D-wave B_c meson production at LHC

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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.

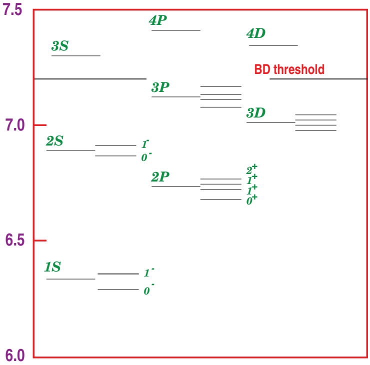
$$h_Q \ \chi_{1Q} \xrightarrow{\text{mixing}} 1^+ \ 1^{+'}$$

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

[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
$|R(B_c^*(2S))(0)| \approx |R(B_c(2S))(0)|$

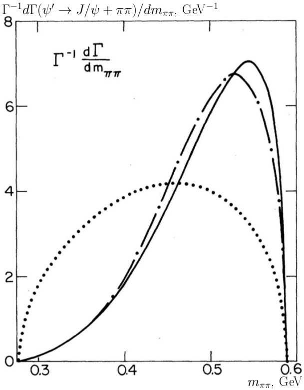
$$\sigma(B_c^*(2S))/\sigma(B_c(2S)) \sim 2.6$$

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]

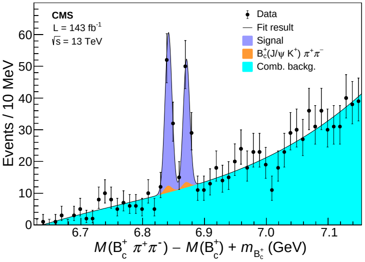
$$\sigma(B_c^*(2S))/\sigma(B_c(2S)) \sim 1 \div 2$$

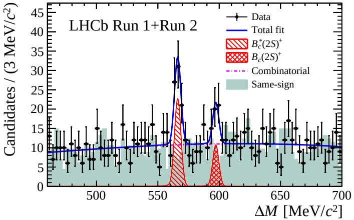


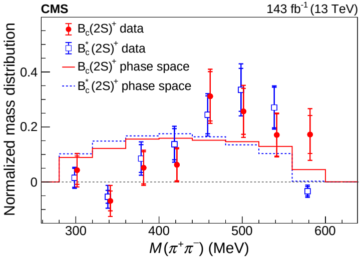
$$\frac{1}{\Gamma}\frac{d\Gamma}{dm_{2\pi}} \sim \frac{|\mathbf{k}_{\pi\pi}|}{M^2}(2x^2 - 1)\sqrt{x^2 - 1}$$

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)]

$B_c(2S)$ observed $B_c^{(*)} + \pi\pi$ spectrum







CMS results (reasonable agreement with predictions!)

$$\frac{\sigma(B_c(2S) \to B_c(1S) + \pi^+\pi^-)}{\sigma(B_c)} = (8.2 \pm 1.1)\ \%$$

$$\frac{\sigma(B_c^*(2S))}{\sigma(B_c(2S))} = (1.35 \pm 0.33)\ \%$$

CMS [Sirunyan et al.(2019)] LHCb [Aaij et al.(2019)] CMS[Sirunyan et al.(2020), CMS(2020)]

D-wave states of B_c-mesons

Predictions for mass of D-wave states of B_c-mesons (MeV):

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

$\sim 20\%$ D could radiate $\pi\pi$ [Eichten and Quigg(1994)] (see also [Asghar et al.(2019)Asghar, Akram, Masud, and Sultan]), and therefore one can expect peak in the same mass distribution as for $B_c(2S)$

$B_c\pi\pi$-peaks from D states

- one narrow peak at ~ 7000 MeV from 1^3D_1 state;
- one broad peak at ~ 6930 MeV form shifted and broadened 1^3D_1-, 1^3D_2-, 1^3D_3 states.

D-wave B_c calculation in hadronic interaction

$$A \sim \int d^3q\, \Psi^*(\vec{q}) \left\{ T(p_i,\vec{q})|_{\vec{q}=0} + q^\alpha \frac{\partial}{\partial q^\alpha} T(p_i,\vec{q})|_{\vec{q}=0} + \frac{1}{2} q^\alpha q^\beta \frac{\partial^2}{\partial q^\alpha \partial q^\beta} T(p_i,\vec{q})|_{\vec{q}=0} + \cdots \right\}$$

$\vec{q}$ is quark three momentum in B_c-meson, $\Psi^*(\vec{q})$ is B_c-meson wave function, and T is the amplitude of four heavy quark gluonic production with momenta p_i (36 diagram in LO).
For D wave state an amplitude is proportional to $R''(0)$ and second derivatives of T over $\vec{q}$.
Spin singlet $(J=2,\ j_z=l_z)$:

$$A^{j_z} = \frac{1}{2}\sqrt{\frac{15}{8\pi}} R''_D(0)\epsilon^{\alpha\beta}(j_z)\ \frac{\partial^2 M(\boldsymbol{q})}{\partial q^\alpha \partial q^\beta}\bigg|_{\boldsymbol{q}=0}$$

Spin triplet $(J=1,2,3;\ j_z=s_z+l_z)$:

$$A^{Jj_z} = \frac{1}{2}\sqrt{\frac{15}{8\pi}} R''_D(0)\Pi^{J,\ \alpha\beta\rho}(j_z)\ \frac{\partial^2 M_\rho(\boldsymbol{q})}{\partial q^\alpha \partial q^\beta}\bigg|_{\boldsymbol{q}=0}$$

$$\Pi^{J,\ \alpha\beta\rho}(j_z) = \sum_{l_z,s_z} \epsilon^{\alpha\beta}(l_z)\epsilon^\rho(s_z)\cdot C^{Jj_z}_{s_z l_z},$$

where $C^{Jj_z}_{s_z l_z}$ are Clebsch-Gordan coefficients.

Amplitude derivatives

$$\mathcal{P}(0,0) = \frac{1}{\sqrt{2}}\{v_+(p_{\bar b}+k)\bar u_+(p_c-k) - v_-(p_{\bar b}+k)\bar u_-(p_c-k)\},$$

$$\mathcal{P}(1,S_z) = \begin{cases} \mathcal{P}(1,1) = v_-(p_{\bar b}+k)\bar u_+(p_c-k) \\ \mathcal{P}(1,0) = \frac{1}{\sqrt{2}}\{v_+(p_{\bar b}+k)\bar u_+(p_c-k) + v_-(p_{\bar b}+k)\bar u_-(p_c-k)\} \\ \mathcal{P}(1,-1) = v_+(p_{\bar b}+k)\bar u_-(p_c-k) \end{cases}$$

$$v_{\lambda_1}(p_{\bar b}+k) = (1 - \frac{\widehat{k}}{2m_b})v_{\lambda_1}(p_{\bar b}),$$

$$\bar u_{\lambda_2}(p_c-k) = (1 - \frac{\widehat{k}}{2m_c})\bar u_{\lambda_2}(p_c),$$

where $p_{\bar b} = \frac{m_b}{m_b+m_c}P_{B_c}$, $p_{\bar c} = \frac{m_c}{m_b+m_c}P_{B_c}$ and $k(\vec q)$ ia a Lorentz boost of $(0,\vec q)$ to the system where B_c momentum is P_{B_c}.

Amplitudes and there derivatives have been calculated numerically as follows:

$$\frac{\partial^2 M}{\partial q_x^2} = \frac{M(p_i,\vec q_x) + M(p_i,-\vec q_x) - 2M(p_i,0)}{\Delta^2}$$

$$\frac{\partial^2 M}{\partial q_x \partial q_y} = \frac{M(p_i,\vec q_x+\vec q_y) + M(p_i,0) - M(p_i,\vec q_x) - M(p_i,\vec q_y)}{\Delta^2}$$

Amplitude squared

Sum of amplitudes squared for states with spin $S = 1$ (1^3D_1-, 1^3D_2-, 1^3D_3):

$$\sum_j^{-1,0,1} |A_{S=1,s=j}|^2 = \left(\frac{5}{16\pi}\right) |R_D^{''}(0)|^2 \times$$
$$\sum_j^{-1,0,1} \left[\left(\left| \frac{\partial^2 M_{S=1,s=j}}{\partial k_x^2} \right|^2 + \left| \frac{\partial^2 M_{S=1,s=j}}{\partial k_y^2} \right|^2 + \left| \frac{\partial^2 M_{S=1,s=j}}{\partial k_z^2} \right|^2 \right) \right.$$
$$+3 \left(\left| \frac{\partial^2 M_{S=1,s=j}}{\partial k_x \partial k_y} \right|^2 + \left| \frac{\partial^2 M_{S=1,s=j}}{\partial k_x \partial k_z} \right|^2 + \left| \frac{\partial^2 M_{S=1,s=j}}{\partial k_y \partial k_z} \right|^2 \right)$$
$$- \mathrm{Re} \left(\frac{\partial^2 M_{S=1,s=j}}{\partial k_x^2} \frac{\partial^2 M^*_{S=1,s=j}}{\partial k_y^2} + \frac{\partial^2 M_{S=1,s=j}}{\partial k_x^2} \frac{\partial^2 M^*_{S=1,s=j}}{\partial k_z^2} + \right.$$
$$\left. \left. + \frac{\partial^2 M_{S=1,s=j}}{\partial k_y^2} \frac{\partial^2 M^*_{S=1,s=j}}{\partial k_z^2} \right) \right].$$

Amplitude squared for spin $S = 0$ (1^3D_1) is given by the analogous equation.

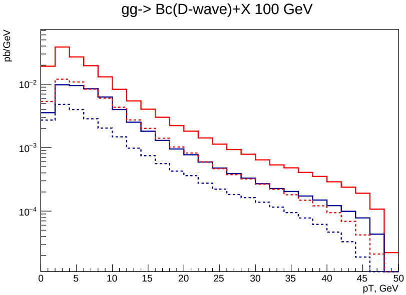
$gg \to B_c(D) + X$ v.s. $gg \to B_c + X$

$$\alpha_s = 0.2$$

$$|R''(0)(D)|^2 = 0.1 \text{ GeV}^7$$

$$|R(0)(S)|^2 = 1.4 \text{ GeV}^3$$

energy, $\sqrt{s_{gg}}$, GeV	σ_{gg}, pb	
	$1S$	$1D$
20	21.9	0.21
30	32.2	0.51
50	29.1	0.60
100	16.1	0.39
200	7.7	0.11



Red lines: $S=1$, blue lines: $S=0$, solid lines: D-waves, dashes lines: S-waves scaled by 0.01

Our predictions for Bc(D)

- $1 \div 2$ % of the total yield
- $\sigma(1^3D_1 + 1^3D_2 + 1^3D_3)/\sigma(1^1D_1) \sim 3$
- kinematical distributions are quite similar to ones for S wave states

To do

- convolute with PDF and obtain hadronic cross section
- estimate uncertainties

Conclusions

- $B_c(2S)$ excitations have been observed. This stimulated us to estimate possibilities to find $B_c(D)$ states at LHC.
- We estimate $B_c(D)$ states yield in hadronic production as $\sim 1 - 2\%$.
- Our estimations for D-wave states of B_c in hadronic production do not contradict the estimations [Cheung and Yuan(1996)] for e^+e^--annihilation.
- We propose find D-excitations in $B_c + \pi\pi$ spectrum at large statics. However it is quite challenging task.

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Thank for your attention!

Backup slides

$B_c(2S)$: what was measured

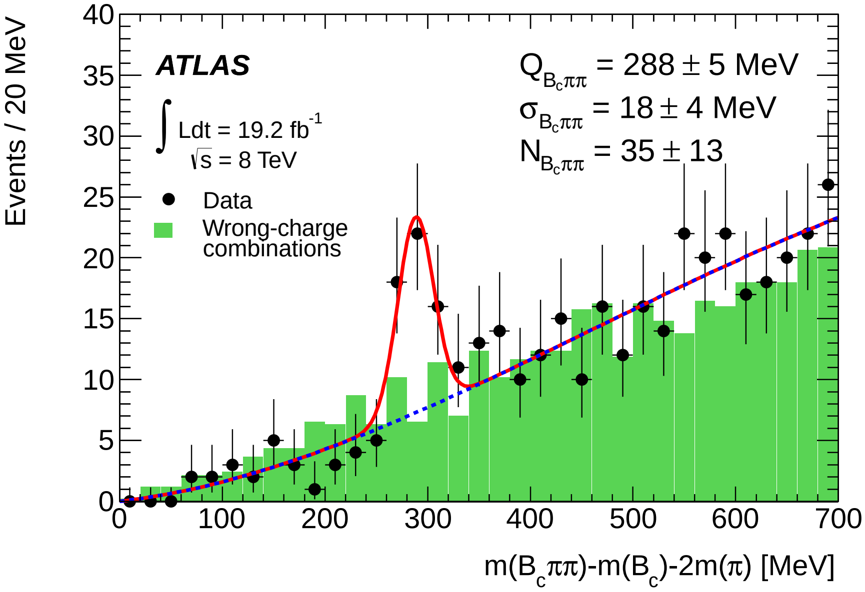
Table: The experimental data on $B_c(2S)$

	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)
nass, MeV	2^3S_1 , shifted	6842 ± 6	6842 ± 2	6841 ± 1
	2^1S_0		6871.0 ± 1.6	6872.1 ± 1.6
ow 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
eal relative yield	2^3S_1		(4.69 ± 0.90) %	
	2^1S_0		(3.47 ± 0.71) %	
	total		(8.16 ± 1.1) %	
$N(2^3S_1)/N(2^1S_0)$			1.35 ± 0.33	2.1 ± 0.9

The registration efficiencies for $\pi^+\pi^-$ are published only by the CMS Collaboration, 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)]
See also recent CMS publications: [Sirunyan et al.(2020), CMS(2020)]

ATLAS results for $B_c(2S)$



The papers with mass predictions of D-wave states of B_c-mesons

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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