$B^0 \to K^{*0} e^+ e^-$ and B_c physics at LHCb

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1. Introduction

2. $B^0 \to K^{*0} e^+ e^-$, new

3. B_c physics
   - Measurement of B_c^+ production
   - Measurement of B_c^+ mass
   - First observation of $B_c^+ \to J/\psi \pi^+ \pi^- \pi^+$
   - First observation of $B_c^+ \to \psi(2S) \pi^+$
   - Prospects

Physics topics at LHCb indirect search for new physics

- Measure FCNC transitions, where New Physics is more likely to emerge, and compare to predictions
  - E.g., OPE expansion for $b \to s$ transitions

$$\mathcal{H}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \frac{e^2}{16\pi^2} \sum_{i=1...10,S,P} (C_i O_i + C_i' O_i') + \text{h.c.}$$

  - New Physics may
    - ★ modify short-distance Wilson coefficients $C^{(\prime)}$
    - ★ add new operators $\sum_j C_j^{\rm NP} O_j^{\rm NP}$

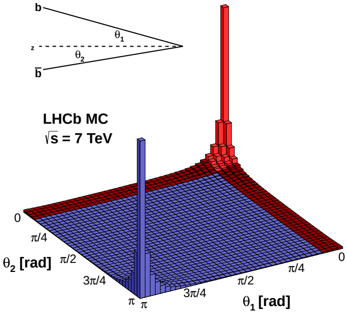
    and change the decay rates, angular distributions, etc
- Precision measurements of elements of the CKM matrix
  - Determine all CKM angles and sides in many different ways, any inconsistency will be a sign of New Physics

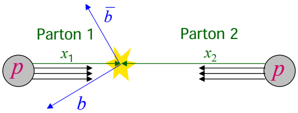
Physics topics at LHCb as general purpose forward detector

- Production
  - Quarkonium, beauty and charm hadrons production, to understand their production mechanism
  - Production cross-section at new energies also required to guide relevant studies
- Spectroscopy
  - Many particles predicted by the SM still remain to be discovered
  - Exotic states, e.g., X(3872), Z(4430), where to fit?
- Decay
  - Precision measurements of decay rates, angular distributions, etc
  - New decay modes of beauty and charm hadrons
- ...
- These measurements are important as well
  - Deepen our understanding of the SM
  - Something new may appear unexpectedly

b and c production at LHC

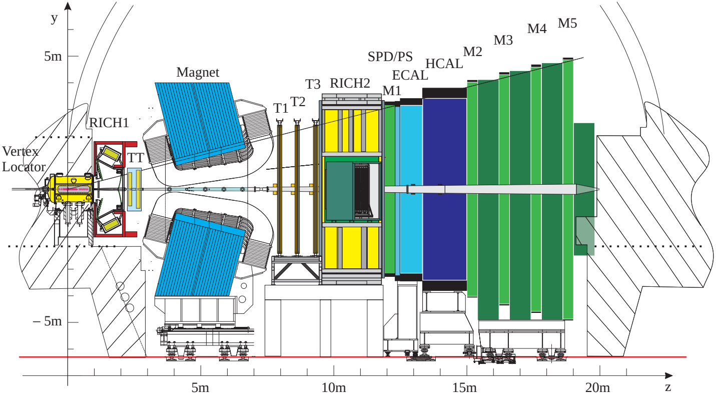
- Large production cross-sections @ $\sqrt{s} = 7$ TeV
  $\sigma_{pp}^{\rm inel}$ ~ 60 mb [JINST 7 (2012) P01010]
  $\sigma(pp \to c\bar{c}X)$ ~ 6 mb [LHCb-CONF-2010-013]
  $\sigma(pp \to b\bar{b}X)$ ~ 0.3 mb [PLB 694 (2010) 209], c.f. $\sigma(e^+e^- \to b\bar{b}) \sim 1$ nb @ $\Upsilon(4S)$
- In high energy collisions, $b\bar{b}/c\bar{c}$ pairs are produced predominantly in forward or backward directions





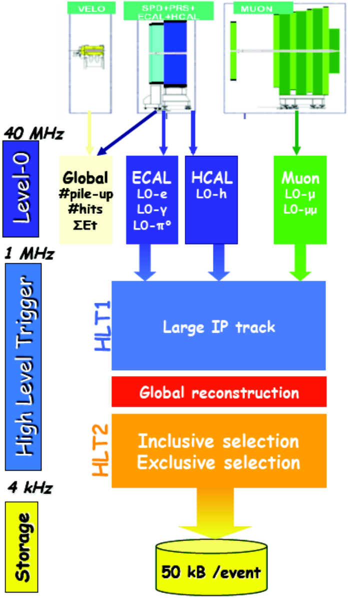
LHCb detector

- Forward spectrometer, $2<\eta<5$



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

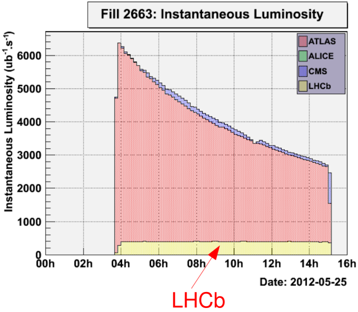
LHCb trigger system



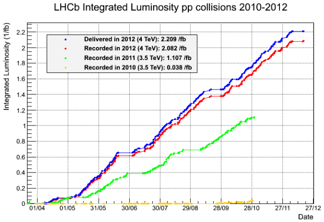
- Level-0, Hardware
  - Fully synchronous at 40 MHz
  - Selection of high p_{T} particles
    - $p_{\mathrm{T}}(\mu) >\sim 1.5$ GeV/c, $p_{\mathrm{T}}(\mu_1) \times p_{\mathrm{T}}(\mu_2) >\sim (1.5\,\mathrm{GeV}/c)^2$
    - $E_{\mathrm{T}}(h, e, \gamma) > 2.5 - 4$ GeV
- High Level Trigger (HLT), software
  - Runs ∼30 k processes
  - Stage 1, add tracking info, impact parameter cuts
  - Stage 2, full reconstruction + selections
- Global event cuts (GEC) applied on the hit multiplicity of sub-detectors to remove events with high occupancy.

LHCb data taking

- Luminosity levelling
  - $\mathcal{L} = 4 \times 10^{32}$ cm^{-2}s^{-1} (2$\times$design)
  - Continuously adjust beam overlaps in collision region, luminosity kept flat at optimal level



- Integrated luminosity (recorded)
  - 2012: 2 fb^{-1} @ $\sqrt{s} = 8$ TeV
  - 2011: 1 fb^{-1} @ $\sqrt{s} = 7$ TeV
  - 2010: 37 pb^{-1} @ $\sqrt{s} = 7$ TeV

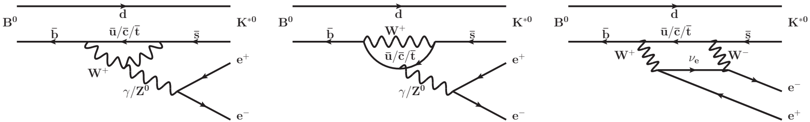


Measurement of $\mathcal{B}(B^0 \to K^{*0} e^+ e^-)$ at low q^2

[LHCb-Paper-2013-005]

$B^0 \to K^{*0} e^+ e^-$, motivation

- FCNC process, sensitive to new physics beyond the SM



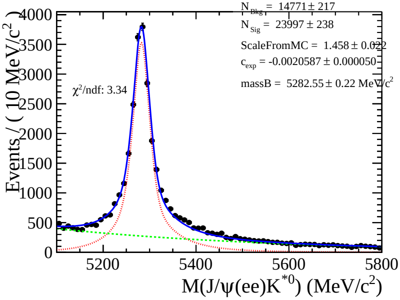
- At low $q^2 = M^2(e^+e^-)$, dilepton more likely to come from virtual photon
- In the SM, photon predominantly left-handed, right-handed component is at the 5% level [Y. Grossman, D. Pirjol, JHEP 06 (2000) 029].
- $B^0 \to K^{*0} e^+ e^-$, compared to $B^0 \to K^{*0} \mu^+ \mu^-$
  - electron mass negligible, formalism simpler, and also have access to lower q^2 $\Rightarrow$ more sensitivity
  - muon, experimentally cleaner, more easy to trigger and select $\Rightarrow$ more statistics

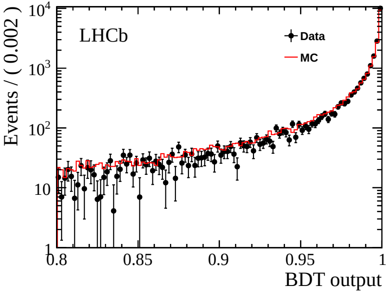
Measurement of $\mathcal{B}(B^0 \to K^{*0} e^+ e^-)$ at low q^2

- First step towards measuring photon polarization
- Choice of the q^2 region, $M(e^+e^-)$ range 30 - 1000 MeV/c^2
  - 30 MeV/c^2, the ϕ resolution degrades due to multiple scattering effects, and the contamination from $B^0 \to K^{*0}\gamma$, with γ converted to e^+e^- increase significantly as $q^2 \to 0$.
  - 1 GeV/c^2, loss sensitivity to photon polarization, also want to stay far away from the J/ψ radiative tail
- Take $B^0 \to K^{*0} J/\psi(e^+e^-)$ as normalization channel, most of potentially large systematic uncertainties cancel
- Expected $\mathcal{B}$
  - Following [Y. Grossman, D. Pirjol, JHEP 06 (2000) 029], roughly,
    $\mathcal{B}(B^0 \to K^{*0} e^+ e^-)^{30-1000\ \mathrm{MeV/c^2}}$
    $\sim \mathcal{B}(B^0 \to K^{*0}\gamma) \times \left(\frac{\alpha}{3\pi} log \frac{1000^2}{30^2}\right) = 2.4 \times 10^{-7}$
  - A recent calculation [S. Jager, J. Martin Camalich, arXiv:1212.2263] gives,
    $\mathcal{B}(B^0 \to K^{*0} e^+ e^-)^{30-1000\ \mathrm{MeV/c^2}} = 2.43^{+0.66}_{-0.47} \times 10^{-7}$

Event selection

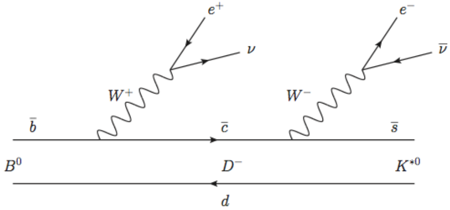
- Loose pre-selection + BDT based selection
- BDT trained with simulated $B^0 \to K^{*0} e^+ e^-$ sample for signal, and upper mass sideband in data for background
- BDT responses in data and simulation for background subtracted $B^0 \to K^{*0} J/\psi(e^+e^-)$ candidates (using J/ψ mass constraint) agrees well



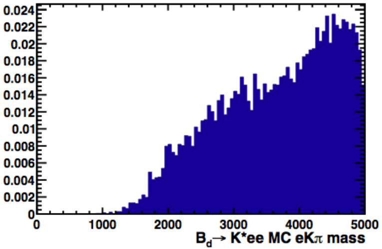


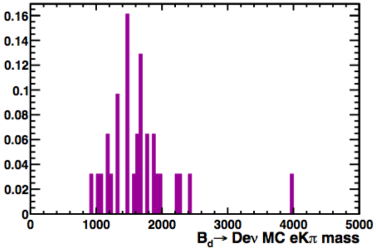
Specific backgrounds

- $B^0 \to D^- e^+ \nu$ ($\mathcal{B}: 2.2\%$), with $D^- \to K^{*0} e^- \bar{\nu}$ ($\mathcal{B}: 5.5\%$)



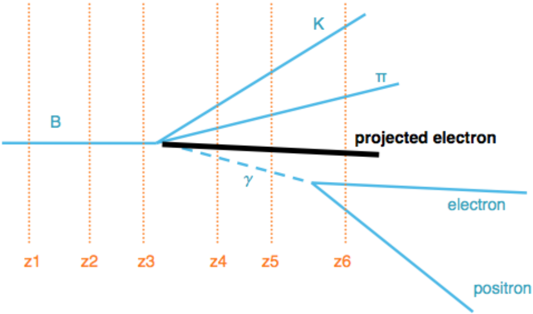
- Largely reduced by requiring $M(K^{*0}e^-) > 1.9\ \mathrm{GeV}/c^2$





Specific backgrounds (cont.)

- $B^0 \to K^{0*}\gamma$ ($\mathcal{B}: 4.3 \times 10^{-5}$), peaks under the signal peak and populates the low $M(e^+e^-)$ region
- $M(e^+e^-) > 30$ MeV/c^2 (and previous selections) kill a large fraction but more veto cuts still needed
  - Good vertex, $\sigma_{vtx}(e^+e^-) < 30$ mm
  - $|z_{\text{FirstExpected}} - z_{\text{FirstMeasurement}}| < 30$ mm

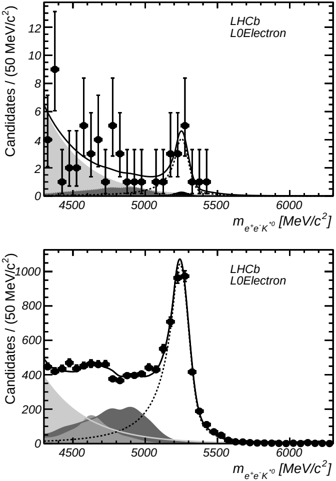


Fitting procedure

- Signal, sum of two Crystal Ball functions
  - Tail and resolution parameters from MC. The MC events reweighted to match relevant distributions in data
  - B mass and a scale factor accounting for different resolution in MC and data, float for $B^0 \to K^{*0} J/\psi(e^+e^-)$, then fixed for $B^0 \to K^{*0} e^+e^-$
- Partially reconstructed backgrounds, shape from MC
  - Hadronic background, i.e., from higher K^* resonances, ratio to the number of signal float for $B^0 \to K^{*0} J/\psi(e^+e^-)$, then fixed for $B^0 \to K^{*0} e^+e^-$
  - J/ψ background, i.e., from higher charmonium states, only for $B^0 \to K^{*0} J/\psi(e^+e^-)$, ratio float
- Combinatorial background, exponential function
- The way how events are triggered at L0 affects signal resolution, background rates. Events split into two categories:
  - L0TIS, events Triggered Independently of the Signal (TIS)
  - L0Electron, one of the electrons fired the L0 electron line (and not L0TIS)

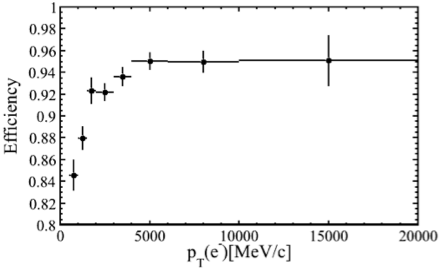
Signal yields

- $B^0 \to K^{*0} e^+ e^-$ (4.8σ)
  L0Electron: $15.0^{+5.1}_{-4.5}$ (4.1σ), L0TIS: $14.1^{+7.0}_{-6.3}$ (2.4σ)
- $B^0 \to K^{*0} J/\psi$, L0Electron: 5082 ± 104, L0TIS: 4305 ± 101



Efficiencies

- PID efficiencies from calibration samples, e.g., $J/\psi \to e^+e^-$ using tag-and-probe method



- L0 efficiency from $B^0 \to K^{*0}J/\psi(e^+e^-)$
- The rest from simulated events

Systematic uncertainty

- Systematic uncertainties on $\mathcal{B}(B^0 \to K^{*0} e^+ e^-)$ (in 10^{-7})

Source	L0Electron category	L0TIS category
Simulation sample statistics	0.06	0.05
Trigger efficiency	0.07	-
PID efficiency	0.08	0.10
Fit procedure	$^{+0.09}_{-0.22}$	$^{+0.07}_{-0.23}$
$B^0 \to K^{*0}\gamma$ contamination	0.08	0.08
Total LHCb	$^{+0.17}_{-0.26}$	$^{+0.16}_{-0.27}$
$\mathcal{B}(B^0 \to J/\psi K^{*0})$ and $\mathcal{B}(J/\psi \to e^+ e^-)$	0.21	0.17

Results and prospects

- Results of each trigger category:

$$\mathcal{B}(B^0 \to K^{*0} e^+ e^-)^{30-1000\ \mathrm{MeV}/c^2}_{\mathrm{L0Electron}} = (3.3^{+1.1}_{-1.0}\ {}^{+0.2}_{-0.3} \pm 0.2(\mathcal{B})) \times 10^{-7}$$

$$\mathcal{B}(B^0 \to K^{*0} e^+ e^-)^{30-1000\ \mathrm{MeV}/c^2}_{\mathrm{L0TIS}} = (2.8^{+1.4}_{-1.2}\ {}^{+0.2}_{-0.3} \pm 0.2(\mathcal{B})) \times 10^{-7}$$

- Combined one

$$\mathcal{B}(B^0 \to K^{*0} e^+ e^-)^{30-1000\ \mathrm{MeV}/c^2} = (3.1^{+0.9}_{-0.8}\ {}^{+0.2}_{-0.3} \pm 0.2(\mathcal{B})) \times 10^{-7}$$

consistent with theoretical prediction $(2.43^{+0.66}_{-0.47}) \times 10^{-7}$

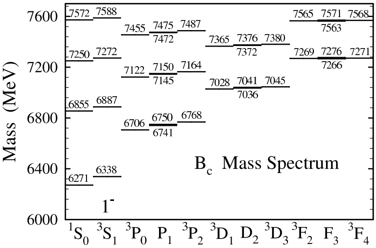
[S. Jager, J. Martin Camalich, arXiv:1212.2263]

- Sensitivity to photon polarization
  - With 2011+2012 data, about 100 signal events expected, statistical uncertainty on $\frac{A_R}{A_L}$ would be ~ 0.15, according to
    [J. Lefrancois, M-H. Schune, LHCb-PUB-2009-008]

B_c physics

B_c spectrum

- B_c: Mesons formed by two different heavy flavour 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(6)(4) MeV/c^2
    TWQCD, [arXiv:0704.3495]
  - PDG'12: 6277 ± 6 MeV/c^2



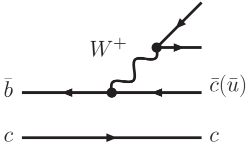
S.Godfrey, [PRD 70 (2004) 054017]

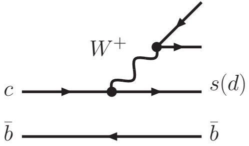
*Charge conjugates implied in this talk

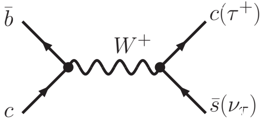
B_c decays

- B_c mesons' decays
  - Excited states (below BD threshold), decay through Strong or EM interactions into B_c^+
  - Ground state B_c^+: decay only weakly
- B_c^+ decay modes
  - $\bar{b} \to \bar{c}W^+$ ($\sim$20%), e.g., $J/\psi(3)\pi$, $J/\psi D_s^+$ $J/\psi \ell^+ \nu_\ell$
  - $c \to sW^+$ ($\sim$70%), e.g., $B_s^0 \pi^+$, $B_s^0 \ell^+ \nu_\ell$
  - $c\bar{b} \to W^+$ ($\sim$10%), 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

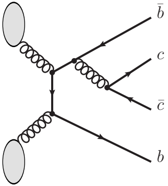
    V. V. Kiselev, *et al.*, [NPB 585 (2000) 353]
  - PDG'12: 0.453 ± 0.041 ps







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 (in nb) C.-H.Chang, *et al.*, [PRD 71 (2005) 074012]

-	$\vert({}^1S_0)_\mathbf{1}\rangle$	$\vert({}^3S_1)_\mathbf{1}\rangle$	$\vert({}^1S_0)_\mathbf{8}g\rangle$	$\vert({}^3S_1)_\mathbf{8}g\rangle$	$\vert({}^1P_1)_\mathbf{1}\rangle$	$\vert({}^3P_0)_\mathbf{1}\rangle$	$\vert({}^3P_1)_\mathbf{1}\rangle$	$\vert({}^3P_2)_\mathbf{1}\rangle$
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

  - ★ $\sigma({}^3S_1)/\sigma({}^1S_0) \sim 2.5$
  - ★ Colour 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 $|R_{2S}(0)/R_{1S}(0)|^2 \approx 0.6$
  - Including contributions of these states, $\sigma(B_c^+) \sim 0.9$ µb for $\sqrt{s} = 14$ TeV; or ~ 0.4 µb for $\sqrt{s} = 7$ TeV
    - ★ $\sim$ 10% from 1st P-wave states
    - ★ $\sim$ 1/3 from $2S$ states

$^\dagger \sqrt{s} = 14$ TeV

Experimental status, mass and lifetime

- Mass and lifetime

Collab.	$\mathcal{L}$ [fb^{-1}]	Mode	Signal yields	Mass [MeV/c^2]	Lifetime [ps]
CDF	0.11	$J/\psi\ell^+\nu$	$20.4^{+6.2}_{-5.5}$	$6400 \pm 390 \pm 130$	$0.46^{+0.18}_{-0.16} \pm 0.03$
D0	0.21	$J/\psi\mu^+X$	$95 \pm 12 \pm 11$	$5950^{+140}_{-130} \pm 340$	$0.45^{+0.12}_{-0.10} \pm 0.12$
CDF	0.36	$J/\psi\pi^+$	14.6 ± 4.6	$6285.7 \pm 5.3 \pm 1.2$	—
CDF	0.36	$J/\psi e^+\nu_e$	238	—	$0.463^{+0.073}_{-0.065} \pm 0.036$
CDF	2.4	$J/\psi\pi^+$	108 ± 15	$6275.6 \pm 2.9 \pm 2.5$	—
D0	1.3	$J/\psi\pi^+$	54 ± 12	$6300 \pm 14 \pm 5$	—
D0	1.3	$J/\psi\mu^+X$	881 ± 80	—	$0.448^{+0.038}_{-0.036} \pm 0.032$
CDF	1.0	$J/\psi\ell^+\nu$	—	—	$0.475^{+0.053}_{-0.049} \pm 0.018$
CDF	6.7	$J/\psi\pi^+$	308 ± 39	$(6274.6 \pm 2.9)^{\ddagger}$	$0.452 \pm 0.048 \pm 0.027$
LHCb	0.37	$J/\psi\pi^+$	179 ± 17	$6273.7 \pm 1.3 \pm 1.6$	—

‡fit value

Experimental status, production

- Production

Collab.	$\mathcal{L}$ [fb^{-1}]	Signal yields	Result
CDF	0.11	$20.4^{+6.2}_{-5.5}$	$\frac{\sigma(B_c^+)\times\mathcal{B}(B_c^+\to J/\psi\ell^+\nu)}{\sigma(B^+)\times\mathcal{B}(B^+\to J/\psi K^+)} = 0.132^{+0.041}_{-0.037}\,(\text{stat.}) \pm 0.031\,(\text{syst.})\,^{+0.032}_{-0.020}\,(\text{lifetime})$ for $p_{\text{T}}(B) > 6$ GeV/c and $\lvert y\rvert < 1$
CDF†	1.0	—	$\frac{\sigma(B_c^+)\times\mathcal{B}(B_c^+\to J/\psi\mu^+\nu)}{\sigma(B^+)\times\mathcal{B}(B^+\to J/\psi K^+)} = 0.227 \pm 0.033(\text{stat.})^{+0.024}_{-0.017}(\text{syst.}) \pm 0.014(p_{\text{T}}\text{ spect.})$ for $p_{\text{T}}(B) > 6$ GeV/c and $\lvert y\rvert < 1$
LHCb	0.37	162 ± 18	$\frac{\sigma(B_c^+)\times\mathcal{B}(B_c^+\to J/\psi\pi^+)}{\sigma(B^+)\times\mathcal{B}(B^+\to J/\psi K^+)} = (0.68 \pm 0.10\,(\text{stat.}) \pm 0.03\,(\text{syst.}) \pm 0.05(\text{lifetime}))\,\%$ for $p_{\text{T}}(B) > 4$ GeV/c and $2.5 < \eta(B) < 4.5$

†: preliminary

Experimental status, decay

- Decay

Collab.	$\mathcal{L}$ [fb^{-1}]	Mode	Signal yields	Result
LHCb	0.8	$J/\psi\pi^+\pi^-\pi^+$	135 ± 14	$\frac{\mathcal{B}(B_c^+ \to J/\psi\pi^+\pi^-\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} = 2.41 \pm 0.30\,(\text{stat.}) \pm 0.33\,(\text{syst.})$
LHCb	1.0	$\psi(2S)\pi^+$	20 ± 5	$\frac{\mathcal{B}(B_c^+ \to \psi(2S)\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} = 0.250 \pm 0.068\,(\text{stat}) \pm 0.014\,(\text{syst}) \pm 0.006\,(\mathcal{B})$
LHCb	1.0			$f_c/f_u \cdot \mathcal{B}(B_c \to X)$ @ 90% CL
		$D_s^+\phi$	0	$< 0.8 \times 10^{-6}$
		D^+K^{*0}	1	$< 0.5 \times 10^{-6}$
		$D^+\overline{K}^{*0}$	0	$< 0.4 \times 10^{-6}$
		$D_s^+K^{*0}$	0	$< 0.7 \times 10^{-6}$
		$D_s^+\overline{K}^{*0}$	1	$< 1.1 \times 10^{-6}$

Measurement of B_c^+ production

[PRL 109 (2012) 232001]

Measurement of B_c^+ production

- Based on 0.37 fb^{-1} of data taken in 2011, we measured

$$R_{c/u} = \frac{\sigma(B_c^+) \times \mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+) \times \mathcal{B}(B^+ \to J/\psi K^+)}$$
$$= \frac{N\left(B_c^+ \to J/\psi\pi^+\right)}{\varepsilon_{\rm tot}^c} \times \frac{\varepsilon_{\rm tot}^u}{N(B^+ \to J/\psi K^+)}$$
$$= \frac{N\left(B_c^+ \to J/\psi\pi^+\right)}{N(B^+ \to J/\psi K^+)} \times \varepsilon_{\rm tot}^{\rm rel},$$

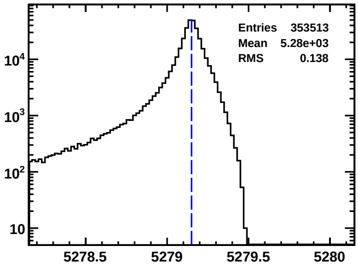
  for $p_{\rm T}(B) > 4$ GeV/c and $2.5 < \eta(B) < 4.5$
- Cut based selection, as similar as possible for B_c^+ and B^+

Signal line shape

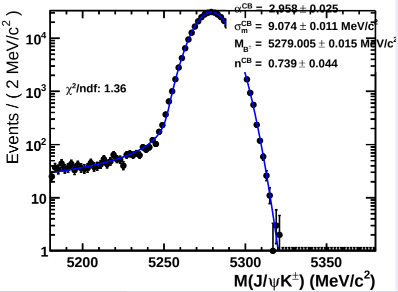
- Studied using $B^+ \to J/\psi K^+$ generator level events
- While ignoring the J/ψ FSR, i.e., take true J/ψ momentum, signal well described by Crystal ball function:

$$CB(m|M,\sigma,\alpha,n) = \begin{cases} e^{-\frac{(m-M)^2}{2\sigma^2}}, & \text{if } \alpha\frac{m-M}{\sigma} \geq -\alpha^2 \\ \frac{(\frac{n}{|\alpha|})^n e^{-\alpha^2/2}}{(\frac{n}{|\alpha|}-|\alpha|-\frac{\alpha}{|\alpha|}\cdot\frac{m-M}{\sigma})^n} & \text{for the other cases} \end{cases}$$

True $J/\psi K^+$ mass



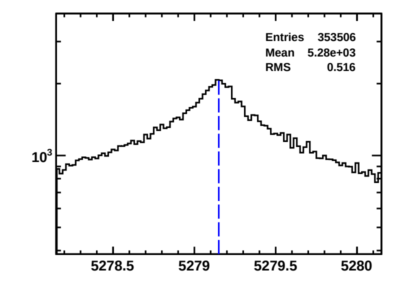
Smeared



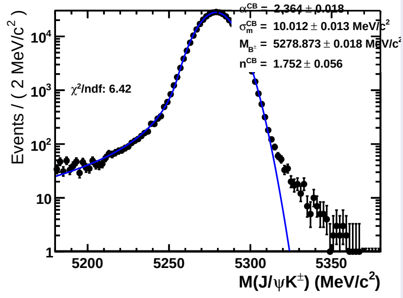
Signal line shape (cont.)

- J/ψ FSR and mass constraint vertex fit cause tail on the right side

True $\mu^+\mu^-K^+$ mass



Smeared

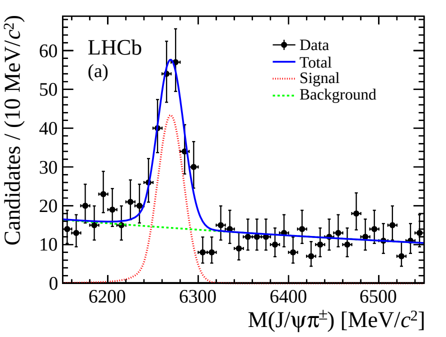


- A double-sided Crystal ball function used as signal line shape, tail parameters parametrized as function of fitted mass resolutions.

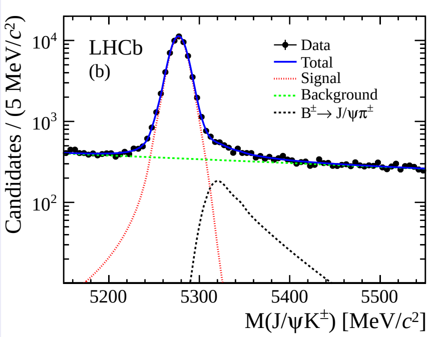
Signal yields

- B_c^+, a double-sided CB, $B_c^+ \to J/\psi K^+$ ignored
- B^+, two double-sided CB, $B^+ \to J/\psi \pi^+$ considered, and ratio to the number of signal fixed to 0.38%, as measured by LHCb [PRD 85 (2012) 091105]

B_c^+, 162 ± 18



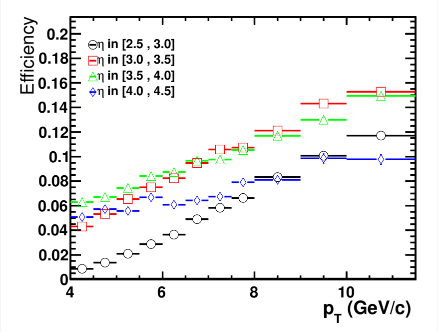
B^+, $56\,243 \pm 256$



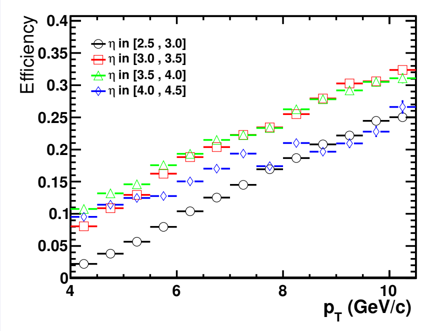
Efficiencies in bins of (p_{T}, η)

- $R_{c/u}$ would be biased if the predicted (p_{T}, η) distributions different from those in data while using the overall (relative) efficiency
- To reduce the dependence on theoretical predictions, efficiencies binned in (p_{T}, η), signal yields in each bin obtained using sPlot
- Model independent $R_{c/u} = (0.68 \pm 0.10)\%$

B_c^+



B^+



Systematic uncertainties

Quantity	Systematic uncertainty (%)
Fit model	1.0
Cabbibo suppressed background	negligible
Selection	negligible
B_c^+ lifetime	7.3
GEC	negligible
Trigger	4.4
Tracking	negligible
Nuclear interaction	2.0
Weight procedure	negligible
Total	8.8

Results

- First measurement at 7 TeV, to guide B_c studies at LHC

  $R_{c/u} = (0.68 \pm 0.10\,(\mathrm{stat.}) \pm 0.03\,(\mathrm{syst.}) \pm 0.05(\mathrm{lifetime}))\%$

  for $p_{\mathrm{T}}(B) > 4$ GeV/c and $2.5 < \eta(B) < 4.5$
- Comparison with theoretical prediction, taking
  - $\sigma(B_c^+) = 0.4\ \mu\mathrm{b}$
  - $\mathcal{B}(B_c^+ \to J/\psi\pi^+) = 0.29\%$, C.-F. Qiao *et al.*, [arXiv:1209.5859]
  - $\sigma(B^+, p_{\mathrm{T}}(B) < 40\,\mathrm{GeV}/c, 2.0 < y < 4.5) = 41.4 \pm 1.5 \pm 3.1\ \mu\mathrm{b}$, measured by LHCb [JHEP 04 (2012) 093]
  - $\mathcal{B}(B^+ \to J/\psi K^+) = (0.1016 \pm 0.0033)\%$, PDG'12

  and the efficiencies of acceptance from Monte Carlo, we obtain

  $R_{c/u}^{\mathrm{Theo.}} = 0.56$

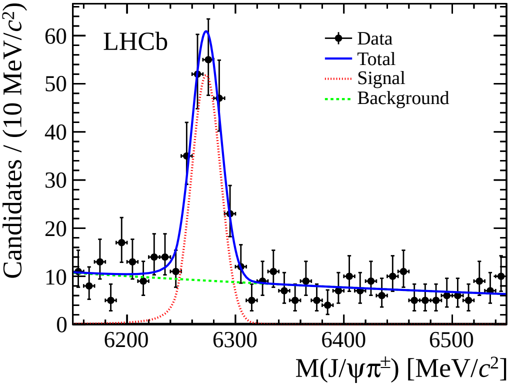
  before considering theoretical uncertainties.

Measurement of B_c^+ mass

[PRL 109 (2012) 232001]

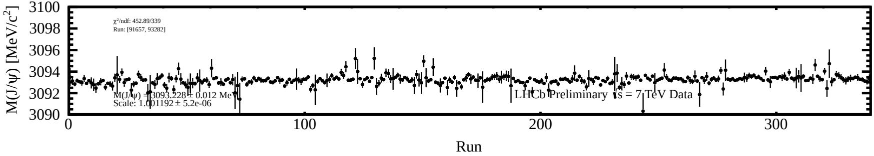
Measurement of $B_c^{\pm}$ mass

- Based on 0.37 fb^{-1} 2011 data
- Selection almost the same as that used for production measurement, except
  - Trigger and η requirements removed
  - PID cut added to reduce contamination of $B_c^+ \to J/\psi K^+$
  - $\sigma_m(B_c) < 20$ MeV/c^2



Calibration of momentum scale

- Momentum scale calibrated with J/ψ run by run, split into 5 run periods, e.g.,



- Momentum scale verified with K^0_S, Υ, difference between J/ψ and Υ, 0.06% taken as systematic uncertainty

Systematic uncertainties

- Also measured the mass difference with respect to B^+, $\Delta M = M(B_c^+) - M(B^+)$, systematic uncertainties evaluated in the same way
- Summary of systematic uncertainties (in MeV/c^2)

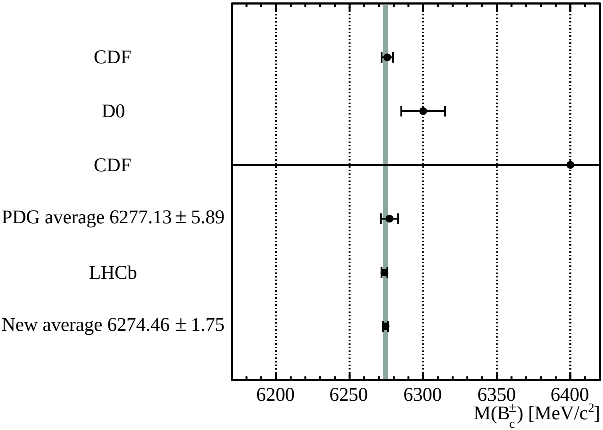
Source of uncertainty	$M(B_c^+)$	ΔM
Mass fitting:		
– Signal model	0.1	0.1
– Background model	0.3	0.2
Momentum scale:		
– Average momentum scale	1.4	0.5
– η dependence	0.3	0.1
Detector description:		
– Energy loss correction	0.1	-
Detector alignment:		
– Vertex detector (track slopes)	0.1	-
– Tracking stations	0.6	0.3
Quadratic sum	1.6	0.6

Results, world best to date

- Mass $M(B_c^+) = 6273.7 \pm 1.3\,(\text{stat.}) \pm 1.6\,(\text{syst.})\,\text{MeV}/c^2$
- Mass difference
  $\Delta M = M(B_c^+) - M(B^+) = 994.6 \pm 1.3\,(\text{stat.}) \pm 0.6\,(\text{syst.})\,\text{MeV}/c^2$.
  Taking the world average B^+ mass $(5279.25 \pm 0.17)\,\text{MeV}/c^2$, we obtain,
  $M(B_c^+) = 6273.9 \pm 1.3\,(\text{stat.}) \pm 0.6\,(\text{syst.})\,\text{MeV}/c^2$

New world average

- LHCb result in good agreement with previous measurements and theoretical prediction, 6278(6)(4) MeV/c^2 TWQCD, [arXiv:0704.3495]



First observation of $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$

[PRL 108 (2012) 251802]

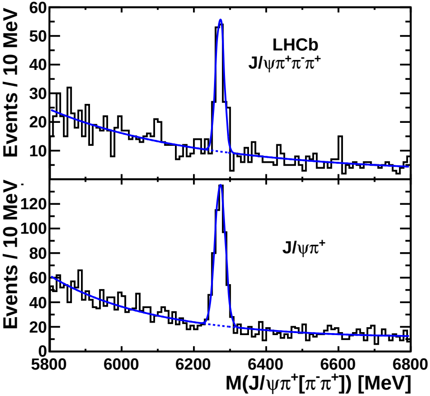
First observation of $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$

- Based on ~ 0.8 fb^{-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
- Measured

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

Signal yields

- $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$, 135 ± 14, first observation
- $B_c^+ \to J/\psi\pi^+$, 414 ± 25



Ratio of branching fractions

- Total efficiencies computed from MC.
- Systematic uncertainties
  - Signal yields
    - ★ Signal and background line shapes, 3%
  - Efficiencies
    - ★ Decay model, 9%
    - ★ Tracking efficiency, 5%
    - ★ B_c^+ lifetime, 4%
    - ★ Trigger efficiency, 4%
- Results

$$\frac{\mathcal{B}(B_c^+ \to J/\psi\pi^+\pi^-\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} = 2.41 \pm 0.30(\text{stat.}) \pm 0.33(\text{syst.})$$

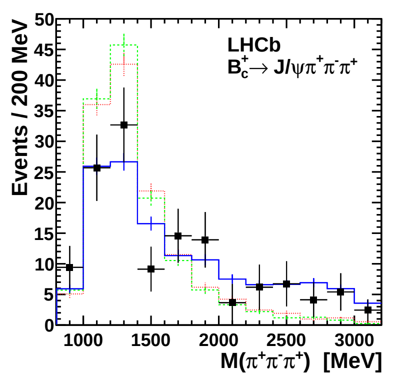
Theoretical predictions:

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

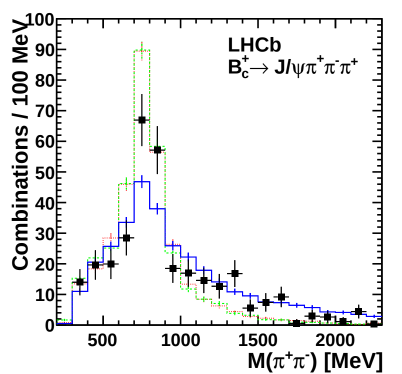
$M(\pi^+\pi^-\pi^+)$ & $M(\pi^+\pi^-)$ distributions of B_c^+ signal

- 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 virtual $a_1^+(1260) \to \rho^0\pi^+$ decay model [PRD 81 (2010) 014015] [arXiv:1104.0808] used in MC (blue line)

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



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



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

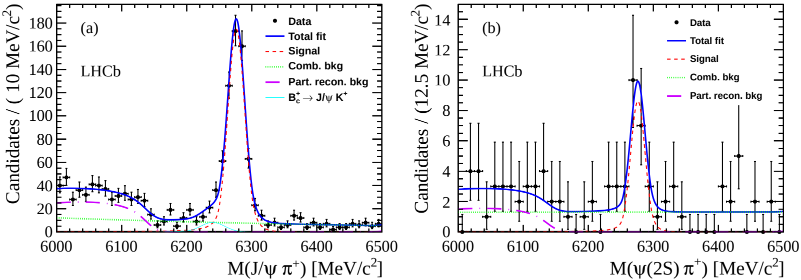
First observation of $B_c^+ \to \psi(2S)\pi^+$

- Based on $\sim 1.0\ \text{fb}^{-1}$ data collected in 2011
- Cut based pre-selection + BDT
- Use $B_c^+ \to J/\psi\pi^+$ as control channel
- Measured

$$\frac{\mathcal{B}(B_c^+ \to \psi(2S)\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} = \frac{N(B_c^+ \to \psi(2S)\pi^+)}{N(B_c^+ \to J/\psi\pi^+)} \times \varepsilon_{\text{tot}}^{\text{rel}}$$

Results

- Signal yield, $B^+ \to \psi(2S)\pi^+$, 20 ± 5 (5.2σ), first observation



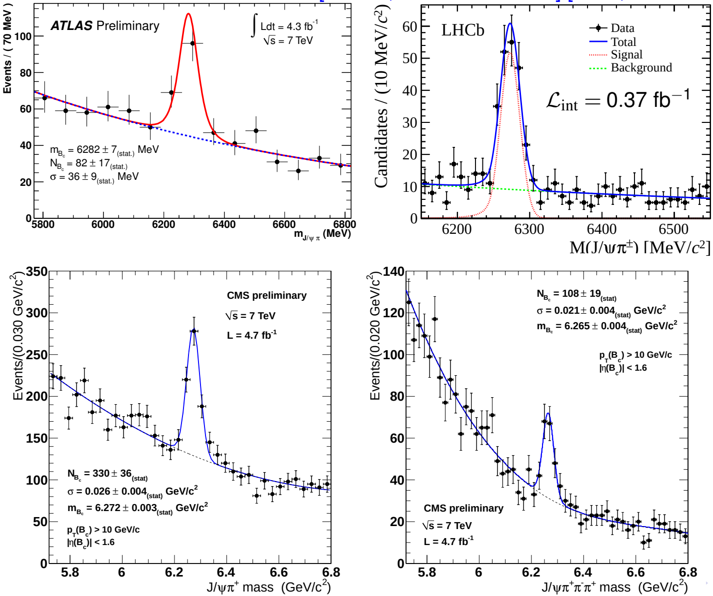
- Results

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

consistent with theoretical prediction, in a range of 0.13-0.42.

B_c^+ signals from other experiments at LHC

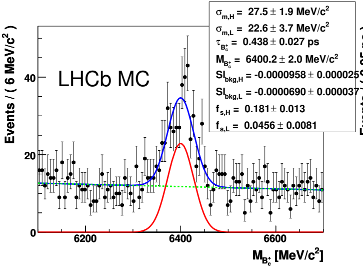
[ATLAS, CONF-2012-028] [CMS, PAS-BPH-11-003]



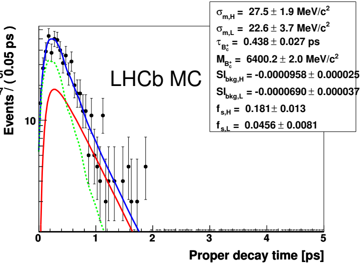
Prospects

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

- Based on MC studies [CERN-LHCb-2008-077]
- Acceptance determined from MC, two $p_{\mathrm{T}}(B_c^+)$ bins (5-12, $>$ 12 GeV/c) to reduce dependence on $p_{\mathrm{T}}(B_c^+)$ 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-driven method to determine acceptance [CERN-LHCb-2007-053]

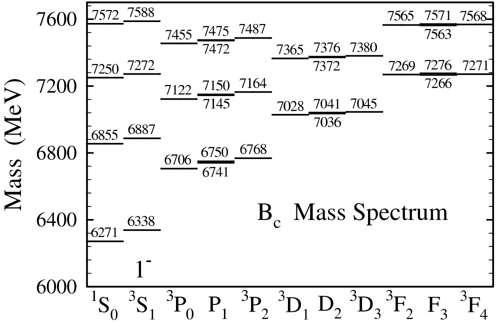
Prospects Lifetime measurement with $B_c^+ \to J/\psi\mu^+X$

- $B_c^+ \to J/\psi(\mu^+\mu^-)\mu^+\nu_\mu$, 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 $\sim$ 5 k reconstructed $B_c^+ \to J/\psi(\mu^+\mu^-)\mu^+\nu_\mu$ from 1 fb^{-1} of data @ $\sqrt{s} = 7$ TeV, analysis ongoing to measure B_c^+ lifetime

- B_c^+ production
  - Measuring differential cross-section down to zero $p_{\mathrm{T}}(B)$, with 2012 data ($\sqrt{s} = 8$ TeV)
- B_c^+ mass,
  - Updating with all 2011+2012 data
  - Statistical uncertainty below 0.3 MeV/c^2, better understanding of momentum scale to control systematic uncertainty
- In the pipeline, $B_c^+ \to J/\psi K^+$, $B_c^+ \to J/\psi D_s^+$
- $B_c^+ \to B_s^0 \pi^+$
  - Self-tagged channel
  - With $B_s^0 \to J/\psi \phi$ or $B_s^0 \to D_s \pi$
  - Analysis with 2011+2012 data ongoing
- Annihilation
  - Possible channel, e.g, $B_c^+ \to \bar{K}^{*0} K^+$, $\mathcal{B} \sim O(10^{-6})$, c.f., S. Descotes-Genon, et al., [PRD 80, 114031 (2009)]

Prospects, search for excited states

- $B_c^{*+} \to B_c^+ \gamma$, very soft photon, difficult for LHCb
- 1st P-wave states, small cross-section, mass difference among four states are small, need more data
- $2S$ states, analysis with 2011+2012 data ongoing
  - $B_c(2^1S_0) \to B_c^+ \pi^+ \pi^-$
  - $B_c(2^3S_1) \to B_c^{*+}(B_c^+ \gamma)\pi^+\pi^-$, when photon is missing, invariant mass peak shifted down by $M(B_c^{*+}) - M(B_c^+)$ but not washed out



Summary

- $B^0 \to K^{*0} e^+ e^-$
  - LHCb performed the 1st measurement of $\mathcal{B}(B^0 \to K^{*0} e^+ e^-)$ at low $M(e^+ e^-)$
  - Angular analysis with all 2011+2012 to measure photon polarization is ongoing
- B_c physics
  - LHCb performed the world-best measurements of B_c^+ production and mass, and observed $B_c^+ \to J/\psi \pi^+ \pi^- \pi^+, \psi(2S)\pi^+$ for the first time
  - Lifetime measurements, observation of several new B_c^+ decay modes are in the pipeline
  - Production and mass measurements are being updated, search for new decay modes and excited states are ongoing