Prospects for heavy flavour photoproduction at HERA

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Abstract: I discuss few selected topics in heavy flavour photoproduction at HERA which require large integrated luminosity in order to be experimentally investigated. I present phenomenological predictions for bottom production. As a possible application of measurements involving double-tagged charm events, I outline a method for the direct measurement of the gluon density in the proton. The possibility of using charm data in polarized electron-proton collisions to constrain the polarized gluon density in the proton is also discussed.

Charm quarks are copiously produced at HERA. Total cross sections in photoproduction have been measured [1, 2], and appear to be in reasonable agreement with next-to-leading order QCD calculations [3, 4, 5, 6]. Recently, the first results on single-inclusive distributions have been presented [2]. Although in substantial agreement with experiments, the theory displays the tendency to undershoot the data. On the other hand, preliminary results by the ZEUS collaboration [7] show sizeable discrepancies in the comparison with next-to-leading order QCD, especially in the pseudorapidity distribution.

The limited statistics of the data prevents from any definite conclusion on the capability of fixed-order QCD calculations to correctly describe charm photoproduction at the large center-of-mass energies available at HERA. It has to be pointed out that the resummation of logarithms which in certain regions of the phase space may grow large and spoil the convergence of the perturbative expansion, can not improve the comparison between theory and experiments (see ref. [8] and references therein). The luminosity upgrade of the HERA collider will allow to increase the statistics of present measurements, and to perform new ones. The underlying theoretical picture will therefore face a severe test. Detailed phenomenological predictions for total rates and single-inclusive distributions of charm quarks in photoproduction at HERA have been available for some time [9, 10, 11]. In the following, I will deal with quantities whose measurement has not yet been performed.

1 Bottom production

Due to the higher value of the quark mass, perturbative QCD predictions for bottom production are more reliable than those for charm. In monochromatic photon-proton collisions, the pointlike component has an uncertainty of a factor of 2 if all the parameters are varied *together* in the direction that makes the cross section larger or smaller. At $\sqrt{S_{\gamma p}} = 100$ GeV, the lower and upper limits of the pointlike component are 16 nb and 35 nb respectively, while at $\sqrt{S_{\gamma p}} = 280$ GeV we get 41 nb and 101 nb [10]. The hadronic component has larger uncertainties, but much smaller than for charm, since in bottom production the small-x region is probed to a lesser extent than in charm production, and the sensitivity of the result to the photon densities is therefore milder; we get an uncertainty of a factor of 3 (to be compared with a factor of 10 in the case of charm). The hadronic component can still be the dominant

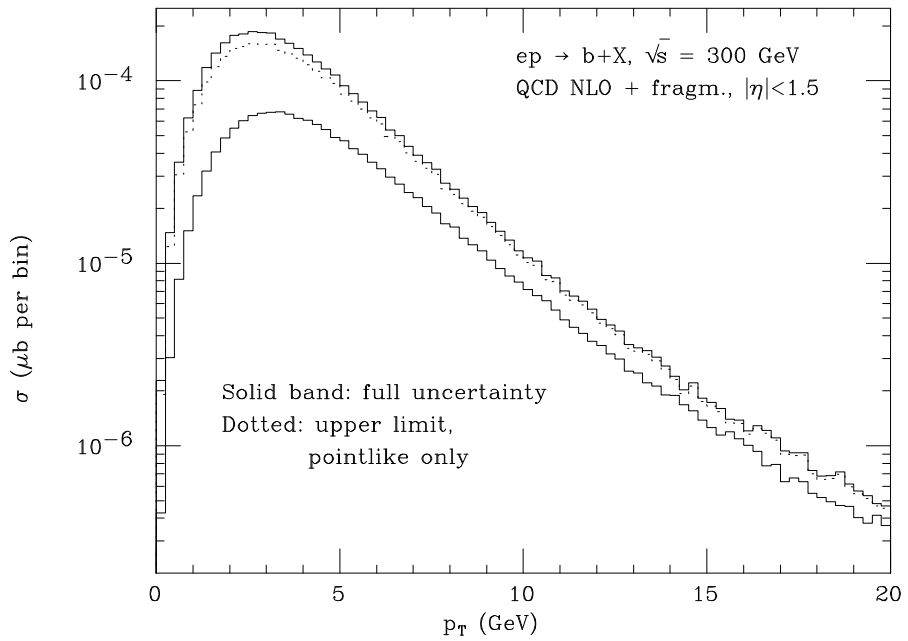

Figure 1: *Full uncertainty on the transverse momentum distribution for bottom electroproduction (Weizsäcker-Williams approximation) with Peterson fragmentation and a pseudorapidity cut.*

contribution to the photoproduction cross section, if the gluon in the photon is as soft as the LAC1 parameterization suggests.

The bottom rates are about a factor of 200 smaller than the charm ones. To perform a statistically significant study of bottom production, the luminosity upgrade at HERA is necessary. In any case, it is very likely that a comparison with the theory could only be done by considering the electroproduction (in the Weizsäcker-Williams approximation) process. In this case the sensitivity of the theoretical predictions to the input parameters is sizeably reduced, and a reliable comparison between theory and data can be performed. For example, in electroproduction the hadronic component contribution to the total cross section is at most 75% of the pointlike contribution, even if the LAC1 set is used. The most interesting results are however obtained when considering more exclusive quantities, like single-inclusive distributions [4, 11]. In particular, as shown in fig. 1, the transverse momentum of the bottom quark at HERA can be predicted by perturbative QCD quite accurately. It is clear that even with the LAC1 set the hadronic component affects the prediction only marginally; this fact is basically a consequence of the applied pseudorapidity cut. Figure 1 can therefore be regarded as a reliable prediction of QCD for the p_T spectrum of B mesons at HERA. The comparison of this prediction with the data would be extremely useful in light of the status of the comparison between theory and data for b production at the Tevatron.

2 The gluon density in the proton

As discussed in ref. [8], the experimental efficiency for double-tagged charm events is quite low, and in order to study fully-exclusive quantities, like the correlations between the charm and

the anticharm, a large integrated luminosity is mandatory. The comparison between theoretical predictions and experimental results for correlations constitutes the most stringent test for the underlying theory, and it is therefore extremely interesting for a complete understanding of the production mechanism of heavy flavours. However, at present it is not particularly useful to present detailed predictions for double-differential distributions, since data will not be available for a long time. In the following, I will therefore concentrate on a possible application of measurements involving double-tagged charm events, namely the determination of the gluon density in the proton ($f_g^{(p)}$).

At present, no *direct* measurement of $f_g^{(p)}$ has been performed. In principle, this quantity could be determined by investigating the exclusive properties of hard scattering processes initiated by gluons. In practice, this procedure is quite difficult; the data on direct photon production and on inclusive jet production, which depends upon $f_g^{(p)}$ already at the leading order in QCD, are not as statistically significant as DIS data are (DIS data allow a direct and accurate determination of the quark densities). Direct photon and inclusive jet data are used to constrain, in complementary regions of x and Q^2, the gluon density. Furthermore, in a next-to-leading order QCD evolution, $f_g^{(p)}$ affects the quark densities through the Altarelli-Parisi equations, and therefore has an impact on the description of DIS data on $F_2(x, Q^2)$ (for a detailed presentation of the determination of parton densities from a global QCD analysis, see for example refs. [12, 13]).

A direct measurement of the gluon density is therefore highly desirable. In ref. [14] it was argued that charm production in high energy ep collisions may help to solve this problem. To proceed explicitly, I begin by writing the heavy-quark cross section at the leading order in the following form

$$\frac{d\sigma^{(0)}}{dy_{Q\overline{Q}}\, dM^2_{Q\overline{Q}}} = x_g \frac{d\sigma^{(0)}}{dx_g\, dM^2_{Q\overline{Q}}} = \frac{1}{E^2}\, f_\gamma^{(e)}(x_\gamma, \mu_0^2) f_g^{(p)}(x_g, \mu_F^2) \hat{\sigma}^{(0)}_{\gamma g}(M^2_{Q\overline{Q}}), \tag{1}$$

where $M_{Q\overline{Q}}$ is the invariant mass of the heavy-quark pair, and $y_{Q\overline{Q}}$ is the rapidity of the pair in the electron-proton center-of-mass frame (I choose positive rapidities in the direction of the incoming proton). $E = \sqrt{S}$ is the electron-proton center-of-mass energy, and

$$x_\gamma = \frac{M_{Q\overline{Q}}}{E} \exp(-y_{Q\overline{Q}}), \tag{2}$$

$$x_g = \frac{M_{Q\overline{Q}}}{E} \exp(y_{Q\overline{Q}}). \tag{3}$$

The function $f_\gamma^{(e)}$ is the Weizsäcker-Williams function [15] (for a discussion on its use in production processes involving heavy particles, see ref. [16]); the explicit expression for the leading-order cross section $\hat{\sigma}^{(0)}_{\gamma g}$ can be found in ref. [3]. The factorization and renormalization scales (μ_F and μ_R) are set equal to $2\mu_0$ and μ_0 respectively, where μ_0 is a reference scale; when studying correlations, it is customary to choose [5]

$$\mu_0 = \sqrt{(p_T^2 + \bar{p}_T^2)/2 + m^2}, \tag{4}$$

where p_T and $\bar{p}_T$ are the transverse momenta of the heavy quark and of the heavy antiquark respectively.

Assuming that the left-hand side of eq. (1) is identified with the data, the equation can be inverted, and we can get a first determination of $f_g^{(p)}$:

$$f_g^{(0)}(x_g,\mu_F^2) = x_g \frac{d\sigma^{\rm data}}{dx_g\, dM^2_{Q\bar{Q}}} \frac{E^2}{f_\gamma^{(e)}(x_\gamma,\mu_0^2)\hat{\sigma}^{(0)}_{\gamma g}(M^2_{Q\overline{Q}})}. \tag{5}$$

The inclusion of radiative corrections does not pose any problem. I write the full cross section as

$$x_g \frac{d\sigma}{dx_g\, dM^2_{Q\overline{Q}}} = \frac{1}{E^2}\; f_\gamma^{(e)}(x_\gamma,\mu_0^2) f_g^{(p)}(x_g,\mu_F^2)\hat{\sigma}^{(0)}_{\gamma g}(M^2_{Q\overline{Q}}) + \Delta(f_g^{(p)}, x_g, M^2_{Q\overline{Q}}), \tag{6}$$

where Δ represents all the radiative effects. In Δ I have also indicated explicitly the functional dependence upon the gluon density in the proton. The light quarks, which enter at the next-to-leading order via the $\gamma q \to q Q \bar{Q}$ process, give a small contribution (less than 5% for all values of x_g and $M_{Q\overline{Q}}$ considered here). I now write $f_g^{(p)}$ as

$$f_g^{(p)}(x,\mu_F^2) = f_g^{(0)}(x,\mu_F^2) + f_g^{(1)}(x,\mu_F^2), \tag{7}$$

where the second term is the next-to-leading order correction, and plug it back into eq. (6). Then

$$f_g^{(1)}(x_g,\mu_F^2) = -\frac{E^2\Delta(f_g^{(0)}, x_g, M^2_{Q\overline{Q}})}{f_\gamma^{(e)}(x_\gamma,\mu_0^2)\;\hat{\sigma}^{(0)}_{\gamma g}(M^2_{Q\overline{Q}})}. \tag{8}$$

I have neglected the $f_g^{(1)}$ piece contained in the Δ term, the corresponding contribution being of order $\alpha_{\rm em}\alpha_S^3$. It could also be easily incorporated by iterating eq. (8), using the full gluon density in the right-hand side.

The charm cross section receives a large contribution from the hadronic component, which was neglected in the above derivation. In order to extract the gluon density in the proton with the method previously outlined, we have to consider only those kinematical regions where the hadronic component is suppressed by the dynamics. I study this possibility in figure 2, where I present the next-to-leading order QCD predictions for the variable x_g, defined in eq. (3), in electron-proton collisions at $\sqrt{S} = 314$ GeV. The partonic densities in the proton are given by the MRSG set, while both the LAC1 and GRV-HO sets for the photon are considered, in order to account for the uncertainty affecting the gluon density in the photon. Figs. 2(a)-2(c) show the effect of applying a cut on the invariant mass of the pair. Even in the case of the smallest invariant-mass cut, there is a region of small x_g where the hadronic component is negligible with respect to the pointlike one. When the invariant-mass cut is increased, the hadronic component can be seen to decrease faster than the pointlike one. This is due to the fact that, for large invariant masses of the pair, the production process of the hadronic component is suppressed by the small value of the gluon density in the photon at large x. By pushing the invariant-mass cut to 20 GeV, it turns out that the pointlike component is dominant over the hadronic one for x_g values as large as 10^{-1}. The conclusion can be drawn that the theoretical uncertainties affecting the charm cross section, in the range $10^{-3} < x_g < 10^{-1}$, are small enough to allow for a determination of the gluon density in the proton by using invariant-mass cuts to suppress the hadronic component. In a more realistic configuration, like the present one of the detectors at HERA, additional cuts are applied to the data. Fig. 2(d) shows the effect on the x_g distribution due to a small-p_T and a pseudorapidity cut, applied to both the charm and the anticharm. In this case, even without an invariant-mass cut, the pointlike component is dominant in the whole kinematically accessible range. Taking into account experimental efficiencies [8], a statistically significant measurement of the gluon density requires an integrated luminosity of at least 250 pb^{-1}.

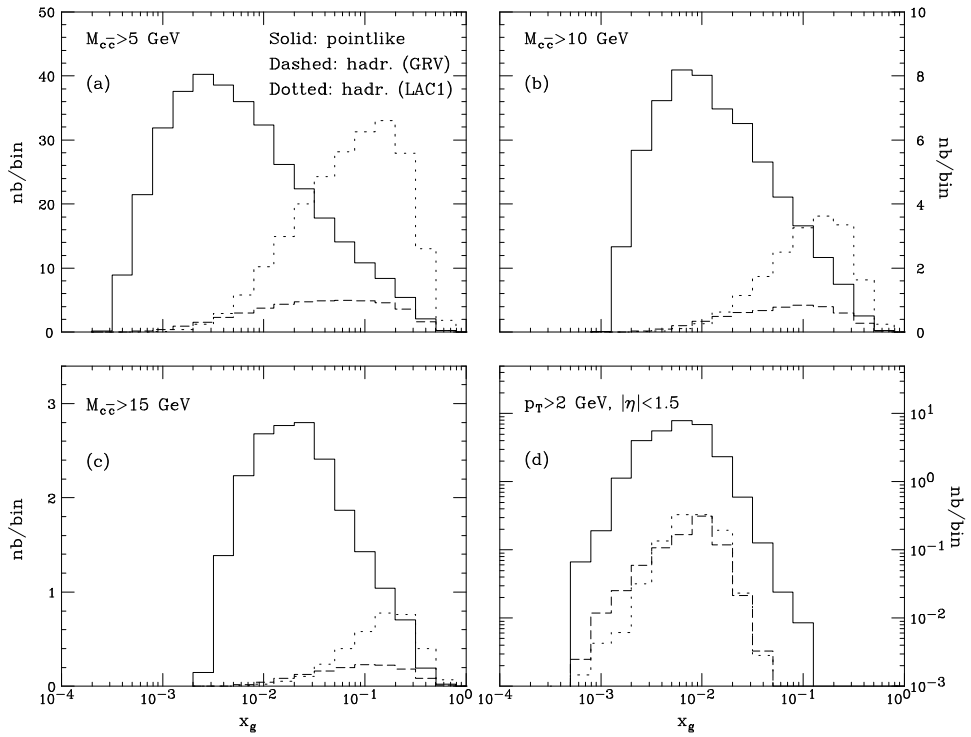

Figure 2: *x_g distribution in ep collisions (Weizsäcker-Williams approximation) at HERA, for $m_c = 1.5$ GeV. The proton parton density set adopted is MRSG.*

3 Polarized ep collisions

It is conceivable that in the future the HERA collider will be operated in a polarized mode. The heavy flavour cross section in polarized ep scattering is dependent already at the leading order in QCD upon the polarized gluon density in the proton, $\Delta g^{(p)}$. Therefore, data on charm production could be used to directly measure $\Delta g^{(p)}$, as previously shown for the unpolarized case. In practice, the situation for the polarized scattering is much more complicated. First of all, a full next-to-leading order calculation is not available for the partonic processes relevant for polarized heavy flavour production. Furthermore, there is no experimental information on the partonic densities in the polarized photon. It is reasonable, however, to think that charm production at the HERA collider in the polarized mode can help in constraining the polarized gluon density in the proton. This possibility was first suggested in ref. [17], and recently reconsidered in refs. [18, 19].

The next-to-leading and higher order corrections to the polarized cross section are expected to be sizeable, therefore casting doubts on the phenomenological relevance of leading-order predictions. To overcome this problem, one possibility is to present predictions [18] for the ratio $\Delta\sigma/\sigma$ (asymmetry), where σ is the unpolarized cross section and

$$\Delta\sigma = \frac{1}{2}\left(\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}\right). \tag{9}$$

Here $\sigma^{\uparrow\uparrow}$ and $\sigma^{\uparrow\downarrow}$ are the cross sections for $c\bar{c}$ production with parallel and antiparallel polarizations of the incoming particles respectively. One might expect that the effect of the radiative

corrections approximately cancels in the ratio. It has to be stressed that, for consistency reasons, the unpolarized cross section σ appearing in the asymmetry must be calculated at the leading order, as the polarized one.

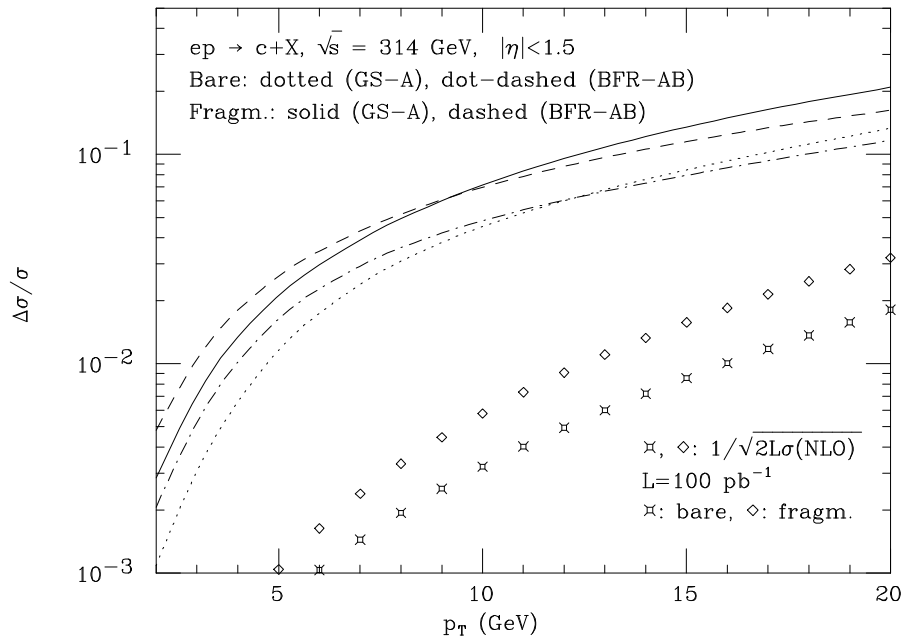

Figure 3: *Asymmetry cross section versus transverse momentum in polarized ep collisions (Weizsäcker-Williams approximation) at* $\sqrt{S} = 314$ *GeV. The minimum observable asymmetry, computed at next-to-leading order, is also displayed.*

The next-to-leading order value of σ can then be used to estimate the sensitivity of the experiment. A rough estimate of the minimum value of the asymmetry observable at HERA can be obtained by requiring the difference between the numbers of events with parallel and antiparallel polarizations of the initial state particles to be larger than the statistical error on the total number of observed events. This gives

$$\left[\frac{\Delta\sigma}{\sigma}\right]_{min} \simeq \frac{1}{\sqrt{2\sigma\mathcal{L}\epsilon}}, \tag{10}$$

where $\mathcal{L}$ is the integrated luminosity and the factor ϵ accounts for the experimental efficiency for charm identification and for the fact that the initial beams are not completely polarized. This procedure can be applied to total cross sections, as well as to differential distributions; in this case, the values of σ and $\Delta\sigma$ have to be interpreted as *cross sections per bin* in the relevant kinematical variable.

In ref. [18] it was shown that total cross section asymmetries for the pointlike component are quite small in absolute value, and can be measured only if ϵ is equal or larger than 1% (0.1%), assuming $\mathcal{L} = 100$ pb^{-1} (1000 pb^{-1}). Therefore, even with a vertex detector (see ref. [8]), it appears to be unlikely that this kind of measurements will be performed at HERA. Furthermore, in ref. [19] a rough estimate of the hadronic contribution to the polarized cross section has been given, assuming polarized parton densities in the photon to be identical to

zero or to the unpolarized densities to get a lower and an upper bound on the cross section. It was found that a non-negligible contamination of the pointlike result might indeed come from the hadronic process. The situation clearly improves when considering more exclusive quantities; in ref. [18] it was found that at moderate p_T values the asymmetry for the pointlike component can be rather large, well above the minimum observable value (in this region, the experimental efficiency is sizeable [8]); this is shown in fig. 3. In ref. [19] it was argued that the hadronic component should have a negligible impact in this case. I conclude that, with an integrated luminosity of 100 pb^{-1}, charm data in high-energy polarized ep collisions will help in the determination of the polarized gluon density in the proton. In order to distinguish among different parameterizations for $\Delta g^{(p)}$, a larger luminosity is likely to be needed.

4 Conclusions

I have discussed few selected topics in heavy flavour physics which will become of practical interest at HERA after that the planned upgrades of the machine will be carried out. With an integrated luminosity $\mathcal{L} = 100$ pb^{-1}, about 10^5 bottom quarks are predicted by QCD to be produced in ep collisions at $\sqrt{S} = 300$ GeV. If the experimental efficiency for B-meson identification will be large enough, this will provide with the possibility of a detailed study of the bottom production mechanism, and of an interesting comparison with the results at the Tevatron. In order to study charm-anticharm correlations, $\mathcal{L}$ must be equal to or larger than 250 pb^{-1}. As a possible application of measurements involving double-tagged charm events, I presented a method for the direct measurement of the gluon density in the proton. Charm data in polarized ep collisions could also be used to constrain the *polarized* gluon density in the proton. In this case, an integrated luminosity of at least 100 pb^{-1} is required.

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