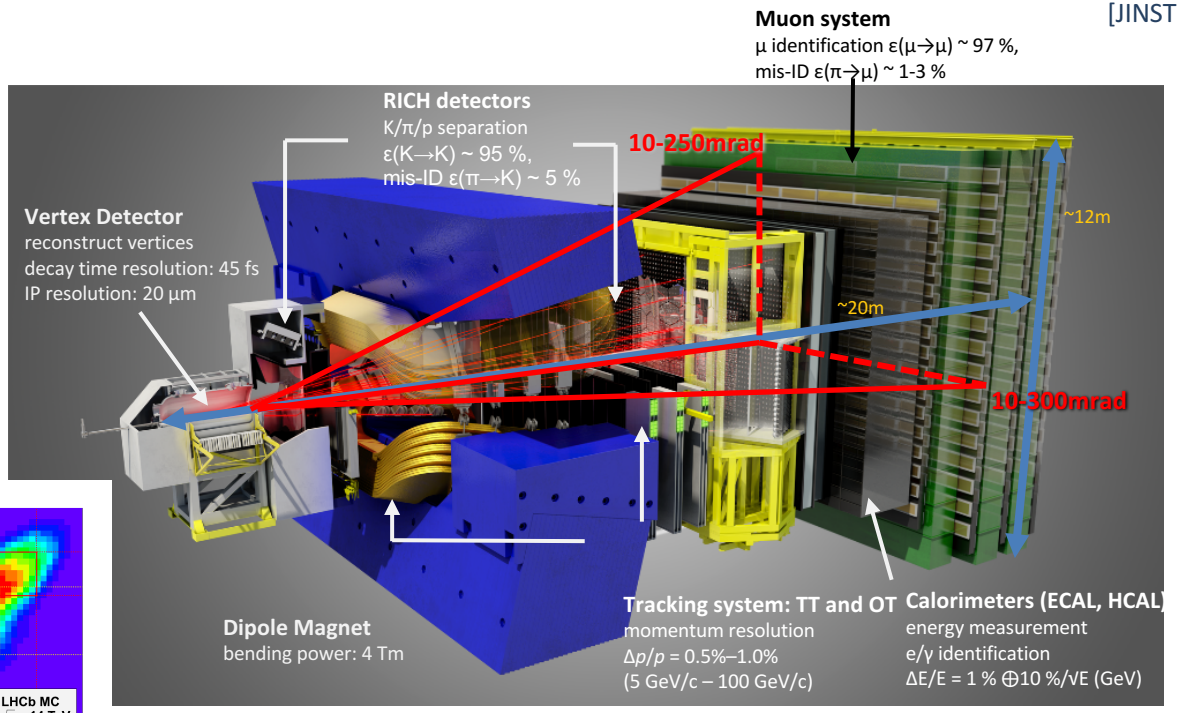
10th FCPPL Workshop, Tsinghua University, 27-30 March 2017

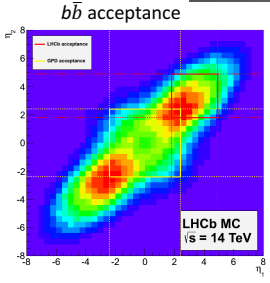
LHCb Results on B_c

Patrick Robbe (LHCb Collaboration), LAL Orsay, 29 Mar 2017

The LHCb experiment

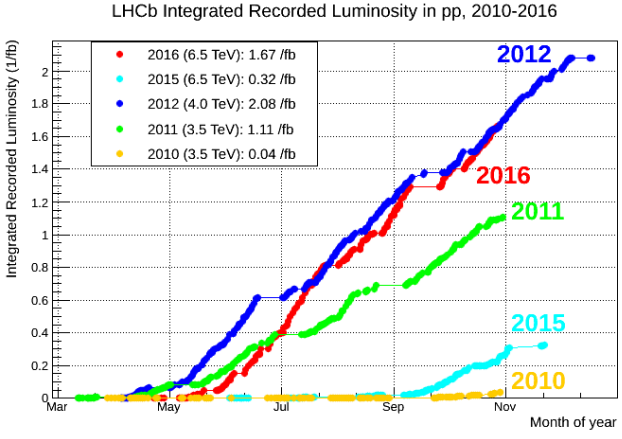
[IJMPA 30 (2015) 1530022]
[JINST 3 (2008) S08005]

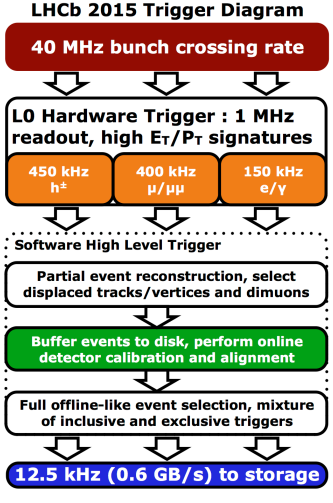




The LHCb data taking

- **3 fb^{-1}** collected in *Run 1*
- **2 fb^{-1}** collected in *2015* and *2016*, ~1.5 fb^{-1} expected in 2017
  - Higher run 2 energy: beneficial for LHCb core physics program: $b\bar{b}$ production (and B_c production) cross-section almost doubled
  - Since 2015, calibration and alignment performed *online*: analysis can be done directly on the trigger output.





LHCb recent highlights: $B_s \rightarrow \mu^+\mu^-$

- Rare decay sensitive to new physics:

[arXiv:1703.05747]

Standard model diagram

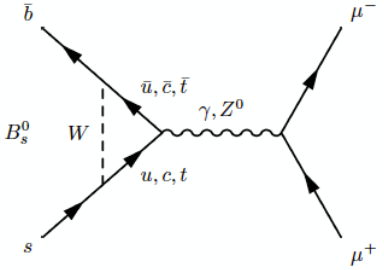
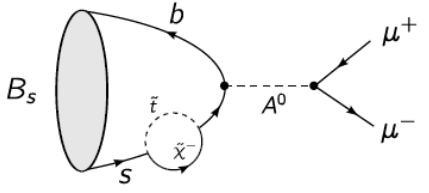
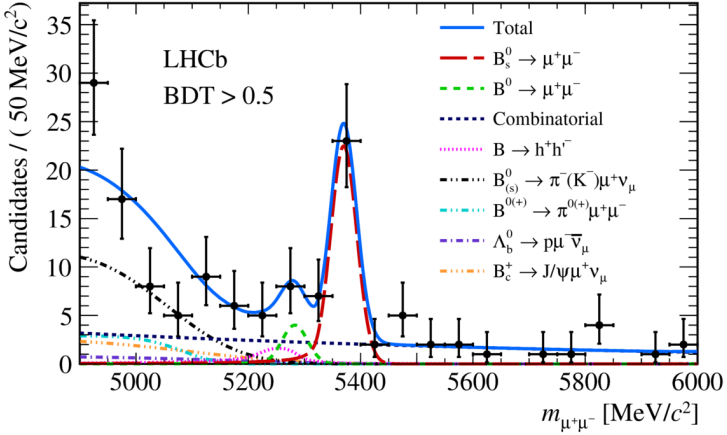


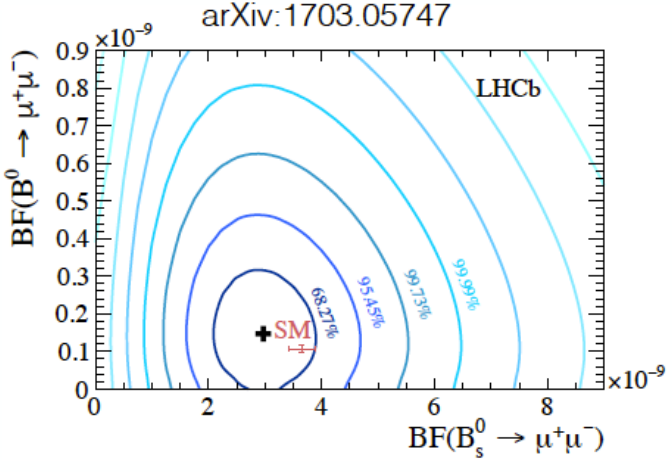
Diagram with new particles in loops



Using Run 1+2 data, first signal observation of 7.8σ by LHCb alone

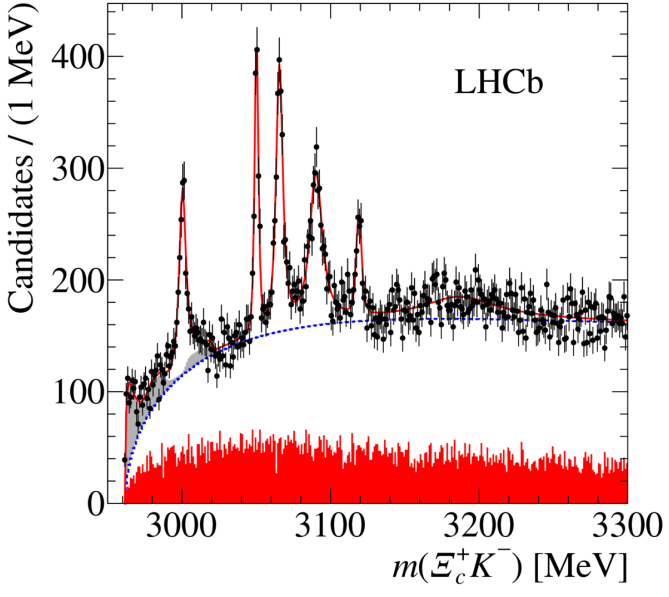


$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = \left(3.0 \pm 0.6\,^{+0.3}_{-0.2}\right) \times 10^{-9}$$

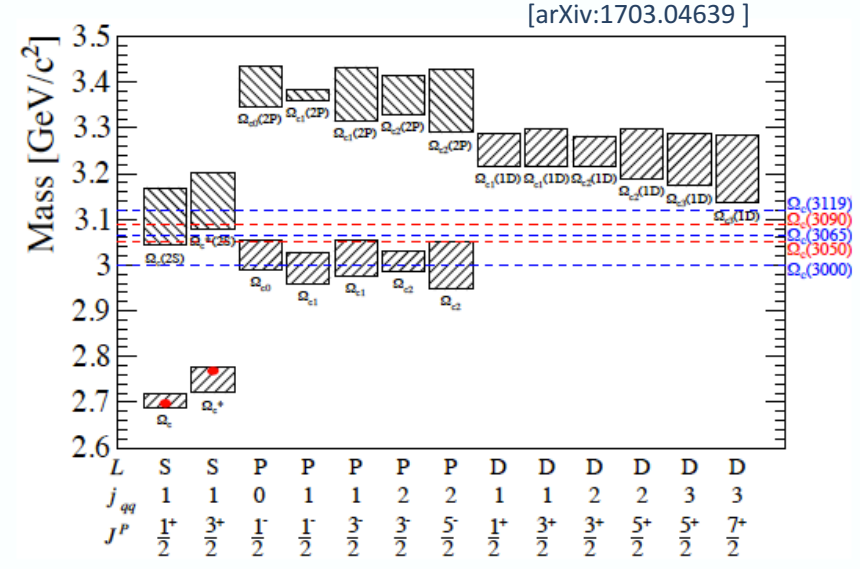


LHCb recent highlights: Ω_c spectrum

Only two members of the Ω_c (css baryon) spectrum observed so far.
Reconstruction with Run 1 + 2015 data of the decay $\Omega_c^0 \rightarrow \Xi_c^+ K^-$



[arXiv:1703.04639]



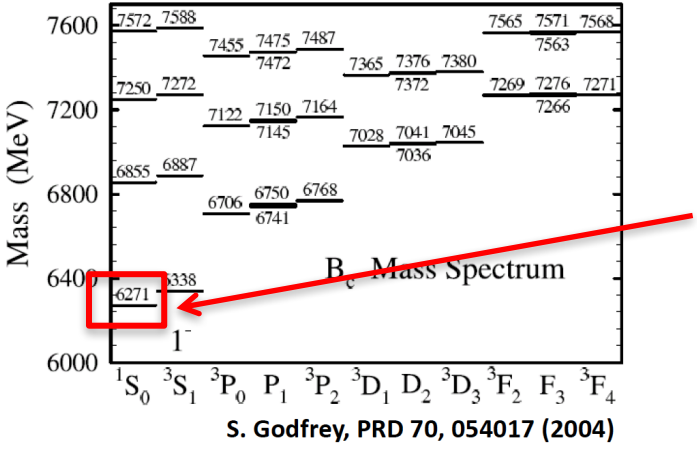
Observation of 5 narrow Ω_c^0 new states, bringing important information on quark bindings and HQET.

LAL/Tsinghua collaboration

- Started in 2006
- Current members:
  - LAL: Patrick Robbe, Marie-Helene Schune, Sergey Barsuk, Yanxi Zhang
  - Tsinghua: Yuanning Gao, Zhenwei Yang, Liupan An
- Activities, data analysis at LHCb:
  - Quarkonium and B hadron production in *pp* and *p*Pb collisions
  - Measurements of the B_c meson
- Long term exchanges:
  - 2009 – 2012: Jibo He, CNRS post-doc (now UCAS researcher)
  - 2007 – 2010: Wenbin Qian, Embassy co-tutelle PhD (now post-doc at Warwick University)
  - 2011 – 2012: Bo Liu, CSC grant, one year at LAL
  - 2014 – 2016: Yiming Li, CNRS post-doc (now at IHEP)
  - Since 2015: Yanxi Zhang, CNRS post-doc

B_c Meson

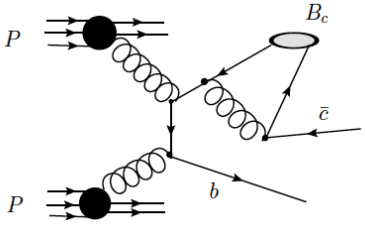
- Unique family of meson formed with 2 different heavy flavours: ($\bar{b}c$).
- It is considered as a quarkonium state, because the study of its **production** properties can give constraints for the understanding of production mechanisms of heavy-quark states.
- Study of its **mass**, **lifetime**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

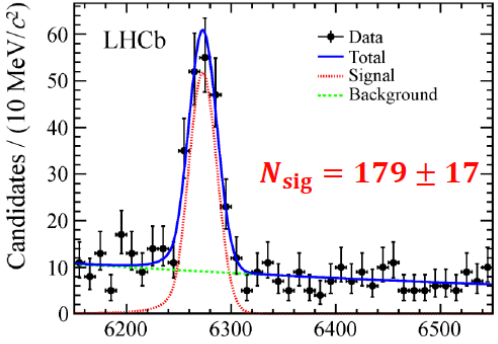


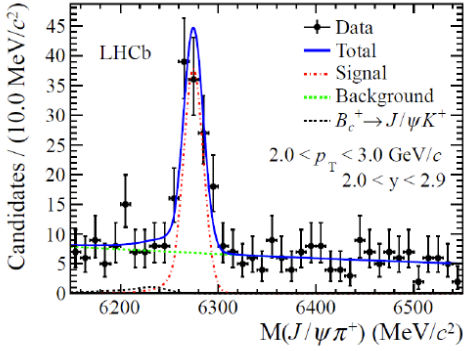
S. Godfrey, PRD 70, 054017 (2004)

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

B_c Production







Typical production diagram (α_s^4)

7 TeV: [PRL 109 (2012) 232001]
8 TeV: [PRL 114 (2015) 132001]

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

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

7 TeV

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

Integrated over $p_T > 4$ GeV/c and $2.5<\eta<4.5$

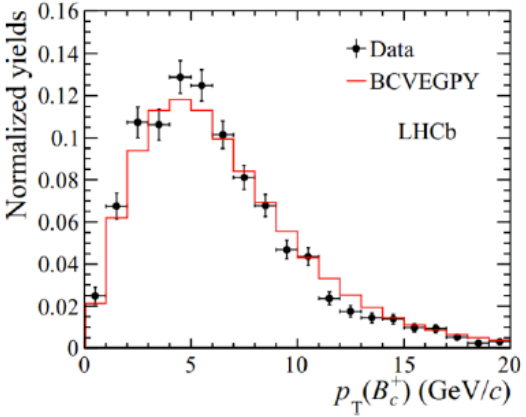
8 TeV

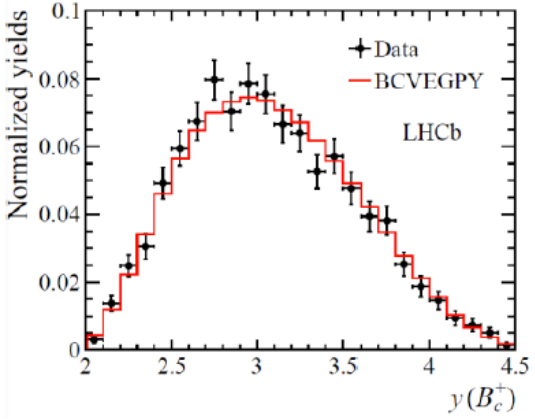
$R_{c/u} = (0.683 \pm 0.018 \pm 0.009)\%$

Integrated over $p_T < 20$ GeV/c and $2<y<4.5$

B_c Production

- At 8 TeV, enough statistics to perform a differential measurement as a function of p_T and y.
- Compare with NRQCD at fixed order, implemented in the BCVEGPY generator [C.-H. Chang et al., CPC 174 (2006) 241], which can describe well the B_c production.
- NB: implementing this generator in LHCb was the object of the first LAL/Tsinghua meeting in Tsinghua in 2006.





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

B_c Decays

- Very little is known about them but this improves very fast
- PDG 2016 section for B_c^+:

LAL/Tsinghua contributions

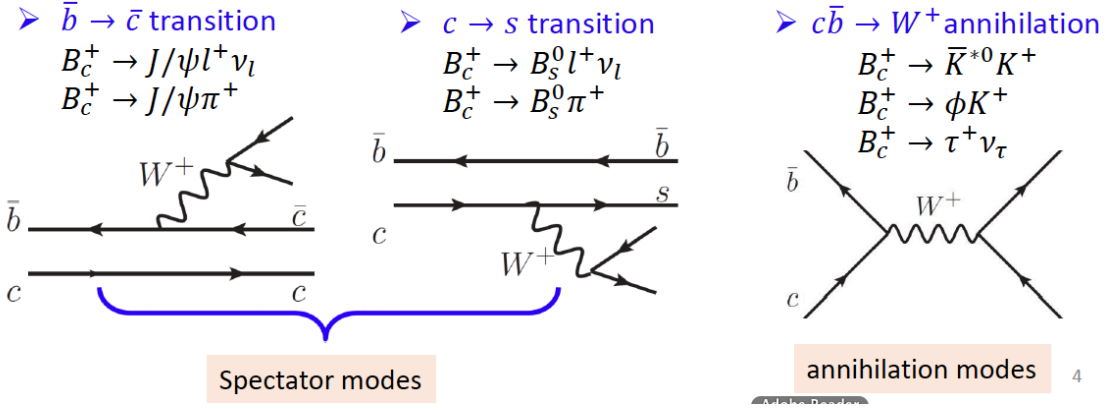
B_c^+ DECAY MODES × B($\bar{b} \to B_c$)

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

	Mode	Fraction (Γ_i/Γ)	Confidence level
	The following quantities are not pure branching ratios; rather the fraction $\Gamma_i/\Gamma \times$ B($\bar{b} \to B_c$).		
Γ_1	$J/\psi(1S)\ell^+\nu_\ell$ anything	$(5.2\ ^{+2.4}_{-2.1}) \times 10^{-5}$	
Γ_2	$J/\psi(1S)\mu^+\nu_\mu$		
Γ_3	$J/\psi(1S)\pi^+$	seen	
Γ_4	$J/\psi(1S)K^+$	seen	
Γ_5	$J/\psi(1S)\pi^+\pi^+\pi^-$	seen	
Γ_6	$J/\psi(1S)a_1(1260)$	$< 1.2 \times 10^{-3}$	90%
Γ_7	$J/\psi(1S)K^+K^-\pi^+$	seen	
Γ_8	$J/\psi(1S)\pi^+\pi^+\pi^+\pi^-\pi^-$	seen	
Γ_9	$\psi(2S)\pi^+$	seen	
Γ_{10}	$J/\psi(1S)D_s^+$	seen	
Γ_{11}	$J/\psi(1S)D_s^{*+}$	seen	
Γ_{12}	$J/\psi(1S)p\bar{p}\pi^+$	seen	
Γ_{13}	$D^*(2010)^+\overline{D}^0$	$< 6.2 \times 10^{-3}$	90%
Γ_{14}	D^+K^{*0}	$< 0.20 \times 10^{-6}$	90%
Γ_{15}	$D^+\overline{K}^{*0}$	$< 0.16 \times 10^{-6}$	90%
Γ_{16}	$D_s^+K^{*0}$	$< 0.28 \times 10^{-6}$	90%
Γ_{17}	$D_s^+\overline{K}^{*0}$	$< 0.4 \times 10^{-6}$	90%
Γ_{18}	$D_s^+\phi$	$< 0.32 \times 10^{-6}$	90%
Γ_{19}	K^+K^0	$< 4.6 \times 10^{-7}$	90%
Γ_{20}	$B_s^0\pi^+$ / B($\bar{b} \to B_s$)	$(2.37^{+0.37}_{-0.35}) \times 10^{-3}$	

B_c Decays

- They decay through weak interaction.
- Different processes:



- Proportion of the different modes is linked to the B_c lifetime (~0.5 ps), shorter than the other B hadron lifetimes. Known precisely from LHCb measurements.

B_c^+ MEAN LIFE

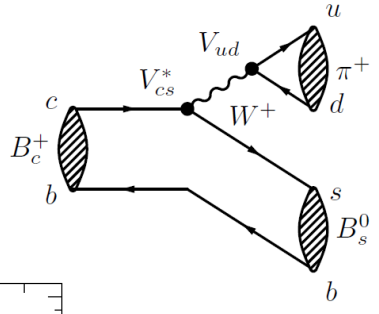
"OUR EVALUATION" is an average using rescaled values of the data listed below. The average and rescaling were performed by the Heavy Flavor Averaging Group (HFAG) and are described at http://www.slac.stanford.edu/xorg/hfag/. The averaging/rescaling procedure takes into account correlations between the measurements.

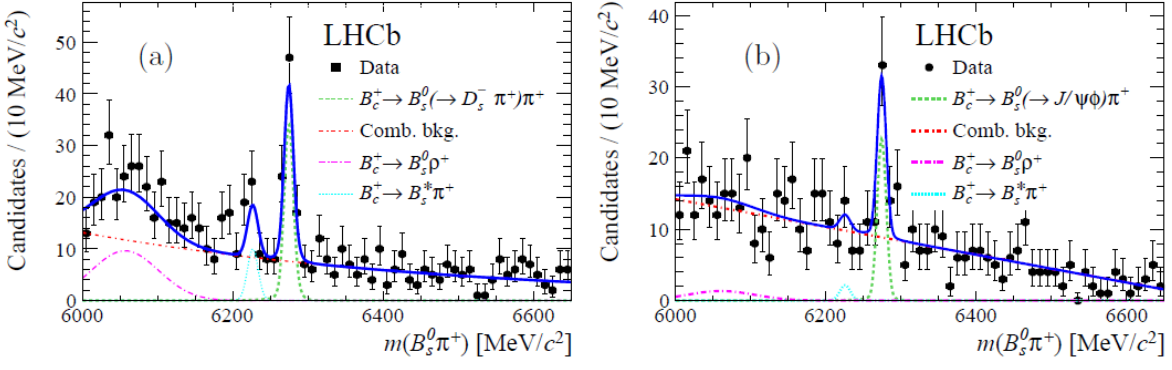
VALUE (10^{-12} s)			DOCUMENT ID		TECN	COMMENT
0.507	**±0.009**	**OUR EVALUATION**				
0.507	**±0.009**	**OUR AVERAGE**				
0.5134	±0.0110	±0.0057	[1,2] AAIJ	15G	LHCB	pp at 7, 8 TeV
0.509	±0.008	±0.012	[3] AAIJ	14G	LHCB	pp at 8 TeV
0.452	±0.048	±0.027	[2] AALTONEN	13	CDF	$p\overline{p}$ at 1.96 TeV
0.448	$^{+0.038}_{-0.036}$	±0.032	[4] ABAZOV	09H	D0	$p\overline{p}$ at 1.96 TeV
0.463	$^{+0.073}_{-0.065}$	±0.036	[4] ABULENCIA	06O	CDF	$p\overline{p}$ at 1.96 TeV
0.46	$^{+0.18}_{-0.16}$	±0.03	[4] ABE	98M	CDF	$p\overline{p}$ 1.8 TeV

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

[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 $J/\psi\,\phi$ and $D_s\,\pi$ modes.



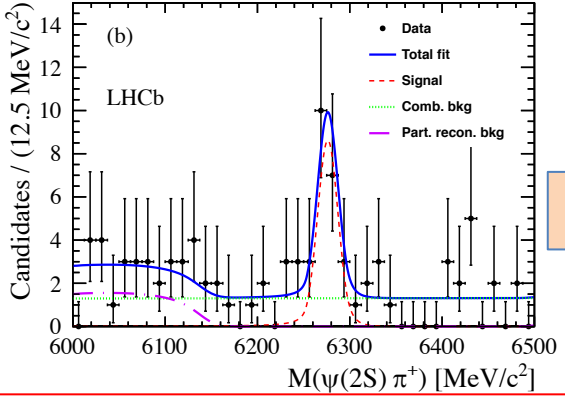


$$\frac{\sigma(B_c^+)}{\sigma(B_s^0)} \times \mathcal{B}(B_c^+ \to B_s^0\pi^+) = \left(2.38 \pm 0.35\,(\text{stat}) \pm 0.11\,(\text{syst}) \,^{+0.17}_{-0.12}\,(\tau_{B_c^+})\right) \times 10^{-3}$$

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

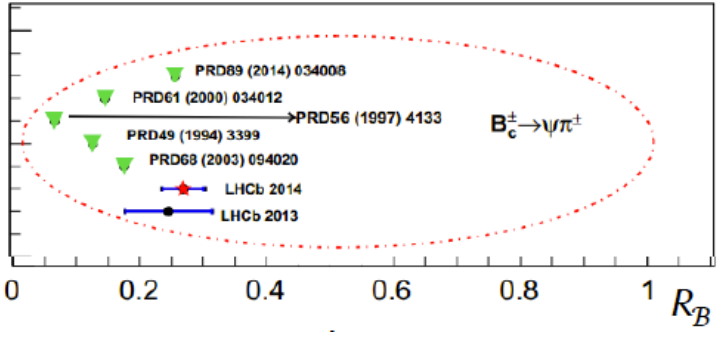
- $B_c^+ \to J/\psi\,\pi^+$ is the reference decay mode
- Similar modes discovered:
  - $B_c^+ \to \psi(2S)\,\pi^+$ [Phys. Rev. D 87 (2013) 071103], updated in [Phys. Rev. D 87 (2013) 071103]
  - Cabibbo suppressed counterpart, $B_c^+ \to J/\psi\,K^+$ [J. High Energy Phys. 09 (2013) 075]
  - First baryonic decay, $B_c^+ \to J/\psi\,p\,\bar{p}$ [Phys. Rev. Lett. 113 (2014) 152003]
  - Measured consistent with expectations

$B_c^+ \to \psi(2S)\,\pi^+$



Theory predictions

$B_c^+ \to \psi(2S)\,\pi^+$

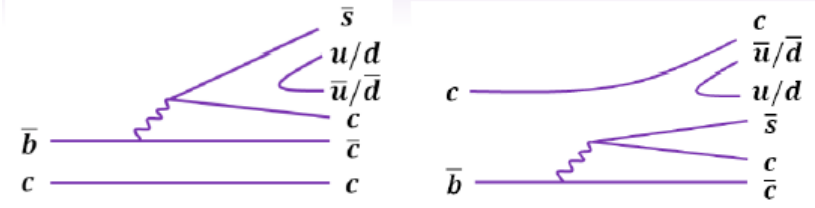


7 TeV $\dfrac{\mathcal{B}(B_c^+ \to \psi(2S)\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\,\pi^+)} = 0.250 \pm 0.068\,(\text{stat}) \pm 0.014\,(\text{syst}) \pm 0.006\,(\mathcal{B})$

8 TeV $R_B = 0.268 \pm 0.032\ (\text{stat}) \pm 0.007\ (\text{syst}) \pm 0.006\ (\text{BF})$

Study of $B_c^+ \to J/\psi\, D^{(*)}\, K^{(*)}$

- Most recent LAL/Tsinghua analysis, published in 2017:
  - Phys. Rev. D95 (2017) 032005.
- This is a favored $b \to c\bar{c}s$ transition, giving the final states: $B_c^+ \to J/\psi\, D^{(*)0}\, K^+$ *and* $B_c^+ \to J/\psi\, D^{(*)+}\, K^{*0}$



- Can be used to explore D_s spectroscopy in $D_{sJ} \to D^{(*)}K^{(*)}$ decays

Substantial $\mathcal{B}(D_{s1}(2536) \to D^*K)$

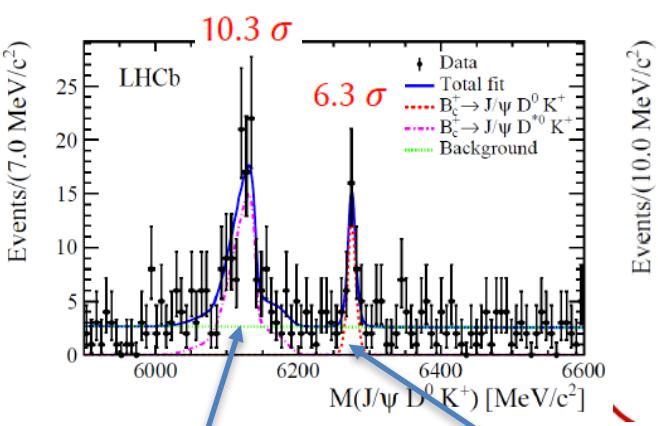
final state f	$\mathcal{B}(B_c^+ \to \bar{f})$	$\mathcal{B}(B_c^- \to f)$
$J/\psi\, D_{s1}^-(2460)$	5.339×10^{-3}	5.348×10^{-3}
$J/\psi\, D_{s1}^-(2536)$	1.123×10^{-3}	1.124×10^{-3}

Fu et al, JHEP 1106 (2011) 015

- Complex final state, with up to 7 charged tracks:
  - $J/\psi \to \mu^+\mu^-$, $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $K^{*0} \to K^+\pi^-$
  - D^{*0} and D^{*+} are only ***partially*** reconstructed, *ie* the soft π^0, π^+ or γ in their decays are not reconstructed: $D^{*0} \to D^0\pi^0$, $D^{*0} \to D^0\gamma$, $D^{*+} \to D^0\pi^+$

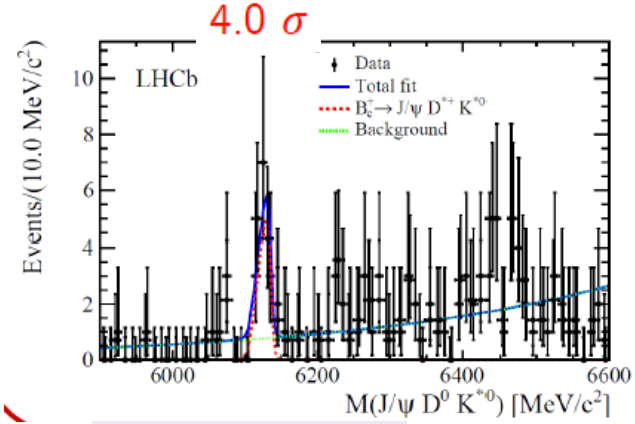
Study of $B_c^+ \to J/\psi\, D^{(*)}\, K^{(*)}$

- With Run 1 data, two observations and two evidences of these new decay modes

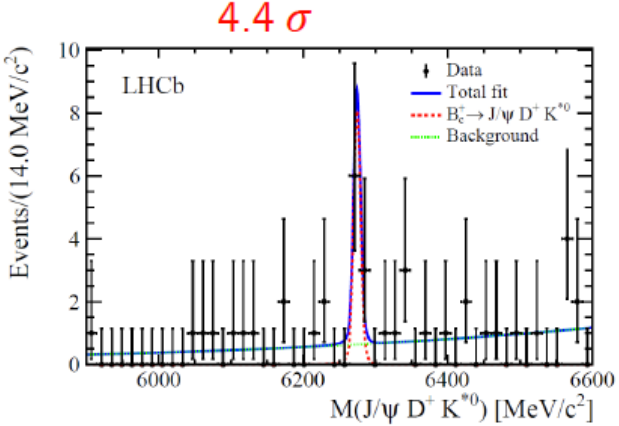


$B_c^+ \to J/\psi D^0 K^+$

$B_c^+ \to J/\psi D^{*0} K^+$



$B_c^+ \to J/\psi D^{*+} K^{*0}$



$B_c^+ \to J/\psi D^+ K^{*0}$

$$\frac{\mathcal{B}(B_c^+ \to J/\psi D^0 K^+)}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)} = 0.432 \pm 0.136 \pm 0.028,$$

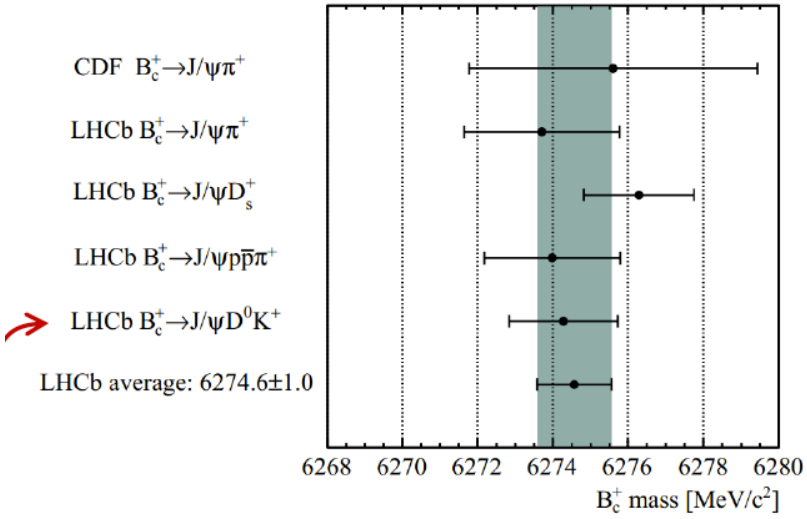
$$\frac{\mathcal{B}(B_c^+ \to J/\psi D^{*0} K^+)}{\mathcal{B}(B_c^+ \to J/\psi D^0 K^+)} = 5.1 \pm 1.8 \pm 0.4,$$

$$\frac{\mathcal{B}(B_c^+ \to J/\psi D^{*+} K^{*0})}{\mathcal{B}(B_c^+ \to J/\psi D^0 K^+)} = 2.10 \pm 1.08 \pm 0.34,$$

$$\frac{\mathcal{B}(B_c^+ \to J/\psi D^+ K^{*0})}{\mathcal{B}(B_c^+ \to J/\psi D^0 K^+)} = 0.63 \pm 0.39 \pm 0.08,$$

B_c mass measurement with $B_c^+ \rightarrow J/\psi\, D^{(*)}\, K^{(*)}$

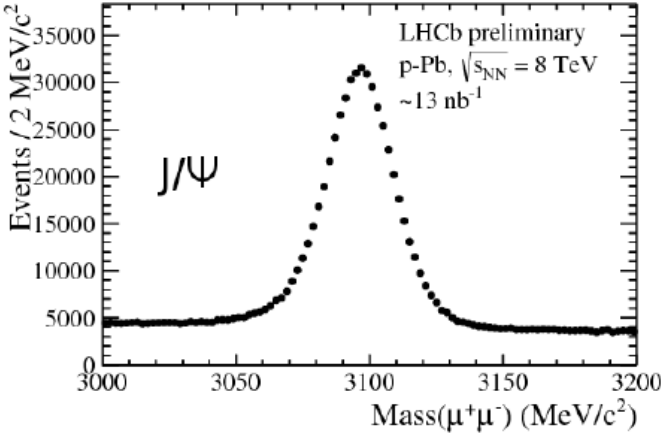
- Because of the small q^2 value in the decay, it can give a precise measurement of the B_c mass
- With this analysis, the value obtained is $M(B_c^+) = 6274.28 \pm 1.40 \pm 0.32\ \text{MeV}/c^2$ which is the single most precise measurement.
- Combining with other measurements:

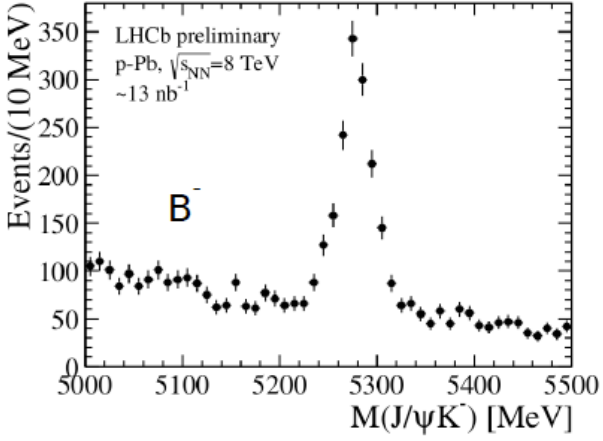


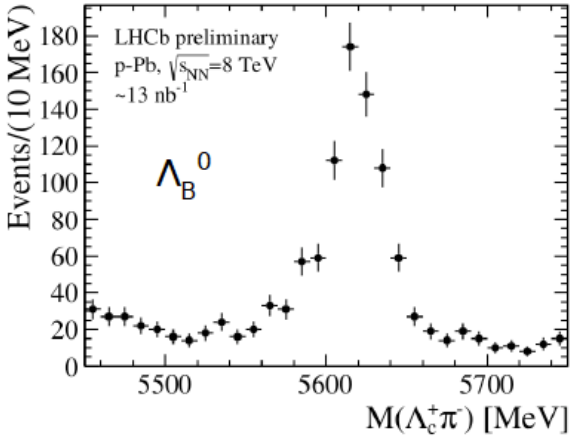
New LHCb average: **6274.6 ± 1.0 MeV/c^2**

Quarkonium and *b* hadron production in *p*Pb collisions

- First publications obtained by the LAL/Tsinghua collaboration were about J/ψ [Eur.Phys.J.C71 (2011) 1645] and B^+ [JHEP 08 (2013) 117] production in *pp* collisions at 7 TeV.
- Re-use this expertise to perform charmonium and *b* hadron measurements in *p*Pb and Pb*p* collisions at 8 TeV: a large dataset was recorded end of 2016, in which several clean signals are seen, promissing precise production measurements.







- An undergraduate student from Tsinghua will join LAL for 3 months this summer to participate to these analyses.

Conclusions

- LHCb recorded high quality *pp* and *p*Pb data since the beginning of Run 2.
- LAL/Tsinghua collaboration is involved in many of the B_c results from LHCb, and will continue with analyses requiring more statistics:
  - Excited B_c states
  - Annihilation decays such as $B_c^+ \to \phi K^+$
- Upgrade after LS2 will also boost B_c physics at the LHC