B_c study at LHC

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LHCb
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE
cnrs IN2P3 Les deux infinis

25/09/2015, "New possibilities in quarkonia physics" workshop

Content

- Introduction
- Knowledge before LHC era
- Experimental results from LHC
  - Production
  - Spectroscopy
  - Mass
  - Lifetime
  - Decays
- Prospects

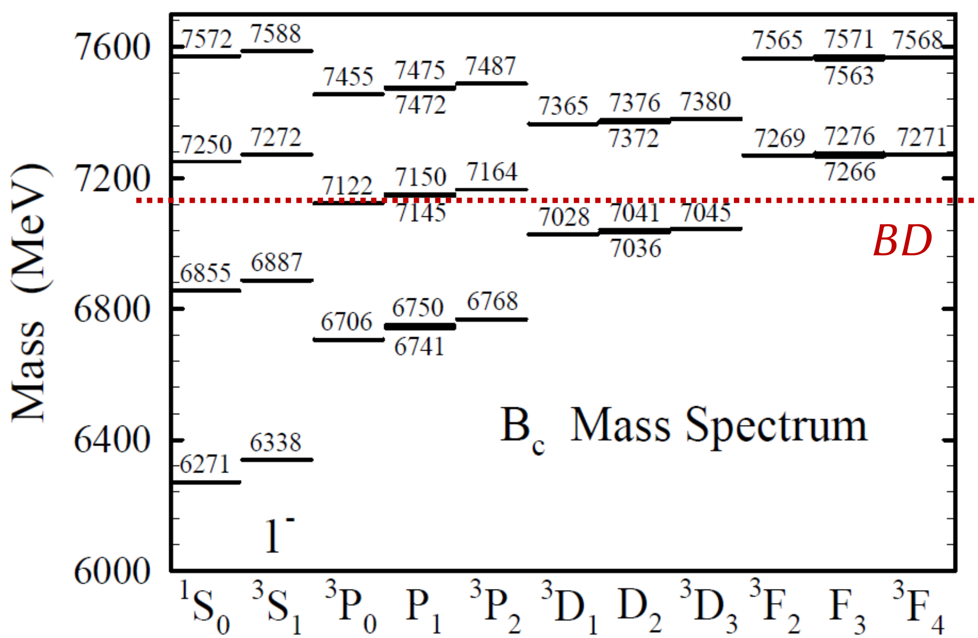
Introduction

- B_c is the only meson (family) in SM formed by two different heavy flavour quarks
- Similar to charmonia and bottomonia, a rich spectrum expected

- Below BD threshold all excited states decay to the ground state
- The ground state decays only weakly

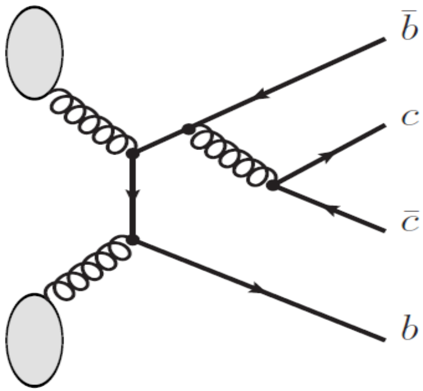
- Due to the great variety of decay modes, B_c has a much shorter lifetime than other B mesons

Godfrey, PRD70 (2004) 054017



Production

- B_c is produced mainly through gluon-gluon fusion at hadron colliders.
  - Only accessible at high energy hadron colliders with high luminosity
- Production cross-section grows fast wrt $\sqrt{s}$
  - $\sigma_{\text{LHC}}/\sigma_{\text{Tevatron}} \sim \mathcal{O}(10)$
  - $\sigma(B_c^+) \sim 0.47$ μb @ $\sqrt{s} = 8$ TeV
    ~ 0.9 μb @ $\sqrt{s} = 14$ TeV;



- A considerable fraction of B_c^+ from higher states
  - $\sim 1/3$ from $B_c(2S)$, $\sim 10\%$ from $B_c(1P)$

Predicted cross-section (in nb)

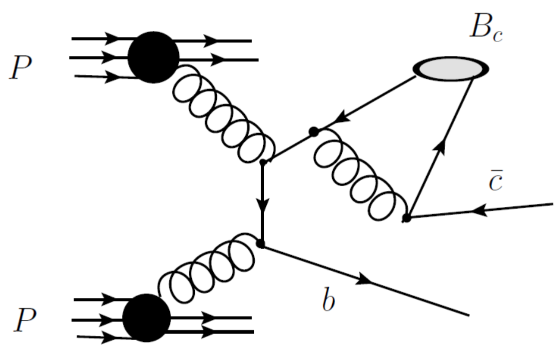
-	$\|(^1S_0)_1\rangle$	$\|(^3S_1)_1\rangle$	$\|(^1S_0)_8 g\rangle$	$\|(^3S_1)_8 g\rangle$	$\|(^1P_1)_1\rangle$	$\|(^3P_0)_1\rangle$	$\|(^3P_1)_1\rangle$	$\|(^3P_2)_1\rangle$
LHC	71.1	177.	(0.357, 3.21)	(1.58, 14.2)	9.12	3.29	7.38	20.4
TEVATRON	5.50	13.4	(0.0284, 0.256)	(0.129, 1.16)	0.655	0.256	0.560	1.35

C-H Chang et al, PRD71 (2005) 074012

Theoretical predictions for production

- Two approaches based on NRQCD factorization

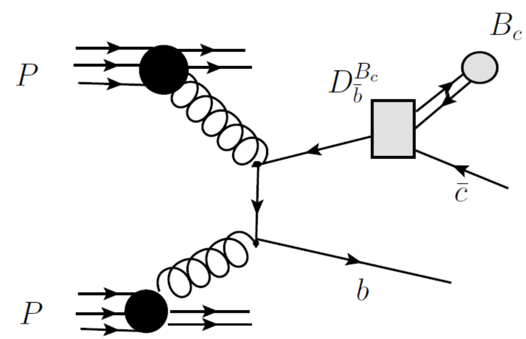
Fixed-order approach



- Also provides information for accompany b and $\bar{c}$
- BCVEGPY generator adopts this approach, and is used in the LHC simulations

C-H Chang et al, Comput.Phys.Commun. 174 (2006) 241

Fragmentation approach



- Only valid when B_c produced with very high p_{T}, not relevant for current experiments

What we know before LHC era

- B_c first observed by CDF at Tevatron

  … and was only studied by CDF and D0
- Three decays observed: $J/\psi\pi^+$, $J/\psi e^+\nu_e$, $J/\psi\mu^+\nu_\mu$
- Mass: 6.277 ± 0.006 GeV
- Lifetime: 0.45 ± 0.04 ps

} PDG 2012

- Production:

p_T > 6 GeV, |y| < 1

$$\frac{\sigma(B_c)\cdot BR(B_c \to J/\psi\, \ell\nu)}{\sigma(B)\cdot BR(B \to J/\psi\, K)} = 0.132^{+0.041}_{-0.037}\,(\text{stat.}) \pm 0.031\,(\text{syst.})\,^{+0.032}_{-0.020}\,(\text{lifetime})$$

CDF, PRD58(1998)112004

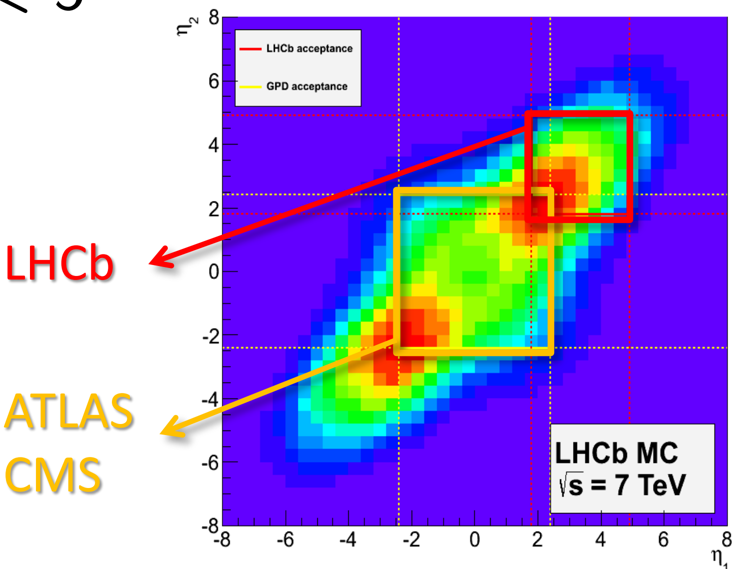
- No sign of excited state

Advantage of LHC experiments

- Higher energy = Larger cross-section!
  - $\sigma_{\mathrm{LHC}}/\sigma_{\mathrm{Tevatron}} \sim \mathcal{O}(10)$

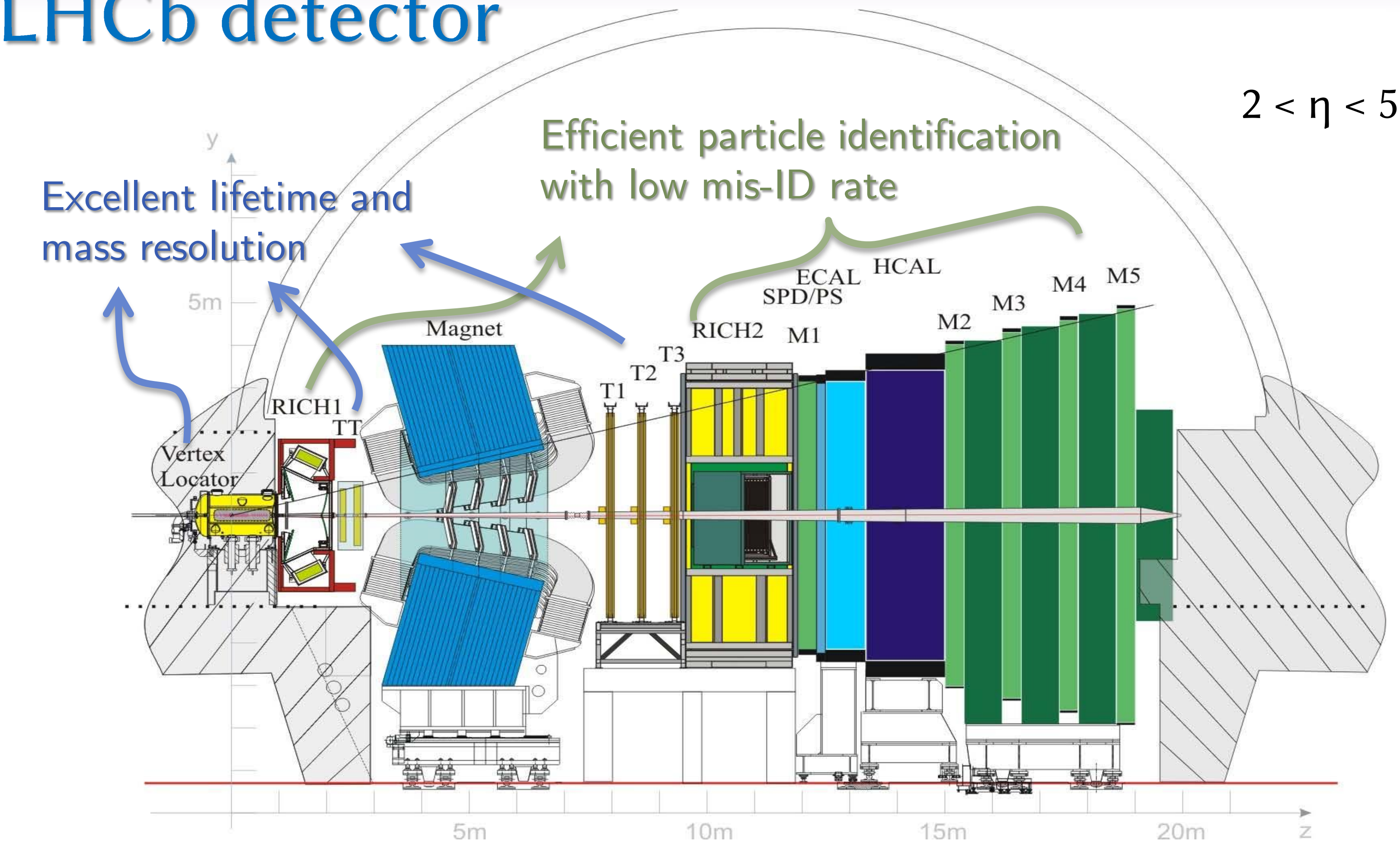
- LHC experiments cover complementary kinematic ranges
  - ATLAS, CMS: high p_{T}, low rapidity
  - LHCb: lower p_{T}, $2 < \eta < 5$

- Not to mention that LHCb is specifically designed for *b*-physics!



LHCb detector

$2 < \eta < 5$



Run I: 1 fb^{-1} *pp* collision @ $\sqrt{s}$ = 7 TeV
+ 2 fb^{-1} *pp* collision @ $\sqrt{s}$ = 8 TeV

Production at LHC

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

- $\sqrt{s} = 7$ TeV:
  - LHCb (0.37 fb^{-1}): $p_T > 4$ GeV, $2.5 < \eta < 4.5$ *PRL 109 (2012) 232001*

    $R = \mathbf{(0.68 \pm 0.10 \pm 0.03 \pm 0.05(\tau_{B_c}))\%}$
  - CMS (5.1 fb^{-1}): $p_T > 15$ GeV, $|y| < 1.6$ *JHEP 01 (2015) 063*

    $R = \mathbf{(0.48 \pm 0.05 \pm 0.03 \pm 0.05(\tau_{B_c}))\%}$
- A lower R value at higher p_T is expected, since B_c^+ has softer p_T distribution than B^+.
- Comparing to CDF result using $B_c^+ \to J/\psi l\nu$: $p_T > 6$ GeV, $|y| < 1$

$$\frac{\sigma(B_c^+)\mathcal{B}(B_c^+ \to J/\psi l^+\nu)}{\sigma(B^+)\mathcal{B}(B^+ \to J/\psi K^+)} = 0.132^{+0.041}_{-0.037} \pm 0.031^{+0.032}_{-0.020}(\tau_{B_c})$$

  - LHCb measured $\frac{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)} = (4.69 \pm 0.28 \pm 0.46)\%$
  - $\Rightarrow R \sim 0.6\%$

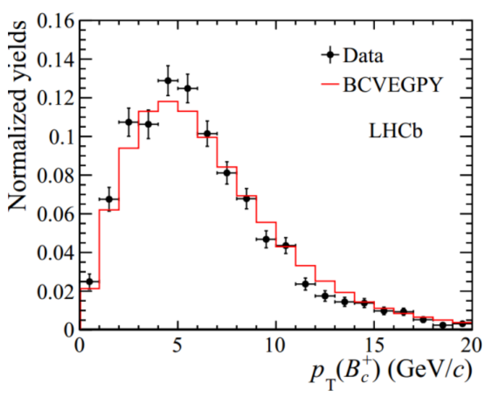
PRD 90 (2014) 032009

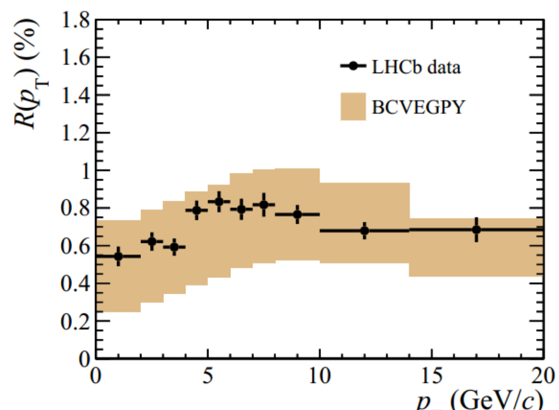
Production at LHC

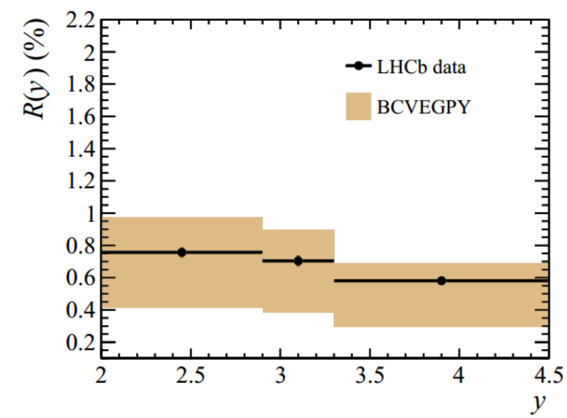
$$R = \frac{\sigma(B_c^+)\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+)\mathcal{B}(B^+ \to J/\psi K^+)}$$

PRL 114 (2015) 132001

- LHCb recently measured R @ 8 TeV
  - $0 < p_{\mathrm{T}} < 20$ GeV, $2 < y < 4.5$
  - $R =$ **$(0.683 \pm 0.018 \pm 0.009)\%$**
  - Consistent with 7 TeV result
- The sufficient statistics allow double differential ratio measurement
  - R as function of p_{T}, y agree with theory (FONLL for B, BcVegPy for B_c)







BcVegPy well describe the p_{T} spectrum

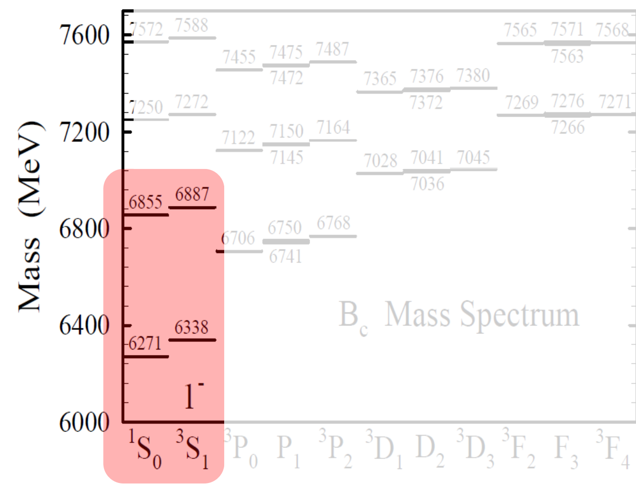
Normali-zation:

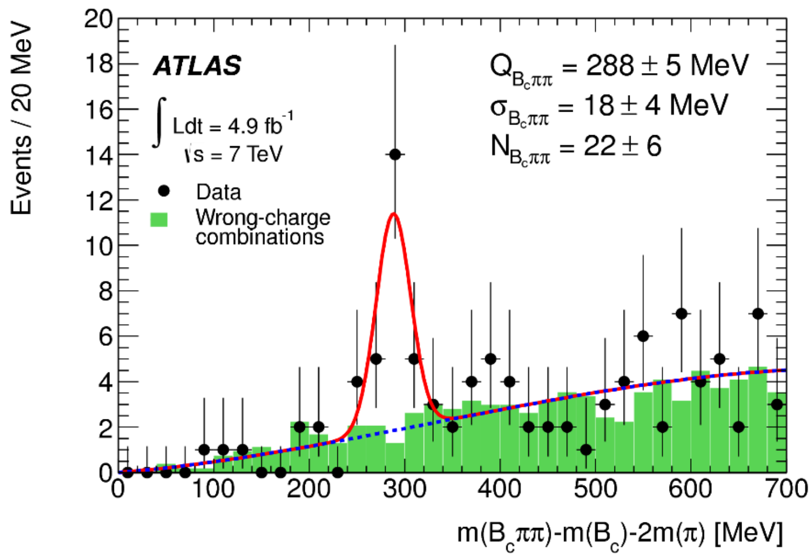
- ★ $\sigma(B_c^+) = 0.47$ μb, theoretical prediction by BcVegPy
- ★ $\mathcal{B}(B_c^+ \to J/\psi\pi^+) = 0.33\%$ [C.-F. Qiao *et al.*, PRD 89 (2014) 034008]
- ★ $\sigma(B^+, p_{\mathrm{T}}(B) < 40\,\mathrm{GeV}/c, 2.0 < y < 4.5) = 38.9$ μb at $\sqrt{s} = 7$ TeV, measured by LHCb [JHEP 08 (2013) 117], scaled up by 1.2 for 8 TeV
- ★ $\mathcal{B}(B^+ \to J/\psi K^+) = (0.1016 \pm 0.0033)\%$, PDG'12

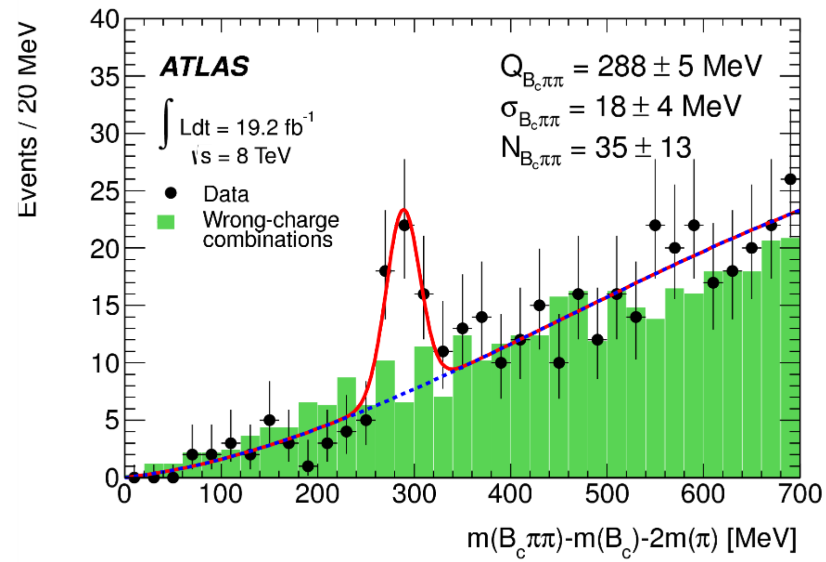
Spectroscopy

PRL 113 (2014) 212004

- Theoretically we expect: $B_c(2^1S_0) \rightarrow B_c\pi\pi$, $B_c(2^3S_1) \rightarrow B_c^*\pi\pi \rightarrow B_c\gamma\pi\pi$
- ATLAS observe peaking structure in $B_c\pi^+\pi^-$ invariant mass, consistent with $B_c(2S)$ – likely mixture of 2^1S_0 and 2^3S_1
- M = **6842 ± 4 ± 5 MeV**
- No $\sigma(B_c(2S))$ or efficiency quoted, difficult to draw direct comparison from other expr.







B_c^+ mass

- PDG 2012: 6277 ± 6 MeV
- LHCb measured the mass in several final states:
  - $B_c^+ \to J/\psi\pi^+$: (0.37 fb^{-1} @ 7 TeV) *PRL 109 (2012) 232001*

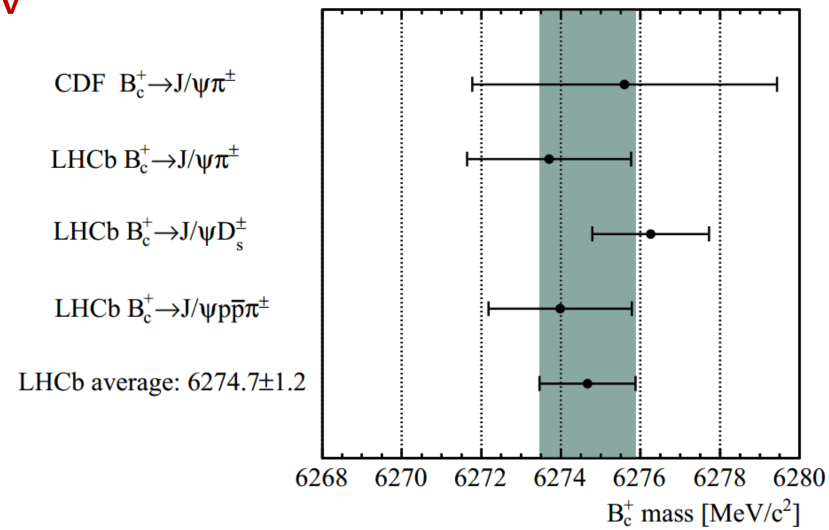
    $M = 6273.7 \pm 1.3 \pm 1.6$ MeV
  - $B_c^+ \to J/\psi D_s^+$: (3 fb^{-1} @ 7+8 TeV) *PRD 87 (2013) 112012*

    $M = 6276.28 \pm 1.44 \pm 0.36$ MeV
  - $B_c^+ \to J/\psi p\bar{p}\pi^+$: (3 fb^{-1} @ 7+8 TeV) *PRL 113 (2014) 152003*

    $M = 6274.0 \pm 1.8 \pm 0.4$ MeV
- LHCb average:

  6274.7 ± 1.2 MeV
  - Consistent with lattice QCD prediction : 6278(4)(8) MeV

    HPQCD, PRD 86(2012) 094510



B_c^+ lifetime

- PDG 2012: 0.45 $\pm$ 0.04 ps $\Rightarrow$ systematics in measurement of σ, $\mathcal{B}$ ...
- LHCb performed two independent lifetime measurements

- $B_c^+ \to J/\psi \mu^+ \nu_\mu$

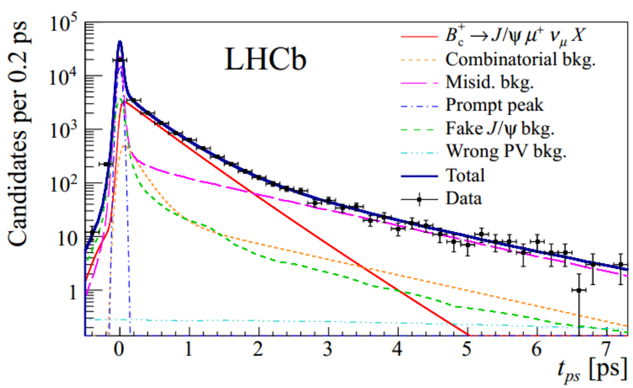
Partial reconstruction, measures pseudo-decaytime $t^* = (M_{J/\psi\mu} \cdot L)/P_{J/\psi\mu}$

$\tau =$ **509 $\pm$ 8 $\pm$ 12 fs**

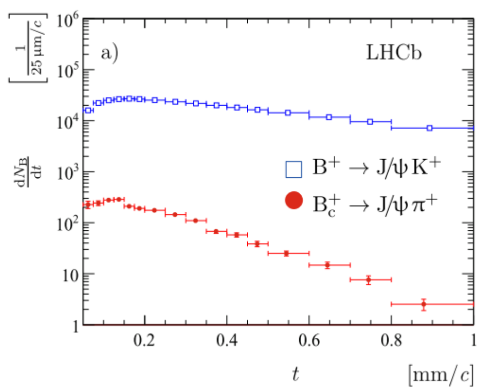
- $B_c^+ \to J/\psi \pi^+$

Measures lifetime ratio $\tau(B_c^+)/\tau(B^+)$, where $\tau(B^+)$ is more precisely known

$\tau =$ **513.4 $\pm$ 11.0 $\pm$ 5.7 fs**



EPJC 74 (2014) 2839

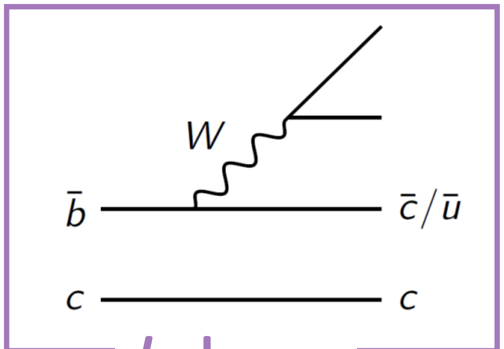


PLB 742 (2015) 29

Combined LHCb result:
511.4 $\pm$ 9.3 fs
Precision largely improved!

B_c^+ decays

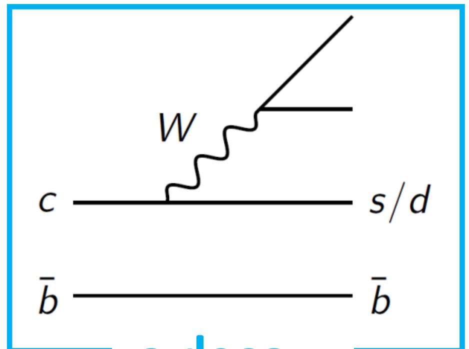
- A large variety of decay modes
  - Hence the shorter lifetime than other B mesons



b decay

$\sim$ **20%**

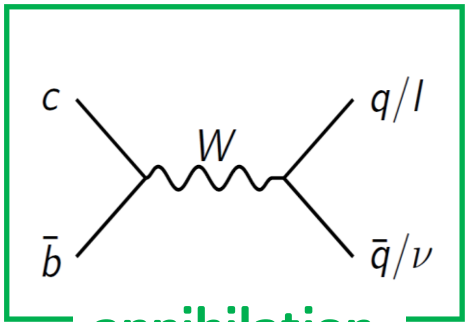
- with $c\bar{c}$ easier to detect esp. $\rightarrow \mu^+\mu^-$
- Most observed channels in this category



c decay

$\sim$ **70%**

- Though larger in fraction, efficiency is low
- $B_c^+ \rightarrow B_s^0\pi^+$ observed

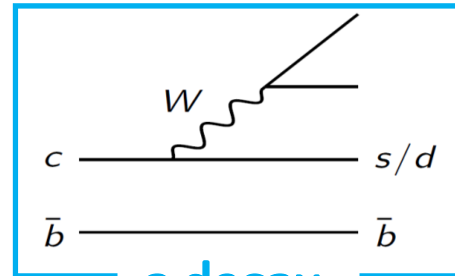


annihilation

$\sim$ **10%**

- Not observed yet. K^*K, ϕK...

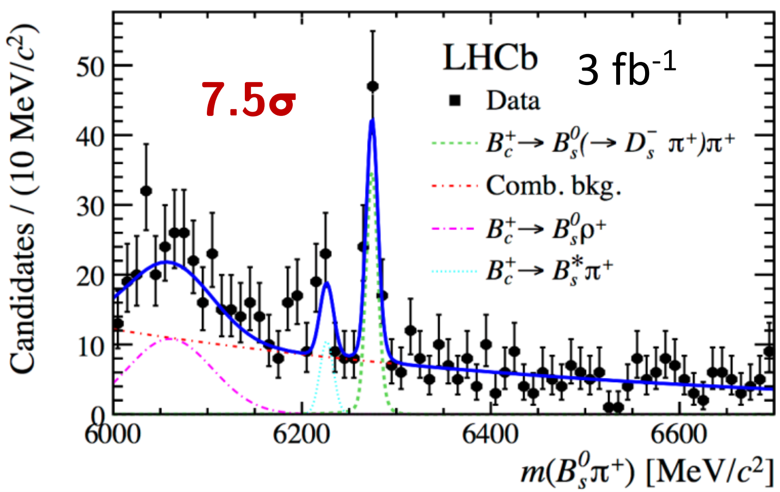
$B_c^+ \to B_s^0 \pi^+$



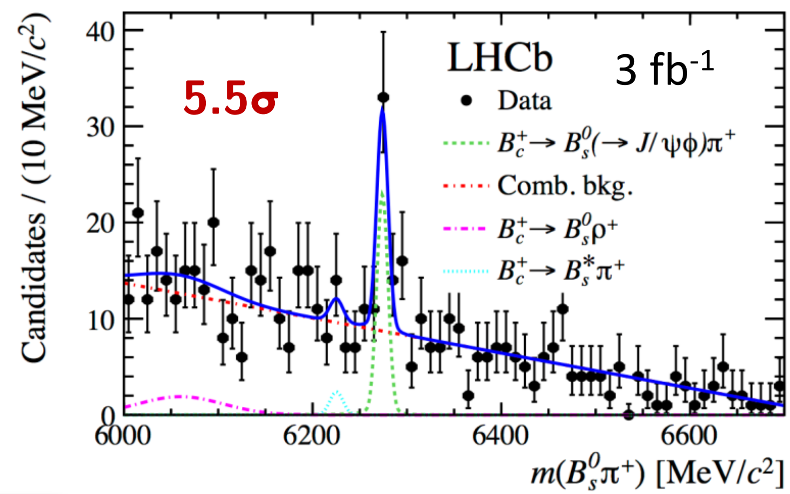
c decay

- The first observed c decay in B_c
- $B_s^0 \to D_s^- \pi^+$ or $J/\psi\ \phi$ *LHCb PRL 111(2013)181801*

$B_c^+ \to \boldsymbol{B_s^0(\to D_s^- \pi^+)}\pi^+$



$B_c^+ \to \boldsymbol{B_s^0(\to J/\psi\ \phi)}\pi^+$



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

$\mathcal{B}(B_c \to B_s \pi) \sim 10\%$

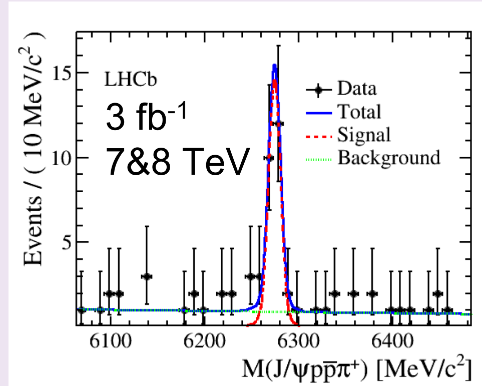
This also provides additional information on B_c production

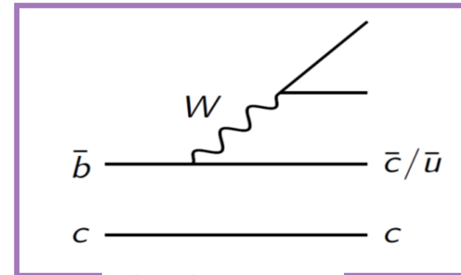
B_c decay: c as spectator - 1

- $B_c^+ \to J/\psi p\bar{p}\pi^+$ @ LHCb
- First B_c baryonic decay

$$R_{\mathcal{B}} = 0.143^{+0.039}_{-0.034} \pm 0.013$$

PRL 113 (2014) 152003



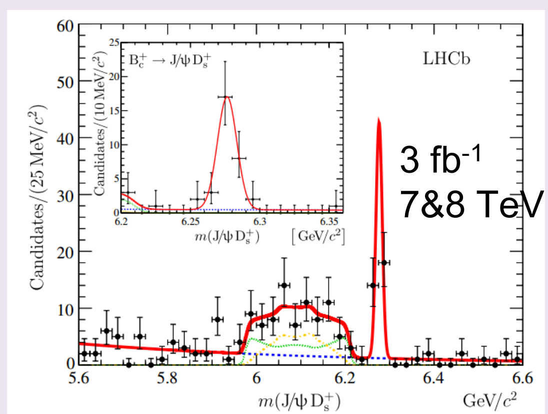


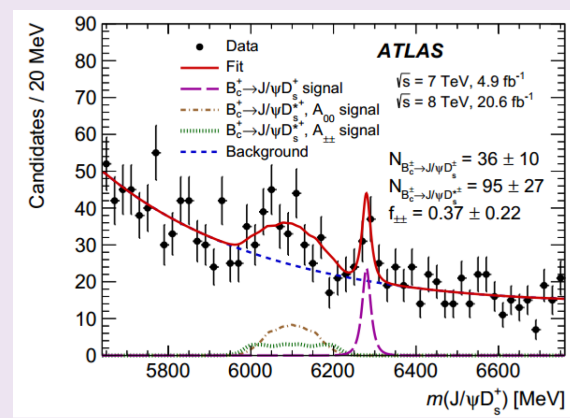
b decay

$$R_{\mathcal{B}} = \frac{\mathcal{B}(B_c^+ \to \ldots)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}$$

- $B_c^+ \to J/\psi D_s^{(*)+}$ @ LHCb and ATLAS

- $J/\psi D_s^*$ partial reconstruction; info on helicity $A_{\pm\pm}/A_{00}$
- $J/\psi D_s$ used for mass measurement



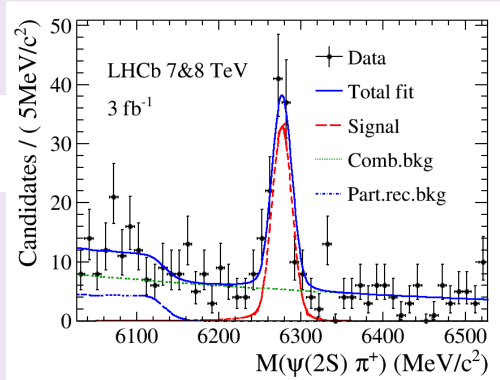


Phys. Rev. D 87 (2013) 112012

arXiv : 1507.07099

B_c decay: c as spectator - 2

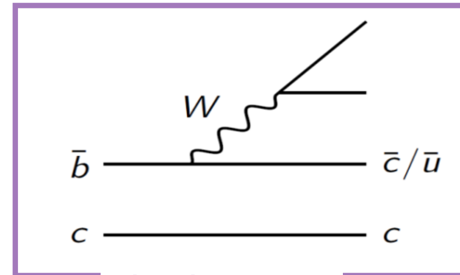
- $B_c^+ \to \psi(2S)\pi^+$ @ LHCb



$$R_{\mathcal{B}} = 0.268 \pm 0.032 \pm 0.007 \pm 0.006(\mathrm{BF})$$

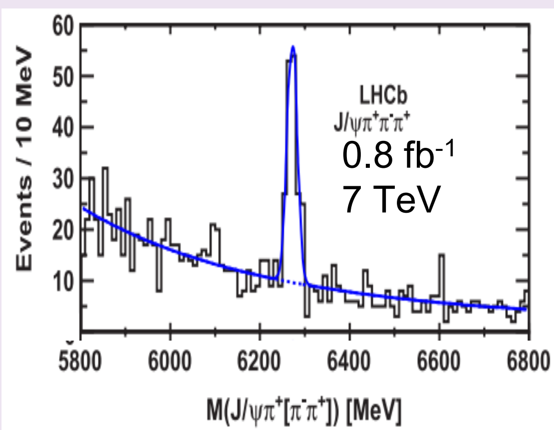
Recently updated with 3/fb

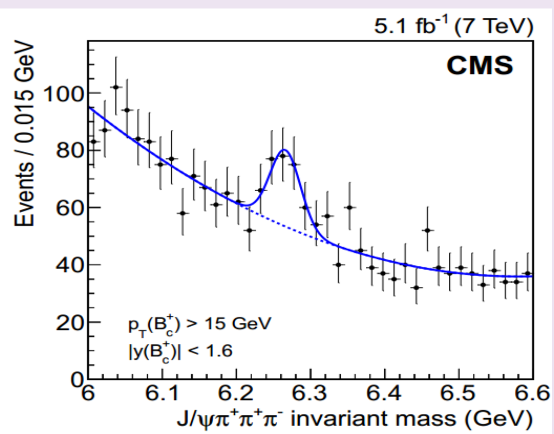
arXiv : 1507.03516



$$R_{\mathcal{B}} = \frac{\mathcal{B}(B_c^+ \to \dots)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}$$

- $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$ @ LHCb and CMS





$$R_{\mathcal{B}} = 2.41 \pm 0.30 \pm 0.33$$

LHCb, PRL 108 (2012) 251802

$$2.55 \pm 0.80 \pm 0.33^{+0.04}_{-0.01}(\tau(B_c))$$

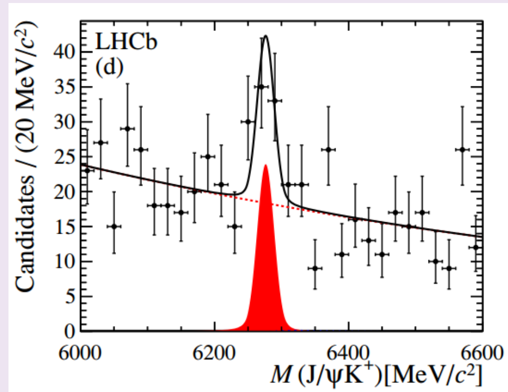
CMS, JHEP 01 (2015) 063

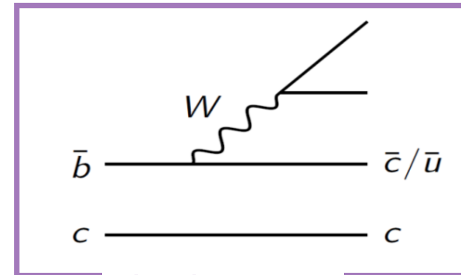
B_c decay: c as spectator - 3

- $B_c^+ \to J/\psi K^+$ @ LHCb

$$R_{\mathcal{B}} = 0.069 \pm 0.019 \pm 0.005$$

JHEP 09 (2013) 075

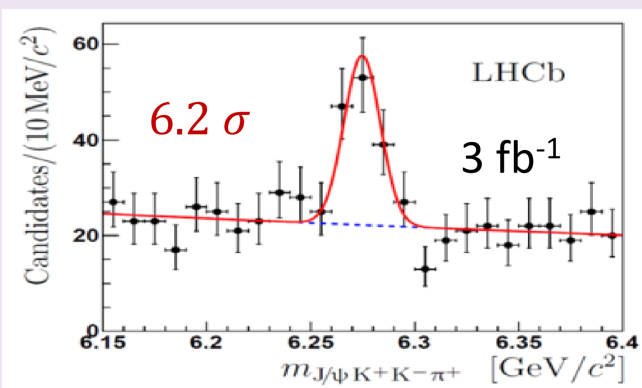




b decay

$$R_{\mathcal{B}} = \frac{\mathcal{B}(B_c^+ \to \ldots)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}$$

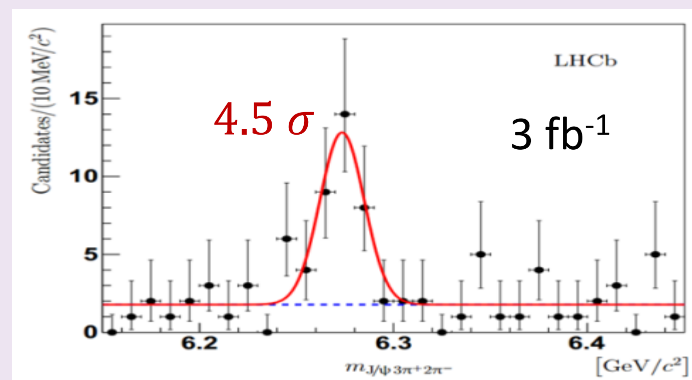
- $B_c^+ \to J/\psi K^+ K^- \pi^+$ @ LHCb



$$R_{\mathcal{B}} = 0.53 \pm 0.10 \pm 0.05$$

JHEP 1311 (2013) 094

- $B_c^+ \to J/\psi 3\pi^+ 2\pi^-$ @ LHCb



$$R_{\mathcal{B}} = 1.74 \pm 0.44 \pm 0.24$$

arXiv: 1404.0287

Conclusion and prospect

- No doubt LHC has greatly improved our knowledge on B_c
- Analyses on Run-I data still on-going
  - So still room for surprises
- With Run-II starting smoothly, $\sigma(B_c)$ expected to (almost) double
  - At higher energy, with more luminosity, more discoveries are awaiting us: more luck in the mass spectrum? Surely more new decays: annihilation? …
- Meanwhile we should keep thinking more clever ways to look at our data
  - Eg: Can we eventually measure $\sigma(B_c)$ from all the indirect measurements? $\frac{\sigma(B_c)\mathcal{B}(B\to J/\psi K)}{\sigma(B)\mathcal{B}(B_c\to J/\psi\pi)}$, $\frac{\sigma(B_c)}{\sigma(B_s)}\mathcal{B}(B_c \to B_s\pi)$, …
  - Exotic search in $B_c \to DDX$
  - CP violation study in eg. $B_c \to D^0 D_s/\overline{D}^0 D_s$

BACKUP

Predicted decay rates of excited B_c

State	Decay	GKLRY *	Godfrey †
1^3S_1	$1^1S_0+\gamma$	100	100
1^3P_2	$1^3S_1+\gamma$	100	100
$1P_1'$	$1^3S_1+\gamma$	6	12.1
	$1^1S_0+\gamma$	94	87.9
$1P_1$	$1^3S_1+\gamma$	87	82.2
	$1^1S_0+\gamma$	13	17.8
1^3P_0	$1^3S_1+\gamma$	100	100
2^1S_0	$1^1S_0+\pi\pi$	74	88.1
	$1P_1'+\gamma$		9.4
	$1P_1+\gamma$		2.0
	$1^3S_1+\gamma$		0.5
2^3S_1	$1^3S_1+\pi\pi$	58	79.6
	$1^3P_2+\gamma$		8.0
	$1P_1'+\gamma$		1.0
	$1P_1+\gamma$		6.6
	$1^3P_0+\gamma$		4.0
	$2^1S_0+\gamma$		0.01
	$1^1S_0+\gamma$		0.8

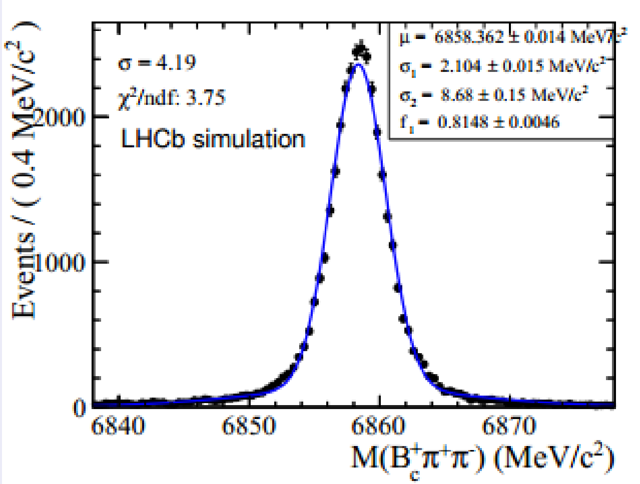
* [I. P. Gouz, *et al.*, Phys. Atom. Nucl. 67 (2004) 1559]

† [S.Godfrey, PRD 70 (2004) 054017]

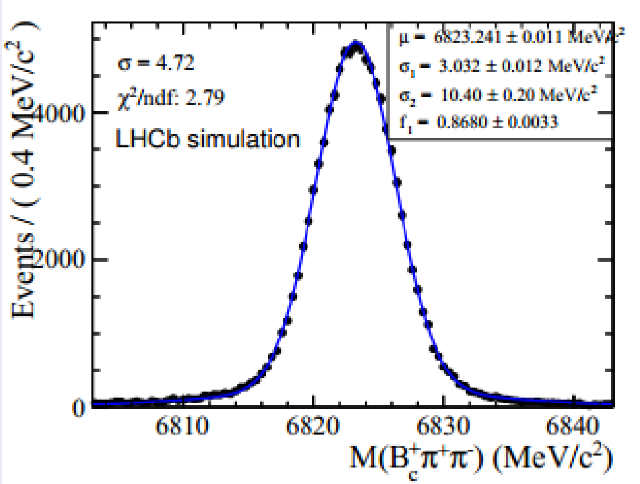
Prospects for excited B_c at LHCb

- B_c excited states, $B_c^+(2^3S_1) \to B_c^{*+}(B_c^+\gamma)\pi^+\pi^-$, mass shifted down by $\Delta M(1^3S_1 - 1^1S_0)$ (input 67 MeV) when missing the soft photon, slightly degraded mass resolution, peak not washed out
- Possible to distinguish $B_c^+(2^1S_0)$ (input 6858 MeV), and $B_c^+(2^3S_1)$ (input: 6890 MeV) if $\Delta M(1^3S_1 - 1^1S_0) \neq \Delta M(2^3S_1 - 2^1S_0)$

$B_c^+(2^1S_0)$, $\sigma \sim 4.2$ MeV



$B_c^+(2^3S_1)$, $\sigma \sim 4.7$ MeV



- ATLAS results
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults

- CMS results
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH