On the energy dependence of hadronic B_c production [1, 2]

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Abstract

An estimate is presented of the production cross section of B_c mesons between threshold and LHC energies using lowest-order perturbation theory and non-relativistic bound state approximation. It is shown that the ratio of the production cross sections for B_c mesons and for b quarks varies strongly with energy.

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The results of References [1-3] are sometimes used to estimate the production rate of B$_c$ mesons at lower energies than they were intended for. In Ref. [1] the HERWIG parton shower Monte Carlo code is used to determine the ratio of the B_c and $b\bar{b}$ cross sections, while in Refs. [2, 3] the probability for a $\bar{b}$ quark to fragment into a B_c meson is calculated perturbatively in the nonrelativistic bound state approximation. Both estimates suggest a probability of order 10^{-3} for b-quark fragmentation into B_c mesons relative to fragmentation into B mesons.

By direct perturbative calculation [4, 5, 6] of the complete reaction, pp (and $p\bar{p}$) $\rightarrow B_c b\bar{c}X$, it has been shown that at high energies and large transverse momenta, hadronic B_c production is indeed well described by b-quark fragmentation. However, at low energies near threshold and at small B_c transverse momenta, both $\bar{b}$-quark fragmentation and $\bar{b}c$ recombination processes are expected to contribute. This puts some doubt on the validity of the fragmentation description

$$d\hat{\sigma}(B_c) = d\hat{\sigma}(b\bar{b}) \otimes D_{\bar{b}\rightarrow B_c\bar{c}}(z) \tag{1}$$

for estimates of total production rates. Here, the familiar short-hand notation for the convolution integral over the fragmentation function $D_{\bar{b}\rightarrow B_c\bar{c}}(z)$ is used. To clarify the issue, we have calculated the production rates of B_c mesons focussing on the threshold region.

At low energy, two subprocesses contribute to the production of B_c mesons:

$$\begin{aligned} gg &\rightarrow B_c b\bar{c}, & & (2)\\ q\bar{q} &\rightarrow B_c b\bar{c}, \qquad q = u, d, s. & & (3)\end{aligned}$$

At larger energies gluon-gluon fusion dominates so that the pp and $p\bar{p}$ cross sections become equal. In leading order, one has to calculate the $O(\alpha_s^4)$ hard scattering amplitudes for the $2 \rightarrow 4$ processes gg (and $q\bar{q}$) $\rightarrow b\bar{b}c\bar{c}$, and convolute them with the wave function describing the bound state formation $\bar{b}c \rightarrow B_c$. In the nonrelativistic approximation, the binding energy and relative momentum of the $\bar{b}$- and c-quarks are neglected. Moreover, the product of the $\bar{b}$- and c-quark spinors appearing in the amplitudes of $b\bar{b}c\bar{c}$ production are substituted by spin and energy projectors [7]. In particular, for the pseudoscalar and vector ground states one has

$$v(p_{\bar{b}})\bar{u}(p_c) = \frac{f_{B_c^{(*)}}}{\sqrt{48}}(\not{p} - m_{B_c})\Pi_{SS_Z}, \tag{4}$$

where the spin projector Π_{SS_Z} is equal to γ_5 for the B_c and to $\not\epsilon$ for the B_c^*. The decay constants $f_{B_c^{(*)}}$ being related to the S-wave function at the origin, can be estimated in potential models or by QCD sum rules. Finally, the cross sections of the subprocesses (2) and (3) are to be folded with the parton densities of the proton. A detailed description of the calculation for the gluon-fusion process (2) can be found in [4].

Taking $m_b = 4.8$ GeV, $m_c = 1.5$ GeV, $m_{B_c^{(*)}} = 6.3$ GeV and $f_{B_c^{(*)}} = 0.4$ GeV [8], and using the parametrization of structure functions from Ref. [9], we get, at the HERA–B energy of $\sqrt{s} = 40$ GeV:

$$\sigma(B_c) = 2.5\,\mathrm{fb}, \tag{5}$$

$$\sigma(B_c^*) = 8.3\,\mathrm{fb}. \tag{6}$$

Here we have used the running coupling constant $\alpha_s(\mu^2)$ in leading logarithmic approximation for five flavours and with the fixed scale $\mu^2 = 4m_{B_c}^2$. As expected, the scale-dependence of the prediction is very strong. For illustration, the above cross sections shrink by a factor 3 when choosing $\mu^2 = 4x_1x_2s$ and increase by a factor 10 when taking $\mu^2 = \frac{1}{4}(p_T^2 + m_{B_c}^2)$. Because of this huge uncertainty which can only be reduced by including higher order corrections, it is more sensible to consider the cross section ratio $\sigma(B_c + B_c^*)/\sigma(b\bar{b})$, where some of the scale dependence can be expected to cancel. The ratio is shown in Fig. 1 as a function of the c.m. energy. We see that the theoretical uncertainty due to the scale ambiguity is indeed reduced to a factor 3 to 4. In particular, at $\sqrt{s} = 40$ GeV, we predict:

$$\frac{\sigma(B_c + B_c^*)}{\sigma(b\bar{b})} = 0.35\,(1.2) \times 10^{-5}, \tag{7}$$

for $\mu^2 = 4x_1x_2s$ ($\mu^2 = \frac{1}{4}(p_T^2 + m_{B_c}^2)$). The ratio rises to about 10^{-4} at Tevatron energies and continues to increase slowly as one approaches the LHC energy. It should be noted that uncertainties due to the quark masses, decay constants, etc. are not included in the above estimates.

Taking into account that not all b-quarks lead to B-mesons and that there are heavier $\bar{b}c$ bound states with masses below the BD production threshold which decay into the B_c ground state, the ratio $\sigma(B_c)/\sigma(B)$ of inclusive cross sections may actually reach the value 10^{-4} at HERA–B and 10^{-3} at Tevatron energies. A more detailed investigation shows that the fragmentation description fails at $p_T \leq 5$ GeV, leading to an overestimate of the integrated B_c cross section, in particular in the threshold region.

References

[1] M. Lusignoli, M. Masetti, S. Petrarca, Phys. Lett. B 266 (1991) 142.

[2] K. Cheung, Phys. Rev. Lett. 71 (1993) 3413; K. Cheung, T.C. Yuan, Phys. Rev. D 53 (1996) 1232.

[3] C.-H. Chang, Y.-Q. Chen, Phys. Rev. D 46 (1992) 3845; E. Braaten, K. Cheung, T.C. Yuan, Phys. Rev. D 48 (1993) R5049.

[4] K. Kołodziej, A. Leike, R. Rückl, Phys. Lett. B 355 (1995) 337.

[5] C.-H. Chang, Y.-Q. Chen, G.-P. Han, H.-T. Jiang, Phys. Lett. B 364 (1995) 78; C.-H. Chang, Y.-Q. Chen, R.J. Oakes, Phys. Rev. D 54 (1996) 4344.

[6] A.V. Berezhnoi, A.K. Likhoded, M.V. Shevlyagin, Phys. Atom. Nucl. 58 (1995) 672; A.V. Berezhnoi, A.K. Likhoded, O.P. Yushchenko, Phys. Atom. Nucl. 59 (1996) 709; A.V. Berezhnoi, V.V. Kiselev, A.K. Likhoded, Z. Phys. A 356 (1996) 79.

[7] B. Guberina, J.H. Kühn, R.D. Peccei, R. Rückl, Nucl. Phys. B 174 (1980) 317.

[8] S. Reinshagen and R. Rückl, in Proc. of the Workshop on Quantum Field Theory Aspects of High Energy Physics, eds. B. Geyer and E.-M. Ilgenfritz, Univ. of Leipzig, 1993.

[9] A.D. Martin, W.J. Stirling, R.G. Roberts, Phys. Lett. B 354 (1995) 155.

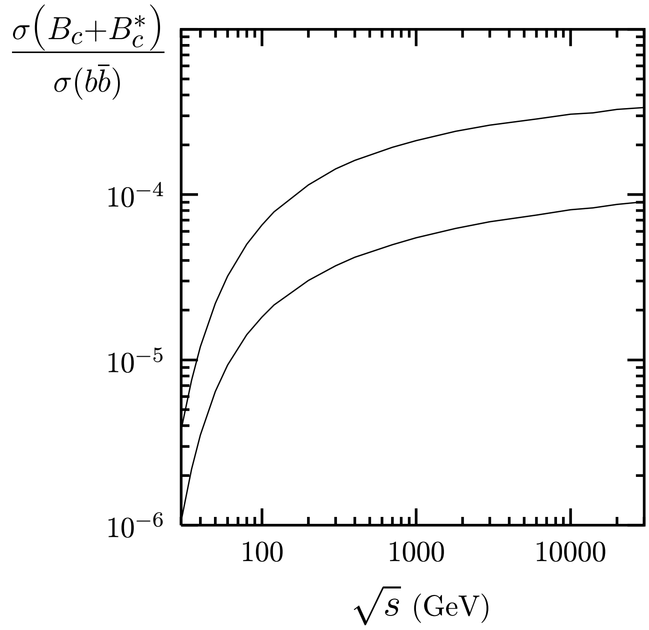

Figure 1: The ratio of the production cross sections for B_c mesons and b quarks as a function of the proton–proton c.m. energy for $\mu^2 = 4x_1x_2s$ (lower curve) and $\mu^2 = \frac{1}{4}(p_T^2 + m_{B_c}^2)$ (upper curve).