Study of B_c^+ physics at LHCb

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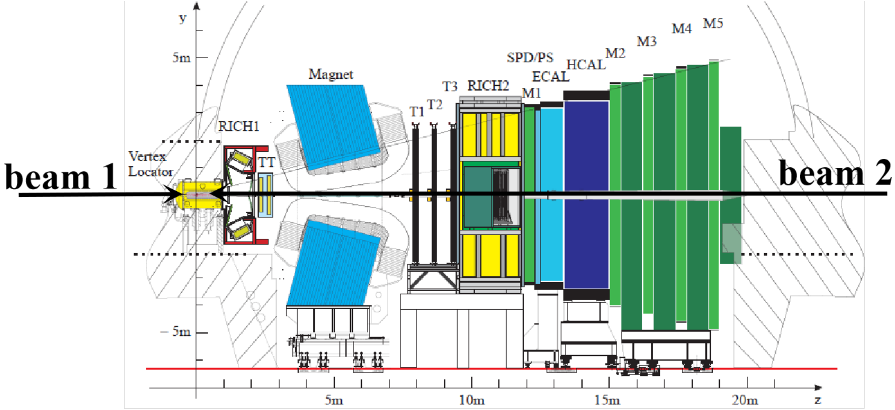
Outline

LHCb detector (for Run1+2)

- Single-arm forward spectrometer
- detector before the upgrade

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

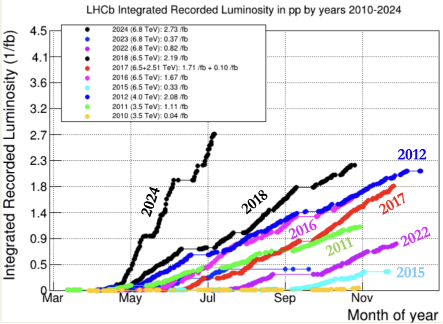


Hadron ID	$\varepsilon(K \to K) \sim 95\%$ mis-ID $\varepsilon(\pi \to K) \sim 5\%$	**Vertex res.**	$\sigma_{IP} = 20\ \mu m$
Muon ID	$\varepsilon(\mu \to \mu) \sim 97\%$ mis-ID $\varepsilon(\pi \to \mu) \sim 1-3\%$	**Time res.**	$\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
ECAL res.	$\Delta E/E = 1\% \oplus 10\%/\sqrt{E\ (\mathrm{GeV})}$	**Momentum res.**	$\Delta p/p = 0.4 \sim 0.6\%$ $(5-100\ \mathrm{GeV}/c)$
		Mass	$\sigma_m = 8\ \mathrm{MeV}/c^2$ for $B \to J/\psi X$

LHCb data

- The table displays important details (such as $\mathcal{L}_{int}$ and $\sqrt{S}$) about the data that will be discussed in the following work.

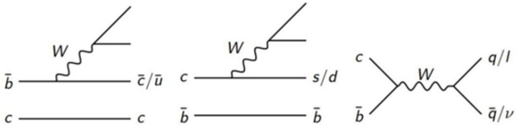
Year	$\mathcal{L}_{int}$	$\sqrt{S}$
2011	$1.0 fb^{-1}$	7TeV
2012	$2.0 fb^{-1}$	8TeV
2015	$0.3 fb^{-1}$	13TeV
2016	$1.6 fb^{-1}$	
2017	$1.7 fb^{-1}$	
2018	$2.1 fb^{-1}$	



- $\sigma(b\bar{b})$:200~500 μb @ 7-14 TeV
- All b hadrons: B^0, $B^{\pm}$, $B_c^{\pm}$, B_s^0...
- LHCb: $\sigma(p\bar{p} \to B_c^+)_{incl} \approx 0.3\ \mu b$

B_c^+ physics

- Unique state that contains two heavy quarks of different flavors
- Mass Spectra are calculated in QCD models
  - B_c^+ was first observed by CDF (PRL.81.24(1998)32) in 1998, confirmed by D0
  - A precise measurement of the B_c^+ meson mass at LHCb (JHEP 07 (2020)123) M=6274.47±0.27(stat)±0.17(syst)MeV/c^2
  - Precise measurement for $B_c^+(2S)$, $B_c^{*+}(2S)$ at LHCb (PRL 109(2019)232001)
- Decay modes:
  - b quark decay ∼20%
  - c quark decay ∼70%
  - annihilation ∼10%



- Precise measurements of mass, lifetime, branching fractions can provide information to validate theoretical models

B_c^+ studies at LHCb

- 30+ results about B_c^+ reported

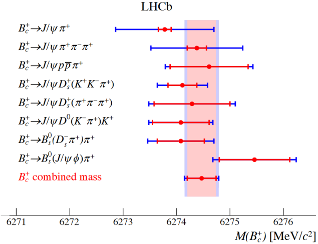
Mass	M($B_c^+ \to J/\psi\pi^+$)(PRL 109(2012)232001)	M($B_c^+ \to J/\psi D_s^+$)(PRD 87(2013)112012)
	M($B_c^+ \to J/\psi p\bar{p}\pi^+$)(PRL 113(2014)152003)	M($B_c^+ \to J/\psi D^* K^*$) (PRD 95(2017)032005)
	most precise measurement (JHEP 07(2020)123)	
Lifetime	$\tau(B_c^+ \to J/\psi\mu^+\nu_\mu X)$(EPJC 74(2014)2839)	$\tau(B_c^+ \to J/\psi\pi^+)$ (PLB 742(2015)39)
Production	$\frac{\sigma(B_c^+)\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+)\mathcal{B}(B^+ \to J/\psi K^+)}$ (PRL 109.(2012)232001)	$\frac{\sigma(B_c^+)\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+)\mathcal{B}(B^+ \to J/\psi K^+)}$ (PRL 114.(2015)132001)
	production asymmetry (PRD 100(2019)11,112006)	
Decays	$B_c^+ \to J/\psi\pi^+\pi^-\pi^+$(PRL 108(2012)251802)	$B_c^+ \to B_s^0\pi^+$ (PRL 111(2013)181801)
	$\frac{\mathcal{B}(B_c^+ \to J/\psi K^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}$(JHEP09(2013)075)	$\frac{\mathcal{B}(B_c^+ \to \psi(2S)\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}$ (PhysRevD 87.07(2013)1103)
	$B_c^+ \to J/\psi K^+K^-\pi^+$ (JHEP 11(2013)094)	$\frac{\mathcal{B}(B_c^+ \to B_s^0\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}$ (PRL 111(2013)181801)
	$B_c^+ \to J/\psi 3\pi^+ 2\pi$ (JHEP 05(2014)148)	$\frac{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)}$ (PRD 90(2014)032009)
	$\frac{\mathcal{B}(B_c^+ \to \psi(2S)\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}$ (PhysRevD 92.07(2015)2007)	$\frac{\mathcal{B}(B_c^+ \to J/\psi K^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}$ (JHEP 09(2016)153)
	$B_c^+ \to p\bar{p}\pi^+$ (PLB 759(2016)313-321)	$B_c^+ \to K^+K^-\pi^+$(PRD 94(2016)091102)
	$B_c^+ \to D^0K^+$(PRL 118(2017)111803)	$\frac{\mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)}$ (PRL 120(2018)12,121801)
	$B_c^+ \to D_{(s)}^{(*)+}\bar{D}^{(*)0}/D_{(s)}^{(*)+}D^{(*)0}$ (NPB 930(2018)563-582)	
	$B_c^+ \to D_s^+\bar{D}^0$ (JHEP 12(2021)117)	$c\bar{c}$ and three light hadrons (JHEP 01(2022)065)
	$B_c^+ \to B_s^0\pi^+$ (JHEP 07(2023)066)	$B_c^+ \to J/\psi K^+K^-\pi^+\pi^+\pi^-$ (JHEP 07(2023)198)
	$B_c^+ \to J/\psi\pi^+\pi^0$ (JHEP 04(2024)151)	$B_c^+ \to \pi^+\mu^+\mu^-$ (EPJC 84(2024)5,468)
	$B_c^+ \to \chi_c\pi^+$ (JHEP 02(2024)173)	
$B_c^{(*)}(2S)^+$	$\sigma\times\mathcal{B}\in$(0.02,0.14)@95%CL (JHEP 01(2018)138)	6.3σ,2.2σ (PRL 122(2019)23,232001)

B_c^+ mass

JHEP 07(2020)123

- The most precise B_c^+ mass measurement so far using full 9 fb^{-1} LHCb dataset
- $M(B_c^+) = 6274.47 \pm 0.27(\text{stat}) \pm 0.17(\text{syst})\ \text{MeV}/c^2$

Decay mode	Yield	Fitted mass [MeV/c^2]	Corrected mass [MeV/c^2]	Resolution [MeV/c^2]
$J/\psi\pi^+$	25181 ± 217	6273.71 ± 0.12	6273.78 ± 0.12	13.49 ± 0.11
$J/\psi\pi^+\pi^-\pi^+$	9497 ± 142	6274.26 ± 0.18	6274.38 ± 0.18	11.13 ± 0.18
$J/\psi p\bar{p}\pi^+$	273 ± 29	6274.66 ± 0.73	6274.61 ± 0.73	6.34 ± 0.76
$J/\psi D_s^+(K^+K^-\pi^+)$	1135 ± 49	6274.09 ± 0.27	6274.11 ± 0.27	5.93 ± 0.30
$J/\psi D_s^+(\pi^+\pi^-\pi^+)$	202 ± 20	6274.57 ± 0.71	6274.29 ± 0.71	6.63 ± 0.67
$J/\psi D^0(K^-\pi^+)K^+$	175 ± 21	6273.97 ± 0.53	6274.08 ± 0.53	3.87 ± 0.57
$B_s^0(D_s^-\pi^+)\pi^+$	316 ± 27	6274.36 ± 0.44	6274.08 ± 0.44	4.67 ± 0.48
$B_s^0(J/\psi\phi)\pi^+$	299 ± 37	6275.87 ± 0.66	6275.46 ± 0.66	5.32 ± 0.74



B_c^+ MASS $\quad$ 6274.47 ± 0.32 MeV

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
6274.47 ±0.27 ±0.17	[1] AAIJ	2020R	LHCB	pp at 7, 8, 13 TeV
• • We do not use the following data for averages, fits, limits, etc. • •				
6274.28 ±1.40 ±0.32	[2] AAIJ	2017L	LHCB	Repl. by AAIJ 2020R
6274.0 ±1.8 ±0.4	[3] AAIJ	2014AQ	LHCB	Repl. by AAIJ 2020R
6276.28 ±1.44 ±0.36	[4] AAIJ	2013AS	LHCB	Repl. by AAIJ 2020R
6273.7 ±1.3 ±1.6	[5] AAIJ	2012AV	LHCB	Repl. by AAIJ 2020R
6275.6 ±2.9 ±2.5	[6] AALTONEN	2008M	CDF	$p\bar{p}$ at 1.96 TeV
6300 ±14 ±5	[6] ABAZOV	2008T	D0	$p\bar{p}$ at 1.96 TeV

B_c^+ lifetime

- B_c^+ lifetime smaller than other b-mesons
- Predict 300-700 fs based on various frameworks in theory
- World average value: 452 ± 33 fs averaged by PDG in 2013
- semileptonic decays:
  $B_c^+ \to J/\psi \mu^+ \nu_\mu X$:
    - EPJC 74(2014)2839
      2012 data in LHCb, 2 fb^{-1}, $\sqrt{s} = 8\,TeV$
    - $\tau(B_c^+) = 509 \pm 8 \pm 12$ fs
- $B_c^+ \to J/\psi \pi^+$:
    - PLB 742(2015)29-37
    - 2011-2012 data in LHCb, 3 fb^{-1}, $\sqrt{s} = 7\&8\,TeV$
    - $\tau(B_c^+) = 513.4 \pm 11.0 \pm 5.7$ fs

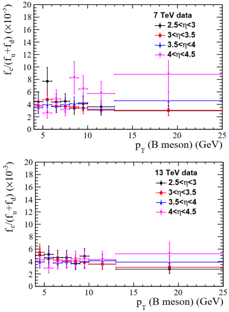
B_c^+ MEAN LIFE $(0.510 \pm 0.009) \times 10^{-12}$ s

VALUE (10^{-12} s)	DOCUMENT ID		TECN	COMMENT
0.510 ± 0.009	**OUR EVALUATION** (Produced by HFLAV)			
0.510 ± 0.009	**OUR AVERAGE**			
$0.541 \pm 0.026 \pm 0.014$	[1] SIRUNYAN	2018BY	CMS	pp at 8 TeV
$0.5134 \pm 0.0110 \pm 0.0057$	[2,3] AAIJ	2015G	LHCB	pp at 7, 8 TeV
$0.509 \pm 0.008 \pm 0.012$	[4] AAIJ	2014G	LHCB	pp at 8 TeV
$0.452 \pm 0.048 \pm 0.027$	[3] AALTONEN	2013	CDF	$p\bar{p}$ at 1.96 TeV
$0.448^{+0.038}_{-0.036} \pm 0.032$	[5] ABAZOV	2009H	D0	$p\bar{p}$ at 1.96 TeV
$0.463^{+0.073}_{-0.065} \pm 0.036$	[5] ABULENCIA	2006O	CDF	$p\bar{p}$ at 1.96 TeV
$0.46^{+0.18}_{-0.16} \pm 0.03$	[5] ABE	1998M	CDF	$p\bar{p}$ 1.8 TeV

- $\tau(B_c^+) = 0.510 \pm 0.009$ ps, $\tau(B^+) = 1.638 \pm 0.004$ ps in PDG
- LHCb measurements dominate world average

Production cross-section

- Obtain the ratio of two decay channels
- Measurements of the B_c^+ production cross-section have been performed at LHCb using different final states
  - $B_c^+ \to J/\psi\pi^+$ (PRL 109.(2012)232001): $\mathcal{R}_{c/u} = \frac{\sigma(B_c^+)\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+)\mathcal{B}(B^+ \to J/\psi K^+)} =$ $(0.68\pm0.10\pm0.03\pm0.05(\text{lifetime}))\%$
  - $B_c^+ \to J/\psi\pi^+$ (PRL 114.(2015)132001): $\mathcal{R}_{c/u} = \frac{\sigma(B_c^+)\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+)\mathcal{B}(B^+ \to J/\psi K^+)}$ $= (0.683 \pm 0.018 \pm 0.009)\%$
  - $B_c^+ \to J/\psi\mu^+\nu_\mu$ (PRD 100(2019)11,112006):



$$\mathcal{R}_{exp} = \frac{f_c}{f_u+f_d} \times \mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)$$
$= (7.07 \pm 0.15(stat) \pm 0.24(syst)) \times 10^{-5}$ (7 TeV)
$= (7.36 \pm 0.08(stat) \pm 0.30(syst)) \times 10^{-5}$ (13 TeV)

Measure absolute $\sigma(B_c^+)$

Absolute branching fractions have not ever been measured. PRD 100(2019)11,112006

- $\mathcal{R}_{exp} = \sigma(B_c^+)\times \mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu) = (7.36 \pm 0.08 \pm 0.30) \times 10^{-5}$
- Take $\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)$ from theoretical prediction

Ref.\Mode	$J/\psi\,\mu^-\overline{\nu}$
[17]	6.4
[18]	
[19]	1.4
[20]	7.5
[21]	1.9
[22]	2.3
[23]	2.7
[24]	1.6
[25]	1.7
[26]	1.7
[27]	1.9
[28]	2.3
[29]	2.2
[30]	2.6
[31]	2.5
[32]	1.3
[33]	1.4
[34]	1.5
[35]	1.9
[36]	2.2

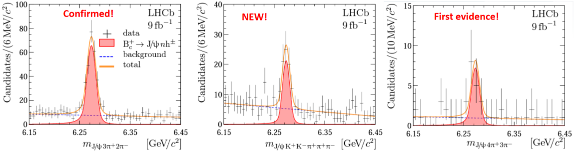
- The **first try** to measure absolute $\sigma(B_c^+)$ using $B_c^+ \to J/\psi\mu^+\nu_\mu$ at LHCb
- A significant range in the available theoretical predictions, making it harder to draw firm conclusions.
  $\frac{f_c}{f_u+f_d} \equiv \sigma(B_c^+)$
  $= (3.63 \pm 0.08 \pm 0.12 \pm 0.86(\text{theory})\ \times 10^{-3}$ (@7 TeV)
  $= (3.78 \pm 0.04 \pm 0.15 \pm 0.89(\text{theory})\ \times 10^{-3}$ (@13 TeV)
- Looking forward to more precise theoretical predictions...

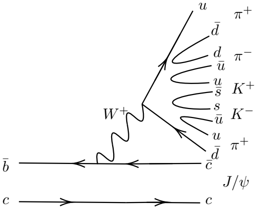
Recently B_c^+ decays at LHCb

- B_c^+ to charmonia plus multi-hadron final states

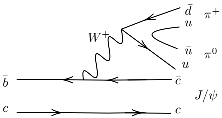
JHEP 07(2023)198

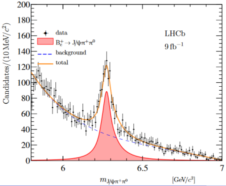
$$\mathcal{R}^{J/\psi K^+K^-\pi^+\pi^+\pi^-}_{J/\psi 3\pi^+2\pi^-} = (33.7 \pm 5.7 \pm 1.6) \times 10^{-2},$$
$$\mathcal{R}^{J/\psi 4\pi^+3\pi^-}_{J/\psi 3\pi^+2\pi^-} = (28.5 \pm 8.7 \pm 2.0) \times 10^{-2},$$
$$\mathcal{R}^{\psi(2S)\pi^+\pi^+\pi^-}_{J/\psi 3\pi^+2\pi^-} = (17.6 \pm 3.6 \pm 0.8) \times 10^{-2},$$

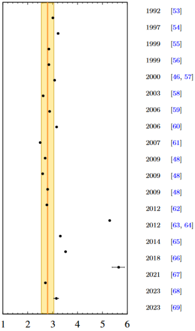




- $B_c^+ \to J/\psi\,\pi^+\pi^0$
  JHEP 04(2024)151
  - $\frac{\mathcal{B}(B_c^+ \to J/\psi\,\pi^+\pi^0)}{\mathcal{B}(B_c^+ \to J/\psi\,\pi^+)} = 2.80 \pm 0.15 \pm 0.11 \pm 0.16$

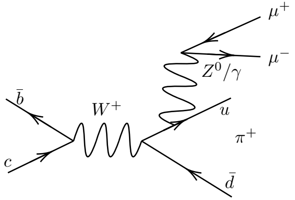


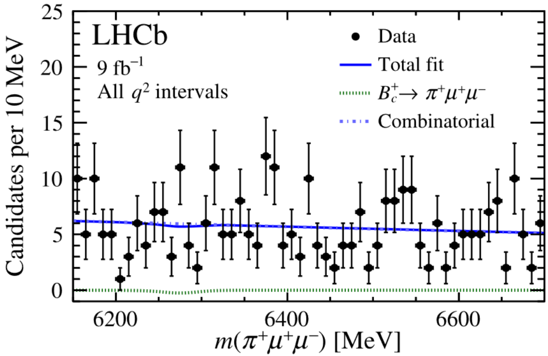




B_c^+ annihilation

- $B_c^+ \to \pi^+\mu^+\mu^-$ EPJC 84(2024)5,468
  - No evidence for an excess of signal events over background
  - $\frac{\mathcal{B}(B_c^+ \to \pi^+\mu^+\mu^-)}{\mathcal{B}(B_c^+ \to \pi^+ J/\psi)} < 2.1 \times 10^{-4}$ @90% confidence level.





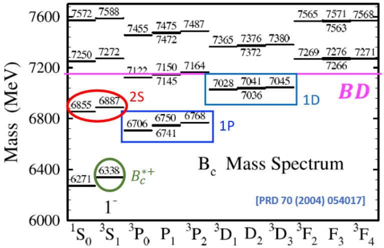
Prediction for Excited B_c^+ states

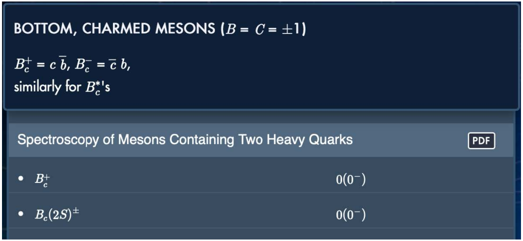
State	Decay	GKLRY *	Godfrey †
1^3S_1	$1^1S_0+\gamma$	100	100
1^3P_2	$1^3S_1+\gamma$	100	100
$1P_1'$	$1^3S_1+\gamma$	6	12.1
	$1^1S_0+\gamma$	94	87.9
$1P_1$	$1^3S_1+\gamma$	87	82.2
	$1^1S_0+\gamma$	13	17.8
1^3P_0	$1^3S_1+\gamma$	100	100
2^1S_0	$1^1S_0+\pi\pi$	74	88.1
	$1P_1'+\gamma$		9.4
	$1P_1+\gamma$		2.0
	$1^3S_1+\gamma$		0.5
2^3S_1	$1^3S_1+\pi\pi$	58	79.6
	$1^3P_2+\gamma$		8.0
	$1P_1'+\gamma$		1.0
	$1P_1+\gamma$		6.6
	$1^3P_0+\gamma$		4.0
	$2^1S_0+\gamma$		0.01
	$1^1S_0+\gamma$		0.8

Phys.Atom.Nucl. 67(2004)1559-1570
PRD 70(2004)054017

- States below BD threshold can only undergo cascade radiative or pionic transitions to the B_c^+ state
- Prediction of production: $\sigma(2S)/\sigma(1S) = |R_{2S}(0)/R_{1S}(0)|^2 \sim 0.6$
  CPC 197(2015)335-338
- $B_c^+(2S)\to B_c^+\pi^+\pi^-$ and $B_c^{*+}(2S)\to (B_c^{*+}\to B_c^+\gamma)\pi^+\pi^-$ are relatively easy to find in experiments

Excited B_c^+ states in Experience

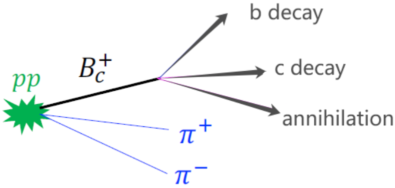




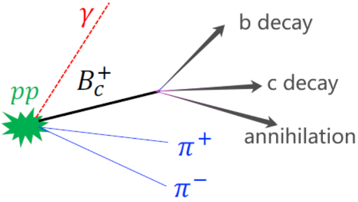
- The ground B_c^+ state was observed by CDF in 1998
- B_c^{*+}: photon too soft to reconstruct
- $B_c(1P)$: search through $B_c^+\ \gamma$
- $B_c(2S)$: fully hadronic mode with large branching ratios
- $B_c(1D)$: mainly decay radiatively to $B_c(1P)$
- Above BD threshold: suffer from much smaller branching ratios of the whole decay chain

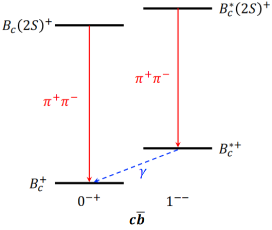
$B_c^{(*)}(2S)^+$ in $B_c^+\pi^+\pi^-$

$B_c(2S)^+ \to B_c^+\pi^+\pi^-$



$B_c^*(2S)^+ \to B_c^{*+}(\to B_c^+\gamma)\pi^+\pi^-$



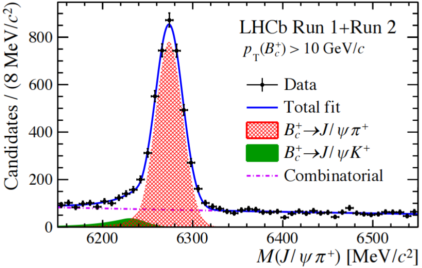


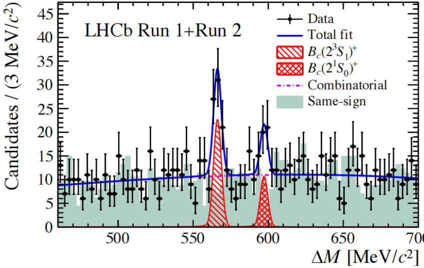
- With the low-energy photon not reconstructed, the $B_c^{(*)}(2S)^+$ peak remains with
- $M(B_c^*(2S)^+)_{rec} = M(B_c^*(2S)^+) - (M(B_c^{*+}) - M(B_c^+))$
- $M(B_c(2S)^+)$ -$M(B_c^*(2S)^+)_{\rm rec}$= $(M(B_c^{*+}) - B(B_c^+)) - (M(B_c^*(2S)^+ - M(B_c(2S)^+))$
- Most predictions give M$(B_c(2S)^+)$>M$(B_c^*(2S)^+)_{\rm rec}$

$B_c^{(*)}(2S)^+$ at LHCb

- $M(B_c^*(2S)^+)$=6842±4(stat)±5(syst)MeV/c^2 in 2014 at ATLAS (PRL 113,21(2014)2004)
- measured $\sigma \times \mathcal{B} \in$(0.02,0.14)@95%CL in 2018 JHEP 01(2018)138
- CMS observed two state $B_c^*(2S)^+$ and $B_c(2S)^+$ for the first time with significance $> 5\ \sigma$ (PRL 122(2019)132001)
- LHCb observed $B_c^*(2S)^+$ with significance >5σ and hint for $B_c(2S)^+$ with global (local) significance of 2.2(3.2) σ PRL 122(2019)23,232001
- the search with the full Run 1+2 data

σ~2.5 MeV/c^2





3785 ± 73 B_c^+ signals

51 ± 10 $B_c^*(2S)^+$; **24 ± 9** $B_c(2S)^+$

- $M(B_c^*(2S)^+)_{rec}$=6841.2±0.6(stat)±0.1(syst)±0.8(B_c^+) MeV/c^2
- $M(B_c(2S)^+)$=6872.1±1.3(stat)±0.1(syst)±0.8(B_c^+) MeV/c^2
- $M(B_c(2S)^+)$-$M(B_c^*(2S)^+)_{rec}$= 31.0±1.4(stat) MeV/c^2

What's next?

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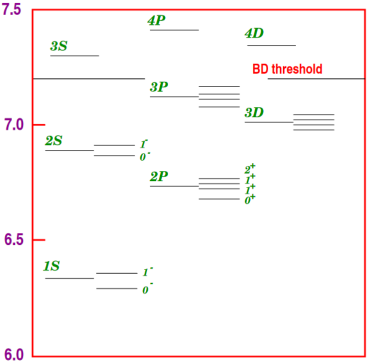

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state	Γ_{tot}, KeV	dominant decay mode	BR, %
1^1S_1	0.06	$1^1S_0+\gamma$	100
2^1S_0	67.8	$1^1S_0+\pi\pi$	74
2^1S_1	86.3	$1^1S_1+\pi\pi$	58
2^1P_0	65.3	$1^1S_1+\gamma$	100
$2P\ 1^+$	89.4	$1^1S_1+\gamma$	87
$2P\ 1'^+$	139.2	$1^1S_0+\gamma$	94
2^3P_2	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

- Below BD threshold:
  - $B_c(2S)$: $B_c^{(*)+}\pi^+\pi^-$ observed
  - $B_c^{(*)+}\to B_c^+\gamma$ with $\Delta M\sim 67$ MeV$/c^2$ $\Rightarrow$ too difficult
  - $B_c(1P)$: $\to B_c^{(*)+}\gamma$ with $\Delta M\sim 300$ MeV$/c^2$ $\Rightarrow$ most promising but challenging
  - $B_c(1D)$: $\to B_c(1P)\gamma$ $\Rightarrow$ further away
- $B_c^{**+}\to BD$ ...

Summary & Outlook

- Summary:
  - LHCb detector designed specifically for studying particles containing b quarks or c quarks
  - 30+ result about B_c^+ reported
    - More B_c^+ decay discovered
    - More precise measurement for $B_c^+(2S)$, $B_c^{*+}(2S)$ at LHCb
    - LHCb measurements dominate world average

- Outlook:
  - $c \to s$ decay for B_c^+ (only one seen now): $B_c^+ \to B^+ K^- \pi^+$...
  - B_c^+ annihilation: $B_c^+ \to K^+ K^- \pi^+$, $B_c^+ \to p\bar{p}\pi^+$...
  - Excited B_c^+ states: $B_c(1P)$...
  - B_c^+ CP violation