B_c excitations at the LHC: first observations and further research prospects

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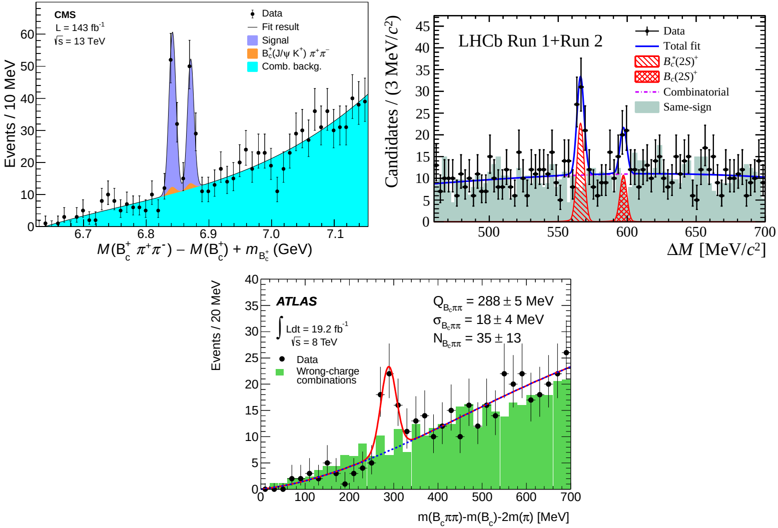
Experimental observation of $B_c(2S)$ states

$$B_c^{(*)}(2S) \to B_c^{(*)}\pi^+\pi^-, \; B_c \to J/\psi\pi$$



ATLAS [Aad et al.(2014)] CMS [Sirunyan et al.(2019)] LHCb [Aaij et al.(2019)]

B_c properties

1. All excitations below the threshold decay into the ground state 1^1S_0.
2. The absence of strong annihilation channels $\Longrightarrow$ the very narrow ground state (practically as B-meson).
3. Spectroscopy can be investigated within the same frame work as for $c\bar{c}$ and $b\bar{b}$ quarkoniums.
4. The small total yield comparing to the $c\bar{c}$ and $b\bar{b}$ quarkonia case.
5. The small relative yield of P-wave excitations comparing to the $c\bar{c}$ and $b\bar{b}$ quarkonia case.

B_c family have a spectroscopy similar to $c\bar{c}$ or $b\bar{b}$ quarkonium spectroscopy and decays like B meson

- The main difference in decays (comparing to B meson): the both quarks in B_c are heavy.
- The main difference in spectroscopy (comparing to $c\bar{c}$ and $b\bar{b}$ quarkonia): charge parity can not be determined.

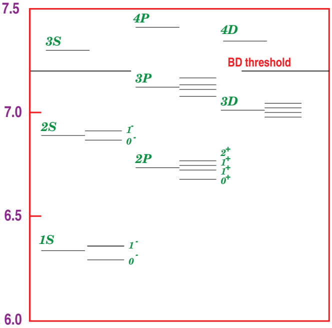
$$h_Q \;\chi_{1Q} \xrightarrow{\text{mixing}} 1^+ \;1^{+'}$$

$$\begin{aligned}
|2P, 1^{'+}\rangle &= 0.294|S=1\rangle + 0.956|S=0\rangle \\
|2P, 1^{+}\rangle &= 0.956|S=1\rangle - 0.294|S=0\rangle \\
|3P, 1^{'+}\rangle &= 0.371|S=1\rangle + 0.929|S=0\rangle \\
|3P, 1^{+}\rangle &= 0.929|S=1\rangle - 0.371|S=0\rangle
\end{aligned}$$

[Kiselev et al.(1995)Kiselev, Likhoded, and Tkabladze, Gershtein et al.(1995)Gershtein, Kiselev, Likhoded, and Tkabladze]

Spectroscopy

All excitations decay into 1^1S_0.



state	Martin	BT
1^1S_0	6.253	6.264
1^1S_1	6.317	6.337
2^1S_0	6.867	6.856
2^1S_1	6.902	6.899
2^1P_0	6.683	6.700
$2P\ 1^+$	6.717	6.730
$2P\ 1'^+$	6.729	6.736
2^3P_2	6.743	6.747
3^1P_0	7.088	7.108
$3P\ 1^+$	7.113	7.135
$3P\ 1'^+$	7.124	7.142
3^3P_2	7.134	7.153
$3D\ 2^-$	7.001	7.009
3^5D_3	7.007	7.005
3^3D_1	7.008	7.012
$3D\ 2'^-$	7.016	7.012

Figure 1: The mass spectrum of $(\bar{b}c)$ with account for the spin-dependent splittings.

[Gouz et al.(2004)Gouz, Kiselev, Likhoded, Romanovsky, and Yushchenko]

What was expected for $B_c^{(*)}(2S) \to B_c^{(*)} + \pi\pi$

$$B_c(2S) \xrightarrow[\sim 50\%]{\pi^+\pi^-} B_c$$

$$B_c^*(2S) \xrightarrow[\sim 40\%]{\pi^+\pi^-} B_c^*$$

$$\sigma^{2S}/\sigma^{\text{total}} \sim 25\ \%$$

$\sim 10\ \%$ of B_c come from $B_c(2S) \to B_c(1S) + \pi^+\pi^-$

Under assumption that
$|R(B_c^*(2S))(0)| \approx |R(B_c(2S))(0)|$

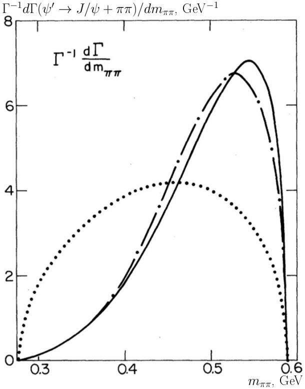
$$\sigma(B_c^*(2S))/\sigma(B_c(2S)) \sim 2.6$$

Relativistic corrections

$|R(B_c^*(2S))(0)|/|R(B_c(2S))(0)| = 0.87$
[Martynenko(2019)]

$|R(B_c^*(2S))(0)|/|R(B_c(2S))(0)| = 0.567$
[Galkin(2019),
Ebert et al.(2011)Ebert, Faustov, and Galkin]

$$\sigma(B_c^*(2S))/\sigma(B_c(2S)) \sim 1 \div 2$$



$$\frac{1}{\Gamma}\frac{d\Gamma}{dm_{2\pi}} \sim \frac{|\mathbf{k}_{\pi\pi}|}{M^2}(2x^2-1)\sqrt{x^2-1}$$

where $x = m_{\pi\pi}/2m_\pi$ and $\mathbf{k}_{\pi\pi}$ is the momentum of $\pi\pi$-pair in the initial quarkonium rest frame.
[Brown and Cahn(1975), Novikov and Shifman(1981), Voloshin(1975), Voloshin and Zakharov(1980)]

σ-meson in the quarkonia decays

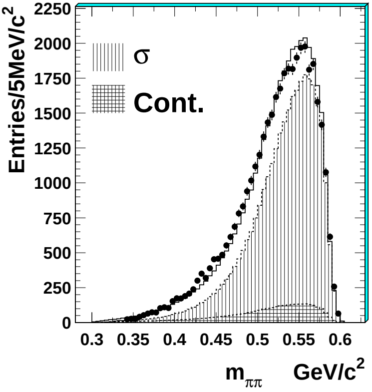


Figure: Distribution over $m_{\pi\pi}$ for the process $\psi' \to J/\psi\pi\pi$. The resonance σ ($f_0(500)$) has been included into the fit (BESII) [Ablikim et al.(2007)].

$f_0(500)$ or σ
$J^{PC} = 0^{++}$
$(400 - 550) - i(200 - 350)$ МэВ

$B_c^*(2S) \to B_c^* \pi\pi$, $B_c^* \to B_c + \gamma^{\text{soft}}$

Detecting of γ^{soft} strongly decreases an efficiency. However, as noted at QFTHEP'13, St.-Petersburg, Repino [Berezhnoy and Likhoded(2013)], the loss of soft photon from B_c^* shifts the vector $2S$-state approximately by ~ 65 MeV and insignificantly broadens the peak:

$$\Delta\tilde{M}_{2S} \sim 2\frac{\Delta M^* \langle\sqrt{\Delta M^2 - m_{\pi\pi}^2}\rangle}{M} < 2\frac{\Delta M^* \sqrt{\Delta M^2 - 4m_\pi^2}}{M} \approx 10 \text{ MeV}$$

M is a ground state mass, $\Delta M^* = M(B_c^*) - M(B_c)$ is a difference between masses of lowest vector and pseudoscalar states and $\Delta M = M(B_c^*(2S)) - M(B_c^*)$.

Cited by CMS and LHCb!

$B_c(2S)$: what was measured

Table: The experimental data on $B_c(2S)$

	experiment	ATLAS	CMS	LHCb
	luminosity (energy)	24.1 fb^{-1} (7, 8 TeV)	140 fb^{-1} (13 TeV)	8.7 fb^{-1} (7, 8, 13 TeV)
mass, MeV	2^3S_1 , shifted	6842 ± 6	6842 ± 2	6841 ± 1
	2^1S_0		6871.0 ± 1.6	6872.1 ± 1.6
row relative yield	2^3S_1		0.0088 ± 0.0014	0.0136 ± 0.0027
	2^1S_0		0.0068 ± 0.0014	0.0063 ± 0.0024
	total	0.18 ± 0.05	0.0156 ± 0.0019	0.0198 ± 0.0036
$N(2^3S_1)/N(2^1S_0)$			1.31 ± 0.32	2.1 ± 0.9

The registration efficiencies for $\pi^+\pi^-$ are not published by the experiment,
thus the relative yields can not be accurately compared.
Unexpectedly large yield at ATLAS.

ATLAS [Aad et al.(2014)] CMS [Sirunyan et al.(2019)]
LHCb [Aaij et al.(2019)]

D wave states of B_c

Table: Mass predictions for D-wave B_c meson states in MeV

State	EQ	GKLT	ZVR	FUI	EFG	GI	MBV	SJSCP	LLLGZ
3^3D_1	7012	7008	7010	7024	7072	7028	6973	6998	7020
$3D_2'$	...	7016	...	...	7079	7036	7003	...	7032
$3D_2$	...	7001	...	...	7077	7041	6974	...	7024
3^1D_2	7009	...	7020	7023	...	...	...	6994	...
3^3D_2	7012	...	7030	7025	...	...	...	6997	...
3^3D_3	7005	7007	7040	7022	7081	7045	7004	6990	7030

D wave yield is small ($\sim 1\%$ in e^+e^- annihilation [Cheung and Yuan(1996)]).
$\sim 20\%$ of D decay in radiating $\pi\pi$ [Eichten and Quigg(1994)]
We should expect one peak for 3^1D_2 state and three peaks for $3^3D_1, 3^3D_2, 3^3D_3$ states shifted by the value close to $\Delta M^* = M_{B_c^*} - M_{B_c}$.

One could expect

- one narrow peak at ~ 7000 MeV
- one broad peak at ~ 6930 MeV

Hadronic production cross section of D wave B_c mesons will be estimated by our group in nearest future.

B_c^* v.s. P wave B_c

$$B_c^*(1^3S_1) \xrightarrow[100\%]{\gamma} B_c(1^1S_0)$$

$$M(B_c^*) - M(B_c) \approx 65 \text{ MeV}$$

Maximum transverse energy ω_T of γ in the lab. system:

$$\omega_T^{max} = \left(1 + \frac{\Delta M}{2M_{B_c^*}}\right)\left(\sqrt{M_{B_c^*}^2 + p_T^2} + p_T\right)\frac{\Delta M}{M_{B_c^*}} \approx 0.01\left(\sqrt{M_{B_c^*}^2 + p_T^2} + p_T\right)$$

B_c^* v.s. B_c^P

- a lot of B_c^*, but hight p_T is needed.
- Small amount of B_c^P, but p_T is not essential.

Seems, that B_c^P family win:

$$\frac{\sigma_{2P}(\omega_T^\gamma > 0.5 \text{ GeV})}{\sigma_{1S}(\omega_T^\gamma > 0.5 \text{ GeV} \Longleftrightarrow p_T^{Bc} > 24 \text{ GeV})} \sim 25 \div 50$$

Table: Decays $P \to 1S + \gamma$

[Godfrey(2004), Gupta and Johnson(1996), Kiselev et al.(1995)Kiselev, Likhoded, and Tkabladze]

state	decay to 1S	Br, %	ΔM, MeV
2^3P_0	$1^3S_1 + \gamma$	100	363-366
$2P1^+$	$1^3S_1 + \gamma$	87	393-400
	$1^1S_0 + \gamma$	13	393-400
$2P1'^+$	$1^1S_0 + \gamma$	94	472-476
	$1^3S_1 + \gamma$	6	472-476
2^3P_2	$1^3S_1 + \gamma$	100	410-426
3^3P_0	$1^3S_1 + \gamma$	2	741
$3P1^+$	$1^3S_1 + \gamma$	8.5	761
	$1^1S_0 + \gamma$	3.3	820
$3P1'^+$	$1^1S_0 + \gamma$	22.6	825
	$1^3S_1 + \gamma$	0.7	769
3^3P_2	$1^3S_1 + \gamma$	18	778

$B_c^*(P) \to B_c^* b + \gamma^{\text{hard}}, B_c^* \to B_c + \gamma^{\text{soft}}$

Peaks from P wave states could look like that:

Only $\sim 20\%$ of $2P$-wave states decay radiating only one photon. In most cases

$$B_c(2P) \xrightarrow{\gamma^{\text{hard}}} B_c^* \xrightarrow{\gamma^{\text{soft}}} B_c$$

The detection of γ^{soft} will crucially decrease efficiency. However, the loss of soft photon leads to broadening of the peak by the value

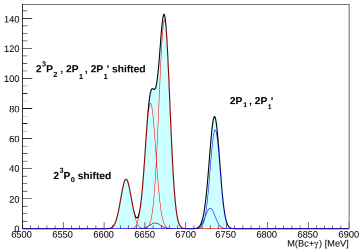
$$\Delta \tilde{M} = \tilde{M}_{max} - \tilde{M}_{min} \approx 2\frac{\Delta M^* \Delta M}{M}$$

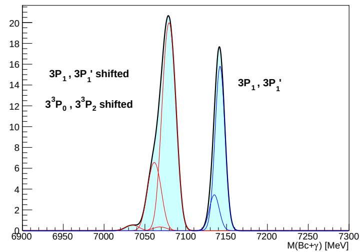
and to the left shifting it by ΔM^*.

$$\Delta \tilde{M}_{2P} \approx 10 \text{ MeV}$$

Considering $\Delta M^* \approx 65$ MeV and $\Delta M \approx 400$ MeV we can get that the value of broadening for $2P$-wave states is
Broadening for $3P$-wave states is also fairly small:

$$\Delta \tilde{M}_{3P} \approx 20 \text{ MeV}$$





To summarize

- Congratulations on the discovery of $B_c(2S)$!
- A reanalysis of the ATLAS results on $B_c(2S)$ ATLAS is awaiting.
- The ratio dependence between yields of 2^3S_1 and 2^1S_0 states of B_c meson on the kinematical conditions can provide a very important information about the B_c meson production mechanisms.
- It worth to search D excitations in $B_c + \pi\pi$ spectrum at large statistics.
- The P wave states of B_c is more perspective for observation in $B_c + \gamma$ spectrum, than B_c^*.
- The hadronic cross section D wave states of B_c will be estimated soon.

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Thank you for your attention!

Groups predicted masses for D wave states of B_c

EQ [Eichten and Quigg(1994)]
GKLT [Gershtein et al.(1995)Gershtein, Kiselev, Likhoded, and Tkabladze]
ZVR [Zeng et al.(1995)Zeng, Van Orden, and Roberts]
FUI [Fulcher(1999)]
EFG [Ebert et al.(2003)Ebert, Faustov, and Galkin]
GI [Godfrey(2004)]
MBV [Monteiro et al.(2017)Monteiro, Bhat, and Vijaya Kumar]
SJSCP [Soni et al.(2018)Soni, Joshi, Shah, Chauhan, and Pandya]
LLLGZ [Li et al.(2019)Li, Liu, Lu, Lü, Gui, and Zhong]

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