AK

DO-TH 95/09

June 1995

Single Inclusive Heavy Quark Production at High Energy Hadronic Colliders

M. Stratmann

Institut für Physik, Universität Dortmund
D-44221 Dortmund, Germany

Abstract

Theoretical uncertainties in the calculation of single inclusive b -quark and B -meson cross sections at high energy $p\bar{p}$ colliders and the agreement between new experimental data and theory are studied in detail taking into account recent results on $\alpha_s(M_Z)$. The need for high energy resummation techniques is discussed by analysing the perturbative stability of the cross sections. For completeness, results for total $t\bar{t}$ pair production are briefly presented.

The consistency between theoretical predictions for single inclusive b -quark and B -meson production at $p\bar{p}$ colliders and experimental results is a long-standing question. Old results from UA1 [1] ($\sqrt{s} = 630$ GeV) agreed well with theoretical calculations [2] whereas first, now superseded Tevatron results ($\sqrt{s} = 1.8$ TeV) from CDF [3] were roughly a factor of 3 above theory. This led to explanations in terms of a drastically modified gluon distribution [4] and resummations of asymptotically large logarithms $\ln s/m_b^2$ appearing in the partonic cross section [5, 6], arguing ‘naively’ that fixed-order perturbation theory is not well behaved in this kinematical regime [2, 5]¹. With new preliminary CDF [8] and DO [9] data becoming available last year it was claimed [10] that agreement between theory and data can be achieved if one pushes all parameters at their limits and allows for a larger value of the QCD scale parameter for five active flavors $\Lambda_{\overline{\text{MS}}}^{(5)}$ (~ 300 MeV) as indicated by LEP measurements of $\alpha_s(M_Z)$ [11]. It is the main purpose of this letter to analyse this in more detail and to disentangle the size of the various existing sources of uncertainties in the theoretical calculations in view of most recent measurements from D0 [12] and CDF [13] and developments which cast serious doubt on the value for $\alpha_s(M_Z)$ quoted by LEP [14]. Finally, for completeness, LO and NLO results for total $t\bar{t}$ pair production are briefly presented and discussed.

The single inclusive cross section for producing a heavy quark h with mass m_h , transverse momentum p_T and rapidity y can be schematically written as

$$\frac{d^2\sigma^{p\bar{p}\rightarrow hX}}{dp_T^2 dy} = \sum_{i,j} \int dx_1 dx_2 f_i(x_1, \mu^2) f_j(x_2, \mu^2) \frac{d\hat{\sigma}_{ij\rightarrow hX}}{dp_T^2 dy} . \quad (1)$$

The partonic cross sections $d\hat{\sigma}_{ij}$ are calculated up to NLO $\mathcal{O}(\alpha_s^3)$ [2]² and can be expressed

¹Such a misleading conclusion is reached if one does not perform a fully consistent and complete leading/next-to-leading order (LO/NLO) analysis but instead considers just ‘leading’ logarithms and α_s -power counting. The perturbatively stable total heavy quark ($h = c, b$) production cross section resulting from a full LO/NLO analysis can be also understood qualitatively [7]: for any *non-flat* ($\lambda > 0$) parton distribution $xf(x, \mu^2) \sim x^{-\lambda}$ as $x \rightarrow 0$, as is always the case in QCD, one has

$$\sigma(s) = \sigma^{(0)} + \sigma^{(1)} \sim (\alpha_s^2/m_h^2)\rho^{-\lambda} \ln \rho^{-1} [1 + \alpha_s]$$

with $\rho = 4m_h^2/s$, i.e., a perturbative expansion in α_s . This is in contrast to the artificial (toy) assumption of flat parton densities, $\lambda = 0$, which implies [7] an expansion in $\alpha_s \ln \rho^{-1}$ which might (erroneously) indicate the need of asymptotic resummations of all powers of $(\alpha_s \ln \rho^{-1})^n$.

²We are grateful to J. Smith for providing us with the Fortran code of these NLO terms.

as (suppressing all dependencies on kinematical variables)

$$d\hat{\sigma}_{ij} = \alpha_s^2(\mu^2) \left[C_{ij}^{(0)} + \frac{\alpha_s(\mu^2)}{2\pi} \left(C_{ij}^{(1)} + \bar{C}_{ij}^{(1)} \ln \frac{\mu^2}{m_h^2} \right) \right] \quad (2)$$

with μ^2 denoting the scale (renormalization and factorization scale are taken to be equal throughout).

In Fig. 1 we compare the NLO predictions with experimental results from $p\bar{p}$ colliders, so far only available for bottom production ($h = b$) with p_T and y being integrated over $p_T > p_T^{min}$ and $|y| < y_{cut}$, respectively, in eq. (1) and analyse the importance of the various ambiguities inherent in the theoretical calculations. First of all one can infer from Fig. 1a, which contains only published data denoted by solid symbols (UA1 [1] ($y_{cut} = 1.5$) and CDF [15], D0 [12] ($y_{cut} = 1$): the methods to detect a b -quark are distinguished by different symbols as listed in Fig. 1b), that variations of m_b within a reasonable range (4.5 - 5.0 GeV) are only sizeable for $m_b \gtrsim p_T^{min}$, i.e., outside the measured region $p_T^{min} \gtrsim 6$ GeV, and thus represent a major uncertainty $\mathcal{O}(30 - 40\%)$ only for calculating total cross sections. The same holds for the choice of parton distributions $f(x, \mu^2)$ in eq. (1) as is demonstrated in Fig. 1b where we show the ‘default quantity’ (data - theory)/theory which provides an easier visualization of the (dis)agreement between data (here we have included also preliminary results from CDF [8] and D0 [9]) and theory. The other theory curves shown in Fig. 1b represent the deviations from the chosen ‘default theory’ (zero line), i.e., (theory' - theory) / theory. Since the cross section is completely dominated by the gluon-gluon fusion subprocess $gg \rightarrow bX$ for p_T^{min} not too large, the observed difference is closely related to the behavior of the chosen gluon distribution in the small- x region: the MRSA' [17] gluon, being slightly flatter as compared to the MRSG [17] or GRV [16] gluon, leads to somewhat smaller results (up to $\mathcal{O}(20\%)$) whereas the results using MRSG [17] or GRV [16] distributions are roughly equal (the difference for $p_T^{min} \lesssim 2$ GeV is due to the slightly larger value of the QCD scale parameter $\Lambda_{\overline{\text{MS}}}^{(4)} = 255$ MeV [17] used in the MRSG fit). Within the measured p_T^{min} -region, which corresponds to $x \gtrsim 2 \times 10^{-3}$, all modern (steep) sets of parton distributions are almost equal, thus leading to no sizeable deviations. The ambiguities due to the choice of the scale μ are by far more pronounced. We

restrict ourselves to the resonable range $2\mu_0 \geq \mu \geq \mu_0/2$ with ³ $\mu_0 = (p_T^2 + m_b^2)^{1/2}$ which leads to a rather satisfactory perturbative stability if p_T^{min} is not too large, as will be demonstrated below. For comparison we also show results for the choice $\mu = 2m_b$ in Fig. 1b which was found to be the optimum scale for calculating hadronic total cross sections up to a multi-TeV region as well as heavy flavor contributions to structure functions [7].

Since the agreement between data and theory at this level is only acceptable for the old UA1 results and otherwise (D0, CDF) is rather poor it was argued in [10] that it is sensible to allow for larger values of the QCD scale parameter for five flavors $\Lambda_{\overline{\text{MS}}}^{(5)}$ (~ 300 MeV instead of ~ 150 MeV typically used in all recent parton distributions [16, 17]) as indicated by LEP measurements of $\alpha_s(M_Z)$ [11], obviously leading to drastically larger results (up to a factor of 2) and thus solving the problem. Most recent analyses [14] both from a theoretical and an experimental point of view independently found that the quoted value [11] for $\alpha_s(M_Z)$ is questionable. Theoretical arguments [14] based on, e.g., QCD sum rules strongly favor smaller values for $\alpha_s(M_Z)$ ($\alpha_s(M_Z) \approx 0.11 \Leftrightarrow \Lambda_{\overline{\text{MS}}}^{(5)} \approx 130 \dots 170$ MeV) in agreement with values from low-energy experiments (DIS) and incorporated in all recent parton distribution analyses [16, 17]. We therefore conclude that the choice of different parton distributions, as presented above, also includes a sensible range for $\Lambda_{\overline{\text{MS}}}^{(5)}$ (131 MeV (GRV [16]) - 168 MeV (MRSG [17])) but for illustration we also include a curve in Fig. 1 with $\Lambda_{\overline{\text{MS}}}^{(5)} = 200$ MeV.

In Fig. 2 we extend our analysis to single inclusive B -meson production where new results from CDF [13] for $d\sigma^{p\bar{p} \rightarrow BX}/dp_T^B$ with $|y| < 1$ have become available recently. Theoretical predictions can be obtained by convoluting the cross section for b -quark production (eq. (1)) with the appropriate fragmentation function $D_b^B(z)$

$$\frac{d\sigma^{p\bar{p} \rightarrow BX}}{dp_T^B} = \int_{\frac{2p_T^B/\sqrt{s}}{(1-4m_b^2/s)^{1/2}}}^1 \frac{dz}{z} \frac{d\sigma^{p\bar{p} \rightarrow bX}(p_T^B/z)}{dp_T^B} D_b^B(z) \quad . \quad (3)$$

As in all experimental analyses [1, 3, 8, 9, 12, 13, 15] we have applied the scale-independent

³The choice of a fixed scale $\mu_0 = ((p_T^{min})^2 + m_b^2)^{1/2}$, sometimes used, leads to slightly larger ($\mathcal{O}(10\%)$) results irrespective of p_T^{min} .

Peterson fragmentation function [18]

$$D_b^B(z) = N \left(z \left[1 - (1/z) - \epsilon_b/(1-z) \right]^2 \right)^{-1} \quad (4)$$

in our calculations, allowing for $0.004 \leq \epsilon_b \leq 0.008$ [19, 13, 8] (leading to rather small variations). The factor N is fixed by the normalization condition [18] $\sum_B \int dz D_b^B(z) = 1$ and the standard assumption [3, 8, 13, 15] that $B^\pm : B^0 : B_s^0 : b$ -baryons are produced in the ratio $0.375 : 0.375 : 0.15 : 0.1$. Deviations from this assumption lead to a constant shift of the theoretical predictions as is illustrated by the vertical bars in Fig. 2 for the two extreme ratios $0.5 : 0.5 : 0 : 0$ (upper end) and $0.25 : 0.25 : 0.25 : 0.25$ (lower end). Again the same trend as for b -quark production shows up: the theoretical predictions are significantly below data especially for small p_T^B . Uncertainties due to a different choice of structure functions and variations of m_b are comparable to the results in Fig. 1 and are thus being neglected here.

Finally let us discuss possible explanations for the observed discrepancies. First of all it should be worthwhile to note that up to now the experimental results themselves might be not reliable enough. One should remember the considerably large reduction of the first CDF results [3] due to an improved knowledge of the branching fractions of a b -quark into the observed Ψ and Ψ' -mesons, but the analyses are still being preliminary [8]. On the contrary, recently published D0 measurements [12] drastically shifted upwards, however, as compared to the results presented in [9] (for illustration we keep both results in Fig. 1b: solid [12] and open [9] circles, respectively). It is therefore not unlikely that the discrepancy could be resolved or at least reduced with future data.

Secondly it was frequently argued [2, 5] that fixed-order perturbation theory is not reliable at the kinematical regime probed by Tevatron. Arguments based on the one hand on inconsistent LO calculations, i.e., using NLO parton distributions and a NLO α_s in combination with Born cross sections, result in large K -factors ($K \equiv d\sigma_{NLO}/d\sigma_{LO} \gtrsim 2$) which are roughly p_T^{min} or p_T independent [2] and, on the other hand, on analyses of the asymptotic high energy (small- x) behavior of the cross sections eqs. (1,2) assuming flat ($\lambda = 0$) parton distributions [5], i.e., $xf(x, \mu^2) \sim x^{-\lambda}$ as $x \rightarrow 0$. This leads to

the conclusion that for large enough s the relevant expansion parameter should become $\alpha_s \ln s/m_b^2$ and thus has to be resummed to all orders. It was demonstrated in [7] that such asymptotic arguments are questionable for modern QCD-motivated non-flat ($\lambda > 0$) parton distributions [16, 17] in agreement with the results of [6] that these small- x resummation effects are indeed small for steep parton distributions. Moreover, it was shown in [7] for total heavy flavor production cross sections that one can achieve reasonable stable results up to a multi-TeV region (even for charm production) if one performs a consistent LO/NLO analysis.

In Fig. 3 we extend the analysis of [7] to the ‘more differential’ quantity $\sigma(p\bar{p} \rightarrow bX, p_T > p_T^{min}, |y| < y_{cut})$ as measured by UA1 and CDF, D0 ⁴. First of all one should note that the K -factor is not a constant and that one obtains a reasonable perturbative stability for $p_T^{min} \lesssim 15$ GeV even for $\sqrt{s} = 14$ TeV relevant for the future pp collider LHC. Only for larger p_T^{min} (i.e., for larger x values probed) where one enters a ‘multi-scale region’ (p_T, m_b, s) the situation becomes worse. This can only partly be attributed to new subprocesses appearing for the first time in NLO and still remains an open question, and perhaps requires additional resummations along the lines of refs. [20].

It should be remarked that if the discrepancy between data and theory will still persist even with future, more reliable data it should be revealing to study if moderate modifications of the shape of the gluon distribution might help (this represents a ‘hidden’ ambiguity in the theoretical calculations not fully included by varying the parton distributions used in the calculation). This would, obviously, require a combined analysis of all available experimental data which constrain the gluon distribution such as, e.g., direct photon production (hopefully also including forthcoming results for heavy flavor production from HERA). In a recent analysis [21] based only on direct photon results it was shown that there is might be enough freedom to improve the situation at least for p_T^{min} not too large.

⁴One should note that one obtains rather similar results for the differential cross section $d\sigma^{p\bar{p} \rightarrow bX}/dp_T$ or if one allows for a variation of the scale in the range $2\mu_0 \geq \mu \geq \mu_0/2$ or if one uses the fixed scale $\mu = 2m_b$.

Finally, for completeness, we present in Fig. 4 the LO and NLO results for the total $t\bar{t}$ pair production cross section according to the formula given in [22], explicitly demonstrating the perturbative stability and the reduced scale dependence of the NLO predictions and thus their reliability (ambiguities due to a different choice of parton distributions can be safely neglected here since only large- x values ($x \gtrsim 0.03$) are probed).

We are thankful to M. Glück and E. Reya for helpful discussions and to E. Reya for carefully reading the manuscript. This work has been supported in part by the ‘Bundesministerium für Forschung und Technologie’, Bonn.

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Figure Captions

Fig. 1 a) Comparison of the theoretical predictions for $\sigma(p\bar{p} \rightarrow bX, p_T > p_T^{min}, |y| < y_{cut})$ according to eqs. (1,2), using the GRV parton distributions [16] and the scale $\mu = \mu_0/2 = \sqrt{p_T^2 + m_b^2}/2$, with the UA1 data [1] and the CDF [15], D0 [12] data ($\sqrt{s} = 630$ GeV, $|y| < 1.5$ and $\sqrt{s} = 1.8$ TeV, $|y| < 1$, respectively). Different symbols denote different methods to detect a b -quark as listed in Fig. 1b. Uncertainties due to variations of m_b are indicated by the shaded bands. Also shown is an extreme choice for $\Lambda_{\overline{MS}}^{(5)}$ (dashed lines).

b) The ‘default quantity’ $(\sigma_{exp} - \sigma_{th})/\sigma_{th}$ for the data of CDF [15, 8] and D0 [12, 9] (the superseded, preliminary D0 results of the μX -analysis (open circles) are included to illustrate possible experimental difficulties) as compared to the NLO prediction $\sigma_{th} = \sigma(p\bar{p} \rightarrow bX, p_T > p_T^{min}, |y| < 1, \sqrt{s} = 1.8 \text{ TeV})$, using the GRV parton distributions [16], $m_b = 4.5$ GeV and the scale $\mu = \mu_0 = \sqrt{p_T^2 + m_b^2}$ (zero line). The other curves $\sigma_{th'}$ represent the shifts $(\sigma_{th'} - \sigma_{th})/\sigma_{th}$ due to a different choice of the scale μ (solid lines), the parton distributions (MRSG, MRSA' [17]; denoted by dot-dashed lines) and an extreme value for $\Lambda_{\overline{MS}}^{(5)}$ (dashed line).

Fig. 2 Theoretical predictions for $d\sigma^{p\bar{p} \rightarrow BX}/dp_T^B$ ($\sqrt{s} = 1.8 \text{ TeV}$, $|y| < 1$) according to eqs. (3,4) using the GRV parton distributions [16], $m_b = 4.5$ GeV and two different scales ($\mu = 2\mu_0$ and $\mu = \mu_0/2$, $\mu_0 = \sqrt{p_T^2 + m_b^2}$), compared to CDF data [13, 8]. Variations due to a different choice of ϵ_b and the normalization N in eq. (4) are indicated by dotted lines and vertical bars (see text), respectively.

Fig. 3 LO and NLO predictions for $\sigma(pp, p\bar{p} \rightarrow bX, p_T > p_T^{min}, |y| < y_{cut})$ according to eqs. (1,2) for various values of $\sqrt{s}$, using the LO and NLO GRV parton distributions [16], $m_b = 4.5$ GeV and the scale $\mu = \sqrt{p_T^2 + m_b^2}/2$.

Fig. 4 LO and NLO predictions for the total $t\bar{t}$ pair production cross section for different scales $2m_{top} \geq \mu \geq m_{top}/2$ as a function of m_{top} , using the formula of [22] and the LO and NLO GRV parton distributions [16]. Data are taken from [23].

Fig. 1

Fig. 2

Fig. 3

Fig. 4