

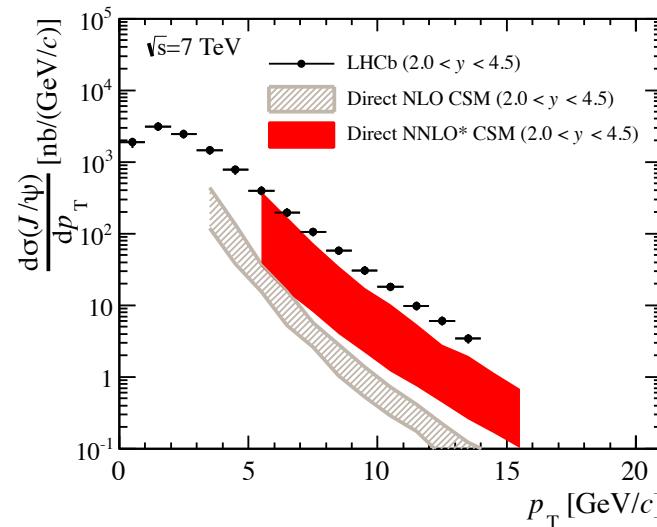
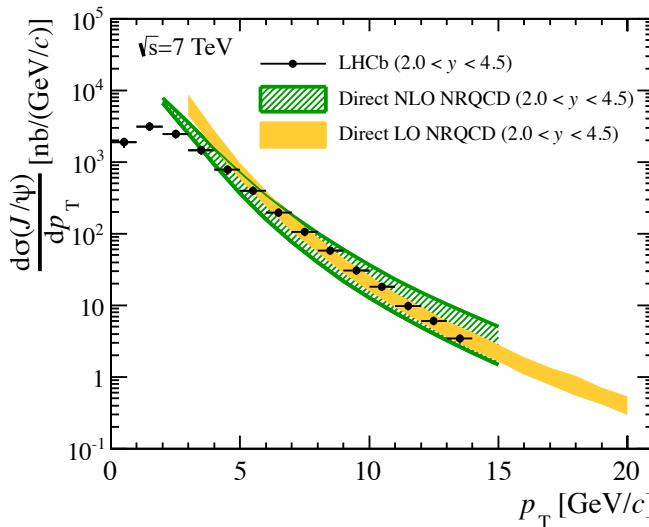


Quarkonium in LHCb

Patrick Robbe, LAL Orsay, 5 April 2013

Introduction

- The LHC experiments obtained and complementary precise measurements of production cross-sections of J/ψ , $\psi(2S)$, Υ in the $\mu^+\mu^-$ decay channel.
- However, they cannot yet allow distinguishing between the several QCD mechanisms for the formation of these « simple » mesons in hadron collisions:



LHCb prompt J/ψ production cross-section measurements compared with:

Non Relativistic QCD

(large color octet component)

Color Singlet Model

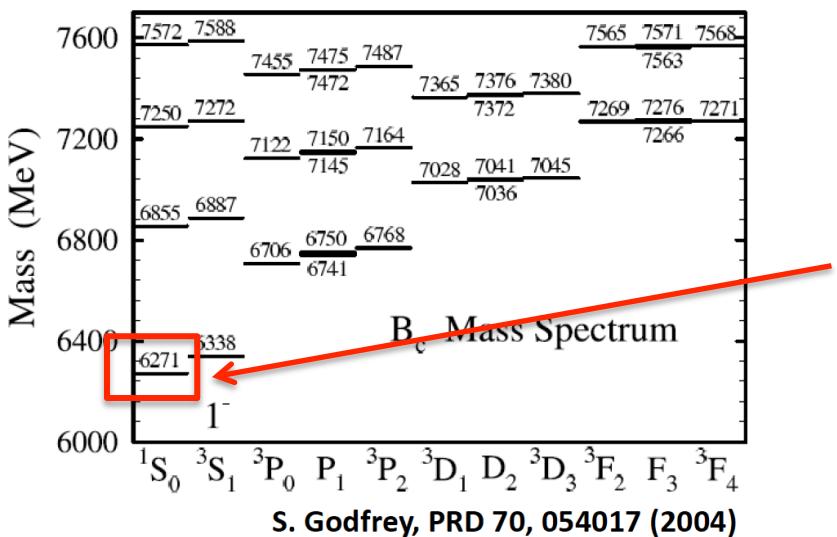
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Introduction

- There are still possible improvements on the experimental side to understand better the situation:
 - Measurement of the J/ψ and Υ polarization at production, for which the models predict different behaviours: first measurements by ALICE and CMS.
 - These measurements need a precise knowledge of the contribution of the decay of higher quarkonium states ($\chi_c \rightarrow J/\psi \gamma$ or $\chi_b \rightarrow \Upsilon \gamma$ [ATLAS])
 - Study of production (and decay) of other quarkonium states:
 - $h_c, \eta_c \rightarrow p\bar{p}$ (Poster by Maksym Teklishyn)
 - B_c

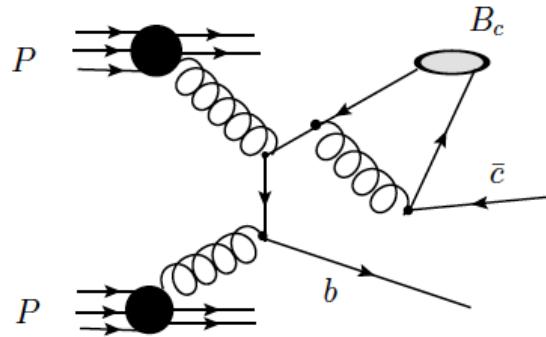
B_c meson

- Unique family of meson formed with 2 different heavy flavours: ($\bar{b}c$).
- It is considered as a quarkonium state, because the study of its production properties can give constraints for the understanding of production mechanisms of heavy-quark states.
- Study of its mass, lifetime and decay channels can be used to test and constrain QCD calculations similar to these in the quarkonium sector.



B_c^+ : ground state, only one observed so far
(1998, CDF)

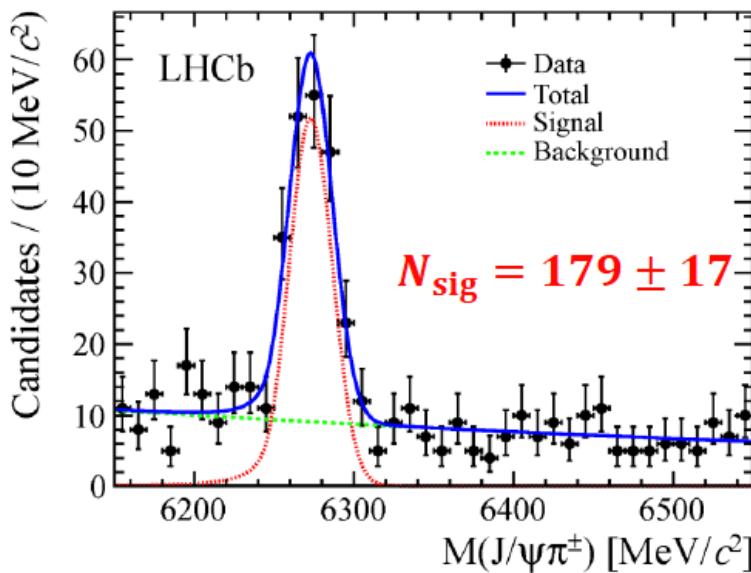
B_c production



Typical production diagram (α_s^4)

Measured with the decay mode $B_c^+ \rightarrow J/\psi \pi^+$, relative to the B^+ production ($B^+ \rightarrow J/\psi K^+$)

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



$$\mathcal{R}_{c/u} = (0.68 \pm 0.10_{\text{stat}} \pm 0.03_{\text{syst}} \pm 0.05_{\text{lifetime}})\%$$

For $p_T < 4 \text{ GeV}/c$ and $2.5 < \eta < 4.5$

The absolute BR of $B_c^+ \rightarrow J/\psi \pi^+$ is not known, but using theoretical estimates, this means
 $\sigma(B_c^+) \sim \sigma(B^+)/100$

B_c decays

- Very little is known about them !
- PDG 2012 sections for B_c^+ and B_c^0 :

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

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

B_c^\pm

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

I, J, P need confirmation.

Quantum numbers shown are quark-model predictions.

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

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

B_c^- modes are charge conjugates of the modes below.

$B_c^+ \text{ DECAY MODES} \times B(\bar{b} \rightarrow B_c)$	Fraction (Γ_i/Γ)	Confidence level (MeV/c)	p
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The following quantities are not pure branching ratios; rather the fraction

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

$J/\psi(1S) \ell^+ \nu_\ell \text{ anything}$	$(5.2 \pm 2.4) \times 10^{-5}$	—	
$J/\psi(1S) \pi^+$	$< 8.2 \times 10^{-5}$	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
$D^*(2010)^- \bar{D}^0$	$< 6.2 \times 10^{-3}$	90%	2468

$B_c^0 \text{ DECAY MODES}$	Fraction (Γ_i/Γ)	Confidence level	Scale factor / Confidence level (MeV/c)	p
$\ell^+ \nu_\ell \text{ anything}$	[ppp]	(10.33 ± 0.28) %	—	
$e^+ \nu_e X_c$	[ppp]	(10.1 ± 0.4) %	—	
$D \ell^+ \nu_\ell \text{ anything}$	[ppp]	(9.2 ± 0.8) %	—	
$D^- \ell^+ \nu_\ell$	[ppp]	(2.18 ± 0.12) %	2309	
$D^- \pi^+ \nu_\tau$	[ppp]	(1.1 ± 0.4) %	1909	
$D^*(2010)^- \ell^+ \nu_\ell$	[ppp]	(4.95 ± 0.11) %	2257	
$D^*(2010)^- \pi^+ \nu_\tau$	[ppp]	(1.5 ± 0.5) %	S=1.4	1837
$D_0^*(2400)^- \ell^+ \nu_\ell$	[ppp]	(4.3 ± 0.6) $\times 10^{-3}$	2308	
$D_0^*(2400)^- \ell^+ \nu_\ell \times$ $B(D_0^+ \rightarrow \bar{D}^0 \pi^-)$	[ppp]	(3.0 ± 1.2) $\times 10^{-3}$	S=1.8	—
$D_2^*(2400)^- \ell^+ \nu_\ell \times$ $B(D_2^+ \rightarrow \bar{D}^0 \pi^-)$	[ppp]	(1.21 ± 0.33) $\times 10^{-3}$	S=1.8	2065
$\bar{D}^*(*) \pi \ell^+ \nu_\ell (\geq 1)$	[ppp]	(2.3 ± 0.5) %	—	
$\bar{D}^0 \pi^- \ell^+ \nu_\ell$	[ppp]	(4.9 ± 0.8) $\times 10^{-3}$	2256	
$D_1(2420)^- \ell^+ \nu_\ell \times$ $B(D_1^+ \rightarrow \bar{D}^0 \pi^-)$	[ppp]	(2.80 ± 0.28) $\times 10^{-3}$	—	
$D_1'(2430)^- \ell^+ \nu_\ell \times$ $B(D_1' \rightarrow \bar{D}^0 \pi^-)$	[ppp]	(3.1 ± 0.9) $\times 10^{-3}$	—	
$D_2'(2460)^- \ell^+ \nu_\ell \times$ $B(D_2' \rightarrow \bar{D}^0 \pi^-)$	[ppp]	(6.8 ± 1.2) $\times 10^{-4}$	2065	
$\pi^- \ell^+ \nu_\ell$	[ppp]	(2.34 ± 0.28) $\times 10^{-4}$	2583	
$\pi^- \ell^+ \nu_\ell$	[ppp]	(1.44 ± 0.05) $\times 10^{-4}$	2638	
Inclusive modes				
$K^\pm \text{ anything}$		(78 ± 8) %	—	
$D^0 X$		(8.1 ± 1.5) %	—	
$\bar{D}^0 X$		(47.4 ± 2.8) %	—	
$D^+ X$		< 3.9 %	CL=90%	—
$D^- X$		(36.9 ± 3.3) %	—	
$D_s^+ X$		(10.3 ± 2.1) %	—	
$D_s^- X$		< 2.6 %	CL=90%	—
$\Lambda_c^0 X$		< 3.1 %	CL=90%	—
$\bar{\Lambda}_c^0 X$		(5.0 ± 2.1) %	—	
τX		(95 ± 5) %	—	
$c X$		(24.6 ± 3.1) %	—	
$\bar{c} \bar{c} X$		(119 ± 6) %	—	
$D, D^*, \text{ or } D_s$ modes				
$D^- \pi^+$		(2.68 ± 0.13) $\times 10^{-3}$	2306	
$D^- \rho^+$		(7.8 ± 1.3) $\times 10^{-3}$	2235	
$D^- K^0 \pi^+$		(4.9 ± 0.9) $\times 10^{-4}$	2259	
$D^- K^*(892)^+$		(4.5 ± 0.7) $\times 10^{-4}$	2211	
$D^- \omega \pi^+$		(2.8 ± 0.6) $\times 10^{-3}$	2204	
$D^- K^+$		(1.97 ± 0.21) $\times 10^{-4}$	2279	
$D^- K^+ K^0$		< 3.1 $\times 10^{-4}$ CL=90%	2188	
$D^- K^+ K^*(892)^0$		(8.8 ± 1.9) $\times 10^{-3}$	2070	
$\bar{D}^0 \pi^+ \pi^-$		(8.4 ± 0.9) $\times 10^{-4}$	2301	
$D^*(2010)^- \pi^+$		(2.76 ± 0.13) $\times 10^{-3}$	2255	
$D^- \pi^+ \pi^+ \pi^-$		(6.4 ± 1.5) $\times 10^{-3}$	2287	
$(D^- \pi^+ \pi^+ \pi^-) \text{ nonresonant}$		(3.9 ± 1.9) $\times 10^{-3}$	2287	
$D^- \pi^+ \rho^0$		(1.1 ± 1.0) $\times 10^{-3}$	2206	
$D^- a_1(1260)^+$		(6.0 ± 3.3) $\times 10^{-3}$	2121	
$D^*(2010)^- \pi^+ \rho^0$		(1.5 ± 0.5) %	2247	
$D^*(2010)^- \rho^+$		(6.8 ± 0.9) $\times 10^{-3}$	2180	
$D^*(2010)^- K^+$		(2.14 ± 0.16) $\times 10^{-4}$	2226	
$D^*(2010)^- K^0 \pi^+$		(3.0 ± 0.8) $\times 10^{-4}$	2205	

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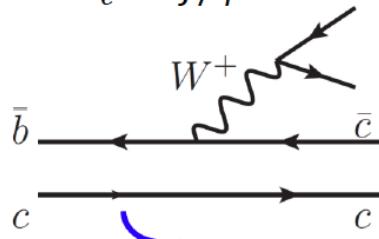
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B_c decays

- They decay through weak interaction.
- Different processes:

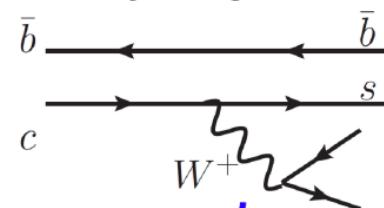
➤ $\bar{b} \rightarrow \bar{c}$ transition

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



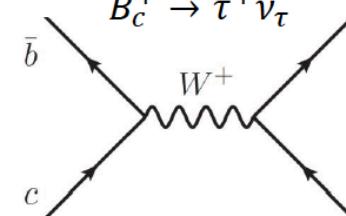
➤ $c \rightarrow s$ transition

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



➤ $c\bar{b} \rightarrow W^+$ annihilation

$$B_c^+ \rightarrow \bar{K}^{*0} K^+$$
$$B_c^+ \rightarrow \phi K^+$$
$$B_c^+ \rightarrow \tau^+ \nu_\tau$$



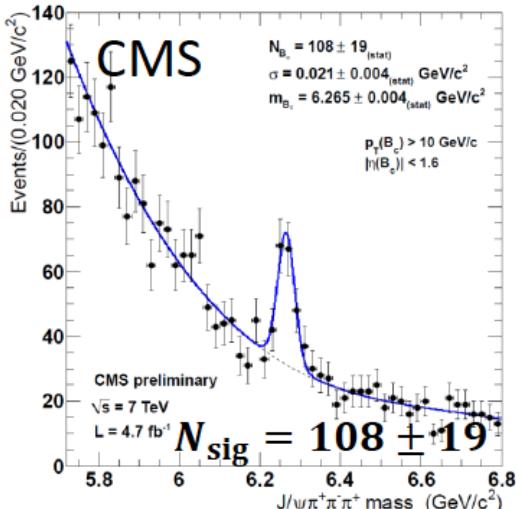
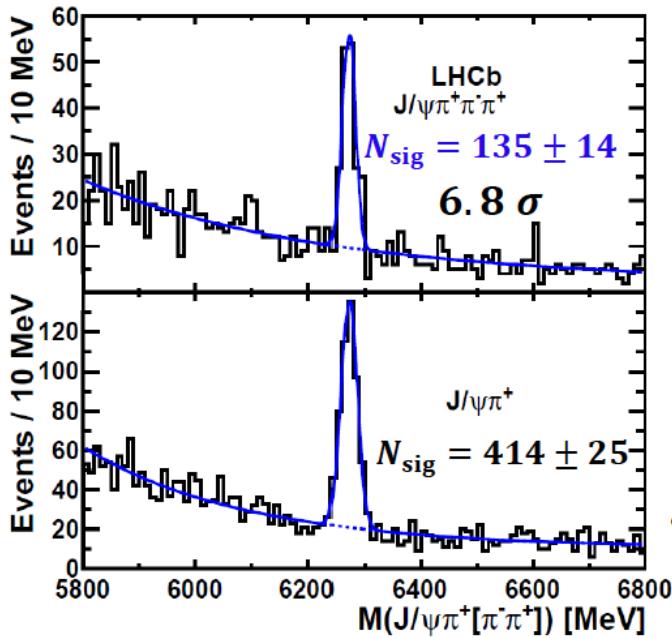
Spectator modes

annihilation modes

4

- Proportion of the different modes is linked to the B_c lifetime (~ 0.4 ps): important to measure precisely its lifetime.

New decay modes discovered



- Observation of $B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$, with 0.8 fb^{-1} of 2011 data.

- Theory predictions:

$$\frac{\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)} \sim 1.5 \quad \text{Rakitin et al, PRD 81 (2010) 014005}$$

$$\sim 1.9 - 2.3 \quad \text{Likhoded et al, PRD 81 (2010) 014015}$$

- Result:

$$\frac{\text{Br}(B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+)}{\text{Br}(B_c^+ \rightarrow J/\psi \pi^+)} = 2.41 \pm 0.30_{\text{stat}} \pm 0.33_{\text{syst}}$$

- Systematics dominated by the knowledge of the $\pi^+ \pi^- \pi^+$ structure

New decay modes discovered

- $B_c^+ \rightarrow \psi(2S) \pi^+$, with 1fb^{-1} of 2011 data.

– Theoretical predictions:

$$\frac{\mathcal{B}(B_c^+ \rightarrow \psi(2S)\pi^+)}{\mathcal{B}(B_c^+ \rightarrow J/\psi\pi^+)} \sim 0.13 - 0.42$$

– Result:

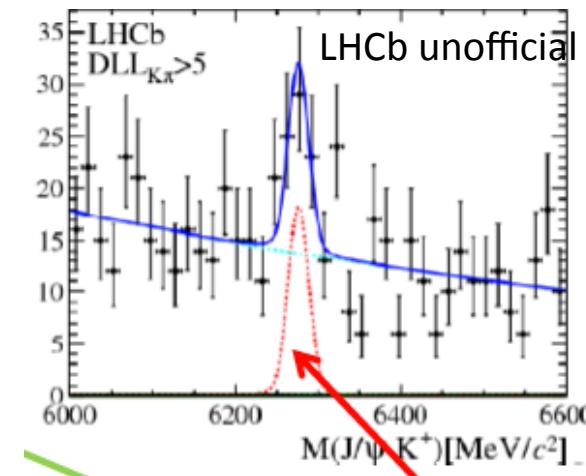
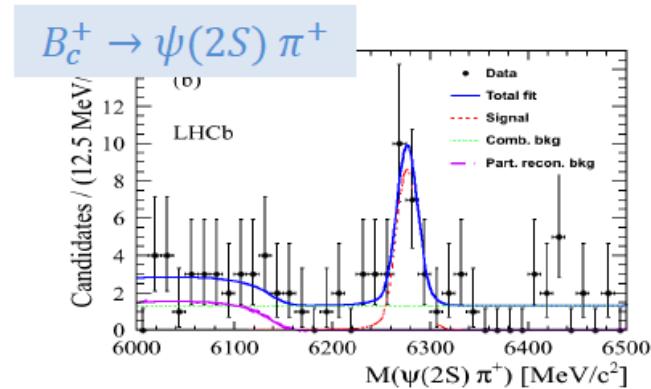
$$\frac{\mathcal{B}(B_c^+ \rightarrow \psi(2S)\pi^+)}{\mathcal{B}(B_c^+ \rightarrow J/\psi\pi^+)} = 0.250 \pm 0.068_{\text{stat}} \pm 0.014_{\text{syst}} \pm 0.006_{\mathcal{B}}$$

LHCb preliminary

- $B_c^+ \rightarrow J/\psi K^+$, with 1fb^{-1} of 2011 data.

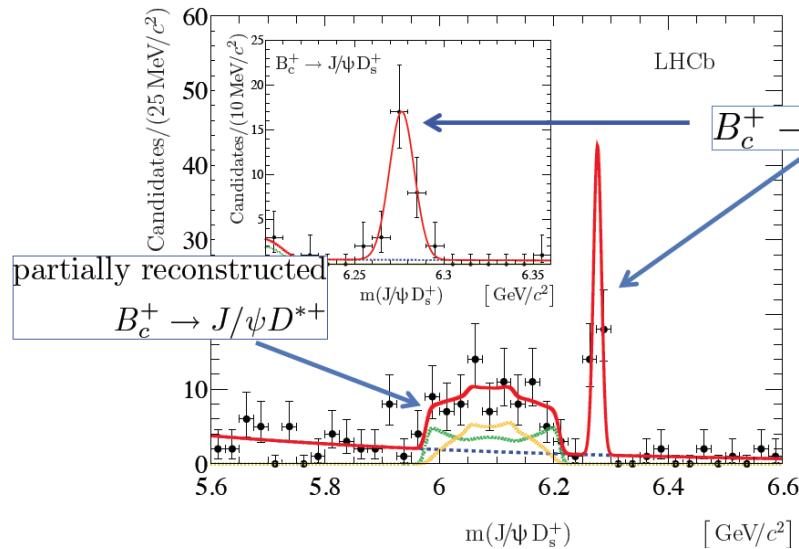
$$\frac{\mathcal{B}(B_c^+ \rightarrow J/\psi K^+)}{\mathcal{B}(B_c^+ \rightarrow J/\psi\pi^+)} = 0.068 \pm 0.019 \pm 0.005$$

– Consistent with $|V_{us}|^2/|V_{ud}|^2$



New decay modes discovered

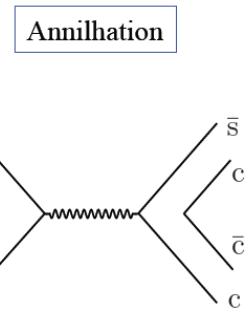
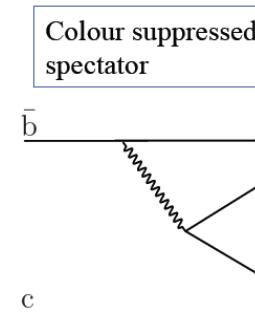
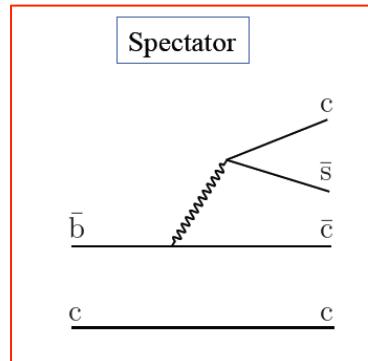
- $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ with 3 fb^{-1} of 2011+2012 data



$$\frac{\mathcal{B}(B_c^+ \rightarrow J/\psi D_s^+)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)} = 2.96 \pm 0.67 \text{ (stat)} \pm 0.25 \text{ (syst)}$$

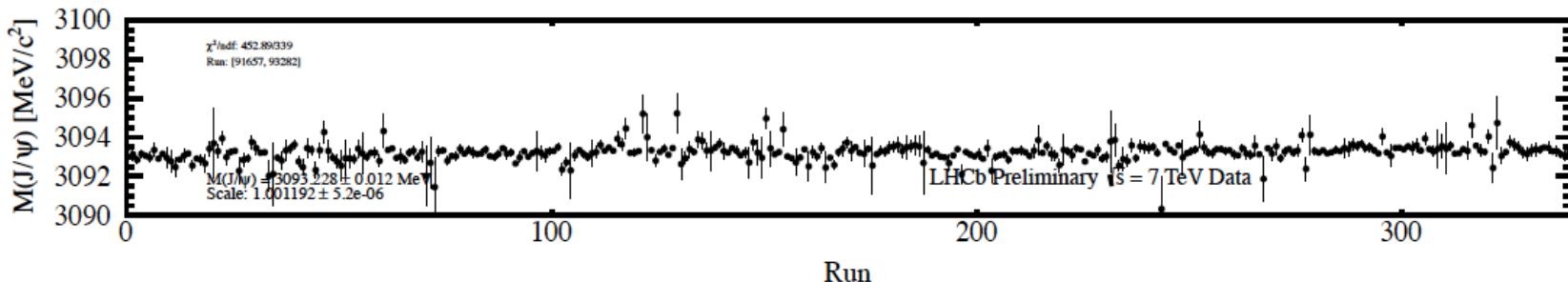
$$\frac{\mathcal{B}(B_c^+ \rightarrow J/\psi D_s^{*+})}{\mathcal{B}(B_c^+ \rightarrow J/\psi D_s^+)} = 2.36 \pm 0.56 \text{ (stat)} \pm 0.10 \text{ (syst)}$$

- Results consistent with dominance of external spectator diagram, as expected.

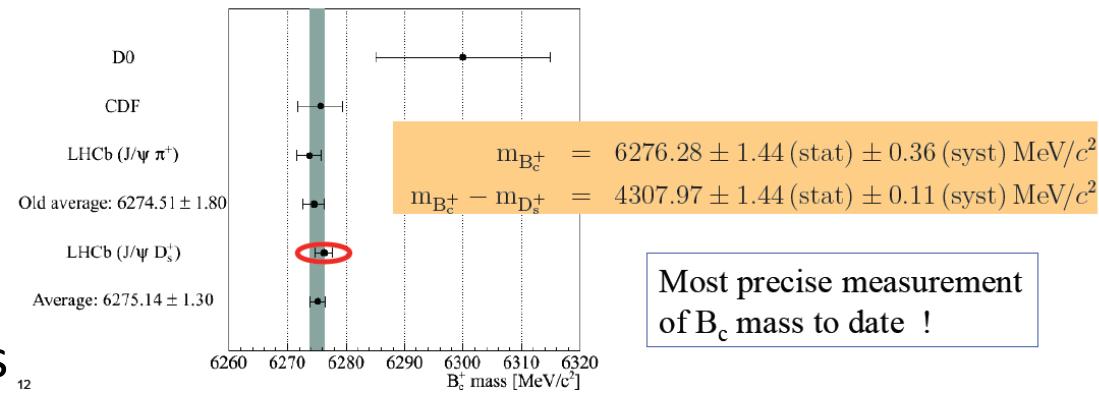


Precise B_c mass measurements

- Momentum scale of the detector is known with precision, calibrated with J/ψ run by run:



- Allows to obtain precise B_c^+ mass measurement from $B_c^+ \rightarrow J/\psi \pi^+$ and $J/\psi D_s^+$.
- Value compatible with QCD predictions
- Uncertainty of 1.3 MeV, was ₁₂ 6 MeV in 2011.



Conclusions

- New areas of quarkonium studies are being explored: B_c^+ production and decay.
- B_c properties knowledge improved greatly with first LHCb data. More to come, in particular ongoing analyses for:
 - $B_c^+ \rightarrow B_s^0 \pi^+$ (c quark decay – b spectator)
 - Excited B_c states
 - B_c precise lifetime measurement.