7th FCPPL Workshop, Clermont-Ferrand, 8-10 April 2014

LHCb Summary

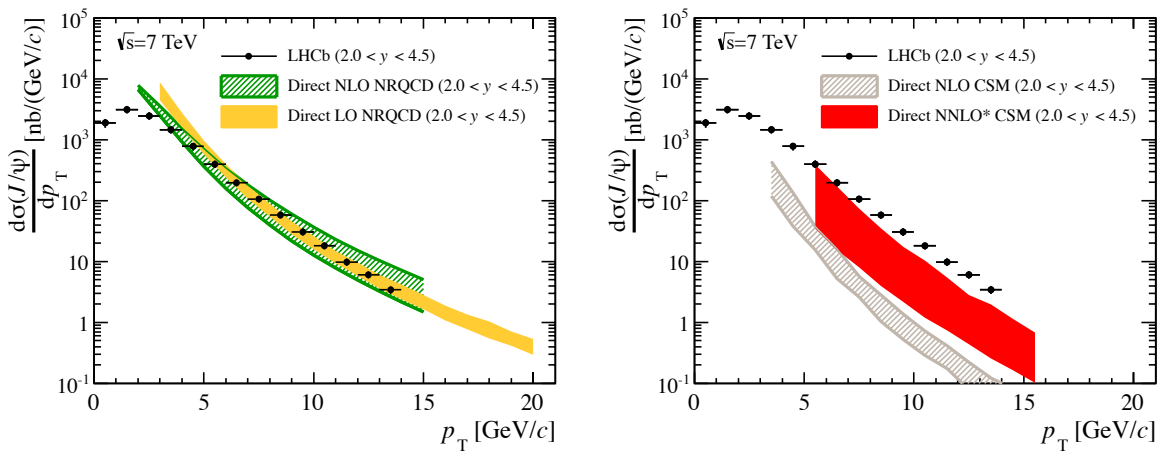
Patrick Robbe (LHCb Collaboration), LAL Orsay, 9 Apr 2014

LAL/Tsinghua collaboration

- Started in 2006
- Current members:
  - LAL: Patrick Robbe, Marie-Helene Schune, Sergey Barsuk
  - Tsinghua: Yuanning Gao, Zhenwei Yang, Yiming Li, Liupan An
- Activities, data analysis at LHCb:
  - Quarkonium production
  - Measurements of the B_c meson
- Long term exchanges:
  - Jibo He, CNRS post-doc (now CERN fellow)
  - Wenbin Qian, Embassy co-tutelle PhD (now post-doc at LAPP Annecy)
  - Bo Liu, CSC grant, one year at LAL (now post-doc in Cagliari)

Quarkonium Production

- Initially meant as first step towards B_c^+ analyses: understand detector, trigger, J/ψ reconstruction, ….
- But developped as major part of the LHCb physics program.
- Measurement of J/ψ production (prompt and from *B* decays), as a function of p_T and *y*, for 2.76 TeV, 7 TeV and 8 TeV energies.

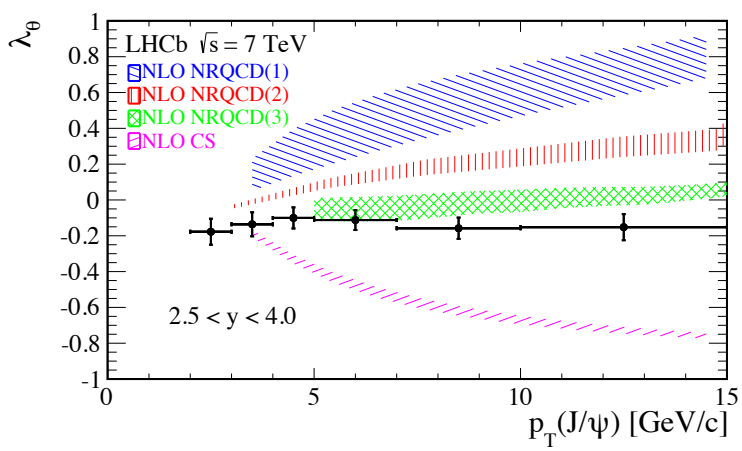


Thesis of Wenbin Qian, Eur.Phys.J.C71 (2011) 1645, one of the most cited paper of LHCb

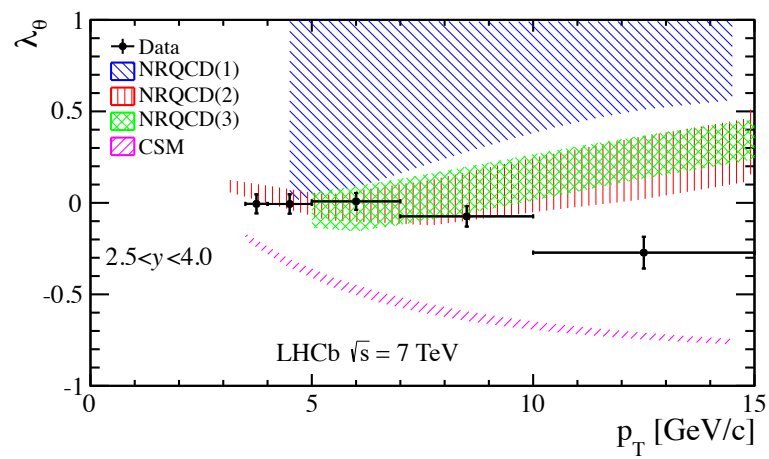
Quarkonium Polarization

- Quarkonium production mechanisms not so clear, test them with measurement of polarization.

$$\frac{d^2N}{d\cos\theta\, d\phi}(\lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi) \propto 1 + \lambda_\theta \cos^2\theta + \lambda_{\theta\phi} \sin 2\theta \cos\phi + \lambda_\phi \sin^2\theta \cos 2\phi,$$



J/ψ polarization [*Eur. Phys. J. C* 73 (2013) 2631]

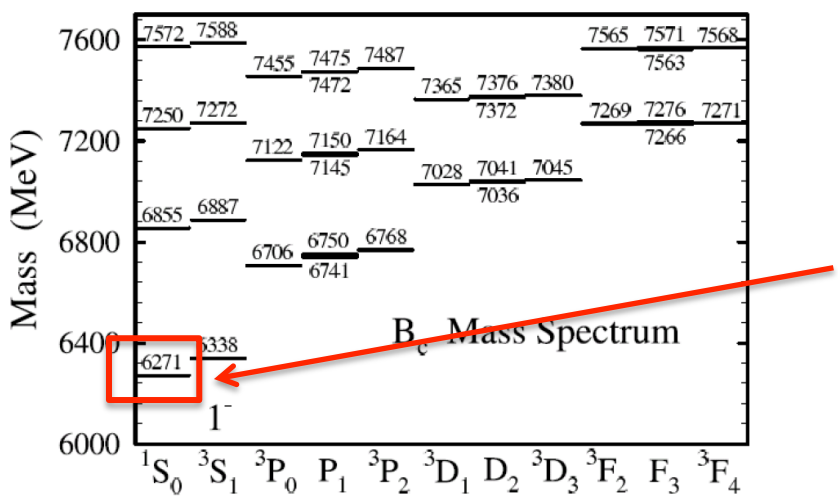


ψ(2S) polarization [arXiv:1403.1339]

PhD Thesis of Yanxi Zhang, defended in May 2013

B_c Meson

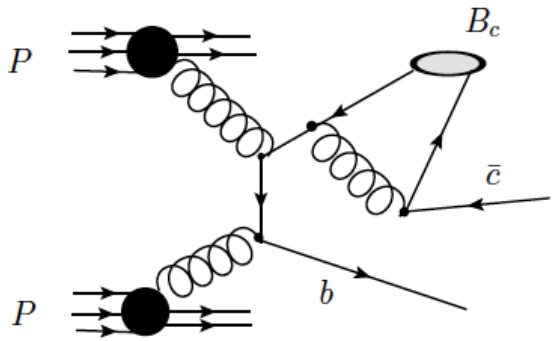
- Unique family of meson formed with 2 different heavy flavours: ($\bar{b}c$).
- It is considered as a quarkonium state, because the study of its production properties can give constraints for the understanding of production mechanisms of heavy-quark states.
- Study of its mass, lifetime and decay channels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



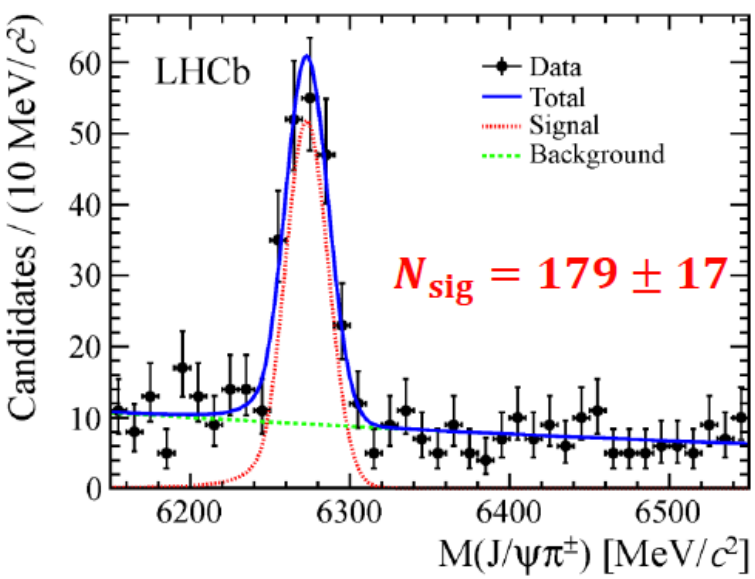
S. Godfrey, PRD 70, 054017 (2004)

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 $B_c^+ \to J/\psi\, \pi^+$, relative to the B^+ production ($B^+ \to J/\psi\, K^+$)

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

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

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

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

LHCb: PRL 109 (2012) 232001, PhD Thesis of Bo Liu.
The analysis is repeated to obtain a different cross-section (pT and y), in an extended collaboration with Cagliari (Giulia Manca)

B_c Decays

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

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

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

$B_c^\pm$

$I(J^P) = 0(0^-)$
I, J, P need confirmation.

Quantum numbers shown are quark-model predicitions.

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.

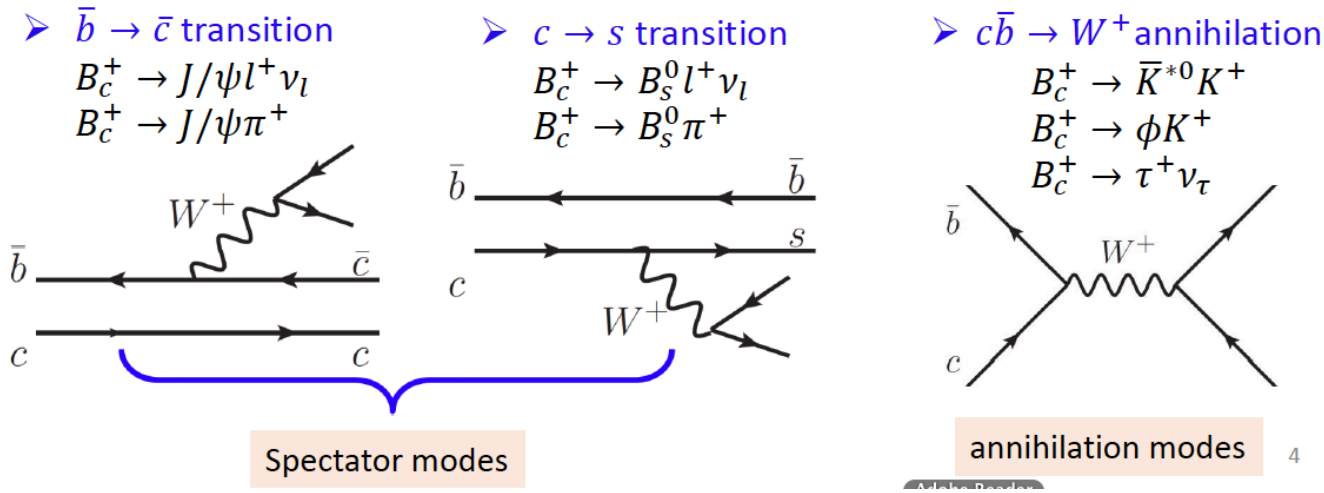
B_c^+ DECAY MODES × B($\bar{b} \to B_c$)	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
The following quantities are not pure branching ratios; rather the fraction $\Gamma_i/\Gamma \times$ B($\bar{b} \to B_c$).			
$J/\psi(1S)\ell^+\nu_\ell$ anything	$(5.2^{+2.4}_{-2.1}) \times 10^{-5}$		–
$J/\psi(1S)\pi^+$	$< 8.2 \times 10^{-5}$	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

B^0 DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\ell^+\nu_\ell$ anything	[ppp]	(10.33 ± 0.28) %		–
$e^+\nu_e X_c$		(10.1 ± 0.4) %		–
$D\ell^+\nu_\ell$ anything		(9.2 ± 0.8) %		–
$D^-\ell^+\nu_\ell$	[ppp]	(2.18 ± 0.12) %		2309
$D^-\tau^+\nu_\tau$		(1.1 ± 0.4) %		1909
$D^*(2010)^-\ell^+\nu_\ell$	[ppp]	(4.95 ± 0.11) %		2257
$D^*(2010)^-\tau^+\nu_\tau$		(1.5 ± 0.5) %	S=1.4	1837
$\overline{D}^0\pi^-\ell^+\nu_\ell$		$(4.3 \pm 0.6) \times 10^{-3}$		2308
$D_0^*(2400)^-\ell^+\nu_\ell \times$ B($D_0^{*-} \to \overline{D}^0\pi^-$)		$(3.0 \pm 1.2) \times 10^{-3}$	S=1.8	–
$D_2^*(2400)^-\ell^+\nu_\ell \times$ B($D_2^{*-} \to \overline{D}^0\pi^-$)		$(1.21 \pm 0.33) \times 10^{-3}$	S=1.8	2065
$\overline{D}^{(*)}n\pi\ell^+\nu_\ell(n \geq 1)$		(2.3 ± 0.5) %		–
$\overline{D}^{*0}\pi^-\ell^+\nu_\ell$		$(4.9 \pm 0.8) \times 10^{-3}$		2256
$D_1(2420)^-\ell^+\nu_\ell \times$ B($D_1^- \to \overline{D}^{*0}\pi^-$)		$(2.80 \pm 0.28) \times 10^{-3}$		–
$D_1'(2430)^-\ell^+\nu_\ell \times$ B($D_1'^- \to \overline{D}^{*0}\pi^-$)		$(3.1 \pm 0.9) \times 10^{-3}$		–
$D_2^*(2460)^-\ell^+\nu_\ell \times$ B($D_2^{*-} \to \overline{D}^{*0}\pi^-$)		$(6.8 \pm 1.2) \times 10^{-4}$		2065
$\rho^-\ell^+\nu_\ell$	[ppp]	$(2.34 \pm 0.28) \times 10^{-4}$		2583
$\pi^-\ell^+\nu_\ell$	[ppp]	$(1.44 \pm 0.05) \times 10^{-4}$		2638
Inclusive modes				
$K^\pm$ anything		(78 ± 8) %		–
D^0X		(8.1 ± 1.5) %		–
$\overline{D}^0X$		(47.4 ± 2.8) %		–
D^+X		< 3.9 %	CL=90%	–
D^-X		(36.9 ± 3.3) %		–
D_s^+X		$(10.3^{+2.1}_{-1.8})$ %		–
D_s^-X		< 2.6 %	CL=90%	–
Λ_c^+X		< 3.1 %	CL=90%	–
$\overline{\Lambda}_c^-X$		$(5.0^{+2.1}_{-1.5})$ %		–
τX		(95 ± 5) %		–
cX		(24.6 ± 3.1) %		–
$\overline{c}cX$		(119 ± 6) %		–
***D*, *D**, or D_s modes**				
$D^-\pi^+$		$(2.68 \pm 0.13) \times 10^{-3}$		2306
$D^-\rho^+$		$(7.8 \pm 1.3) \times 10^{-3}$		2235
$D^-K^0\pi^+$		$(4.9 \pm 0.9) \times 10^{-4}$		2259
$D^-K^*(892)^+$		$(4.5 \pm 0.7) \times 10^{-4}$		2211
$D^-\omega\pi^+$		$(2.8 \pm 0.6) \times 10^{-3}$		2204
D^-K^+		$(1.97 \pm 0.21) \times 10^{-4}$		2279
$D^-K^+\overline{K}^0$		$< 3.1 \times 10^{-4}$	CL=90%	2188
$D^-K^+\overline{K}^*(892)^0$		$(8.8 \pm 1.9) \times 10^{-4}$		2070
$\overline{D}^0\pi^+\pi^-$		$(8.4 \pm 0.9) \times 10^{-4}$		2301
$D^*(2010)^-\pi^+$		$(2.76 \pm 0.13) \times 10^{-3}$		2255
$D^-\pi^+\pi^+\pi^-$		$(6.4 \pm 0.7) \times 10^{-3}$		2287
$(D^-\pi^+\pi^+\pi^-)$ nonresonant		$(3.9 \pm 1.9) \times 10^{-3}$		2287
$D^-\pi^+\rho^0$		$(1.1 \pm 1.0) \times 10^{-3}$		2206
$D^-a_1(1260)^+$		$(6.0 \pm 3.3) \times 10^{-3}$		2121
$D^*(2010)^-\pi^+\pi^0$		(1.5 ± 0.5) %		2247
$D^*(2010)^-\rho^+$		$(6.8 \pm 0.9) \times 10^{-3}$		2180
$D^*(2010)^-K^+$		$(2.14 \pm 0.16) \times 10^{-4}$		2226
$D^*(2010)^-K^0\pi^+$		$(3.0 \pm 0.8) \times 10^{-4}$		2205
$D^*(2010)^-K^*(892)^+$		$(3.3 \pm 0.6) \times 10^{-4}$		2155
$D^*(2010)^-K^+\overline{K}^0$		$< 4.7 \times 10^{-4}$	CL=90%	2131
$D^*(2010)^-K^+\overline{K}^*(892)^0$		$(1.29 \pm 0.33) \times 10^{-3}$		2007
$D^*(2010)^-\pi^+\pi^+\pi^-$		$(7.0 \pm 0.8) \times 10^{-3}$	S=1.3	2235
$(D^*(2010)^-\pi^+\pi^+\pi^-)$ non-resonant		$(0.0 \pm 2.5) \times 10^{-3}$		2235
$D^*(2010)^-\pi^+\rho^0$		$(5.7 \pm 3.2) \times 10^{-3}$		2150
$D^*(2010)^-a_1(1260)^+$		(1.30 ± 0.27) %		2061
$D^*(2010)^-\pi^+\pi^+\pi^-\pi^0$		(1.76 ± 0.27) %		2218
$D^{*-}3\pi^+2\pi^-$		$(4.7 \pm 0.9) \times 10^{-3}$		2195
$\overline{D}^*(2010)^-\omega\pi^+$		$(2.89 \pm 0.30) \times 10^{-3}$		2148
$D_1(2430)^0\omega \times$ B($D_1(2430)^0 \to D^{*-}\pi^+$)		$(4.1 \pm 1.6) \times 10^{-4}$		1992
$\overline{D}^{**-}\pi^+$	[ttt]	$(2.1 \pm 1.0) \times 10^{-3}$		–
$D_1(2420)^-\pi^+ \times$ B($D_1^- \to D^-\pi^+\pi^-$)		$(1.00^{+0.21}_{-0.25}) \times 10^{-4}$		–
$D_1(2420)^-\pi^+ \times$ B($D_1^- \to D^{*-}\pi^+\pi^-$)		$< 3.3 \times 10^{-5}$	CL=90%	–
$\overline{D}_2^*(2460)^-\pi^+ \times$ B($D_2^*(2460)^- \to D^0\pi^-$)		$(2.15 \pm 0.35) \times 10^{-4}$		2062
$\overline{D}_0^*(2400)^-\pi^+ \times$ B($D_0^*(2400)^- \to D^0\pi^-$)		$(6.0 \pm 3.0) \times 10^{-5}$		2090
$D_2^*(2460)^-\pi^+ \times$ B(($D_2^*)^- \to D^{*-}\pi^+\pi^-$)		$< 2.4 \times 10^{-5}$	CL=90%	–
$\overline{D}_s^*(2460)^-\rho^+$		$< 4.9 \times 10^{-3}$	CL=90%	1975
$D^0\overline{D}^0$		$< 4.3 \times 10^{-5}$	CL=90%	1868
$D^{*0}\overline{D}^0$		$< 2.9 \times 10^{-4}$	CL=90%	1794
D^-D^+		$(2.11 \pm 0.31) \times 10^{-4}$	S=1.2	1864
$D^-D_s^+$		$(7.2 \pm 0.8) \times 10^{-3}$		1812
$D^*(2010)^-D_s^+$		$(8.0 \pm 1.1) \times 10^{-3}$		1735
$D^-D_s^{*+}$		$(7.4 \pm 1.6) \times 10^{-3}$		1732
$D^*(2010)^-D_s^{*+}$		(1.77 ± 0.14) %		1649
$D_{s0}(2317)^-K^+ \times$ B($D_{s0}(2317)^- \to D_s^-\pi^0$)		$(4.2 \pm 1.4) \times 10^{-5}$		2097
$D_{s0}(2317)^-\pi^+ \times$ B($D_{s0}(2317)^- \to D_s^-\pi^0$)		$< 2.5 \times 10^{-5}$	CL=90%	2128
$D_{sJ}(2457)^-K^+ \times$ B($D_{sJ}(2457)^- \to D_s^-\pi^0$)		$< 9.4 \times 10^{-6}$	CL=90%	–
$D_{sJ}(2457)^-\pi^+ \times$ B($D_{sJ}(2457)^- \to D_s^-\pi^0$)		$< 4.0 \times 10^{-6}$	CL=90%	–
$D_s^-D_s^+$		$< 3.6 \times 10^{-5}$	CL=90%	1759

+ .....

B_c Decays

- They decay through weak interaction.
- Different processes:

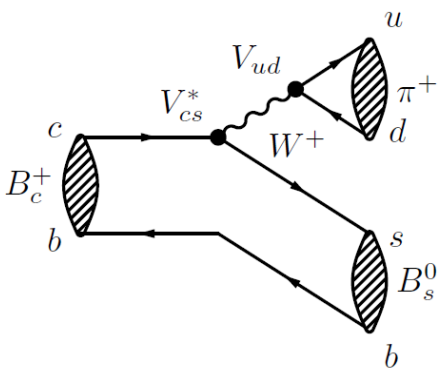


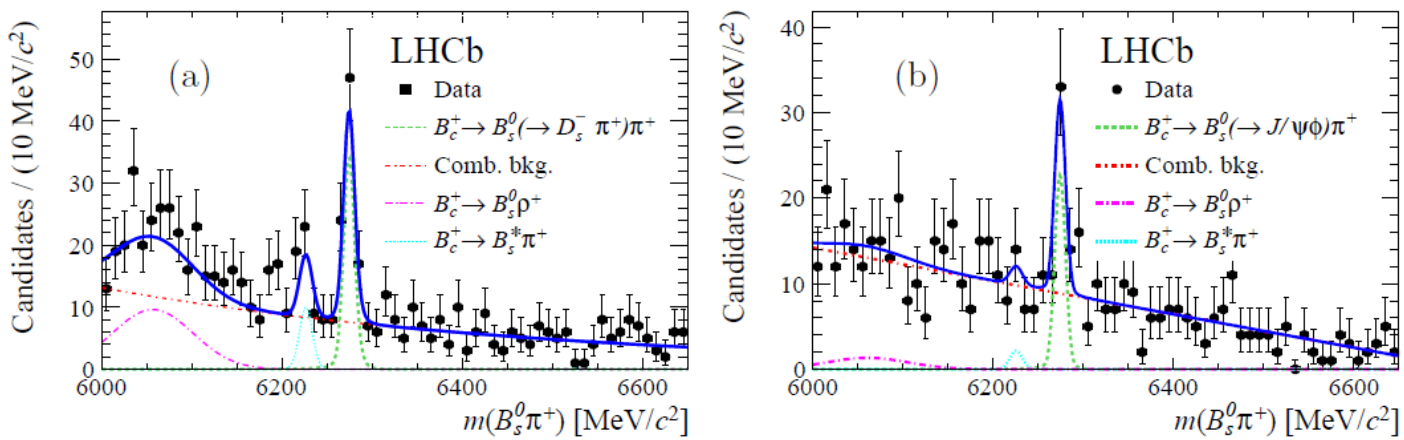
- Proportion of the different modes is linked to the B_c lifetime (~0.4 ps): important to measure precisely its lifetime.

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

Phys. Rev. Lett. **111** (2013) 181801

- First observation of a decay with a *b* spectator quark.
- Important to know dilution due to B_s^0 from B_c^+ decays in B_s^0 CP violation measurements
- B_s^0 reconstructed in the J/ψ φ and D_s π modes.

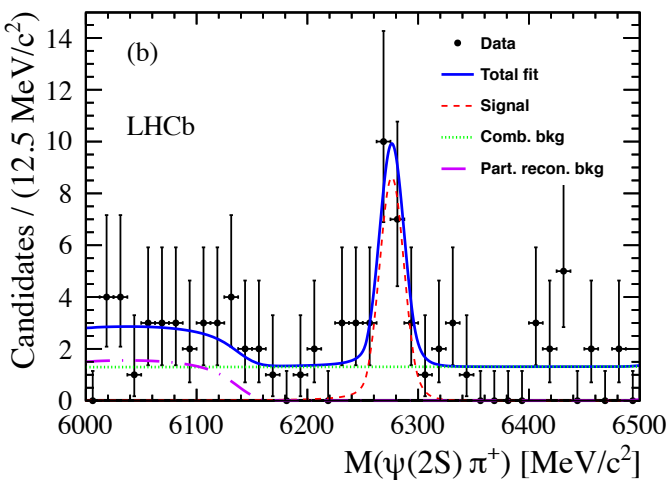




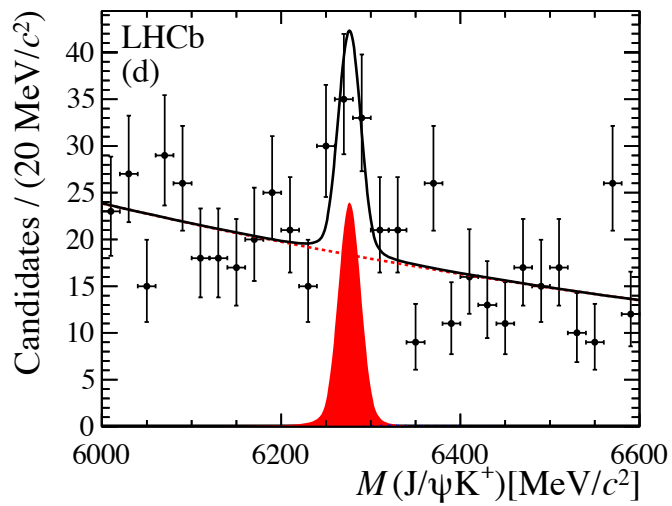
$$\frac{\sigma(B_c^+)}{\sigma(B_s^0)} \times \mathcal{B}(B_c^+ \to B_s^0\pi^+) = \left(2.38 \pm 0.35\,(\text{stat}) \pm 0.11\,(\text{syst})\,^{+0.17}_{-0.12}\,(\tau_{B_c^+})\right) \times 10^{-3}$$

$B_c^+ \to J/\psi\,\pi^+$ and friends

- $B_c^+ \to J/\psi\,\pi^+$ is the reference decay mode
- Similar modes discovered:
  - $B_c^+ \to \psi(2S)\,\pi^+$ [*Phys. Rev. D* 87 (2013) 071103]
  - Cabibbo suppressed counterpart, $B_c^+ \to J/\psi\,K^+$ [*J. High Energy Phys.* 09 (2013) 075]
  - Measured consistent with expectations



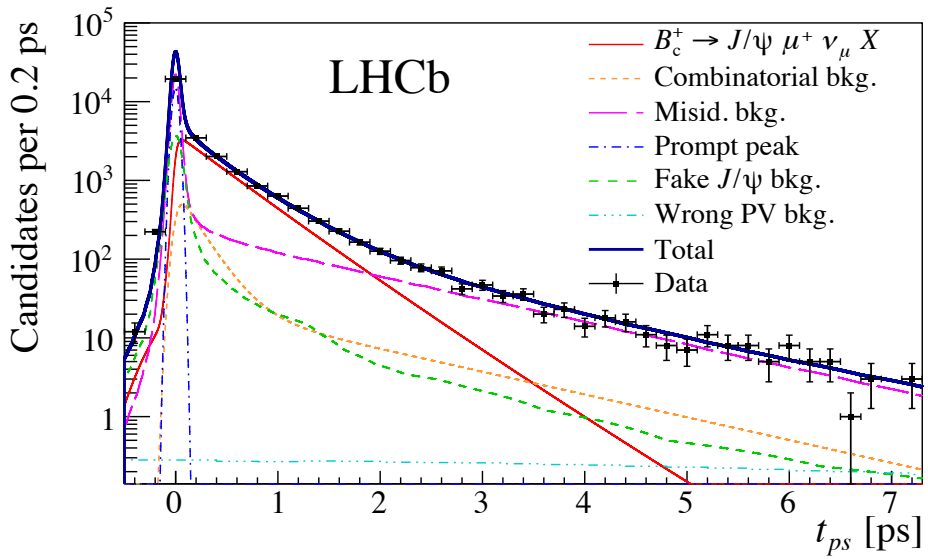
$$\frac{\mathcal{B}(B_c^+ \to \psi(2S)\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\,\pi^+)} = 0.250 \pm 0.068\,(\text{stat}) \pm 0.014\,(\text{syst}) \pm 0.006\,(\mathcal{B})$$



$$\frac{\mathcal{B}(B_c^+ \to J/\psi\,K^+)}{\mathcal{B}(B_c^+ \to J/\psi\,\pi^+)} = 0.069 \pm 0.019 \pm 0.005$$

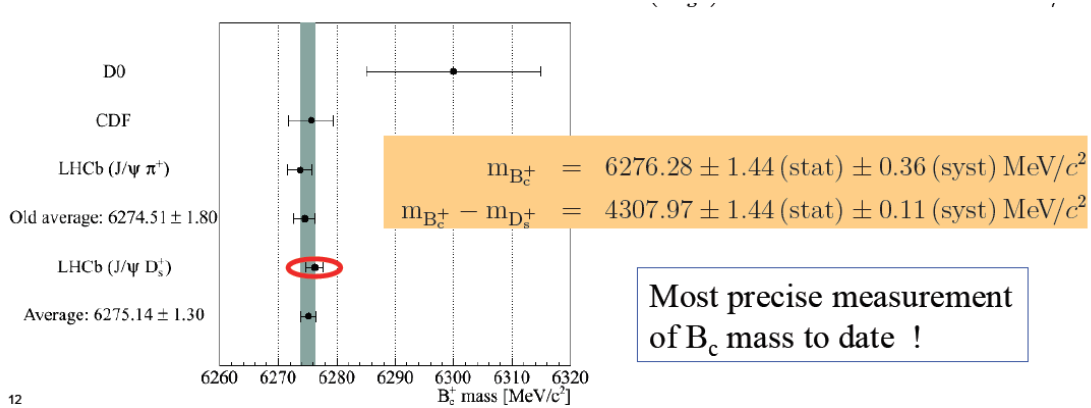
B_c^+ lifetime

- Measured with semi-leptonic decays [arXiv:1401.6932]
- **<u>τ=509±8±12 fs</u>**, most precise measurement to date, with uncertainty half of the previous average
- Measurement ongoing with $B_c \rightarrow J/\psi\ \pi^+$ decays (smaller systematic uncertainty)



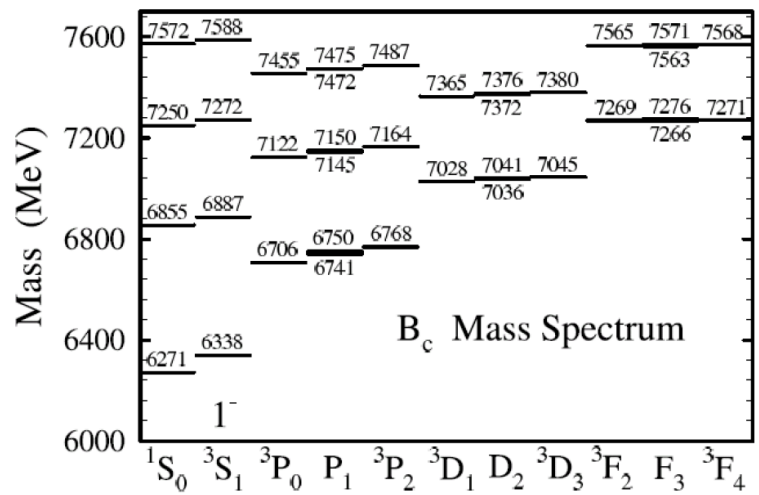
Other B_c^+ measurements in LHCb

- I showed only the measurements where we were involved but others were done with LHCb data:
  - Observation of $B_c^+ \rightarrow J/\psi\ K^+K^-\pi^+$ [arXiv:1309.0587]
  - Observation of $B_c^+ \rightarrow J/\psi\ \pi^+\ \pi^-\ \pi^+\ \pi^-\ \pi^+$ [arXiv:1404.0287]
  - Observation of $B_c^+ \rightarrow J/\psi\ D_s^{(*)+}$ [*Phys. Rev. D* 87 (2013) 112012]
  - Mass measurement with $B_c^+ \rightarrow J/\psi\ \pi^+$ and $J/\psi\ D_s^+$



Future of our project

- Precise production cross-section: in collaboration with Cagliari (G. Manca), with 3fb^{-1} of data
- Search of excited states:
  - Decaying to $B_c\gamma$, $B_c\pi^0$, $B_c\pi^+\pi^-$ or BD if above threshold
  - Important to understand cross-section
  - There could be exotic (BD molecules or tetraquarks) similar to the X(3872) in the charmonium sector



S. Godfrey, PRD 70, 054017 (2004)

- No absolute branching fraction is known yet: measure as many modes as possible to constrain them:
  - In particular, annihilation modes, like $B_c^+ \to \phi K^+$
  - Triply charmed decays, like $B_c^+ \to J/\psi D^0 K^+$

Conclusions

- LHCb searching for indirect evidence of New Physics through precision measurements, excellent results, but no sign of deviation from Standard Model
- LAL/Tsinghua collaboration involved in many of the B_c results from LHCb
- Upgrade of the experiment will increase a lot the statistics available

	Run 1			LS1		Run 2			LS2		
	Start-up	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019 … 20xx
										LHCb Upgrade	
$\sqrt{s}$ (TeV):		0.9 - 7	-	8	-		13 -14				
$\mathcal{L}$ ($cm^{-2}s^{-1}$):		10^{32}		$3\text{-}4\times10^{32}$			4×10^{32}			$10 - 20\times10^{32}$	
$\int \mathcal{L}dt$		3 fb^{-1}					8 (=3+5) fb^{-1}			> 50 fb^{-1}	