B_c physics at LHCb

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On behalf of the LHCb collaboration

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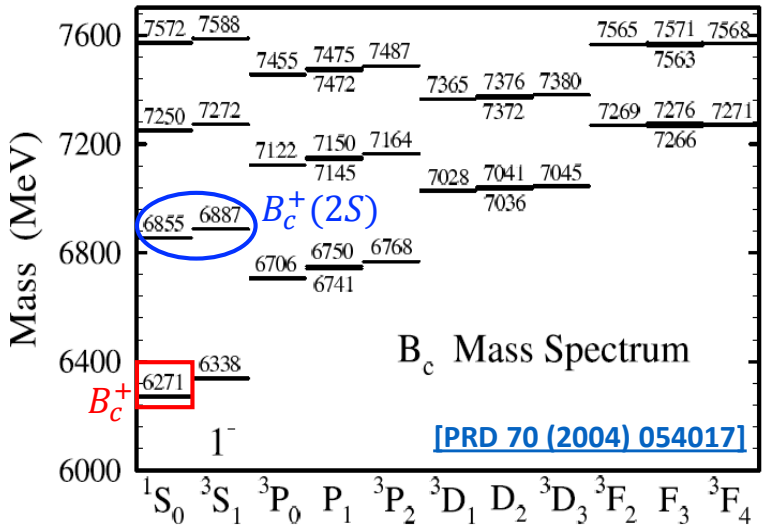
Outline

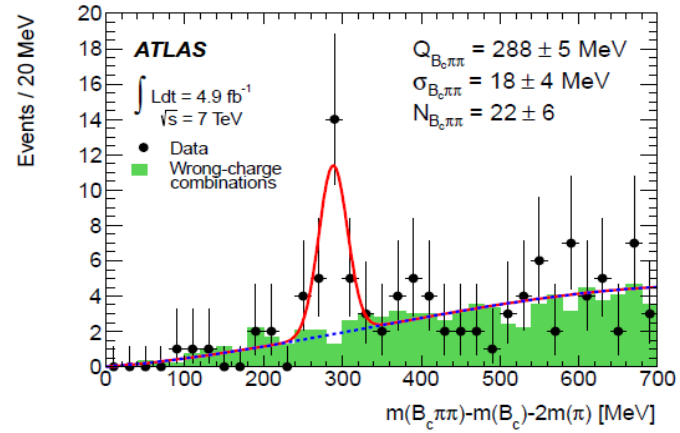
- Introduction
- The LHCb detector
- B_c^+ measurements at LHCb
  - ✓First observation of a baryonic B_c^+ decay [PRL 113 (2014) 152003]
  - ✓Measurement of B_c^+ production in proton-proton collisions at $\sqrt{s} = 8\ \mathrm{TeV}$ [PRL 114 (2015) 132001]
  - ✓Measurement of the lifetime of the B_c^+ meson using the $B_c^+ \to J/\psi\pi^+$ decay mode [PLB 742 (2015) 29-37]
  - ✓Measurement of the branching fraction ratio $\mathcal{B}(B_c^+ \to \psi(2S)\pi^+)/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$ [PRD 92 (2015) 072007]
  - ✓Search for B_c^+ decays to the $p\bar{p}\pi^+$ final state [PLB 759 (2016) 313-321]
- Summary and prospects

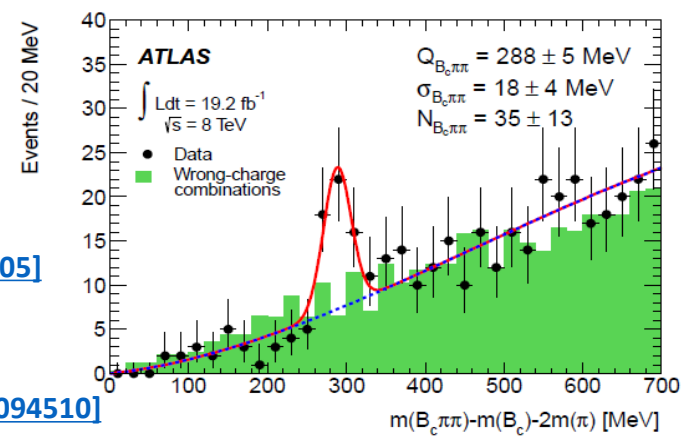
Introduction

- B_c: unique meson family consisting of two different heavy flavor quarks
  - ✓Spectrum
    - Predicted using various potential models



[PRD 70 (2004) 054017]





[PRL 113 (2014) 212004]

- ATLAS claimed observation of $B_c^+(2S)$
- B_c^+ (ground state) mass

  Potential models: $6.2 - 6.4\ \mathrm{GeV}/c^2$ [CERN-2005-005]

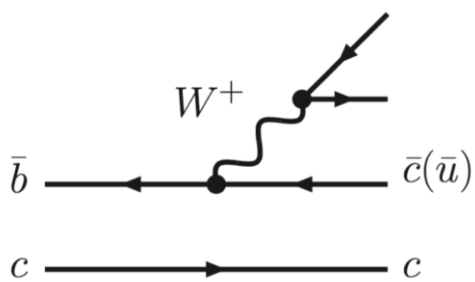
  pQCD: $6326^{+29}_{-9}\ \mathrm{MeV}/c^2$ [PRD 62 (2000) 094019]

  Lattice QCD: $6278 \pm 4 \pm 8\ \mathrm{MeV}/c^2$ [PRD 86 (2012) 094510]

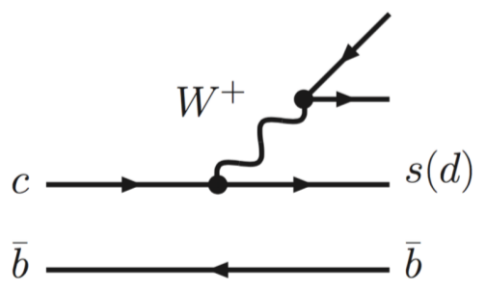
  PDG2015: $6275.1 \pm 1.0\ \mathrm{MeV}/c^2$

Introduction (cont.)

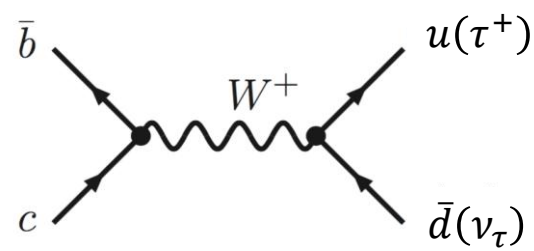
- B_c: unique meson family consisting of two different heavy flavor quarks
  - ✓Production
    - Difficult to produce at e^+e^- colliders
    - At hadron colliders, production mechanism is mainly $gg \to B_c + b + \bar{c}$
    - Theoretical prediction with complete $\mathcal{O}(\alpha_s^4)$ calculation:
      $\sigma(B_c^+) \sim 0.47\ \mu\text{b}$ @ 8 TeV;
      $\sigma(B_c^+)_{\text{LHC@14 TeV}} / \sigma(B_c^+)_{\text{Tevatron@1.96 TeV}} \sim \mathcal{O}(10)$. [PRD 71 (2005) 074012]
  - ✓Decays
    - Excited states: decay via strong or EM interactions into B_c^+
    - B_c^+: decays only weakly but has a rich set of decay modes



e.g. $J/\psi\pi^+, J/\psi\ell^+\nu_\ell$



e.g. $B_s^0\pi^+, B_s^0\ell^+\nu_\ell$

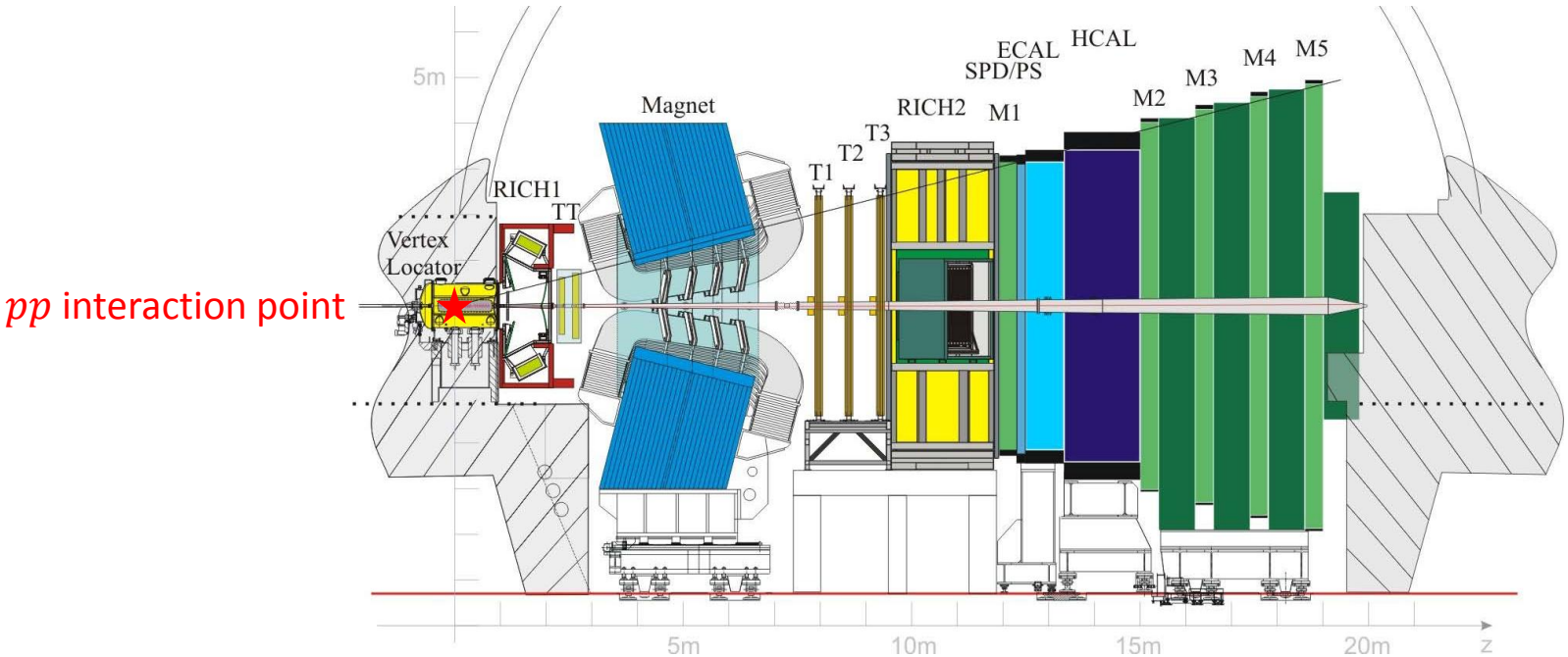


e.g. $K^*K^+, \tau^+\nu_\tau$

- B_c^+ lifetime
  Prediction: 0.48 ± 0.05 ps [NPB 585 (2000) 353]
  PDG2015: 0.507 ± 0.009 ps

LHCb detector

- A single-arm forward region spectrometer covering $2 < \eta < 5$
- RunI (2011-2012): $\mathcal{L}_{\text{int}} = 1\ \text{fb}^{-1}$ @ 7 TeV & $2\ \text{fb}^{-1}$ @ 8 TeV; $\sigma(b\bar{b}) \approx 250\ \mu\text{b}^{-1}$ @ 7 TeV
  - ✓ Collected the largest B_c^+ sample so far
- RunII (2015-2018): $\mathcal{L}_{\text{int}} = 5\ \text{fb}^{-1}$ @ 13 TeV ; $\sigma(b\bar{b}) \approx 500\ \mu\text{b}^{-1}$ @ 13 TeV



[JINST 3 (2008) S08005]

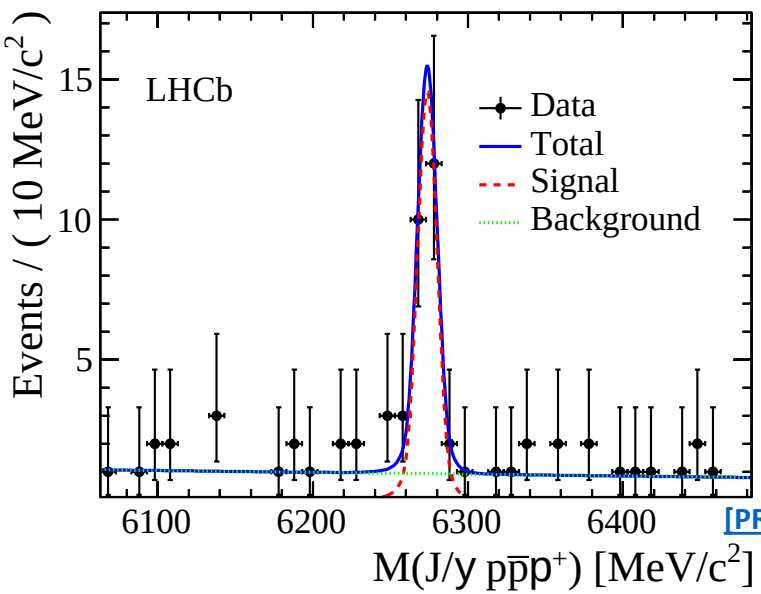
- ✓ **Vertex Locator:** $\sigma_{\text{PV},x/y} \sim 10\ \mu\text{m}$, $\sigma_{\text{PV},z} \sim 60\ \mu\text{m}$
- ✓ **Tracking (TT, T1-T3):** $\Delta p/p = 0.5 - 0.6\%$ for $5 < p < 100\ \text{GeV}/c$
- ✓ **RICHs:** $\varepsilon(K \to K) \sim 95\%$ @ misID rate $(\pi \to K) \sim 5\%$
- ✓ **Muon system (M1-M5):** $\varepsilon(\mu \to \mu) \sim 97\%$ @ misID rate $(\pi \to \mu) \sim 1 - 3\%$
- ✓ **ECAL:** $\sigma_E/E \sim 10\% / \sqrt{E} \otimes 1\%$ (E in GeV)
- ✓ **HCAL:** $\sigma_E/E \sim 70\% / \sqrt{E} \otimes 10\%$ (E in GeV)

B_c^+ measurements at LHCb

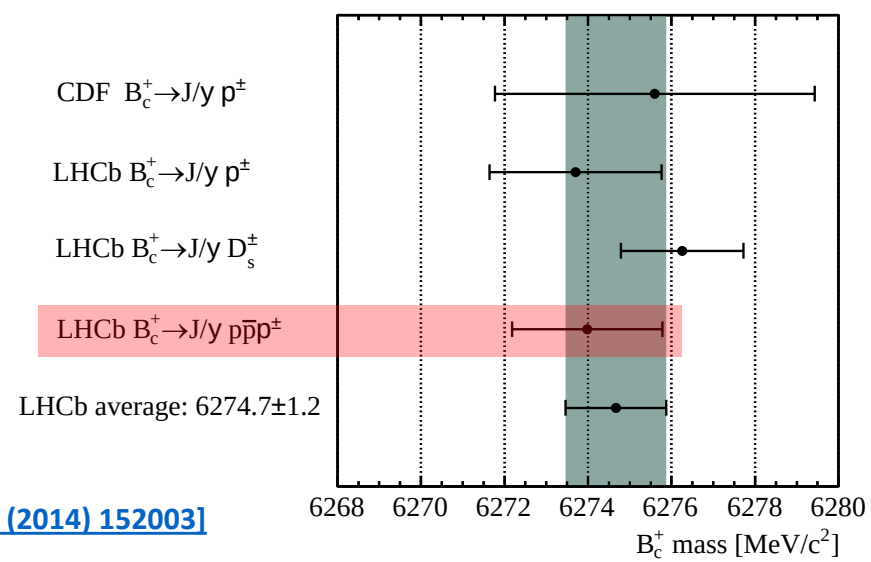
Mass	$M(B_c^+ \to J/\psi\pi^+)$	[PRL 109 (2012) 232001]
	$M(B_c^+ \to J/\psi D_s^+)$	[PRD 87 (2013) 112012]
	$M(B_c^+ \to J/\psi p\bar{p}\pi^+)$ *	[PRL 113 (2014) 152003]
Production	$\frac{\sigma(B_c^+)}{\sigma(B^+)}\frac{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\mathcal{B}(B^+ \to J/\psi K^+)}$	[PRL 109 (2012) 232001] **7 TeV** [PRL 114 (2015) 132001] **8 TeV**
	$\frac{\sigma(B_c^+)}{\sigma(B_s^0)}\mathcal{B}(B_c^+ \to B_s^0\pi^+)$ *	[PRL 111 (2013) 181801]
Lifetime	$\tau(B_c^+ \to J/\psi\mu^+\nu_\mu X)$	[EPJC 74 (2014) 2839]
	$\tau(B_c^+ \to J/\psi\pi^+)$	[PLB 742 (2015) 29-37]
Decays (also *)	$B_c^+ \to J/\psi\pi^+\pi^-\pi^+$	[PRL 108 (2012) 251802]
	$B_c^+ \to J/\psi K^+$	[JHEP 09 (2013) 075]
	$B_c^+ \to \psi(2S)\pi^+$	[PRD 87 (2013) 112012] **7 TeV** [PRD 92 (2015) 072007] **7&8 TeV**
	$B_c^+ \to J/\psi D_s^{(*)+}$	[PRD 87 (2013) 112012]
	$B_c^+ \to J/\psi K^+K^-\pi^+$	[JHEP 1311 (2013) 094]
	$B_c^+ \to J/\psi 3\pi^+2\pi^-$(evidence)	[JHEP 1405 (2014) 148]
	$\frac{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)}$	[PRD 90 (2014) 032009]
	$B_c^+ \to p\bar{p}\pi^+$(upper limit)	[PLB 759 (2016) 313-321]

B_c^+ mass with $B_c^+ \to J/\psi p\bar{p}\pi^+$

- Small systematic uncertainty due to small energy release ($Q-$value)
  $J/\psi\pi^+$: 3039 MeV; $J/\psi D_s^+$: 1211 MeV; $J/\psi p\bar{p}\pi^+$: 1163 MeV
- Using 3.0 fb^{-1} data at $\sqrt{s} = 7$ & 8 TeV
- Candidate selection
  - ✓ Trigger & loose preselection
  - ✓ Boosted decision tree (BDT) selection & $\mathcal{P}_p \times \mathcal{P}_{\bar{p}}$ ($\mathcal{P}$: PID discriminant)
    - Optimized at the same time to maximize signal significance $\varepsilon/(3/2+\sqrt{B})$
- $M(B_c^+) = 6274.0 \pm 1.8(\text{stat}) \pm 0.4(\text{syst})\ \text{MeV}/c^2$ (dominated by statistical uncertainty)



[PRL 113 (2014) 152003]

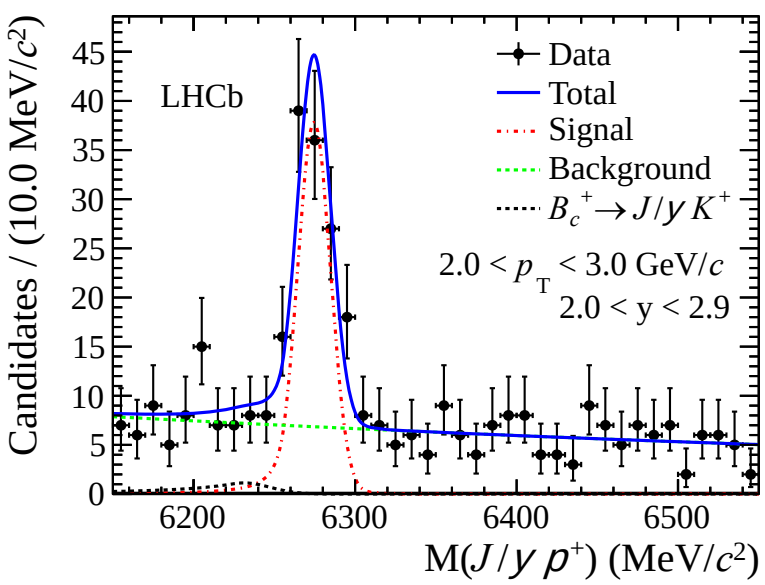


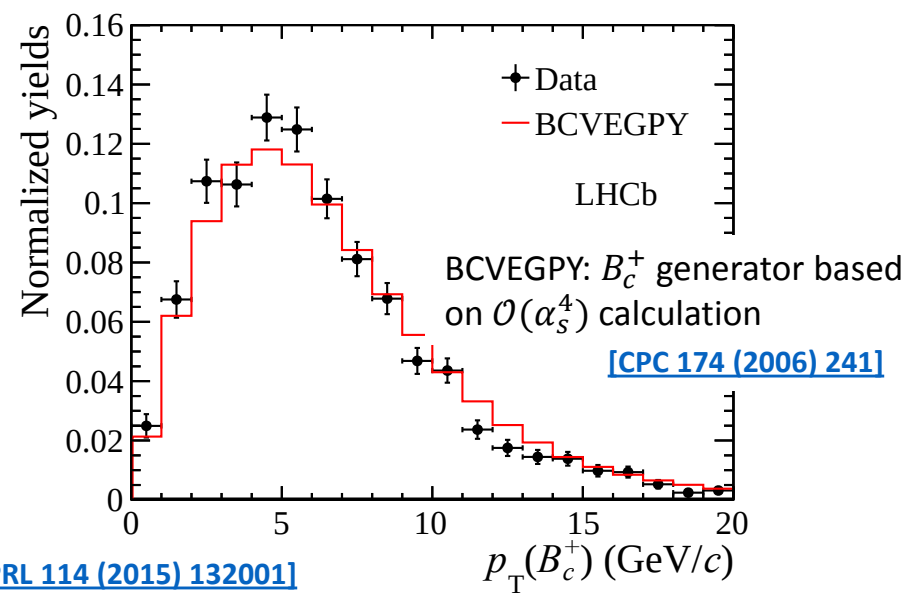
- ✓ First observation of a baryonic B_c^+ decay
- ✓ Significance 7.3σ

- ✓ LHCb average: $6274.7 \pm 1.2\ \text{MeV}/c^2$, consistent with Lattice QCD prediction $6278 \pm 4 \pm 8\ \text{MeV}/c^2$

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

- Measure $\mathcal{R} = \frac{\sigma(B_c^+)}{\sigma(B^+)} \frac{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\mathcal{B}(B^+ \to J/\psi K^+)}$
- Using 0.37 fb^{-1} data at $\sqrt{s} = 7$ TeV ($\tau_{B_c^+} = 0.453$ ps)
  - ✓ Fiducial region: B_c^+ and $B^+ \in p_T > 4$ GeV/c, $2.5 < y < 4.5$
  - ✓ $\mathcal{R} = \left(0.68 \pm 0.10(\text{stat}) \pm 0.03(\text{syst}) \pm 0.05(\tau_{B_c^+})\right)\%$
- Using 2.0 fb^{-1} data at $\sqrt{s} = 8$ TeV ($\tau_{B_c^+} = 0.509$ ps)
  - ✓ Fiducial region: B_c^+ and $B^+ \in p_T < 20$ GeV/c, $2.0 < y < 4.5$
  - ✓ $\mathcal{R}$ measured as a function of p_T and y for the first time
  - ✓ BDT selection; same for $B_c^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$ candidates
  - ✓ Efficiency determined from simulation; good agreement between data and simulation

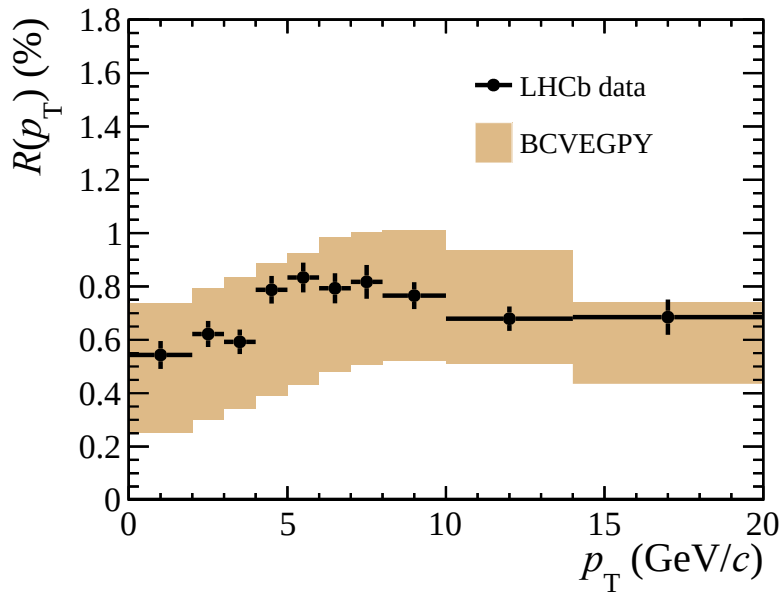


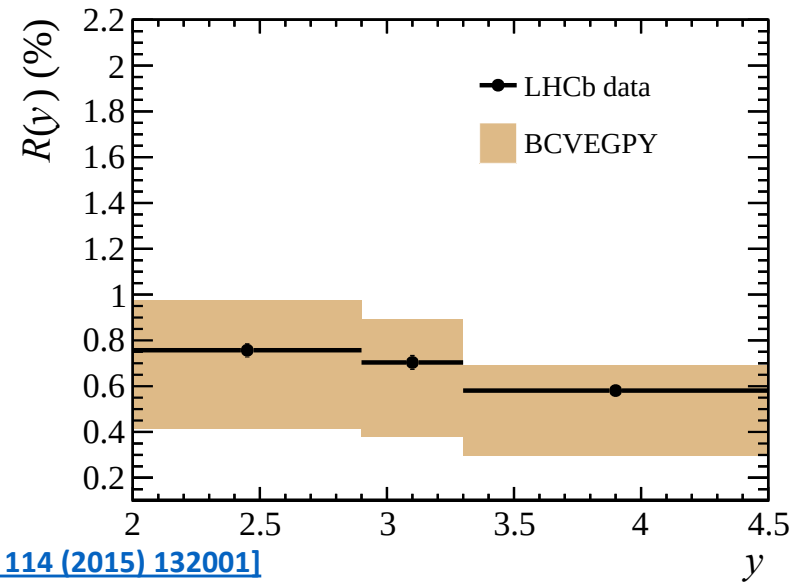


[PRL 114 (2015) 132001]

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

- $\mathcal{R} = (0.683 \pm 0.018(\text{stat}) \pm 0.009(\text{syst}))\%$
- Comparison between 7 TeV and 8 TeV with $\tau_{B_c^+} = 0.509$ ps in $4 < p_T < 20$ GeV/c, $2.5 < y < 4.5$
  - ✓ 7 TeV: $(0.61 \pm 0.12)\%$
  - ✓ 8 TeV: $(0.698 \pm 0.023)\%$
- Differential production cross-sections





[PRL 114 (2015) 132001]

- ✓ Theoretical prediction: B_c^+ by BCVEGPY following the α_s^4 approach; B^+ based on FONLL [JHEP 10 (2012) 137]
- ✓ Normalization: taking $\sigma_{B_c^+} = 0.47$ μb and $\mathcal{B}(B_c^+ \to J/\psi\pi^+) = 0.33\%$ [PRD 89 (2014) 034008]
- ✓ Good agreement!

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

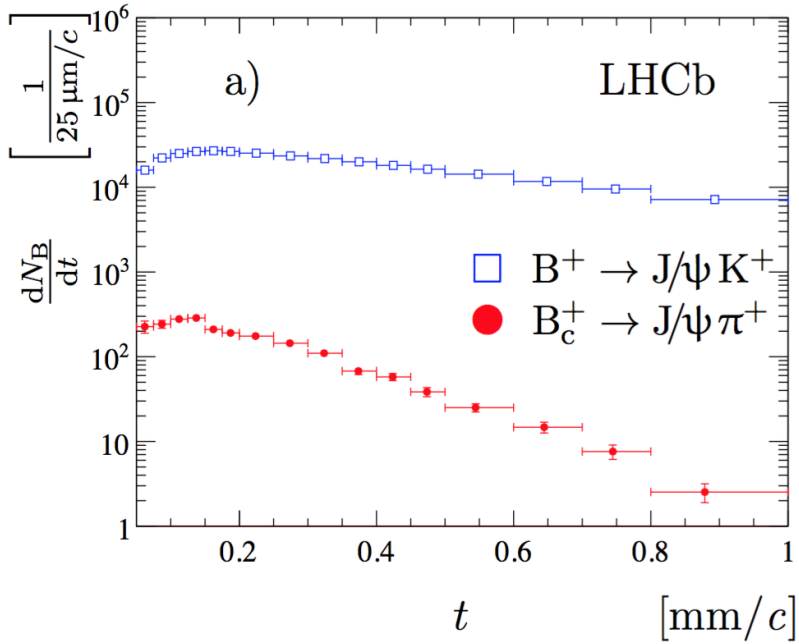
- Using 3.0 fb^{-1} data at $\sqrt{s} = 7$ TeV & 8 TeV
- Strategy

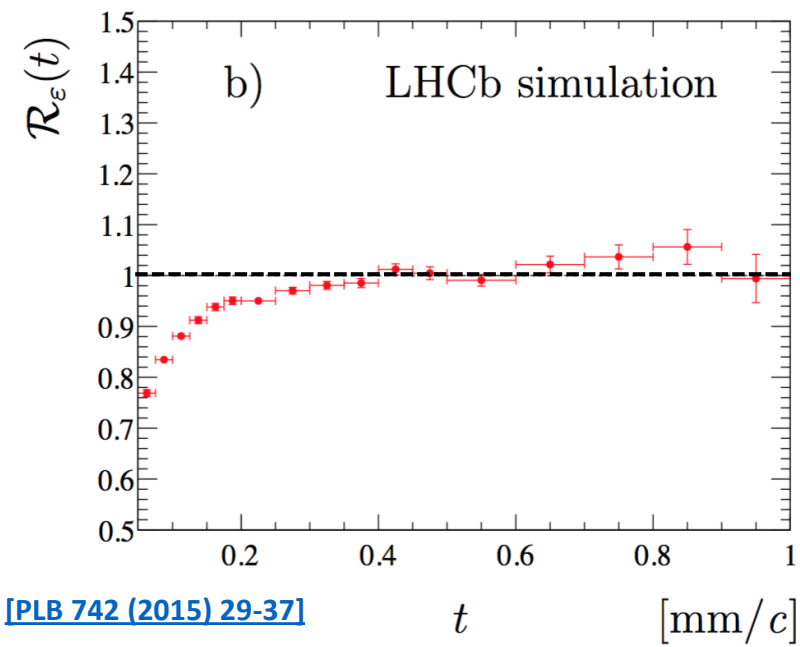
$$\mathcal{R}(t) \propto \frac{\varepsilon_{B_c^+}(t)}{\varepsilon_{B^+}(t)} \frac{E_{\tau_{B_c^+}}(t)}{E_{\tau_{B^+}}(t)} \equiv \mathcal{R}_\varepsilon(t)\, e^{-\Delta\Gamma t}$$

$$\text{with} \quad \Delta\Gamma \equiv \Gamma_{B_c^+} - \Gamma_{B^+} = \frac{1}{\tau_{B_c^+}} - \frac{1}{\tau_B}\,,\ \mathcal{R}(t) \equiv N_{B_c^+}(t)/N_{B^+}(t)$$

- MLP classifier; same for $B_c^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$ candidates
  - ✓ Input variables independent of the $B_c^+(B^+)$ decay time
- Signal yields determined using fits to the invariant mass distributions for $B_c^+(B^+)$
- $\mathcal{R}_\varepsilon(t)$ determined using the simulation

✓ Variation due to requirement on J/ψ decay length

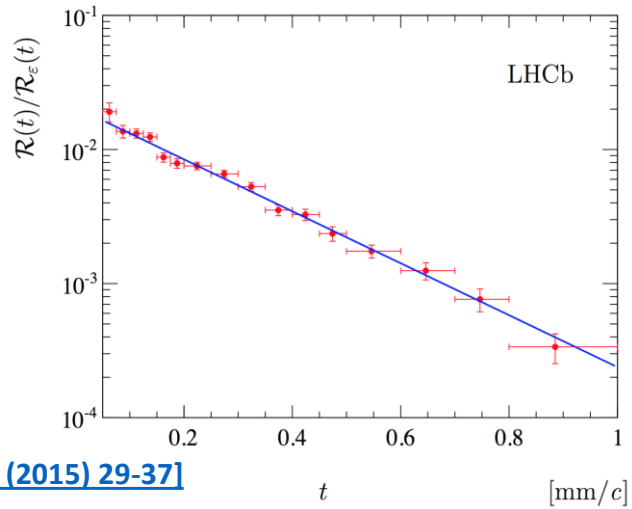




[PLB 742 (2015) 29-37]

B_c^+ lifetime with $B_c^+ \to J/\psi\pi^+$ (cont.)

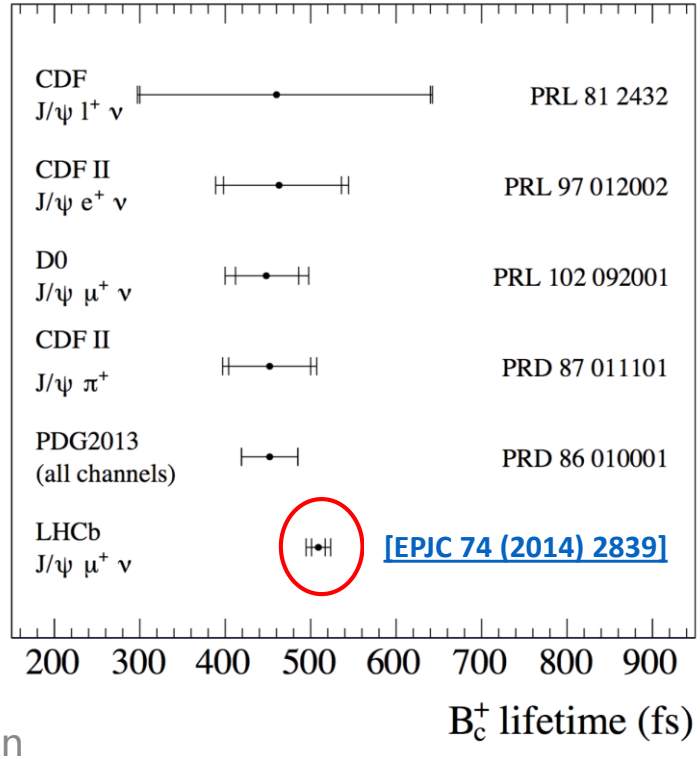
- $\Delta\Gamma = 4.46 \pm 0.14\ \mathrm{mm}^{-1}c$ determined from fit to $\mathcal{R}(t)/\mathcal{R}_\varepsilon(t)$



[PLB 742 (2015) 29-37]

Source	$\sigma_{\Delta\Gamma}$ [$\mathrm{mm}^{-1}c$]
Fit model (signal and background)	0.012
ct fit range	0.040
ct binning	0.016
Acceptance	
Simulation sample size	0.011
MLP filtering	0.025
J/ψ displacement	0.050
Total	0.072

- $\Delta\Gamma = 4.46 \pm 0.14(\mathrm{stat}) \pm 0.07(\mathrm{syst})\ \mathrm{mm}^{-1}c$
- $\tau_{B_c^+} = 513.4 \pm 11.0(\mathrm{stat}) \pm 5.7(\mathrm{syst})$ fs
  with $\tau_{B^+} = 1.638 \pm 0.004$ ps

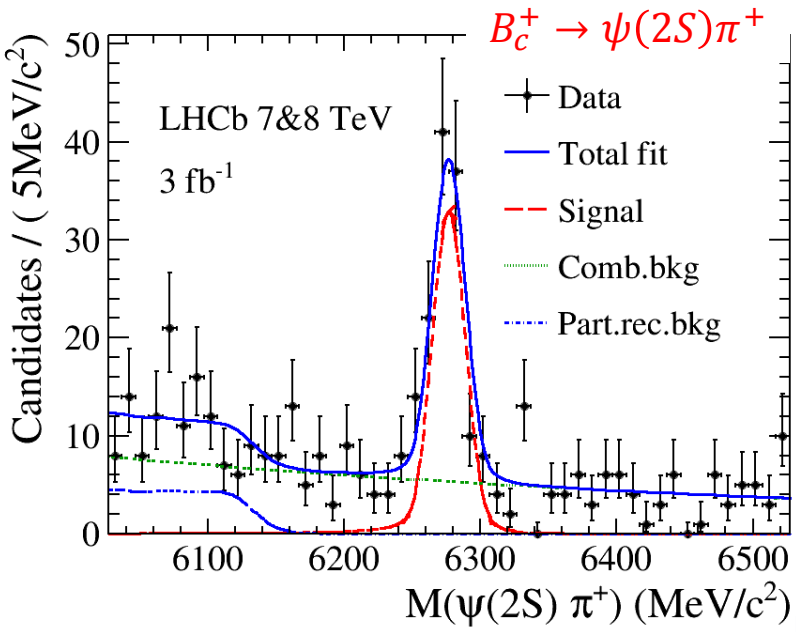


- ✓ In good agreement with previous LHCb measurement $\tau_{B_c^+} = 509 \pm 8 \pm 12$ fs using $B_c^+ \to J/\psi\mu^+\nu_\mu X$; has comparable precision
- ✓ Dominated by statistical uncertainty

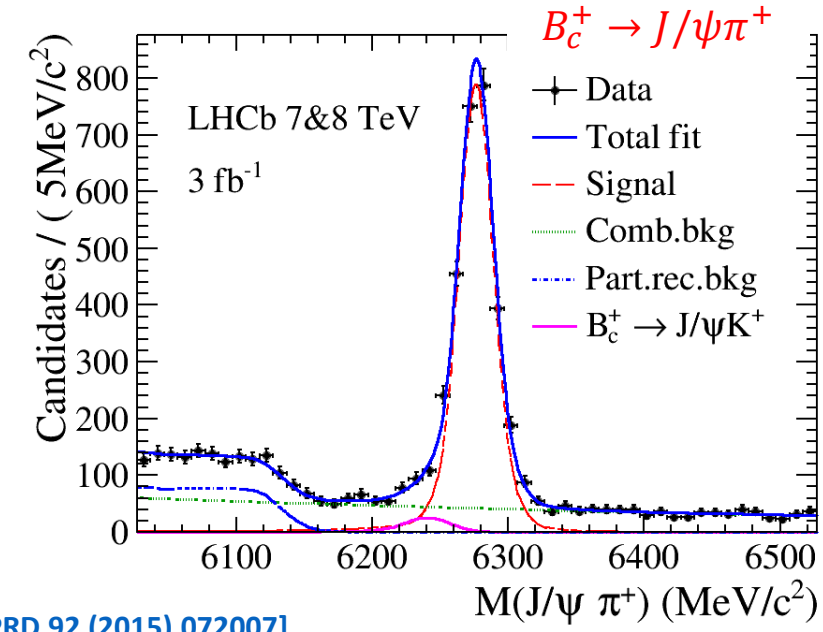
$B_c^+ \to \psi(2S)\pi^+$

- Measure $R_{\mathcal{B}} \equiv \mathcal{B}(B_c^+ \to \psi(2S)\pi^+)/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$
- Theoretical predictions: $0.07 - 0.29$
- Using 1.0 fb^{-1} data at $\sqrt{s} = 7$ TeV
  - ✓ First observation
  - ✓ $R_{\mathcal{B}} = 0.250 \pm 0.068(\text{stat}) \pm 0.014(\text{syst}) \pm 0.006(\text{BF})$ [PRD 87 (2013) 112012]

    BF: uncertainty on $\mathcal{B}(J/\psi \to \mu^+\mu^-)/\mathcal{B}(\psi(2S) \to \mu^+\mu^-)$
  - ✓ Result dominated by **statistical uncertainty**
- Using 3 fb^{-1} data at $\sqrt{s} = 7$ & 8 TeV
  - ✓ BDT selection; same for $B_c^+ \to \psi(2S)\pi^+$ and $B_c^+ \to J/\psi\pi^+$



Yield: 105 ± 12



Yield: 2745 ± 61

[PRD 92 (2015) 072007]

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

- Using 3 fb^{-1} data at $\sqrt{s} = 7$ & 8 TeV
  - ✓ $\boldsymbol{\pi^\pm}$ **PID efficiency calibrated** using pions from $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ decays;
    Other efficiencies determined using simulated samples;
    Most of the efficiencies cancelled due to the same final states
  - ✓ Systematics

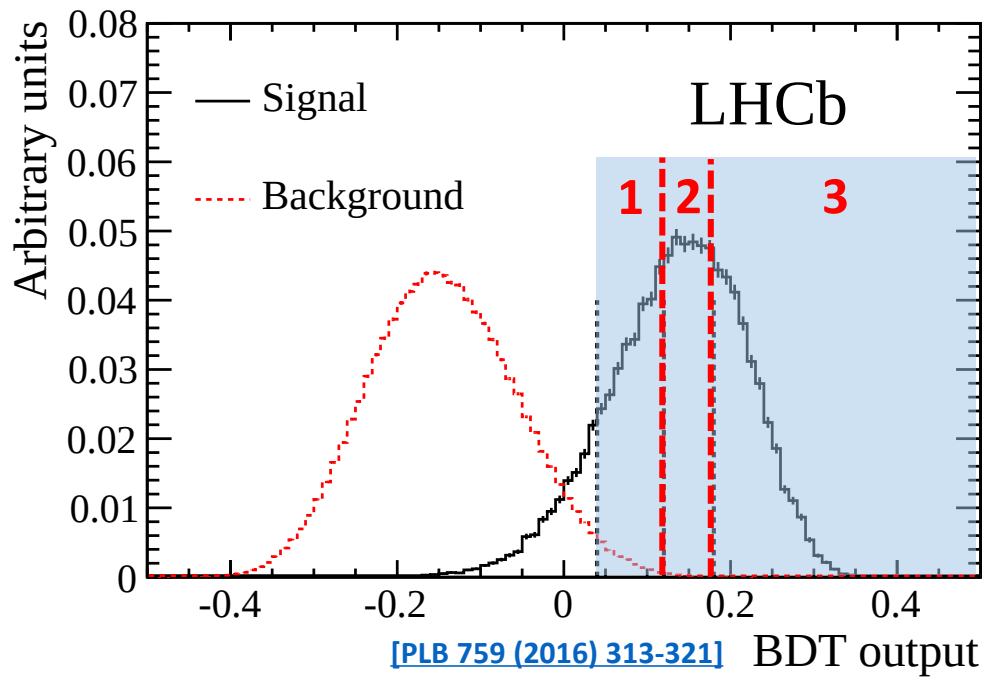
Component	Uncertainty
Signal shape	0.6%
Background shape	2.4%
BDT classifier	0.2%
Monte-Carlo Statistics	0.3%
Trigger efficiency	1.1%
B_c^+ lifetime	0.1%
Total	2.7%

- $R_{\mathcal{B}} = 0.268 \pm 0.032(\mathrm{stat}) \pm 0.007(\mathrm{syst}) \pm 0.006(\mathrm{BF})$ [PRD 92 (2015) 072007]
  - ✓ Dominated by statistical uncertainty
  - ✓ Consistent with the 7 TeV measurement
    $R_{\mathcal{B}} = 0.250 \pm 0.068(\mathrm{stat}) \pm 0.014(\mathrm{syst}) \pm 0.006(\mathrm{BF})$ [PRD 87 (2013) 112012]
  - ✓ Consistent with theoretical predictions $(0.07 - 0.29)$, especially
    - Non-relativistic QCD at next-to-leading order: $0.26^{+0.05}_{-0.06}$ [PRD 89 (2014) 034008]
    - Perturbative QCD based on k_{T} factorization: $0.29^{+0.17}_{-0.11}$ [EPJC (2015) 75:293]

$B_c^+ \to p\bar{p}\pi^+$

- First search for B_c^+ annihilation decay mode
- Using 3.0 fb^{-1} data at $\sqrt{s} = 7\ \mathrm{TeV}\ \&\ 8\ \mathrm{TeV}$
- Derive $R_p \equiv \frac{f_c}{f_u} \times \mathcal{B}(B_c^+ \to p\bar{p}\pi^+)$ with normalization channel $B^+ \to p\bar{p}\pi^+$
- Kinematic region: $m(p\bar{p}) < 2.85\ \mathrm{GeV}/c^2, p_{\mathrm{T}}(B) < 20\ \mathrm{GeV}/c, 2.0 < y(B) < 4.5$
  - ✓ Below charmonium threshold
- Loose preselection + joint BDT & PID optimization
- Signal yield determined from simultaneous fit in 3 BDT bins to gain sensitivity

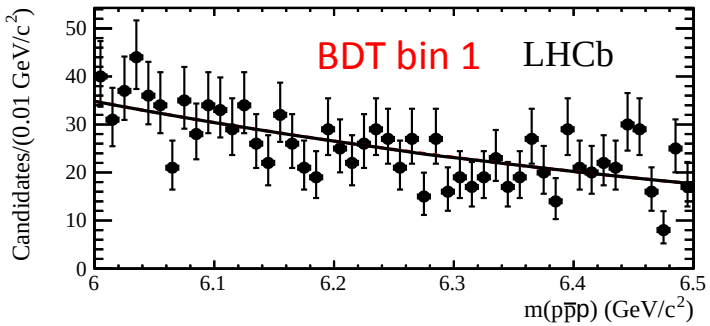
✓ Binning chosen to have the same expected yield

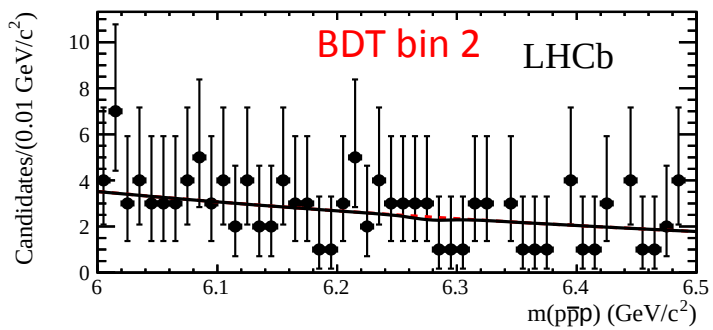


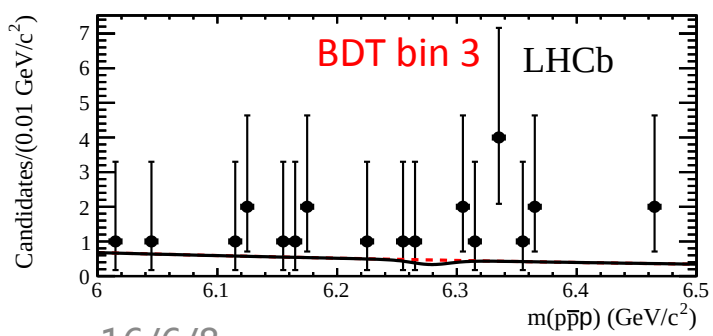
[PLB 759 (2016) 313-321]

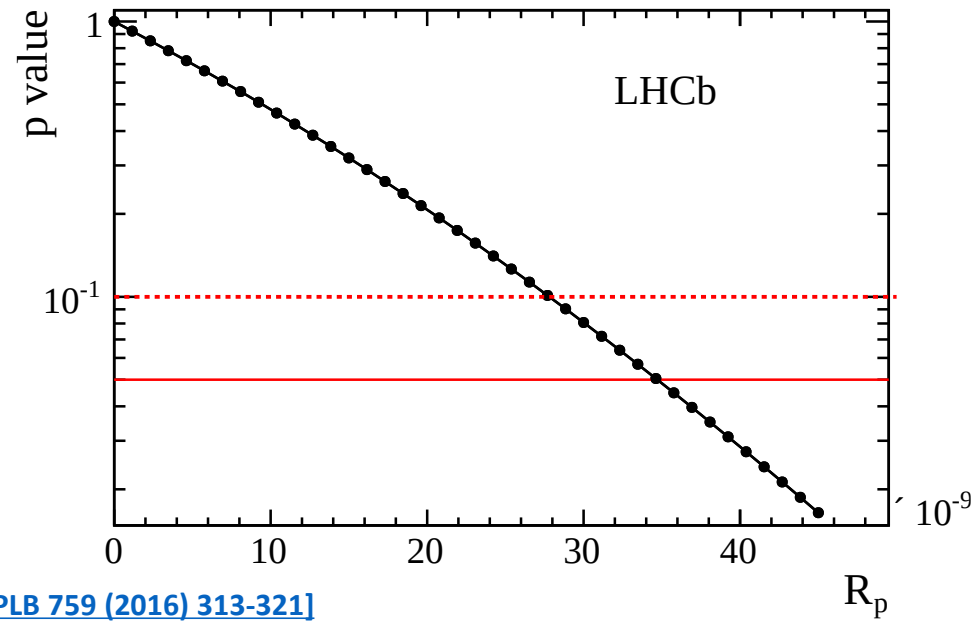
$B_c^+ \to p\bar{p}\pi^+$ (cont.)

- No signal observed: $N(B_c^+ \to p\bar{p}\pi^+) = -2.7 \pm 6.3$ (statistical uncertainty only)
- Upper limits estimated from p-value profile for R_p, which is the ratio of the "signal+background" and "background-only" p-values









[PLB 759 (2016) 313-321]

- No signal observed
- Upper limit is $R_p < 3.6 \times 10^{-8}$ at 95% confidence level

Summary

- Various B_c^+ measurements performed at LHCb
  - ✓The most precise measurement of B_c^+ mass, production and lifetime
  - ✓Many new B_c^+ decay modes first observed/searched
    - $J/\psi\pi^+\pi^-\pi^+, J/\psi K^+, \psi(2S)\pi^+, J/\psi D_s^{(*)+}, J/\psi K^+K^-\pi^+, J/\psi p\bar{p}\pi^+, J/\psi 3\pi^+2\pi^-$(evidence)
    - $B_s^0\pi^+$
    - $p\bar{p}\pi^+$(upper limit)

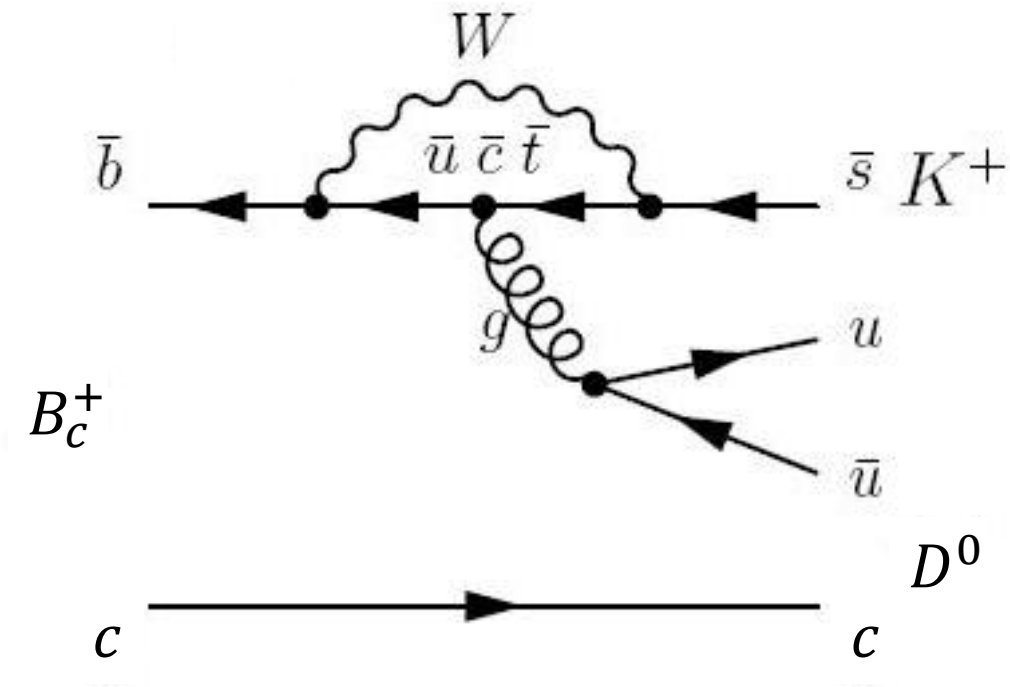
- Prospects
  - ✓Search for new decay modes
    - $B_c^+ \to J/\psi D^{(*)}K^{(*)}$ is coming!
  - ✓Search for B_c^+ excited states
  - ✓RunII is bringing more statistics

Thank you!

Back up

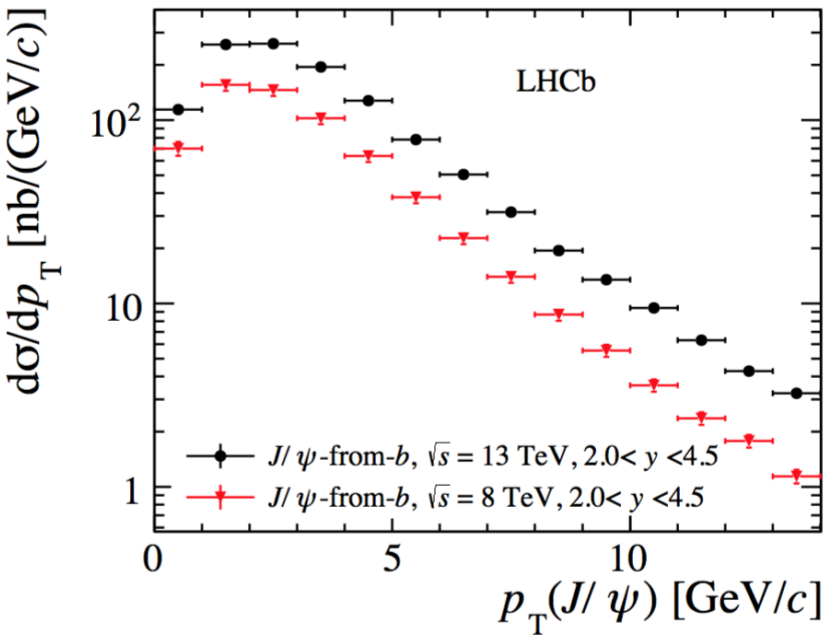
Box diagram

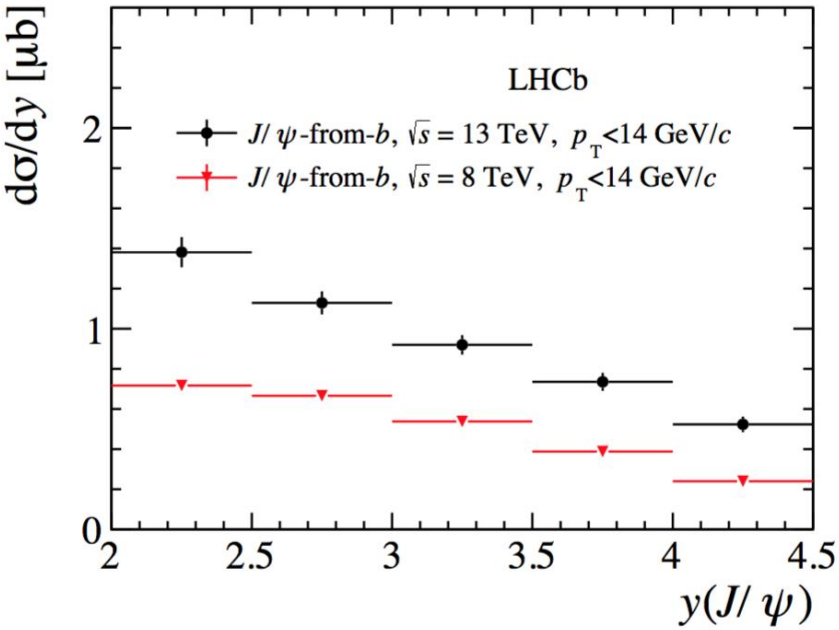
E.g. $B_c^+ \to D^0 K^+$



LHCb RunII

➢J/ψ-from-b production cross-section comparison between 8 & 13 TeV





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