B_c physics at LHCb

Jibo HE
(on behalf of the LHCb collaboration)

CERN

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B_c spectrum

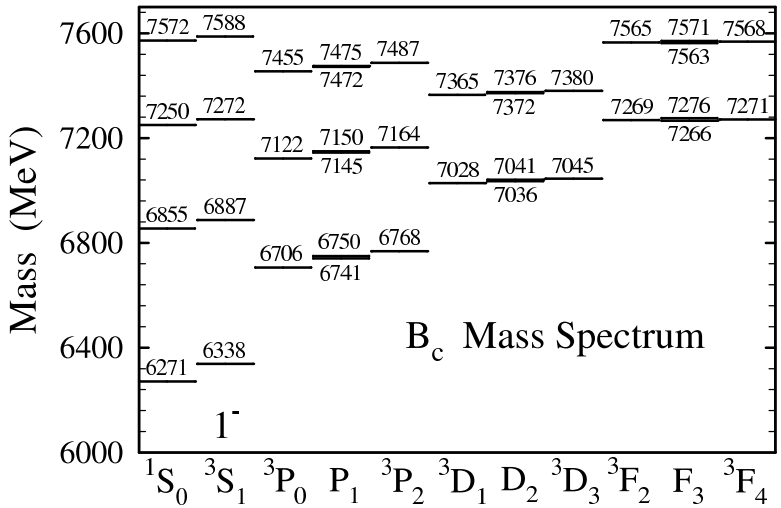
- B_c: Mesons formed by two different heavy flavor quarks, the $\bar{b}$ quark and the c quark*
  - Unique in the Standard Model because the top quark is too heavy and decays before forming any bound states

- B_c spectrum
  - Estimated using potential models
- B_c^+ mass
  - Potential models: 6.2-6.4 GeV/c^2

    [CERN-2005-005], and refs. therein
  - pQCD: 6326^{+29}_{-9} MeV/c^2

    [N. Brambilla & A. Vairo, PRD 62 (2000) 094019]
  - Lattice QCD: 6278(4)(8) MeV/c^2

    [HPQCD, PRD 86 (2012) 094510]
  - PDG'14: 6275.6 ± 1.1 MeV/c^2



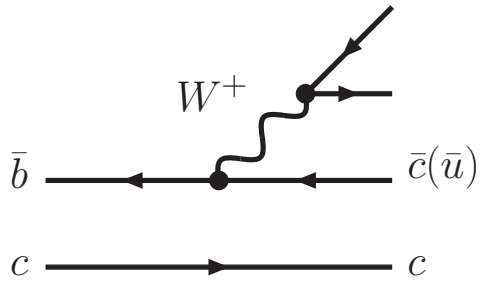
[S. Godfrey, PRD 70 (2004) 054017]

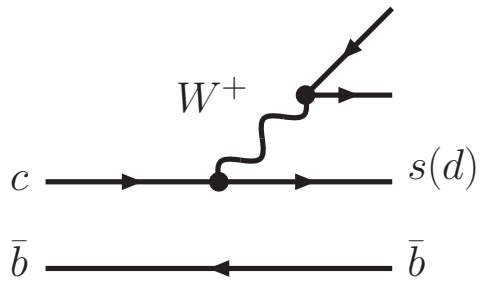
*Charge conjugates implied in this talk

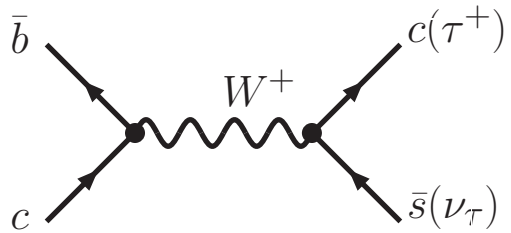
B_c decays

- B_c mesons' decays
  - Excited states (below BD threshold), decay through the Strong or EM interactions into B_c^+
  - Ground state B_c^+: decay only weakly
- B_c^+ decay modes
  - $\bar{b} \to \bar{c} W^+$, e.g., $J/\psi \pi^+$, $J/\psi \ell^+ \nu_\ell$
  - $c \to s W^+$, e.g., $B_s^0 \pi^+$, $B_s^0 \ell^+ \nu_\ell$
  - $c\bar{b} \to W^+$, e.g., $\bar{K}^{*0} K^+$, ϕK^+, $\tau^+ \nu_\tau$
- B_c^+ lifetime predictions
  - Inclusive rates or $\sum$(exclusive rates)
  - $\tau(B_c^+)_{\rm SR} = 0.48 \pm 0.05$ ps

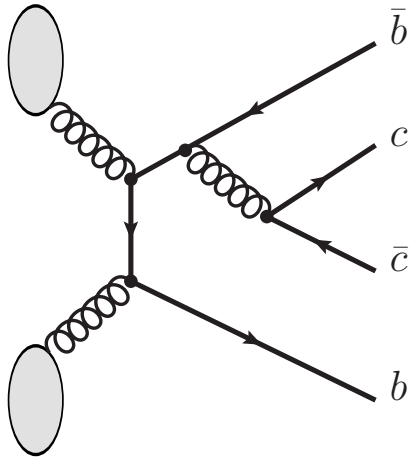
    [V. V. Kiselev, *et al.*, NPB 585 (2000) 353]
  - PDG'14: 0.500 ± 0.013 ps







B_c production



- B_c production
  - Difficult to produce at e^+e^- colliders
  - At hadron colliders, B_c produced mainly through $gg \to B_c + b + \bar{c}$
- B_c^+ production rate
  - Theoretical prediction (in nb) [C.-H. Chang, *et al.*, PRD 71 (2005) 074012]

-	$\|(^1S_0)_1\rangle$	$\|(^3S_1)_1\rangle$	$\|(^1S_0)_8 g\rangle$	$\|(^3S_1)_8 g\rangle$	$\|(^1P_1)_1\rangle$	$\|(^3P_0)_1\rangle$	$\|(^3P_1)_1\rangle$	$\|(^3P_2)_1\rangle$
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

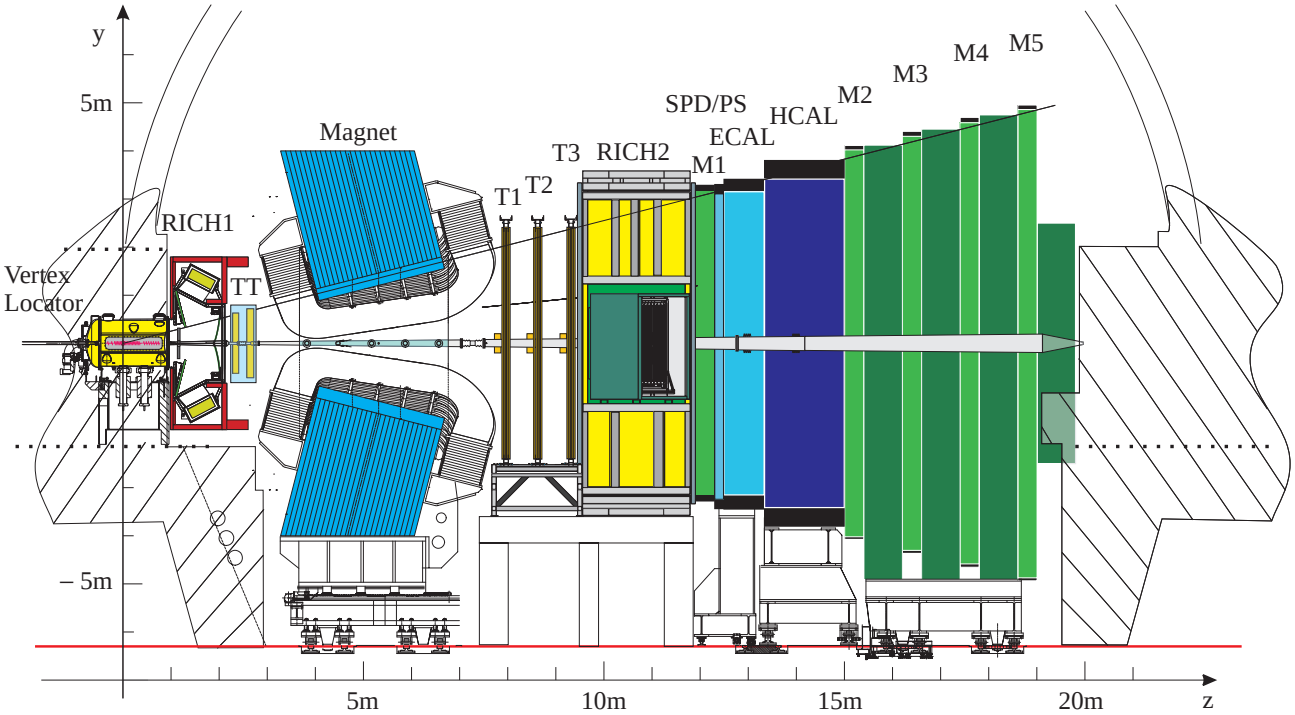
    - ★ $\sigma(^3S_1)/\sigma(^1S_0) \sim 2.5$
    - ★ Color octets and 1st P-wave contributions are small
    - ★ $\sigma(B_c^+)_{\rm LHC}/\sigma(B_c^+)_{\rm Tevatron} \sim {\rm O}(10)$
  - $\sigma(2S)/\sigma(1S)$ would be $|R_{2S}(0)/R_{1S}(0)|^2 \approx 0.6$
  - Considering the contributions of the decays of these states, $\sigma(B_c^+) \sim 0.9$ μb for $\sqrt{s} = 14$ TeV; or ~ 0.47 μb for $\sqrt{s} = 8$ TeV

† $\sqrt{s} = 14$ TeV

The LHCb detector

[JINST 3 (2008) S08005]

- Acceptance $2<\eta<5$, with excellent vertexing, tracking, PID
- $\mathcal{L}_{\rm int} = 1$ fb^{-1} @ 7 TeV in 2011, & 2 fb^{-1} @ 8 TeV in 2012



Vertex Locator	$\sigma_{\rm PV,x/y} \sim 10$ μm, $\sigma_{\rm PV,z} \sim 60$ μm
Tracking (TT, T1-T3)	$\Delta p/p$: 0.4% at 5 GeV/c, to 0.6% at 100 GeV/c
RICHs	$\varepsilon(K \to K) \sim 95\%$, mis-ID rate $(\pi \to K) \sim 5\%$
Muon system (M1-M5)	$\varepsilon(\mu \to \mu) \sim 97\%$, mis-ID rate $(\pi \to \mu) = 1-3\%$
ECAL	$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 1\%$ (E in GeV)
HCAL	$\sigma_E/E \sim 70\%/\sqrt{E} \oplus 10\%$ (E in GeV)

B_c^+ studies in LHCb

Production	$\frac{\sigma(B_c^+)}{\sigma(B^+)} \frac{\mathcal{B}(B_c^+ \to J/\psi \pi^+)}{\mathcal{B}(B^+ \to J/\psi K^+)}$	[PRL 109 (2012) 232001]
	$\frac{\sigma(B_c^+)}{\sigma(B_s^0)} \mathcal{B}(B_c^+ \to B_s^0 \pi^+)$	[PRL 111 (2013) 181801]
	$\frac{\sigma(B_c^+)}{\sigma(B^+)} \frac{\mathcal{B}(B_c^+ \to J/\psi \pi^+)}{\mathcal{B}(B^+ \to J/\psi K^+)}$ double differential ratio	[LHCb-Paper-2014-050, in preparation]
Mass	$M_{B_c^+ \to J/\psi \pi^+}$	[PRL 109 (2012) 232001]
	$M_{B_c^+ \to J/\psi D_s^+}$	[PRD 87 (2013) 112012]
	$M_{B_c^+ \to J/\psi p\bar{p}\pi^+}$	[PRL 113 (2014) 152003]
Lifetime	$\tau_{B_c^+ \to J/\psi \mu^+ \nu_\mu X}$	[EPJC 74 (2014) 2839]
	$\tau_{B_c^+ \to J/\psi \pi^+}$	[LHCb-Paper-2014-060, in preparation]
Decay	$B_c^+ \to J/\psi 3\pi$	[PRL 108 (2012) 251802]
	$B_c^+ \to J/\psi K^+$	[JHEP 09 (2013) 075]
	$B_c^+ \to \psi(2S)\pi^+$	[PRD 87 (2013) 071103(R)]
	$B_c^+ \to J/\psi D_s^{(*)+}$	[PRD 87 (2013) 112012]
	$B_c^+ \to J/\psi K^+ K^- \pi^+$	[JHEP 1311 (2013) 094]
	$B_c^+ \to J/\psi 3\pi^+ 2\pi^-$	[JHEP 1405 (2014) 148]
	$B_c^+ \to J/\psi p\bar{p}\pi^+$	[PRL 113 (2014) 152003]
	$\frac{\mathcal{B}(B_c^+ \to J/\psi \pi^+)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)}$	[PRD 90 (2014) 032009]
	$B_c^+ \to B_s^0 \pi^+$	[PRL 111 (2013) 181801]

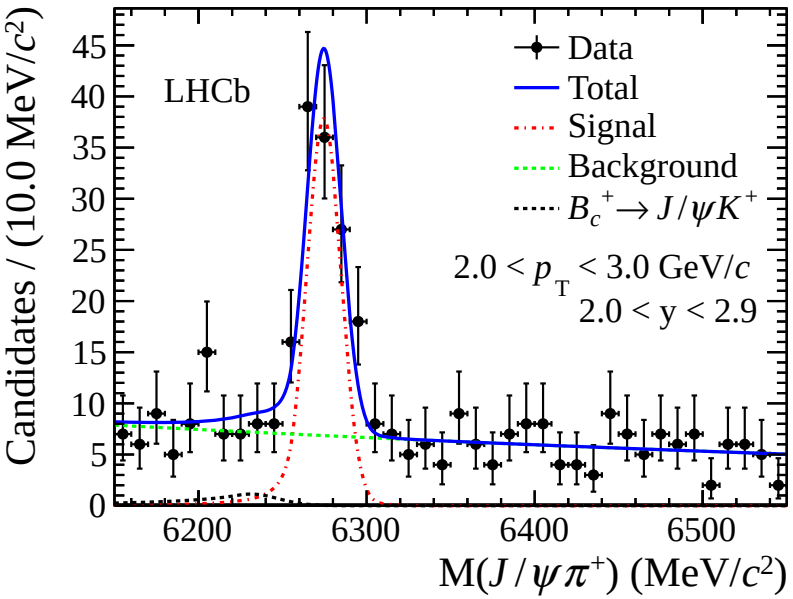
B_c^+ production, with $B_c^+ \to J/\psi\,\pi^+$ New

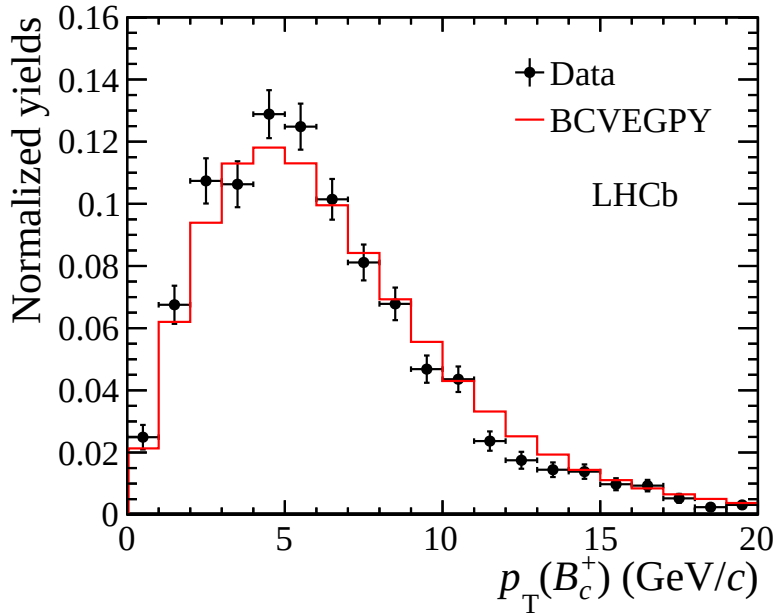
LHCb preliminary

[LHCb-Paper-2014-050, in preparation]

- With 2011 (7 TeV) data
  $\mathcal{R} = \frac{\sigma(B_c^+)\times\mathcal{B}(B_c^+\to J/\psi\,\pi^+)}{\sigma(B^+)\times\mathcal{B}(B^+\to J/\psi\,K^+)} = (0.68 \pm 0.10 \pm 0.03 \pm 0.05\,(\tau_{B_c^+}))\%$, for $p_{\rm T}(B) > 4$ GeV/c and $2.5 < \eta(B) < 4.5$
- With 2012 (8 TeV) data, $\mathcal{R}$ measured as function of $(p_{\rm T}, y)$, for $p_{\rm T}(B) < 20$ GeV/c and $2 < y(B) < 4.5$
  - MVA-based selection, $B^+ \to J/\psi\,K^+$ as control channel
  - $p_{\rm T}(B_c^+)$ well described by BcVegPy (complete α_s^4 calculation)

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



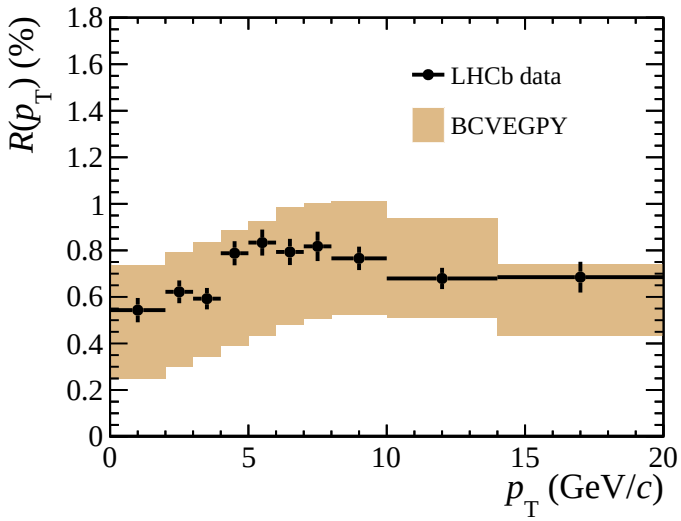


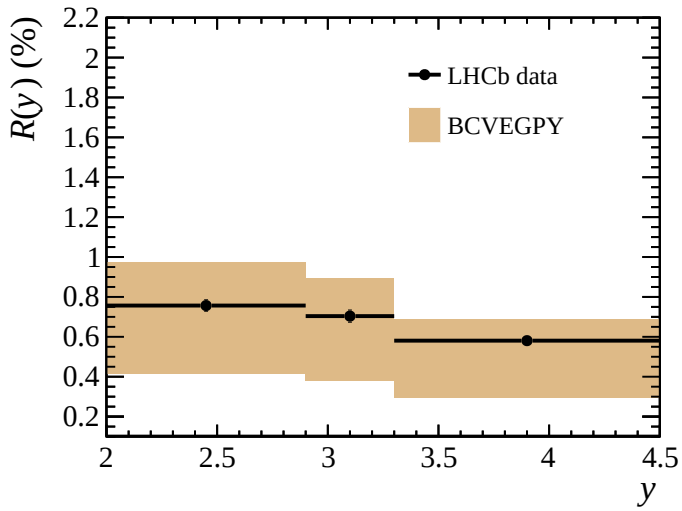
B_c^+ production, with $B_c^+ \to J/\psi\,\pi^+$ (cont.) New

[LHCb-Paper-2014-050, in preparation]

LHCb preliminary

- Good agreement with theoretical predictions
  - Differential $p_{\rm T}$ shapes, B^+ from FONLL, B_c^+ from BcVegPy (α_s^4)
  - Normalization
    - ★ $\sigma(B_c^+) = 0.47\ \mu$b, theoretical prediction by BcVegPy
    - ★ $\mathcal{B}(B_c^+ \to J/\psi\,\pi^+) = 0.33\%$ [C.-F. Qiao *et al.*, PRD 89 (2014) 034008]
    - ★ $\sigma(B^+,\ p_{\rm T}(B) < 40\ {\rm GeV}/c,\ 2.0 < y < 4.5) = 38.9\,\mu$b 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





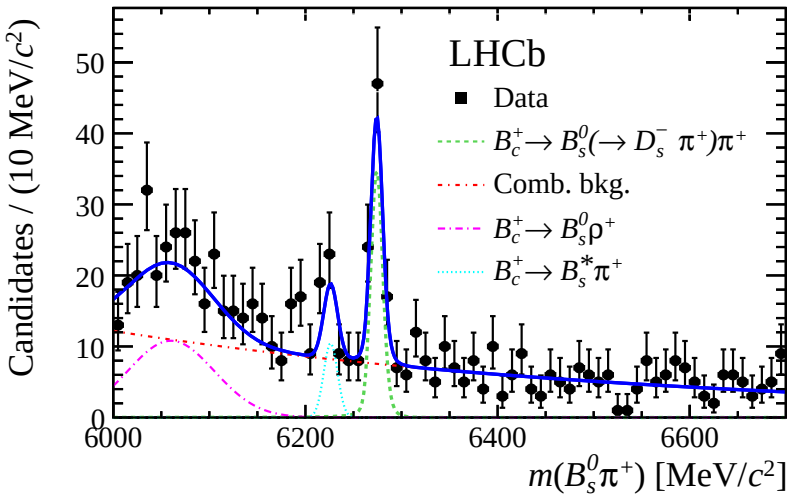
- Production ratio in the range $0 < p_{\rm T} < 20\,{\rm GeV}/c$ and $2.0 < y < 4.5$
  $\mathcal{R} = (0.683 \pm 0.018 \pm 0.009)\%$ (3% relative precision)

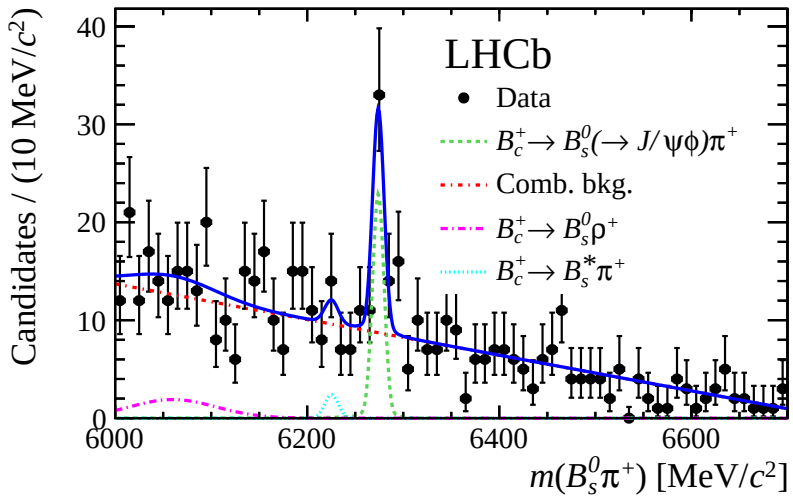
B_c^+ production, with $B_c^+ \to B_s^0 \pi^+$

[PRL 111 (2013) 181801]

- $\frac{\sigma(B_c^+)}{\sigma(B_s^0)} \cdot \mathcal{B}(B_c^+ \to B_s^0 \pi^+)$ measured using 2011 + 2012 data, for $2 < \eta(B) < 5$.
- Measured with $B_s^0 \to D_s^- \pi^+$ and $B_s^0 \to J/\psi\,\phi$ independently, results consistent with each other
- Combined results

$$\frac{\sigma(B_c^+)}{\sigma(B_s^0)} \cdot \mathcal{B}(B_c^+ \to B_s^0 \pi^+) = \left(2.37 \pm 0.31 \pm 0.11\, ^{+0.17}_{-0.12}(\tau_{B_c^+})\right) \times 10^{-3}$$



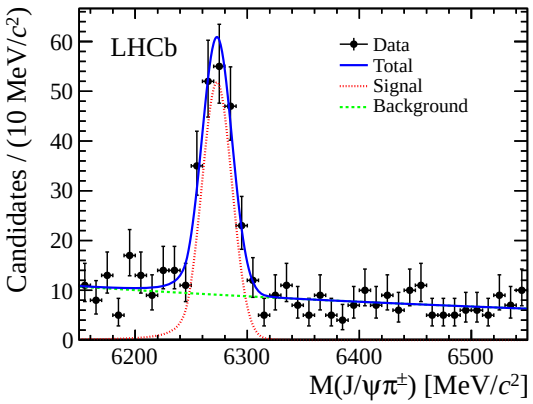


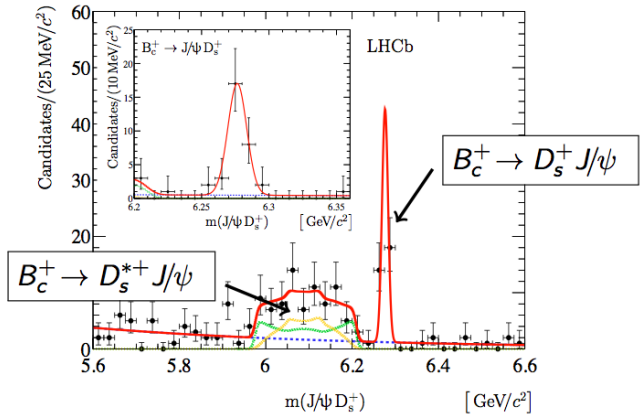
- First observation of $B_c^+ \to B_s^0 \pi^+$

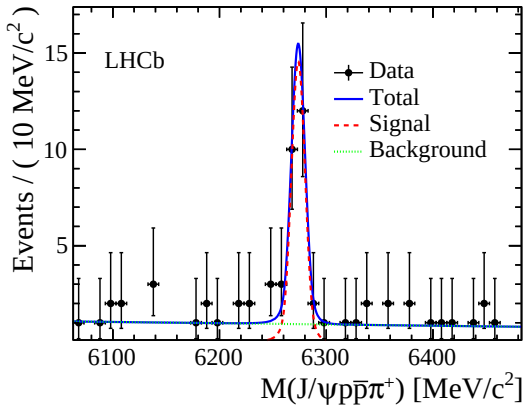
B_c^+ mass

[PRL 109 (2012) 232001] [PRD 87 (2013) 112012] [PRL 113 (2014) 152003]

- With 0.37 fb^{-1} of 2011 data, momentum scale (0.06%)
  - $M_{B_c^+ \to J/\psi \pi^+} = 6273.7 \pm 1.3 \pm 1.6$ MeV
- With all Run-I data (3 fb^{-1}), momentum scale (0.03%)
  - $M_{B_c^+ \to J/\psi D_s^+} = 6276.28 \pm 1.44 \pm 0.36$ MeV
  - $M_{B_c^+ \to J/\psi p\bar{p}\pi^+} = 6274.0 \pm 1.8 \pm 0.4$ MeV

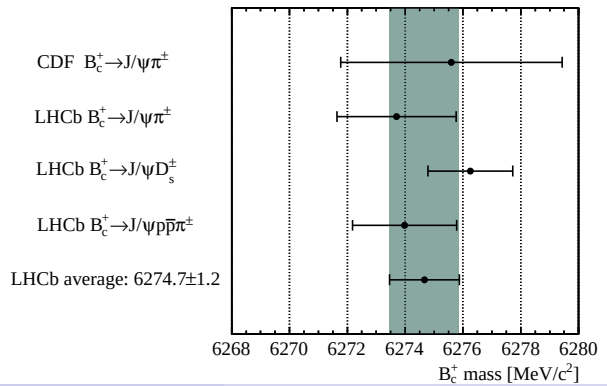






- LHCb average: 6274.7 ± 1.2 MeV, consistent with lattice QCD: $M(B_c^+) = 6278(4)(8)$ MeV

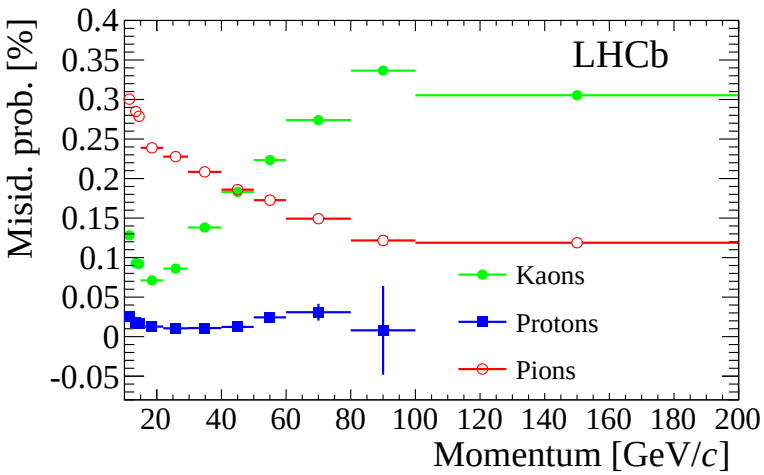
[HPQCD, PRD 86 (2012) 094510]

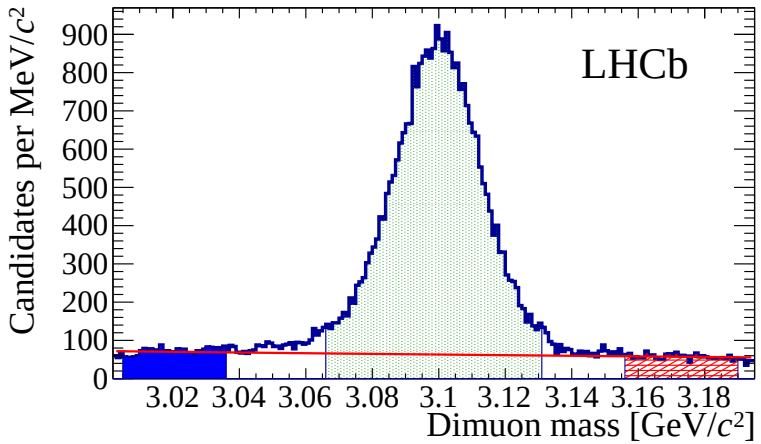


B_c^+ lifetime, with $B_c^+ \to J/\psi\,\mu^+\nu_\mu X$

[EPJC 74 (2014) 2839]

- Measured with 2012 data, $J/\psi + \mu^+$, lifetime unbiased selection
- Background mostly determined from data
  - Dominated by J/ψ + hadron misidentified as μ
  - Fake J/ψ background determined using side-band
- Partially reconstructed, pseudo decay time $t^* = M_{J/\psi\,\mu^+}\frac{L}{P_{J/\psi\,\mu^+}}$, K-factor from simulation used to correct for missing energy

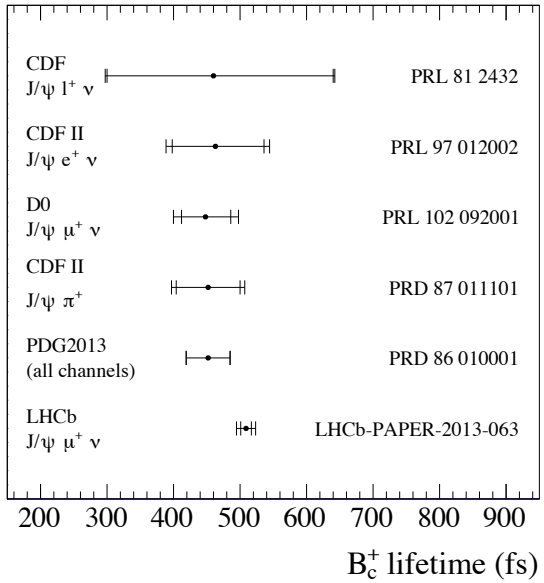


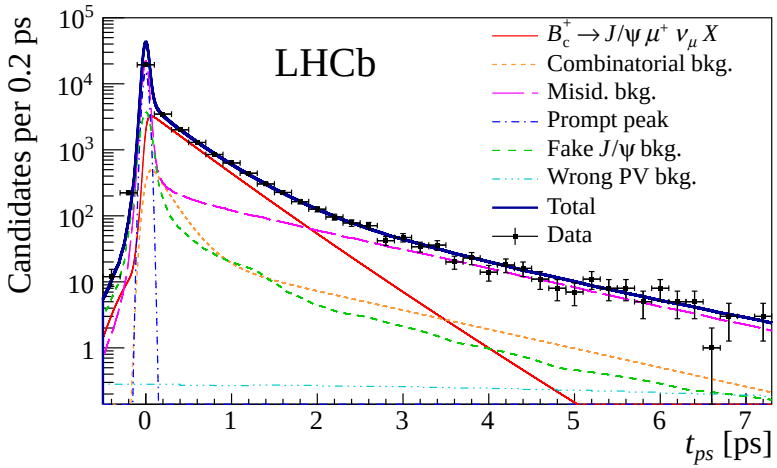


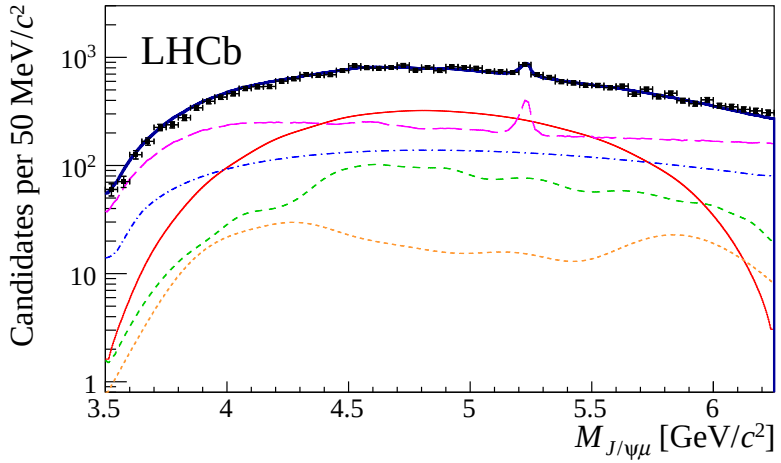
B_c^+ lifetime, with $B_c^+ \to J/\psi\,\mu^+\nu_\mu X$ (cont.)

[EPJC 74 (2014) 2839]

- $\tau_{B_c^+}$ determined by mass-time combined fit
- Systematic uncertainty dominated by background model
- $\tau_{B_c^+} = 509 \pm 8 \pm 12$ fs, most precise measurement







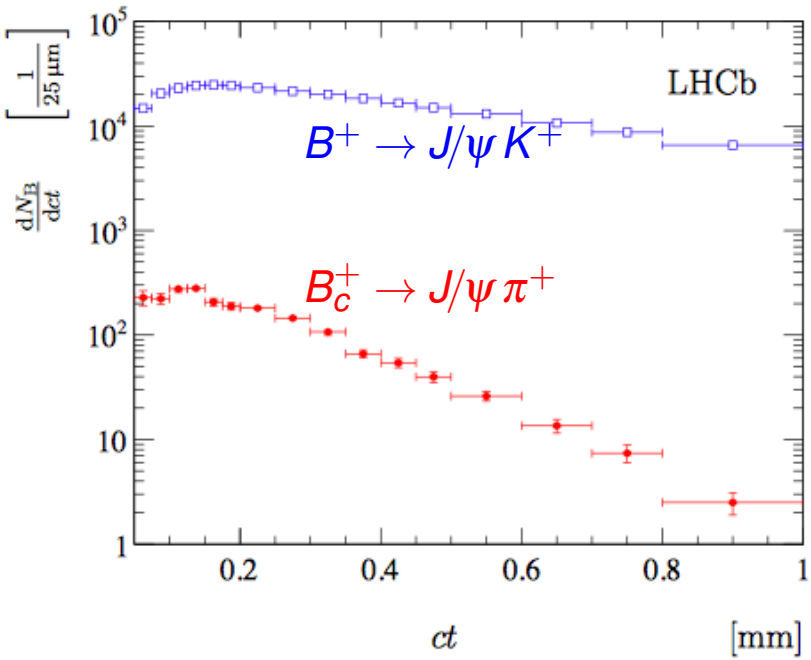
B_c^+ lifetime, with $B_c^+ \to J/\psi\,\pi^+$ New

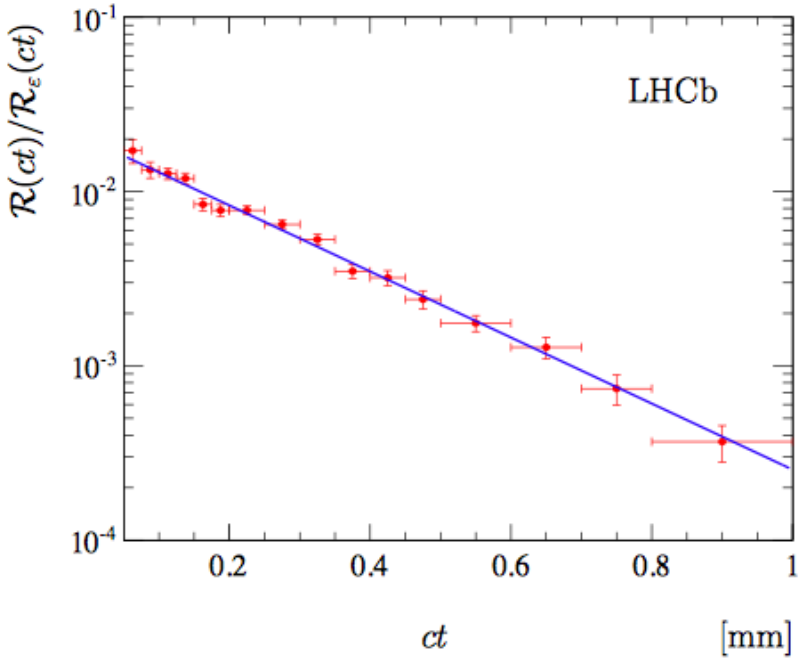
[LHCb-Paper-2014-060, in preparation]

LHCb preliminary

- With all Run-I data, measured $\tau_{B_c^+}/\tau_{B^+}$, with $B_c^+ \to J/\psi\,\pi^+$ and $B^+ \to J/\psi\,K^+$, same method used to measure Λ_b^0 and B_s^0 lifetime
- MVA-based selection, the same for B_c^+ and B^+
- Decay time acceptance ratio from simulation
- With $\tau_{B^+} = 1638 \pm 4$ fs (PDG'14)

  $\Rightarrow \tau_{B_c^+} = 513 \pm 11 \pm 6$ fs c.f., $\tau_{B_c^+ \to J/\psi\,\mu^+\nu_\mu X} = 509 \pm 8 \pm 12$ fs

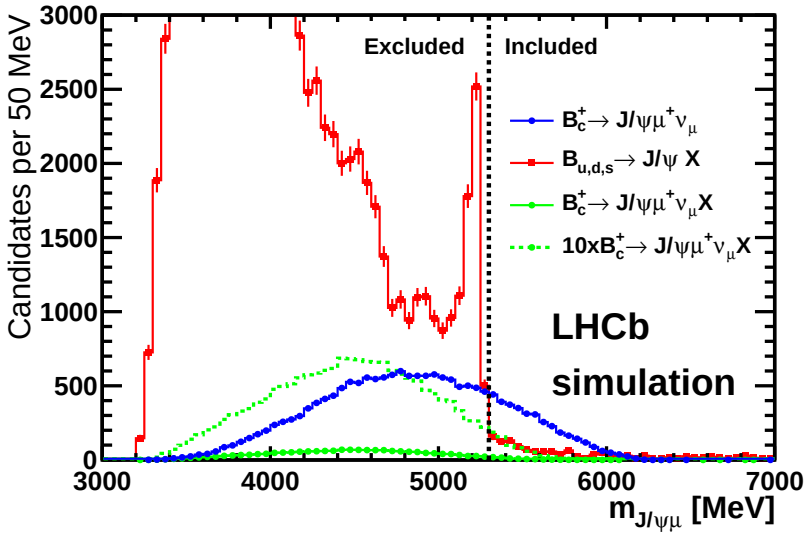


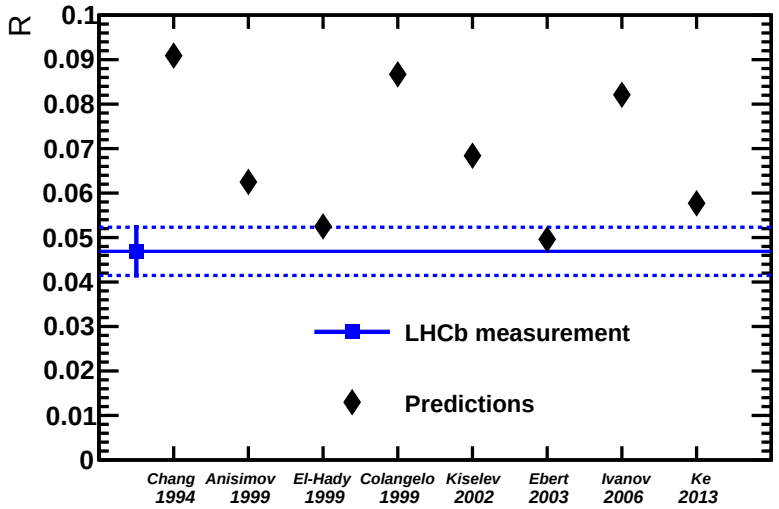


Measurement of $\frac{\mathcal{B}(B_c^+ \to J/\psi\,\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)}$

[PRD 90 (2014) 032009]

- Theoretical predictions of $\frac{\mathcal{B}(B_c^+ \to J/\psi\,\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)}$ have large spread
- Measured with 2011 data, with $M(J/\psi\,\mu^+) > 5.3$ GeV
- Extrapolated to full phase space
  $\frac{\mathcal{B}(B_c^+ \to J/\psi\,\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)} = (4.69 \pm 0.28 \pm 0.46)\%$
  at the lower end of theoretical predictions

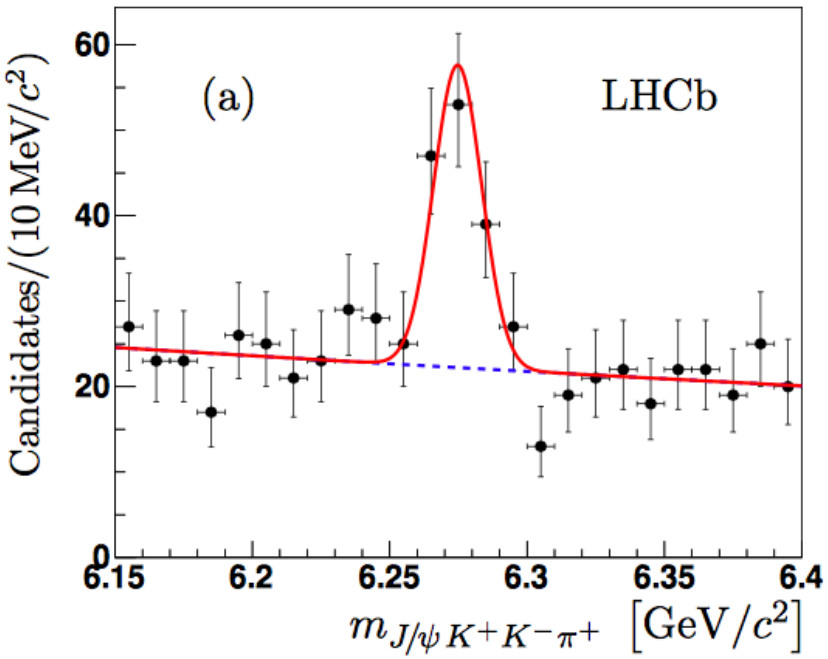


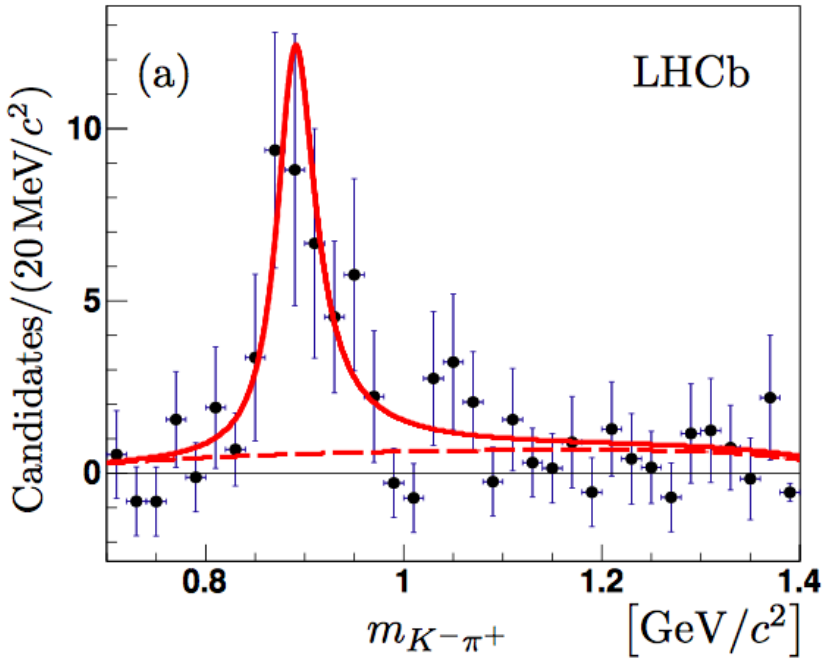


Observation of $B_c^+ \to J/\psi K^+ K^- \pi^+$

[JHEP 1311 (2013) 094]

- With all Run-I data, $N_{\rm sig} = 78 \pm 14$
- $D_s^+ \to K^+K^-\pi^+$ and $B_s^0 \to J/\psi K^+K^-$ mass regions excluded
- Largest contribution from $B_c^+ \to J/\psi K^+ \bar{K}^{*0}$
- $\frac{\mathcal{B}(B_c^+ \to J/\psi K^+K^-\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)} = 0.53 \pm 0.10 \pm 0.05$,
  consistent with theoretical prediction [A.V. Luchinsky, arXiv:1307.0953]

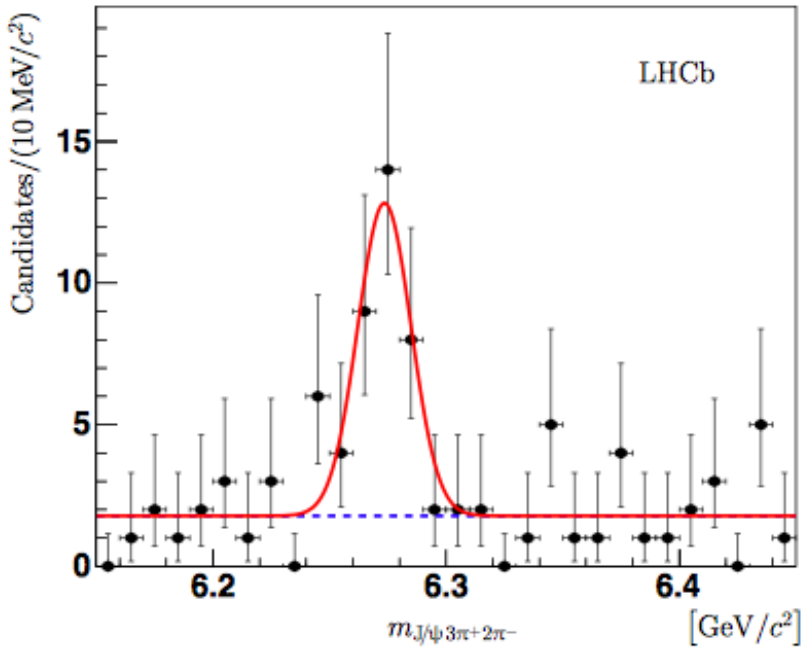


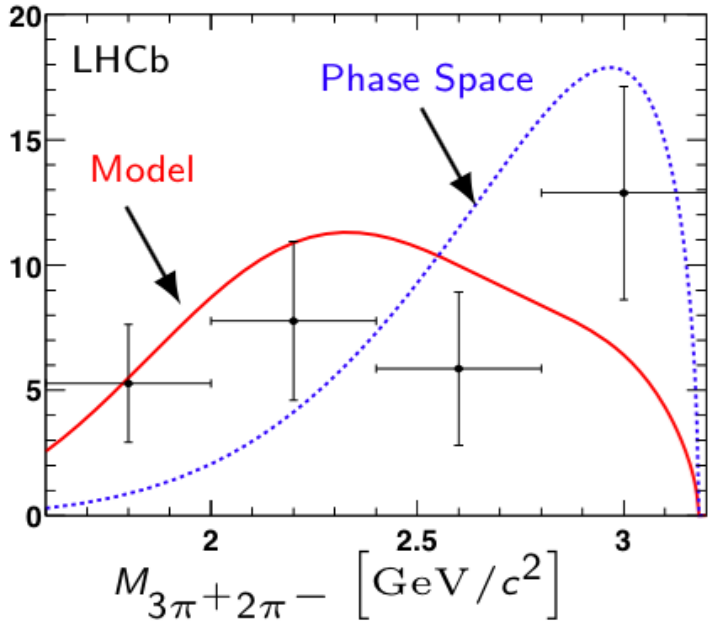


Evidence of $B_c^+ \to J/\psi 3\pi^+ 2\pi^-$

[JHEP 1405 (2014) 148]

- Searched with all Run-I data, $N_{\rm sig} = 32 \pm 8$ (4.5σ)
- No resonant structures found yet in the final states combinations
- $\frac{\mathcal{B}(B_c^+ \to J/\psi 3\pi^+ 2\pi^-)}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)} = 1.74 \pm 0.44 \pm 0.24$, consistent with $\frac{\mathcal{B}(B^0 \to D^{*-} 3\pi^+ 2\pi^-)}{\mathcal{B}(B^0 \to D^{*-} \pi^+)} = 1.70 \pm 0.34$, $\frac{\mathcal{B}(B^+ \to \bar{D}^{*0} 3\pi^+ 2\pi^-)}{\mathcal{B}(B^0 \to \bar{D}^{*0} \pi^+)} = 1.10 \pm 0.24$ and theoretical prediction [A. V. Luchinsky, PRD 86 (2012) 074024]

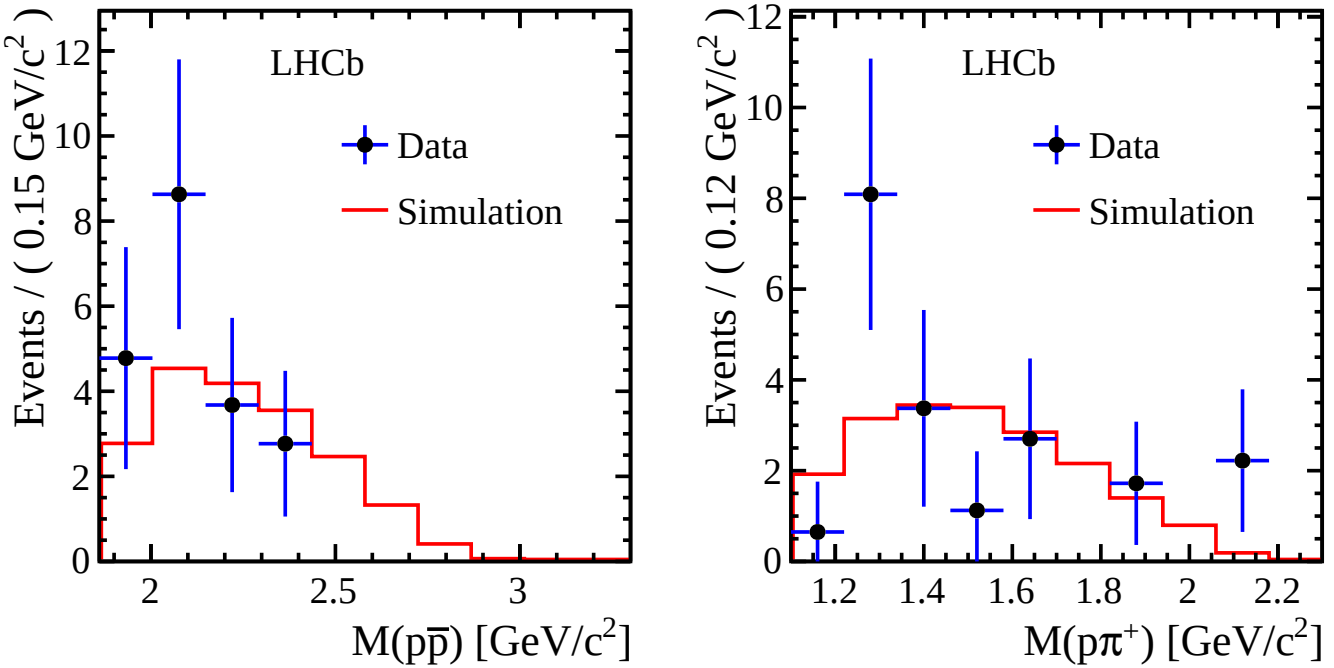




Observation of $B_c^+ \to J/\psi\, p\bar{p}\pi^+$

- Searched with all Run-I data, $N_{\rm sig} = 23.9 \pm 5.3$ [PRL 113 (2014) 152003]
- $\frac{\mathcal{B}(B_c^+ \to J/\psi\, p\bar{p}\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\, \pi^+)} = 0.143^{+0.039}_{-0.034} \pm 0.013$

  consistent with $\frac{\mathcal{B}(B^0 \to D^{*-} p\bar{p}\pi^+)}{\mathcal{B}(B^0 \to D^{*-} \pi^+)} = 0.17 \pm 0.02$ (PDG)
- $M(p\bar{p})$ and $M(p\pi^+)$ distributions consistent with phase-space distribution, no significant structure yet

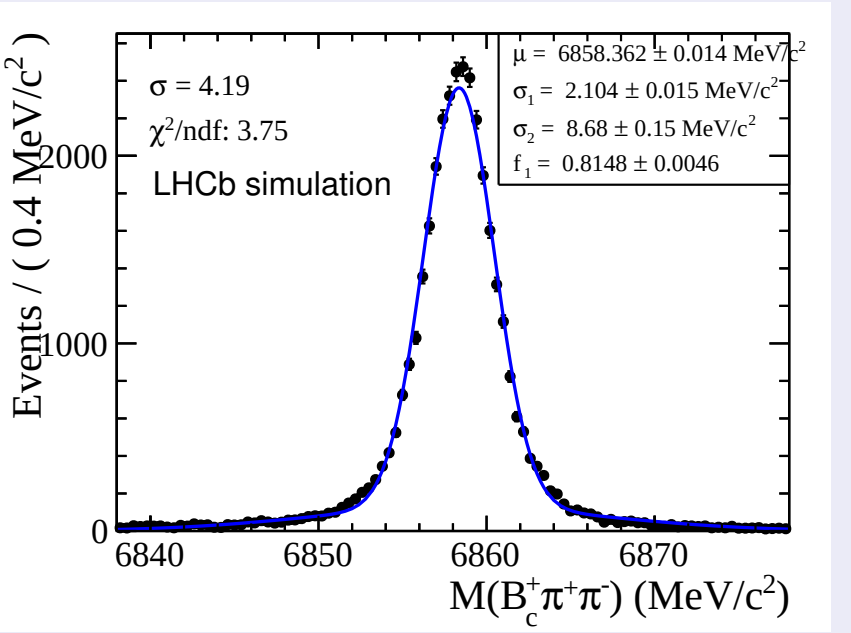


- First observation of baryonic B_c^+ decay

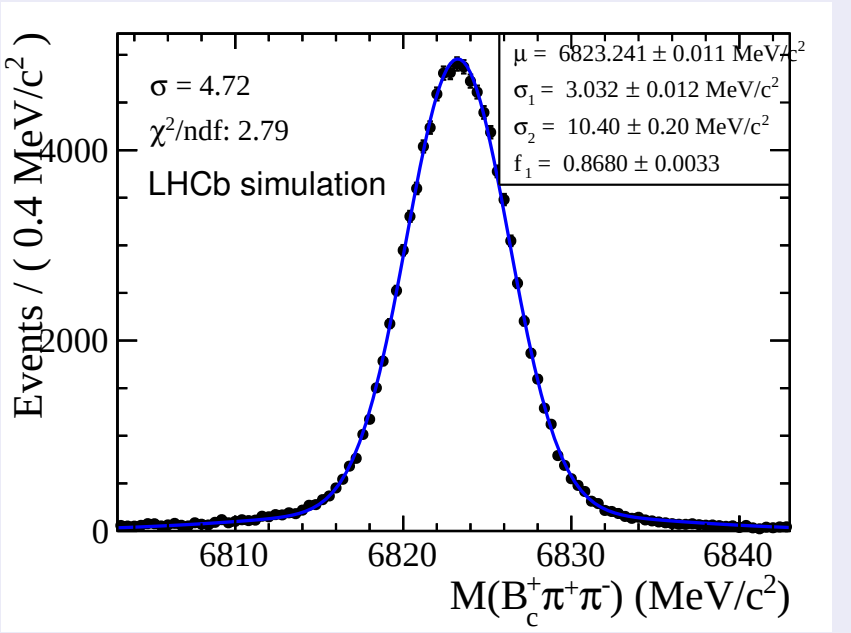
B_c excited states, prospects

- 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



Summary

- LHCb has performed many measurements on B_c^+ physics
  - B_c^+ double differential production ratio measured for the first time
  - Most precise measurements of B_c^+ mass and lifetime
  - Many new B_c^+ decay modes observed
    - ★ $J/\psi 3\pi$, $J/\psi K^+$, $\psi(2S)\pi^+$, $J/\psi D_s^{(*)+}$, $J/\psi K^+K^-\pi^+$, $J/\psi 3\pi^+2\pi^-$, $J/\psi p\bar{p}\pi^+$
    - ★ $B_s^0\pi^+$
- Prospects
  - More B_c^+ decay modes, especially annihilation type
  - Observation of B_c excited states