B_c^+ physics at LHCb

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August 7th, 2015
Ann Arbor, MI – United States of America

Introduction

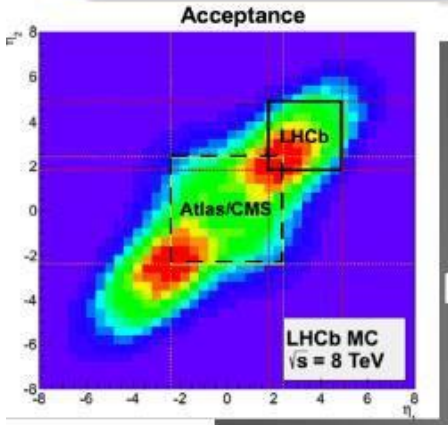
- *B_c^+ meson is the **ground state** of the $(\bar{b}c)$ bound states.*
- *It is a **unique state** in the Standard Model, being composed of a heavy quark-antiquark pair of different flavours.*
- *Discovered at CDF in 1995*
- *Production disfavored in e^+e^- collisions*

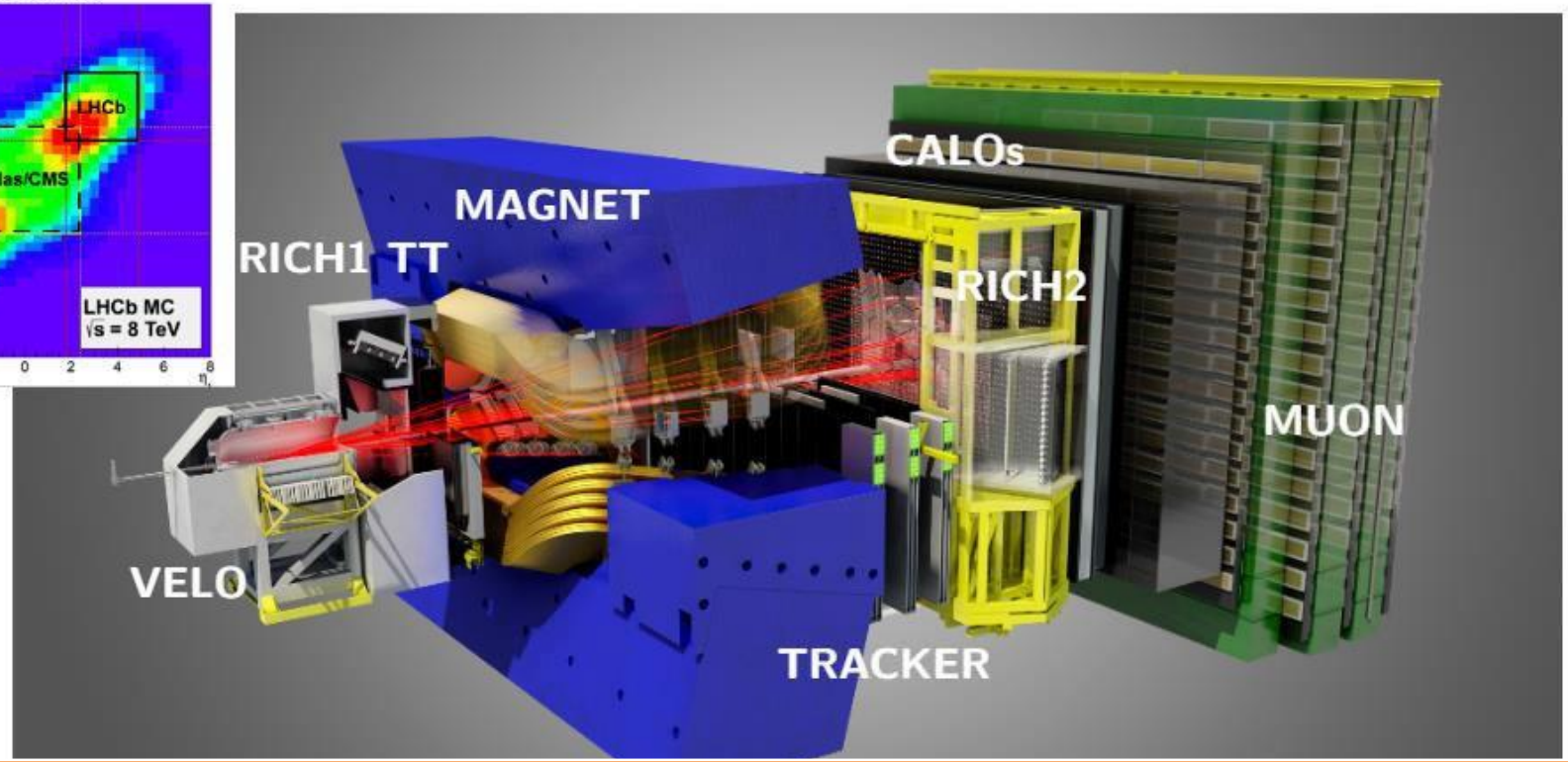
  (and forbidden at b-factories)
- *Great potential for the LHC, and especially the LHCb experiment.*

Outline		
The LHCb detector	Int. J. Mod. Phys. A30 (2015) 1530022	
Production in pp collisions at $\sqrt{s} = 8$ TeV	PRL 114 (2015) 132001	2012 data, 2 fb^{-1}
Lifetime measurement		
with $B_c^+ \to J/\psi\mu^+\nu X$	EPJC74 (2014) 5, 2839	2012 data, 2 fb^{-1}
with $B_c^+ \to J/\psi\pi^+$	PLB 742 (2014) 29	Run-1 data, 3 fb^{-1}
Mass measurement		
with $B_c^+ \to J/\psi\pi^+$	PRL 109 (2012) 232001	2011 data, 370 pb^{-1}
with $B_c^+ \to J/\psi D_s^+$	PRD 87 (2013) 112012	Run-1 data, 3 fb^{-1}
with $B_c^+ \to J/\psi\, p\bar{p}\pi^+$	PRL (2014) 152003	Run-1 data, 3 fb^{-1}
Study of $B_c^+ \to \psi(2S)\pi^+$	arXiv:1507.03516	Run-1 data, 3 fb^{-1}

New

LHCb: A wonderful detector to study B_c^+ decays





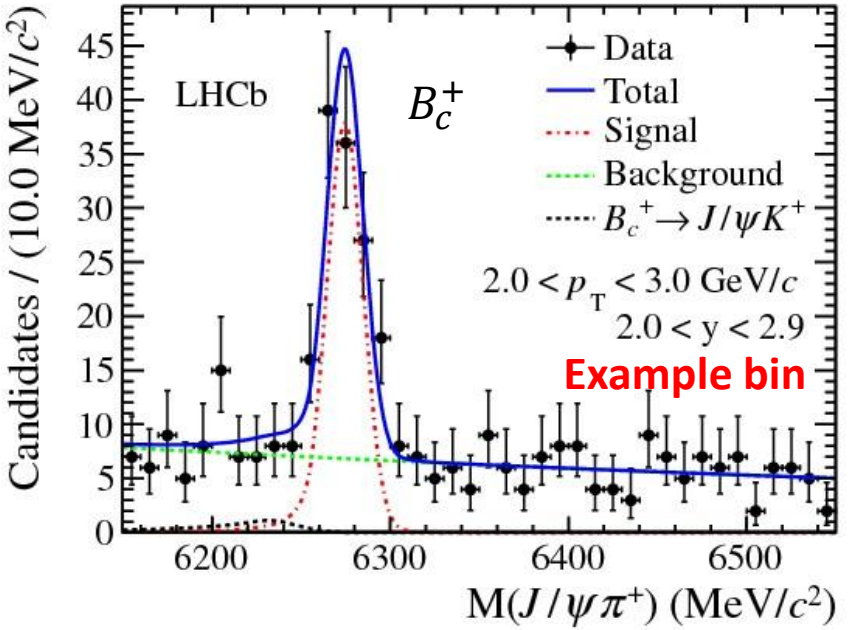
Key features	Int. J. Mod. Phys. A30 (2015) 1530022
Unique geometrical acceptance	$2 < \eta < 5$; ~40% of b quarks in acceptance
Excellent Vertex Locator (VELO)	$\sigma_{PV\,xy} \sim 10\ \mu m$, $\sigma_{PV\,z} \sim 60\ \mu m$
Tracking system	$\Delta p/p \sim 0.5\ - 1\%$
Muon system	$\epsilon(\mu \to \mu) \sim 97\%$, MisID rate$(h \to \mu) \sim 1\%$

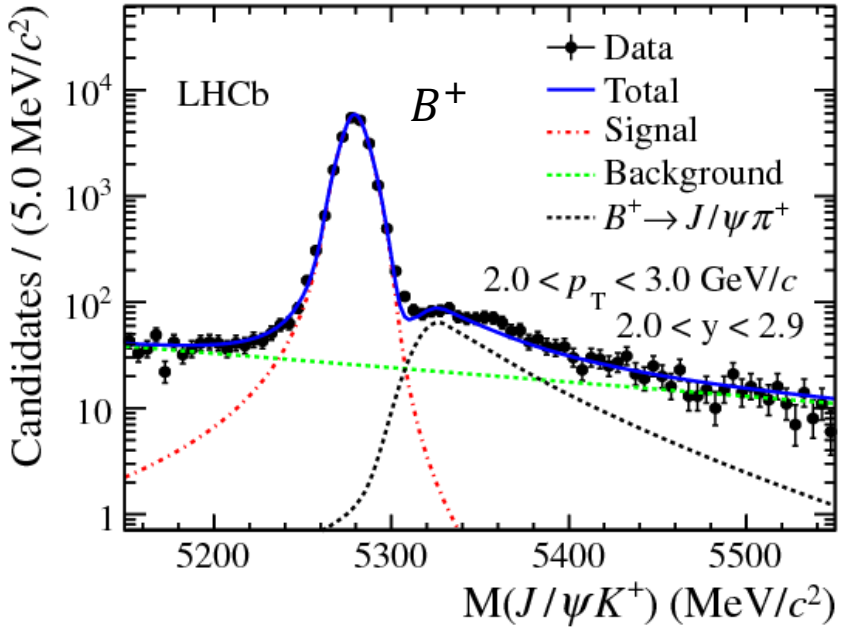
Production measurement

- *Proton-Proton collisions **at 8 TeV** in the center of mass.*
- *2.0 fb^{-1} of data collected in 2012*
- *Decay mode: $B_c^+ \to J/\psi\pi^+$*
- *Control channel: $B^+ \to J/\psi K^+$*

- *First **double-differential** measurement of B_c^+ **production cross-section***

- *Range:*
  $0 < p_T < 20\ GeV/c$ and $2 < y < 4.5$



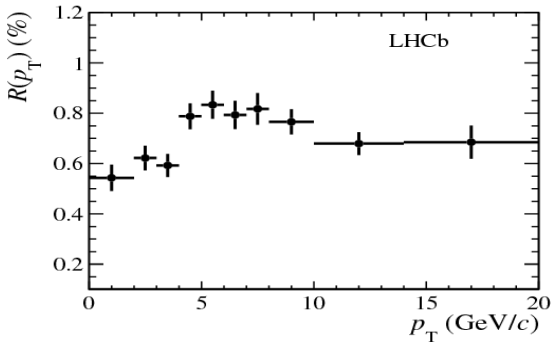


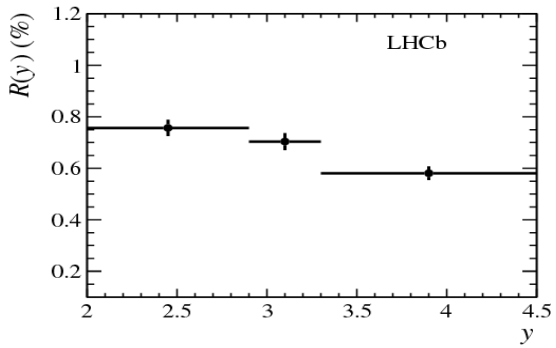
Production measurement

Excellent agreement observed with the full α_s^4 calculation implemented in the Event generator **BcVegPy** [Comp. Phys. Commun. 159 (2003) 192]

Ratio $\frac{\sigma(pp\to B_c^+ X)\times Br(B_c^+\to J/\psi\pi^+)}{\sigma(pp\to B^+ X)\times Br(B^+\to J/\psi K^+)}$, normalized to the full range is:

$$R = \left(0.638 \pm 0.018\ (stat) \pm 0.09\ (syst)\right)\%$$

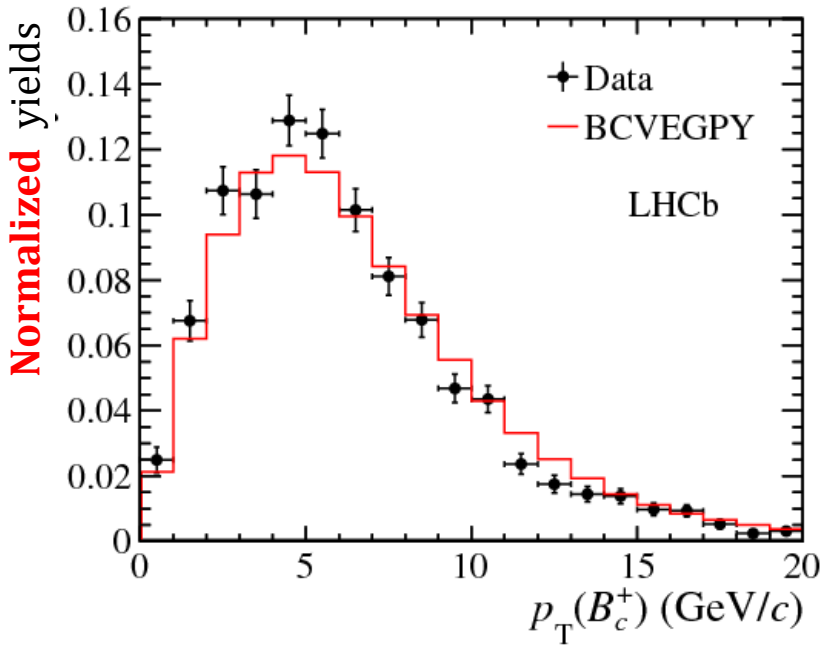


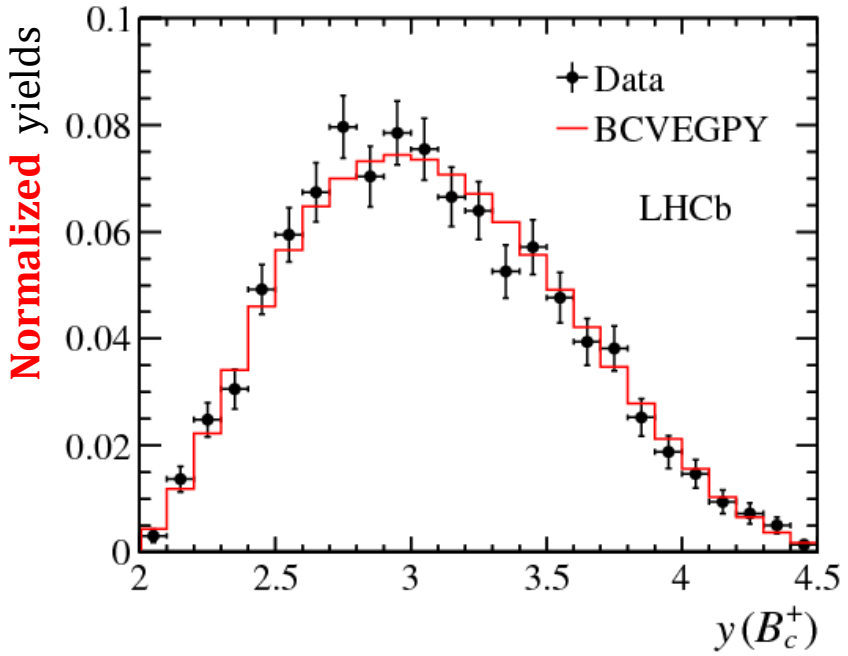


LHCb published the same ratio for pp collisions at 7 TeV:

$$\left(0.68 \pm 0.10\ (stat) \pm 0.03\ (syst) \pm 0.16(\tau)\right)\%$$

where the last uncertainty is inherited from the B_c^+ **lifetime**.





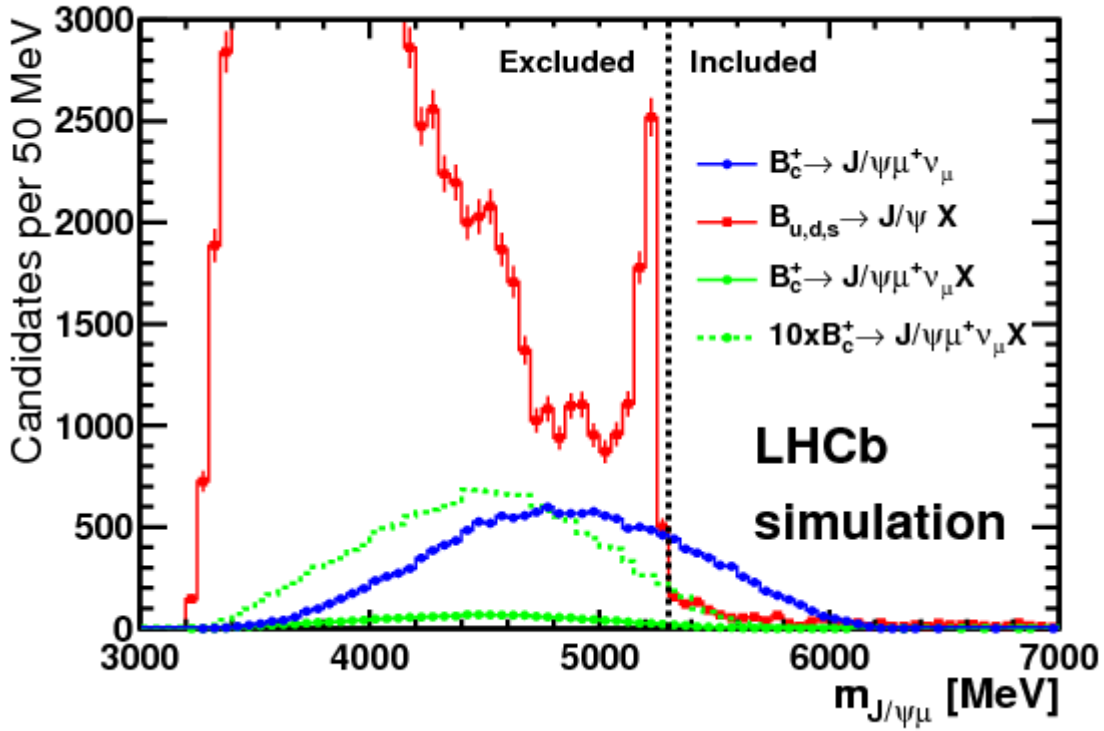
Production and semileptonic decay

The production measurements can be combined to the measurement of

$$R_{\pi\mu} = \frac{Br(B_c^+ \to J/\psi\pi^+)}{Br(B_c^+ \to J/\psi\mu^+\nu)}$$

The computation of $Br(B_c^+ \to J/\psi\mu^+\nu)$ is theoretically cleaner, **opening to absolute branching fraction measurements.**

$$R_{\pi\mu} = 0.0469 \pm 0.0028 \pm 0.0046$$



The measurement is performed using the data with

$$m_{J/\psi\mu} \in [m_{Bu}, 7\ GeV/c^2]$$

with much smaller background from B decays.

Lifetime measurement

Lifetime can be directly related to the sum of all the decay widths, it represents a «*checksum*» of the theoretical models describing B_c^+ decays.

LHCb has performed B_c^+ lifetime measurements using the decay modes

- $B_c^+ \to J/\psi \mu^+ \nu X$, **partially reconstructed**, high statistics, lifetime unbiased selection
- $B_c^+ \to J/\psi \pi^+$, **fully reconstructed**, suppressed decay width, and thus smaller statistics.
  Selection based on Neural Network.

The two measurements (described below) are **competitive** and **complementary**, with fully uncorrelated statistical and systematic uncertainties

Theoretical model	Lifetime prediction (ps)
Lusignoli, Masetti (1990) Rome preprint 774	Pontential Models (PM): 0.5
Eichten, Quigg (1994) FERMILAB-CONF-94-117-T	PM with $c \to s$ suppression: 1.3
Bigi (1995) hep-ph/9508408	Heavy Quark Expansion: 0.4
Kiselev *et al.* (2000) Nucl.PB 585 (2000) 353-382	Potential models: 0.55 ± 0.15 QCD sum rules: 0.48 ± 0.05
Chang *et al.* (2000) PRD64 (2001) 014003	Fit of b and c hadron lifetimes: 0.37 – 0.47

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

Dataset:
2012 pp data
(2 fb^{-1})

Excellent experimental signature: 3 muons

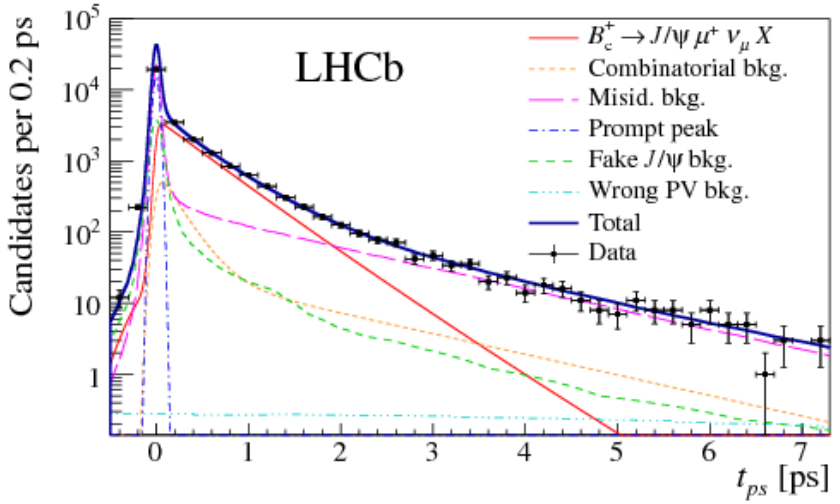
Good statistics (wrt. $B_c^+ \to J/\psi\pi^+$)

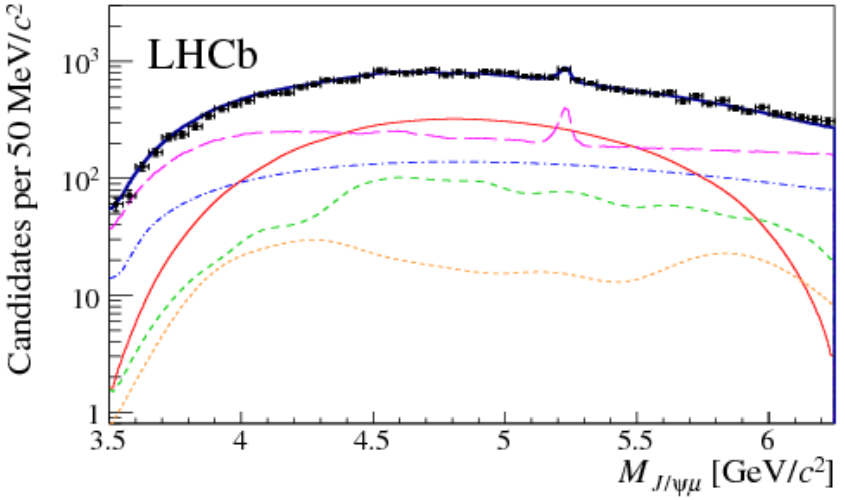
Allows **lifetime unbiased** selection strategy

Time dependence of the efficiency is often an important source of systematic uncertainty!

Result obtained from 2D maximum likelihood unbinned fit.
Fit variables are:

- **Pseudo-proper decay time (t_{ps})** defined in the $J/\psi\mu^+$ rest frame
- **Invariant mass of the $J/\psi\mu^+$ combination.** Because of partial reconstruction $m(J/\psi\mu^+) \in [3.5, 6.3]\mathrm{GeV}/c\text{^}2$



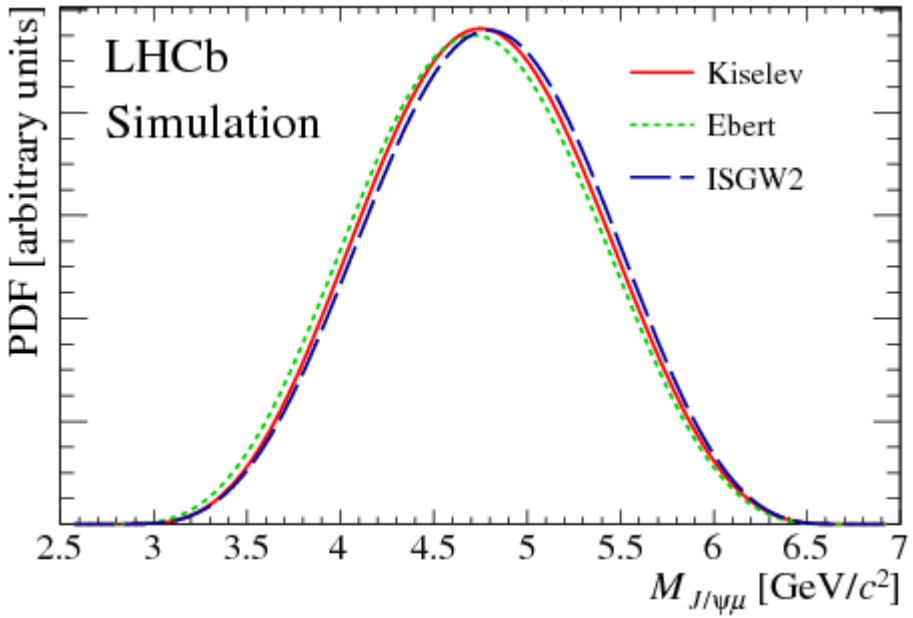


Lifetime measurement with $B_c^+ \to J/\psi\mu^+\nu X$

The correction *k* between the *pseudo-proper* and *proper decay time* relies on **theoretical decay models** for:

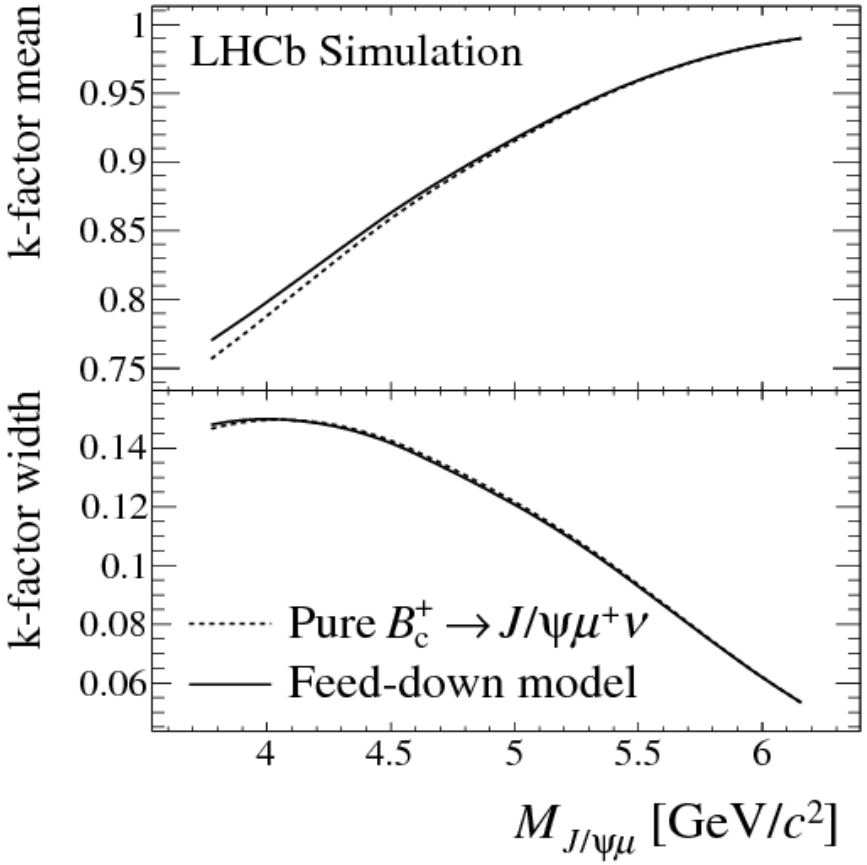
- **Decay form factor** (accounting for ν missing energy)
- **Feed down modes** (missing energy from other particles)

- $B_c^+ \to J/\psi\tau^+$
- $B_c^+ \to \psi(2S)\mu^+\nu$
- $B_c^+ \to \chi_c\mu^+\nu$
- …



Lifetime:
$(509 \pm 8 \pm 12)$ fs

The *k* factor is a statistical correction whose distribution depends on the mass $m(J/\psi\mu^+)$



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

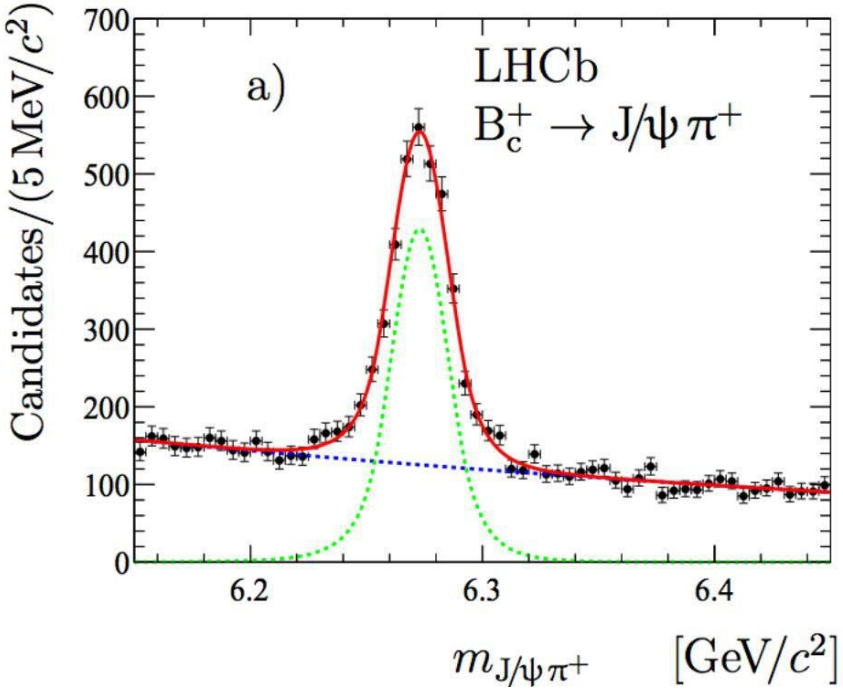
Same quantity, completely uncorrelated measurement.

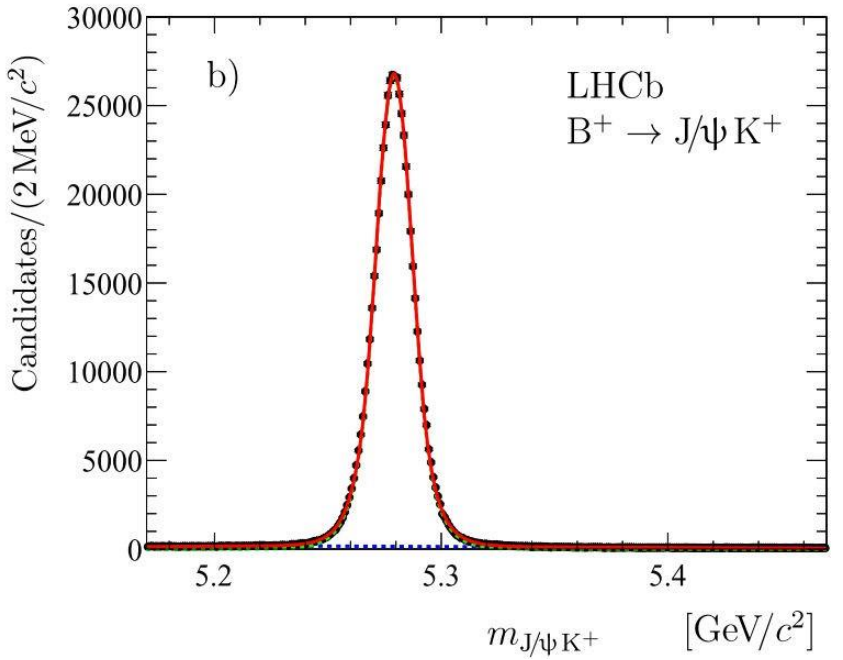
Hadronic channel allows **good signal/background separation** based on the peaking distribution $m(J/\psi\pi^+)$

The large number of π^+ from primary vertex forces **lifetime biased selection strategy.**

The latter relies on a *Neural Network* classifier introducing a non-flat **efficiency** as a function of the decay times.

Normalization channel, $B^+ \to J/\psi K^+$ used to «*measure*» the **efficiency** function directly from data.





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

$$N_{Bu}(t) \propto \epsilon_{Bu}(t) \times \exp\left(-\frac{t}{\tau_{Bu}}\right)$$

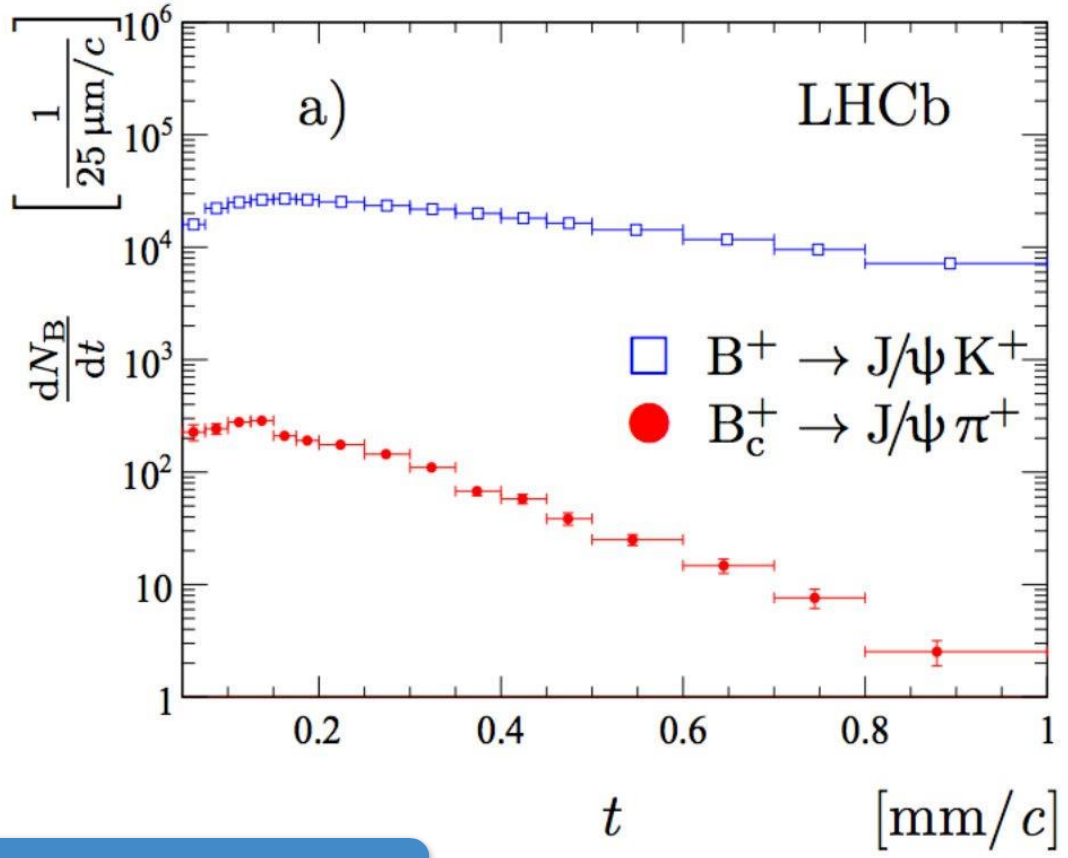
$$N_{Bc}(t) \propto \epsilon_{Bc}(t) \times \exp\left(-\frac{t}{\tau_{Bc}}\right)$$

$$R(t) = \frac{N_{Bc}(t)}{N_{Bu}(t)} \propto \frac{\epsilon_{Bc}(t)}{\epsilon_{Bu}(t)} \times \exp\left(-t\left(\frac{1}{\tau_{Bc}} - \frac{1}{\tau_{Bu}}\right)\right)$$

$\frac{\epsilon_{Bc}(t)}{\epsilon_{Bu}(t)}$ is very close to unity (in range [0.8,1.1])

$\left(\frac{1}{\tau_{Bc}} - \frac{1}{\tau_{Bu}}\right)$ got from fit to «ratio histogram»

τ_{Bu} is taken from PDG



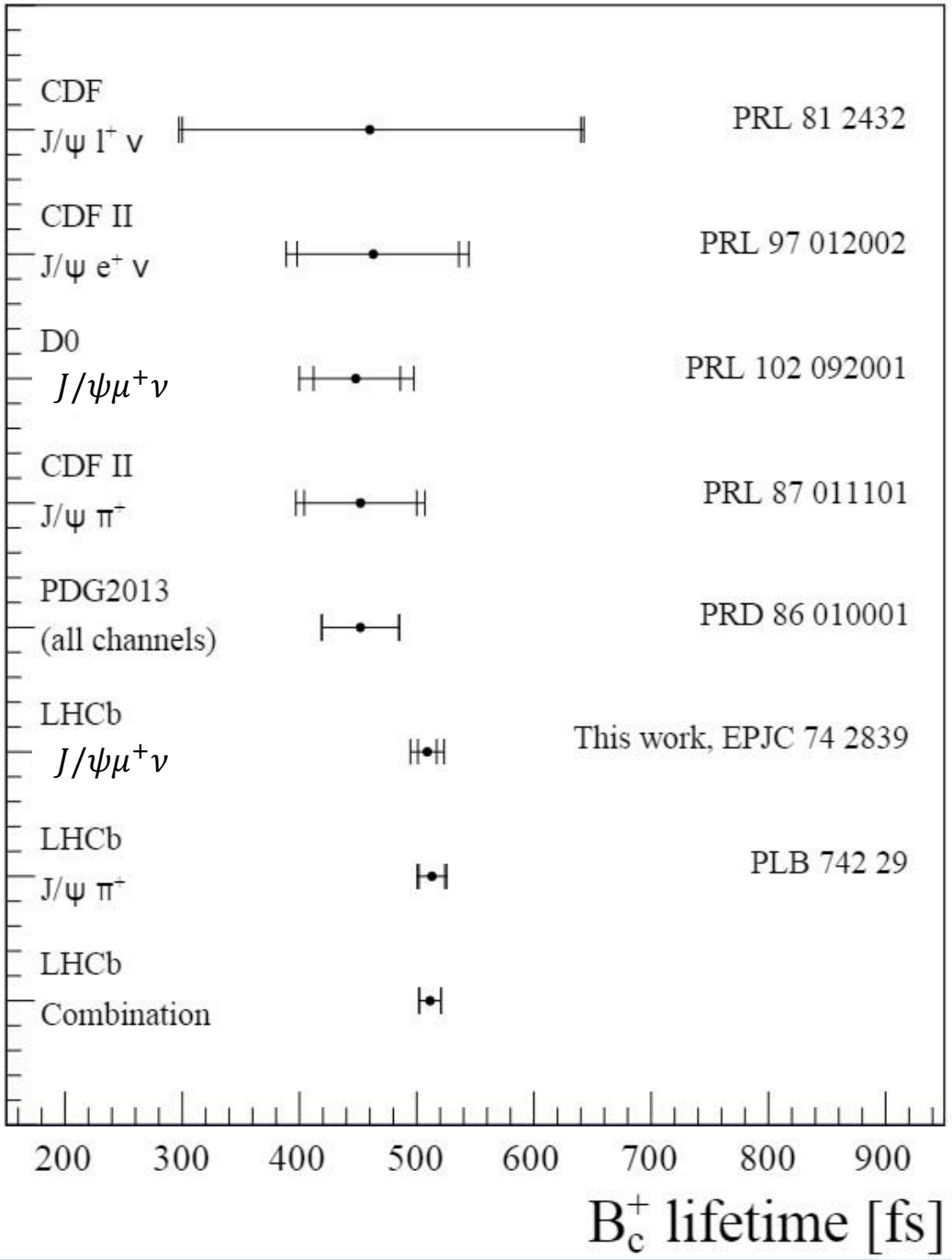
Measured Lifetime: 513 ± 11.0 ± 5.7 fs

Lifetime measurements

Great improvement in the World Average for the B_c^+ lifetime during the Run-1 of the LHC.

This heavily reduces the systematic uncertainty on most of the **other measurements** of B_c^+.

	Lifetime (fs)
$B_c^+ \to J/\psi\mu^+\nu$	$509 \pm 8 \pm 12$
$B_c^+ \to J/\psi\pi^+$	$513.4 \pm 11.0 \pm 5.7$
New World Average [HFAG Fall2014, arXiv:1412.7515]	507 ± 9



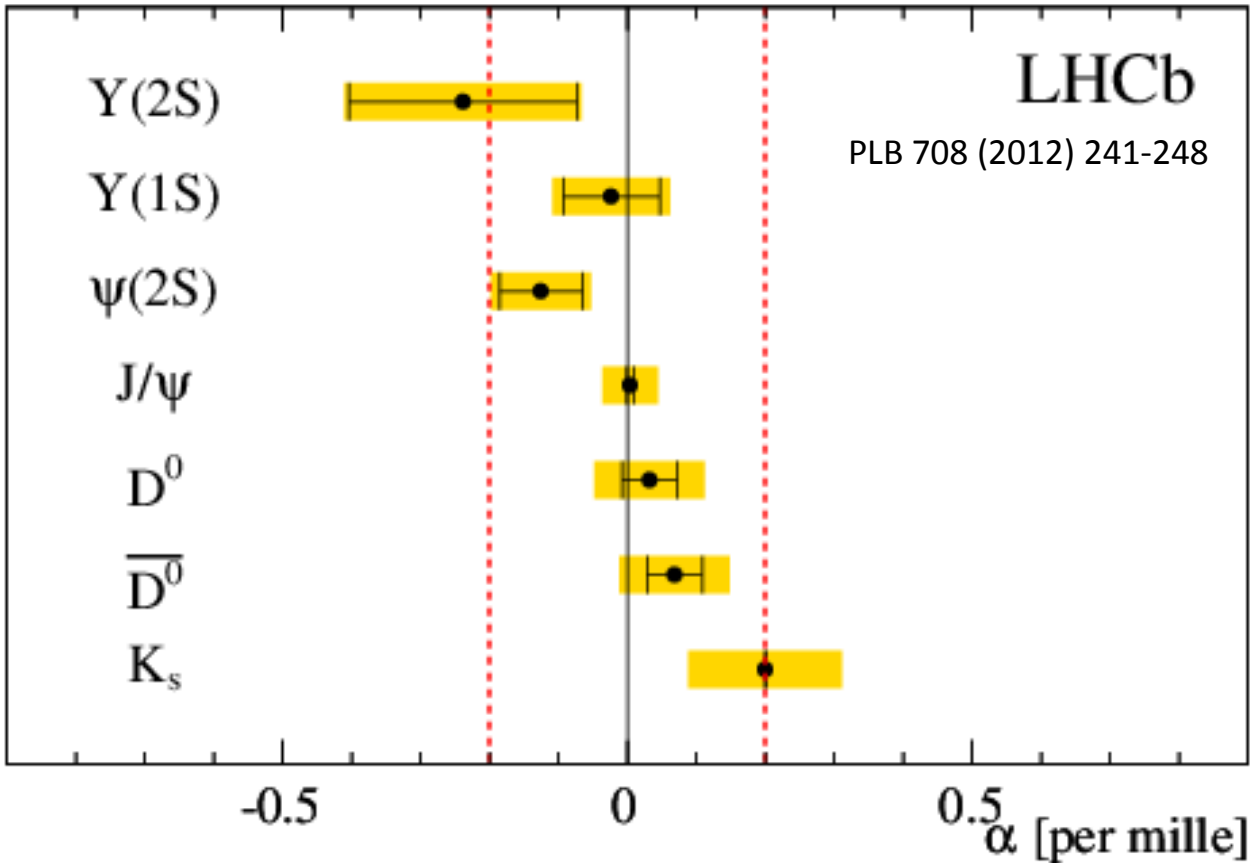
Mass measurement

Mass is an important test for non-perturbative QCD predictions.

A dominant systematic uncertainty in mass measurements is due to **momentum scale calibration.**

Calibration and systematic assessment are performed using K_S^0, D^0, $c\bar{c}$, and $b\bar{b}$ 2-body decays.

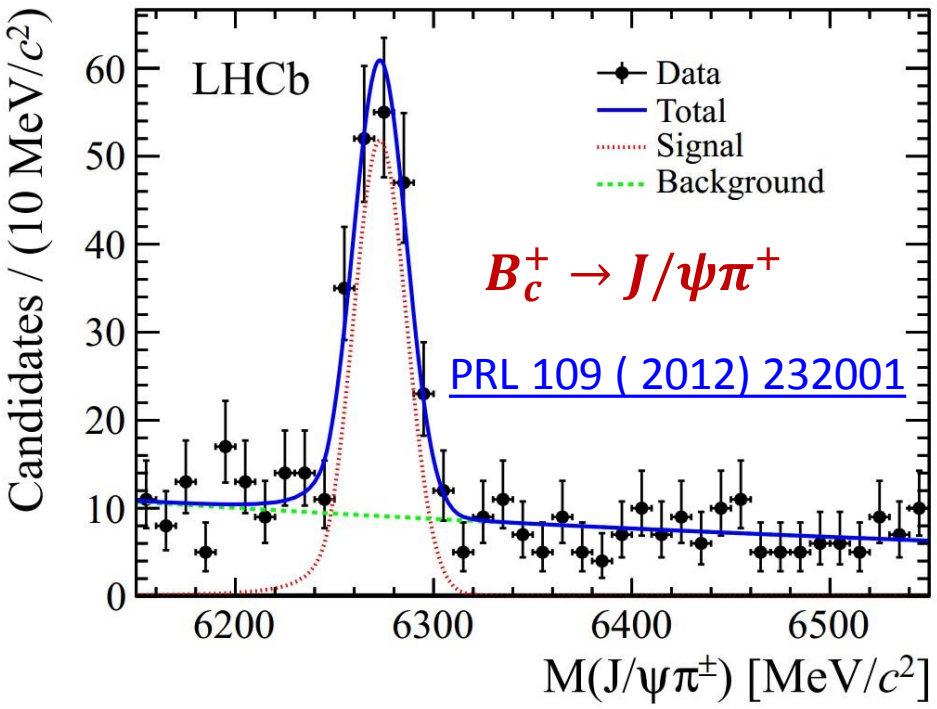
Reconstructed and world-average masses are compared to measure the momentum bias α.



α is the correction to the momentum needed to obtain the PDG mass.
Error bars: statistical error
Yellow band: statistical $\oplus$ systematic err.

To reduce impact of calibration on mass measurement, one uses low-Q decay modes.

Mass measurement



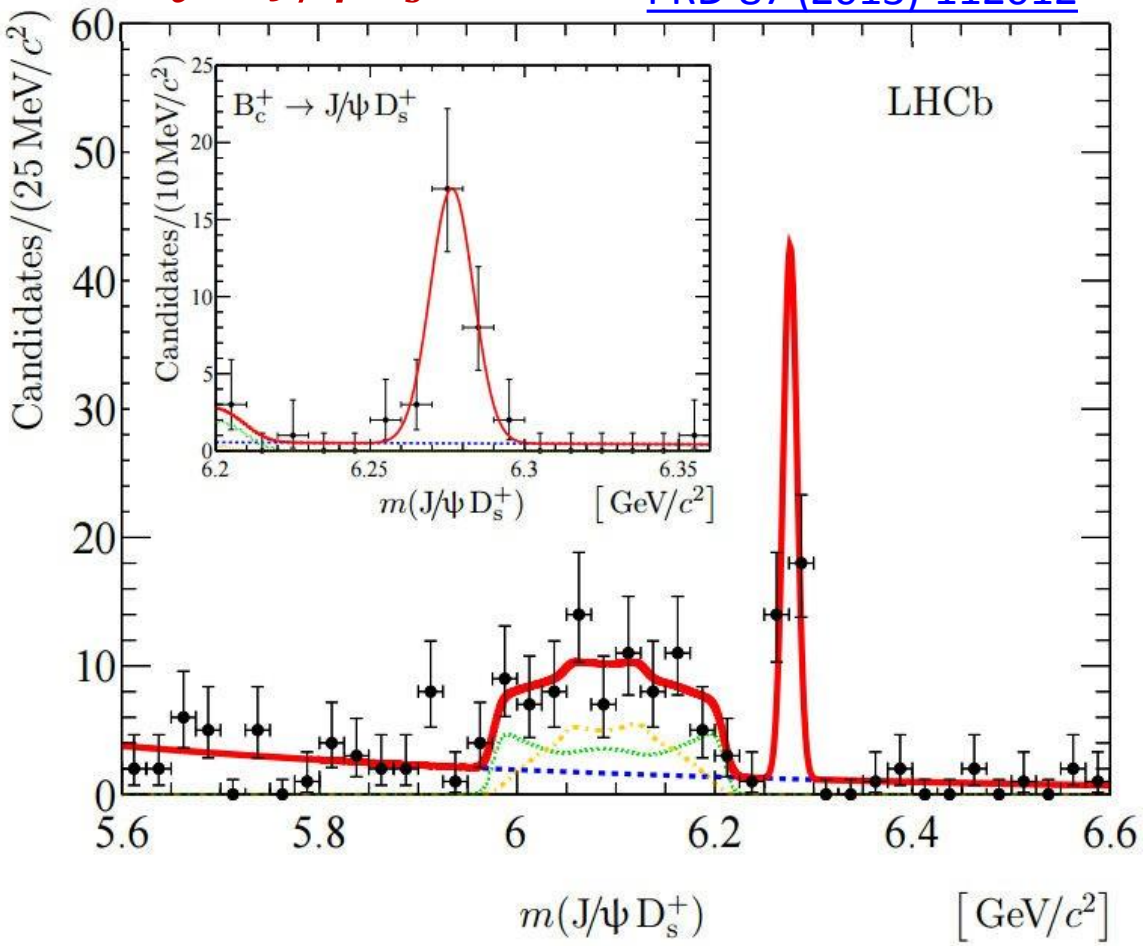
PRL 109 (2012) 232001

Dataset: Early 2011 ($\sqrt{s} = 7$ TeV, Luminosity 370 pb^{-1})
Measured mass:

$6273 \pm 1.3\ (stat) \pm 1.6\ (syst)$ MeV/c^2

$B_c^+ \to J/\psi D_s^+$

PRD 87 (2013) 112012



Dataset: Full Run1 ($\sqrt{s} = 7 + 8$ TeV, 1 + 2 fb^{-1})
Measured mass:

$6276.28 \pm 1.44\ (stat) \pm 0.36\ (syst)$ MeV/c^2

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

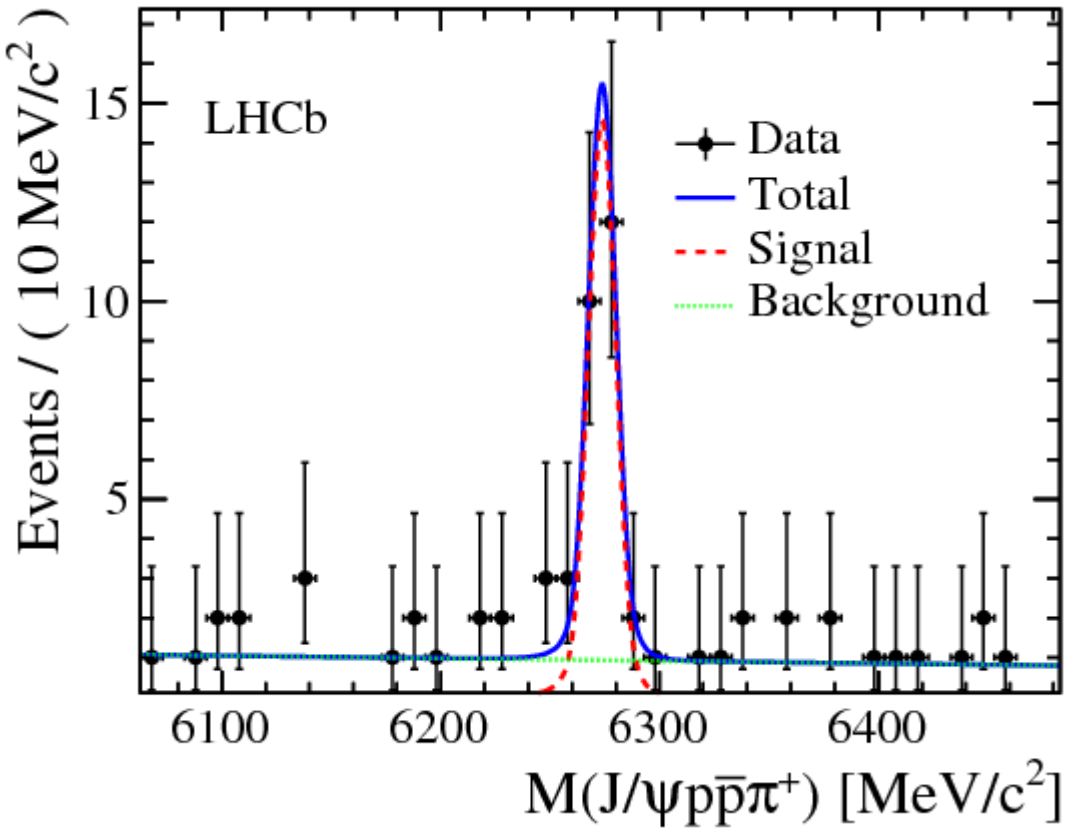
First observation of baryonic B_c^+ decays

Dataset: Full Run-1 ($\sqrt{s}$ = 7+8 TeV, 1+2 fb^{-1})
Measured mass:

$$6274.0 \pm 1.8\,(stat) \pm 0.4\,(syst)\ \text{MeV}/c^2$$

The $B_c^+ \to J/\psi\pi^+$ channel was used as normalization

$$\frac{Br(B_c^+ \to J/\psi p\bar{p}\pi^+)}{Br(B_c^+ \to J/\psi\pi^+)} = 0.143^{+0.039}_{-0.034} \pm 0.013$$



Mass measurements

CDF $B_c^+ \to J/\psi\pi^\pm$

JHEP 01 (2015) 63

LHCb $B_c^+ \to J/\psi\pi^\pm$

PRL 109 (2012) 232001

LHCb $B_c^+ \to J/\psi D_s^\pm$

PRD 87 (2013) 112012

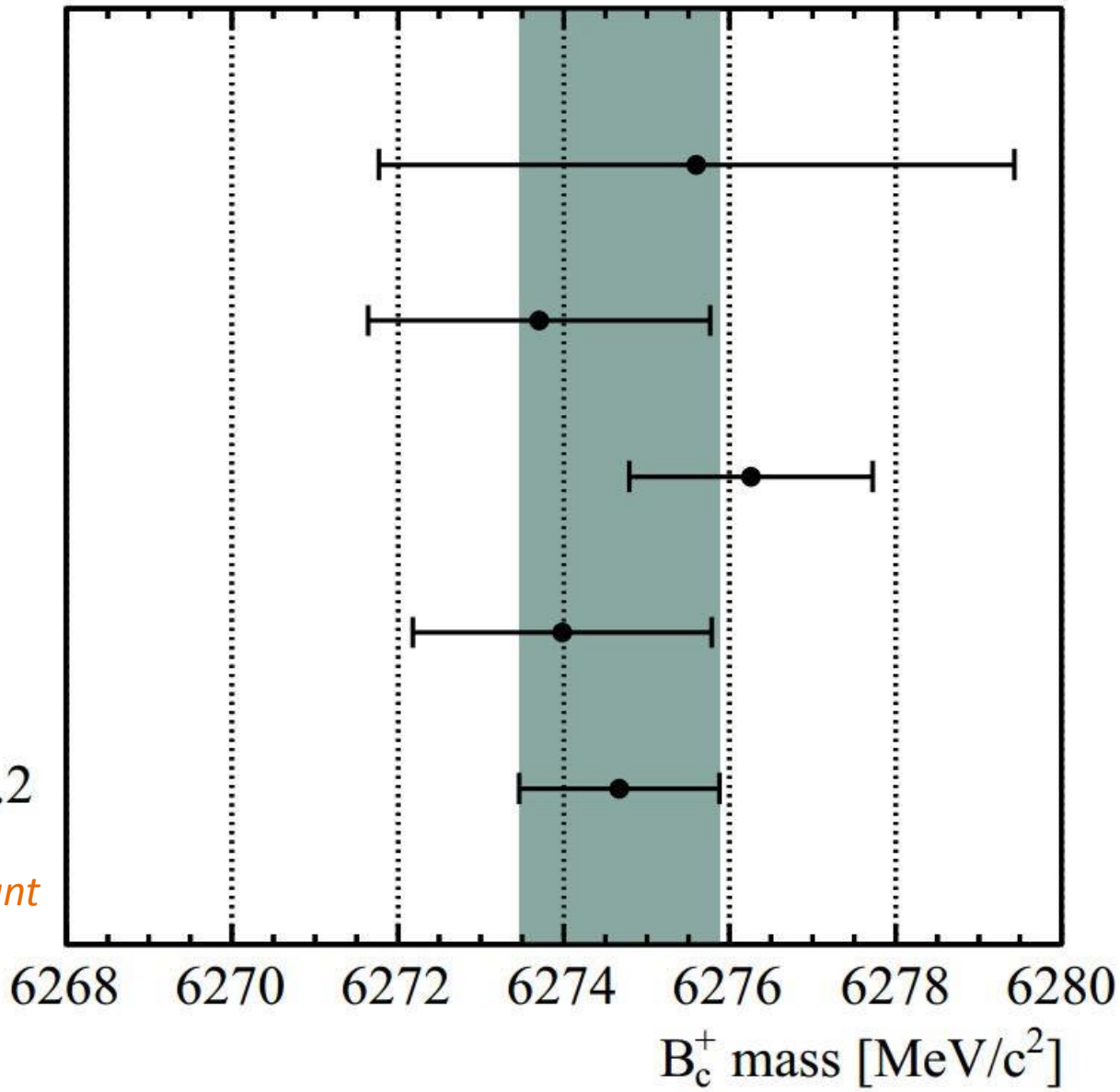
LHCb $B_c^+ \to J/\psi p\bar{p}\pi^\pm$

PRL 113 (2014) 152003

LHCb average: 6274.7±1.2

PRL 113 (2014) 152003

Correlations are properly taken into account



arXiv:1507.03516

$$\frac{Br(B_c^+ \to \psi(2S)\pi^+)}{Br(B_c^+ \to J/\psi\pi^+)}$$

Decay discovered by LHCb with 2011 data [PRD87 (2012) 071103]
Update of the relative branching fraction using full Run-1 statistics (3 fb^{-1} based on 2 independently trained *Boosted Decision Trees* (BDT), applied to statistically independent halves of the sample.

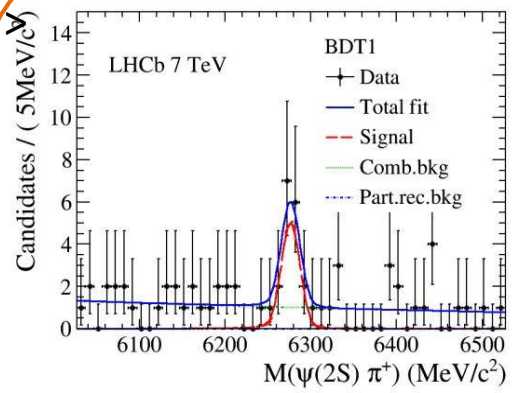
	2011 (1 fb^{-1})		2012 (2 fb^{-1})	
	BDT1	**BDT2**	**BDT1**	**BDT2**
Signal yield	437 ± 24	475 ± 26	883 ± 34	950 ± 36
BDT efficiency	$(62.99 \pm 0.007)\%$	$(62.29 \pm 0.06)\%$	$(62.33 \pm 0.6)\%$	$(68.50 \pm 0.06)\%$
Product of all other efficiencies	$(1.392 \pm 0.003)\%$		$(1.339 \pm 0.003)\%$	

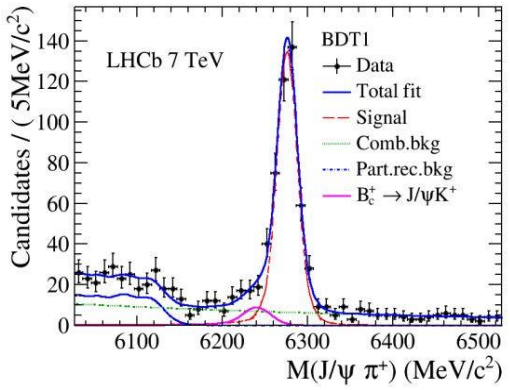
arXiv:1507.03516

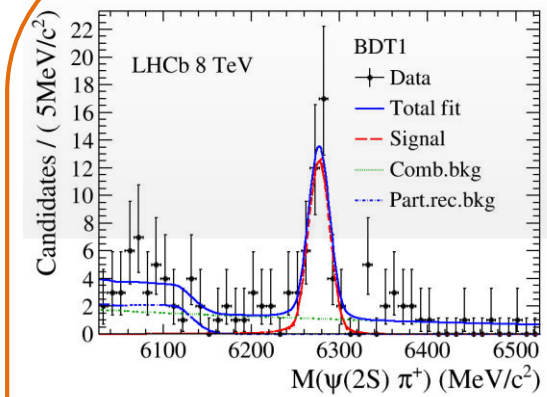
$$R = \frac{Br(B_c^+ \to \psi(2S)\pi^+)}{Br(B_c^+ \to J/\psi\pi^+)}$$

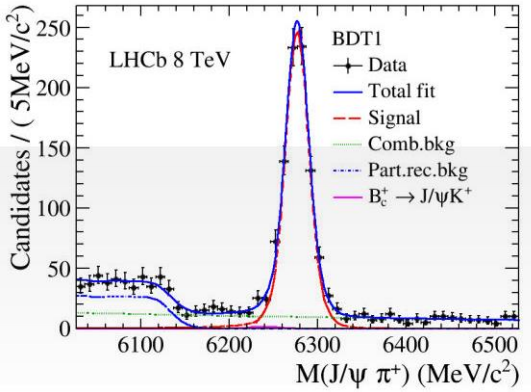
2011 2012

BDT1

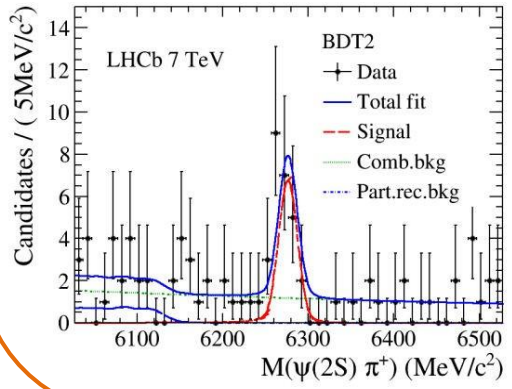


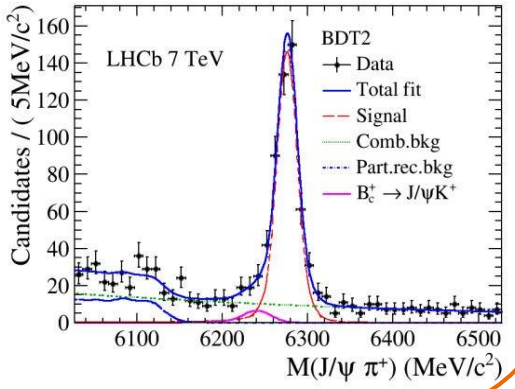


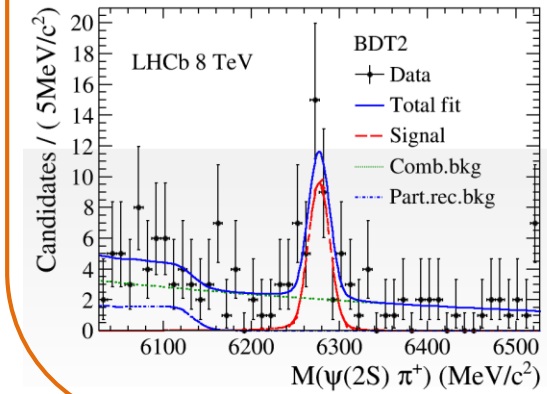


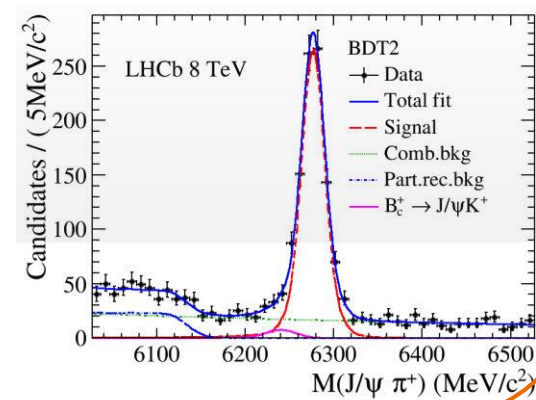


BDT2









$R^{2015} = 0.268 \pm 0.032 \pm 0.007 \pm 0.006\ (Br)$ arXiv:1507.03516

$R^{2012} = 0.250 \pm 0.068 \pm 0.014 \pm 0.006\ (Br)$ PRD87 (2012) 071103

Conclusion

LHCb is today leading the field with the world-best measurements of

- **Mass(6274.7 ± 1.2) MeV/c^2**,
- **Lifetime (506 ± 9) fs** , and
- **production cross-section**.

The **second run of the LHC**, at higher luminosity and with enhanced cross-section, is expected to be the door to **precision measurements of the B_c^+ meson**, yielding to new exciting results, for example concerning **excited states.**

LHCb Papers on the B_c^+ meson	
PRD 87 (2013) 071103	Observation of $B_c^+ \to \psi(2S)\pi^+$
PRD 87 (2013) 112012	Observation of $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J\psi D_s^{*+}$
PRL (2012) 251802	First observation of $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$
PRL 109 (2012) 232001	B_c^+ production and mass with $B_c^+ \to J/\psi\pi^+$
JHEP 09 (2013) 075	First observation of $B_c^+ \to J/\psi K^+$
PRL 111 (2013) 181801	First observation of $B_c^+ \to B_s^0\pi^+$
JHEP 1311 (2013) 094	Observation of decay $B_c^+ \to J\psi K^+K^-\pi^+$
EPJC 74 (2014) 2839	Lifetime measurement with $B_c^+ \to J/\psi\mu^+\nu X$
JHEP 05 (2014) 148	Evidence of $B_c^+ \to J/\psi 3\pi^+ 2\pi^-$
PRD 90 (2014) 032009	$Br(B_c^+ \to J/\psi\mu^+\nu)/Br(B_c^+ \to J/\psi\pi^+)$
PRL 113 (2014) 152003	Observation of $B_c^+ \to J/\psi p\bar{p}\pi^+$
PRL 114 (2015) 132001	B_c^+ production at $\sqrt{s} = 8$ TeV
PLB 742 (2015) 29	B_c^+ lifetime with $B_c^+ \to J/\psi\pi^+$
arXiv:1507.03516	Update $B_c^+ \to \psi(2S)\pi^+$

Additional figures

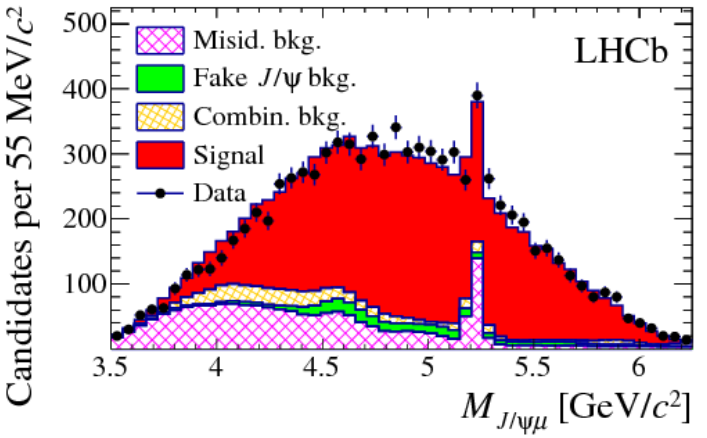
Lifetime measurement

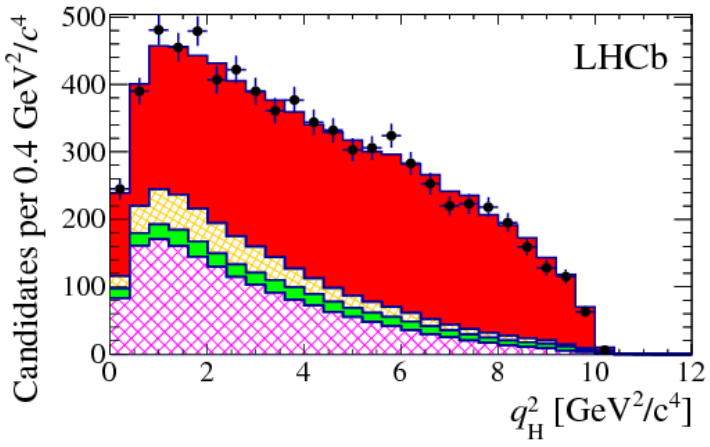
To assess in a data-driven way the effect of theoretical inputs to the signal model, we deform the simulated Dalitz plane with two deformation parameters α_ν and α_ψ, and perform the full 2D fit.

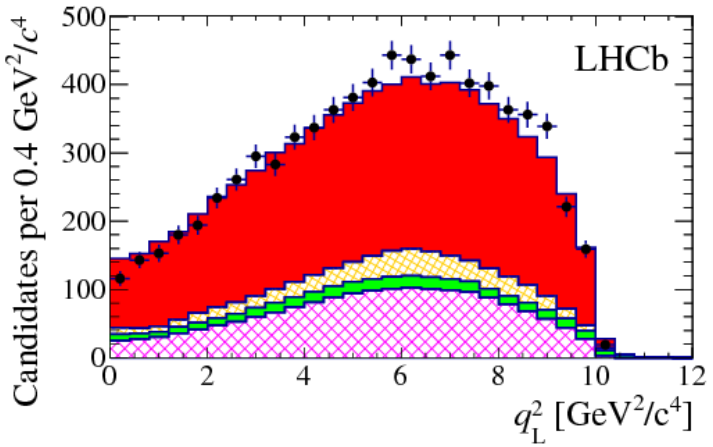
The goodness of each fit is measured with a binned method comparing the distributions of $m(J/\psi\mu^+)$ and of the two solutions of q^2 got from partial reconstruction.

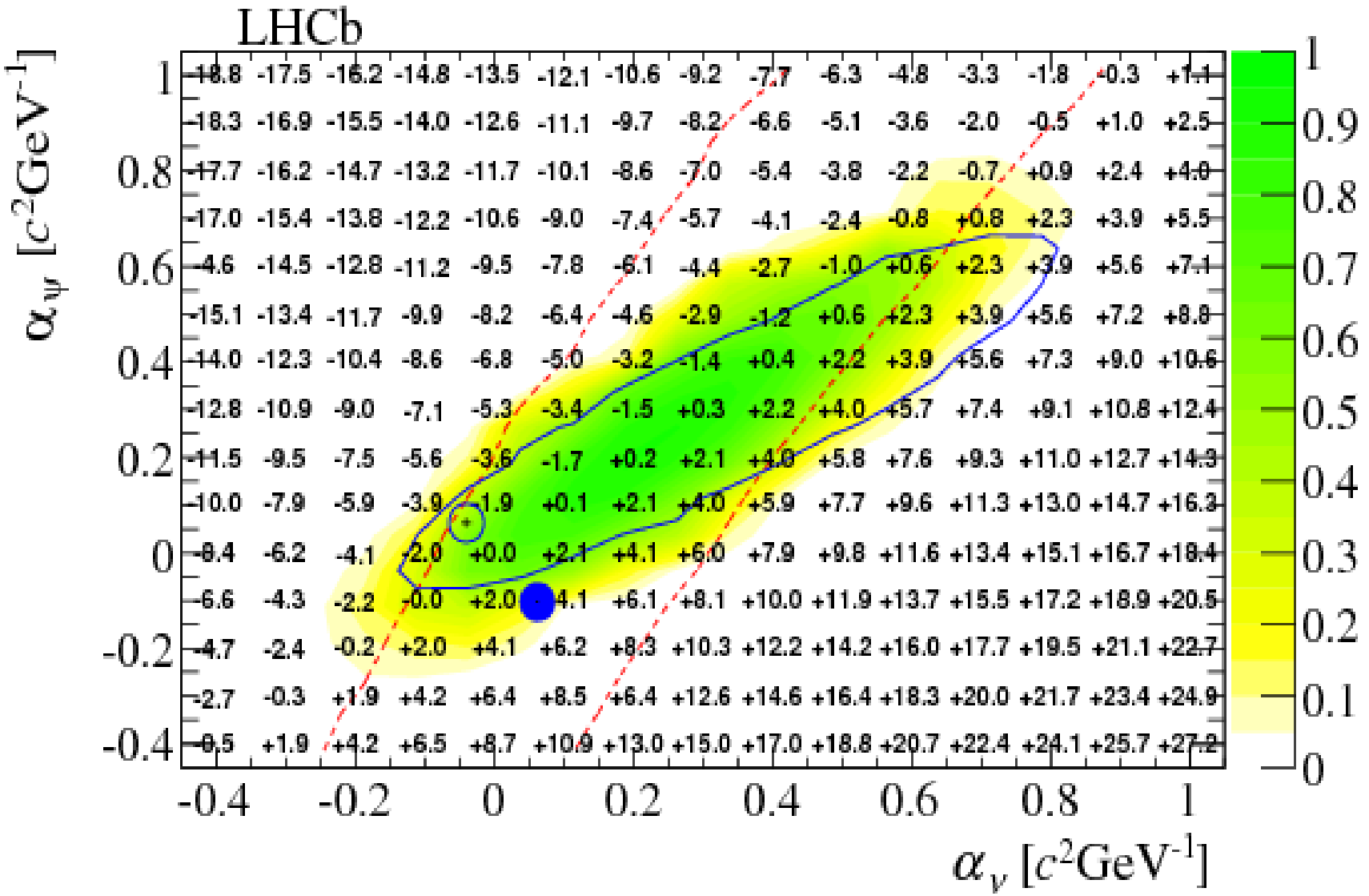
No offset larger than 5 fs (1% of τ_{Bc}) is found to be consistent with data.

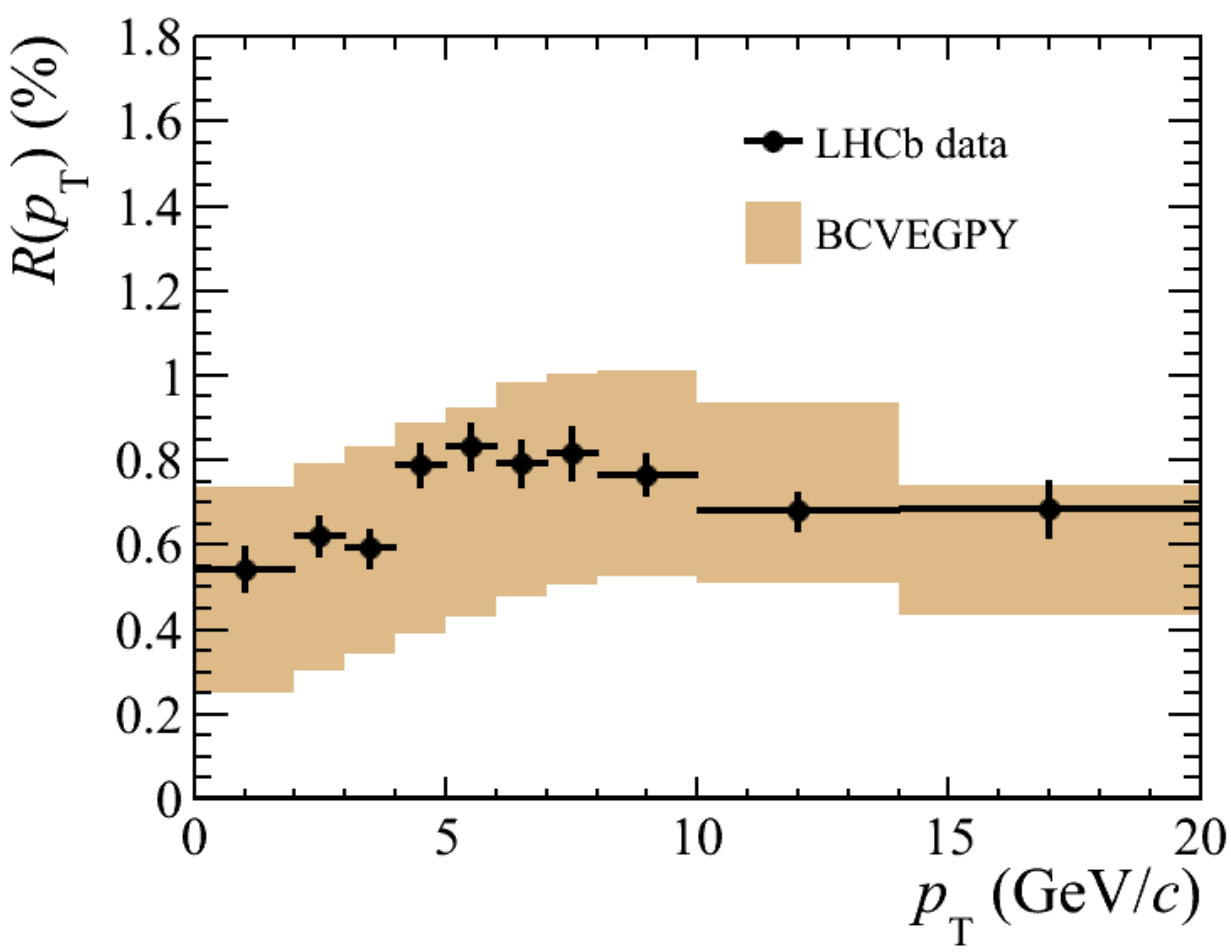
5 fs is thus taken as systematic uncertainty on theoretical inputs.

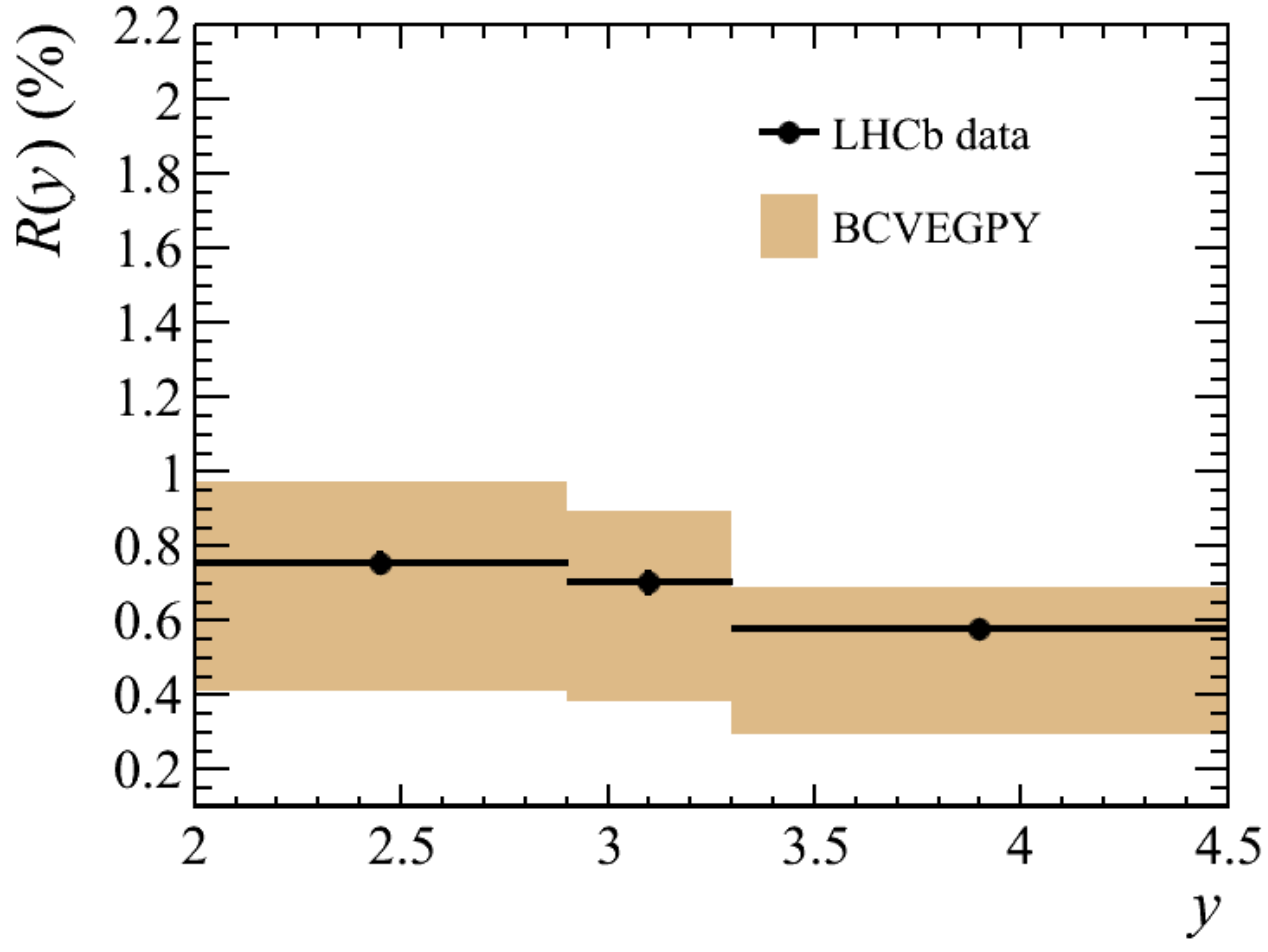







LHCb
α_ψ [c^2GeV^{-1}]
α_ν [c^2GeV^{-1}]
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.4 -0.2 0 0.2 0.4 0.6 0.8 1
0.9
0.7
0.5
0.3
0.1


$R(p_T)$ (%)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
p_T (GeV/c)
LHCb data
BCVEGPY


$R(y)$ (%)
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
2
2.5
3
3.5
4
4.5
y
LHCb data
BCVEGPY