B_c spectroscopy at LHCb

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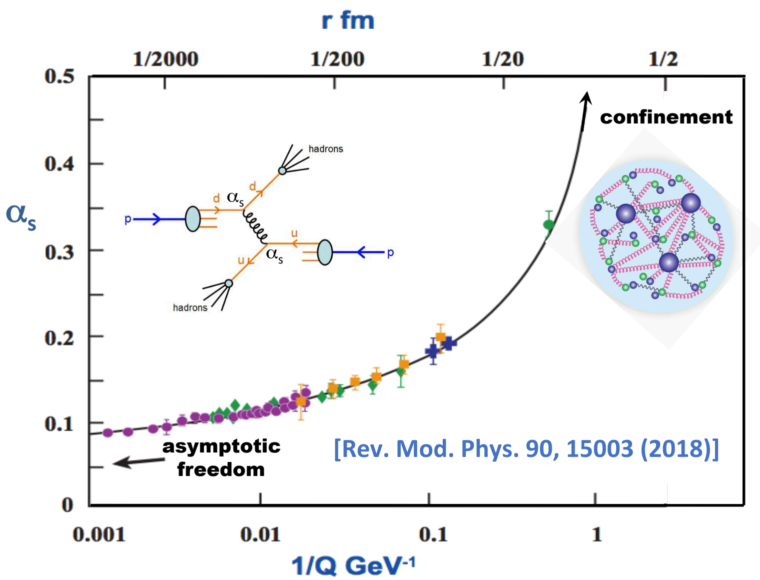
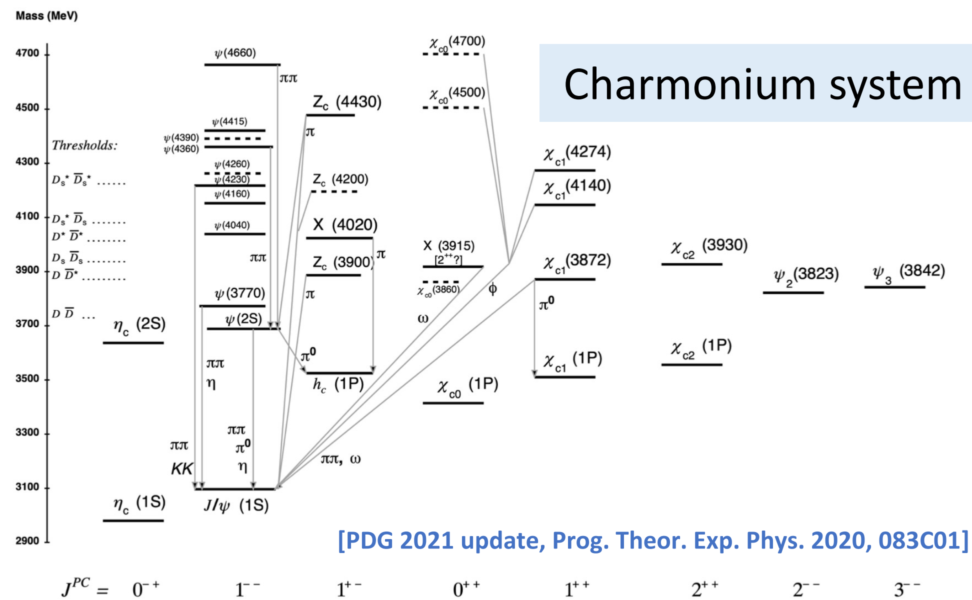
Topical meeting on B_c decays @ B&Q, June 22nd 2023

QCD and B_c spectroscopy

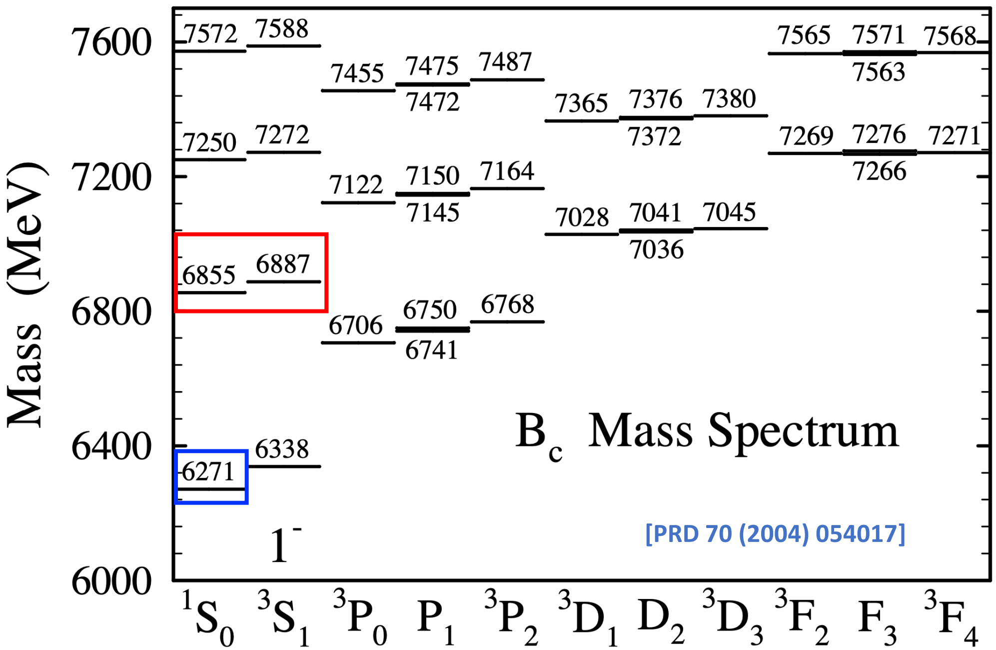
- ➢ Fully heavy hadrons provide key laboratory for QCD study
  - ✓ Large separation of heavy quark masses from QCD scale allows for QCD factorization
  - ✓ QCD potential models can be constructed, since heavy quark and anti-quark are non-relativistic in the hadron rest frame

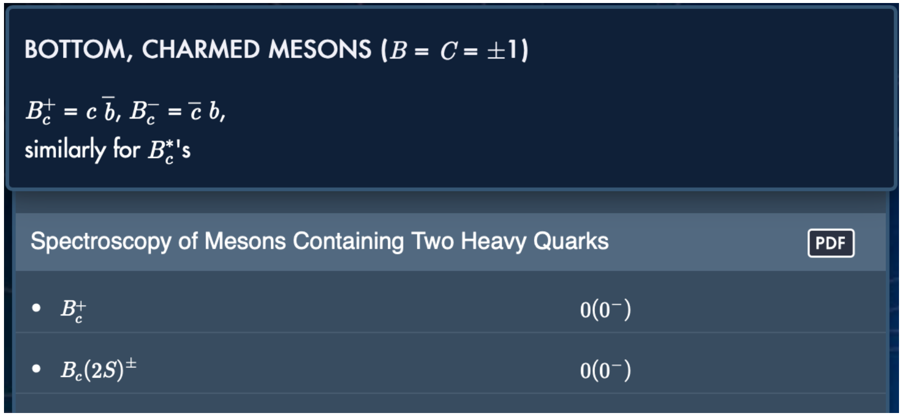




- ◆ Quarkonium: theoretical models well established & extensive experimental studies
- ◆ B_c (quarkonium-like):
  - ✓ Theoretically, relativistic effects may be more important
  - ✓ Experimentally, much less explored due to small production rate (requires $b\bar{b} + c\bar{c}$ prod.)

B_c spectrum





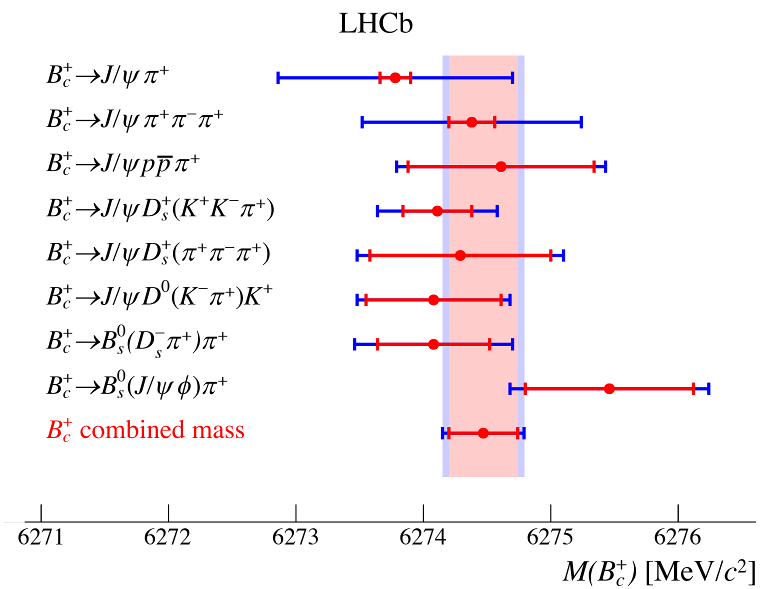
- ➢The ground B_c^+ state was observed by CDF in 1998
- ➢No excited B_c^+ state seen until the observation of $B_c^{(*)}(2S)^+$ by ATLAS in 2014 [PRL 113 (2014) 212004]
- ➢The LHC opens a new era for B_c physics
- ➢LHCb has made major contributions to B_c studies: mass, lifetime, production, decays, spectrum…

B_c^+ mass

[JHEP 07 (2020) 123]

➢The most precise B_c^+ mass measurement so far using full 9 fb^{-1} LHCb dataset

$$M(B_c^+) = 6274.47 \pm 0.27(\text{stat}) \pm 0.17(\text{syst})\ \text{MeV}/\text{c}^2$$



B_c^+ MASS 6274.47 ± 0.32 MeV

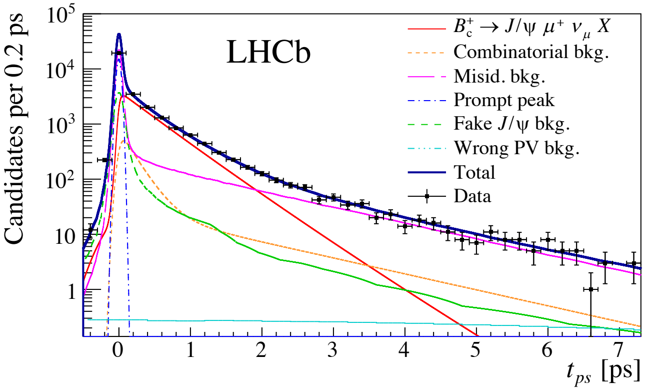
VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
6274.47 ±0.27 ±0.17	[1] AAIJ	2020R	LHCB	pp at 7, 8, 13 TeV
• • We do not use the following data for averages, fits, limits, etc. • •				
6274.28 ±1.40 ±0.32	[2] AAIJ	2017L	LHCB	Repl. by AAIJ 2020R
6274.0 ±1.8 ±0.4	[3] AAIJ	2014AQ	LHCB	Repl. by AAIJ 2020R
6276.28 ±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
6285.7 ±5.3 ±1.2	[6] ABULENCIA	2006C	CDF	Repl. by AALTONEN 2008M
6400 ±390 ±130	[7] ABE	1998M	CDF	$p\bar{p}$ at 1.8 TeV
6320 ±60	[8] ACKERSTAFF	1998O	OPAL	$e^+e^- \to Z$

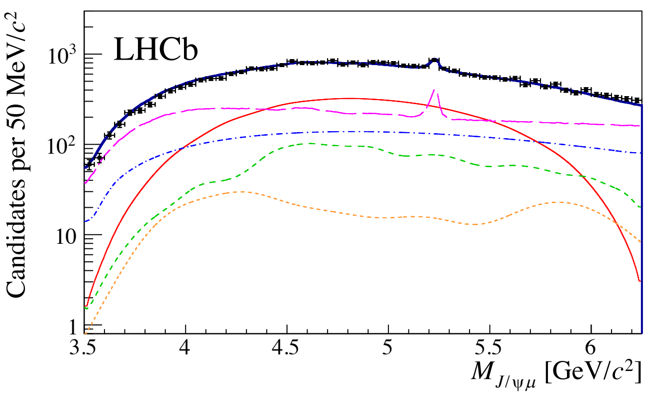
Decay mode	Yield	Fitted mass [MeV/c^2]	Corrected mass [MeV/c^2]	Resolution [MeV/c^2]
$J/\psi\,\pi^+$	25181 ± 217	6273.71 ± 0.12	6273.78 ± 0.12	13.49 ± 0.11
$J/\psi\,\pi^+\pi^-\pi^+$	9497 ± 142	6274.26 ± 0.18	6274.38 ± 0.18	11.13 ± 0.18
$J/\psi\,p\bar{p}\pi^+$	273 ± 29	6274.66 ± 0.73	6274.61 ± 0.73	6.34 ± 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^+ lifetime

- B_c^+ lifetime significant smaller than other b-mesons
  - ✓ $\tau(B_c^+) = (0.507 \pm 0.009)$ ps, compared to $\tau(B^+) = (1.638 \pm 0.004)$ ps
- LHCb measurements dominate world average

✓ $B_c^+ \to J/\psi \mu^+ \nu_\mu$ w/ 2.0 fb^{-1} data at $\sqrt{s} = 8$ TeV





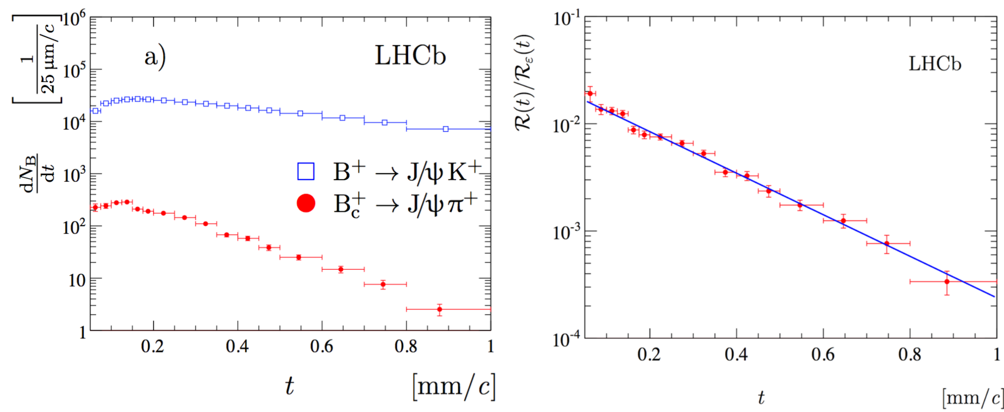
$\tau_{B_c^+} = 509 \pm 8 \pm 12$ fs

[EPJC 74 (2014) 2839]

✓ $B_c^+ \to J/\psi \pi^+$ w/ 3.0 fb^{-1} data at $\sqrt{s} = 7\&8$ TeV

$$\mathcal{R}(t) \propto \frac{\varepsilon_{B_c^+}(t)}{\varepsilon_{B^+}(t)} \frac{E_{\tau_{B_c^+}}(t)}{E_{\tau_{B^+}}(t)} \equiv \mathcal{R}_\varepsilon(t)\, e^{-\Delta\Gamma t}$$

$$\text{with} \quad \Delta\Gamma \equiv \Gamma_{B_c^+} - \Gamma_{B^+} = \frac{1}{\tau_{B_c^+}} - \frac{1}{\tau_B}, \; \mathcal{R}(t) \equiv N_{B_c^+}(t)/N_{B^+}(t)$$



$\tau_{B_c^+} = 513.4 \pm 11.0 \pm 5.7$ fs

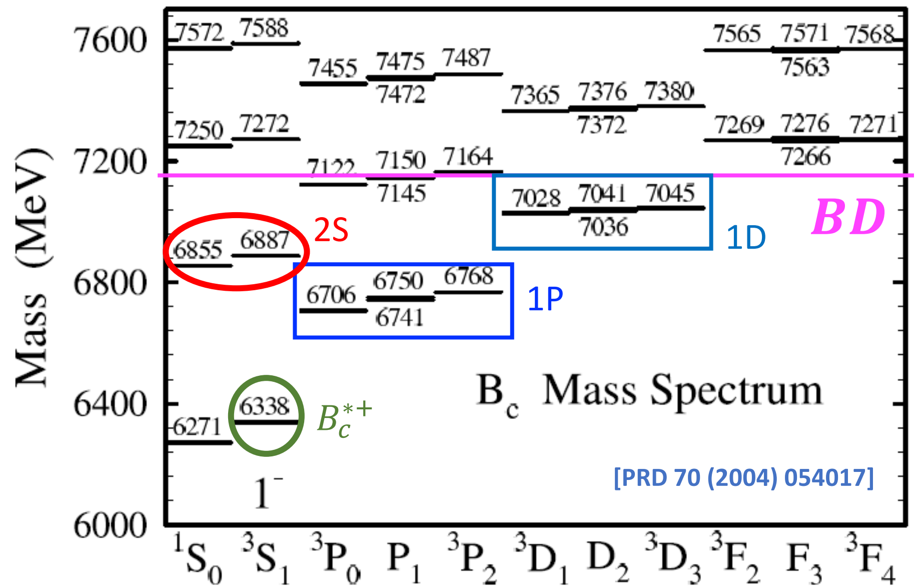
[PLB 742 (2015) 29-37]

Excited B_c^+ states

✓Prediction of decay: [Phys. Atom. Nucl. 67 (2004) 1559] [PRD 70 (2004) 054017]

States below BD threshold can only undergo cascade radiative or pionic transitions to the B_c^+ state

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



- B_c^{*+}: photon too soft to reconstruct
- $B_c(1P)$: search through $B_c^+\gamma$
- **$B_c(2S)$: fully hadronic mode with large Br!**
- $B_c(1D)$: mainly decay radiatively to $B_c(1P)$
- Above BD threshold: suffer from much smaller Br of the whole decay chain

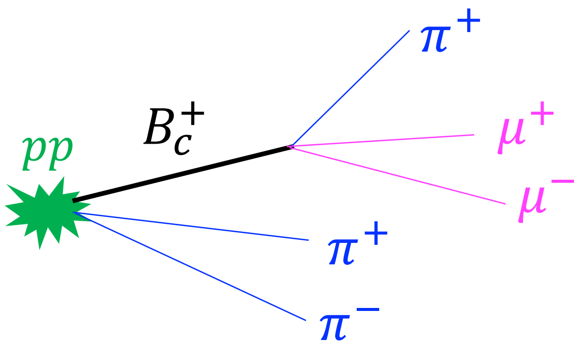
✓Prediction of production

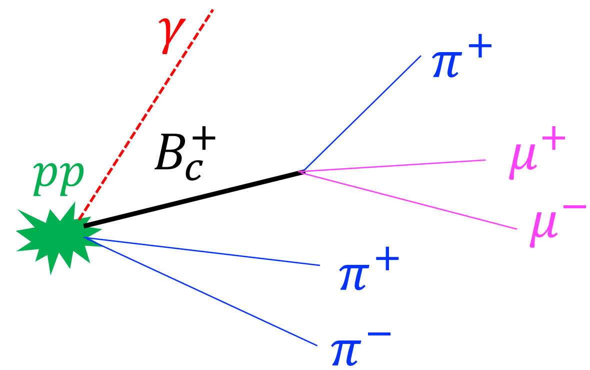
$$\sigma(2S)/\sigma(1S) = |R_{2S}(0)/R_{1S}(0)|^2 \sim 0.6$$

[CPC 197 (2015) 335-338]

$\Rightarrow B_c(2S) \rightarrow B_c\pi^+\pi^-$ is the best option

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





- With the low-energy photon not reconstructed, the $B_c^*(2S)^+$ peak remains with

$$M(B_c^*(2S)^+)_{\rm rec} = M(B_c^*(2S)^+) - \Delta M(1S) = M(B_c^*(2S)^+) - (M(B_c^{*+}) - M(B_c^+))$$

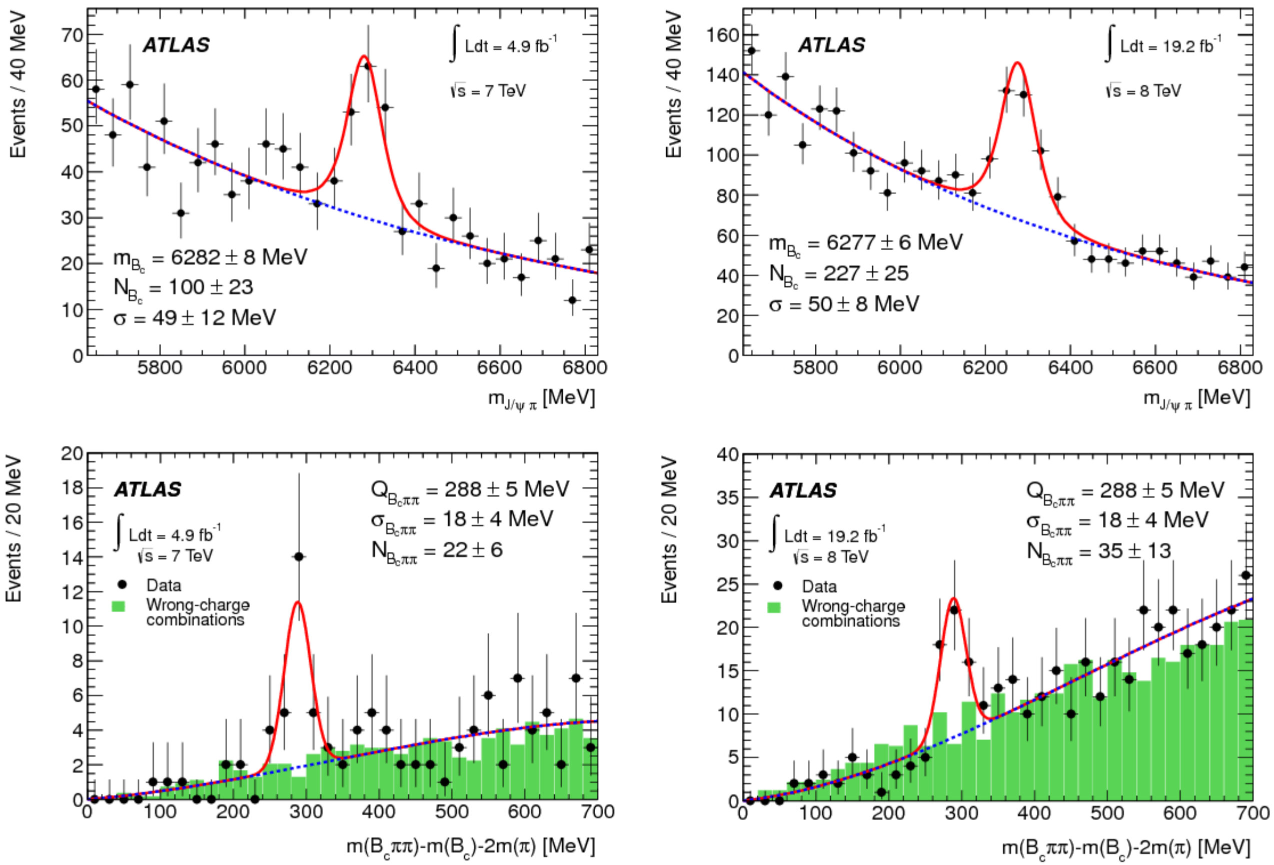
$$\begin{aligned} M(B_c(2S)^+) - M(B_c^*(2S)^+)_{\rm rec} &= \Delta M(1S) - \Delta M(2S) \\ &= \left(M(B_c^{*+}) - M(B_c^+)\right) - \left(M(B_c^*(2S)^+) - M(B_c(2S)^+)\right) \end{aligned}$$

- Most predictions give $M(B_c(2S)^+) > M(B_c^*(2S)^+)_{\rm rec}$

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

[PRL 113 (2014) 212004]

➢ In 2014, ATLAS observed a state consistent with $B_c^{(*)}(2S)^+$ in $B_c^+\pi^+\pi^-$ spectrum



✓ $p_T(\pi^\pm) > 4$ GeV/c
✓ $p_T(B_c^+) > 15\ (18)$ GeV/c for 7(8) TeV

$\sigma \sim 18$ MeV/c^2

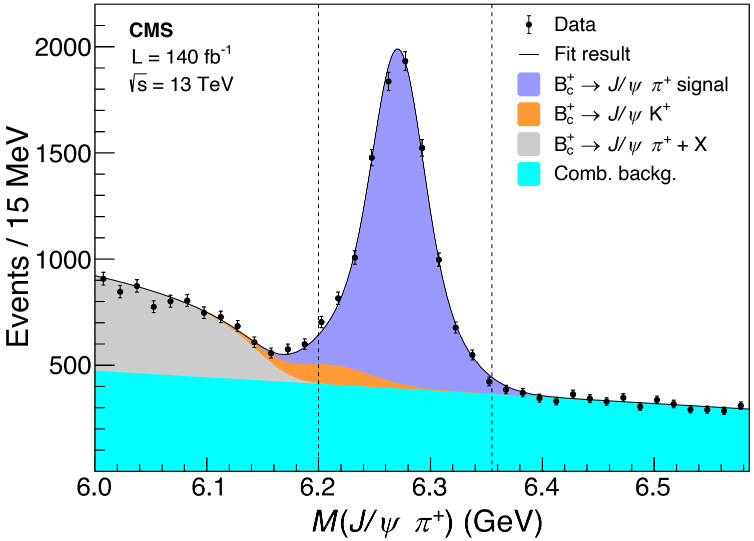
$B_c(2S)^+$ and/or $B_c^*(2S)^+$?

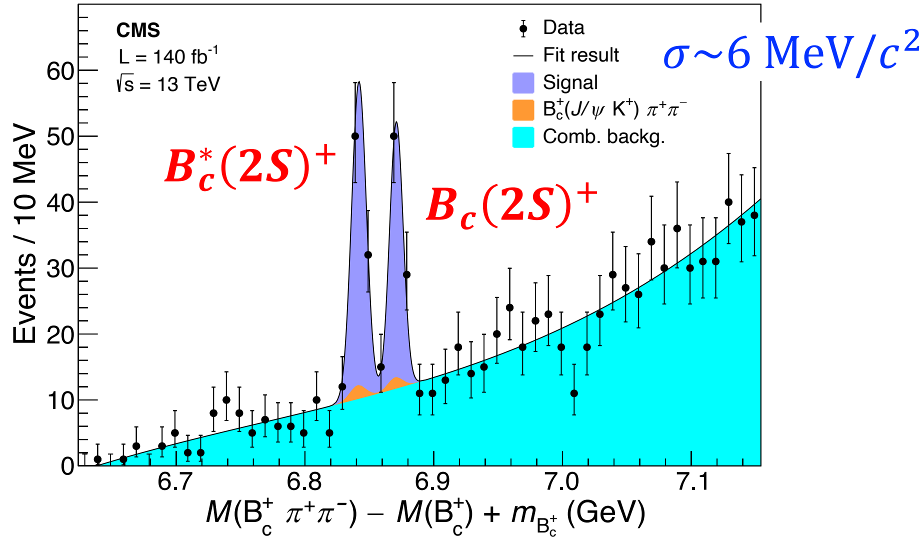
$$M\left(B_c^{(*)}(2S)^+\right) = 6842 \pm 4(\text{stat}) \pm 5(\text{syst})\ \text{MeV}/c^2$$

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

[PRL 122 (2019) 132001]

- CMS performed the search with the full 140 fb^{-1} Run 2 data
- Selection criterion designed based on the event topology
- Kinematic requirements: $p_\text{T}(B_c^+) > 15$ GeV/c, one pion $p_\text{T} > 800$ MeV/c, the other pion $p_\text{T} > 600$ MeV/c
- $B_c^*(2S)^+$ and $B_c(2S)^+$ resolved for the first time with significance $> 5\,\sigma$





7495 ± 225 B_c^+ signals

66 ± 10 $B_c^*(2S)^+$; **51 ± 10** $B_c(2S)^+$

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

$$M(B_c(2S)^+) - M(B_c^*(2S)^+)_\text{rec} = 29.0 \pm 1.5(\text{stat}) \pm 0.7(\text{syst})\ \text{MeV}/c^2$$

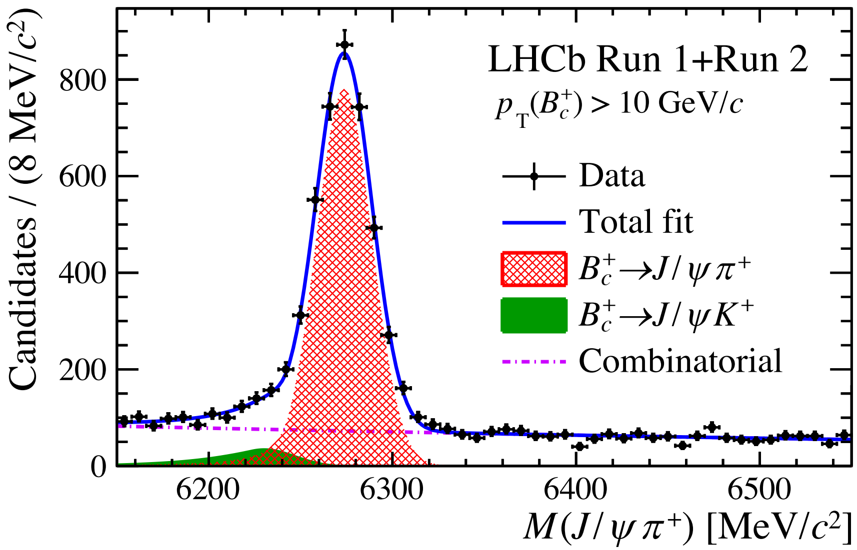
$$M(B_c^*(2S)^+) - M(B_c^{*+}) = 567.1 \pm 1.0(\text{stat})\ \text{MeV/c}^2$$

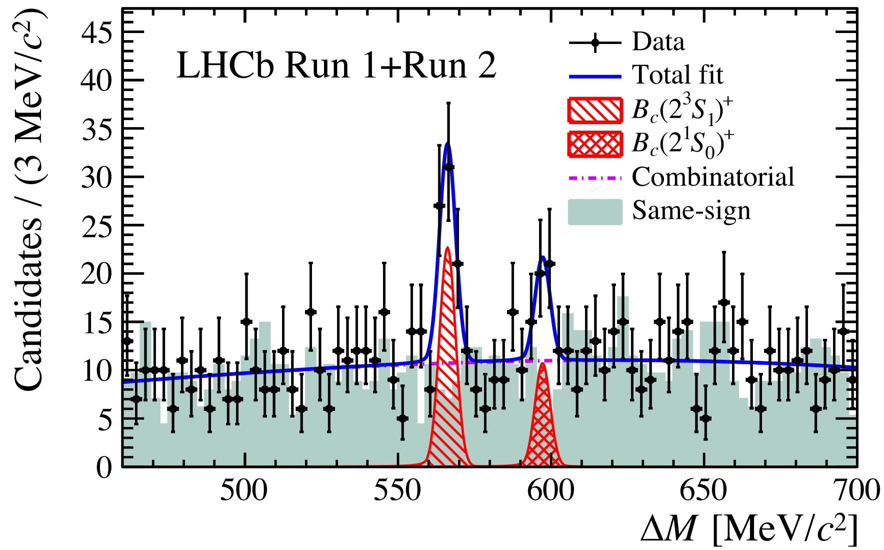
$B_c^{(*)}(2S)^+$ at LHCb

[PRL 122 (2019) 232001]

- LHCb performed the search with 8.5 fb^{-1} Run 1 + Run 2 data
- Kinematic requirements: $p_\mathrm{T}(B_c^+) > 10\ \mathrm{GeV}/c$, $p_\mathrm{T}(\pi^\pm) > 300\ \mathrm{MeV}/c$
- $B_c^*(2S)^+$ observed with significance $> 5\ \sigma$
- Hint for $B_c(2S)^+$ with global (local) significance of 2.2 (3.2) σ

$\sigma \sim 2.5\ \mathrm{MeV}/c^2$





3785 ± 73 B_c^+ signals

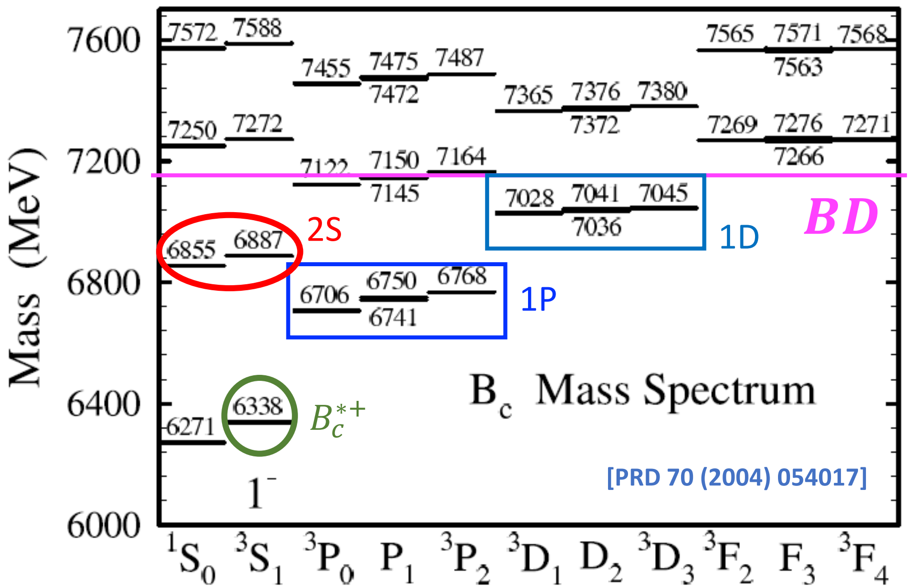
51 ± 10 $B_c^*(2S)^+$; **24 ± 9** $B_c(2S)^+$

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

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

$$M(B_c(2S)^+) - M(B_c^*(2S)^+)_\mathrm{rec} = 31.0 \pm 1.4(\mathrm{stat})\ \mathrm{MeV}/c^2$$

What's next?



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[Phys. Atom. Nucl. 67 (2004) 1559]
[PRD 70 (2004) 054017]

Below BD threshold:

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

$B_c^{**+} \to BD$

$\sigma(B^+) \sim 86.6\ \mu b$ at $\sqrt{s} = 13$ TeV [JHEP 12 (2017) 026]

$$\frac{f_c}{f_u + f_d} = (3.78 \pm 0.04 \pm 0.15 \pm 0.89) \cdot 10^{-3} \text{ for } 13\,\text{TeV},$$ [PRD 100 (2019) 112006]

$$\Rightarrow \sigma(B_c^+) \sim \frac{f_c}{f_u + f_d} \times \sigma(B^+) \times 2 \sim 0.65\ \mu b$$

- Suppose $B_c^{**+} \to B^+ D^0$ entirely,

$\mathcal{B}(B^+ \to J/\psi K^+) = (1.020 \pm 0.019) \times 10^{-3}$

$\mathcal{B}(J/\psi \to \mu^+ \mu^-) = (5.961 \pm 0.033)\%$

$\mathcal{B}(D^0 \to K^- \pi^+) = (3.947 \pm 0.030)\%$

$\varepsilon(B^+ \to J/\psi K^+) \sim 5\%$

$\varepsilon(D^0 \to K^- \pi^+) \sim 6\%$

Very rough estimation.
Do not take the exact numbers seriously.

With 1 fb^{-1} data, we can see $\sim 5 \times \frac{\sigma(B_c^{**+})}{\sigma(B_c^+)}$ signal candidates

$\Rightarrow$ more statistics needed

Update of BcVegPy

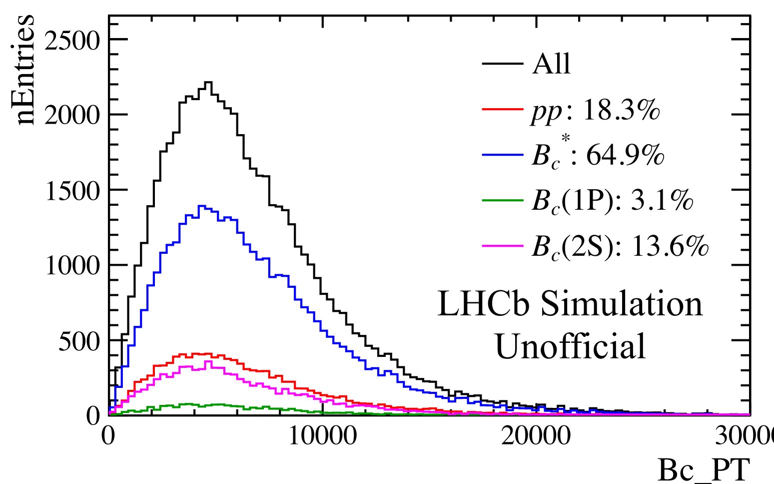
- In LHCb official simulation, the B_c state is produced using a dedicated generator **BcVegPy**

B_c*-	-543	-1	6.602 GeV
B_c*+	543	1	6.602 GeV
B_c2*-	-545	-1	7.35 GeV
B_c2*+	545	1	7.35 GeV

→

B_c+	77	541	1.0	6.27447000
B_c-	78	-541	-1.0	6.27447000
B_c*+	382	543	1.0	6.33330000
B_c*-	383	-543	-1.0	6.33330000
B_c0*+	607	10541	1.0	6.70600000
B_c0*-	608	-10541	-1.0	6.70600000
B_c1(L)+	609	10543	1.0	6.74100000
B_c1(L)-	610	-10543	-1.0	6.74100000
B_c1(H)+	693	20543	1.0	6.75000000
B_c1(H)-	694	-20543	-1.0	6.75000000
B_c2*+	384	545	1.0	6.76800000
B_c2*-	385	-545	-1.0	6.76800000
B_c(2S)+	100541	100541	1.0	6.87210000
B_c(2S)-	100542	-100541	-1.0	6.87210000
B_c*(2S)+	100543	100543	1.0	6.90000000
B_c*(2S)-	100544	-100543	-1.0	6.90000000

✓ The update enables the production of $B_c(1P)$ and $B_c(2S)$ states with expected masses



Summary

- Our knowledge on B_c spectroscopy is still limited
- LHCb has been playing a major role in the B_c spectroscopy studies so far
- With increasing statistics, chances will emerge for the discovery of more excited B_c states
- We are prepared for further B_c spectroscopy studies
- Theoretical inputs are crucial to experimental research!
  We look forward to more theoretical ideas

Thank you!

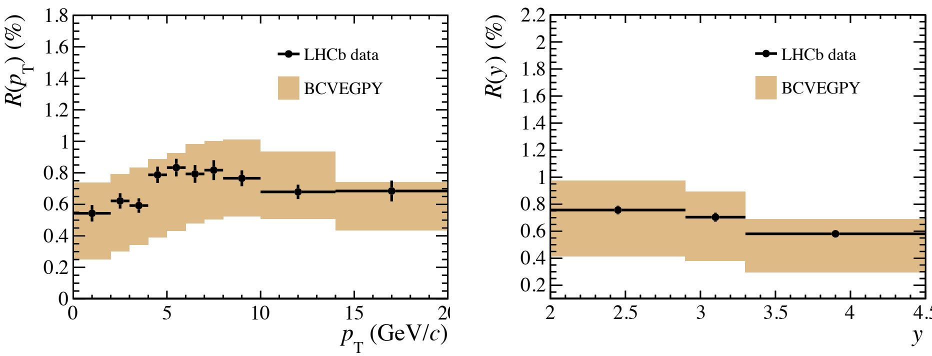
Backup

B_c^+ production

- Measurement of B_c^+ production is a crucial test of the non-relativistic QCD effective theory widely used for predictions of quarkonia production
- No available B_c^+ absolute branching fraction measurement so far

✓ $B_c^+ \to J/\psi\pi^+$ w/ 2.0 fb^{-1} data at $\sqrt{s} = 8$ TeV

- Measure $\mathcal{R} = \frac{\sigma(B_c^+)}{\sigma(B^+)} \frac{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\mathcal{B}(B^+ \to J/\psi K^+)}$

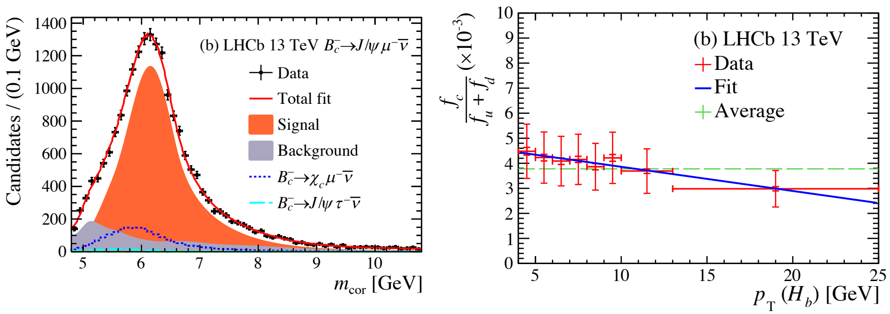


- Good agreement with calculations of BcVegPy: a B_c^+ generator based on $\mathcal{O}(\alpha_s^4)$ calculation

[PRL 114 (2015) 132001]

✓ $B_c^+ \to J/\psi\mu^+\nu$ w/ 1.0(1.7) fb^{-1} data at $\sqrt{s} = 7(13)$ TeV

- The first try to measure absolute production cross-section of B_c^+, taking $\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\nu)$ from theoretical prediction



$$\frac{f_c}{f_u + f_d} = (3.63 \pm 0.08 \pm 0.12 \pm 0.86) \cdot 10^{-3} \text{ for } 7\,\text{TeV},$$
$$\frac{f_c}{f_u + f_d} = (3.78 \pm 0.04 \pm 0.15 \pm 0.89) \cdot 10^{-3} \text{ for } 13\,\text{TeV},$$

[PRD 100 (2019) 112006]