Inclusive D^*-Meson Photoproduction in the GM-VFNS

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I describe the calculation of inclusive production of D^* mesons at next-to-leading in the general-mass variable-flavour-number scheme. In this approach, large logarithms of the charm transverse momentum are resummed and finite terms depending on m^2/p_T^2 are kept in the hard scattering cross sections. Numerical results are presented for photoproduction and for ep collisions at very small Q^2 at HERA and compared with recent experimental measurements.

1 Schemes for heavy quark production

The improved precision of recent measurements of scattering processes with heavy quarks requires a careful analysis of mass effects at higher orders of perturbative QCD. The purpose of this contribution [1] is to summarize the ideas underlying the *general-mass variable flavor-number scheme* (GM-VFNS) used in calculations for one-particle inclusive production of heavy mesons with charm quarks. This framework allows one to take into account not only effects due to non-zero quark masses, but also resummed logarithmic contributions which are important at high momenta. In addition, I will present recent results for the production of D^*-mesons at HERA in photoproduction and at low-Q^2 deep inelastic scattering.

Theoretical predictions for the production of heavy-quark mesons at high transverse momentum p_T are technically difficult to obtain due to the presence of the two different scales p_T and the heavy-quark mass m. On the one hand, the heavy-quark mass can be considered the large scale, since $m > \Lambda_{\rm QCD}$, making perturbative QCD applicable. When m is the only large scale, as for example in the calculation of the total cross section or in predictions of the p_T distribution close to the production threshold where $p_T \simeq m$, predictions from a fixed-order calculation are reliable. On the other hand, if the transverse momentum p_T of the produced heavy quark is large compared with the heavy quark mass, $p_T \gg m$, then p_T should be used as the dominant large scale for the perturbative calculation and the quark mass can be neglected. In this case, large logarithms $\ln(p_T^2/\mu^2)$ arise at all orders, so that fixed-order perturbation theory is not valid anymore. These logarithms have to be resummed in order to obtain meaningful numerical predictions.

In the first case, for $p_T \lesssim m$, the traditionally used approach is called fixed flavor-number scheme (FFNS) [2]. It is based on the assumption that the gluon and the light partons (u, d, s) are the only active partons. The heavy quark appears only in the final state, produced in the hard scattering process of light partons. The heavy-quark mass m is explicitly taken into account together with the transverse momentum p_T of the produced heavy meson assuming that m and p_T are of the same order. However, the complexity of such a calculation restricts one to the next-to-leading order, at present. In this scheme, the non-zero heavy-quark mass acts as a cutoff for initial and final-state collinear singularities. Instead of singular terms one finds logarithmic contributions containing $\log(p_T/m)$. Their presence restricts the applicability of the FFNS to the region of low transverse momenta;

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since $m \neq 0$ is retained in the calculation, predictions are reliable, on the other hand, close to the threshold of heavy-quark production.

In the second case, at large transverse momentum, the large logarithmic terms have to be resummed. In order to do that, one has to isolate these terms in the higher-order corrections to the hard scattering cross section and move them to parton distribution and fragmentation functions (PDFs and FFs). The well-known factorization theorem provides the foundation of this re-ordering of higher-order corrections and there is a straightforward procedure for incorporating PDFs and FFs into order-by-order perturbative calculations. Resummation of logarithmic contributions can then be obtained with the help of the DGLAP evolution equations. This approach requires therefore to treat the heavy quark as a parton, and as a consequence, one has to take into account additional processes where heavy quarks occur as incoming partons. Also, heavy mesons are not only produced by a non-perturbative transition from heavy quarks in the final state; in addition one has to consider processes where light partons fragment into the heavy meson. Since the heavy quark is treated like any other massless parton, quark or gluon, it is plausible to neglect the heavy-quark mass altogether. This approach is usually called zero-mass variable flavor-number scheme (ZM-VFNS). The PDFs for heavy quarks and the FFs needed in this approach contain non-perturbative contributions and have to be obtained from a comparison with experimental data. Usually one assumes that these functions are zero below a starting scale, taken of the order of m. At this transition point, one switches from a description with n_f light partons to one with $n_f + 1$ partons. The predictions in this scheme are expected to be reliable only in the region of very large transverse momenta, since terms of the order of m^2/p_T^2 present in the hard-scattering cross sections are neglected.

In fact, it is not necessary to neglect the heavy-quark mass altogether in a variable flavor-number scheme. Instead, it is possible to absorb the large logarithms $\ln(p_T/m)$ into PDFs and FFs where they are resummed by imposing DGLAP evolution, as in the ZM-VFNS, while at the same time, mass-dependent terms proportional to m^2/p_T^2 as obtained in the FFNS are retained in the hard-scattering cross section. This so-called general-mass variable-flavor number scheme (GM-VFNS) thus combines the virtues of the FFNS and the ZM-VFNS. The required subtraction of logarithmic terms, which are related to initial- and final-state singularities, have to be defined with the usual $\overline{\text{MS}}$ prescription. This guarantees the universality of parton distribution and fragmentation functions and allows for a meaningful comparison of data from different measurements.

The determination of the collinear singularities and their accompanying finite terms has been described in detail in [3]. Subraction terms needed to define the hard scattering cross sections in the GM-VFNS take into account that a genuinely massless $\overline{\text{MS}}$ calculation differs from a calculation with finite heavy quark masses,

$$d\sigma_{\text{sub}} = \lim_{m \to 0} d\tilde{\sigma}(m) - d\hat{\sigma}_{\overline{\text{MS}}}\,. \tag{1}$$

One can obtain hard scattering cross sections including mass-dependent terms in the $\overline{\text{MS}}$ factorization scheme by subtraction of this difference:

$$d\hat{\sigma}(m) = d\tilde{\sigma}(m) - d\sigma_{\text{sub}}\,. \tag{2}$$

Here, $d\hat{\sigma}_{\overline{\text{MS}}}$ is the cross section obtained in a calculation where the heavy-quark mass is set to zero from the beginning and singularities are removed following the $\overline{\text{MS}}$ prescription, while $d\tilde{\sigma}(m)$ denotes the cross section from a calculation with $m \neq 0$ where ultraviolet and collinear singularities due to massless partons have been removed also according to $\overline{\text{MS}}$ factorization. The difference between the two calculations, i.e. the subtraction terms $d\sigma_{\text{sub}}$ comprise logarithms of the heavy-quark mass as well as accompanying finite terms. The partonic cross section $d\hat{\sigma}(m)$ obtained after subtraction includes the complete regular m-dependence of the massive calculation, i.e. all terms containing powers of m^2/p_T^2 of $d\tilde{\sigma}(m)$. After subtraction, the resulting partonic cross sections are defined in the conventional $\overline{\text{MS}}$ factorization scheme in such a way that they can be combined with universal PDFs $f_i^A(x, \mu_F)$ and FFs $d_k^H(z, \mu'_F)$, also defined in the $\overline{\text{MS}}$ scheme, in the well-known factorization formula.

DGLAP evolution couples the set of PDFs for light quarks and the gluon to those for the heavy quark. In a similar way, one needs FFs for the transition of not only the heavy quark to the considered heavy meson, but also fragmentation starting from light quarks and the gluon has to be taken into account and must be described by corresponding FFs.

The GM-VFNS for inclusive production of heavy mesons has been developed in a series of papers, starting with $\gamma\gamma$ scattering and the photoproduction process $\gamma + p \to D^* + X$ in [4]. The application to charmed-meson production in $p\bar{p}$ scattering has been described in [5]. In the following I describe numerical results for photoproduction of D^*-mesons. In contrast to our previous work in [4], the present results are based on a complete NLO calculation where all contributions are consistently obtained in the GM-VFNS. More details can be found in the original publications [6, 7].

2 Photoproduction of D^*-mesons

A particular complication in the calculation of predictions for photoproduction is due to the fact that two interaction modes contribute: first, the photon can scatter off a parton originating from the proton through a point-like coupling (direct contribution) and, secondly, the photon can act as a source of partons which scatter off the partons from the proton through the strong interaction (resolved contribution). At leading order, the two interaction mechanisms appear to be independent, but at next-to-leading order, the separation into direct and resolved contributions is scheme dependent since singular corrections to the direct part have to be factorized into parton distribution functions of the photon. It is therefore important that direct and resolved parts are treated in a consistent way.

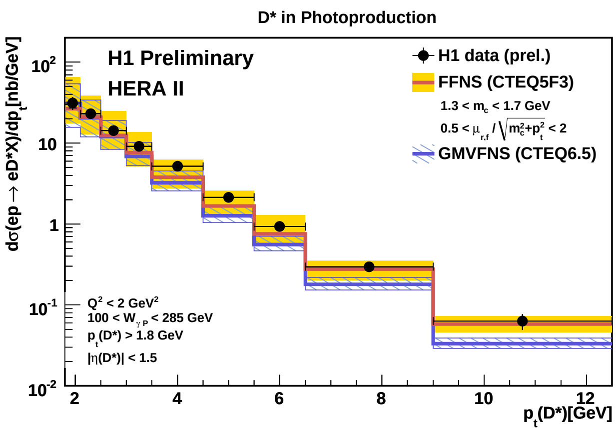

Figure 1: Comparison of NLO predictions in the GM-VFNS for $d\sigma/dp_T$ (hashed (blue) band) with H1 preliminary data [9] for $\gamma + p \to D^* + X$. The shaded (yellow) band shows the prediction of a calculation in the fixed-flavor number scheme [2]. $100 < W_{\gamma p} < 285$ GeV, $Q^2 < 2$ GeV^2, $|\eta| \le 1.5$.

Mass terms proportional to powers of m^2/p_T^2 enter in subprocesses where the heavy quark is created through scattering of light particles. The resolved part contains contributions from scattering processes where one or both of the incoming partons are replaced by a charm or an anti-charm quark. These latter processes have to be calculated with $m = 0$ since here the heavy quark is treated as a parton. Finally, also subprocesses where both incoming and outgoing partons are light quarks or gluons contribute through fragmentation of light quarks and gluons to the heavy meson.

Measurements of inclusive $D^{*\pm}$ meson production in photon-proton collisions have been performed by the two collaborations H1 and ZEUS. The most recent results have been published in Refs. [8, 9] (for previous measurements, see [10, 11]). Photoproduction in ep collisions is characterized by an almost vanishing virtuality of the exchanged photon, imposed usually by the experimental requirement that no scattered electron or positron is observed in the final state. For the HERA experiments this condition restricts Q^2 to values below $\simeq 1$ GeV^2. In [12], a measurement of $D^{*\pm}$-meson production in deep inelastic scattering with an observed $e^\pm$ in the Q^2-range $0.05 < Q^2 < 0.7$ GeV^2 has been described. One can expect that for these very small Q^2-values, the approximation to neglect Q^2 altogether is still a reliable one, as in the case of photoproduction.

We have calculated differential cross sections for both experimental conditions. A comparison with preliminary experimental data for photoproduction from the H1 collaboration [9] is shown in Fig. 1 and in Fig. 2 for low-Q^2 deep inelastic scattering with data from the ZEUS collaboration [12]. Kinematical cuts are defined as in the respective experimental analyses. As input for the parton distribution functions we have used parametrizations of the CTEQ collaboration, set CTEQ6.5 [13] in the case of photoproduction and CTEQ6.6 [14] for predictions for low-Q^2 ep scattering. Photon PDFs are taken from the set GRV92 [15] (transformed to the $\overline{\mathrm{MS}}$ scheme). The fragmentation u, d, s, c, $g \to D^*$ is described by the purely non-perturbative fits described in Ref. [16], the Global-GM fit for photoproduction and the fit based on the Belle/CLEO data for low-Q^2 ep scattering. α_s is calculated at two-loop with $n_f = 4$ and $\Lambda^{(n_f=4)}_{\overline{\mathrm{MS}}} = 328$ MeV corresponding to $\alpha_s(m_Z) = 0.118$. The charm mass is taken to be $m = 1.5$ GeV.

A detailed study of theoretical uncertainties can be found in Ref. [6]. It was found that the dominating source of uncertainties is due to the ambiguity in the choice of the renormalization and factorization scales. In the figures we show therefore error bands that were obtained by varying renormalization and factorization scales only. The scale parameters are taken proportional to the transverse mass $m_T = \sqrt{p_T^2 + m^2}$ with coefficients that are varied between 1/2 and 2, but keeping all ratios of renormalization and factorization scales always smaller than 2.

The p_T distributions agree, in general, with the data points inside errors. Scale variations are largest for the smallest p_T-values. Since rapidity distributions were obtained by integrating over p_T with relatively small lower cuts, $p_T \geq 1.8$ GeV for photoproduction from H1 and $p_T \geq 1.5$ GeV for low-Q^2 data from ZEUS, the η-distribution appears with scale variations that are large over the whole considered range.

Effects from finite mass-dependent contributions are found to be important at small p_T, first of all for the contribution from direct photoproduction. However, the presence of charm-initiated contributions, which are calculated with zero mass, and cancellations between mass-dependent terms in the direct and the resolved contribution, lead to a suppression of mass effects in the complete cross section.

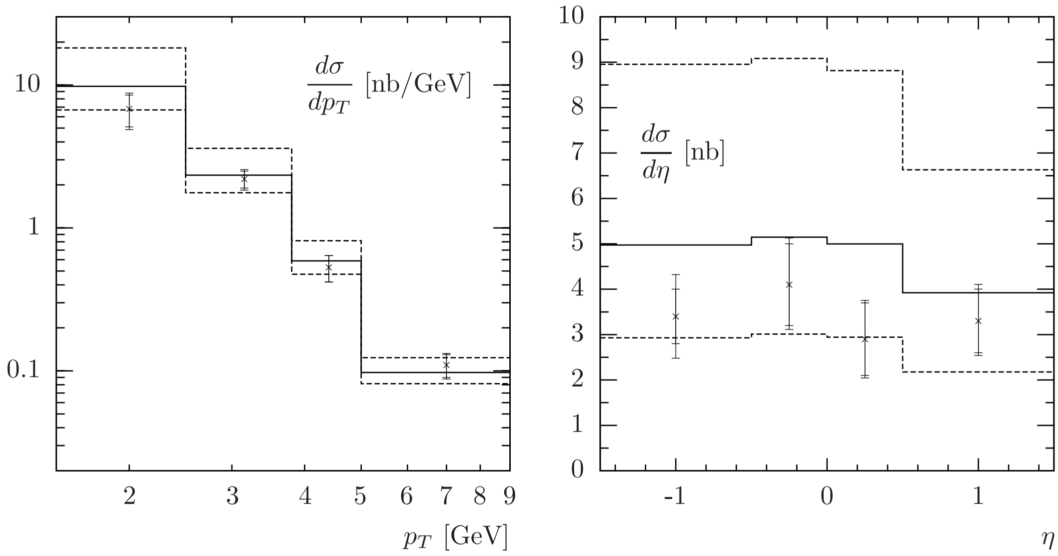

Figure 2: Differential cross sections for D^* meson production in low-Q^2 ep scattering compared with ZEUS data [12]. The default choice for the renormalization and factorization scales is $m_T = \sqrt{p_T^2 + m^2}$ (full lines) and error bands are obtained by varying the scale parameters by a factor of 2 (dashed lines). The kinematic range is given by $0.05 < Q^2 < 0.7$ GeV^2, $0.02 < y < 0.85$, $1.5 < p_T < 9.0$ GeV and $|\eta| < 1.5$.

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