Beauty Quark Production at the Tevatron in the Semi-Hard QCD Approach and the Unintegrated Gluon Distribution

A.V. Lipatov[a], V.A. Saleev[b], N.P. Zotov[c]

[a] Dep. of Physics, MSU, 119899 Moscow, Russia,
[b] Dep. of Physics, Samara Univ., 443011 Samara, Russia,
[c] INP, MSU, 119992 Moscow, Russia

Abstract

Processes of heavy quark production at TEVATRON energies are considered using the semi-hard (k_T factorization) QCD approach with emphasis on the BFKL dynamics of gluon distributions. We investigate the dependence of the p_T distribution of heavy quark production (presented in the form of integrated cross-sections) on different forms of the unintegrated gluon distribution. The theoretical results are compared with recent D0 and CDF experimental data on beauty production.

1 Introduction

It is very well known that from heavy (c and b) quark production processes one can obtain unique information on gluon structure function of the proton and the three-gluon QCD vertex because of the dominance of the gluon-gluon fusion subprocess in the framework of QCD. These issues are important for physics at future colliders (such as LHC): many processes at these colliders will be determined by small x gluon distributions.

Recently D0 and CDF Collaborations have reported [1, 2] new experimental data on the cross section of inelastic open beauty production at the TEVATRON energies. A comparison of these results with NLO pQCD calculations shows that the calculations underestimate the cross section by a factor of ~ 2. Therefore, it would be certainly reasonable to try a different way.

In the energy range of modern colliders (HERA, TEVATRON and LHC) the interaction dynamics is governed by the properties of parton distributions in the small x region. This domain is characterized by the double inequality $s \gg \mu^2 \simeq \hat{s} \gg \Lambda^2$, which shows that the typical parton interaction scale μ (mass m_c or p_T of heavy quark) is much higher than the QCD parameter Λ, but is much lower than the total center of mass energy $\sqrt{s}$. The situation is therefore classified as "semi-hard": the processes occur in small x region ($x \simeq M^2/s \ll 1$) and the cross sections of heavy quark production processes are determined by the behavior of gluon distributions in this region.

It is known also that in the small x region the factorization of QCD subprocess cross section and parton structure functions in a hadron assumed by the standard parton model is broken [3]-[7]. The resummation [3, 4, 6, 7] of the terms $[\ln(\mu^2/\Lambda^2)\,\alpha_s]^n$, $[\ln(\mu^2/\Lambda^2)\ln(1/x)\,\alpha_s]^n$ and $[\ln(1/x)\,\alpha_s]^n$ in the semi-hard (k_T-factorization) approach (SHA) of QCD results in the unintegrated gluon distributions $\Phi(x, q_T^2, \mu)$, which determine the probability to find a gluon carrying the longitudinal momentum fraction x and transverse momentum q_T at the probing scale μ^2. They obey the BFKL equation [4] and reduce to the conventional gluon density once the q_T dependence is integrated out ($\mu^2 \equiv Q^2$):

$$\int_0^{Q^2} \Phi(x, q_T^2, Q_0^2)\; dq_T^2 = x\, G(x, Q^2). \tag{1}$$

To calculate the cross section of a physical process, the unintegrated functions Φ_i have to be convoluted with off-mass shell matrix elements corresponding to the relevant partonic sub-processes. In the off-mass shell matrix element the virtual gluon polarization tensor is taken in the form of the SHA prescription [3, 4]:

$$L_{\mu\nu}^{(g)} = \overline{\epsilon_2^{\mu}\epsilon_2^{*\nu}} = p^{\mu}p^{\nu}x^2/|q_T|^2 = q_T^{\mu}q_T^{\nu}/|q_T|^2 \tag{2}$$

Here study of heavy quark production processes in $p\bar{p}-$collisions at TEVATRON with the SHA is presented. Similar investigations have been done by many authors [5],[8]-[11] earlier. But in the recent papers [10, 11] obtained results contradict each other.

We investigate the sensitivity of the inelastic cross section of heavy quark production processes at TEVATRON to different uintegrated gluon distributions. Special attention is given to the unintegrated gluon distributions obtained from BFKL evolution equation [1].

2 SHA QCD Cross-Section for Heavy Quark Production in $p\bar{p}$ Collisions

We calculate the total and differential cross sections of heavy quark production $p\bar{p} \to Q\bar{Q}X$ via the gluon-gluon fusion QCD subprocess in the framework of the SHA. First of all we take into account the transverse momentum of initial gluons ($\vec{q}_{1,2T}$), their virtualities ($q_{1,2}^2 = -\vec{q}_{1,2T}^{\,2}$) and the alignment of gluon polarization vectors along their transverse momenta given by (2) [3, 4, 6, 7]. Let us define Sudakov variables of the process $p\bar{p} \to Q\bar{Q}X$

$$\begin{aligned} p_1 = \alpha_1 P_1 + \beta_1 P_2 + p_{1T},\;\; p_2 = \alpha_2 P_1 + \beta_2 P_2 + p_{2T} \\ q_1 = x_1 P_1 + q_{1T},\;\; q_2 = x_2 P_2 + q_{2T}, \end{aligned} \tag{3}$$

where

$$p_1^2 = p_2^2 = M^2,\;\; q_1^2 = q_{1T}^2,\;\; q_2^2 = q_{2T}^2,$$

p_1, p_2 and q_1, q_2 are 4-momenta of the heavy quarks and the gluons respectively, p_{1T}, p_{2T} and q_{1T}, q_{2T} are transverse 4-momenta of quarks and gluons. In the center of mass frame of colliding particles we can write $P_1 = (E, 0, 0, E)$, $P_2 = (E, 0, 0, -E)$, where $E = \sqrt{s}/2$, $P_1^2 = P_2^2 = 0$ and $(P_1 P_2) = s/2$. The differential cross section of heavy quark production has the following form:

$$\begin{aligned} d\sigma(p\bar{p} \to Q\bar{Q}\,X) = \tfrac{dx_1}{x_1}\,\Phi(x_1,\, q_{1T}^2,\, Q^2)\,\tfrac{d\phi_1}{2\pi}\,dq_{1T}^2 \times \\ \times\,\tfrac{dx_2}{x_2}\,\Phi(x_2,\, q_{2T}^2,\, Q^2)\,\tfrac{d\phi_2}{2\pi}\,dq_{2T}^2\,d\hat{\sigma}(g^* g^* \to Q\bar{Q}), \end{aligned} \tag{4}$$

[1]The preliminary results have been reported at Workshop DIS 2001, Bologna, 27 April - 1 May 2001.

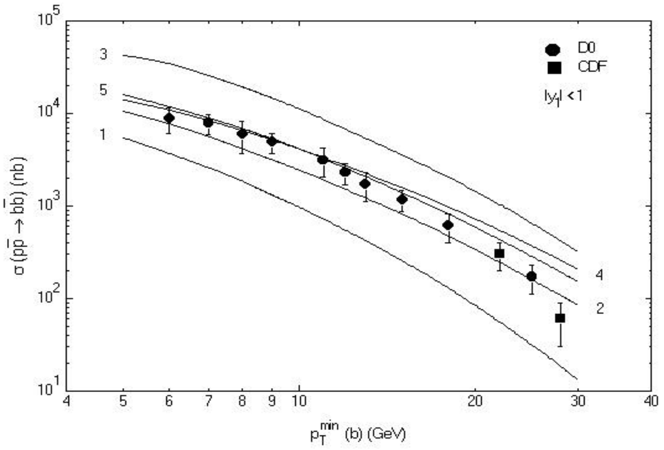

Figure 1: The $b\bar{b}$ production cross section at $\sqrt{s} = 1.8$ TeV.

where $\Phi(x,\, q_T^2, Q^2)$ is an unintegrated gluon distribution in the proton, $d\hat{\sigma}(g^*g^* \to Q\bar{Q})$ is the differential cross section of gluon-gluon fusion subprocess. We used the following form:

$$d\hat{\sigma}(g^*g^* \to Q\bar{Q}) = \frac{(2\pi)^4}{2\hat{s}} \sum |M|^2_{SHA}(g^*g^* \to Q\bar{Q})\, \frac{d^3p_1}{(2\pi)^3\, 2p_1^0}\, \frac{d^3p_2}{(2\pi)^3\, 2p_2^0}\, \delta^{(4)}(q_1+q_2-p_1-p_2), \tag{5}$$

where $\sum |M|^2_{SHA}(g^*g^* \to Q\bar{Q})$ is the off mass shell matrix element. In (5) $\sum$ indicates an averaging over polarizations of initial gluons and a sum over polarizations of final quarks. Integrating out the p_{2T}^2, x_1 and x_2 dependences in (4) and (5) we obtain the following formula for the differential cross section of the process $p\bar{p} \to Q\bar{Q}X$ in the framework of the SHA [2]:

$$\begin{aligned} d\sigma(p\bar{p} \to Q\bar{Q}\,X) = \tfrac{1}{16\pi(x_1\,x_2\,s)^2}\, \Phi(x_1,\ , q_{1T}^2,\, Q^2)\, \Phi(x_2,\, q_{2T}^2,\, Q^2) \times \\ \times \sum |M|^2_{SHA}(g^*g^* \to Q\bar{Q})\, dy_1^*\, dy_2^*\, dp_{1T}^2\, dq_{1T}^2\, dq_{2T}^2\, \tfrac{d\phi_1}{2\pi}\tfrac{d\phi_2}{2\pi}\,\tfrac{d\phi_3}{2\pi}. \end{aligned} \tag{6}$$

3 Results of Calculations

In our calculations we used four different parametrizations of the unintegrated gluon distributions which were considered earlier [13, 14]. Calculations of the heavy quark hadroproduction cross section in the SHA have been made according to Eq. (6) for $\vec{q}_T^{\,2} > q_0^2$ GeV^2. For $\vec{q}_T^{\,2} \le q_0^2$ GeV^2 we set $|\vec{q}_T| = 0$ in the matrix elements of sub-processes, took $\sum |M|^2_{PM}(gg \to Q\bar{Q})$ instead of $|M|^2_{SHA}(g^*g^* \to Q\bar{Q})$ and used the standard parton model (SPM). The choice of the critical value of parameter $\vec{q}_T^{\,2} = q_0^2 = (1 \div 4)$ GeV^2 is determined by the requirement of the small value of $\alpha_s(\vec{q}_T^{\,2})$ in the region $\vec{q}_T^{\,2} > (1 \div 4)$ GeV^2, where in fact $\alpha_s(\vec{q}_T^{\,2}) \le 0.26$.

[2]More detailed formulas may be found in ref. [12].

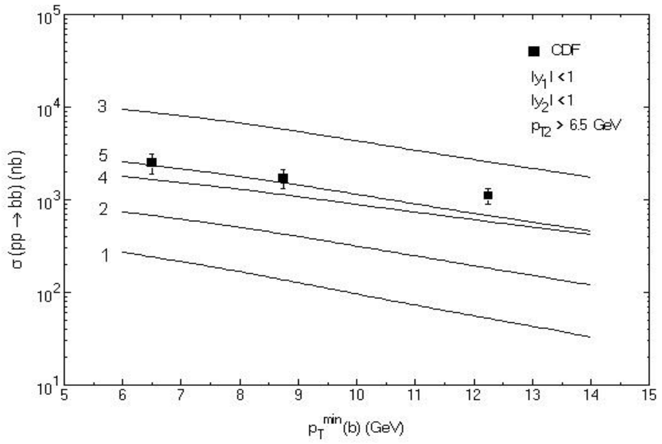

Figure 2: The $b\bar{b}$ production cross section at $\sqrt{s} = 1.8$ TeV.

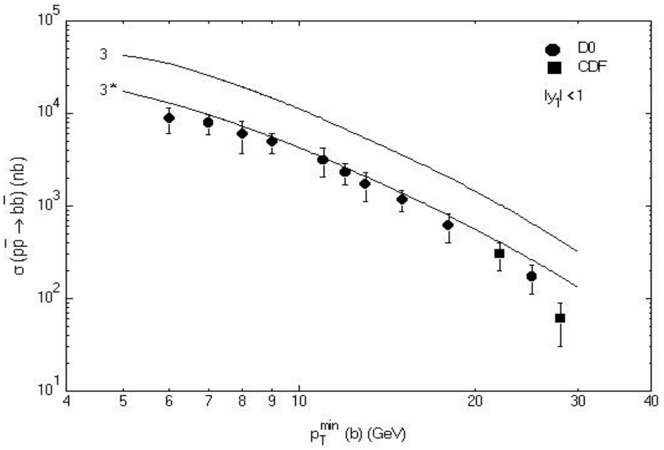

Figure 3: The $b\bar{b}$ production cross section at $\sqrt{s} = 1.8$ TeV. Curves 3 and 3^* correspond to the SHA calculations with the LRSS unintegrated gluon distribution at $m_b = 4.75$ GeV, $\Lambda_{QCD} = 150$ MeV, $Q_0^2 = 2$ GeV^2 and $m_b = 5.0$ GeV, $\Lambda_{QCD} = 100$ MeV, $Q_0^2 = 4$ GeV^2 accordingly.

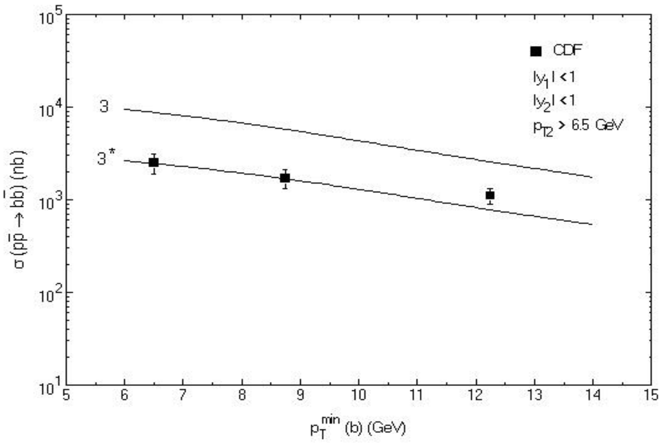

Figure 4: The $b\bar{b}$ production cross section at $\sqrt{s} = 1.8$ TeV. Curves 3 and 3^* are the same as in Fig. 3.

The results of our calculations of the cross sections of $b\bar{b}$ production at TEAVTRON are shown in Figs. $1 \div 5$. These figures show the p_{1T}^{min} dependence of the $b\bar{b}$ production cross section at TEVATRON energies calculated with $m_b = 4.75$ GeV, $\Lambda_{QCD} = 150$ MeV and $|y_1^*| < 1$ (Fig. 1) [1], and $|y_1^*| < 1$, $|y_2^*| < 1$, $p_{2T} > 6.5$ GeV (Fig. 2) [2] [3]. In Figs. 1, 2 the curves 1 correspond to calculations in the framework of the SPM using the gluon density $xG(x, Q^2)$ from the standard GRV set [15]. The curves 2, 3, 4, 5 are the results of calculations in the framework of the SHA using the unintegrated gluon distribution in form of the RS ($Q_0^2 = 4$ GeV^2) [16], LRSS ($Q_0^2 = 2$ GeV^2) [5], BFKL ($Q_0^2 = 1$ GeV^2) [17] parametrizations and the so called "derivative" gluon distribution ($Q_0^2 = 1$ GeV^2) [3, 4, 18] accordingly.

One can see that the SHA curves 2, 4 and 5 describe the D0 and CDF experimental data very well in comparison with the SPM results (curves 1). The LRRS parameterization of the unintegrated gluon distribution overestimates the experimental $b\bar{b}$ production cross section [1, 2].

We tried to describe these experimental data with the help the LRSS parametrization fitting the Q_0^2, m_b and Λ_{QCD} parameters in the region 1 GeV$^2 \leq Q_0^2 \leq 4$ GeV^2, 4.5 GeV $\leq m_b \leq 5.0$ GeV and 100 MeV $\leq \Lambda_{QCD} \leq 250$ MeV. We obtained a good agreement of the theoretical results (curves 3^* in Figs. 3 and 4) with the TEVATRON experimental data for the following values of the parameters: $Q_0^2 = 4$ GeV^2, $m_b = 5.0$ GeV and $\Lambda_{QCD} = 100$ MeV [4].

In Fig. 5 we show the results obtained using the our off-mass shell matrix elements of

[3]The cross section does not depend on p_{1T}^{min} in the region 1 GeV$\leq p_{1T}^{min} \leq 5$ GeV approximately.

[4]The experimental data for $b\bar{b}$ photoproduction obtained by the H1 and ZEUS Collaborations [19, 20] were described in the framework of the SHA with LRSS parametrization of the unintegrated gluon distribution at $Q_0^2 = 2$ GeV^2 only (at $m_b = 4.75$ GeV and $\Lambda_{QCD} = 200$ MeV)[14].

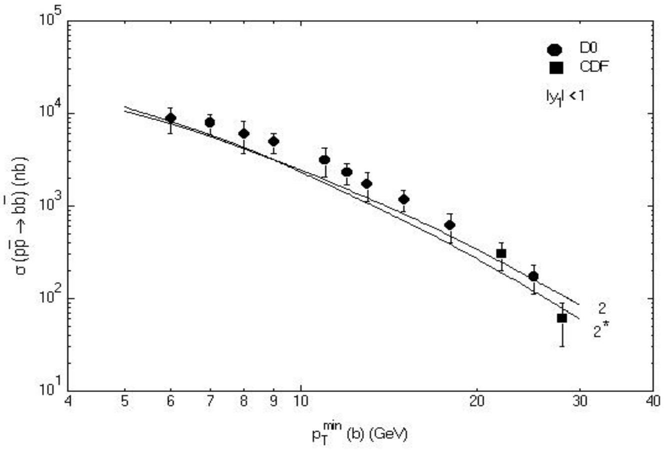

Figure 5: The $b\bar{b}$ production cross section at $\sqrt{s} = 1.8$ TeV. Curves 2 and 2^* correspond to the SHA calculations with the RS parametrization of unintegrated gluon distribution using the our matrix elements and the ones from ref. [6].

gluon-gluon fusion sub-processes and the ones from ref. [6] using the RS parametrization of unintegrated gluon distribution as an example. We see that these results are in a very good correspondence with each other.

4 Conclusions

We considered the process of inelastic heavy quark production at TEVATRON in the framework of the semi-hard QCD approach with emphasis on the BFKL dynamics of gluon distributions. We investigated the cross section $\sigma(p_T > p_T^{min})$ of inelastic $b-$quark hadroproduction as a function of different unintegrated gluon distributions. It is shown that the description of the $b-$quark inelastic cross section at TEVATRON energies is achieved[5] in the cases of the RS, BFKL parametrizations and also the "derivative" parametrization at realistic values of QCD parameters ($m_b = 4.75$ GeV and $\Lambda_{QCD} = 150$ MeV). The LRSS parametrization describes the D0 and CDF experimental data with another values of parameters ($m_b = 5.0$ GeV and $\Lambda_{QCD} = 100$ MeV) in comparison with the description of the $b\bar{b}$ quark photoproduction data at HERA in the framework of the SHA [9].

One of the main goals of our investigations consists in a search in the framework of the SHA of the "universal" unintegrated gluon distribution. In our opinion, the studies of many high energy heavy quark production processes in the framework of the SHA [9],[23]-[25] have shown that the so-called BFKL unintegrated gluon distribution function [17] is

[5]When the present paper has been prepared to publication the ref. [21, 22] appeared, in which it was obtained the similar results in the framework of the k_T factorization approach.

one of the candidates for the role of the universal gluon distribution.

5 Acknowledgments

One of us (N.Z.) would like to thank S. Baranov, H. Jung and L. Jönsson for numerous discussions of different aspects of the QCD SHA, the Elementary Particle Department of Institute of Physics of Lund University for hospitality. This work has been supported in part by RFFI grant 02-02-17513 and the Royal Swedish Academy of Sciences. N.Z. thanks also I. Korzhavina for careful reading the manuscript and useful remarks.

References

[1] D0 Collaboration, C. Abachi et al., *Phys. Lett.*, **B 487** (2000) 264; hep-ex/9905024.

[2] CDF Collaboration, F. Abe et al. Phys. Rev., **D 55** (1997) 2546

[3] L.V. Gribov, E.M. Levin, M.G. Ryskin, *Phys. Rep.*, **100** (1983) 1

[4] E. Kuraev, L. Lipatov, V. Fadin, *Sov. Phys. JETP*, **44** (1976) 443
E. Kuraev, L. Lipatov, V. Fadin, *Sov. Phys. JETP*, **45** (1977) 199
Y. Balitskii, L. Lipatov, *Sov. J. Nucl. Phys.*, **28** (1978) 822

[5] E.M. Levin, M.G. Ryskin, Yu.M. Shabelski, A.G. Shuvaev, *Sov. J. Nucl. Phys.*, **53** (1991) 657

[6] S. Catani, M. Ciafoloni, F. Hautmann, *Nucl. Phys.*, **B 366** (1991) 135

[7] J.C. Collins and R.K. Ellis, *Nucl. Phys.*, **B 360** (1991) 3

[8] M.G. Ryskin, Yu.M. Shabelski, A.G. Shuvaev, *Z. Phys.*, **C 69** (1996) 269

[9] M.G. Ryskin, Yu.M. Shabelski, A.G. Shuvaev, *Phys. Atom. Nucl.*, **64** (2001) 120; hep-ph/0007238; hep-ph/0011111.

[10] S.P. Baranov, M. Smizanska, *Phys. Rev.*, **D 62** (2000) 014012

[11] P. Hagler et al.,*Phys. Rev.*, **D62** (2000) 071502

[12] A.V. Lipatov, V.A. Saleev, N.P. Zotov, Lund University preprint LUNFD6/(NFFL-7207), Sweden, 2001; hep-ph/0112114

[13] V.A. Saleev, N.P. Zotov, *Mod. Phys. Lett.*, **A 9** (1994) 151; 1517; **A 11** (1996) 25

[14] A.V. Lipatov, N.P. Zotov, *Mod. Phys. Lett.*, **A 15** (2000) 695
A.V. Lipatov, V.A. Saleev, N.P. Zotov,*Mod. Phys. Lett.*, **A 15** (2000) 1727

[15] M. Gluck, E. Reya, A. Vogt, *Z. Phys.*, **C 67** (1995) 433

[16] M.G. Ryskin, Yu.M. Shabelski, A.G. Shuvaev, *Z. Phys.*, **C 61** (1994) 517; **C 66** (1995) 151

[17] J. Blumlein, Preprint DESY 95-121

[18] N. Nikolaev, B. Zakharov, *Phys. Lett.*, **B 333** (1994) 250

[19] H1 Collaboration, S. Adloff et al., *Phys. Lett.*, **B 467** (1999) 156

[20] ZEUS Collaboration, J. Breiweg et al., *Eur. Phys. J.*, **C 18** (2001) 625

[21] Yu.M. Shabelski, A.G. Shuvaev, hep-ph/0107106

[22] H. Jung, hep-ph/0110034

[23] S.P. Baranov, N.P. Zotov, *Phys. Lett.*, **B 458** (1999) 389; **B 491** (2000) 111

[24] S.P. Baranov, H.Jung, N.P. Zotov, in *Proceedings of the Workshop on Monte Carlo Generators for HERA Physics*, ed. by A. Doyle, G. Grindhammer, G. Ingelman, H. Jung (DESY, Hamburg, 1999), p. 484; hep-ph/9910210

[25] S.P. Baranov, H.Jung, N.P. Zotov, *Nucl.Phys. Proc. Suppl.*, **99** (2000) 192; hep-ph/0011127