Search for excited B_c^{**} at LHCb

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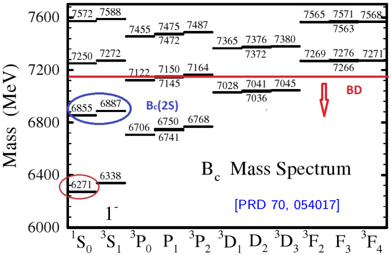
Introduction

- The B_c is a unique system in the SM
  - Doubly heavy meson with different flavours ($\bar{b}c$)
  - The B_c^+ can decay only weakly
    - ➜ Longer lifetimes than quarkonia but smaller than other B–mesons
- Small production cross-section: $\mathcal{O}(\alpha_s^4)$
  - At hadron colliders the B_c production is mainly due to gg fusion
  - Requires the production of both $b\overline{b}$ and $c\overline{c}$
  - $\sigma_{B_c} \sim 10^{-3}\sigma_B$
- Scarce information before LHC
  - The B_c^+ was discovered in 1998 by CDF at Tevatron
  - Mass and lifetime by CDF and D0 at Tevatron (Run II)
- $\sigma(B_c)_{\text{LHC}}/\sigma(B_c)_{Tevatron} \sim \mathcal{O}(10)$
  - Many decay modes observed
  - High precision measurements of mass and lifetime
  - Relative production measurements
  - Starting the study of the excited states

B_c Spectrum



$n^{2S+1}L_J$

- n: Radial quantum number
- S: Total spin of two quarks
- L: Relative angular momentum
- J: Total angular momentum

B_c excited states – Predicted BF (%)

	State	Decay	Gouz	Godfrey	Fulcher
B_c^{*+}	1^3S_1	$1^1S_0+\gamma$	100	100	100
	1^3P_2	$1^3S_1+\gamma$	100	100	100
	$1P_1'$	$1^3S_1+\gamma$	6	12.1	17
		$1^1S_0+\gamma$	94	87.9	83
	$1P_1$	$1^3S_1+\gamma$	87	82.2	70
		$1^1S_0+\gamma$	13	17.8	30
	1^3P_0	$1^3S_1+\gamma$	100	100	100
$B_c^+(2S)$	2^1S_0	$1^1S_0+\pi\pi$	74	88.1	72 ± 10
		$1P_1'+\gamma$		9.4	19 ± 2
		$1P_1+\gamma$		2.0	9 ± 1
		$1^3S_1+\gamma$		0.5	
$B_c^{*+}(2S)$	2^3S_1	$2^3S_1+\pi\pi$	58	79.6	56 ± 8
		$1^3P_2+\gamma$		8.0	16 ± 1
		$1P_1'+\gamma$		1.0	3 ± 0.2
		$1P_1+\gamma$		6.6	15 ± 1
		$1^3P_0+\gamma$		4.0	11 ± 1
		$2^1S_0+\gamma$		0.01	
		$1^1S_0+\gamma$		0.8	

- The spectrum is predicted by many models and Lattice QCD
- Observation of these states can test the validity of the various approaches
- The states below the *BD* threshold decay to the ground state only by radiative or hadronic transitions
- Only B_c^+ and $B_c^+(2S)$ observed so far
- Theory predicts also:

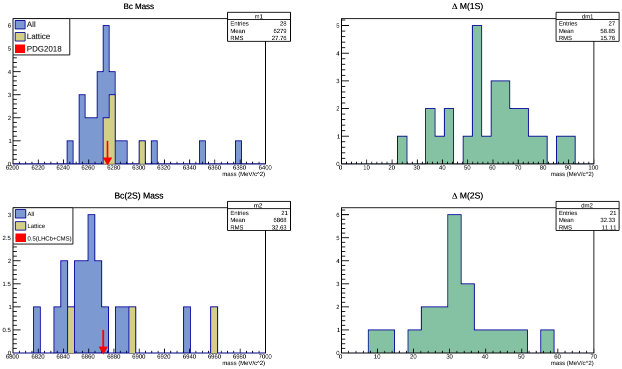
$$R_{B_c}=\sigma B_c^{*+}(2S)/\sigma B_c^+(2S)\sim 2.4\div 2.6$$ [arXiv:1902.09735] [arXiv:1904.06732]

Theory predictions for the B_c mass

- Incomplete list of theory prediction of the $(1S/2S)$ masses (in MeV)

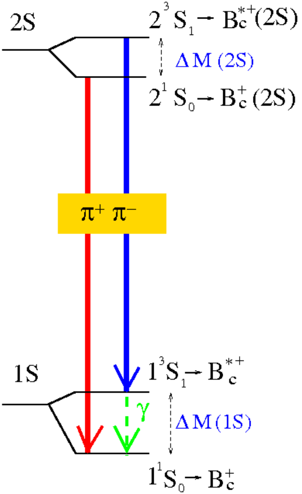
		1^1S_0	1^3S_1	ΔM(1S)	2^1S_0	2^3S_1	ΔM(2S)
Model	PRD46(1992)1165	6314	6355	41	6890	6917	27
	PRD49(1994)5845	6264	6337	73	6856	6899	43
	PRD51(1995)1248	6255	6320	65	–	6900	–
	PRD51(1995)3613	6253	6317	64	6867	6902	35
	PRD52(1995)5229	6260	6340	80	6850	6900	50
	PRD53(1995)312	6247	6308	61	6853	6886	33
	PRD60.074006	6286	6341	55	6882	6914	32
	PRD61.054013	6283	6356	73	-	-	-
	PRD62.114024	6258	6334	76	-	6883	-
	PRD67.014027	6270	6332	62	6835	6881	46
	PRD70.054017	6271	6338	67	6855	6887	32
	EPJ37(2004)323	6263	6354	91	-	6894	-
	PRD71.034006	6380	6416	36	6875	6896	21
	Pram.66(2006)953	6349	6373	24	6821	6855	24
	PRD81.076005	6270	6335	66	6863	6895	32
	1902.09735	6275	6329	54	6867	6898	31
Latice QCD	PLB382(1996)131	6280±30 ± 190	6321±20	41	6960±80	6890±80	30
	PRL94.172001	$6304\pm12^{+18}_{-0}$	-	-	-	-	-
	PLB651(2007)171	6278	6375	37	-	-	-
	PRD86.094510	6278±9	6332±9	54±3	6894±19 ± 8	6922±19 ± 8	28
	PRD92.054504	6276±9	6333±3	57	6844±6	6879±6	35
	PRL121.202002	6276±3 ± 6	6331±4 ± 6	55	6712±18 ± 7	6736±17 ± 7	24
	PDG2018	**6274.9±0.8**			**6842**±4 ± 5		

- Average for B_c^+ mass is close to the PDG value
- Few predictions for LQCD but closer to the observed one
- Average ok also for the $B_c^+(2S)$



Excited B_c states

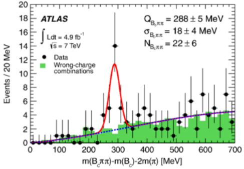
- Theory predicts $\Delta M(1S) \sim \mathcal{O}(60)$MeV; $\Delta M(2S) \sim \mathcal{O}(35)$MeV
- 1S transition: experimentally very challenging to detect such a low energy γ
- 2S transition: can use the $\pi\pi$ emission to (1S) levels
- But:
  - B_c^+(2S) goes to the ground state directly
  - $B_c^{*+}(2S) \rightarrow B_c^{*+}(1S) + \pi^+\pi^-$
  - Followed by $B_c^{*+}(1S) \rightarrow B_c^+ + \gamma$
- If the experimental resolution is good enough the $B_c^+\ \pi^+\pi^-$ invariant mass distribution will have a two peaks structure
- $M(B_c^{*+}(2S))_{REC} = M(B_c^+(2S)) - \Delta M(1S) + \Delta M(2S)$
- Since $\Delta M(1S) > \Delta M(2S)$ the $B_c^{*+}(2S)_{REC}$ will be the lower peak

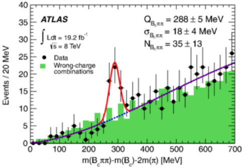


Excited B_c states – Experimental situation

- In 2014 ATLAS [PRL 113.212004] observed a state consistent with expectations for the (2S) state

  $\mathrm{m} = 6842 \pm 4(\text{stat.}) \pm 5(\text{syst.})\ \mathrm{MeV/c^2}$
- No discrimination between $B_c^{*+}(2S)$ and $B_c^{+}(2S)$



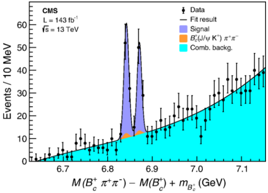


- In 2018 LHCb, using a data sample of only $2\,\mathrm{fb}^{-1}$, did not find any structure in the invariant mass distribution [JHEP 01 (2018) 138]

- In a recent work CMS [PRL 122.132001], using the 2015–2018 data, reports two peaks in the invariant $B_c^+\ \pi^+\pi^-$ separated by

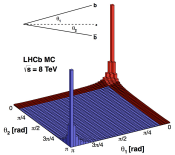
  $\mathrm{m} = 29 \pm 1.5(\text{stat.}) \pm 0.7(\text{syst.})\ \mathrm{MeV/c^2}$
- And a $B_c^+(2S)$ mass of

  $\mathrm{m} = 6871.0 \pm 1.2(\text{stat.}) \pm 0.8(\text{syst.}) \pm 0.8(B_c^+)\ \mathrm{MeV/c^2}$

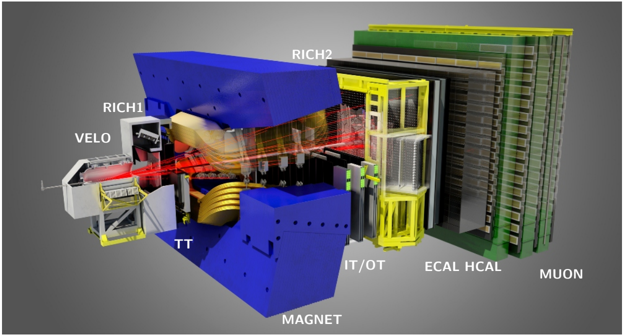


The LHCb detector

- Originally designed to measure CP violation in the *b* sector today is also devoloping a rich physics program in the forward region



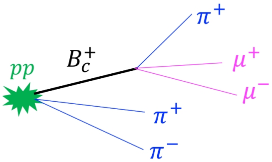
- Acceptance
  10 mrad $< \theta <$ 300 mrad
  $2 < \eta < 5$ coverage
- Vertex detector (VELO)
  $\sigma_{IP} \sim 10\ \mu m,\ \sigma_{\tau} \sim 45$ fs
- Tracking (TT and IT/OT)
  $\Delta p/p = 0.5 - 1.0\%$
  (5 GeV/c–200 GeV/c)
- RICH
  $\epsilon(K \rightarrow K) \sim 95\%$
  mis–ID $(\pi \rightarrow K) \sim 5\%$
- CALO (ECAL, HCAL)
  $\Delta E/E = 1\% \oplus 10\%/\sqrt{(E)}$ GeV
- Muon
  $\epsilon(\mu \rightarrow \mu) \sim 97\%$
  misID $(\pi \rightarrow \mu) \sim 1 - 3\%$



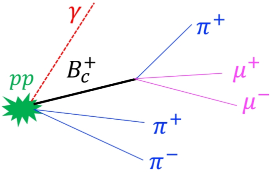
[JINST 3 (2008) S08005] [IntJModPhys A 30 (2015) 1530022]

[arXiv:1904.00081]

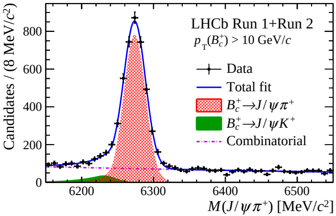
$B_c(2S)^+ \to B_c^+\pi^+\pi^-$



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



- Run I + Run II data sample: 8.5 fb^{-1}
- Common selection for $B_c^+(2S)$ or $B_c^{*+}(2S)$ candidates
- Use the decay: $B_c^+ \to J/\Psi\pi^+$
- Pre–selection cuts + BDT classifier
- To further improve S/B: $P_T(B_c^+) > 10$ GeV/c



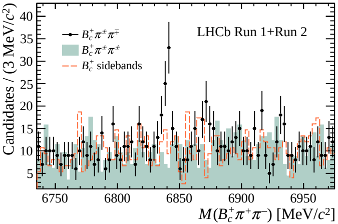
B_c^+ signal yield: 3785±73

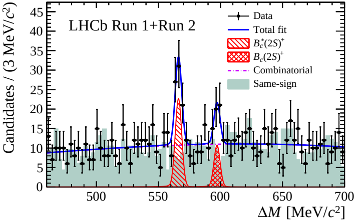
[arXiv:1904.00081]

- Combine the B_c^+ candidate with a pair of tracks from the PV
    - Opposite charge
    - Identified as π
- Check that selection does not produce artifical peaks in the $M(B_c^+\pi^+\pi^-)$ distribution ➜ Apply the same cuts to same–sign sample: $B_c^+\ \pi^+\pi^+$, $B_c^+\ \pi^-\pi^-$
- One peak approximately at 6840 MeV/c^2 and another structure at $\sim$6870 MeV/c^2
- No peaks in the same sign/sidebands sample
- Extract the masses and yields of $B_c^{(*)+}(2S)$ by fitting:

$$\Delta M = M(B_c^+\pi^+\pi^-) - M(B_c^+)_{REC}$$

to eliminate the dependence on the reconstructed B_c^+ mass

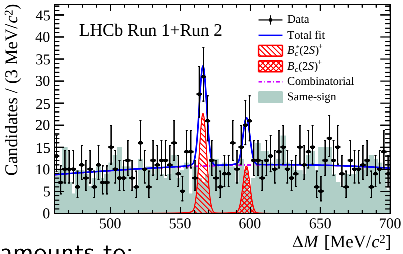




Results

[arXiv:1904.00081]

	$B_c^*(2S)^+$	$B_c(2S)^+$
Signal yield	51 ± 10	24 ± 9
Peak ΔM value (MeV/c^2)	566.2 ± 0.6	597.2 ± 1.3
Resolution (MeV/c^2)	2.6 ± 0.5	2.5 ± 1.0
Local significance	$6.8\,\sigma$	$3.2\,\sigma$
Global significance	$6.3\,\sigma$	$2.2\,\sigma$



- The mass difference of the two peaks amounts to:
  $\Delta M_{1-2} = 31.0 \pm 1.4(stat.)$ MeV/c^2
- Adding the B_c^+ mass from PDG to the fitted peaks
  $M(B_c^{*+}(2S))_{REC} = 6841.2 \pm 0.6(stat.) \pm 0.8(B_c^+)$ MeV/c^2

  $M(B_c^+(2S)) = 6872.1 \pm 1.3(stat.) \pm 0.8(B_c^+)$ MeV/c^2
- Systematic studies
  - Momentum scale
  - Missing photon
  - Signal and background models
- Total systematic contribution: 0.1 MeV/c^2

Summary

[arXiv:1904.00081]

- Using the data collected from 2011 to 2018 corresponding to an integrated luminosity of 8.5 fb^{-1} LHCb has observed an excited B_c^+ state
- It is consistent with being a $B_c^{*+}(2S)$ state with the low energy photon of the decay to ground state missing

$$M(B_c^{*+}(2S))_{REC} = 6841.2 \pm 0.6(stat.) \pm 0.1(syst.) \pm 0.8(B_c^+)\ \text{MeV/c}^2$$

- Hint also for a second structure consistent with $B_c^+(2S)$

$$M(B_c^+(2S)) = 6872.1 \pm 1.3(stat.) \pm 0.1(syst.) \pm 0.8(B_c^+)\ \text{MeV/c}^2$$

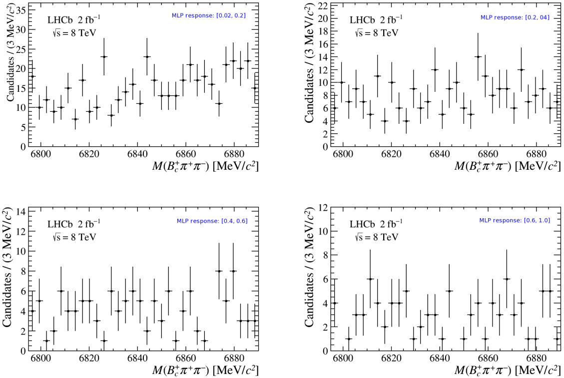
- These findings are in agreement with the recent CMS results and within the range of theory predictions

BACKUP

Search for excited B_c^+ states

[JHEP 01 (2018) 138]

- LHCb previously searched for excited B_c^+ states using the 2012 data
- MLP (neural network) bin with worst S/B removed
- Invariant mass distribution in MLP response bins
- The $M(B_c^+\pi^+\pi^-)$ distribution was consistent with background only

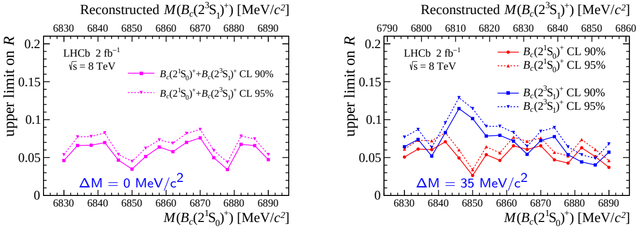


Search for excited B_c^+ states

- Setting an upper limit on $\mathcal{R}$

[JHEP 01 (2018) 138]

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



- Evaluated for 4 values of ΔM = ΔM(1S) - ΔM(2S) (0, 15, 25, 35 MeV/c^2)
- $\mathcal{R} \sim 0.09$ at $\sim$6840 MeV/c^2 at 95%CL using 2012 data
- Using the full data sample of Run1 and Run2 (this analysis): $\mathcal{R} = 0.08 \pm 0.03$
- Consistent with the upper limit previously obtained

Theory predictions for the B_c mass

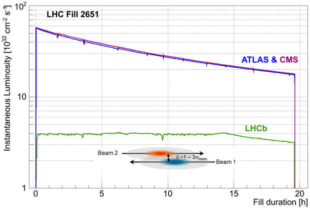
- Additional theory prediction of the $(1S/2S)$ masses (in MeV)

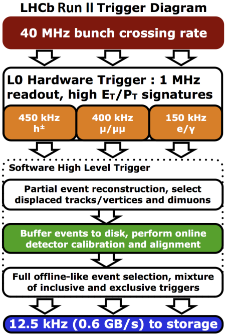
	1^1S_0	1^3S_1	ΔM(1S)	2^1S_0	2^3S_1	ΔM(2S)
EPJA50(2014)154	6278	6331	53	6863	6873	10
PRC78(2008)055202	6269	6337	68	6743	6767	24
EPJC71(2011)1825	6272	6333	61	6842	6882	40
NPA848(2010)299	6256	6343	87	6939	6997	58
EPJC78(2018)592	6272	6321	49	6864	6900	36
PRD95.054016	6275	6314	39	6838	6850	12
PDG2018	**6274.9 ± 0.8**			**6842**$\pm 4 \pm 5$		

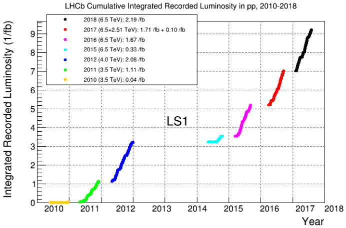
Model

Trigger and data processing

- Upgrade of the trigger system during LS1
- Improved computing resources
- New HLT architecture
- Fast automated calibration
- More than double stored event rate







	Run I (2011+2012)	Run II (2015→2018)
$\sqrt{(s)}$	7 TeV+8 TeV	13 TeV
$\int \mathcal{L}$	1+2 fb^{-1}	5.5 fb^{-1}
Bunch spacing	50 ns	25 ns