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Production of B_c mesons via fragmentation in the k_T-factorization approach

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Abstract

In the framework of the k_T-factorization approach we have calculated in the fragmentation model the p_T-spectra of B_c mesons at the energies of the Tevatron and the LHC Colliders and at the large p_T domain. We compare the obtained results with the existing experimental data and with the predictions obtained in the collinear parton model.

1. Introduction

Recently, B_c mesons were observed experimentally [1,2]. These particles have a special place in the doubly heavy meson family, because they consist of quarks of different flavors. The B_c meson spectroscopy has the same features as the spectroscopies of charmonia and bottomonia, however the decay and production properties of B_c mesons are unique. There is no annihilation channel for B_c mesons into hadrons via the gluons and, consequently, the lifetime of the ground state of the $\bar{b}c$ system is large, given by $\tau \approx 0.46$ ps [2]. The main channel of B_c meson decay occurs through the weak decays of the b-quark or the c-quark, which are respectively about 25% and 65% of the total decay width.

The B_c meson hadroproduction cross section is approximately 100 times smaller than the $(b\bar{b})$-pair production cross section, because the two pairs of the heavy quarks are produced in a parton subprocess. The mass spectrum and the decay properties of the B_c mesons are studied in detail in the framework of potential quark models [3], in

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the QCD sum rules methods [4] and in the OPE approach [5]. The predictions at leading order in α_s for the B_c meson production rates in the $\gamma\gamma$, γp and pp interactions were obtained in the collinear parton model [6–10].

The B_c meson production cross section became large enough to study experimental (~ 1 nb) only in the region of very high energy or in the region of very small $x \sim M/\sqrt{s} \sim 10^{-2}$, where x is the argument of the gluon distribution function in a proton (the quark contribution to the hadronic production of B_c mesons is very small). In this region the k_T-factorization approach [12,13] is more adequate for describing the perturbative evolution of the gluon distribution function, which satisfies the BFKL [14] or CCFM [15] evolution equations, in comparison with the collinear parton model, which is based on the DGLAP equations [11].

In this Letter we have calculated B_c meson p_T-spectra at the energy range of the Tevatron and the LHC Colliders in the fragmentation model and in the framework of the k_T-factorization approach. In the fragmentation model we have taken into consideration only the main contribution originating from fragmentation of a b-quark into a B_c meson [16].

2. The k_T-factorization approach

In the k_T-factorization approach [12,13], which generalizes the collinear parton model to the region of small x, the hadronic and partonic cross sections are related as follows:

$$\sigma^{\mathrm{KT}}(p\bar{p} \to b\bar{b}X, s) = \int \frac{dx_1}{x_1} \int d|\vec{k}_{1T}|^2 \int \frac{d\varphi_1}{2\pi} \Phi\big(x_1, |\vec{k}_{1T}|^2, \mu^2\big) \int \frac{dx_2}{x_2} \int d|\vec{k}_{2T}|^2 \times \int \frac{d\varphi_2}{2\pi} \Phi\big(x_2, |\vec{k}_{2T}|^2, \mu^2\big) \hat{\sigma}\big(g^\star g^\star \to b\bar{b}, \hat{s}\big), \tag{1}$$

where $\Phi(x, |\vec{k}_T|^2, \mu^2)$ is the unintegrated gluon distribution function in a proton (unintegrated refers to the transverse momentum), $|\vec{k}_{i,T}|^2$ is the virtuality of the initial reggeized gluon, $k_i = x_i p_i + k_{i,T}$ is the 4-momentum of the initial gluon, $k_{i,T} = (0, \vec{k}_{i,T}, 0)$ is the transverse momentum of the initial gluon, φ_i is the angle between the gluon transverse momentum and the fixed axis OX in the plane XOY, $\hat{s} = x_1 x_2 s - |\vec{k}_{1T}|^2 - |\vec{k}_{2T}|^2$. In the numerical calculations we have used the following parameterizations for the unintegrated gluon distribution function in a proton: JB by Blumlein [17], JS by Jung and Salam [18] and KMR by Kimber, Martin and Ryskin [19].

To calculate the amplitude of partonic processes in the k_T-factorization approach the polarization vector for the reggeized gluon in the initial state is taken to be [12,13]

$$\varepsilon^\mu(k_T) = \frac{k_T^\mu}{|\vec{k}_T|}. \tag{2}$$

The squared amplitude for one of the processes in B_c meson production in the k_T-factorization approach, namely

$$g^\star + g^\star \to b + \bar{b} \tag{3}$$

was obtained earlier in [12]. Here we use our original results from Ref. [20]

$$\overline{\big|M\big(g^\star + g^\star \to Q + \bar{Q}\big)\big|^2} = 8\pi^2\alpha_s^2(M_{11} + M_{22} + M_{33} + 2M_{12} + 2M_{13} + 2M_{23}), \tag{4}$$

where

$$\begin{aligned} M_{11} = \frac{1}{3\tilde{t}^2}\Big(&\kappa_1(4\beta_1 - \kappa_1)\big(\kappa_1^2 + \kappa_2^2 - 4\beta_2\kappa_2\big) + 4\lambda\beta_2(\kappa_1 - 2\beta_1)\big(4\kappa_2^2 + \tilde{t}\big) + 4\kappa_1^3(\lambda\kappa_2 - \beta_1) \\ &+ 4\beta_2^2\big(\kappa_1^2 + 4\beta_1\kappa_1 - 4\lambda\kappa_1\kappa_2\big) + 4\lambda\kappa_2(\lambda\kappa_2 - 2\beta_1)\big(\kappa_1^2 - 4\beta_2^2\big) - 4\beta_1^2(2\beta_2 - \kappa_2)^2 + \kappa_1^4 \\ &+ 4\lambda\kappa_2(2\lambda\beta_2 + \beta_1)\big(2\kappa_2^2 + \tilde{t}\big) + 8\lambda\beta_1\kappa_2^3 + 4\lambda\kappa_2(\hat{s} + \tilde{u})(\kappa_1 + \lambda\kappa_2) + \tilde{t}\tilde{u}\Big), \end{aligned} \tag{5}$$

$$
\begin{aligned}
M_{22} = \frac{1}{3\tilde{u}^2}\Big(&\kappa_2^4 - 4\beta_2\kappa_2^3 - 4\beta_2^2\big(\kappa_1^2+\kappa_2^2\big) + 16\beta_1\beta_2^2(\kappa_1-\beta_1) \\
&+ 4\lambda\big(4\beta_1\kappa_1^2(\kappa_2-2\beta_2) + \tilde{t}\tilde{u} + \kappa_1\big(\kappa_2^3 - 2\beta_2\kappa_2^2 + (\kappa_2-\beta_2)\big(\hat{s}+\tilde{t}-4\beta_1^2\big) - \beta_2\tilde{u}\big) \\
&\quad - \beta_1(2\beta_2-\kappa_2)\tilde{u}\big) - 16\lambda^2\beta_1^2\kappa_1^2 + 4\lambda^2\kappa_1\big(4\beta_1\kappa_1^2 - \kappa_1\big(\kappa_1^2+\tilde{u}\big) + 2\beta_1\tilde{u}\big) \\
&+ \kappa_2(4\beta_2-\kappa_2)\big(\big(2\beta_1^2-\kappa_1\big)^2+\kappa_2^2\big) + 4\kappa_2^2\beta_2^2\Big),
\end{aligned} \tag{6}
$$

$$
\begin{aligned}
M_{33} = \frac{3}{4\hat{s}^2}\Big(&\big(\kappa_1^2+\kappa_2^2\big)\hat{s} - 4(\beta_2\kappa_1-\beta_1\kappa_2)^2 + 4\lambda\beta_1\kappa_2\big(\kappa_1^2-\kappa_2^2-\hat{t}+\hat{u}\big) \\
&-\lambda^2\big(\kappa_1^4+\kappa_2^4 - 8\beta_1\kappa_1^3 - 8\beta_2\kappa_2^3 - \hat{s}^2 + \hat{t}^2 + 8\beta_1\kappa_1\big(\kappa_2^2 - 4\beta_2\kappa_2 + \hat{t} - \hat{u}\big) - 2\hat{t}\hat{u} + \hat{u}^2 \\
&\quad - 2\kappa_1^2\big(\kappa_2^2 - 4\beta_2\kappa_2 - 8\beta_1^2 + \hat{t} - \hat{u}\big) + 2\kappa_2^2\big(8\beta_2^2+\hat{t}-\hat{u}\big) - 8\beta_2\kappa_2(\hat{t}-\hat{u})\big) \\
&- 2\lambda\big(8\beta_2^2\kappa_1\kappa_2 + 2\beta_2\big(\kappa_1^3 - 4\beta_1\kappa_1^2 - 4\beta_1\kappa_2^2 - \kappa_1\big(\kappa_2^2+\hat{t}-\hat{u}\big)\big) + \kappa_1\kappa_2\big(8\beta_1^2-\hat{s}\big)\big)\Big),
\end{aligned} \tag{7}
$$

$$
\begin{aligned}
M_{12} = -\frac{1}{48\tilde{t}\tilde{u}}\Big(&4\beta_1\kappa_1^3 + \kappa_2^2\big(\hat{s} - 8\beta_1^2 - \tilde{t} - \tilde{u}\big) + 32\beta_1\beta_2(\beta_1\kappa_2-\beta_1\beta_2) + \hat{s}^2 - \tilde{t}^2 - \tilde{u}^2 \\
&- \kappa_1^2\big(\kappa_2^2 - \kappa_1^2 - 8\beta_2\kappa_2 + 8\beta_2^2 - 2\hat{s}\big) + 4\beta_1\kappa_1\big(2\kappa_2^2 - 8\beta_2\kappa_2 + 8\beta_2^2 - \kappa_1^2\big) \\
&+ 2\lambda^2\big(\kappa_1^4+\kappa_2^4 - \hat{s}^2 + \tilde{t}^2 + \tilde{u}^2 + 4\beta_2\kappa_2\tilde{u} + 2\kappa_2^2\tilde{t} + 2\kappa_1^2(4\beta_2\kappa_2+\tilde{u}) \\
&\quad + 4\beta_1\kappa_1\big(2\kappa_2^2 - 4\beta_2\kappa_2 + \tilde{t}\big)\big) \\
&- 4\lambda\big(4\beta_2^2\kappa_2(\kappa_1-2\beta_1) - \kappa_2\big(-4\beta_1^2\kappa_1 + \beta_1\big(3\kappa_1^2+\kappa_2^2-\hat{s}\big) + \kappa_1\hat{s}\big) \\
&\quad - \beta_2\big(\kappa_1^3 - 4\beta_1\kappa_1^2 + \kappa_1\big(3\kappa_2^2 + 8\beta_1^2 - \hat{s}\big) + 2\beta_1\big(\hat{s} - 3\kappa_2^2 - \kappa_1^2\big)\big)\big)\Big),
\end{aligned} \tag{8}
$$

$$
\begin{aligned}
M_{13} = -\frac{3}{16\hat{s}\tilde{t}}\Big(&2\big(\lambda^2-1\big)\kappa_1^4 + 2\kappa_1^3\big(2\beta_1 - \lambda\kappa_2 - 3\beta_1\lambda^2 + 3\lambda\beta_2\big) \\
&+ 2\beta_1\lambda\big(2\kappa_2^3 + 4\beta_2\kappa_2^2 + 4\beta_2(\hat{t}-\hat{u}) - \kappa_2\big(16\beta_2^2 - 2\tilde{u}\big)\big) \\
&- \kappa_1^2\big(2\big(1+\lambda^2\big)\kappa_2^2 - 2\big(\big(5\lambda^2-2\big)\beta_2 + 6\beta_1\lambda\big)\kappa_2 + 24\lambda\beta_1\beta_2 - 8\beta_2^2 + 2\hat{s} \\
&\quad - \lambda^2\hat{s} + \lambda^2\tilde{t} + 2\tilde{u} - 3\lambda^2\tilde{u}\big) + 2\kappa_2\beta_2\big(8\beta_1^2+\tilde{t}+\tilde{u}\big) - 4\beta_1^2\kappa_2 - \kappa_2\tilde{u} \\
&+ \lambda^2\big(4\kappa_2^4 - 22\beta_2\kappa_2^3 - \hat{s}^2 + (\hat{t}-\hat{u})^2 - \kappa_2^2\big(\hat{s} - 32\beta_2^2 - 5\tilde{t} + 3\tilde{u}\big) + 2\beta_2\kappa_2(\hat{s} - 7\tilde{t} + 5\tilde{u})\big) \\
&+ 2\kappa_1\big(\beta_1\lambda^2\big(5\kappa_2^2 - 16\beta_2\kappa_2 - 3\hat{s} + \tilde{t} - 3\tilde{u}\big) + \beta_1\big(4\kappa_2^2 - 8\beta_2^2 + 2\hat{s} + \tilde{t} + \tilde{u}\big) \\
&\quad + \lambda\big(3\kappa_2^3 - 11\beta_2\kappa_2^2 + \kappa_2\big(16\beta_2^2 - 8\beta_1^2 + 2\tilde{t} - \tilde{u}\big) + \beta_2\big(16\beta_1^2 + \hat{s} - 3\hat{t} + 3\hat{u}\big)\big)\big)\Big),
\end{aligned} \tag{9}
$$

$$
\begin{aligned}
M_{23} = -\frac{3}{16\hat{s}\tilde{u}}\Big(&\lambda^2\big(4\kappa_1^4 + 2\kappa_2^4 - 22\beta_1\kappa_1^3 - \hat{s}^2 + 2\beta_1\kappa_1\big(5\kappa_2^2 - 16\beta_2\kappa_2 + \hat{s} + 5\tilde{t} - 7\tilde{u}\big) \\
&\quad - \kappa_1^2\big(2\kappa_2^2 - 16\beta_2\kappa_2 - 32\beta_1^2 + \hat{s} + 3\tilde{t} - 5\tilde{u}\big) + \kappa_2^2(\hat{s} + 3\tilde{t} - \tilde{u}) + (\hat{t}-\hat{u})^2 + 8\beta_2\kappa_2\tilde{u}\big) \\
&- 2\big(\kappa_1^2\big(\kappa_2^2 - 3\beta_2\kappa_2 + 4\beta_2^2 + \tilde{t}\big) + \kappa_2\big(\kappa_2^3 - \beta_2\kappa_2^2 + \kappa_2\big(\hat{s} - 4\beta_1^2 + \tilde{t}\big) + \beta_2\big(8\beta_1^2 - \hat{s}\big)\big) \\
&\quad - \beta_1\kappa_1\big(8\beta_2^2 - 2\kappa_2^2 + \tilde{t} + \tilde{u}\big)\big) \\
&+ 2\lambda\big(\kappa_1^3(\kappa_2+2\beta_2) + \beta_1\kappa_1^2(4\beta_2 - 11\kappa_2) \\
&\quad + \beta_1\big(4\beta_2(\hat{u} - \hat{t}) + 3\kappa_2^3 - 12\beta_2\kappa_2^2 + \kappa_2\big(16\beta_2^2 + \hat{s} + 3\hat{t} - 3\hat{u}\big)\big) \\
&\quad - \kappa_1\big(3\kappa_2^3 - 8\beta_2\kappa_2^2 - \kappa_2\big(16\beta_1^2 - 8\beta_2^2 - 2\hat{s} - 3\tilde{t} + \tilde{u}\big) + \beta_2\big(16\beta_1^2 - \tilde{t}\big)\big)\big)\Big),
\end{aligned} \tag{10}
$$

where

$$\tilde{t} = \hat{t} - m_Q^2, \tag{11}$$

$$\tilde{u} = \hat{u} - m_Q^2, \tag{12}$$

$$\beta_1 = |\vec{p}_T| \cos\varphi_1, \tag{13}$$

$$\beta_2 = |\vec{p}_T| \cos\varphi_2, \tag{14}$$

$$\kappa_1 = |\vec{k}_{1T}|, \tag{15}$$

$$\kappa_2 = |\vec{k}_{2T}|, \tag{16}$$

$$\lambda = \cos(\varphi_1 - \varphi_2) \tag{17}$$

and $\vec{p}_T$—transverse momentum of anti-quark. Since these are more suitable for numerical calculations. In those calculations, which were in the framework of the collinear parton model, we used the GRV [24] parameterization for the gluon distribution function.

3. The fragmentation model

The analysis of the B_c meson gluon–gluon production in the framework of the collinear parton model shows [6–8] the dominant role of the fusion mechanism up to $p_T \approx 30$ GeV. It takes into account the total gauge invariant set of the diagrams which describes the parton process

$$g + g \to B_c + b + \bar{c}. \tag{18}$$

Thus, the fragmentation approximation, incorporating factorization of the heavy quark production process and the soft process of a meson creation in the final state, applies only at $p_T > 30$ GeV. Of course, at the Tevatron Collider this region of p_T is far from being available for experimental study. On the other hand, at the LHC Collider the $p_T \leqslant 50$ GeV region will be under consideration.

In the fragmentation model, the B_c meson production cross section can be presented as follows:

$$d\sigma(pp \to B_c X) = \sum_i \int dz\, D_{i\to B_c}(z) \cdot d\hat{\sigma}(pp \to i), \tag{19}$$

where the sum is taken over all the relevant partons $i = c$, b and g (but the main contribution comes from b-quark fragmentation).

The fragmentation functions for the b-quark splitting into a vector B_c^* and pseudoscalar B_c meson at the starting scale of the perturbative QCD evolution were obtained in Ref. [22,23]

$$\begin{aligned} D_{\bar{b}\to B_c}(z,\mu_0) = {} & \frac{8\alpha_s^2(\mu_0)|\Psi_{B_c}(0)|^2}{81 m_c^3} \frac{r(1-z)^2 z}{(1-(1-r)z)^6} \\ & \times \big(6 - 18(1-2r)z + \big(21 - 74r + 68r^2\big)z^2 - 2(1-r)\big(6 - 19r + 18r^2\big)z^3 \\ & + 3(1-r)^2\big(1 - 2r + 2r^2\big)z^4\big), \end{aligned} \tag{20}$$

$$\begin{aligned} D_{\bar{b}\to B_c^\star}(z,\mu_0) = {} & \frac{8\alpha_s^2(\mu_0)|\Psi_{B_c}(0)|^2}{27 m_c^3} \frac{r(1-z)^2 z}{(1-(1-r)z)^6} \\ & \times \big(2 - 2(3-2r)z + 3\big(3 - 2r + 4r^2\big)z^2 - 2(1-r)\big(4 - r + 2r^2\big)z^3 \\ & + (1-r)^2\big(3 - 2r + 2r^2\big)z^4\big), \end{aligned} \tag{21}$$

where $r = \frac{m_c}{m_c+m_b}$. $|\Psi_{B_c}(0)|^2$ is the squared B_c meson wave function at the origin, which can be calculated using the nonrelativistic potential quark model [21]. In the numerical calculations, we used the result $\Psi_{B_c}(0) = \sqrt{\frac{m_{B_c}}{12}} f_{B_c}$, where $f_{B_c} = 490$–560 MeV is the B_c meson leptonic decay constant.

The QCD evolution of the fragmentation functions $D_{\bar{b}\to B_c}$ and $D_{\bar{b}\to B_c^\star}$ are described by the DGLAP [11] evolution equation

$$\mu^2 \frac{\partial D}{\partial \mu^2}(z, \mu^2) = \frac{\alpha_s(\mu^2)}{2\pi} \int_z^1 \frac{dx}{x} P_{q\to q}\left(\frac{x}{z}\right) D(x, \mu^2), \tag{22}$$

where $P_{q\to q}(z)$ is the standard quark–quark splitting function.

4. The results

The results of our calculation for the p_T-spectra of the $B_c^\star$ meson are shown in Fig. 1 for the energy of the Tevatron Collider $\sqrt{s} = 1.8$ TeV, and in the Fig. 2 for the energy of the LHC Collider $\sqrt{s} = 14$ TeV. The spectra that we obtain are compared with those obtained earlier in the collinear parton model via the fragmentation mechanism. The curves in Fig. 1 correspond to a choice of the parameters from Ref. [16]: $m_c = 1.5$ GeV, $m_b = 4.9$ GeV,

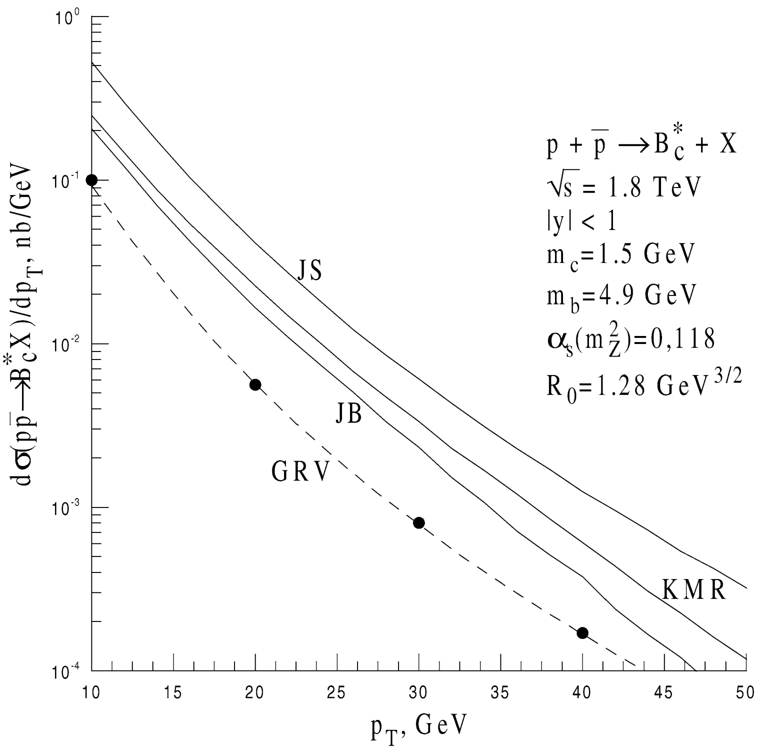

Fig. 1. The $B_c^\star$ meson p_T-spectrum at $\sqrt{s} = 1.8$ TeV and $|y| < 1$ in the fragmentation model. The continuous lines are a result of calculations in the k_T-factorization approach with the different parameterizations of the unintegrated gluon distribution function. The dashed line is the prediction from the collinear parton model. The points show the results obtained in the Ref. [16].

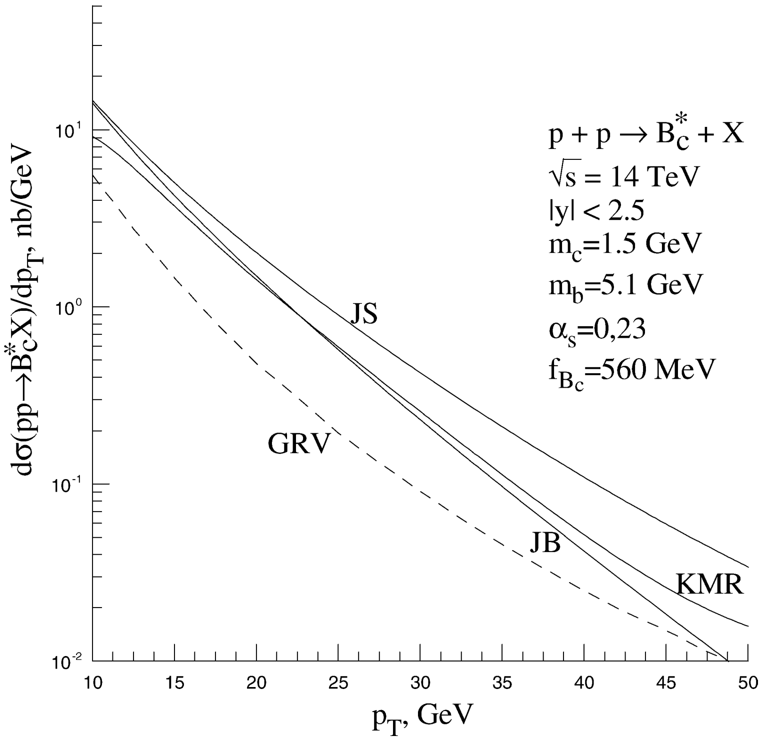

Fig. 2. The $B_c^\star$ meson p_T-spectrum at $\sqrt{s} = 15$ TeV and $|y| < 2.5$ in the fragmentation model. The continuous lines are results of calculations in the k_T-factorization approach with the different parameterizations of the unintegrated gluon distribution function. The dashed line is the prediction from the collinear parton model.

$\alpha_s = \alpha_s(p_T^2 + m_{B_c})$ and $f_{B_c} = 490$ MeV. The curves in Fig. 2 were obtained using the set of parameters from Ref. [6]: $m_c = 1.5$ GeV, $m_b = 5.1$ MeV, $\alpha_s \simeq 0.23$ and $f_{B_c} = 560$ MeV.

Fig. 1 shows that our result obtained in the collinear parton model agrees well with the result obtained earlier in Ref. [16]. The curves obtained in the k_T-factorization approach lie approximately 2–5 times higher than the collinear parton model prediction in the region $p_T > 10$ GeV. The maximum value of the B_c meson production cross section is obtained using the JS [18] parameterization of the unintegrated gluon distribution function, and the minimum value is obtained using the JB [17] parameterization.

Note that the slopes of the p_T-spectra obtained in the collinear parton model and in the k_T-factorization approach are equal, and the situation is the same as in the case of $D^\star$ meson production in ep interactions [25,26].

At present, there is no experimental information on the p_T spectra of B_c mesons. It is known that the integrated production cross section in the region $p_T > 6$ GeV, $|y| < 1$ and $\sqrt{s} = 1.8$ TeV is given by $\sigma_{B_c} \simeq 10 \pm 6$ nb [1,2]. As shown in Ref. [6], the uncertainties in the calculations are about $\sim 50\%$. This value depends on the choice of the masses, the α_s constant and the leptonic decay constant f_{B_c}. Furthermore, our calculations performed in the k_T-factorization approach show that the B_c meson production cross section has a strong dependence on the choice of the unintegrated gluon distribution function—a variation by a factor of 2 was observed.

The obtained values of the integrated B_c and $B_c^\star$ meson production cross section at the energies of the Tevatron and the LHC Colliders are presented in Table 1. One can see that, with the fragmentation model, the results obtained in the collinear parton model are smaller to those obtained in the k_T-factorization approach. The theoretical predictions are shown together with their uncertainties, which are significantly larger in the k_T-factorization approach. The absolute value of the cross section obtained in the collinear parton model ($\sigma_{B_c} = 1.7 \pm 0.8$ nb) is

Table 1
The summed B_c and $B_c^\star$ meson production cross sections in the different models at the energies of the Tevatron and LHC Colliders. The data from the CDF Collaboration [1,2] are shown. The cross sections are in nb

$\sqrt{s}$, TeV	$\lvert y\rvert$	$p_{T,\min}$, GeV	Parton model	k_T-factorization approach	Experimental data
1.8	< 1	6	1.7 ± 0.8	7.4 ± 5.4	10 ± 6
14	< 2.5	10	28 ± 14	122 ± 90	–

much smaller than the CDF experimental data ($\sigma_{B_c} = 10 \pm 6$ nb) [1,2]. On the other hand, the prediction of the k_T-factorization approach agrees well with the data ($\sigma_{B_c} = 7.4 \pm 5.4$ nb).

Taking into account the relative roles of the fusion and fragmentation mechanisms in B_c meson hadroproduction, one can suppose that the cross section calculated in the fusion model and in the k_T-factorization approach will be more large than that obtained in the fragmentation model and in the k_T-factorization approach. The calculation of the B_c meson hadroproduction rates via the partonic subprocess (18) with the reggeized initial gluons will be presented in our forthcoming paper.

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