Fermi National Accelerator Laboratory

May 1993 FERMILAB-Conf-93/95-T

QCD Corrections to Heavy Quark Structure Functions

Eric Laenen

Fermi National Accelerator Laboratory
P.O.Box 500, MS 106, Batavia, Illinois 60510

Talk presented at the XXVIIIth Rencontres de Moriond,
'QCD and High Energy Hadronic Interactions', March 1993

Abstract

I present the results of the calculation of the $O(\alpha_S)$ corrections to the inclusive heavy quark structure functions $F_2(x, Q^2, m^2)$ and $F_L(x, Q^2, m^2)$, and their differential distributions with respect to p_t and y of the detected heavy quark. These results have consequences for the determination of the gluon distribution function $g(x, Q^2)$ at HERA. In addition, I show that the use of a constant K-factor for parametrizing the QCD corrections for the p_t (and y) distributions is not justified.

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

The study of heavy flavor production in ep colliders such as HERA is interesting for several reasons, some of which are unique to this collider type. (See [1] for a general overview.)

Firstly, there is the opportunity of measuring powerlaw scaling violations [2], which occur due to the passing of a heavy flavor threshold. Secondly, there is information to be gained on the heavy quark content of the proton. Thirdly, because heavy flavor production at HERA is dominated by boson-gluon fusion, one can thus inductively study the gluon distribution function $g(x, Q^2)$ at x ranges smaller than hitherto possible [3], roughly $x > 10^{-4}$. Besides having an intrinsic interest, this last issue is important for physics at future colliders such as SSC or LHC: many processes at these colliders will be initiated by small-x gluons.

The determination of the size of the $O(\alpha_S)$ corrections to heavy flavour production at HERA is important in order to understand where finite order perturbative QCD approximations are a good estimate of the all order result. Experimentally, two different production mechanisms can be distinguished by whether the scattered electron is tagged or not (in which case it should be understood as going down the beampipe). In the no-tag situation the heavy quarks are produced mainly through photo-production (the exchanged photon is real), or electroproduction in the Weizsäcker-Williams approximation (the exchanged photon is almost real, $Q^2 < 4$ $(\mathrm{GeV}/c)^2$). For this case the $O(\alpha_S)$ corrections have already been calculated in [4] and [5] for the single particle inclusive case. These no-tag production mechanisms have contributions from two types of photon-modes: pointlike and hadronic. In the latter case it is the partons in the hadronic photon that participate in the hard scattering. The parton densities of the photon are at present however quite poorly known, and thus 'contamimate' the results, rendering the extraction of the gluon distribution function difficult [6]. However, by going to the tagged situation the photon participating in the hard interaction is forced further off shell, making it more pointlike, and thus suppressing the hadronic photon contribution. A drawback is the lower event rate compared to photoproduction. What is presented here is an outline of the results of the calculation of the $O(\alpha_S)$ corrections to the latter case. Full details can be found in [7].

We address the reaction in Fig.1, single particle inclusive production of heavy quarks:

$$e^-(l_1) + P(p) \to e^-(l_2) + Q(p_1) + X. \tag{1}$$

In the single photon exchange approximation the four-fold differential cross section can be expressed in terms of two differential heavy quark structure functions

$$\frac{d^4\sigma(S,T_1,U_1,x,y)}{dxdydT_1dU_1} = \frac{2\pi\alpha^2}{Q^2}\frac{1}{xy}\Big[[1+(1-y)^2]\frac{d^2F_2(S,T_1,U_1,Q^2)}{dT_1dU_1} - y^2\frac{d^2F_L(S,T_1,U_1,Q^2)}{dT_1dU_1}\Big]\,, \tag{2}$$

where the kinematical variables are defined by $S=(p+q)^2$, $T_1=(p-p_1)^2-m^2$, $U_1=(q-p_1)^2-m^2$, $Q^2=-q^2$, $x=Q^2/2p\cdot q$, $y=p\cdot q/p\cdot l_1$.

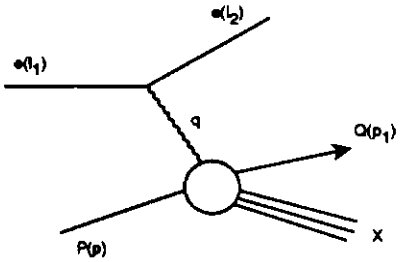

Fig.1. The basic reaction for deep-inelastic heavy flavour production.

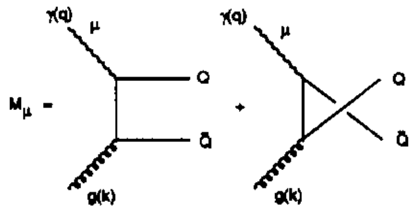

Fig.2. The Born amplitude for the reaction $\gamma^*(q)+g(k)\rightarrow Q(p_1)+\bar{Q}(p_2)$.

Out of the objects dF_i/dT_1dU_1 one constructs dF_i/dp_t and dF_i/dy, where p_t, y refers to the transverse momentum and rapidity of the heavy quark, respectively, and the index i is either 2 or L. For now we integrate over T_1, U_1. To calculate the $O(\alpha_S)$ corrections to F_2 and F_L we employ the factorization theorem, and we have up to $O(\alpha_S^2)$, schematically

$$F_k^{(j)}(x,Q^2,m^2) \propto \alpha_S^2 \sum_l \int_x^{z_{\max}} \frac{dz}{z}\, f_l(\frac{x}{z},M^2)\,[c_{k,l}^{(j)}(\eta(z),\frac{Q^2}{m^2}) + \bar{c}_{k,l}^{(j)}(\eta(z),\frac{Q^2}{m^2})\ln\frac{M^2}{m^2}]\,, \quad k=2,L \quad , \quad z_{\max}=\frac{Q^2}{4m^2+Q^2} \tag{3}$$

where M^2 is the mass factorization scale (chosen equal to the renormalization scale), $f_l(x,M^2)$ is the parton distribution function for flavor l $(g,u,d,\ldots)$, and j labels the order (0 or 1). The partonic (Wilson) coefficient functions $c_i^{(j)}, \bar{c}_i^{(j)}$ are defined by projections $P_i^{\mu\nu}$, $i=T,L$ (and $c_2=c_T+c_L$) on the square of the amplitude $M_\mu^* M_\nu$.

The born amplitude is depicted in Fig.2. The $O(\alpha_S)$ corrections $c_i^{(1)}$, $\bar{c}_i^{(1)}$, $i=T,L$, consist of all one loop corrections to the Born graphs in Fig.2, plus the bremsstrahlung process

$$\gamma^*(q)+g(k_1)\rightarrow g(k_2)+Q(p_1)+\bar{Q}(p_2)\,. \tag{4}$$

In addition, at this order a new production mechanism arises:

$$\gamma^*(q)+q(k_1)\rightarrow q(k_2)+Q(p_1)+\bar{Q}(p_2)\,. \tag{5}$$

Its contribution to the results in the following, while not neglible, is generally small. In Fig.3 we plot $c^{(0)}_{T,g}$, $c^{(1)}_{T,g}$ and $\bar{c}^{(1)}_{T,g}$ as a function of the variable $\eta = (s - 4m^2)/4m^2$, where s is the photon parton cms energy squared, for different values of Q^2: the solid-, short-dashed- and long-dashed lines corresponding to $Q^2 = 0$, 10 and 100 $(\mathrm{GeV}/c)^2$ respectively. Renormalization and mass factorization have both been carried out in the $\overline{\mathrm{MS}}$ scheme.

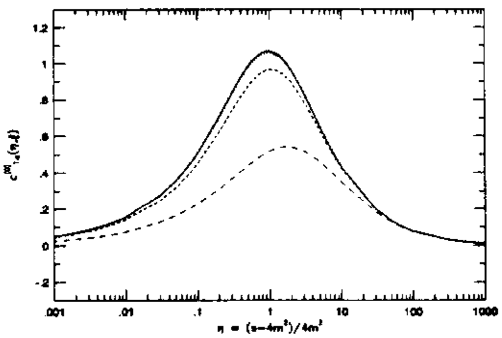

Fig.3a Coefficient function $c^{(0)}_{T,g}(\eta)$

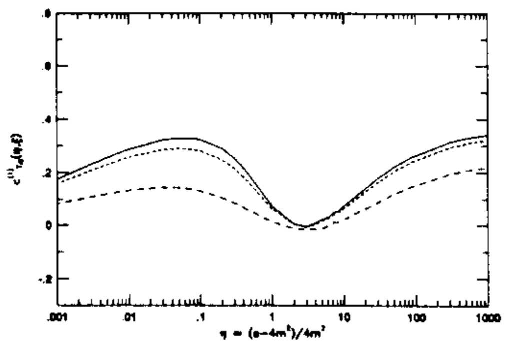

Fig.3b Coefficient function $c^{(1)}_{T,g}(\eta)$

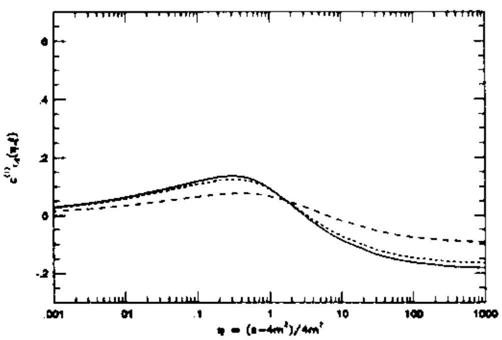

Fig.3c Coefficient function $\bar{c}^{(1)}_{T,g}(\eta)$

One observes that, whereas the Born coefficient $c^{(0)}_{T,g}$ peaks around $\eta = 1$, and vanishes at small and large η – which corresponds to large and small x in [3] respectively, the reverse happens for the $c^{(1)}_{T,g}$. Both $c^{(1)}_{T,g}$ and $\bar{c}^{(1)}_{T,g}$ exhibit a plateau at large η, which is due to soft gluon exchange in the t-channel. The increase at small η for $c^{(1)}_{T,g}$ can be attributed to initial state soft gluon bremsstrahlung. The 'dip' in the central region, which even turns negative at $\eta \approx 2$, is due to a combination of virtual graphs and mass factorization. (The coefficient functions $c^{(1)}_{T,q}$ and $\bar{c}^{(1)}_{T,q}$ due to the reaction (5) also show a plateau at large η, for the same reason as for $c^{(1)}_{T,g}$ and $\bar{c}^{(1)}_{T,g}$ [7].)

Let us now see what the results are when these coefficient functions are combined with parton distribution functions in (3). We chose for the latter the Morfín-Tung (MT) parametrizations [8], fit B1 in the $\overline{\mathrm{MS}}$ scheme with $\Lambda_4 = 0.194$ GeV/c, with a two loop running coupling. Furthermore the charm mass was chosen $m = m_c = 1.5$ GeV/c^2. In this report I will not discuss bottom production, but results for this flavor can be found in [7].

In Fig.4a we plot $F_2(x, Q^2, m_c^2)$ for $Q^2 = 10$ $(\mathrm{GeV}/c)^2$ (dashed pair) and $Q^2 = 100$ $(\mathrm{GeV}/c)^2$ (solid pair), showing both the lowest order result and the $O(\alpha_S)$ corrected one, the latter always being the upper curve of the pair. Here we chose the mass factorization scale $M^2 = M_0^2 = Q^2 + 4m_c^2$. In order to exhibit the size of the corrections relative to the Born result, we plot for the same two values of Q^2 in Fig.4b the ratio

$$R_2(x, Q^2, m^2) = \frac{F_2^{(0)}(x, Q^2, m^2) + F_2^{(1)}(x, Q^2, m^2)}{F_2^{(0)}(x, Q^2, m^2)}, \tag{6}$$

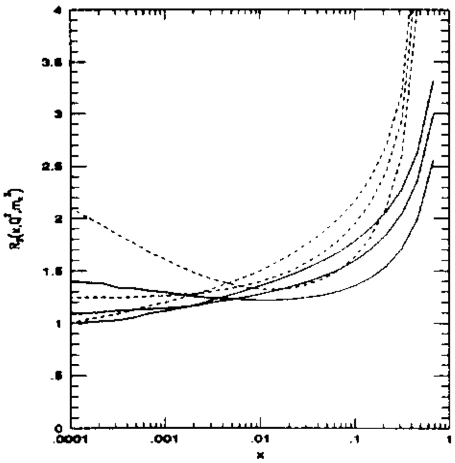

Fig.4a $F_2(x, Q^2, m_c^2)$ vs.x

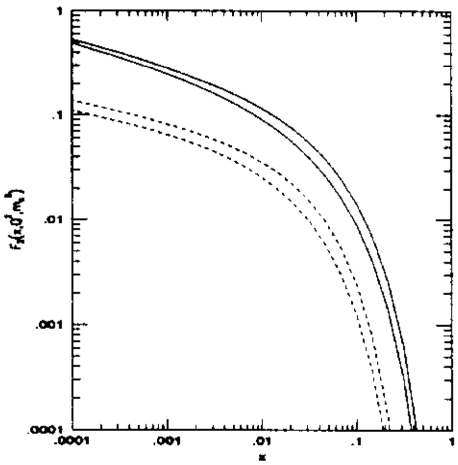

Fig.4b. The ratio R_2 (6) vs. x

for three choices of mass factorization scale as a function of x, the upper curve at $x = 10^{-4}$ of each set of three corresponding to the $M = M_0/2$, the middle one to $M = M_0$, and the lower to $M = 2M_0$. The figure reveals that there are large corrections when x tends towards its maximum. These come from the enhancement at small η in $c_{T,g}^{(1)}(\eta)$, which was due to soft gluon bremsstrahlung. Corrections are also large when $x \to 0$, depending on the choice of mass factorization scale. This behavior can be traced to the plateau's at large η in Fig.3. This η-region contributes heavily in the integral (3) in the limit $x \to 0$. The strong dependence on the mass factorization scale can then be understood from (3) as simply adding, or subtracting, plateau's. Thus for very small x ($x < 10^{-3}$) this method of determining the gluon distribution function, while suppressing the uncertainty due the hadronic photon component, is plagued by other uncertainties. However, Fig.4b shows that the corrections for $10^{-3} < x < 10^{-2}$ are not too large relative to the Born result. Thus, in this region, our results could be used to extract the gluon distribution function.

We now turn to the effects the $O(\alpha_S)$ corrections have on the p_t distribution of the heavy quark. As stated above, the quantity dF_i/dp_t can be constructed from d^2F_i/dT_1dU_1. Details, including the analogous discussion for the rapidity distribution of the heavy quark, can be found in [7].

Fig.5a is a plot of $dF_2(x, Q^2, m_c^2, p_t)/dp_t$ vs. p_t, for representative values of x and Q^2. In Fig.5b a similar ratio as in Fig.4b is plotted, viz.

$$R_2(x, Q^2, m^2, p_t) = \frac{dF_2^{(0)}(x, Q^2, m^2, p_t)/dp_t + dF_2^{(1)}(x, Q^2, m^2, p_t)/dp_t}{dF_2^{(0)}(x, Q^2, m^2, p_t)/dp_t}, \qquad (7)$$

at $Q^2 = 10$ $(\mathrm{GeV}/c)^2$, with the mass factorization scale $M^2 = Q^2 + 4(m_c^2 + p_t^2)$, for $x = 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}$, corresponding to the curves with increasing values at $p_t = 0$, respectively. The conclusion from these figures is that one cannot use a constant 'K-factor' to describe the QCD corrections to dF_2/dp_t (this also holds for dF_L/dp_t and $dF_{2/L}/dy$ [7]), and that the corrections are large, especially for larger x values.

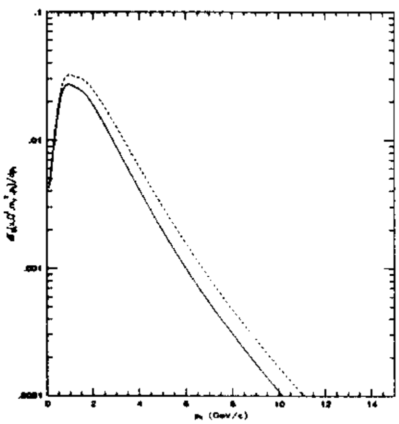

Fig.5a dF_2/dp_t vs.p_t,$x = 10^{-3}$, $Q^2 = 10$ $(\mathrm{GeV}/c)^2)$

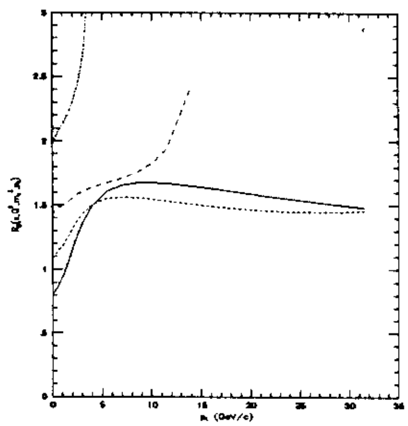

Fig.5b. The ratio R_2 (6) vs. p_t

In summary, the $O(\alpha_S)$ corrections to single particle inclusive deep-inelastic heavy flavour production have been calculated, both for the inclusive case and for the distibutions with respect to the p_t and y of the heavy quark. These results should be useful for the program of extracting the gluon distribution from heavy flavour production at HERA. I would like to thank S. Riemersma, J. Smith and W.L. van Neerven for a fruitful collaboration.

References

[1] A. Ali and D. Wyler, in 'Physics at HERA', Proceedings of the Workshop, DESY, Hamburg, eds. W. Büchmuller and G. Ingelman, vol. 2, p 669, 1991.

[2] M. Glück, R. Godbole, E. Reya, Z.Phys.**C38** (1988) 441; M. Glück, in Proceedings of the HERA workshop, Hamburg (1987), ed. R. Peccei, vol.1, 119.

[3] R. van Woudenberg et al., in 'Physics at HERA', Proceedings of the Workshop, DESY, Hamburg, eds. W. Büchmuller and G. Ingelman, vol. 2, p 669, 1991.

[4] R.K. Ellis and Z. Kunszt, Nucl. Phys. **B303** (1988) 653; R.K. Ellis and P. Nason, Nucl. Phys. **B312** (1989) 551.

[5] J. Smith and W.L. van Neerven, Nucl. Phys.**B374** (1992) 36

[6] S. Riemersma, J. Smith and W.L. van Neerven, Phys.Lett **B282** (1992) 171

[7] E. Laenen, S. Riemersma, J. Smith and W.L. van Neerven, Nucl. Phys. **B392** (1993) 162, 229.

[8] J.G. Morfín and W-K. Tung, Z.Phys. **C52**, (1991) 13.