Associative production of $B_c$ and $\bar{D}$ mesons at LHC.

A. V. Berezhnoy, $^{1,*}$ A. K. Likhoded, $^{2,\dagger}$ and A. A. Martynov $^{3,\ddagger}$

$^1$SINP of Moscow State University, Russia
$^2$Institute for High Energy Physics, Protvino, Russia
$^3$Physical Department of Moscow State University, Russia

It is shown that the study of correlations in the associative production of $B_c$ and $\bar{D}$ mesons at LHC allows one to obtain essential information about the $B_c$ production mechanism.

I. INTRODUCTION

Recent measurements of $B_c$ meson mass and lifetime in CDF $^1$ and D0 $^2$ experiments are the first steps in the experimental research of quarkonia with open flavor. The measurement results are in a good agreement with the theoretical predictions for the $B_c$ mass $^3$:

$$m_{B_c}^{\text{CDF}} = 6.2756 \pm 0.0029(\text{stat.}) \pm 0.0025(\text{sys.}) \text{ GeV},$$

$$m_{B_c}^{\text{D0}} = 6.3000 \pm 0.0014(\text{stat.}) \pm 0.0005(\text{sys.}) \text{ GeV},$$

as well as for the decay time $^6, 7$:

$$\tau_{B_c}^{\text{CDF}} = 0.448^{+0.038}_{-0.036}(\text{stat.}) \pm 0.032(\text{sys.}) \text{ ps},$$

$$\tau_{B_c}^{\text{D0}} = 0.475^{+0.053}_{-0.049}(\text{stat.}) \pm 0.018(\text{sys.}) \text{ ps},$$

$$\tau_{B_c}^{\text{theor}} = 0.48 \pm 0.05 \text{ ps}.$$

Unfortunately, the experimental estimations of the cross section value were not published. Thus, the mechanism of $B_c$ meson production can not be understood from the obtained data due to poor experimental statistics, as well as due to large uncertainties in the theoretical

*Electronic address: Alexander.Berezhnoy@cern.ch
†Electronic address: Anatolii.Likhoded@ihep.ru
‡Electronic address: aler1x@yandex.ru
predictions. Only the planned experimental research at LHC, where about $10^{10}$ events with $B_c$ mesons per year are expected, will improve the situation. This huge amount of events will allow to obtain the information on the production cross section distributions, on the decay branching fractions, and in some cases, on the distributions of decay products. Obviously, the new experimental data on $B_c$ meson from LHC experiments have to stimulate new theoretical studies.

At first sight the production of $B_c$ meson can be represented as the heavy $\bar{b}$ quark production followed by the fragmentation of $\bar{b}$ quark into $B_c$ meson by analogy with the production of $B$ mesons, at least for transverse momenta larger than the $B_c$ meson mass\footnote{Within fragmentation approach it is assumed that $\bar{b}\bar{b}$ phase space can be factorized from the total phase space. This assumption is not valid for final state $B_c + b + \bar{c}$ at small momenta, because $c$ quark is massive.}. But, as it was shown in the framework of pQCD, there is a large nonfragmentation contribution into this process \cite{8-11}. The nonfragmentation terms in the production amplitude enlarge the total cross section and increase the ratio between yields of $B_c^*$ and $B_c$ states by a factor of two even at large transverse momenta.

However, our previous analysis showed that it is quite difficult to obtain a clear experimental evidence of the nonfragmentation contribution into the production \cite{8}. In this article we try to fill the gap in our understanding of $B_c$ production and show that the study of correlations in the associative production of $B_c$ and $\bar{D}$ meson at LHC could be an essential information source of $B_c$ production mechanism. The cross section distributions of the $B_c$ meson production in hadronic and gluonic interactions have been obtained by us within the numerical calculation method developed in our previous studies \cite{8}.

II. FRAGMENTATION AND RECOMBINATION CONTRIBUTIONS INTO $B_c$ PRODUCTION

The $B_c$ production amplitude within the discussed approach can be subdivided into two parts: the hard production of two heavy quark pairs calculated in the framework of perturbative QCD and the soft nonperturbative binding of $\bar{b}$ and $c$ quarks into quarkonium described by nonrelativistic wave function. The production amplitude within this approach
can written as follows:
\[ A^{Sj_z} = \int T^{Ss_z}_{bb\bar{c}}(p_i, k(q)) \cdot (\Psi^{Ll_z}_{bc}(q))^* \cdot C^{Jj_z}_{s_z} \frac{d^3\tilde{q}}{(2\pi)^3}, \]  

where \( T^{Ss_z}_{bb\bar{c}} \) is an amplitude of the hard production of two heavy quark pairs; 
\( \Psi^{Ll_z}_{bc} \) is the quarkonium wave function; 
\( J \) 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; 
\( C^{Jj_z}_{s_z} \) are Clebsh-Gordon coefficients; 
\( p_i \) are four momenta of \( B_c \) meson, \( b \) quark and \( \bar{c} \) quark; 
\( q \) is three momentum of \( \bar{b} \) quark in the \( B_c \) rest frame (in this frame \( (0, q) = k(q) \)).

Under the assumption of small dependence of \( T^{Ss_z}_{bb\bar{c}} \) on \( k(q) \)
\[ A \sim \int d^3q \Psi^*(q) \left\{ T(p_i, q) \bigg|_{q=0} + \tilde{q} \frac{\partial}{\partial \tilde{q}} T(p_i, \tilde{q}) \bigg|_{q=0} + \cdots \right\} \]  

and particularly for the \( S \) wave states
\[ A \sim R_S(0) \cdot T^{bb\bar{c}}(p_i) \bigg|_{q=0}, \]  

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

The calculations within the discussed technique are the most simple for the process of 
\( B_c \) production in the \( e^+e^- \) annihilation, where only four leading diagrams contribute to the 
process amplitude (see Fig. 1). As it was shown in [10, 12, 13], the diagrams (3) and (4) are 
suppressed as \( m^2_c/m^2_b \) for the \( S \) wave state production due to the large gluonic virtuality. 
The special choice of gluonic field gauge allows to neglect the contribution of diagram (2) 
at large energies \( \sqrt{s} \gg M_{B_c} \). The remained contribution of diagram (1) can be naturally 
interpreted as the \( \bar{b} \) quark production followed by the fragmentation of \( \bar{b} \) quark into \( B_c \) 
meson. Thus, in \( e^+e^- \) annihilation at large energies the consideration of leading diagrams 
for the \( B_c \) meson production leads the well known factorized formulas for the cross section 
distribution over \( z = 2E_{B_c}/\sqrt{s} \) and over \( B_c \) transverse momentum \( p_T \):
\[ \frac{d\sigma}{dz} = \sigma_{bb} \cdot D(z), \]  
\[ \frac{d\sigma_{B_c}}{dp_T} = \int_{2p_T/\sqrt{s}}^1 \frac{d\sigma_{bb}}{dk_T} \left( \frac{p_T}{z} \right) \frac{D(z)}{z} dz, \]  

\[ 2p_T/\sqrt{s} \]
Figure 1: The leading order diagrams for the process $e^+e^- \rightarrow B_c + b + \bar{c}$.

Figure 2: The fragmentation functions for the processes $\bar{b} \rightarrow B_c^*$ (solid curve) and $\bar{b} \rightarrow B_c$ (dashed curve) calculated within pQCD.

where $k_T$ is a transverse momentum of $\bar{b}$-quark.

The analytical forms of fragmentation functions for $S$ wave states are known from [12, 13] (see Fig. 2):

$$D_{\bar{b} \rightarrow B_c}(z) = \frac{2\alpha_s^2|R_S(0)|^2}{81\pi m_c^3} \frac{rz(1-z)^2}{(1-(1-r)z)^6} \left[6 - 18(1-2r)z + (21 - 74r + 68r^2)z^2 - 2(1-r)(6-19r + 18r^2)z^3 + 3(1-r)^2(1-2r + 2r^2)z^4\right],$$

$$D_{\bar{b} \rightarrow B_c^*}(z) = \frac{2\alpha_s^2|R_S(0)|^2}{27\pi m_c^3} \frac{rz(1-z)^2}{(1-(1-r)z)^6} \left[2 - 2(3-2r)z + 3(3-2r + 4r^2)z^2 - 2(1-r)(4-r + 2r^2)z^3 + (1-r)^2(3-2r + 2r^2)z^4\right],$$

where $\alpha_s$ is a strong coupling constant and $r = \frac{m_b}{m_b + m_c}$.

The graphics presented in figures 2-9 have been obtained for the following parameter values: $\alpha_s = 0.2$, $m_c = 1.5$ GeV, $m_b = 4.8$ GeV, $R_S(0) = 2.14$ GeV$^3$. As it is shown in [14] the uncertainties in these parameters leads to the quite large uncertainties in the absolute
cross section values. In this work we study the production characteristics which weakly depend on these parameters: the cross section distribution shapes and the ratio between $B_c^*$ and $B_c$ yields.

The relative yield of $B_c^*$ and $B_c$ in $e^+e^-$ annihilation obtained within pQCD calculation $R_{e^+e^-}^{B_c} = \sigma(B_c^*)/\sigma(B_c) \sim 1.4$. Thus the naive spin counting which fairly predicts this ratio for $B^*$ and $B$ ($R_{e^+e^-}^B \sim 3$) can not be applied to $B_c$ and $B_c$ production.\(^2\)

At first sight it would be reasonable to assume that for the gluonic $B_c$ production the fragmentation mechanism is also dominant at least from transverse momenta larger than $B_c$ mass. But as it was shown in [8–11] the other mechanism essentially contribute to this process practically all over the phase space. The thing is that in the leading order of pQCD the gluonic production described by 36 diagrams (see Fig. 3) and only a small part of them belongs to the fragmentation type. The other diagrams can not be interpreted as $\bar{b}$ quark production followed by the fragmentation into $B_c$ meson (see for example the diagram (1) in Fig. 3). One can say that these (recombination) diagrams correspond to the ”independent” creation of $c\bar{c}$ and $b\bar{b}$ pairs. In spite of the suppression by a factor $1/p_T^2$ comparing with the fragmentation diagrams, their contribution into amplitude can not be neglected even at relatively large transverse momenta. As one can see in Fig. 4 the fragmentation approach is valid only at transverse momenta larger than $5 \div 6$ masses of $B_c$. This behavior does not contradict the factorization theorem [15], which predicts the fragmentation dominance at limit of infinite transverse momenta, but says nothing about transverse momentum value at which the nonfragmentation contribution becomes negligible.

\(^2\) Within the valence quark approximation $|B^*\rangle = \{b_\uparrow \bar{q}_\downarrow, (b_\uparrow \bar{q}_\downarrow + b_\downarrow \bar{q}_\uparrow)/\sqrt{2}, b_\uparrow \bar{q}_\uparrow\}$ and $|B\rangle = (b_\uparrow \bar{q}_\downarrow - b_\downarrow \bar{q}_\uparrow)/\sqrt{2}$. Thus, if it is supposed that all possible spin combinations are produced with the same probability, then $\sigma(B^*)/\sigma(B) = 3$. 

Figure 3: The leading order diagrams for the process $gg \rightarrow B_c + b + \bar{c}$. 

\[ g \rightarrow B_c + b + \bar{c}. \]
Figure 4: The cross section distribution on transverse momenta for the $B_c$ gluonic production at interaction energy $\sqrt{s_{gg}} = 100$ GeV obtained within pQCD [8] in comparison with the fragmentation model prediction (see formula (5) for the fragmentation model).

The total gluonic cross section predicted using full set of leading order diagrams essentially differ from the fragmentation approach in absolute value as well as in shapes of interaction energy dependence (see Fig. 5). It is worth to note that near the threshold the fragmentation prediction values are larger than the prediction values obtained within pQCD calculation because of the incorrect phase space counting in fragmentation approach.

To obtain the cross section estimations for real hadronic experiments we need to convolute the partonic cross sections with the parton density functions:

$$\sigma_{\text{hadronic}}(s) = \int \int \sigma_{ij}(s_{ij}, Q_R) f_i(x_i, Q_F) f_j(x_j, Q_F) dx_i dx_j$$  \hspace{1cm} (8)$$

As it is predicted within pQCD [8, 9], about 90% of the $B_c$ mesons at LHC energies will be produced in the gluonic fusion (Fig. 3). Therefore in our pQCD calculations we can neglect the other partonic subprocess.
\[ d\sigma(pp \to B_c^{(*)} + X)/dp_T, \text{nb/GeV} \]

![Graph showing cross section distribution over $p_T$, GeV.](image)

Figure 6: The cross section distribution over the $B_c$ transverse momentum for the process $pp \to B_c + X$ at $\sqrt{s} = 14$ TeV within partonic approach (8) (see also [8]).

The convolution of the gluonic subprocess cross section with the gluonic structure functions partially hides the differences between the pQCD predictions and the fragmentation approach. For example, one can see in Fig. 6 that at hadronic level the difference in shapes of $p_T$ distributions is not so obvious, as at partonic level. The predicted difference of the hadronic cross section values is about of 2. Obviously, such a difference is not essential for the calculations of forth order on $\alpha_s$. Nevertheless, the relative yield of $B_c^*$ and $B_c$ does not depend on $\alpha_s$ and could indicate the production mechanism. Even in the kinematical region where the fragmentation model could be applied the value of $R_{\text{hadr}} = \sigma_{\text{hadr}}(B_c^*)/\sigma_{\text{hadr}}(B_c)$ predicted within pQCD is about 2.6 instead of 1.4 obtained within the fragmentation approach. To measure this value one need to detect $B_c^*$ meson which with unit probability decays into $B_c$ and photon. However, it is quite difficult to detect such a process experi-

\[ d\bar{b}\to B_c^{(*)}(M_{\text{inv}}), \text{GeV}^{-1} \]

![Graph showing cross section distribution over invariant mass.](image)

Figure 7: The normalized cross section distributions over the invariant mass of $B_c$ ($B_c^*$) and $c$-quark within fragmentation approach.

\footnote{To estimate the $B_c$ hadronic production cross section the CTEQ6L parametrization of gluonic structure function has been used on the scale $Q_F = 10$ GeV [16].}
mente due to the expected small mass difference between $B_c^*$ and $B_c$ mesons:

$$\Delta M = M_{B_c^*} - M_{B_c} = 65 \pm 15 \text{ MeV}. \quad (9)$$

Therefore in laboratory system the maximum energy of emitted photon is

$$\omega_{\text{max}} = \left(\gamma + \sqrt{\gamma^2 - 1}\right) \Delta M,$$

where $\gamma$ is $B_c^*$ $\gamma$ factor. Even for $B_c^*$ with energy $\sim 30 \text{ GeV}$ $\omega_{\text{max}} \sim 0.7 \text{ GeV}$. Thus one can conclude that there is no certainty that the method based on separation of $B_c^*$ from $B_c$ can be used to study the $B_c$ production mechanism. This is why in the next chapter we suggest another way to research the $B_c$ production mechanism.

### III. THE CROSS SECTION DISTRIBUTION ON THE INVARIANT MASS OF $D$ AND $B_c$ MESONS

Within fragmentation approach the shape of the cross section distribution over the invariant mass of $B_c$ and $\bar{c}$-quark is roughly determined by $\bar{b}$-quark virtuality (see diagram (1) in Fig. 1). This is why the distribution should be relatively narrow. Our analytical calculations confirm this supposition. Let us denote by $d_{\bar{b}\to B_c}(M_{B_c} + \bar{c})$ and $d_{\bar{b}\to B_c^{*}}(M_{B_c} + \bar{c})$ the normalized cross section distributions over the invariant mass of $B_c$ ($B_c^*$) and $c$-quark within fragmentation approach:

$$d_{\bar{b}\to B_c}(M_{B_c} + \bar{c}) = \frac{1}{\sigma_{\bar{b}b}} \frac{d\sigma_{\text{frag}}^{B_c}}{dM_{B_c} + \bar{c}}, \quad (10)$$

$$d_{\bar{b}\to B_c^{*}}(M_{B_c} + \bar{c}) = \frac{1}{\sigma_{\bar{b}b}} \frac{d\sigma_{\text{frag}}^{B_c^{*}}}{dM_{B_c} + \bar{c}}. \quad (11)$$

It can be easy to obtain from (12) that:

$$d_{\bar{b}\to B_c}(M_{B_c} + \bar{c}) = \frac{8\alpha_s |R(0)|^2 M_{B_c}^2}{27\pi m_{\bar{c}}^3} \frac{1}{dM_{B_c} + \bar{c}} \int dz \Theta(M_{B_c}^2 + \bar{c} - \frac{m_{\bar{c}}^2}{z - 1}) \left(\frac{(1 - z)(1 + rz)^2 M_{B_c}^2}{(1 - (1 - r)z)^2(M_{B_c}^2 + \bar{c} - m_{\bar{c}}^2)^2} - \frac{(2(1 - 2r) - (3 - 4r + 4r^2)z + (1 - r)(1 - 2r)z^2)M_{B_c}^4}{(1 - (1 - r)z)(M_{B_c}^2 + \bar{c} - m_{\bar{c}}^2)^3} - \frac{4r^2(1 - r)M_{B_c}^6}{(M_{B_c}^2 + \bar{c} - m_{\bar{b}}^2)^4}\right). \quad (12)$$
\[ d_{b\to B_c}(M_{B_c+\bar{c}}) = \frac{8\alpha_s |R(0)|^2 M_{B_c+\bar{c}}}{27\pi m_c^3} \int dz \Theta \left( \frac{M^2_{B_c+\bar{c}} - \frac{M^2_{\bar{b}}}{z} - \frac{m^2_c}{1-z}}{1-z} \right) \]

\[
\left(1 - z\right) (1 + 2rz + (2 + r^2)z^2) r M^2_{\bar{b}} - \frac{(2(1 + 2r) - (1 + 12r - 4r^2)z - (1 - r)(1 + 2r)z^2) r M^2_0}{(1 - (1 - r)z)(M^2_{B_c+\bar{c}} - m^2_c)^3} \]

\[ - \frac{12r(1 - r) M^6_0}{(M^2_{B_c+\bar{c}} - m^2_c)^4}, \quad (13) \]

where \( M \) is \( B_c \) meson mass, \( M_{B_c+\bar{c}} \) is the invariant mass of \( B_c \) (\( B^*_c \)) and \( \bar{c} \)-quark.

Integrating over \( z \) leads to the following expressions:

\[ d_{b\to B_c}(M_{B_c+\bar{c}}) = \frac{4\alpha_s |R(0)|^2 M^2_{\bar{b}} r (1 + r) M^2_{B_c+\bar{c}}}{27\pi m_c^3 (1 - r)^4 A^2} \times \]

\[
\left( \frac{1 + 2r}{A^2 M^4_{B_c+\bar{c}}} \right) \left[ - \left\{ M^6_{B_c}(-1 + r)^8(1 + r) - M^4_{B_c}(-1 + r)^4 (4 - 14r + 7r^2 + r^3) M^2_{B_c+\bar{c}} \right. \right. \]

\[ - M^2_{B_c}(-1 + r)^3 (1 - 8r + r^2) M^4_{B_c+\bar{c}} + (2 + 4r - r^2 + r^3) M^6_{B_c+\bar{c}} \} \cdot B \]

\[ - 2M^4_{B_c+\bar{c}} \left\{ M^4_{B_c}(-1 + r)^4 (1 - 4r + 2r^2) \right. \]

\[ - 2M^2_{B_c}(-1 + r)^2 (1 - 2r + 2r^2) M^2_{B_c+\bar{c}} + (1 + 2r^2) M^4_{B_c+\bar{c}} \} \cdot \log \left\{ \frac{A - B}{2M^2_{B_c+\bar{c}}} \right\} \right] \]

(14)

\[ d_{b\to B_c}(M_{B_c+\bar{c}}) = \frac{4\alpha_s |R(0)|^2 r (1 + r)^2 M^2_{\bar{b}} M_{B_c+\bar{c}}}{27\pi m_c^3 (1 - r)^4 A^2} \times \]

\[
\left( - \frac{2 + r}{A} \right) \left[ M^2_{B_c}(-1 + r)^2 (3 - 8r + 2r^2) - (3 + 4r + 2r^2) M^2_{B_c+\bar{c}} \right] \cdot \log \left\{ \frac{A + B}{2M^2_{B_c+\bar{c}}} \right\} + \]

\[ \frac{(1 + r)^2}{M^4_{B_c+\bar{c}} A^2} \left[ - \left\{ M^6_{B_c}(-1 + r)^8 (1 + r) - M^4_{B_c}(-1 + r)^4 (2 - 9r^2 + r^3) M^2_{B_c+\bar{c}} \right. \right. \]

\[ - M^2_{B_c}(-1 + r)^3 (-11 + 8r + r^2) M^4_{B_c+\bar{c}} + (12 + 6r - r^2 + r^3) M^6_{B_c+\bar{c}} \} \cdot B \]

\[ - 2M^4_{B_c+\bar{c}} \left\{ M^4_{B_c}(-1 + r)^4 (3 - 8r + 2r^2) \right. \]

\[ - 2M^2_{B_c}(-1 + r)^2 (3 - 2r + 2r^2) M^2_{B_c+\bar{c}} + (3 + 4r + 2r^2) M^4_{B_c+\bar{c}} \} \cdot \log \left\{ \frac{A - B}{2M^2_{B_c+\bar{c}}} \right\} \right], \quad (15) \]

where

\[ A = (1 + r) \left( M^2_{B_c+\bar{c}} - (1 - r)^2 M^2_{\bar{b}} \right), \quad (16) \]

and

\[ B = (1 - r) \sqrt{M^2_{B_c+\bar{c}} - (1 - r)^2 M^2_0} \left( M^2_{B_c+\bar{c}} - (1 + r)^2 M^2_0 \right). \quad (17) \]
Figure 8: The cross section distributions over the invariant mass of $B_c$ and $\bar{D}$ mesons calculated within pQCD for the process $pp \rightarrow B_c + X$ at $\sqrt{s} = 14$ TeV: without cuts (a) and for $\sqrt{s} > 40$ GeV (b). Solid curves: $D_{c \rightarrow D} = \delta(1 - z)$; dashed curves: $D_{c \rightarrow D} = z^{2.2}(1 - z)$.

The variation of $d\bar{b} \rightarrow B_c$ and $d\bar{b} \rightarrow B_c^*$ with $M_{B_{c+\bar{D}}}$ are shown in Fig. 7.

Here we face the problem how to transform the invariant mass of $B_c$ ($B_c^*$) and $\bar{c}$-quark $M_{B_{c+\bar{D}}}$ to invariant mass of $B_c$ ($B_c^*$) and $\bar{D}$-meson $M_{B_{c+D}}$. Within fragmentation mechanism it naturally to assume that the $\bar{D}$ meson takes away the total momentum of $c$-quark, because the production of $\bar{c}$ quark is the last step of emission process. Such an assumption is not obvious for the recombination contribution. This is why two hadronization models of $\bar{c}$ quark have been chosen:

1. $\bar{D}$ meson takes away the total momentum of $\bar{c}$-quark: $D_{c \rightarrow D} = \delta(1 - z)$;

2. $\bar{D}$ meson takes away part of $\bar{c}$-quark momentum according to Kartvelishvily-Petrov-Likhoded fragmentation function: $D_{c \rightarrow D} = z^{2.2}(1 - z)$ [17].

The cross section distributions over $M_{B_{c+D}}$ are shown in Fig. 8 for the different kinematical regions. One can see that for the total phase space the cross section distribution looks like the obtained within the fragmentation approach. Nevertheless it become essentially wider for large interaction energies, whereas within the fragmentation approach it should remain the same. Thus one can conclude that the recombination contribution is dominant.
Figure 9: The cross section distribution over the cosine of angle between the directions of motion of $B_c$ and $\bar{D}$ mesons predicted within pQCD for the process $pp \to B_c + X$ at $\sqrt{s} = 14$ TeV.

Figure 10: The dependencies of averaged $\bar{c}$ quark energy on $B_c$ meson energy are represented for the different cuts on $b$-jet transverse momenta.

IV. THE ANGLE CORRELATIONS AND THE DECAY LENGTH RATIO IN THE ASSOCIATIVE PRODUCTION OF $B_c$ AND $D$ MESONS.

As it is shown in Fig. [9] the cross section distribution on cosine of the angle between the $B_c$ meson and $\bar{D}$ meson has the sharp maximum at $\cos \theta \sim 1$. Moreover, about a half of $B_c$ mesons is associated by the $\bar{D}$ meson moving in the close direction: $\theta \lesssim 26^\circ$. Therefore, $\bar{D}$ meson can be used to detect $B_c$ meson.

In the Fig. [10] the dependencies of averaged $\bar{c}$ quark energy on $B_c$ meson energy are represented for the different cuts on $b$-jet transverse momenta. It can be concluded from these plots that at any $b$-jet transverse momentum

$$\langle E_{\bar{c}} \rangle \gtrsim 1.2E_{B_c},$$

(18)

$\bar{D}$ meson we obtain that

$$\langle E_{\bar{D}} \rangle \gtrsim 1.2E_{B_c}$$

(19)
for $D_{c\rightarrow D} = \delta(1 - z)$ or

$$\langle E_D \rangle \gtrsim 0.7 E_{B_c}$$

(20)

for $D_{c\rightarrow D} = z^{2.2}(1 - z)$.

The decay lengths depend on particle energies and lifetimes as follows:

$$\langle l_D \rangle \simeq \frac{\langle E_D \rangle}{m_D^c} c \tau_D \quad l_{B_c} \simeq \frac{E_{B_c}}{m_{B_c}} c \tau_D.$$  

(21)

Taking into account that $\tau_D/\tau_{B_c} \simeq 2$ we obtain:

$$\frac{\langle l_D \rangle}{l_{B_c}} \gtrsim 5.$$  

(22)

This value should be compared with the fragmentation model prediction:

$$\frac{\langle l_{\text{frag}} \rangle}{l_{\text{frag}}^{B_c}} \sim 1 \div 2.$$  

(23)

It worth to note that the ratio $\langle l_D \rangle/l_{B_c}$ can not be used to detect the $B_c$ meson because the distributions on $l_D$ at fixed $l_{B_c}$ very wide. Nevertheless the experimental measuring of this ratio could indicate the production mechanism.

V. CONCLUSIONS

The following conclusion can be drawn from the performed calculations:

1. The cross section distribution over the invariant mass of $B_c$ and $\bar{D}$ meson depends essentially on kinematical cuts and can be used to research $B_c$ production mechanism at LHC.

2. In many cases the $B_c$ and $\bar{D}$ mesons move in close directions. It could be useful to detect $B_c$ meson.

3. The energies of $B_c$ and $\bar{D}$ mesons are comparable. The decay length of $\bar{D}$ meson by more than 5 times larger than the decay length of $B_c$ meson. The experimental research of the ratio between $B_c$ meson and $\bar{D}$ meson energies could shed light on $B_c$ production mechanism.
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[1] T. Aaltonen and C. Collaboration, Phys. Rev. Lett. 100, 182002 (2008), arXiv:0712.1506 [hep-ex].
[2] V. M. Abazov et al., Phys. Rev. Lett. 102, 092001 (2009), arXiv:0805.2614 [hep-ex].
[3] S. S. Gershtein, V. V. Kiselev, A. K. Likhoded, and A. V. Tkabladze, Phys.Rev.D 51, 3613 (1995).
[4] E. Eichten, C. Quigg, Phys.Rev.D 49 5845 (1994).
[5] D. Ebert, R. N. Faustov, V. O. Galkin, Phys. Rev. D 67, 014027 (2003).
[6] V. V. Kiselev, A. K. Likhoded, A. I. Onishchenko, Nucl. Phys. B 569, 473 (2000); V. V. Kiselev, A. K. Likhoded, A. E. Kovalsky, Nucl. Phys. B 585, 353 (2000).
[7] V. V. Kiselev, Mod. Phys. Lett. A 10, 1049 (1995); V. V. Kiselev, Int. J. Mod. Phys. A 9, 4987 (1994); V. V. Kiselev, A. K. Likhoded, and A. V. Tkabladze, Phys. Atom. Nucl. 56, 643 (1993), Yad. Fiz. 56, 128 (1993).
[8] A. V. Berezhnoy, V. V. Kiselev, and A. K. Likhoded, Z. Phys. A 356, 79 (1996); A. V. Berezhnoi, V. V. Kiselev, A. K. Likhoded Phys. Atom. Nucl. 60, 289 (1997); A. V. Berezhnoi, V. V. Kiselev, A. K. Likhoded, A. I. Onishchenko, Phys. Atom. Nucl. 60, 1729 (1997); A. V. Berezhnoy, A. K. Likhoded, O. P. Yushchenko, Phys. Atom. Nucl. 59, 709 (1996); A. V. Berezhnoi, A. K. Likhoded, M. V. Shevlyagin, Phys. Atom. Nucl. 58, 672 (1995); A. V. Berezhnoy, Phys. Atom. Nucl. 68, 1866 (2005).
[9] C.-H. Chang, Y.-Q. Chen, G.-P. Han, and H.-Q. Jiang, Phys. Lett. B 364, 78 (1995); C.H. Chang, C. Driouichi, P. Eerola, X.G. Wu, Comput.Phys.Commun.159, 192(2004); C.H. Chang, J.X. Wang and X.G. Wu, Phys.Rev.D 70, 114019 (2004); C.H. Chang, C.F. Qiao, J.X. Wang and X.G. Wu, Phys.Rev.D 72, 114009 (2005); C.H. Chang, J.X. Wang, X.G. Wu, Comput.Phys.Commun.174, 24 (2006); C.H. Chang, J.X. Wang and X.G. Wu, Comput.Phys.Commun., 175 624, (2006).
[10] K. Kołodziej, A. Leike, and R. Rückl, Phys. Lett. B 355, 337 (1995).
[11] S. P. Baranov, Phys. Rev. D 56, 3046 (1997); Nucl. Phys. B (Proc. Suppl.) 55A, 33 (1997);
[12] E. Braaten, K. Cheung and T. C. Yuan, Phys. Rev. D. 48, 4230, 5049 (1993).
[13] V. V. Kiselev, A. K. Likhoded and M. V. Shevlyagin, Z. Phys. C 63, 77 (1994).
[14] C.H. Chang and X.G. Wu, Eur.Phys.J.C 38, 267 (2004)
[15] A. V. Efremov and A. V. Radyushkin, Theor. Math. Phys. 44, 664 (1981); J. C. Collins and D. E. Soper Nucl. Phys B 194, 445 (1982).
[16] J. Pumplin, D.R. Stump, J.Huston, H.L. Lai, P. Nadolsky, W.K. Tung, JHEP 0207:012 (2002) [hep-ph/0201195]; D. Stump, J. Huston, J. Pumplin, W.K. Tung, H.L. Lai, S. Kuhlmann, J. Owens, JHEP 0310:046, 2003. [hep-ph/0303013]
[17] V. G. Kartvelishvili, A. K. Likhoded, and V. A. Petrov, Phys. Lett. B, 78, 615 (1978).