) 353 and I. Gouz et al., Phys. Atom. Nucl. **67** (2004) 1559

QCD re.pot.: <sup>5</sup>P. Colangelo and F. De Fazio, Phys. Rev. **D61** (2000) 034012

NLO & non-fact.: <sup>6</sup>C.-F. Qiao et al., Phys. Rev. **D89** (2014) 034008

Other: <sup>7</sup>A. Rakitin and S. Koshkarev, Phys. Rev. **D81** (2010) 014005 , A.K. Likhoded and A.V. Luchinsky, Phys. Rev. **D81** (2010) 014015

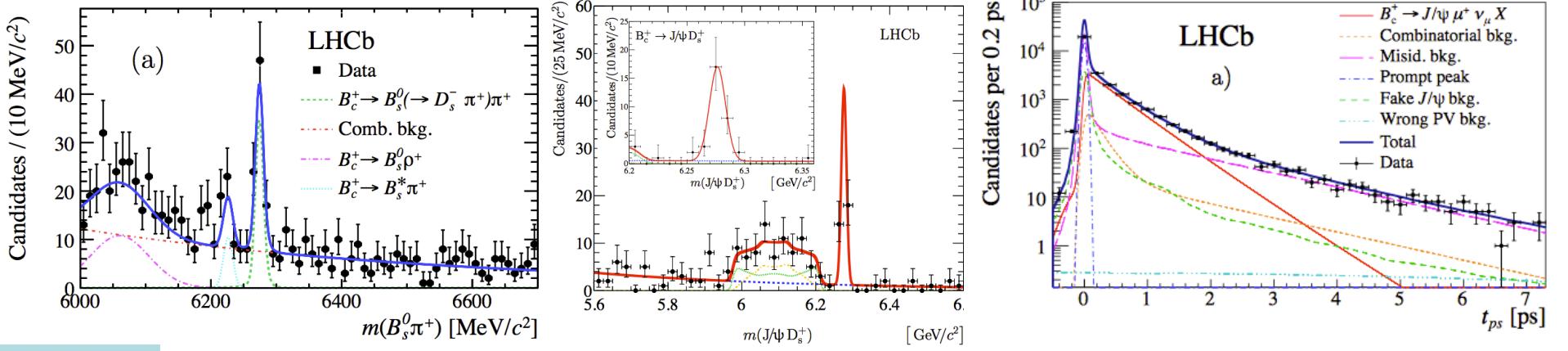
<sup>8</sup>A.V. Luchinsky, arXiv: 1307.0953 , using form factors from 4 and 3(1)

<sup>9</sup>LHCb Collaboration, Phys. Rev. **D87** (2013) 112012

<sup>10</sup>A.V. Luchinsky, Phys. Rev. **D86** (2012) 074024, using form factors from 4 and 3(1)

# Conclusion

- First  $B_c^+ \rightarrow B_s^0$  transition measured
- $B_c^+$  mass precision 6 MeV  $\rightarrow$  1.5 MeV
- $B_c^+$  lifetime relative uncertainty 10%  $\rightarrow$  2.8%
- Many decay modes observed, can be directly compared to QCD models
  
- 9+1 papers on  $B_c^+$  by LHCb so far
- More analyses in pipeline



# Backup

# Bc mass measurements

CDF <sup>1</sup>	Bc → J/ψ π	6275.6 ± 3.8 MeV	(2008)
D0 <sup>2</sup>	Bc → J/ψ π	6300 ± 15 MeV	(2008)
LHCb (0.37 fb-1) <sup>3</sup>	Bc → J/ψ π	6273.7 ± 2.1 MeV	(2012)
LHCb (3 fb-1) <sup>4</sup>	Bc → J/ψ Ds+	6276.28 ± 1.48 MeV	(2013)

<sup>1</sup>T. Aaltonen et al. (CDF collaboration), Phys. Rev. Lett. **100** (2008) 182002

<sup>2</sup>V.M. Abazov et al. (D0 collaboration), Phys. Rev. Lett. **101** (2008) 012001

<sup>3</sup>R. Aaij et al. (LHCb collaboration), Phys. Rev. Lett. **109** (2012) 232001

<sup>4</sup>R. Aaij et al. (LHCb collaboration), Phys. Rev. **D87** (2013) 112012

# Theory predictions

(All in %)	Naimud	Ivanov	Ebert1	Ebert2	Kiselev	Gouz	Colang	Qiao	Rakitin,Likh	Luchin1	LHCb est	Luchin2
$\text{BR}(B_c^+ \rightarrow J/\psi \pi^+)$	0.034	0.17	0.061			0.13	0.13	0.291 +- 0.045?	0.2 (1 <sup>st</sup> ), 0.13 – 0.17			
$\text{BR}(B_c^+ \rightarrow J/\psi \pi^+ \pi^+ \pi^+)$								2.85 * 0.291	0.3 (1 <sup>st</sup> ), 0.52-0.77			
$\text{BR}(B_c^+ \rightarrow \psi(2S) \pi^+)$			0.011				0.019	0.076 +- 0.014?				
$\text{BR}(B_c^+ \rightarrow J/\psi D_s^+)$	0.115	0.34				0.17	0.34				1.6-2.9 *	J/psipi
$\text{BR}(B_c^+ \rightarrow J/\psi D_s^{++})$		0.97				1.97	0.59				2.1-2.2 *	J/psi Ds+
$\text{BR}(B_c^+ \rightarrow J/\psi K^+)$	0.003	0.013	0.005			0.011	0.0068	0.022 +- 0.004?				
$\text{BR}(B_c^+ \rightarrow B_s^0 \pi^+)$	12.01	3.9		2.52	17.5	16.4	4					
$\text{BR}(B_c^+ \rightarrow J/\psi K^+ K\pi^+)$									0.49-0.47 *	Jpsipi		
$\text{BR}(B_c^+ \rightarrow J/\psi 3\pi^+ 2\pi^-)$											0.95 – 1.1 *	Jpsipi

<sup>1</sup>S. Naimuddin et al., Phys. Rev. **D86** (2012) 094028

<sup>2</sup>M.A. Ivanov et al., Phys. Rev. **D73** (2006) 054024

<sup>3</sup>D. Ebert et al., Phys. Rev. D **68** (2003) 094020 and D.Ebert et al., Eur. Phys. J. **C32** (2003) 29

<sup>4</sup>V. Kiselev et al., Nucl. Phys. **B585** (2000) 353 and I. Gouz et al., Phys. Atom. Nucl. **67** (2004) 1559

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