Implications of LHCb measurements and future prospects workshop
8-10 November 2017

bc-hadrons at LHCb

Daria Savrina on behalf LHCb collaboration

Institute of Theoretical and Experimental Physics (Moscow)
Skobeltsyn Institute for Nuclear Research (Moscow)

Outline

Introduction

B_c-mesons

- Searches for the new decays
  - $B^+_c \to J/\psi D^{(*)} K^{(*)}$
  - $B^+_c \to D^{0(*)} h^+$
- Searches for the excited B_c states

Prospects

- B_c spectroscopy
- Studies of the B_c decays
- Towards Ξ_{bc}

bc-hadrons

Three lighest states: B^+_c-meson ([$\bar{b}$c]), Ξ^0_{bc}- and Ξ^+_{bc}-baryons ([bcd], [bcu])

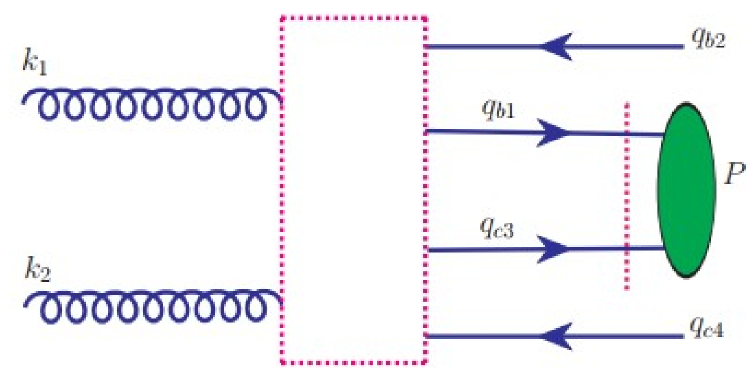
B^+_c-meson observed by the CDF collaboration in 1998 [Phys. Rev. Lett. 81, 2432]

- Not accessible by the B-factories → least studied of all B-meson
- Only 16 decay modes established by now, with major contribution from LHCb

Ξ_{bc} have not been observed by now

Two heavy quarks pairs need to be produced

- suppressed by an order of α_s^2 with respect to quarkonium production



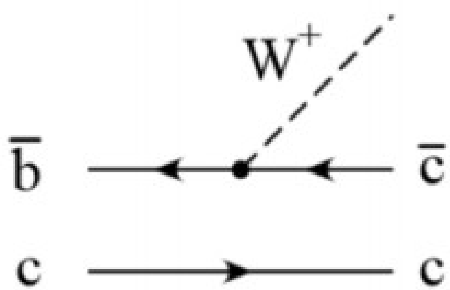
[Phys.Rev. D83 (2011) 034026]

Can decay only through weak interaction

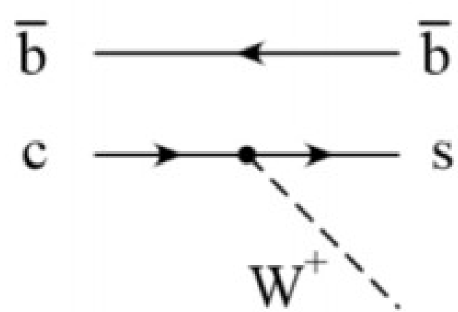
- Leads to a relatively long lifetime

For B^+_c:

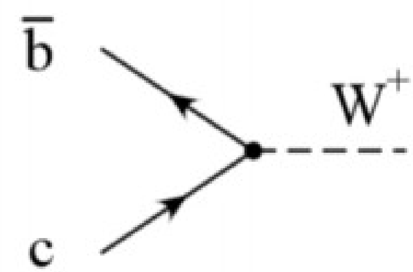
~20%



~70%



~10%



[Phys.Atom.Nucl.67 (2004) 1559]

Searches for new B_c decays

$B^+_c \to J/\psi D^{(*)} K^{(*)}$

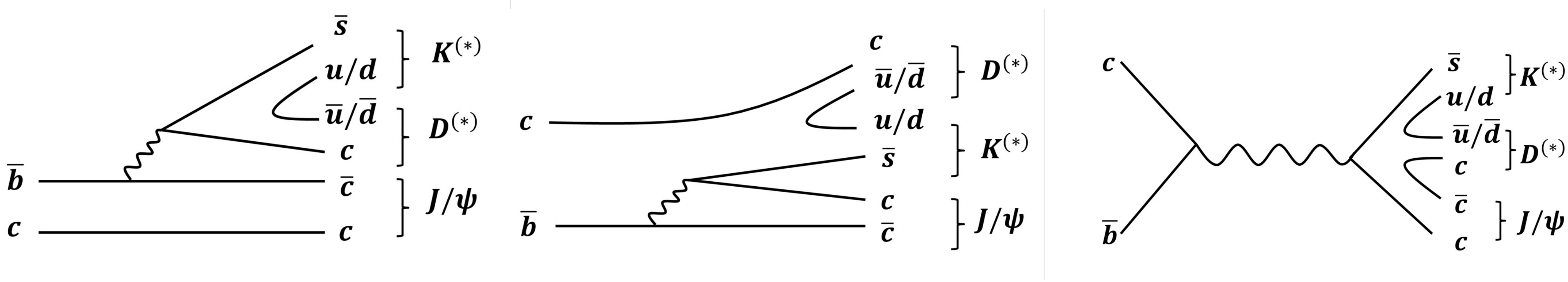
[Phys. Rev. D 95, 032005 (2017)]

Motivation

Information on the $B \to D^{(*)}\overline{D}^{(*)}K^*$ decays branching fraction

Studying the DK system for the D_{SJ} contribution

Opens the door to the possible exotic searches in $J/\psi D$ and close to DD threshold



Modes reconstructed

$B_c^+ \to J/\psi(\to \mu^+\mu^-)D^0(\to K^-\pi^+\pi^-\pi^+)K^+$

$B_c^+ \to J/\psi(\to \mu^+\mu^-)D^0(\to K^-\pi^+)K^+$

Partially reconstructed $B_c^+ \to J/\psi(\to \mu^+\mu^-)D^{*0}(\to D^0 + \gamma/\pi^0)K^+$

$B_c^+ \to J/\psi(\to \mu^+\mu^-)D^+(\to K^-\pi^+\pi^+)K^{*0}(\to K^+\pi^-)$

Partially reconstructed $B_c^+ \to J/\psi(\to \mu^+\mu^-)D^{*+}(\to D^0\pi^+)K^{*0}(\to K^+\pi^-)$

$B^+_c \to J/\psi D^{(*)} K^{(*)}$

[Phys. Rev. D 95, 032005 (2017)]

Data: 3 fb^{-1}, full Run 1 sample

Event selection: common loose preselection+BDT trained separately for each decay

2 first observations and 2 first evidences:

$$\frac{\mathcal{B}(B_c^+ \to J/\psi D^0 K^+)}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)} = 0.432 \pm 0.136 \pm 0.028,$$

$$\frac{\mathcal{B}(B_c^+ \to J/\psi D^{*0} K^+)}{\mathcal{B}(B_c^+ \to J/\psi D^0 K^+)} = 5.1 \pm 1.8 \pm 0.4,$$

$$\frac{\mathcal{B}(B_c^+ \to J/\psi D^{*+} K^{*0})}{\mathcal{B}(B_c^+ \to J/\psi D^0 K^+)} = 2.10 \pm 1.08 \pm 0.34,$$

$$\frac{\mathcal{B}(B_c^+ \to J/\psi D^+ K^{*0})}{\mathcal{B}(B_c^+ \to J/\psi D^0 K^+)} = 0.63 \pm 0.39 \pm 0.08,$$

Most precise single mass measurement:

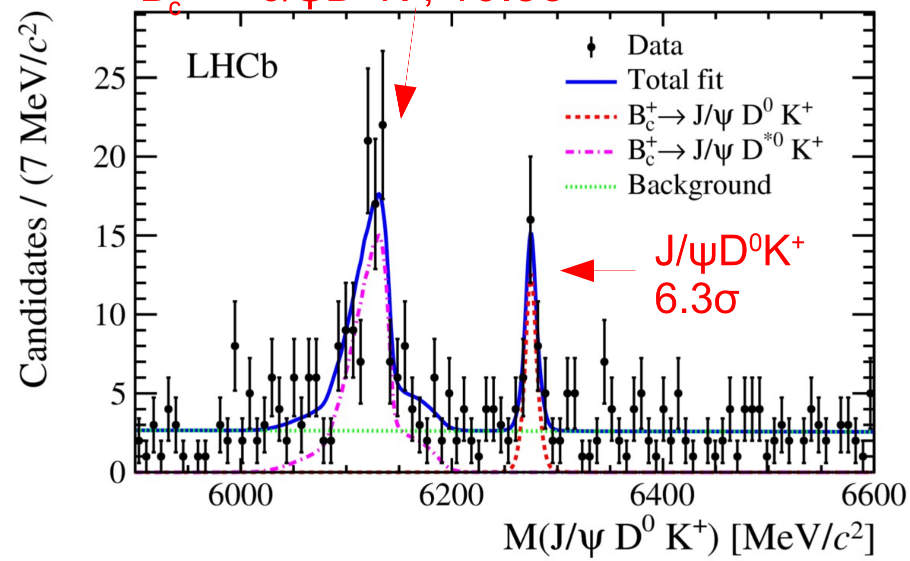
$$M(B_c^+) = 6274.28 \pm 1.40 \pm 0.32 \text{ MeV}/c^2$$

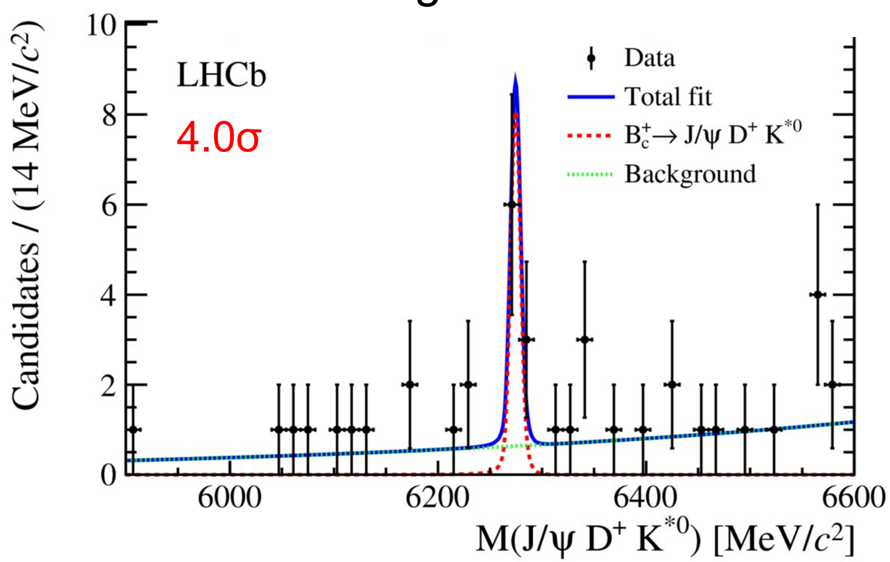
Consistent with previous LHCb measurements and the world average

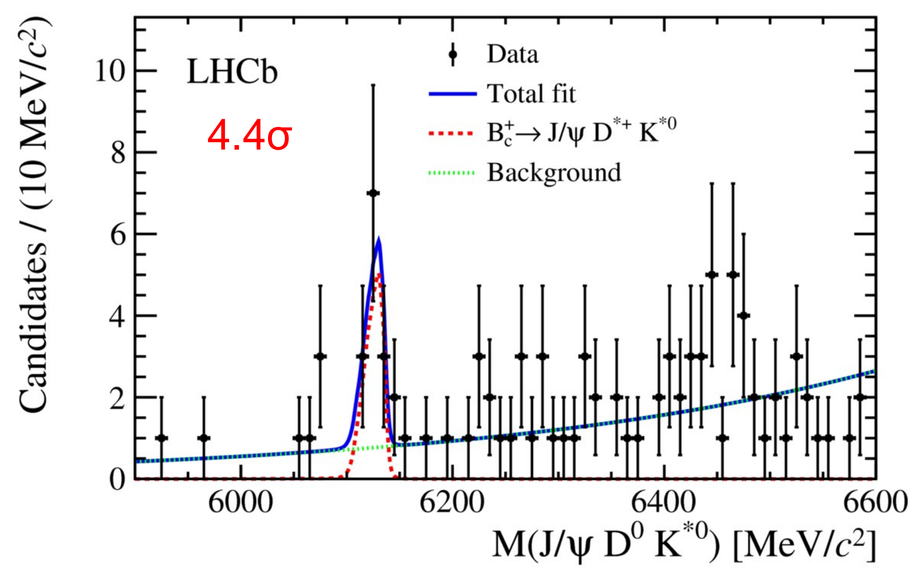
$D^0(\to K^-\pi^+\pi^-\pi^+)$ and $D^0(\to K^-\pi^+)$ combined

Partially reconstructed

$B_c^+ \to J/\psi D^{0*} K^+$, 10.3σ



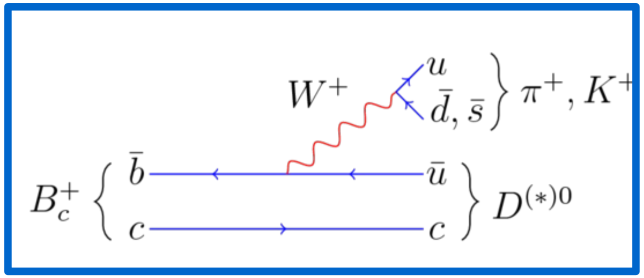


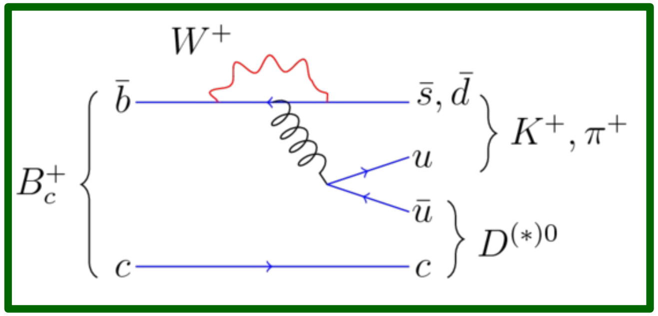


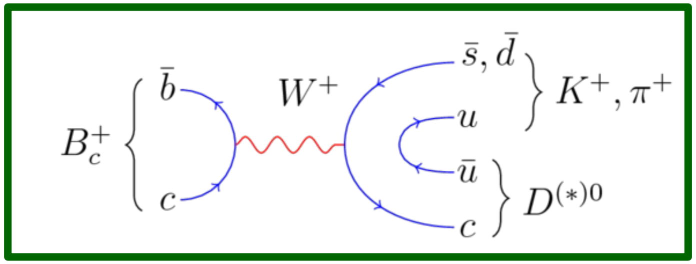
$B^+_c \to D^{0(*)}h^+$

[Phys. Rev. Lett 118, 111803 (2017)]

Cabbibo-suppressed with respect to $B^+_c \to J/\psi\pi$







May enhance the branching fraction

Theoretical predictions vary in a large range

1.3×10^{-7} to 6.6×10^{-5} for $B^+_c \to D^0K^+$

2.3×10^{-7} to 2.3×10^{-6} for $B^+_c \to D^0\pi^+$ [JHEP 1106 (2011) 015]

[Eur.Phys.J.C5 (1998) 705]

[Eur.Phys.J.C63 (2009) 435]

Modes under study (h = K, π):

- $B_c^+ \to D^0(\to K^-\pi^+\pi^-\pi^+)h^+$
- $B_c^+ \to D^0(\to K^-\pi^+)h^+$
- Partially reconstructed $B_c^+ \to D^{*0}(\to D^0+\gamma/\pi^0)h^+$

Measure ratios for all four modes normilizing by the known $B^+ \to \overline{D}\pi$ decay

$$R_{D^{(*)0}h} = \frac{f_c}{f_u} \times \mathcal{B}(B_c^+ \to D^{(*)0}h^+)$$

$B^+_c \to D^{0(*)}h^+$

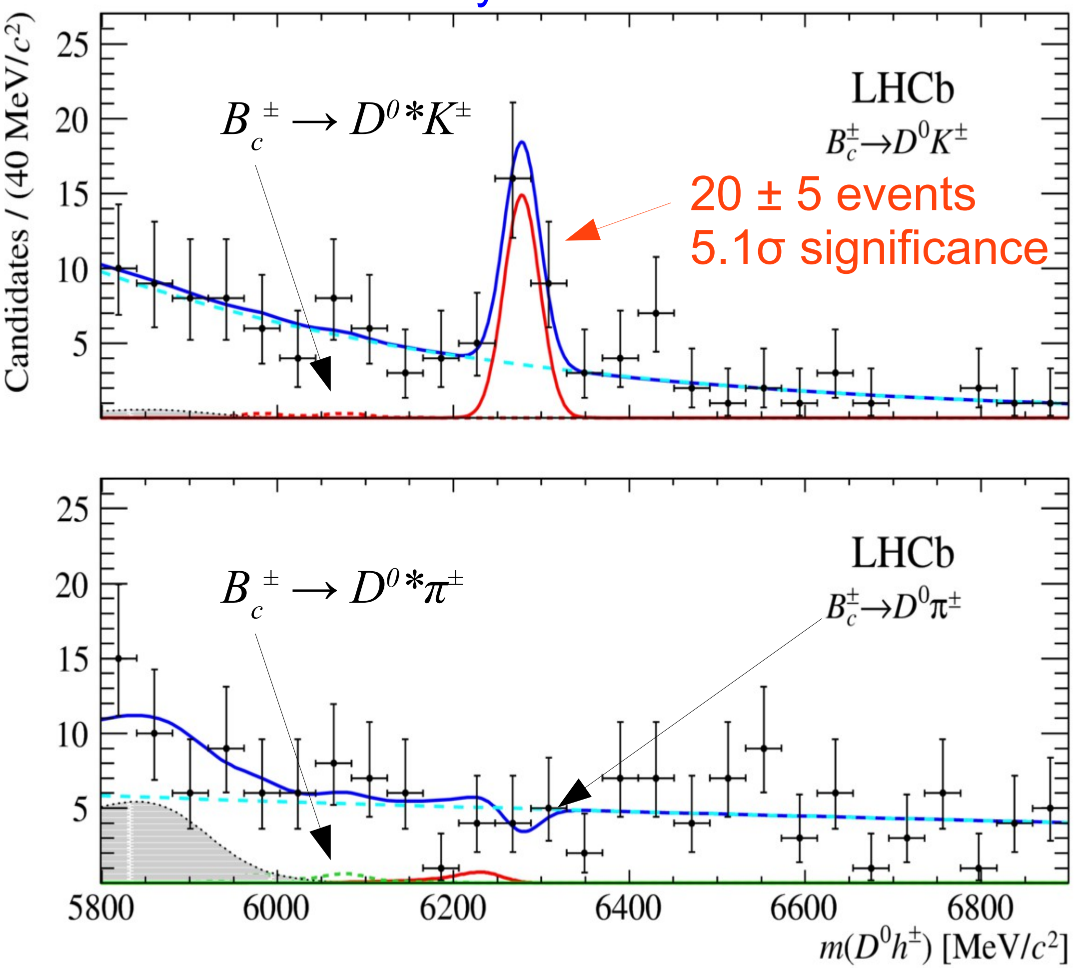
Data: 3 fb^{-1}, full Run 1 sample

[Phys. Rev. Lett 118, 111803 (2017)]

Event selection: loose preselection + 2 BDT trained to remove D^0 and non-D^0 background

Simultaneous fit to 2 decay modes

2- and 4-body D^0 modes combined



For fully reconstructed decays:

- B_c masses fixed to the PDG values
- Resolutions are estimated from the normalization channel

First observation of the $B_c^\pm \to D^0K^\pm$ decay

$$R_{D0K} = (9.3^{+2.8}_{-2.5} \pm 0.6) \times 10^{-7}$$

At the high end of theoretical predictions

Absence of $B_c^\pm \to D^0\pi^\pm$ means that the tree-level contribution is not dominating one

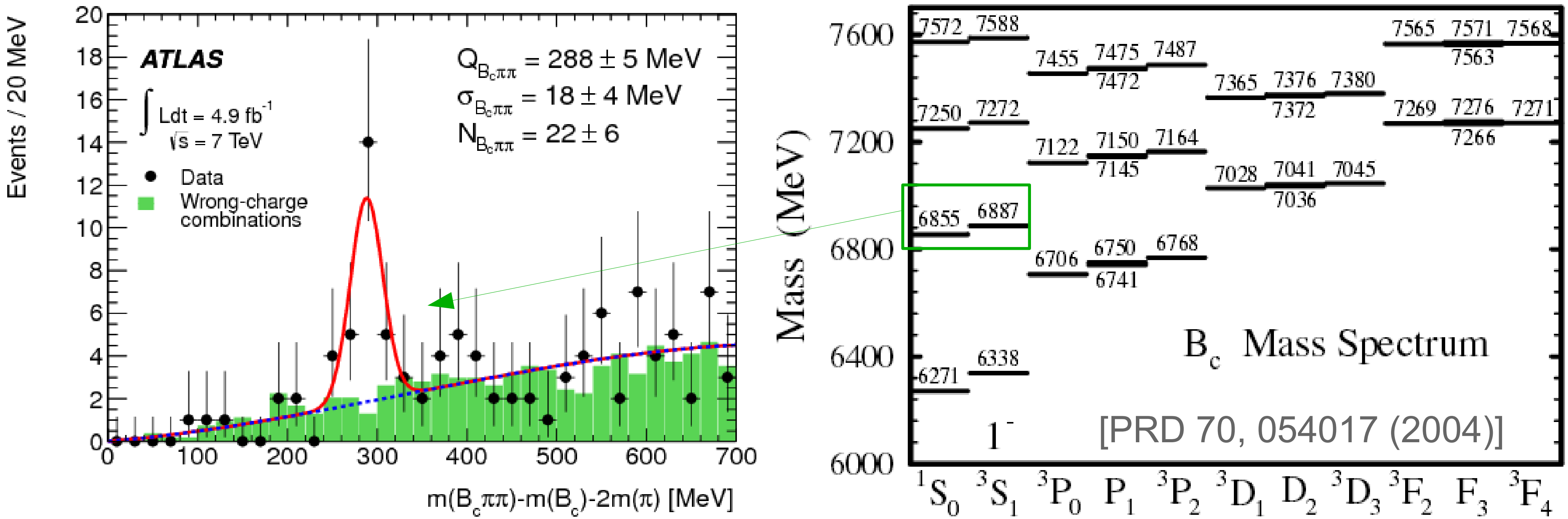
For the other modes the upper limits are set up @95% CL

$$R_{D^0\pi} < 3.9 \times 10^{-7}$$
$$R_{D^{*0}\pi} < 1.1 \times 10^{-6}$$
$$R_{D^{*0}K} < 1.1 \times 10^{-6}.$$

B_c spectroscopy

Excited states

B_c^+ has a large spectrum, the excited states still remain to be observed



Many theoretical predictions for spectroscopy and properties.

[arxiv:9703341], [PRD 71, 074012].

First $B_c(2S)$ observation was recently claimed by ATLAS

$B^+_c\pi^+\pi^-$ final state

Measured mass $6842 \pm 4 \pm 5$ MeV/c^2

[Phys. Rev. Lett. 113, 212004 (2014)]

The most probable interpretation is either $B_c(2^3S_1)$ or sum of $B_c(2^3S_1)$ and $B_c(2^1S_0)$

Search for excited B_c states

[LHCb-PAPER-2017-042] preliminary

Data: 2 fb^{-1}

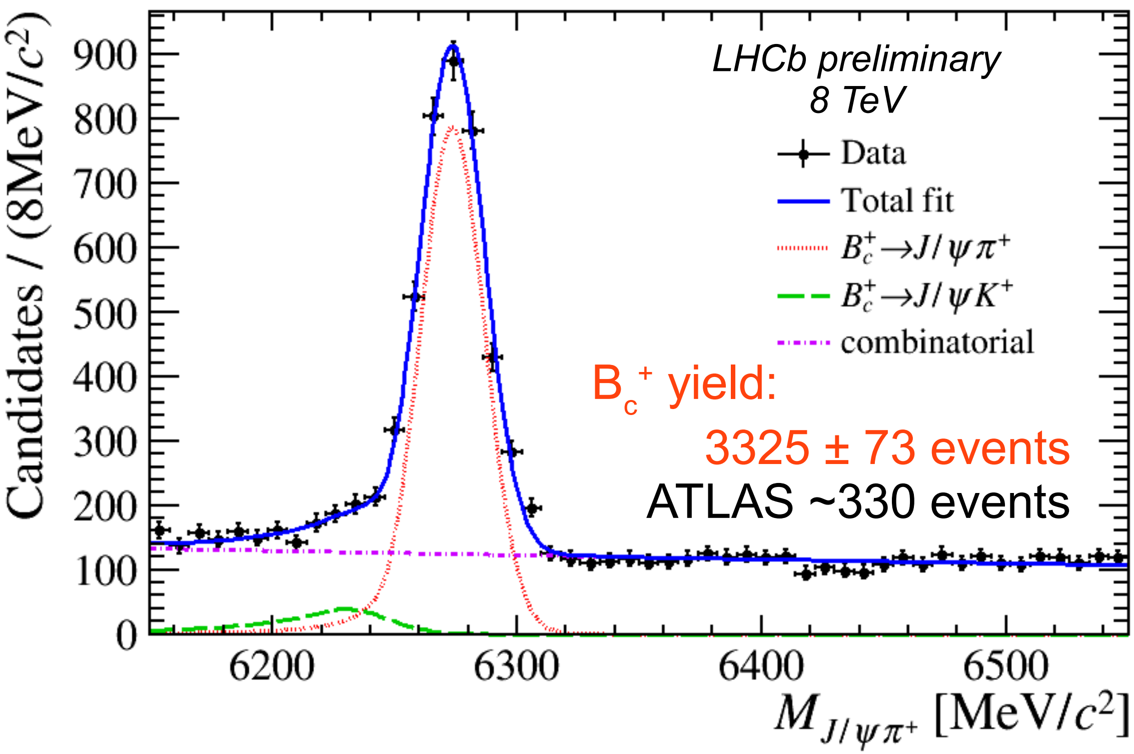
Search for $B_c(2^1S_0)$ and $B_c(2^3S_1)$ states

$B_c(2^1S_0) \to B_c (\to J/\psi\pi^+) \pi^+\pi^-$

$B_c(2^3S_1) \to B_c^*(\to B_c (\to J/\psi\pi^+)\gamma) \pi^+\pi^-$ with missing photon

Branching fractions 39-59%

[Phys. Rev. 239 D70 (2004) 054017], [Phys. Atom. Nucl. 67 (2004) 250 1559]



B_c^+ yield: 3325 ± 73 events

ATLAS ~330 events

No significant signal in the $B_c\pi^+\pi^-$ invariant mass is seen

Upper limits set up for the ratio:

$$\mathcal{R} = \frac{\sigma_{B_c^{(*)+}(2S)}}{\sigma_{B_c^+}} \cdot \mathcal{B}_{B_c^{(*)+}(2S)\to B_c^{(*)+}\pi^+\pi^-}$$

With the help of CL_s method

Scan over wide mass range

$B_c(2^1S_0)$: [6830, 6890] MeV/c^2

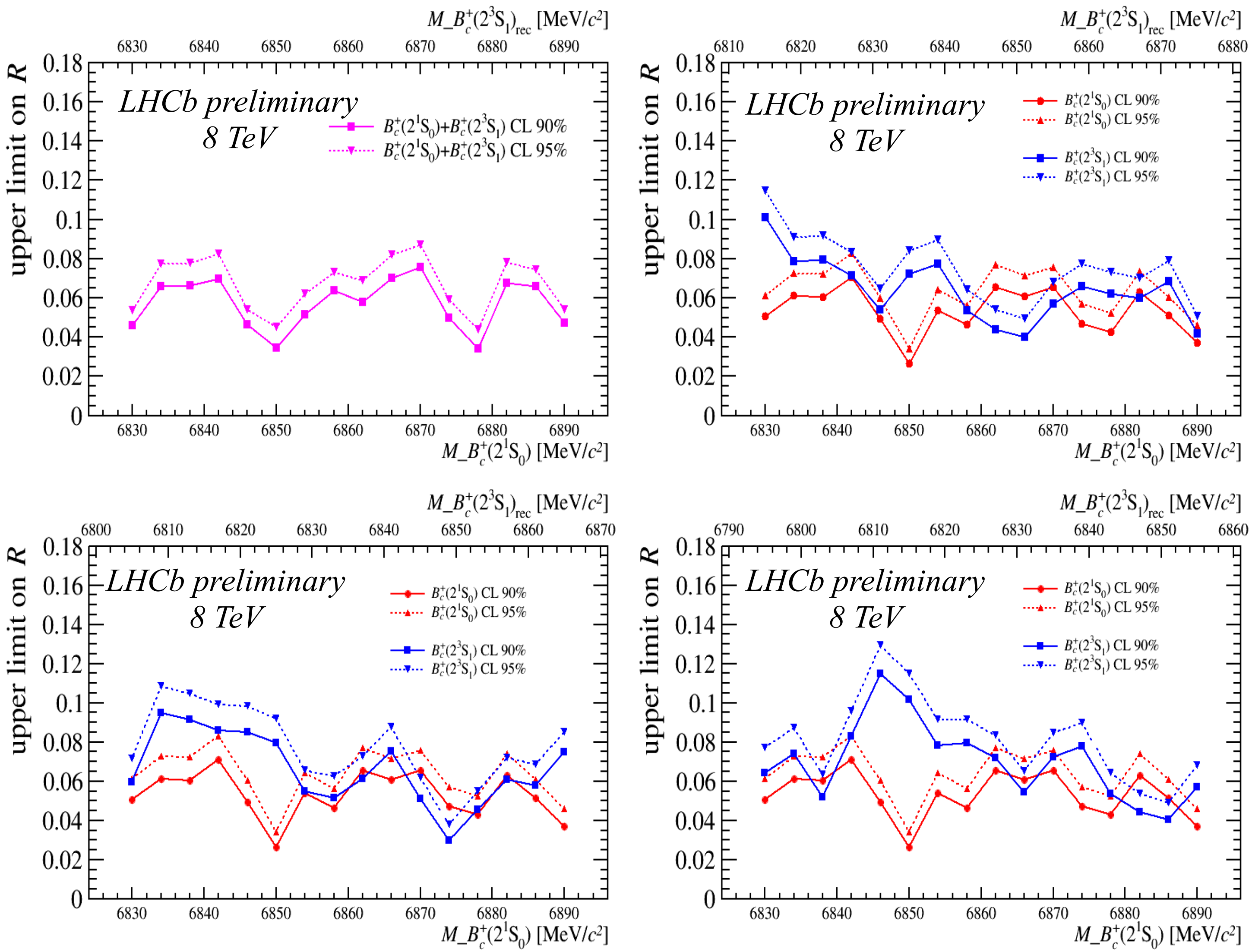
$B_c(2^3S_1)$: [6795, 6890] MeV/c^2

Search for excited B_c states

[LHCb-PAPER-2017-042] preliminary

Mass resolution fixed from simulation, cross-checked with data for $B_c \rightarrow J/\psi\pi^+\pi^+\pi^-$

4 different values of reconstructe mass difference between $B_c(2^1S_0)$ and $B_c(2^3S_1)$



Consistent with background-only hypothesis within 3σ

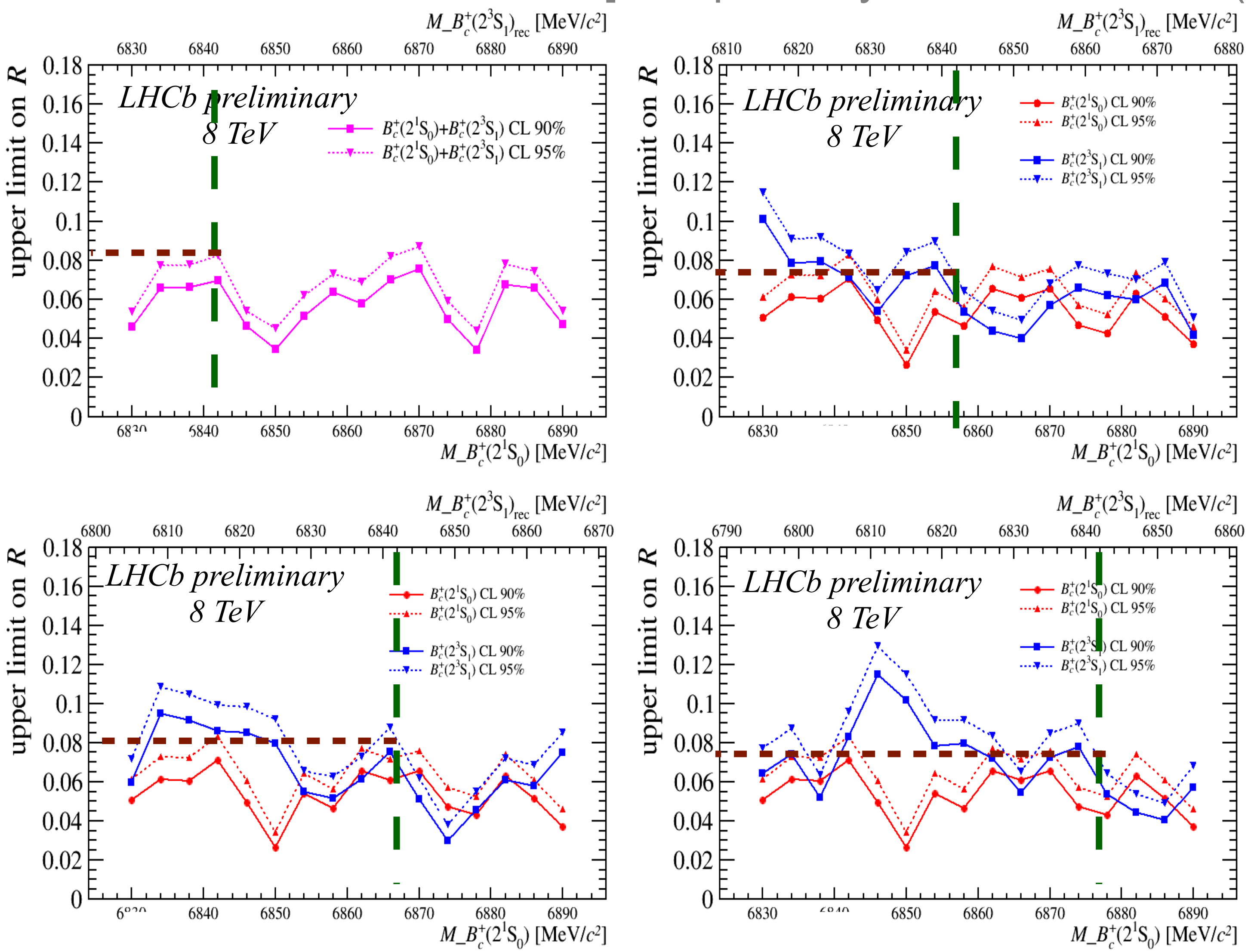
Search for excited B_c states

[LHCb-PAPER-2017-042] preliminary

With the event yields and mass measured by ATLAS 6842 ± 4 ± 5 MeV/c^2 and the expected R would be more than 0.15, which is in some tension with LHCb upper limits

Should not have significant dependence on y and p_T

[Comput. Phys. Commun. 174 (2006) 241]



Prospects

Future

Production rates increase with energy

$\sigma(\Xi_{bc}^{+}) \sim \sigma(\Xi_{bc}^{0}) \sim 10\text{nb} @ 7\text{ TeV}$

$\sigma(\Xi_{bc}^{+}) \sim \sigma(\Xi_{bc}^{0}) \sim 20\text{nb} @14\text{ TeV}$

[Phys.Rev.D 83 034026 (2011)]

$\sigma(B_{c}^{+}) \sim 20\text{ nb} @ 7\text{ TeV}$

$\sigma(B_{c}^{+}) \sim 40\text{ nb} @14\text{ TeV}$

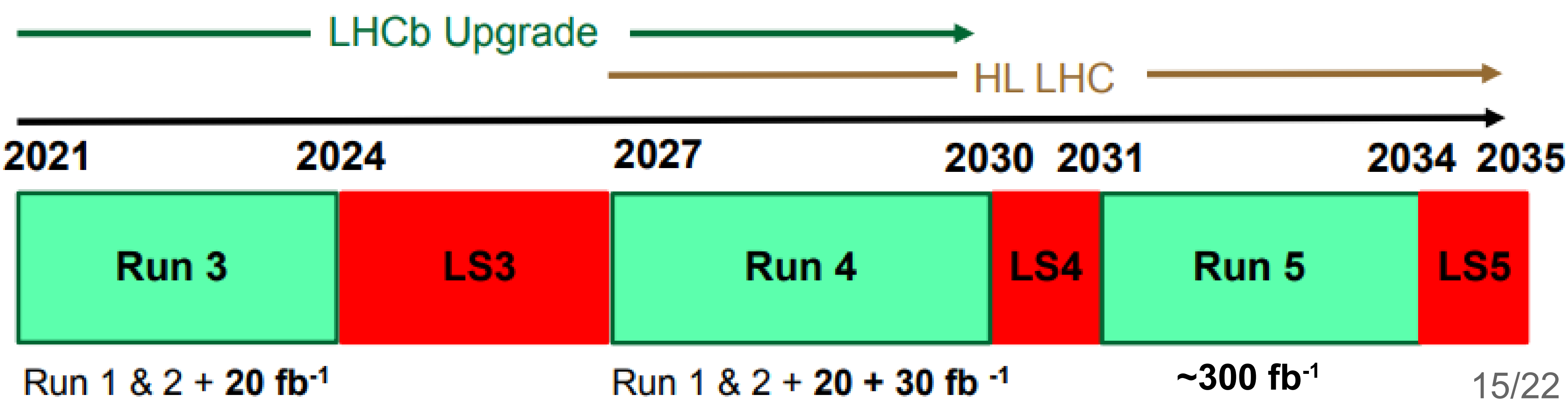
[arXiv:hep-ph/9703341]

Rough estimate ~200 increase of bc-hadrons yields after Run5

Moving towards real-time reconstruction

For some studies allows „offline quality“ already now

Important to have all modes covered by the trigger



B_c spectroscopy

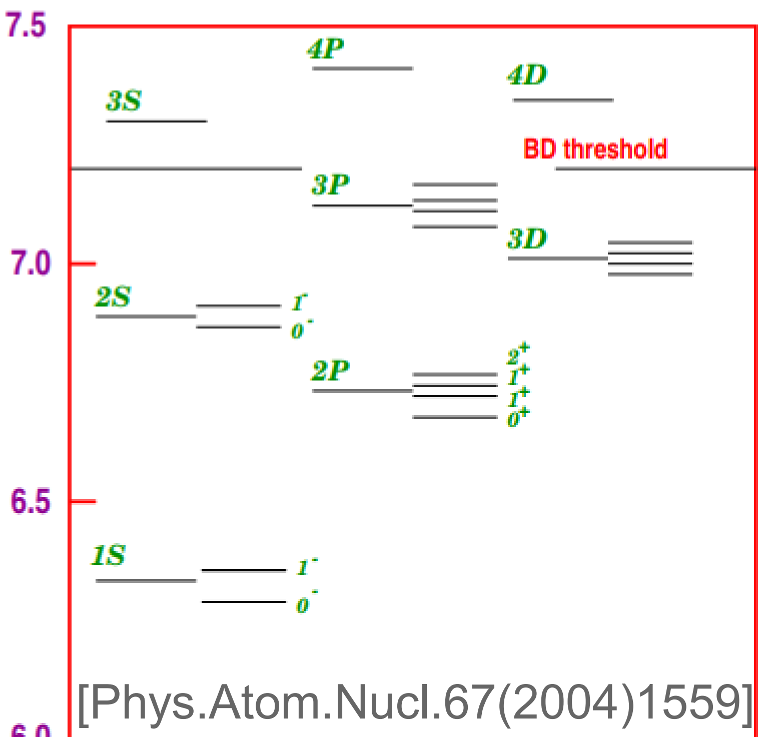
16 states expected below the BD threshold

- 2 S-wave, 2 P-wave and 1 D-wave

Strong decays are disfavoured

- Very narrow: width < 100 keV
- Cascade decays to ground state with emission of γ or ππ
- Plenty of theoretical predictions given

$B_c^{**} \rightarrow BD$ with Run5 data



[Phys.Atom.Nucl.67(2004)1559]

[PRD 70, 054017 (2004)]

Decay Chain	Tevatron	LHC
$1^3S_1 \xrightarrow{\gamma} B_c$	3.4×10^3	3.4×10^5
$2^1S_0 \xrightarrow{\pi\pi} B_c$	1.8×10^3	1.8×10^5
$2^3S_1 \xrightarrow{\pi\pi} 1^3S_1 \xrightarrow{\gamma} B_c$	1.6×10^3	1.6×10^5
$2^3S_1 \xrightarrow{\gamma} B_c$	16	1.6×10^3
$1^3P_2 \xrightarrow{\gamma} 1^3S_1 \xrightarrow{\gamma} B_c$	6.7×10^2	6.7×10^4
$1P_1' \xrightarrow{\gamma} B_c$	5.9×10^2	5.9×10^4
$1P_1 \rightarrow \gamma 1^3S_1 \xrightarrow{\gamma} B_c$	5.5×10^2	5.5×10^4
$1P_1 \xrightarrow{\gamma} B_c$	1.2×10^2	1.2×10^4
$1^3P_0 \xrightarrow{\gamma} 1^3S_1 \xrightarrow{\gamma} B_c$	6.7×10^2	6.7×10^4
$1^3D_3 \xrightarrow{\pi\pi} 1^3S_1 \xrightarrow{\gamma} B_c$	3.5	3.5×10^2
$1^3D_3 \xrightarrow{\gamma} 1^3P_2 \xrightarrow{\gamma} 1^3S_1 \xrightarrow{\gamma} B_c$	64	6.4×10^3
$1D_2' \xrightarrow{\pi\pi} 1^1S_0$	1.7	1.7×10^2
$1D_2' \xrightarrow{\gamma} 1P_1' \xrightarrow{\gamma} B_c$	45	4.5×10^3
$1D_2 \xrightarrow{\pi\pi} 1^1S_0$	1.4	1.4×10^2
$1D_2 \xrightarrow{\gamma} 1P_1' \xrightarrow{\gamma} B_c$	9.5	9.5×10^2
$1D_2 \xrightarrow{\gamma} 1P_1 \xrightarrow{\gamma} B_c$	8.2	8.2×10^2
$1^3D_1 \xrightarrow{\pi\pi} 1^3S_1 \xrightarrow{\gamma} B_c$	3.1	3.1×10^2
$1^3D_1 \xrightarrow{\gamma} 1P_1' \xrightarrow{\gamma} B_c$	2.8	2.8×10^2
$1^3D_1 \xrightarrow{\gamma} 1P_1 \xrightarrow{\gamma} B_c$	3.6	3.6×10^2
$2^3P_2 \xrightarrow{\gamma} 2^3S_1 \xrightarrow{\gamma} B_c$	2.3	2.3×10^2
$2^3P_2 \xrightarrow{\gamma} 1^3S_1 \xrightarrow{\gamma} B_c$	72	7.2×10^3
$2P_1' \xrightarrow{\gamma} B_c$	90	9.0×10^3
$2P_1 \xrightarrow{\gamma} B_c$	12	1.2×10^3
$2P_1 \xrightarrow{\gamma} 2^3S_1 \xrightarrow{\gamma} B_c$	2.2	2.2×10^2
$2^3P_0 \xrightarrow{\gamma} 2^3S_1 \xrightarrow{\gamma} B_c$	2.8	2.8×10^2

[Phys.Atom.Nucl.67(2004)1559]

state	Γ_{tot}, KeV	dominant decay mode	BR, %
1^1S_1	0.06	$1^1S_0 + \gamma$	100
2^1S_0	67.8	$1^1S_0 + \pi\pi$	74
2^1S_1	86.3	$1^1S_1 + \pi\pi$	58
2^1P_0	65.3	$1^1S_1 + \gamma$	100
$2P\ 1^+$	89.4	$1^1S_1 + \gamma$	87
$2P\ 1'^+$	139.2	$1^1S_0 + \gamma$	94
2^3P_2	102.9	$1^1S_1 + \gamma$	100
3^1P_0	44.8	$2^1S_1 + \gamma$	57
$3P\ 1^+$	65.3	$2^1S_1 + \gamma$	49
$3P\ 1'^+$	92.8	$2^1S_0 + \gamma$	63
3^3P_2	71.6	$2^1S_1 + \gamma$	69
$3D\ 2^-$	95.0	$2P\ 1^+ + \gamma$	47
3^5D_3	107.9	$2^3P_2 + \gamma$	71
3^3D_1	155.4	$2^1P_0 + \gamma$	51
$3D\ 2'^-$	122.0	$2P\ 1'^+ + \gamma$	38

Spectroscopy in B_c decays

[EPJ C 73 (2013) 2373]

Conventional spectroscopy

Study of the D^0K^+ final state in $B_c^+ \to J/\psi D^{(*)0}K^+$

Run1: 26 ± 7 events in $B_c^+ \to J/\psi D^0K^+$ mode

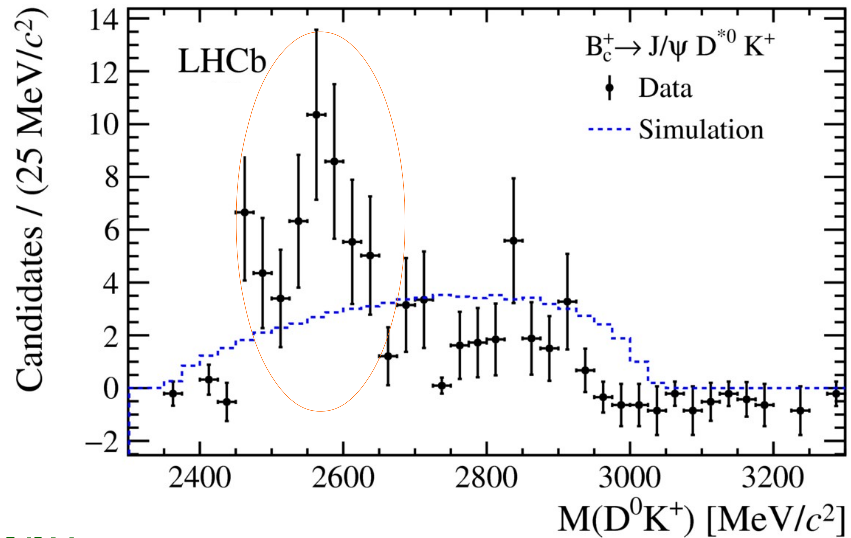
102 ±13 events in $B_c^+ \to J/\psi D^{0*}K^+$ mode

Run 5: 300 fb^{-1} @ 14 TeV

> 5000 $B_c^+ \to J/\psi D^0K^+$

~2×10^4 $B_c^+ \to J/\psi D^{0*}K^+$

[Phys. Rev. D 95, 032005 (2017)]



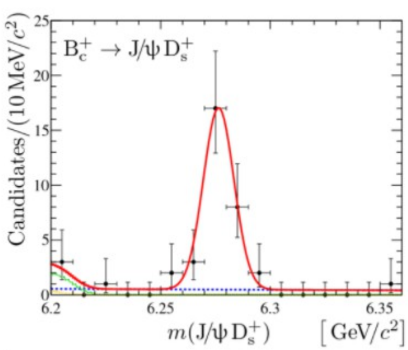
B^0_s spectroscopy

Amplitude analysis of $B_c^+ \to BK\pi^+$

Study of $B_c^+ \to B^0_s\{\gamma,\pi^0\}\pi^+$

Exotic spectroscopy

Doubly charmed tetraquark in $B_c^+ \to D^0\overline{D}{}^0D_s^+$

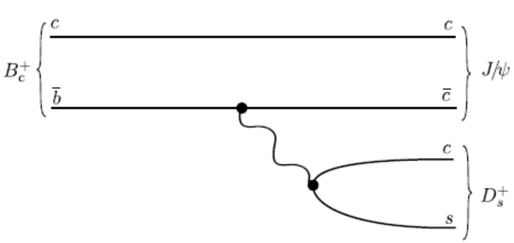


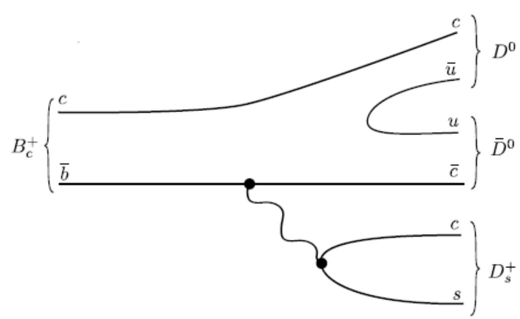
Run1: ~29 $B_c^+ \to J/\psi D_s^+$

Run 5: 300 fb^{-1} @ 14 TeV

~6000 $B_c^+ \to J/\psi D_s^+$

~10^2 $B_c^+ \to D^0\overline{D}{}^0D_s^+$





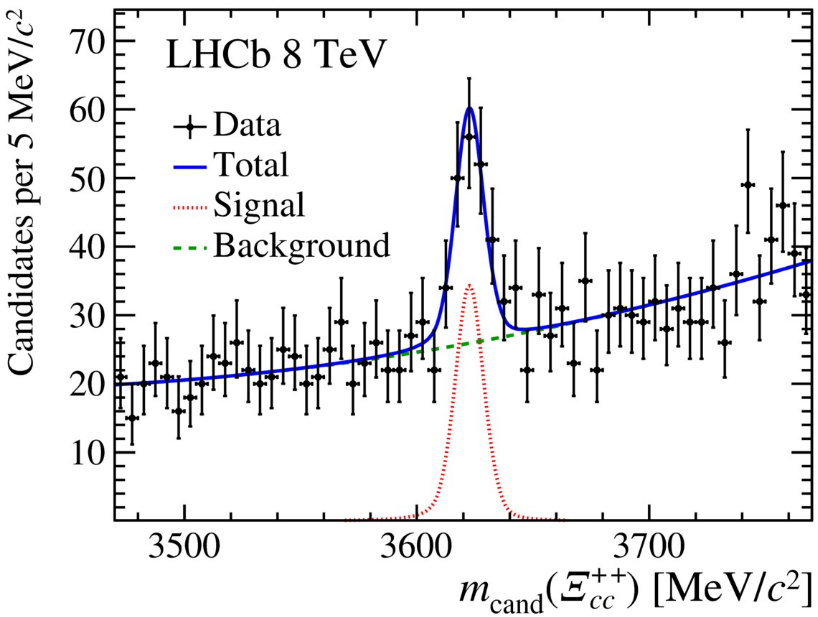
Many ideas of searches of tetraquarks in B^+_c decays

[Phys.Rev.D94(2016)034036]
[Phys.Rev.D88(2013)054029]

Possibility of pentaquark searches

Study of the $B_c^+ \to J/\psi p\bar{p}\pi^+$

Ξ_{bc} studies



[Phys. Rev. Lett. 119(2017)112001]

First double-heavy baryon observed this summer

Should move further!

Production rate

Twice lower than B^+_c

~43% (bc) → Ξ_{bc}^0

~43% (bc) → Ξ_{bc}^+

~13% (bc) → Ω_{bc}^0

[Phys.Rev.D83 (2011) 034026]

Lifetime predictions suffer from large uncertainties :-(

Ξ_{cc}^{++} lifetime ~185-500 fs

Ξ_{bc}^{+} lifetime ~244-340 fs

Ξ_{bc}^{0} lifetime ~ 93-280 fs

[arXiv:hep-ph/0201071]
[Eur.Phys.J.C16 (200) 461]
[Phys. Rev. D 90, 094007 (2014)]
[FERMILAB-PUB-86-189-T]

Many decay modes predicted

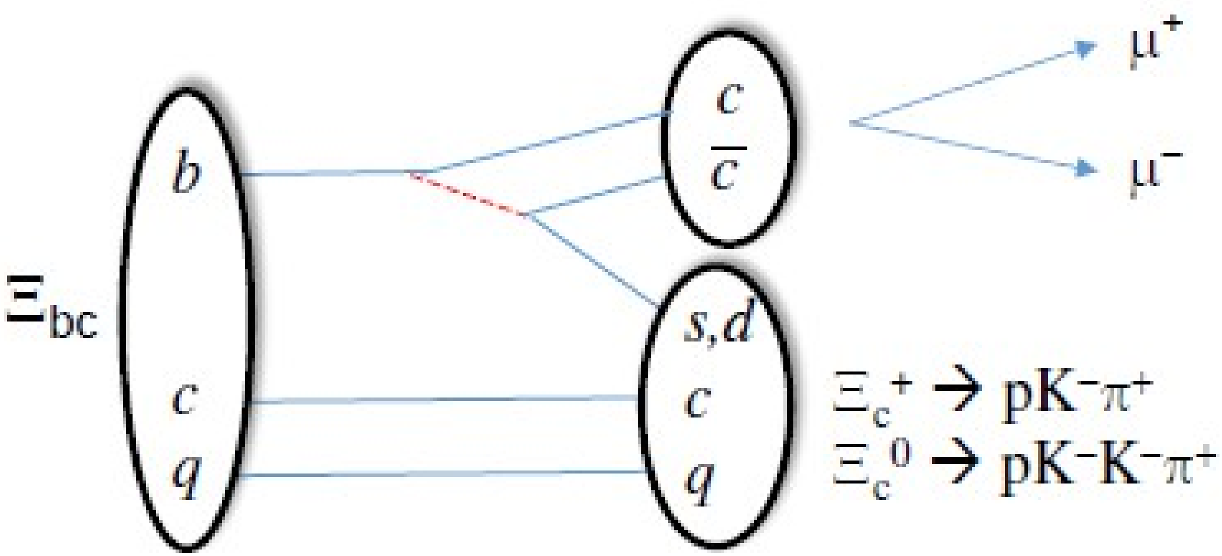
May combine them to increase the statistics!

Hard to predict branching fractions → large uncertainties

Ξ_{bc} most promising channels

Charmonium modes

Cabbibo-favoured



Clear signature and very efficient dimuon trigger

A particle with long decay time in the final state

Easy to compare/normalize by $B^+_c \to J/\psi D_s$

Same diagram vertices

„Golden mode“ $\Xi_{bc}^0 \to J/\psi\Lambda_c^+K^-$

$$\frac{\mathcal{N}(\Xi_{bc} \to J/\psi\Lambda_c^+K^-)}{\mathcal{N}(B_c^+ \to J/\psi D_s^{(*)+})} = \underbrace{\frac{\sigma(pp \to \Xi_{bc}X)}{\sigma(pp \to B_c^+X)}}_{\sim 0.5} \times \underbrace{f_{\Xi_{bc}\to\Xi_{bc}^0}}_{\sim 0.43} \times \underbrace{\frac{\mathcal{B}r(\Xi_{bc} \to J/\psi\Lambda_c^+K^-)}{\mathcal{B}r(B_c^+ \to J/\psi D_s^{(*)+})}}_{\sim 0.2 \text{ (color suppression)}} \times \underbrace{\epsilon_{K^-}}_{\sim 0.7}$$

~100 $B^+_c \to J/\psi D_s$ events observed in Run1, expect

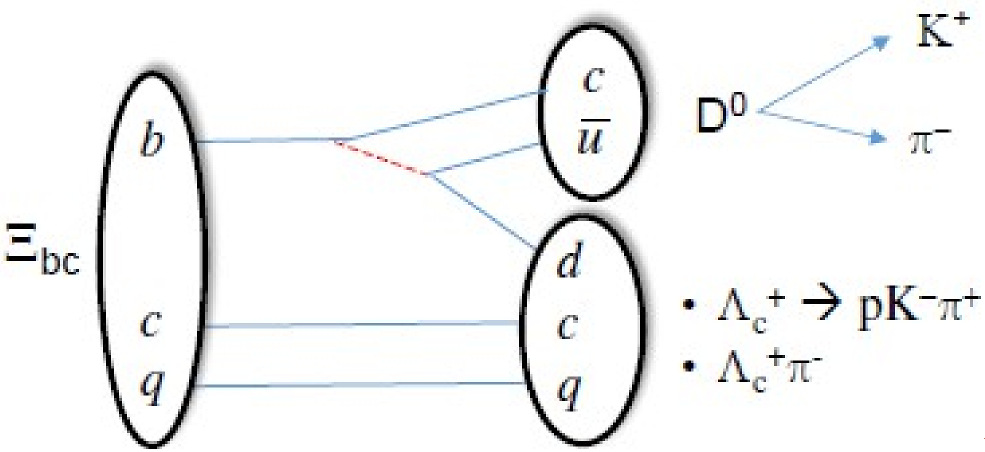
~3 $\Xi_{bc}^0 \to J/\psi\Lambda_c^+K^-$ events in Run1

~600 $\Xi_{bc}^0 \to J/\psi\Lambda_c^+K^-$ events in Run5

Ξ_{bc} most promising channels

Decays to open charm

Cabbibo-favoured



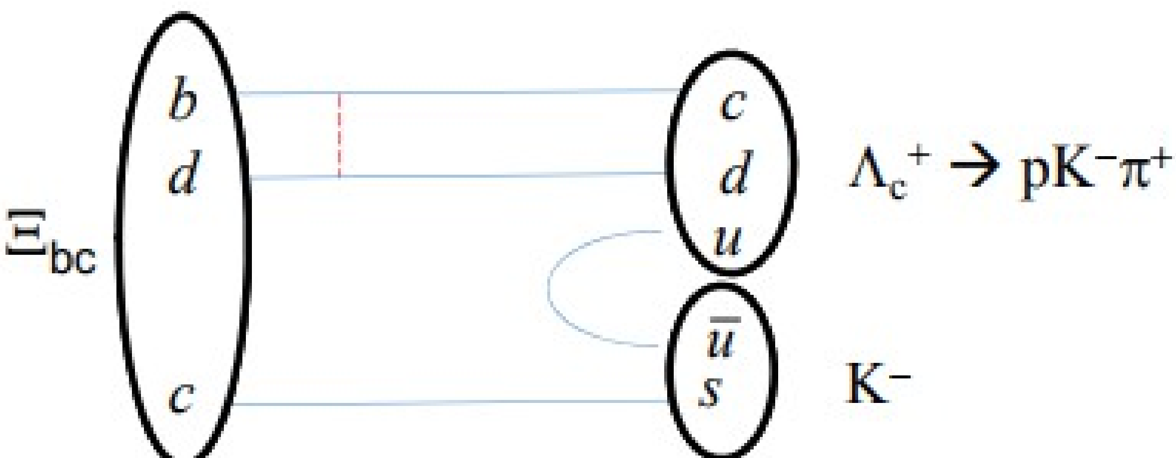
Less efficient hadron trigger

Two particles with long decay time in the final state

Clear signature

Decays with one charm hadron

Exchange or loop diagram



Less efficient hadron trigger

A particle with long decay time in the final state

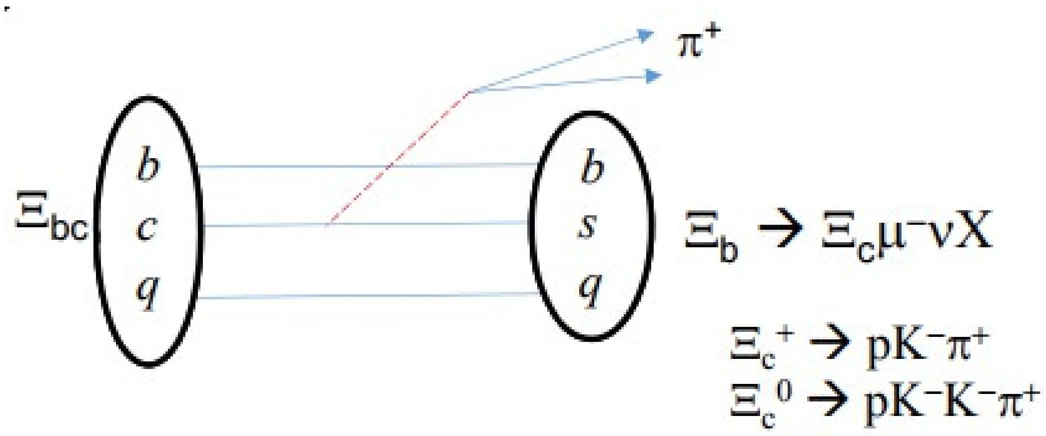
Only one intermediate branching fractions contributes

Ξ_{bc} most promising channels

Semileptonic

The B_c-mesons were first discovered in semileptonic decays

Cabbibo-favoured



Have to deal with missing energy

But Ξ_b semileptonic branching fraction is ~10 times higher than for a hadronic decay

A particle with long decay time in the final state

Optimistic scenario: even having low individual yields in Run1 + Run2, with several modes combined will see the signal

Bit less optimistic scenario: won't see the signal in Run1+Run2, but will reach in through Phase1!

Conclusions

Studies of bc-hadrons is rapidly developing

New channels and new results for B_c-mesons

Not all of them covered in this talk

Search for $B_c^+ \to D^+_{(s)}{}^{(*)}D^{(*)0}$ and UT angle γ measurement

– see talk by Francesca Dordei

Study of the lepton universality in $B_c^+ \to J/\psi\tau\nu_\tau$ decay

(form-factors measurement is on its way)

– see talk by Antonio Vidal

Even more new ideas for the future

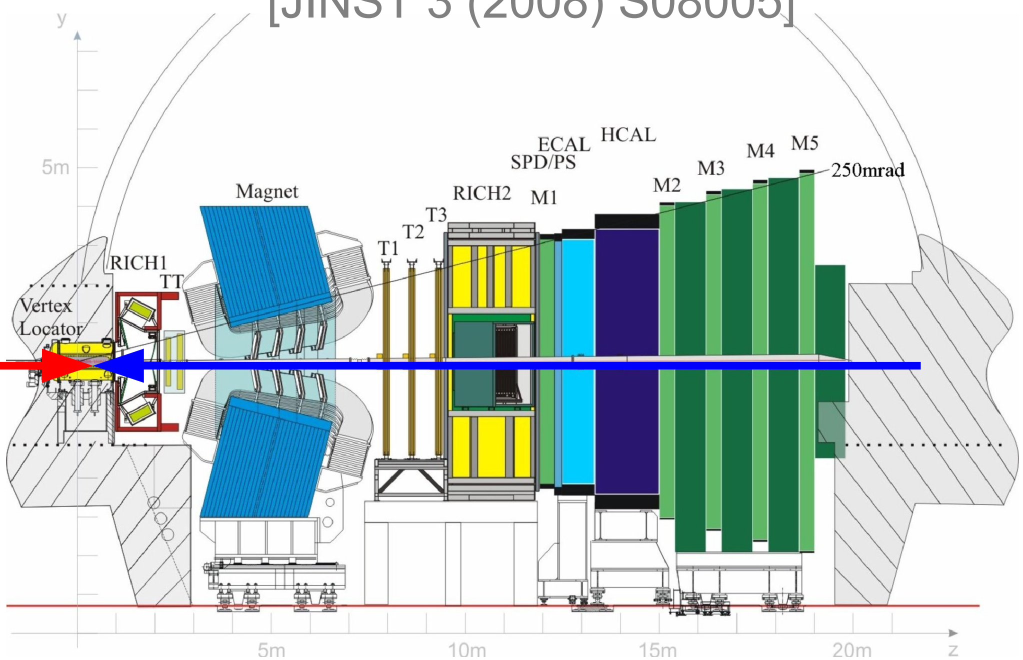
Searches for the bc-baryons – challenging but extremly interesting task

Thank you!

Backup

The LHCb experiment

[JINST 3 (2008) S08005]



LHC:

Cross-sections in the LHCb acceptance:

$\sigma_{pp\to b\bar{b}}$ = 72.0±0.3±6.8 μb @√s = 7TeV

$\sigma_{pp\to b\bar{b}}$ =144 ±1 ±21 μb @√s =13TeV

[Phys. Rev. Lett. 118, 052002 (2017)]

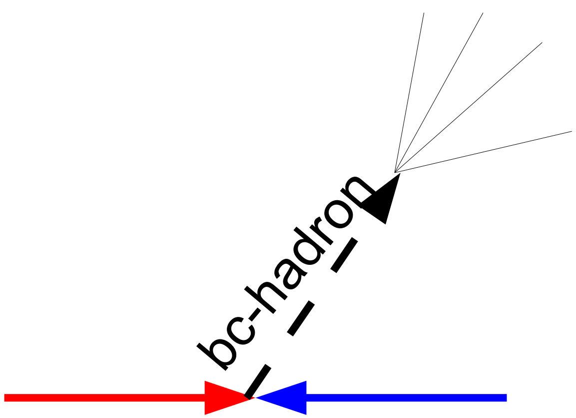
Access to all possible b- and c-hadrons

Fully instrumented rapidity range 2 < η < 5

VELO: Decay time resolution ~45 fs for B-mesons
~100fs for D-mesons

Relative track momentum resolution:
0.5% at low momentum 1.0% at 200 GeV/c

Particle identification:
Kaon ID ~95 % for ~ 5 % π→K mis-id probability
Muon ID ~97 % for 1-3 % π→μ mis-id probability



Muon system: ~90% trigger efficiency for dimuon channels