b-hadron production and spectroscopy at LHCb

Windows on the Universe - Rencontres du Vietnam

R. Märki on behalf of the LHCb collaboration

Ecole Polytechnique Fédérale de Lausanne (EPFL)

14 August 2013

Outline

In this talk I present three recent b-hadron production and spectroscopy results from LHCb

First observation of the decay $B_c^+ \to J/\psi K^+$

LHCB-PAPER-2013-021 – arXiv:1306.6723

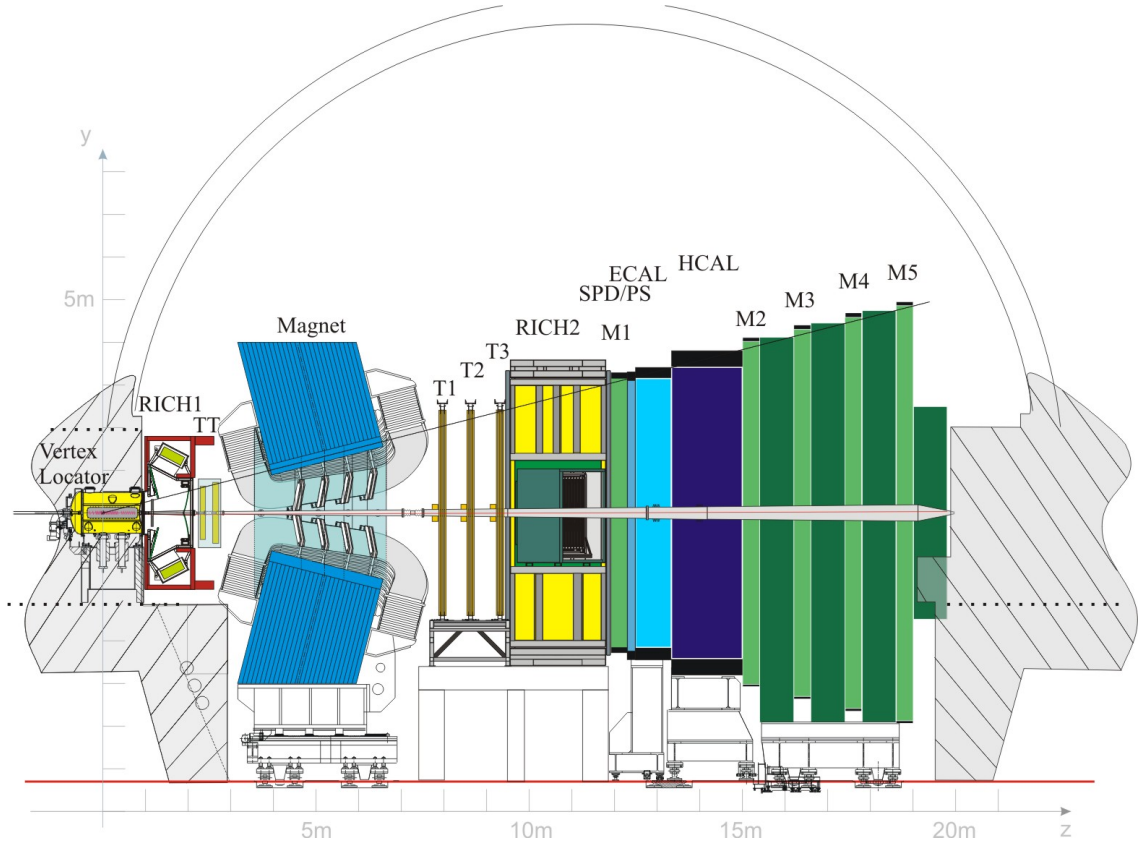
Observation of $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$

LHCB-PAPER-2013-010 – arXiv:1304.4530

Observation of the decay $B_c^+ \to B_s^0 \pi^+$

LHCb-PAPER-2013-044 – new at EPS !

The LHCb experiment at CERN

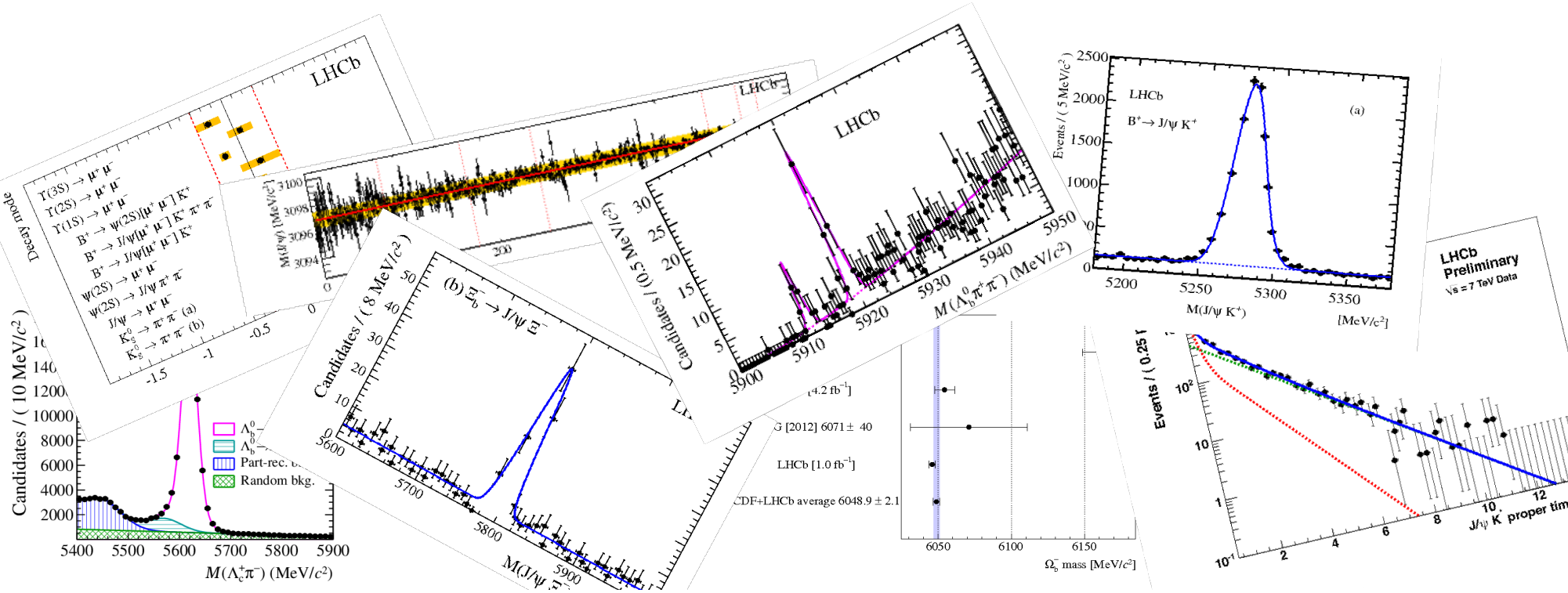


- LHCb - single-arm forward spectrometer at the LHC
- Recording pp collisions with $\sqrt{s} = 7$ TeV (in 2011) and 8 TeV (in 2012)
- Optimized for measurements in heavy-flavour physics
- Comprizes tracking detectors, RICH detectors, calorimeters and muon chambers.
- The experiment has an angular acceptance of $2 < \eta < 5$

b-hadron production and spectroscopy at LHCb

Many b hadrons observed at LHCb

- b mesons (B^0, B^+, B_s^0, B_c^+) observed and measurement of
  - Masses
  - Lifetimes
  - Branching ratios for many modes
- b baryons (Λ_b^0, Ξ_b^-, Ω_b^-, excited Λ_b^0 states) observed
- Also observation of other states like $X(3872)$

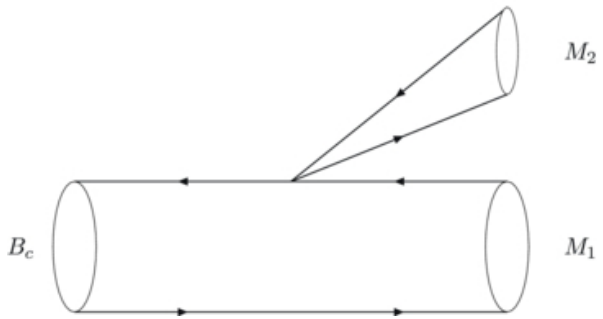


B_c^+ physics

Very recent results at LHCb in the B_c^+ sector

- The B_c^+ meson is composed of two heavy valence quarks, namely b and c
- It is the only weakly decaying doubly heavy meson
- So far only B_c^+ decays where the b quark decays into a c quark have been observed
- Decays where the c quark decays into an s quark are expected to have larger branching ratios ($V_{cs} > V_{cb}$)
- For pp collisions at a centre-of-mass energy of 7 TeV, the total B_c^+ production cross-section is predicted to be one order of magnitude higher than that at the Tevatron

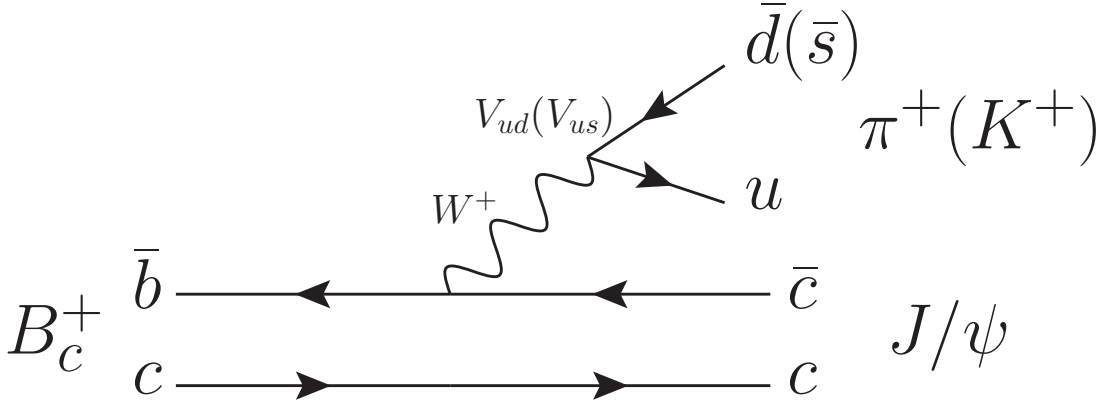
Figure 2 from Zhi-hui Wang et al
2012 J. Phys. G: Nucl. Part. Phys. 39 015009



$B_c^+ \to J/\psi K^+$ (arXiv:1306.6723)

First observation of the decay $B_c^+ \to J/\psi K^+$

- Branching ratio with respect to $B_c^+ \to J/\psi \pi^+$ is predicted (including CKM matrix elements and form factors) to lie in the range $0.054 - 0.088$



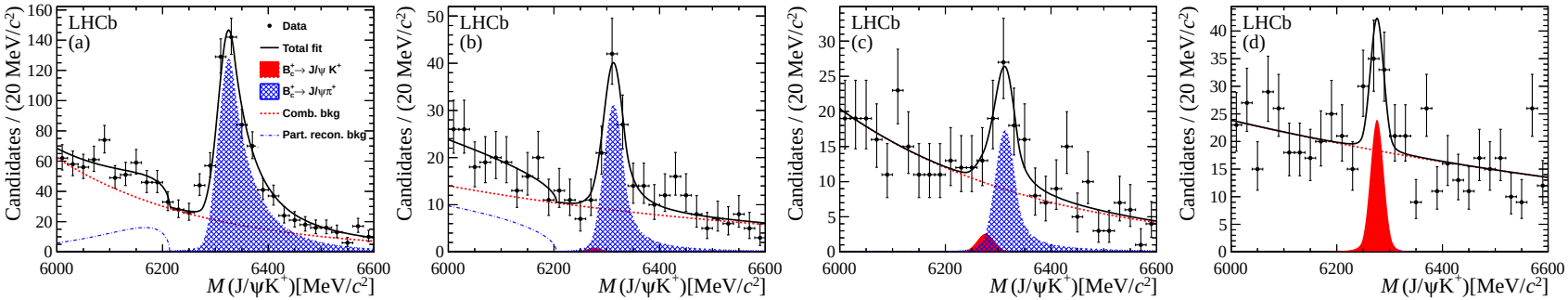
- We used the 2011 data set ($1\ \text{fb}^{-1}$) at $\sqrt{s} = 7\ \text{TeV}$
- Boosted Decision Tree (BDT) selection (categorizing signal and background events by successive binary splits according to kinematic, quality and PID variables)
- $\frac{\mathcal{B}(B_c^+ \to J/\psi K^+)}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)} = \frac{N(B_c^+ \to J/\psi K^+)}{N(B_c^+ \to J/\psi \pi^+)} \cdot \frac{\epsilon(B_c^+ \to J/\psi K^+)}{\epsilon(B_c^+ \to J/\psi \pi^+)}$

$B_c^+ \to J/\psi K^+$ (arXiv:1306.6723)

Unbinned maximum likelihood fit with four components:

- Double sided Crystal Ball function (DSCB) for both channels
- ARGUS for partially reconstructed
- Exponential for combinatorial background

In four bins of $\mathrm{DLL}_{K\pi} = \ln \mathcal{L}(K) - \ln \mathcal{L}(\pi)$



$\mathrm{DLL}_{K\pi} < -5$ $\quad -5 < \mathrm{DLL}_{K\pi} < 0$ $\quad 0 < \mathrm{DLL}_{K\pi} < 5$ $\quad \mathrm{DLL}_{K\pi} > 5$

- Total $B_c^+ \to J/\psi K^+$ yield of 46 ± 12 (5.0 standard deviations)
- Yield ratio with respect to $B_c^+ \to J/\psi \pi^+$ is 0.071 ± 0.020 (stat)
- Efficiency ratio over full $\mathrm{DLL}_{K\pi}$ range taken from simulation is 1.029 ± 0.007 (stat)

$B_c^+ \to J/\psi K^+$ (arXiv:1306.6723)

Systematics summary table

Source	Uncertainty (%)
Mass window	0.9
BDT selection	5.7
$B_c^+ \to J/\psi K^+$ signal model	0.7
$B_c^+ \to J/\psi \pi^+$ signal model	0.5
Choice of signal shape	2.7
Partially reconstructed background shape	2.3
$B_c^+ \to J/\psi K^+$ signals in $\mathrm{DLL}_{K\pi} < 0$ bins	1.8
$\mathrm{DLL}_{K\pi}$ binning choice	1.2
K^+ and π^+ interaction length	2.0
Simulation sample size	0.7
Total	7.5

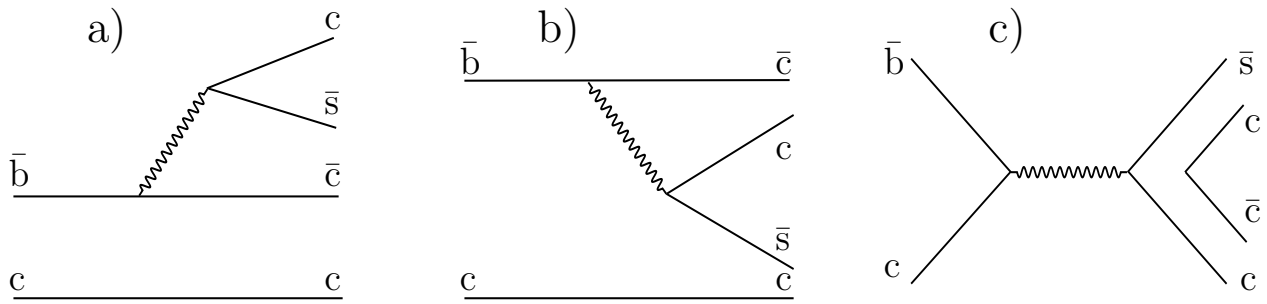
Final LHCb result

$$\frac{\mathcal{B}(B_c^+ \to J/\psi K^+)}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)} = 0.069 \pm 0.019\ (\mathrm{stat}) \pm 0.005\ (\mathrm{syst})$$

It is consistent with predictions and (if using naive factorisation) also with other results like $B_s^0 \to D_s^- K^+(\pi^+)$, $B^+ \to \bar{D}^0 K^+(\pi^+)$ and $B^0 \to D^- K^+(\pi^+)$

Observation of $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$

- The decay $B_c^+ \to J/\psi D_s^+$ is expected to proceed mainly through spectator and colour-suppressed spectator diagrams



- Using both the 2011 data (1 fb^{-1} at $\sqrt{s} = 7$ TeV) and 2012 data (2 fb^{-1} at $\sqrt{s} = 8$ TeV)
- Cut based selection
- $B_c^+ \to J/\psi D_s^{*+}$ being a pseudoscalar decaying into two vector particles, there are three helicity amplitudes (A_{++}, A_{00}, A_{--})

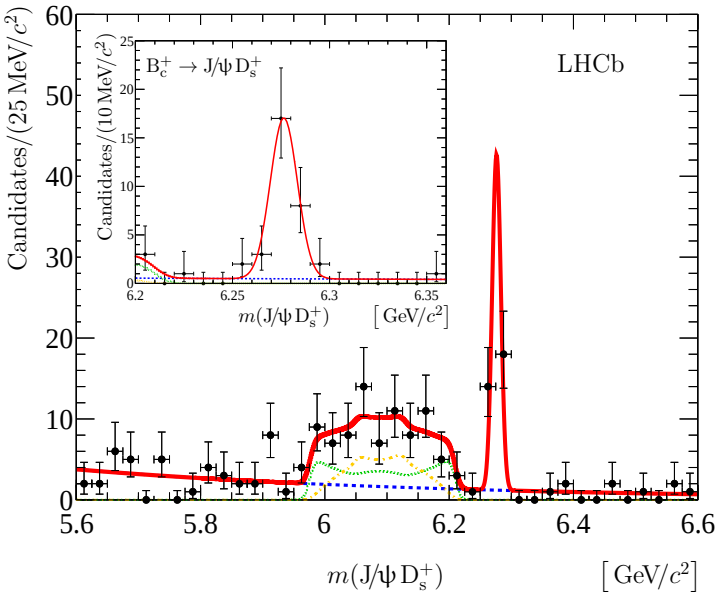
$B_c^+ \to J/\psi\, D_s^+$ and $B_c^+ \to J/\psi\, D_s^{*+}$ (arXiv:1304.4530)

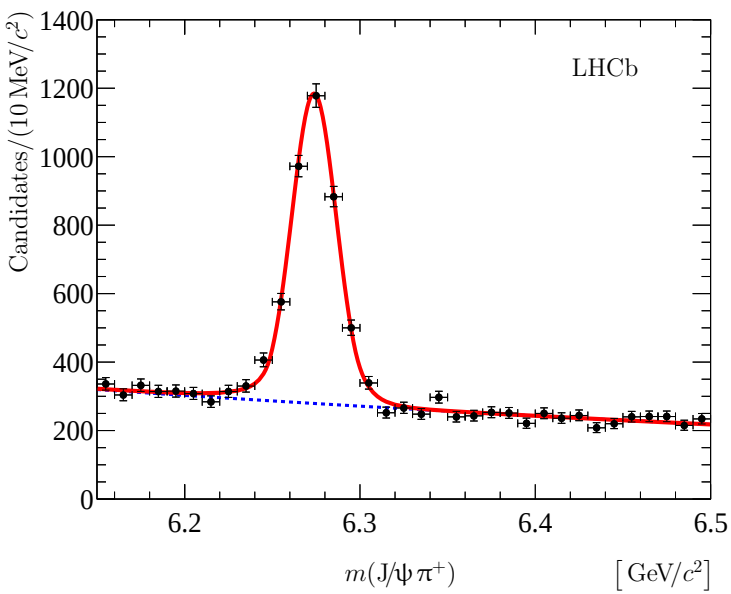
Extended unbinned maximum likelihood fit with four components (left plot):

- Single gaussian for $B_c^+ \to J/\psi\, D_s^+$ signal
- Two shapes from simulation for $B_c^+ \to J/\psi\, D_s^{*+}$ with A_{++}/A_{--} (same mass distribution) or A_{00}
- Exponential function to describe combinatorial background

Extended unbinned maximum likelihood fit with two components (right plot):

- DSCB for $B_c^+ \to J/\psi\, \pi^+$ signal
- Exponential function to describe combinatorial background





- We obtain $N_{B_c^+ \to J/\psi\, D_s^+} = 28.9 \pm 5.6$ (stat) and $N_{B_c^+ \to J/\psi\, D_s^{*+}}/N_{B_c^+ \to J/\psi\, D_s^+} = 2.37 \pm 0.56$ (stat)
- Excess of more than 9 standard deviations for both channels

$B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ (arXiv:1304.4530)

Systematics summary table

Source	Uncertainty (%)
Simulated efficiencies	1.0
Trigger	1.1
Fit model	1.8
Track reconstruction	2×0.6
Hadron interactions	2×2.0
Track quality selection	2×0.4
Kaon identification	3.0
B_c^+ lifetime	1.0
Stability for varous data taking conditions	2.5
$\mathcal{B}(D_s^+ \to (K^-K^+)_\phi \pi^+)$	5.6
Total	8.4

Final LHCb result

$$\frac{\mathcal{B}(B_c^+ \to J/\psi D_s^+)}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)} = 2.90 \pm 0.57\ (\text{stat}) \pm 0.24\ (\text{syst})$$

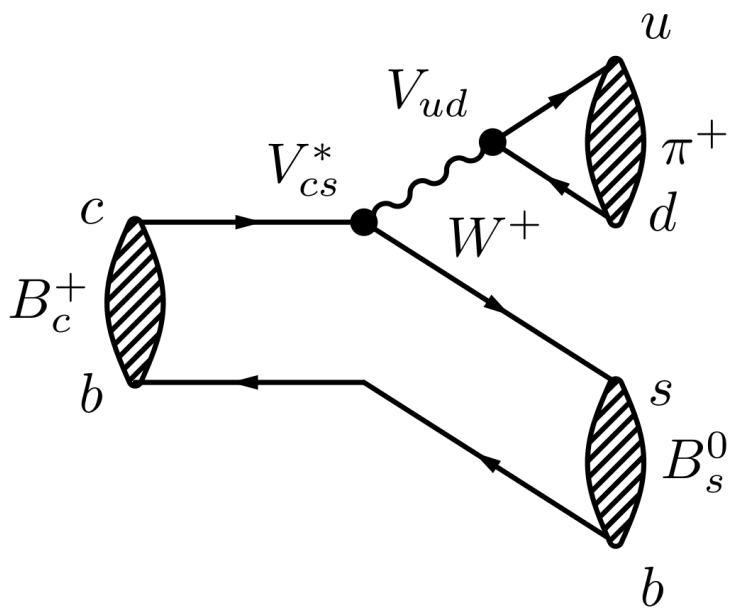
$$\frac{\mathcal{B}(B_c^+ \to J/\psi D_s^{*+})}{\mathcal{B}(B_c^+ \to J/\psi D_s^+)} = 2.37 \pm 0.56\ (\text{stat}) \pm 0.10\ (\text{syst})$$

$$m_{B_c^+} = 6276.28 \pm 1.44\ (\text{stat}) \pm 0.36\ (\text{syst})\ \text{MeV}/c^2$$

$B_c^+ \to B_s^0 \pi^+$ (LHCb-PAPER-2013-044)

Observation of the decay $B_c^+ \to B_s^0 \pi^+$

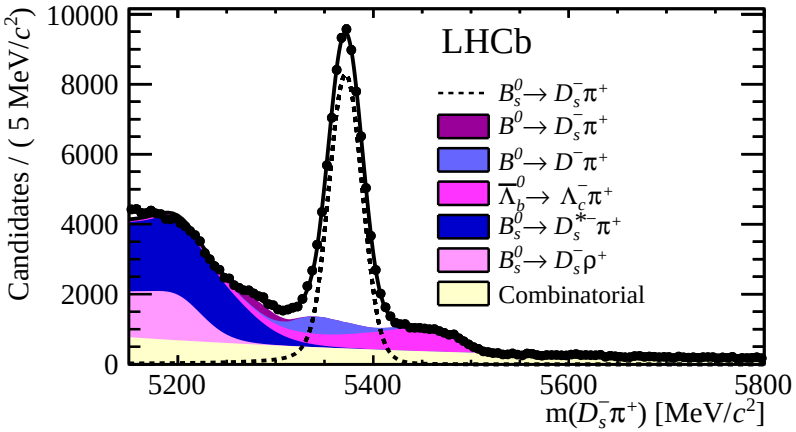
- No B_c^+ decay where the b quark is acting as a spectator has ever been observed
- Predictions for $\mathcal{B}(B_c^+ \to B_s^0 \pi^+)$ cover a broad range
- Experimental confirmation is needed
- Using both the 2011 data ($1\ \text{fb}^{-1}$ at $\sqrt{s} = 7\ \text{TeV}$) and 2012 data ($2\ \text{fb}^{-1}$ at $\sqrt{s} = 8\ \text{TeV}$)
- The B_s^0 are reconstructed either in $B_s^0 \to J/\psi\,\phi$ or $B_s^0 \to D_s^- \pi^+$ with $\phi \to K^+K^-$ and $D_s^- \to K^+K^-\pi^-$
- Boosted Decision Tree (BDT) selection

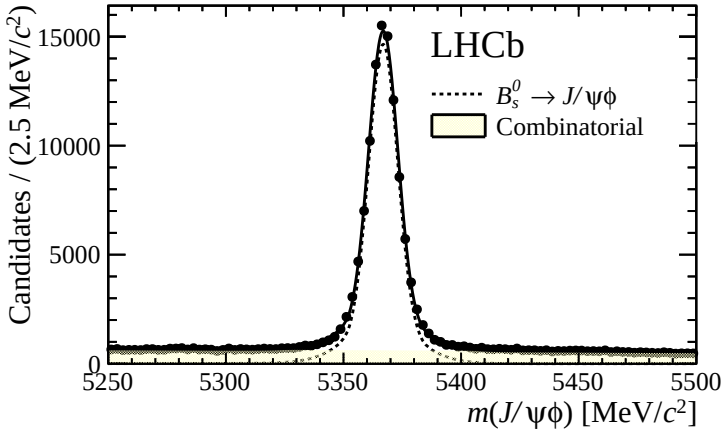


$B_c^+ \to B_s^0 \pi^+$ (LHCb-PAPER-2013-044)

B_s^0 candidates: extended unbinned maximum likelihood fit

- Signals described with double Crystal Ball functions
- Combinatorial background modeled with exponential function
- Other background described with shapes taken from simulation





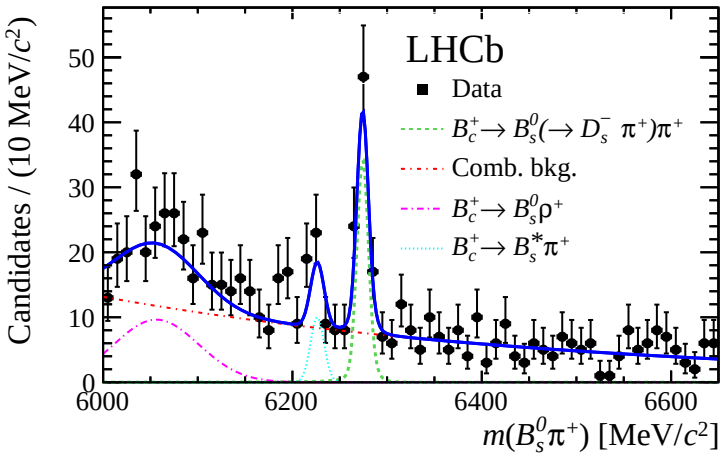
In total we reconstruct

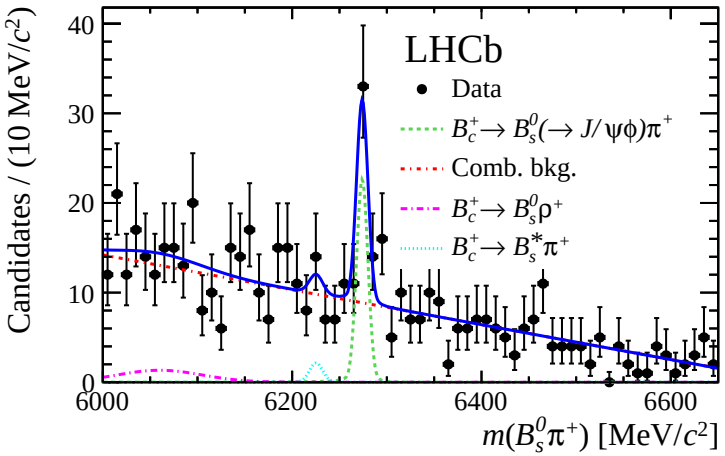
- 103'760 $\pm$ 380 in the $B_s^0 \to J/\psi\,\phi$ channel
- 73'700 $\pm$ 500 in the $B_s^0 \to D_s^- \pi^+$ channel

$B_c^+ \to B_s^0 \pi^+$ (LHCb-PAPER-2013-044)

B_c^+ candidates: extended unbinned maximum likelihood fit

- Signal described with double Crystal Ball functions with parameters taken from simulation
- Combinatorial background modeled with exponential function
- Two other background described with a single Gaussian each with fixed parameters





Signal yield of

- 64 ± 10 for $B_c^+ \to B_s^0(\to D_s^- \pi^+)\pi^+$ (significance of 7.7 σ)
- 35 ± 8 for $B_c^+ \to B_s^0(\to J/\psi\,\phi)\pi^+$ (significance of 6.1 σ)

$B_c^+ \to B_s^0 \pi^+$ (LHCb-PAPER-2013-044)

Systematics summary table

Source	$D_s^- \pi^+$ (%)	$J/\psi \phi$ (%)
B_s^0 fit model	3.0	1.2
B_c^+ mean mass	–	2.0
B_c^+ mass resolution	–	5.2
B_c^+ signal model	1.5	1.7
Combinatorial background model	1.8	0.3
Partially reconstructed background	1.8	1.7
Data-simulation difference	3.7	3.7
B_c^+ lifetime	$^{+6.8}_{-3.5}$	7.4
Total	$^{+9.2}_{-7.1}$	10.4

Final LHCb result

$$\frac{\sigma(B_c^+)}{\sigma(B_s^0)} \times \mathcal{B}(B_c^+ \to B_s^0 \pi^+) = (2.38 \pm 0.35\ (\text{stat}) \pm 0.11\ (\text{syst})^{+0.17}_{-0.12}(\tau_{B_c^+})) \times 10^{-3}$$

Using approximate estimate of $\sigma(B_c^+)$ over $\sigma(B_s^0)$ of 0.02, one obtains a value for $\mathcal{B}(B_c^+ \to B_s^0 \pi^+) \approx 10\%$

Even using the lower estimate, it is the largest exclusive branching fraction of any known weak B meson decay

Summary and outlook

The LHCb experiment shed light on many aspects related to b-hadron production and spectroscopy as illustrated by the recent results about B_c^+ mesons

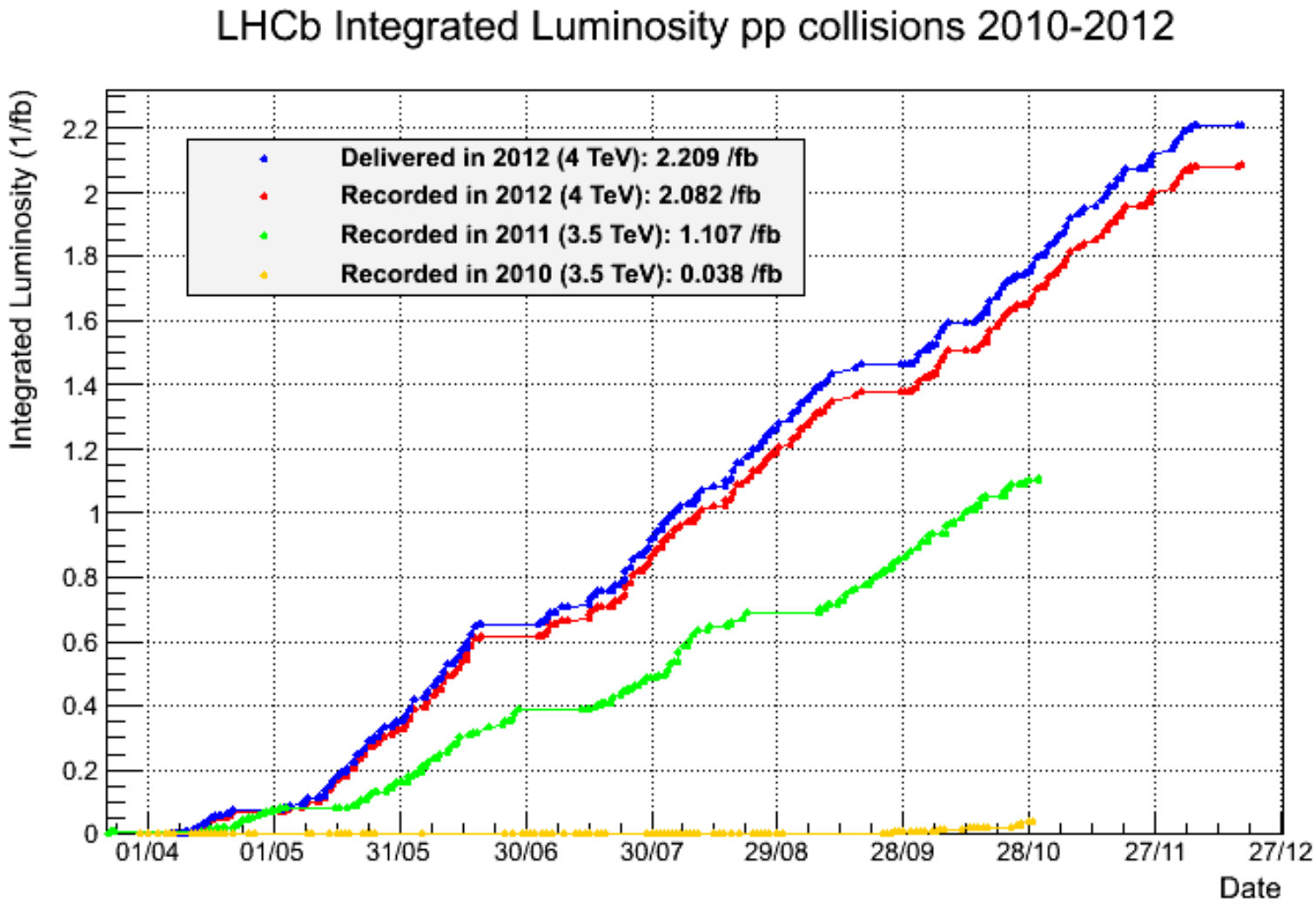
- First observation of $B_c^+ \to J/\psi K^+$
- First observation of $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$
- First observation of $B_c^+ \to B_s^0 \pi^+$

New results and measurements keep coming as 2011 and 2012 data are analysed


Thank you for your attention

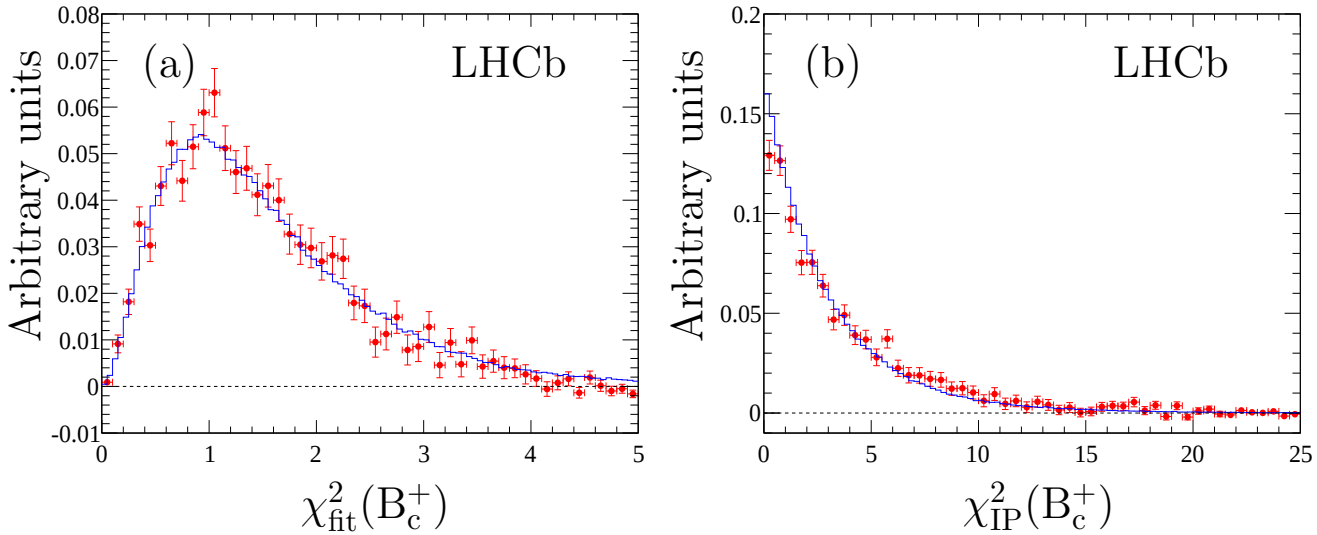
BACKUP SLIDES

LHCb data taking conditions



2010: 38 pb^{-1} at $\sqrt{s} = 7\,\text{TeV}$
2011: 1.1 fb^{-1} at $\sqrt{s} = 7\,\text{TeV}$
2012: 2.1 fb^{-1} at $\sqrt{s} = 8\,\text{TeV}$

Good agreement between background subtracted data (red points) and simulation (blue histogram) for the $\chi^2_{fit}(B_c^+)$ and $\chi^2_{IP}(B_c^+)$ distributions



The background was subtracted using the *sPlot* technique