B_c studies at LHCb

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(on behalf of the LHCb collaboration)

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B_c spectrum

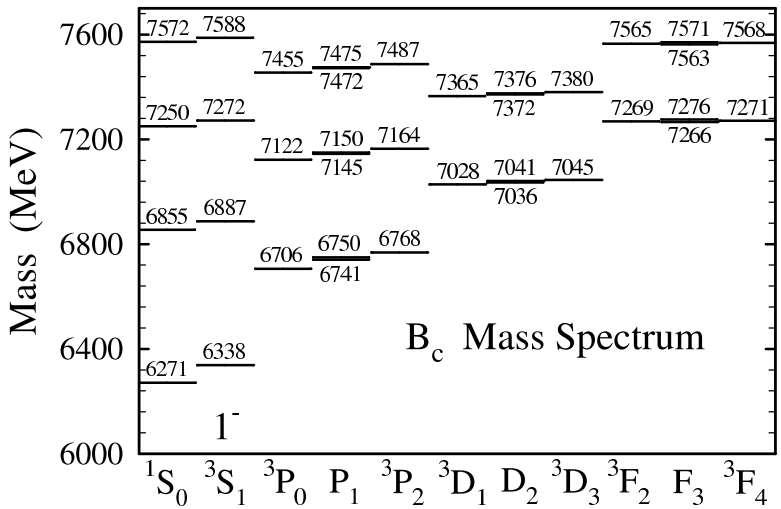
- B_c: Mesons formed by two different heavy flavor quarks, the $\bar{b}$ quark and the c quark [1]
  - Unique in the Standard Model because the top quark is too heavy and decays before forming any bound states

- 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, 094019 (2000)]
  - Lattice QCD: 6278(6)(4) MeV/c^2

    TWQCD, [arXiv:0704.3495]
  - PDG'10: 6277 ± 6 MeV/c^2



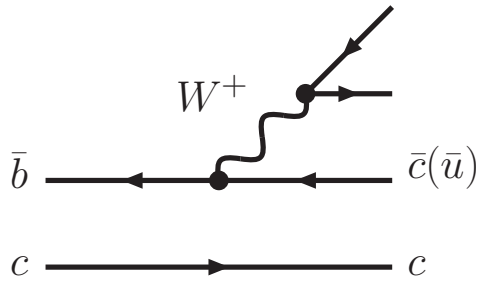
S.Godfrey, [PRD 70, 054017 (2004)]

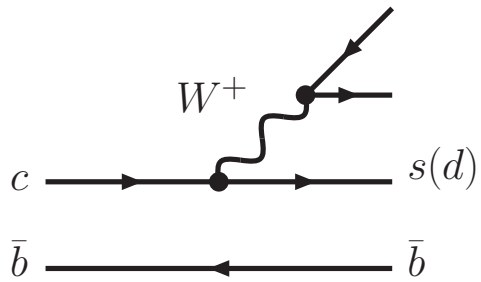
[1] Charge conjugates implied in this presentation

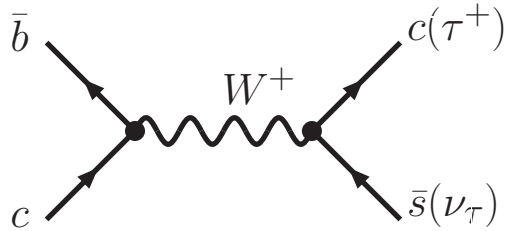
B_c decays

- 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., $J/\psi\pi^+$, $J/\psi\pi^+\pi^-\pi^+$, $J/\psi\ell^+\nu_\ell$
  - $c \to s W^+$, 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

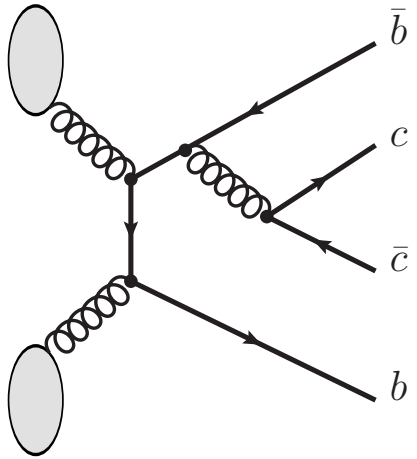
    V. V. Kiselev, et. al, [NPB 585, 353 (2000)]
  - PDG'10: 0.45 ± 0.04 ps







B_c production



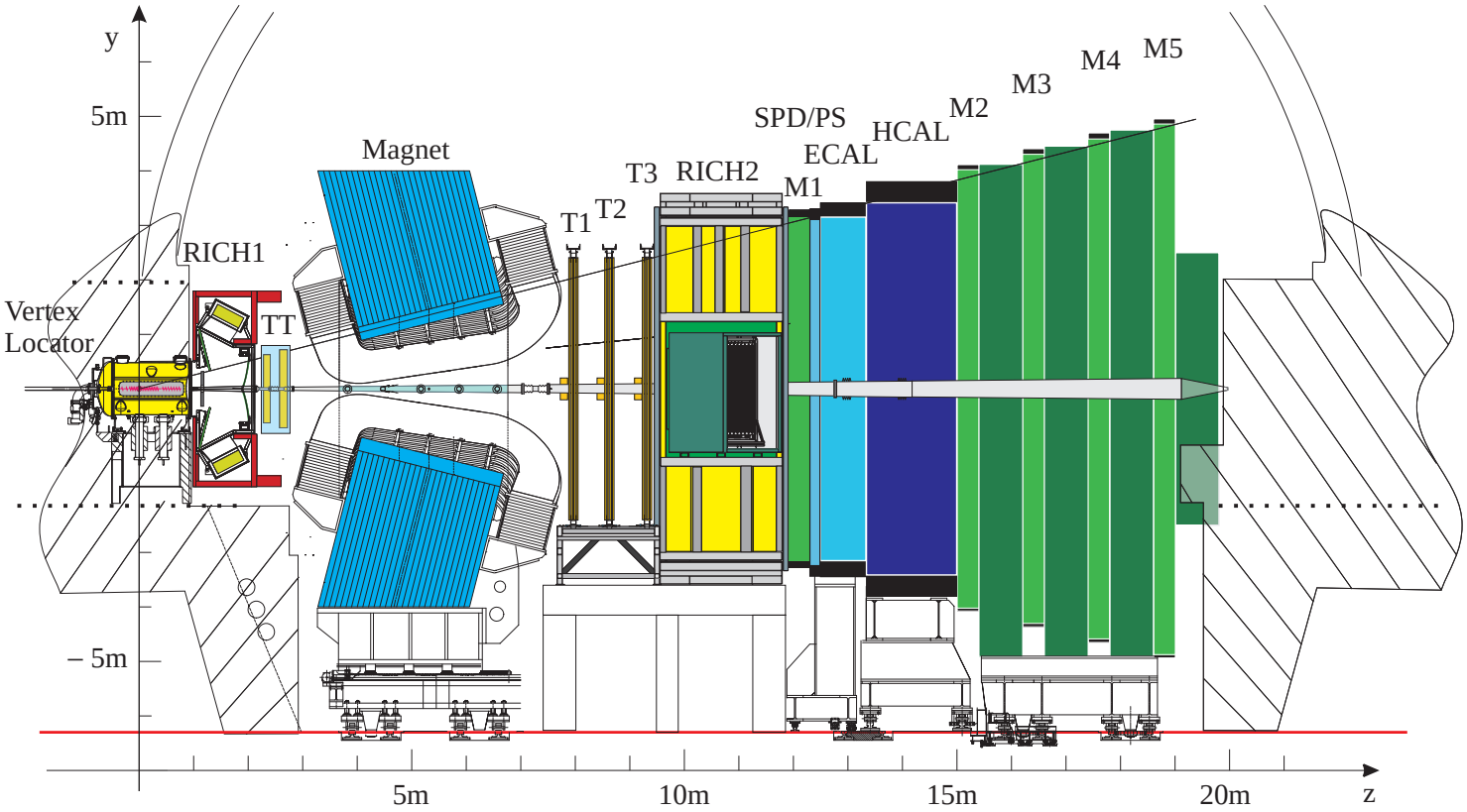
- B_c production
  - Difficult to generate at e^+e^- colliders
  - At hadron colliders, B_c generated mainly through $gg \to B_c + b + \bar{c}$
- B_c^+ production rate
  - Theoretical prediction C.-H.Chang, et al., [PRD 71, 074012 (2005)]

-	$\|(^1S_0)_1\rangle$	$\|(^3S_1)_1\rangle$	$\|(^1S_0)_8 g\rangle$	$\|(^3S_1)_8 g\rangle$	$\|(^1P_1)_1\rangle$	$\|(^3P_0)_1\rangle$	$\|(^3P_1)_1\rangle$	$\|(^3P_2)_1\rangle$
LHC[2]	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
    - ★ $\sigma(B_c^+)_{\rm LHC}/\sigma(B_c^+)_{\rm Tevatron} \sim$ 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, $\sigma(B_c^+) \sim 0.9\ \mu$b for $\sqrt{s} = 14$ TeV; or $\sim 0.4\ \mu$b for $\sqrt{s} = 7$ TeV

[2] $\sqrt{s} = 14$ TeV

The LHCb detector



Geometry acceptance $1.9 < \eta < 4.9$, unique coverage

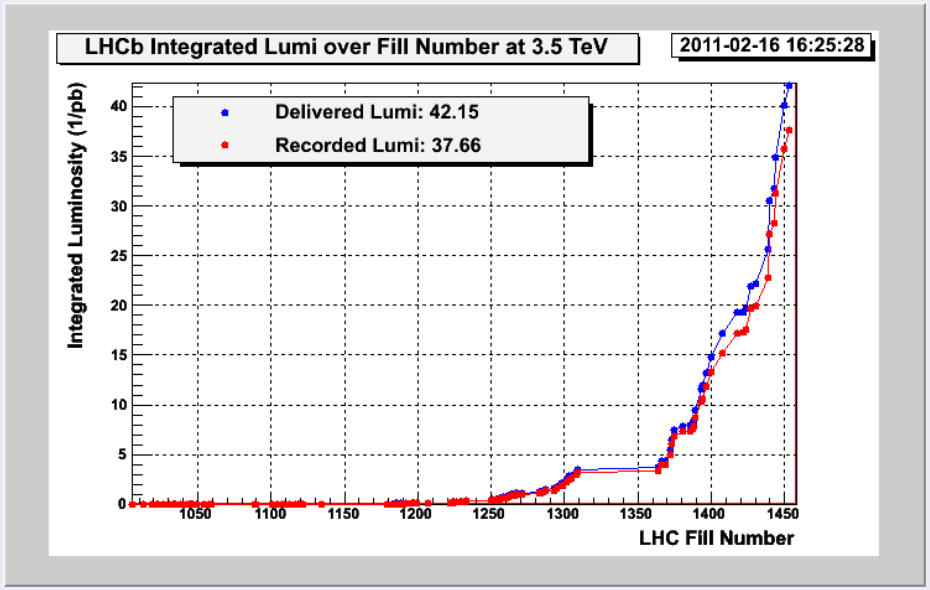
Vertex Locator $\sigma_{\mathrm{PV,x/y}} \sim 10\ \mu$m, $\sigma_{\mathrm{PV,z}} \sim 60\ \mu$m; $\sigma_L \sim 250\ \mu$m

Tracking system (TT, T1-T3) $\Delta p/p$: 0.35%-0.55%

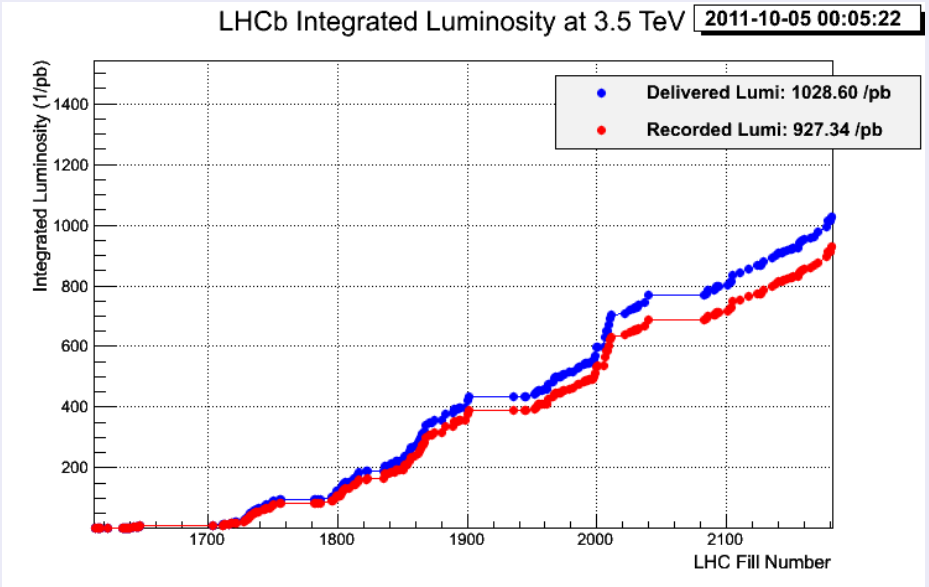
Muon system (M1-M5) $\varepsilon(\mu \to \mu) \sim 97\%$, mis-ID rate $(h \to \mu) \sim 2\%$

The LHCb data-taking

2010 (37 pb^{-1} recorded)



2011 (927 pb^{-1} recorded so far)



- 2010 data
  B_c^+ mass measurement
  B_c^+ production measurement

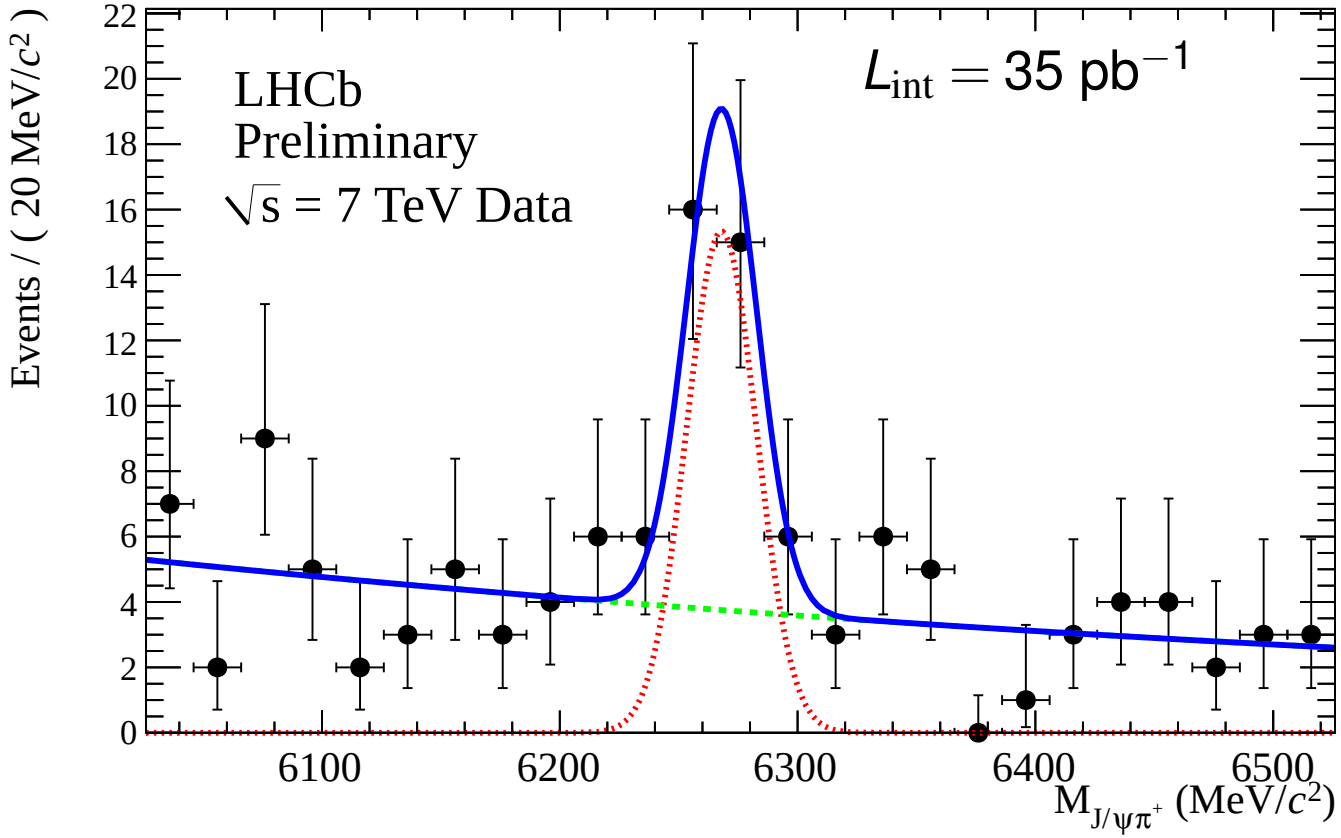
- 2011 data
  Observation of $B_c^+ \to J/\psi 3\pi$

B_c^+ mass measurement

[CERN-LHCb-CONF-2011-027]

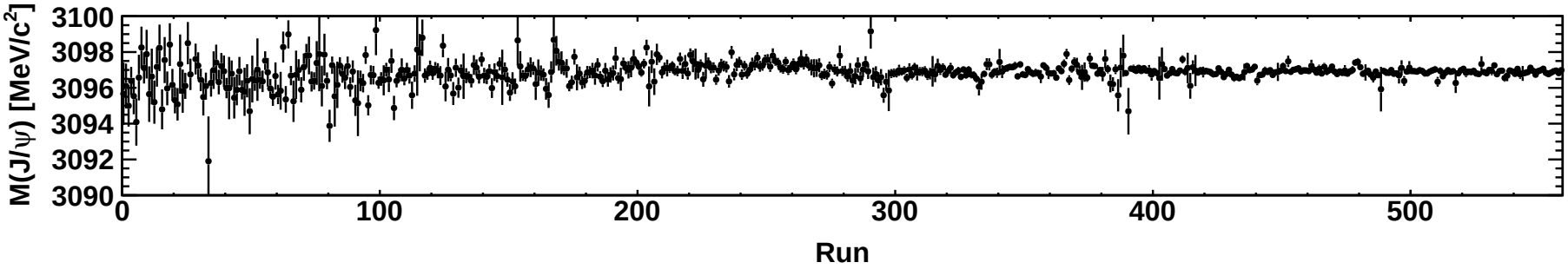
B_c^+ mass measurement

- Based on ~ 35 pb^{-1} of data collected in 2010.
- Cut biased selection. Signal yield, 28 ± 7
- Fit Model
  - Signal: Gaussian
  - Background: Exponential



Momentum scale calibration

- Momentum scale calibrated using large sample of $J/\psi(\mu^+\mu^-)$ and checked with Υ, D^0, K^0_S, and $\psi(2S) \to J/\psi\pi^+\pi^-$



Systematics

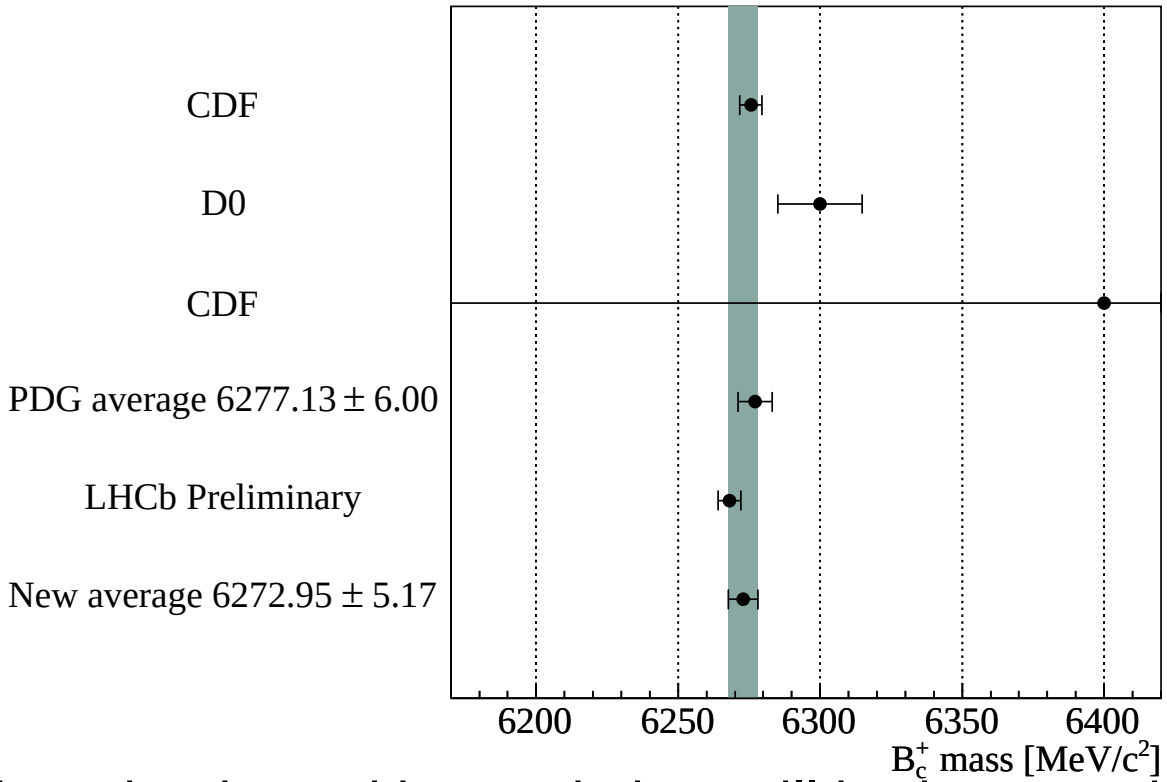
Source of uncertainty	Value [MeV/c^2]
Mass fitting:	
Background model	0.32
Signal model	0.07
Momentum scale calibration:	
Average momentum scale	0.23
η dependence of momentum scale	0.44
Detector description:	
Energy loss correction	0.11
Detector alignment:	
Vertex detector (track slopes)	0.06
Quadratic sum	0.61

B_c^+ mass result

- Preliminary result

  $M(B_c^+) = 6268.0 \pm 4.0(\text{stat}) \pm 0.6(\text{syst})$ MeV/c^2

- Comparison with PDG



- Uncertainty dominated by statistics, will be improved with 2011 data.

B_c^+ cross section measurement

[CERN-LHCb-CONF-2011-017]

B_c^+ cross section measurement

- Based on ~ 33 pb^{-1} data collected in 2010
- Use fully reconstructed $B_c^+ \to J/\psi(\mu^+\mu^-)\pi^+$, relatively clean. Large control sample $B^+ \to J/\psi K^+$ available.
- Measure

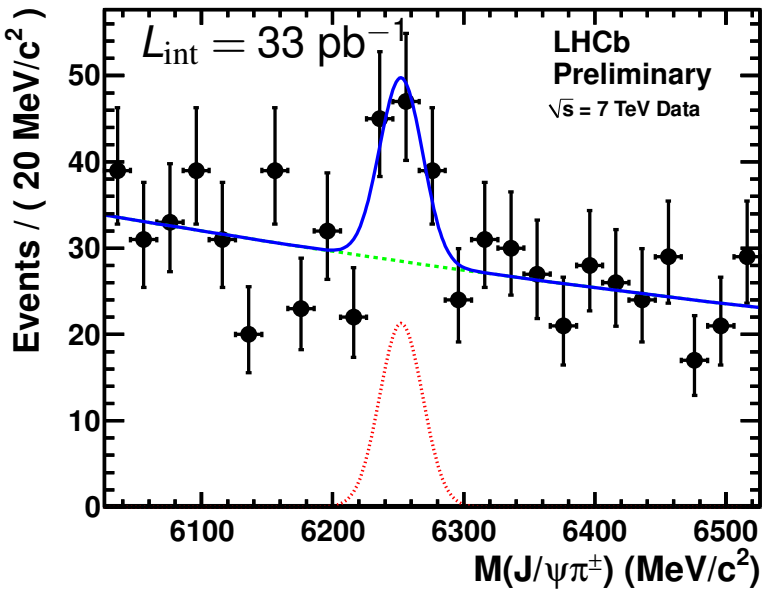
$$\frac{\sigma(B_c^+) \times BR(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+) \times BR(B^+ \to J/\psi K^+)} = \varepsilon_{\rm rel} \times \frac{N(B_c^+)}{N(B^+)}$$

for $p_{\rm T}(B) > 4$ GeV/c and $\eta \in (2.5, 4.5)$

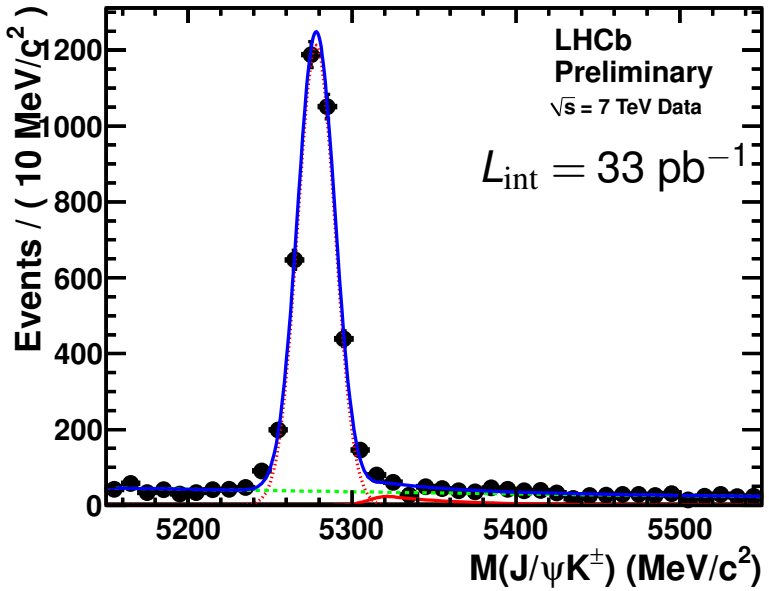
Extraction of $N(B_c^+)$ and $N(B^+)$

- Lifetime unbiased event selection (& trigger), as similar as possible between $B_c^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$
- Cabibbo suppressed background $B^+ \to J/\psi\pi^+$ considered for $B^+ \to J/\psi K^+$
- 43 ± 13 $B_c^+ \to J/\psi(\mu^+\mu^-)\pi^+$ signal

$B_c^+ \to J/\psi\pi^+$
$N_{\rm sig} = 43 \pm 13$



$B^+ \to J/\psi K^+$
$N_{\rm sig} = 3476 \pm 62$



Ratio of production cross section

- Total efficiencies computed from MC, binned in (p_{T}, η) to reduce the dependence on theoretical model
- Systematics dominated by B_c^+ lifetime (0.453 ± 0.041) ps, will be reduced after a better lifetime measurement
- Preliminary result

  $$\frac{\sigma(B_c^+) \times BR(B_c^+ \to J/\psi \pi^+)}{\sigma(B^+) \times BR(B^+ \to J/\psi K^+)} = (2.2 \pm 0.8|_{\mathrm{stat.}} \pm 0.2|_{\mathrm{sys.}})\%$$

  for $p_{\mathrm{T}}(B) > 4$ GeV/c and $\eta \in (2.5, 4.5)$
- This result will be superseded by a measurement using data collected in 2011 ($\sim$10 times more statistics) very soon.

Observation of $B_c^+ \to J/\psi(\mu^+\mu^-)\pi^+\pi^-\pi^+$

[CERN-LHCb-CONF-2011-040]

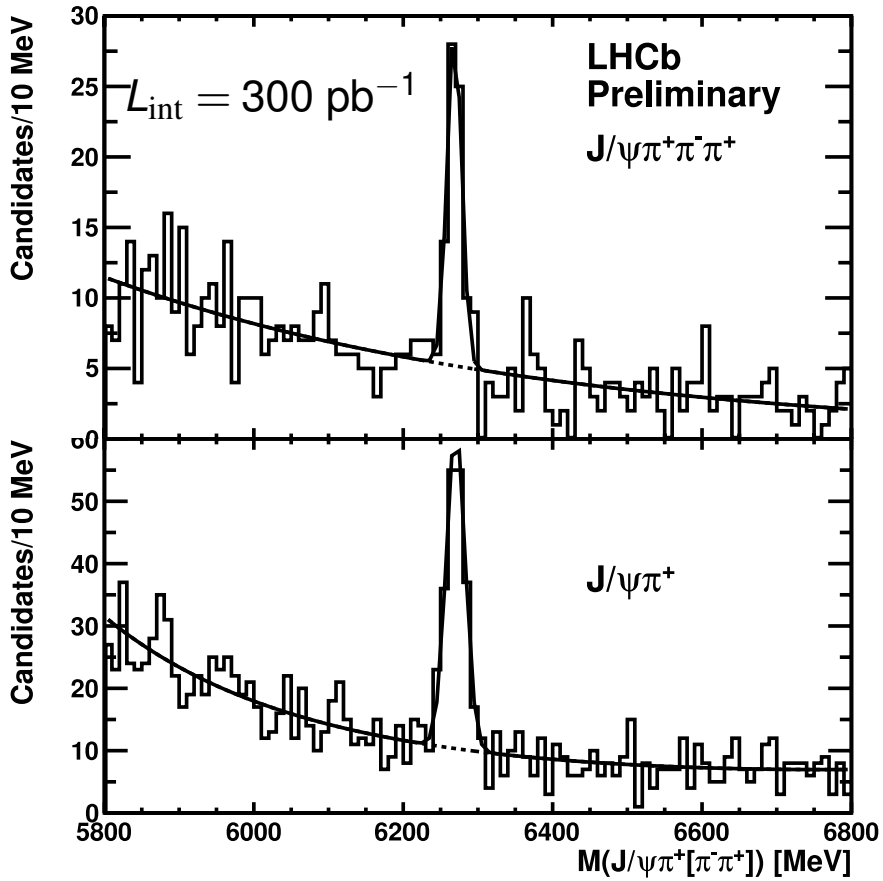
Observation of $B_c^+ \to J/\psi(\mu^+\mu^-)\pi^+\pi^-\pi^+$

- Based on ~ 300 pb^{-1} data collected in 2011
- Cut based pre-selection $+$ S/B likelihood-ratio discrimination
- Use $B^+ \to J/\psi\pi^+\pi^-K^+$ as control channel
- Measure

$$\frac{BR(B_c^+ \to J/\psi\pi^+\pi^-\pi^+)}{BR(B_c^+ \to J/\psi\pi^+)} = \varepsilon_{\rm rel} \times \frac{N(B_c^+ \to J/\psi\pi^+\pi^-\pi^+)}{N(B_c^+ \to J/\psi\pi^+)}$$

Signal yields

- $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$, 58 ± 10, 6.8σ, first observation
- $B_c^+ \to J/\psi\pi^+$, 163 ± 16



Ratio of branching ratios

- Total efficiencies computed from MC.
- Systematics
  - $p_{\mathrm{T}}(B_c^+)$ spectrum, 9%
  - Trigger simulation, 4%
  - B_c^+ lifetime, 3%
  - Background shape, 2.2%
- Preliminary result

$$\frac{BR(B_c^+ \to J/\psi \pi^+ \pi^- \pi^+)}{BR(B_c^+ \to J/\psi \pi^+)} = 3.0 \pm 0.6|_{\mathrm{stat.}} \pm 0.4|_{\mathrm{sys.}}$$

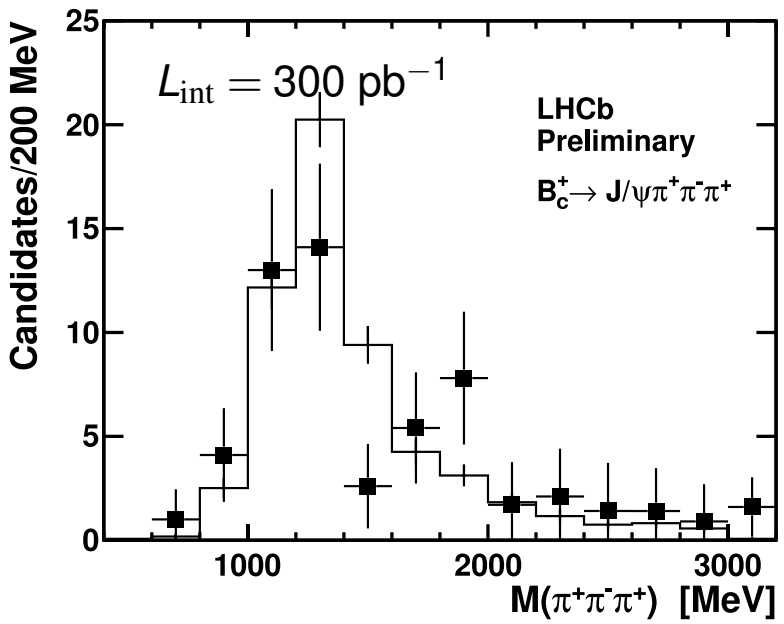
Theoretical predictions:

  - ~ 1.5 by A. Rakitin & S. Koshkarev, [PRD 81, 014005 (2010)]
  - ~ 2.3 by A. K. Likhoded & A. V. Luchinsky, [PRD 81, 014015 (2010)]

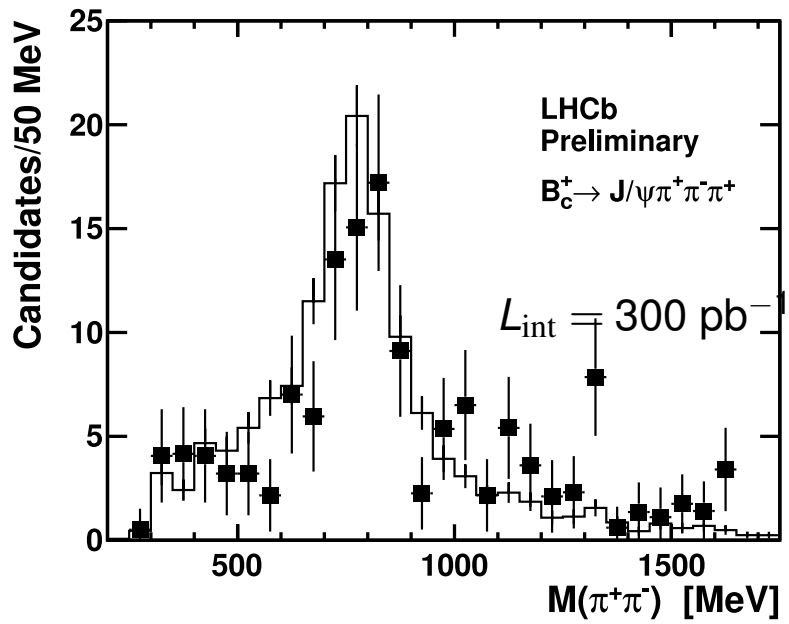
$M(\pi^+\pi^-\pi^+)$ & $M(\pi^+\pi^-)$ distributions of B_c^+ signal

- Background subtracted invariant mass distributions (points with error bars) of $M(\pi^+\pi^-\pi^+)$ & $M(\pi^+\pi^-)$ consistent with $B_c^+ \to J/\psi a_1^+(1260)$, with $a_1^+(1260) \to \rho^0\pi^+$ in MC (histogram)

$M(\pi^+\pi^-\pi^+)$

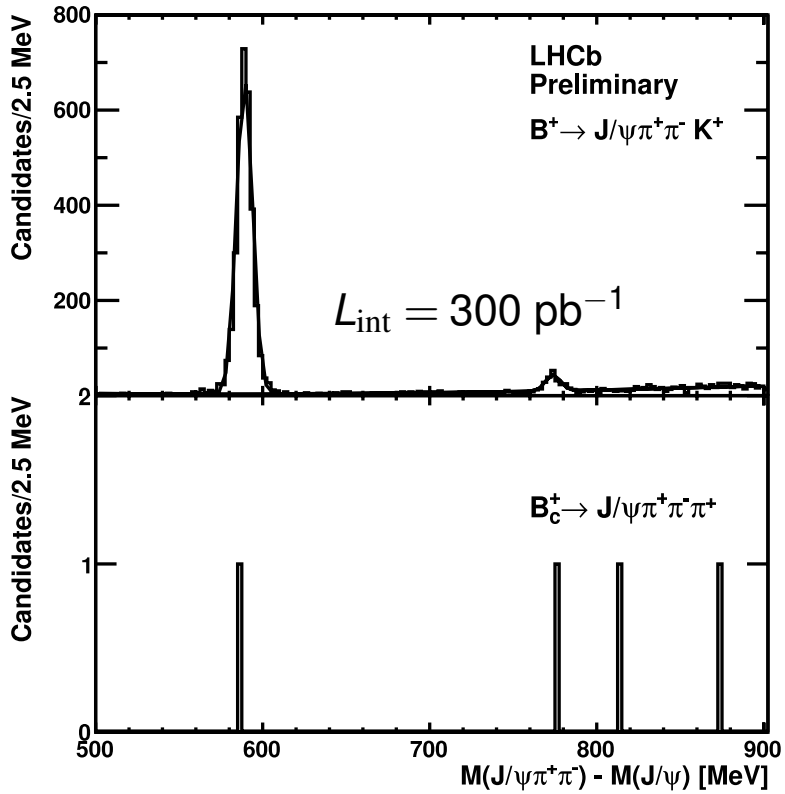


$M(\pi^+\pi^-)$



$M(J/\psi\pi^+\pi^-) - M(J/\psi)$ distributions

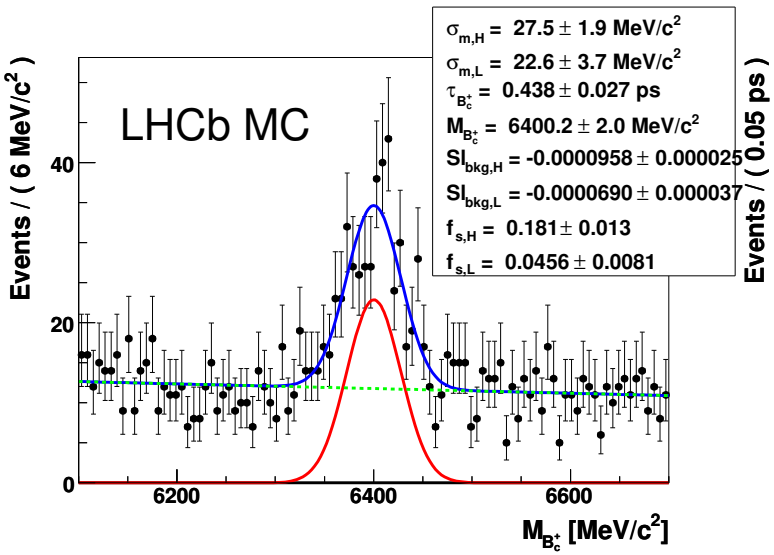
- $B^+ \to J/\psi\pi^+\pi^- K^+$
  - 1401 ± 38, $B^+ \to \psi(2S)K^+$
  - 71 ± 12, $B^+ \to X(3872)K^+$, see M. Needham's talk [slides]
- $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$



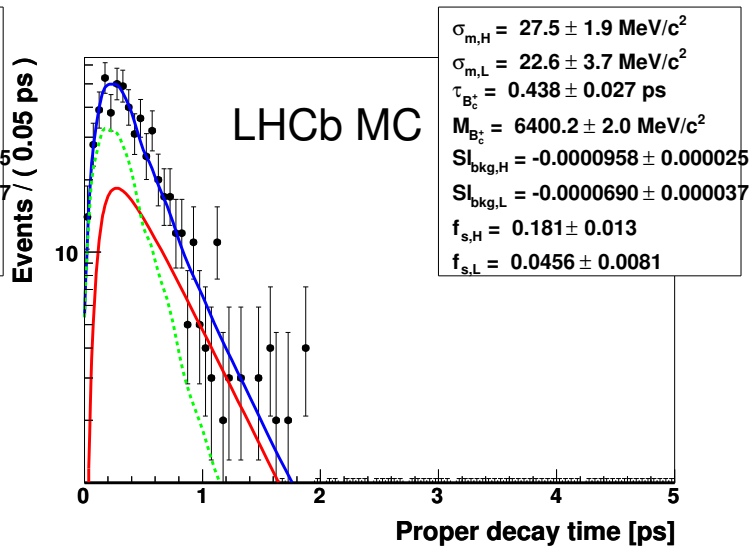
Prospects & Conclusion

Prospects: Lifetime measurement with $B_c^+ \to J/\psi\pi^+$

- Based on MC studies [CERN-LHCb-2008-077]
- Acceptance extracted from MC, two $p_T(B_c^+)$ bins (5-12, >12 GeV/c) to reduce dependence on $p_T(B_c^+)$ distribution.
- Statistical uncertainty below 30 fs achievable with 1 fb^{-1} of data
- Plots in high p_T bin:



(a) Mass



(b) t in signal region

- Will also try data based acceptance extraction [CERN-LHCb-2007-053]

Prospects Lifetime measurement with $B_c^+ \to J/\psi\mu^+X$

- $B_c^+ \to J/\psi(\mu^+\mu^-)\mu^+\nu_\mu$, compared to $B_c^+ \to J/\psi\pi^+$
  - Pro
    - ★ Larger branching ratio, $\sim$1.9%
    - ★ 3 μ in the final states, easier (relatively) to reduce background
      Lifetime unbiased selection would be possible
  - Contra
    - ★ Missing energy caused by neutrino, partially reconstructed. Not easy to use MC-free method to estimate background.
    - ★ Need MC to correct the missing energy while calculating the lifetime
- Tight J/ψ selection, and a tight p_T cut on the bachelor μ.
- Expect $\sim$ 4.7 K reconstructed $B_c^+ \to J/\psi(\mu^+\mu^-)\mu^+\nu_\mu$ from 1 fb^{-1} of data @ $\sqrt{s} = 7$ TeV, will be used to measure lifetime.

Prospects More topics

- $B_c^+ \to J/\psi K^+$, $B_c^+ \to \psi(2S)\pi^+$
- $B_c^+ \to B_s^0 \pi^+$
  - Self-tagged channel
  - With $B_s^0 \to J/\psi\phi$ or $B_s^0 \to D_s\pi$
  - Doable with 2011/2012 data
- Annihilation
  - Possible channel, e.g, $B_c^+ \to \bar{K}^{*0} K^+$, with branching ratio of $O(10^{-6})$, c.f., S. Descotes-Genon, et al., [PRD 80, 114031 (2009)]
- Excited states
  - Possible to see $B_c(2S)$ states with 2011/2012 data.
  - $B_c^{*+} \to B_c^+ \gamma$, very soft γ, difficult for LHCb
  - P-wave states, low cross section, small mass differences among four states

Conclusion

- Using $B_c^+ \to J/\psi\pi^+$, B_c^+ mass and cross section measured with 2010 data collected by LHCb
- First observation of $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$, 6.8σ
- Prospects with 2011 data (~ 1 fb^{-1})
  - Expect ~ 600 $B_c^+ \to J/\psi\pi^+$ signals, B_c^+ mass, production rate measurements will be updated, lifetime will be measured.
  - Expect ~ 200 $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$ signals, may combine with $B_c^+ \to J/\psi\pi^+$ for a more precise measurements of the B_c^+ mass, lifetime, production rate.
  - Yield of $B_c^+ \to J/\psi\mu^\pm X$ one order of magnitude higher, will be used for lifetime measurement
  - Many more channels
  - Excited states
- Many things we can do about B_c, your suggestions on the most important points are always welcome.