

Hadronic B_c production

LHCb MicroWorkshop on B_c Physics

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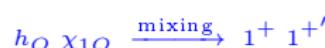
13.07.2016

B_c properties

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

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

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



$$|2P, 1^{' +}\rangle = 0.294|S = 1\rangle + 0.956|S = 0\rangle$$

$$|2P, 1^+ \rangle = 0.956|S = 1\rangle - 0.294|S = 0\rangle$$

$$|3P, 1^{' +}\rangle = 0.371|S = 1\rangle + 0.929|S = 0\rangle$$

$$|3P, 1^+ \rangle = 0.929|S = 1\rangle - 0.371|S = 0\rangle$$

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

B_c family

All excitations decay into 1^1S_0 .

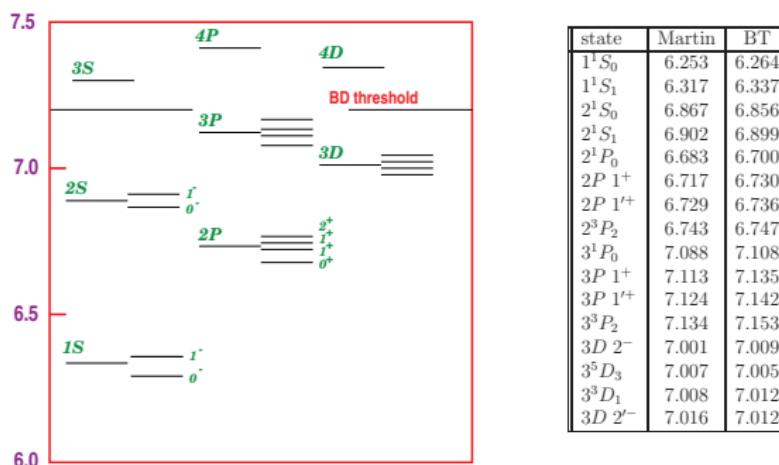


Figure 1: The mass spectrum of $(\bar{b}c)$ with account for the spin-dependent splittings.

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

B_c production amplitude

$$A^{SJjz} = \int T_{b\bar{b}c\bar{c}}^{Ssz}(p_i, k(\vec{q})) \cdot \left(\Psi_{\bar{b}c}^{Ll_z}(\vec{q}) \right)^* \cdot C_{szl_z}^{Jjz} \frac{d^3\vec{q}}{(2\pi)^3},$$

where $T_{b\bar{b}c\bar{c}}^{Ssz}$ is an amplitude of the hard production of two heavy quark pairs;

$\Psi_{\bar{b}c}^{Ll_z}$ is the quarkonium wave function (color singlet, *in some calculations — color octet*);

J and j_z are the total angular momentum and its projection on z -axis in the B_c rest frame;

L and l_z are the orbital angular momentum of B_c meson and its projection on z -axis;

S and s_z are B_c spin and its projection;

$C_{szl_z}^{Jjz}$ are Clebsch-Gordon coefficients;

p_i are four momenta of B_c meson, b quark and \bar{c} quark;

\vec{q} is three momentum of \bar{b} -quark in the B_c rest frame (in this frame $(0, \vec{q}) = k(\vec{q})$).

Under assumption of small dependence of $T_{b\bar{b}c\bar{c}}^{Ssz}$ on $k(\vec{q})$

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

and, particularly, for the S -wave states

$$A \sim R_S(0) \cdot T_{b\bar{b}c\bar{c}}(p_i)|_{\vec{q}=0},$$

where $R_S(0)$ is a value of radial wave function at origin.

Calculation approach

δ -approximation:

- the matrix element for S wave B_c production is proportional to the matrix element for $b\bar{c}c\bar{c}$ production timed by B_c wave function at origin,
- \bar{b} and c quark moves with the same velocities,
- \bar{b} and c quarks are in appropriate spin state.

color model:

- $\bar{b}c$ pair is produced in color singlet (dominant contribution),
- $\bar{b}c$ pair is produced in color octet.

heavy quark matrix element:

- calculated within leading order of QCD.

Papers on B_c production

Hadronic S -wave B_c -meson production:

[Chang et al.(2005)Chang, Qiao, Wang, and Wu,
Berezhnoy et al.(1995)Berezhnoy, Likhoded, and Shevlyagin,
Berezhnoy et al.(1997b)Berezhnoy, Kiselev, Likhoded, and Onishchenko,
Kolodziej et al.(1995)Kolodziej, Leike, and Ruckl,
Chang et al.(1995)Chang, Chen, Han, and Jiang, Baranov(1997a),
Baranov(1997b)].

P -wave B_c -meson:

[Berezhnoy et al.(1996)Berezhnoy, Kiselev, and Likhoded,
Berezhnoy et al.(1997a)Berezhnoy, Kiselev, and Likhoded,
Chang et al.(2004)Chang, Wang, and Wu].

Some more papers on B_c production:

[Berezhnoy(2005), Chang et al.(2006)Chang, Wang, and Wu,
Berezhnoy et al.(2011)Berezhnoy, Likhoded, and Martynov,
Chang et al.(2015)Chang, Wang, and Wu].

First theoretical research of the hadronic four heavy quark production ($gg \rightarrow Q_1\bar{Q}_1Q_2\bar{Q}_2$ and $q\bar{q} \rightarrow Q_1\bar{Q}_1Q_2\bar{Q}_2$):

[Barger et al.(1991)Barger, Stange, and Phillips]

Fragmentation in e^+e^-

In the special gluonic gauge the only diagram (1) contributes to the cross section at

$$\frac{M_{B_c}^2}{s_{e^+e^-}} \rightarrow 0$$

$$\frac{d\sigma_{B_c}}{dz} = D_{\bar{b} \rightarrow B_c}(z) \cdot \sigma_{b\bar{b}}$$

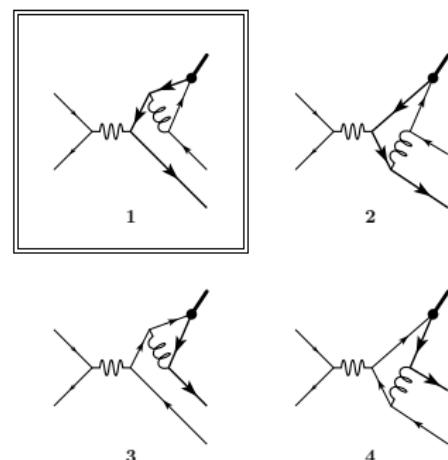
$$D_{\bar{b} \rightarrow B_c^*}(z) =$$

$$\frac{2\alpha^2|R_S(0)|^2}{81\pi m_c^3} \frac{rz(1-z)^2}{(1-(1-r)z)^6} (6 - 18(1-2r)z + (21 - 74r + 68r^2)z^2 - 2(1-r)(6 - 19r + 18r^2)z^3 + 3(1-r)^2(1 - 2r + 2r^2)z^4)$$

$$D_{\bar{b} \rightarrow B_c}(z) =$$

$$\frac{2\alpha^2|R_S(0)|^2}{27\pi m_c^3} \frac{rz(1-z)^2}{(1-(1-r)z)^6} (2 - 2(3 - 2r)z + 3(3 - 2r + 4r^2)z^2 - 2(1-r)(4 - r + 2r^2)z^3 + (1-r)^2(3 - 2r + 2r^2)z^4)$$

$$r = \frac{m_c}{m_c + m_b}$$



[Clavelli(1982), Ji and Amiri(1987),
 Amiri and Ji(1987), Chang and Chen(1992a),
 Chang and Chen(1992b),
 Braaten et al.(1993) Braaten, Cheung, and Yuan,
 Kiselev et al.(1994) Kiselev, Likhoded, and Shevlyagin]

The analog of Peterson function

To describe heavy quark hadronization into heavy-light meson the Peterson FF is usually used:

$$D_{Q \rightarrow (Q\bar{q})}(z) \sim \frac{1}{z \left(1 - \frac{1}{z} - \frac{\epsilon}{1-z}\right)^2}.$$

The dependence of "nonperturbative" Peterson FF is partially determined by denominator of perturbative propagator for $Q^* \rightarrow (Q\bar{q}) + X$ process:

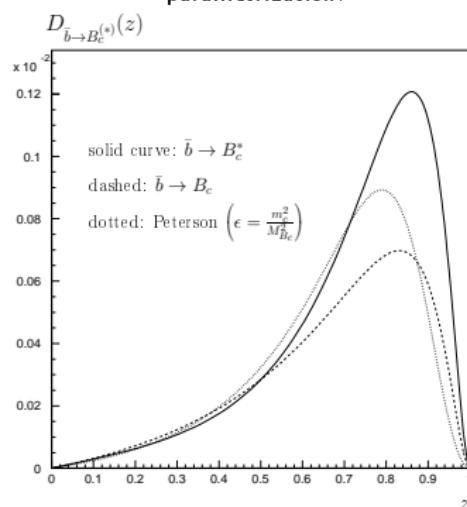
$$m_Q^2 - (P_{(Q\bar{q})} + P_X)^2.$$

$$m_Q^2 - (P_{(Q\bar{q})} + P_X)^2 \approx m_Q^2 - \frac{m_{(Q\bar{q})}^2}{z} - \frac{m_X^2}{1-z}.$$

For $m_Q \approx m_{(Q\bar{q})}$

$$m_Q^2 - (P_{(Q\bar{q})} + P_X)^2 \sim 1 - \frac{1}{z} - \frac{m_X^2}{m_Q^2} \frac{1}{1-z}.$$

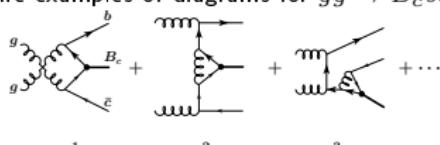
FF for $b \rightarrow B_c^{(*)}$ obtained within pQCD vs. Peterson parametrization:



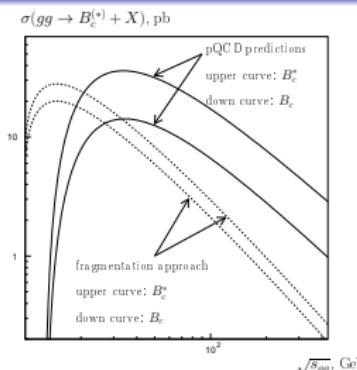
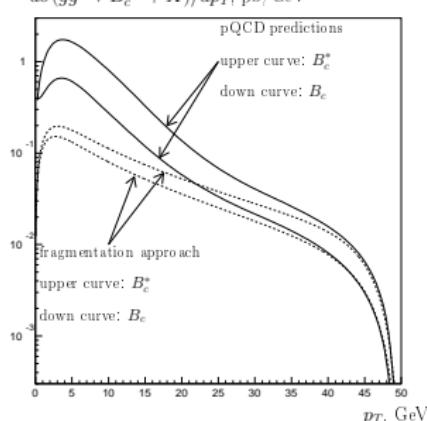
The FFs from the previous slide are used within FONLL to describe $c \rightarrow D$ (r — free parameter).

$gg \rightarrow B_c + X$

The examples of diagrams for $gg \rightarrow B_c b\bar{c}$:



p_T -distribution for $\sqrt{s_{gg}} = 100$ GeV:
 $d\sigma(gg \rightarrow B_c^{(*)} + X)/dp_T, \text{ pb/GeV}$



The difference is partially hidden by convolution with PDFs.

For $P_T(B_c) < 35 - 40$ GeV recombination diagrams (such as 1 and 2) dominates and

$$\frac{\sigma(B_c^*)}{\sigma(B_c)} \sim 2.5 \div 3$$

Fragmentation approach is valid for
 $P_T(B_c) > 35 - 40$ GeV:

$$\frac{\sigma(B_c^*)}{\sigma(B_c)} \sim 1.4$$

Additional contributions

Comparable contributions to the B_c production:

- $gg \rightarrow B_c b\bar{c}$
- $\bar{b}(c)g \rightarrow B_c + \bar{c}(b)$
- Pythia gluonic showering $g \rightarrow B_c$.

Small contributions:

- $q\bar{q} \rightarrow B_c b\bar{c}$ (about 10% $gg \rightarrow B_c b\bar{c}$)
- color octet (unessential for B_c inclusive production).

Problems:

- How to avoid double counting?
- How to take into account the mass of $b(\bar{c})$ -quark from the sea in matrix element?
- How to obtain reasonable p_T distribution?

Methods used for b production

- GM-VFNS** General-mass variable-flavor-number scheme (GM-VFNS): The heavy quark is treated as any other massless parton, the mass is taken into account as large logarithms $\ln(p_T/m)$ in parton distribution and fragmentation functions, where they are resummed by imposing DGLAP evolution
[Kniehl et al.(2012)Kniehl, Kramer, Schienbein, and Spiesberger].
- FONLL** NLO (massive quark) + resummation of large logs: at $p_T < 5m_c$ NLO works without logarithm resummation (see eq. 6.1 in [Cacciari et al.(1998)Cacciari, Greco, and Nason]).
- k_T fact.** LO (massive quark) + virtual initial gluons (It seems that sea c quark is not needed) [Baranov et al.(2005)Baranov, Lipatov, and Zotov].

B_c/B ratio

LHCb experimental value [Aaij et al.(2014a)]:

$$R^{\text{exp}} = \frac{\sigma(B_c^+) \times \mathcal{B}(B_c^+ \rightarrow J/\psi\pi^+)}{\sigma(B^+) \times \mathcal{B}(B^+ \rightarrow J/\psi K^+)} = (0.683 \pm 0.018 \pm 0.009)\%$$

$\mathcal{B}(B^+ \rightarrow J/\psi K^+) \approx 0.1\%$ is known experimentally.
 $\mathcal{B}(B_c^+ \rightarrow J/\psi\pi^+)$ is theoretically predicted within different models. The obtained predictions contradict each other :

$$\mathcal{B}(B_c^+ \rightarrow J/\psi\pi^+) = 0.061 \div 0.29\%$$

$$r_c^{\text{theor.}} \sim \frac{\sigma(B_c^+)}{\sigma(B^+)} \sim 0.1 \div 0.3\%$$

The R^{exp} is in agreement the largest predicted value for $\mathcal{B}(B_c^+ \rightarrow J/\psi\pi^+)$:

$$R_{\text{optimistic}}^{\text{theor.}} \sim 0.3 \div 0.9\%$$

However the choice of $\mathcal{B}(B_c^+ \rightarrow J/\psi\pi^+) \sim (0.06 \div 1.1)\%$ looks more reasonable, because these values obtain within the models [Ebert et al.(2003) Ebert, Faustov, and Galkin, Abd El-Hady et al.(2000) Abd El-Hady, Munoz, and Vary], which describe the the experimentally obtained ratio [Aaij et al.(2014b)]:

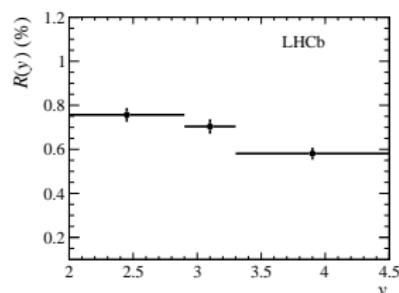
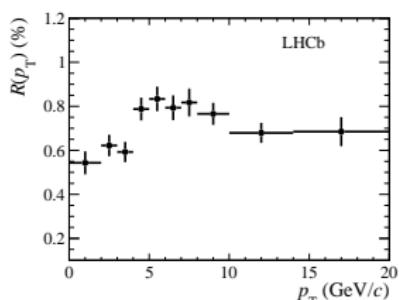
$$\frac{\mathcal{B}(B_c^+ \rightarrow J/\psi\pi^+)}{\mathcal{B}(B_c^+ \rightarrow J/\psi\mu\nu_\mu)} = 0.0469 \pm 0.0028 \pm 0.0046$$

For this case

$$R_{\text{reasonable}}^{\text{theor.}} \sim 0.06 \div 0.3\%$$

It seems that the theoretical predictions underestimate the experimental values.

B_c/B distribution



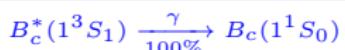
- The distribution shapes can be successfully described within LHCb generator BCVEGPY [Wu(2014)], [Chang et al.(2015) Chang, Wang, and Wu] + FONLL [Cacciari et al.(2012) Cacciari, Frixione, Houdeau, M., and Nas...
- The standalone LO program ($gg \rightarrow B_c \bar{b}c$) do not describe a shape at large p_T , because it do not take into account p_T of initial gluons [Berezhnoy and Likhoded(2015)].
- NLO prediction is needed.

Task for theorists:

- Accurate prediction for one B_c decay.
- NLO for B_c for B_c production (at least real radiation process).

Off topic: NLO corrections for $e^+e^- \rightarrow B_c^{+(*)} B_c^{-(*)}$ essentially change the ratio $\sigma(B_c B_c) : \sigma(B_c^* B_c) : \sigma(B_c^* B_c^*)$.

What will be observed first: B_c^* or B_c^P ?



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

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

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

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:

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

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

[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

What to do with the soft photon from B_c^* decay?

Only $\sim 20\%$ of $2P$ -wave states decay radiating only one photon:

$$2P1^+(B_c) \xrightarrow[\sim 13\%]{\gamma} 1^1S_0(B_c)$$

$$2P1'^+(B_c) \xrightarrow[\sim 94\%]{\gamma} 1^1S_0(B_c)$$

In most cases

$$2P \xrightarrow{\gamma_1^{\text{hard}}} 1^3S_1(B_c^*) \xrightarrow{\gamma_2^{\text{soft}}} 1^1S_0(B_c)$$

To find γ_2 the high p_T of B_c^* is needed.

But, it seems that we can see P -wave excitations without the reconstruction of soft γ_2 .

$$\Delta \approx 2 \frac{(M_{B_c(P)} - M_{B_c^*})(M_{B_c^*} - M_{B_c})}{M_{B_c}}$$

P -wave excitations in $B_c + \gamma$ mass spectrum

Peaks for $2P$ wave excitations ("soft" photon is lost):

- shifted by ~ 65 MeV
- have a width ~ 10 MeV

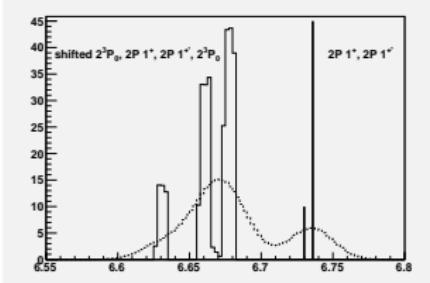
Peaks for $3P$ wave excitations ("soft" photon is lost):

- shifted by ~ 65 MeV
- have a width ~ 20 MeV

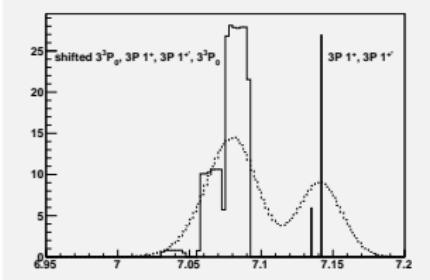
$\sigma(3P) \sim \sigma(2P)$, but only $\sim 20\%$ of $B_c(3P)$ decay electromagnetically into $1^3S_1(B_c^*)$ or $1^1S_0(B_c)$.

ω_T^{\min} , GeV	B_c state	relative yield %
0.3	$B_c(2P)$	~ 5.0
	$B_c(3P)$	~ 1.0
	B_c^*	~ 0.8
0.5	$B_c(2P)$	~ 3.5
	$B_c(3P)$	~ 0.7
	B_c^*	~ 0.06
1.0	$B_c(2P)$	~ 0.9
	$B_c(3P)$	~ 0.4
	B_c^*	~ 0.005

$B_c(2P) \rightarrow B_c + \gamma[+\gamma_{lost}]$



$B_c(3P) \rightarrow B_c + \gamma[+\gamma_{lost}]$



$$B_c(2S) \rightarrow B_c(B_c^*) + \pi\pi$$

$$2^1 S_0(B_c) \xrightarrow[\sim 50\%]{\pi^+ \pi^-} 1^1 S_0(B_c)$$

$$2^3 S_1(B_c) \xrightarrow[\sim 40\%]{\pi^+ \pi^-} 1^3 S_1(B_c)$$

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

$$\sigma(2^3 S_1)/\sigma(2^1 S_0) \sim 2.6$$

feed down from $B_c(2S) \rightarrow B_c(1S) + \pi^+ \pi^- \sim 10 \%$

For $2S$ vector, as well as pseudoscalar

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

where $x = m_{\pi\pi}/2m_\pi$ and $\mathbf{k}_{\pi\pi}$ is the momentum of $\pi\pi$ -pair in the $B_c(2S)$ rest frame.

$$\langle m_{\pi\pi} \rangle \sim 0.5 \text{ GeV}$$

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PHYSICAL REVIEW

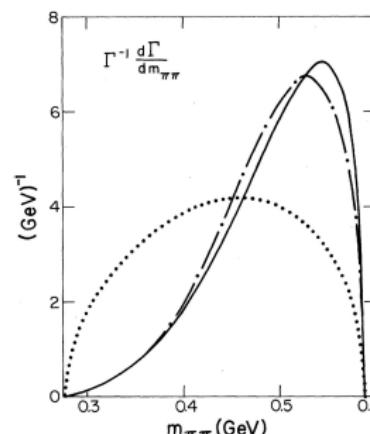
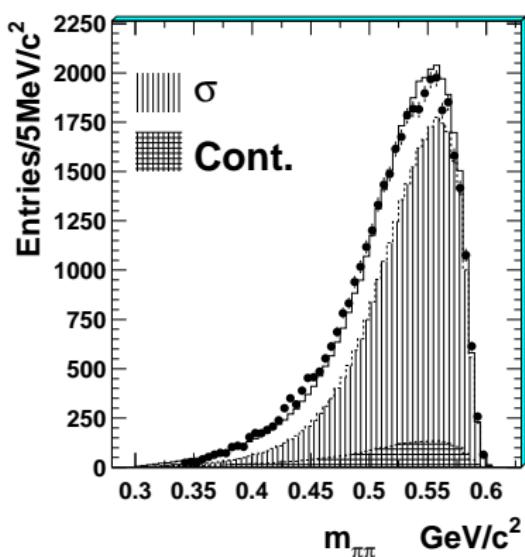


FIG. 1. The decay spectrum $\Gamma^{-1} d\Gamma/dm_{\pi\pi}$ as a function of $m_{\pi\pi}$ given by Eq. (6) (solid line); given by simple phase space (dotted line); and given by Eq. (6) modified by pion-pion rescattering (dot-dashed line).

[Brown and Cahn (1975), Novikov and Shifman (1981), Voloshin (1975), Voloshin and Zakharov (1980)]

σ -meson in the quarkonia decays

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



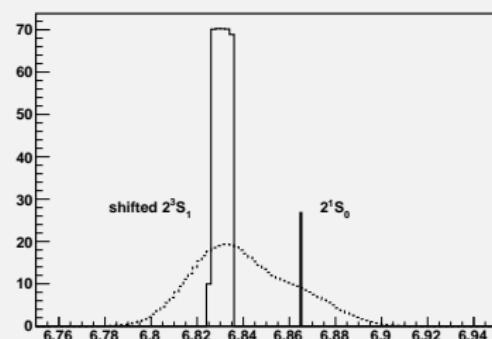
$f_0(500)$ or σ
 $J^{PC} = 0^{++}$
 $(400 - 550) - i(200 - 350)$ MeV

$B_c^*(2S)$ with lost photon

Peak for 2^3S_1 excitation ("soft" photon is lost):

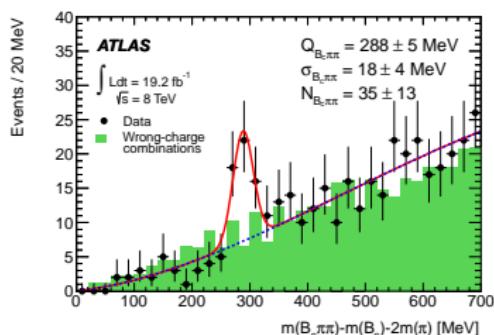
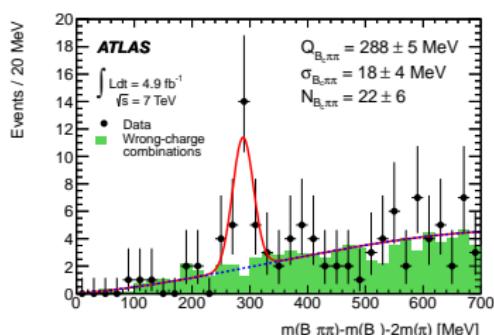
- shifted by ~ 65 MeV \Rightarrow appeared ~ 30 MeV before 2^1S_0
- have a width ~ 10 MeV

$$\Delta \approx 2 \frac{\sqrt{(M_{B_c^*(2S)} - M_{B_c^*})^2 - 4m_\pi^2} (M_{B_c^*} - M_{B_c})}{M_{B_c}}$$



ATLAS results for $B_c(2S)$

ATLAS Coll. [Aad et al.(2014)]



$B_c \rightarrow J/\psi\pi$ (ATLAS)		
Data	Signal events	Peak mean [MeV]
7 TeV	100 ± 23	6282 ± 8
8 TeV	227 ± 25	6277 ± 6

$$\frac{N(B_c(2S) \rightarrow B_c\pi^+\pi^-)}{N(B_c)} \sim 0.17$$

Taking into account $B_c\pi^0\pi^0$ one can obtain

$$\frac{\sigma(B_c(2S))}{\sigma(B_c^{\text{direct}}) + \sigma(B_c(2P)) + \sigma(B_c(3P))} \gtrsim 0.4$$

Accounting acceptance efficiency and pion track efficiency could increase this ratio to extremely large value.

- $B_c(2S)$ yield too large.
- The peak mean value can be interpreted as 2^3S_1 shifted by 65 MeV due to the unreconstructed soft photon ($B_c^*(2S) \rightarrow B_c^* + \pi^+\pi^-$, $B_c^* \rightarrow B_c + \gamma_{\text{lost}}$).
- It could be supposed, that the peak from 2^1S_0 do not seen due to lack of statistics.
- There are now theoretical reason for the suppression of $B_c(2S)$ yield at LHCb.

Conclusions

- There are indications that the theoretical predictions underestimate the experimental values.
- The missing of photon from $B_c^* \rightarrow B_c + \gamma$ shifts peaks by 65 MeV and broadens them by 10 – 20 MeV. The photon is too soft to be detected.
- The best chance to be found first on the $M_{B_c} + \gamma$ spectrum belongs to $2P$ excitations.
- If $B_c(2S) \rightarrow B_c(B_c^*) + \pi^+ \pi^-$ mode is seen at LHCb, it should be seen at LHCb.
- NLO cross section estimations for B_c production are needed.
- Reliable predictions for one of the branching are needed.

Thank for your attention!



Georges Aad et al.

Observation of an Excited B_c^\pm Meson State with the ATLAS Detector.

Phys.Rev.Lett., 113(21):212004, 2014.

doi: 10.1103/PhysRevLett.113.212004.



Roel Aaij et al.

Measurement of B_c^+ production in proton-proton collisions at $\sqrt{s} = 8$ TeV.

2014a.



Roel Aaij et al.

Measurement of the ratio of B_c^+ branching fractions to $J/\psi\pi^+$ and $J/\psi\mu^+\nu_\mu$.

Phys. Rev., D90(3):032009, 2014b.

doi: 10.1103/PhysRevD.90.032009.



A. Abd El-Hady, J. H. Munoz, and J. P. Vary.

Semileptonic and nonleptonic B(c) decays.

Phys. Rev., D62:014019, 2000.

doi: 10.1103/PhysRevD.62.014019.



M. Ablikim et al.

Production of sigma in $\psi(2S) \rightarrow \pi^+ \pi^- J/\psi$.

Phys.Lett., B645:19–25, 2007.

doi: 10.1016/j.physletb.2006.11.056.



F. Amiri and Chueng-Ryong Ji.

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