Correlations in the associative production of $B_c$ and $D$ mesons at LHC

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

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1. 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, 4, 5]:

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

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

$$m_{B_c}^{\text{theor}} = 6.25 \pm 0.03 \text{GeV};$$

as well as for the decay time [6, 7]:

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

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

$$\tau_{B_c}^{\text{theor}} = 0.55 \pm 0.15 \text{ps}.$$

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 predictions. Only the planed 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. In this research we try to fill the gap in our theoretical understanding of $B_c$ production and show that the study of correlations in the associative production of $B_c$ and $D$ meson at LHC could be an essential information source of $B_c$ production mechanism. Here we study the production characteristics which weakly depend on parameters: the cross section distribution shapes and the ratio between $B_c^*$ and $B_c$ yields.

2. 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 calculations within the discussed technique are the most simple for the process of $B_c$ production in the $e^+e^-$ annihilation. As it was shown in [8, 9, 10], the special choice of the gluonic field gauge allows to interpret the $B_c$ production process as the $\bar{b}$ quark production followed by the fragmentation of $\bar{b}$ quark into $B_c$ meson. Thus, in the $e^+e^-$ annihilation at large energies the consideration of leading diagrams for the $B_c$ meson production leads the well known factorized formula for the cross section distribution over $z = 2E_{B_c}/\sqrt{s}$:

$$\frac{d\sigma}{dz} = \sigma_{\bar{b}b} \cdot D(z). \quad (2.1)$$

The analytical forms of fragmentation functions for $S$ wave states are known from [8, 9].
The relative yield of $B^+_c$ and $B_c$ in the $e^+e^-$ annihilation obtained within pQCD calculation
$R_{e^+e^-}^{B_c}=\frac{\sigma(B^+_c)}{\sigma(B_c)} \sim 1.4$. Thus the naive spin counting which fairly predicts this ratio for $B^*$
and $B$ ($R^{B^*}_{e^+e^-} \sim 3$) cannot be applied to $B_c$ and $B_c$ production.

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 [11, 12, 10, 13] the other mechanism essentially contribute to this process practically
all over the phase space and the fragmentation approach is valid only at transverse momenta larger
than $5 \div 6$ masses of $B_c$. 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 shape
of interaction energy dependence.

As it is predicted within pQCD [11, 12], about 90 % of the $B_c$ mesons at LHC energies will
be produced in the gluonic fusion (Fig. 1). Therefore in our pQCD calculations we can neglect
the other partonic subprocess. 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. The predicted ratio between the hadronic crosssection values is about
of 2. Obviously, such a difference is not essential for the calculations of forth order on $\alpha_s$. Never-
theless, the relative yield of $B^+_c$ and $B_c$ does not depend on $\alpha_s$ and could indicate the produc-
tion mechanism. Even in the kinematical region where the fragmentation model could be applied
the value of $R_{\text{hade}} = \frac{\sigma_{\text{hade}}(B^+_c)}{\sigma_{\text{hade}}(B_c)}$ predicted within pQCD is about 2.6 instead of 1.4 ob-
tained 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 experimentally due to the small mass difference between $B^+_c$ and $B_c$ mesons [11]:
$\Delta M = M_{B^+_c} - M_{B_c} = 65 \pm 15$ MeV. 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, and even for $B^*_c$ with energy $\sim 30$ GeV
$\omega_{\text{max}} \sim 0.7$ GeV. Thus one can conclude that there is no certainty that the method based on sepa-
ration of $B^+_c$ from $B_c$ can be used to study the $B_c$ production mechanism. This is why in the next
chapters we suggest another way to research the $B_c$ production mechanism.

### 3. 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 the diagram (3) in Fig. 1).
This why the distribution should be relatively narrow. Our analytical calculations confirm this supposition [14].

Here we face the problem how to transform the invariant mass of $B_c$ ($B^+_c$) and $\bar{c}$-quark $M_{B_c+\bar{c}}$ to
invariant mass of $B_c$ ($B^+_c$) and $D$-meson $M_{B_c+D}$. Within the fragmentation mechanism it is naturally
to assume that the $D$ 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. $D$ meson takes away the total momentum of $\bar{c}$-quark: $D_{\bar{c} \rightarrow D} = \delta(1 - z)$;
2. $D$ meson takes away part of $\bar{c}$-quark momentum according to Kartvelishvily-Petrov-Likhoded
fragmentation function: $D_{\bar{c} \rightarrow D} = z^{2.7}(1 - z)$. 

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Figure 1: The leading order diagrams for the process $gg \rightarrow B_c + b + \bar{c}$.

Figure 2: The normalized cross section distributions over the invariant mass of $B_c (B^*_c)$ and $c$-quark within fragmentation approach.

Figure 3: 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: $D_c \rightarrow D = z^2(1 - z)$.

The cross section distributions over $M_{B_c + \bar{D}}$ are shown in Fig. 3 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, but the cut on interaction energy essentially transforms the distribution shape. It become essentially wider, whereas within the fragmentation approach it
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4. The angle correlations and the decay length ratio in the associative production of $B_c$ and $D$ mesons.

As it is shown in Fig. 4, 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. 5 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

$$\langle E_{\bar{c}} \rangle \gtrsim 1.2 E_{B_c}. \quad (4.1)$$

For $\bar{D}$ meson we obtain that

$$\langle E_{\bar{D}} \rangle \gtrsim 0.7 \div 1.2 E_{B_c}. \quad (4.2)$$

for $D_c \rightarrow \bar{D} = z^{2.2} (1-z)$ and $D_c \rightarrow \bar{D} = \delta (1-z)$, correspondingly.

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

$$\langle l_{\bar{D}} \rangle \simeq \frac{\langle E_{\bar{D}} \rangle}{m_D} c \tau_D, \quad l_{B_c} \simeq \frac{E_{B_c}}{m_{B_c}} c \tau_D. \quad (4.3)$$

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

$$\frac{\langle l_{\bar{B}_c D} \rangle}{l_{B_c}} \gtrsim 5. \quad (4.4)$$
This value should be compared with the fragmentation model prediction:

\[
\frac{\langle \ell_{\text{frag}}^{\bar{D}} \rangle}{\langle \ell_{\text{frag}}^{B_c} \rangle} \sim 1 \div 2.
\]  

(4.5)

5. 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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