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Heavy Quark Production in Deep-Inelastic Scattering

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Abstract: We review recent results from the H1 and ZEUS experiments at HERA on charm and beauty production in *ep* collisions at 300 - 318 GeV centre-of-mass energy.

1. Introduction

Deep inelastic scattering (DIS) at HERA offers unique opportunities to test and refine our understanding of heavy quark production in terms of perturbative QCD. The dominant mechanism here is boson-gluon fusion (BGF): a photon coupling to the scattered positron interacts with a gluon from the proton to form a quark-antiquark pair. A quantitative description of this process requires the gluon momentum distribution in the proton, a partonic matrix element and a fragmentation function. The gluon density is known to an accuracy of a few percent from the analyses of scaling violations of the proton structure function F_2 measured at HERA [1]. The masses of the charm and, even more so, of the beauty quark ensure that a hard scale is present that renders QCD perturbation theory to be applicable to the calculation of the hard subprocess. Fragmentation functions, which account for the long-range effects binding the heavy quarks in observable hadrons, are extracted from e^+e^- annihilation data, where the kinematics of the hard process is well determined; results with high precision appeared recently [2]. Compared with the clean e^+e^- case, the complication in ep collisions lies in the strongly interacting initial state. However, relative to other production environments like hadron-hadron collisions or two-photon interactions, uncertainties related to hadronic structure are reduced to a minimum.

QCD calculations have been performed up to fixed order α_s^2 in the so-called massive scheme, where only gluons and light quarks are active partons in the initial state. They are available in the form of Monte Carlo integration programs [3], which, by using Peterson fragmentation functions [4], provide differential hadronic cross sections. Due to the higher quark mass, the QCD predictions are expected to be more reliable for beauty than for charm. However, we note that the NLO corrections to the predicted DIS cross section are

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around 40% of the LO result in both cases. At very high momentum transfers, a treatment in terms of heavy quark densities in the proton may be more adequate; but differences between these schemes are not yet significant in the range covered by HERA so far [5].

2. Charm

Most of the HERA results on charm make use of the "golden" decay channel $D^{*+} \to D^0\pi^+$ followed by $D^0 \to K^-\pi^+$; ZEUS also uses semileptonic decays. The contribution of charmed final states to DIS is quantified as the ratio F_2^c/F_2, where F_2^c is defined in an analogous way to the proton structure function F_2 by

$$\frac{d^2\sigma(ep \to cX)}{dx\, dQ^2} = \frac{2\pi\alpha^2}{xQ^4}(1+(1-y)^2)\cdot F_2^c(x,Q^2)\ ;$$

x, y, and Q^2 are the standard DIS scaling variables. Measurements of F_2^c by both experiments [6, 7] and by using different channels yield consistent results. The charm contribution F_2^c/F_2 is found to be about 20 to 30 % in most of the kinematic region at HERA. It is large where gluon-induced reactions dominate, and decreases only as Q^2 becomes smaller than $\sim$10 GeV^2, or at higher x values $\gtrsim 0.01$, where the quark content in the proton takes over. Figure 1 displays the measured values of F_2^c. The Q^2 dependence, for fixed values of x, is steeper than for the inclusive structure function. The NLO QCD calculation [3], with a gluon distribution extracted from H1 F_2 data, agrees well with the data, which demonstrates the overall consistency of the boson-gluon-fusion picture. At low x, the data tend to be somewhat higher and to vary stronger with Q^2 than the prediction.

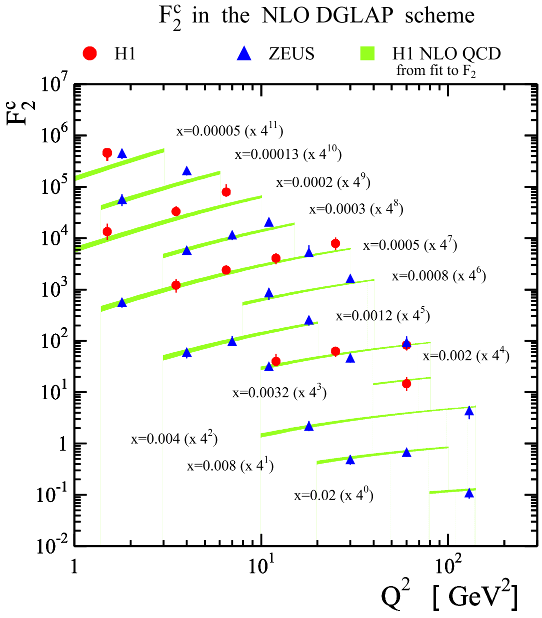

Figure 1: Charm contribution to the proton structure function, compared with NLO QCD.

The available statistics makes more detailed investigations possible. It was observed earlier that the NLO QCD calculations with Peterson fragmentation (HVQDIS) do not reproduce the rapidity (η) distribution of the produced charm meson well in the forward region (the outgoing proton direction) [6, 8]. The double differential D^* cross section [7] displayed in Figure 2 reveals that in the H1 data this is predominantly a feature of the low $p_T(D^*)$ region. The measurement is also compared with the CASCADE Monte Carlo program [9], based on the CCFM evolution equation [10], which resums higher order contributions at low x. Using an unintegrated gluon distribution extracted from inclusive H1

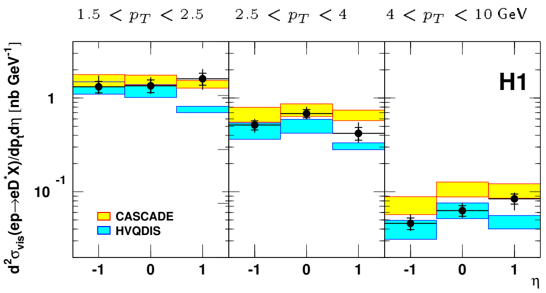

Figure 2: Double differential $D^{*\pm}$ cross section, compared with QCD predictions.

data, it reproduces the data in the low p_T region well, but overshoots at higher p_T. Such shape differences imply that the extrapolated result for F_2^c is model-dependent, but also the F_2^c prediction depends on the evolution scheme. H1 has performed a consistent extraction and comparison in the CCFM scheme and found somewhat better agreement in the low x region than in the standard Altarelli-Parisi scheme.

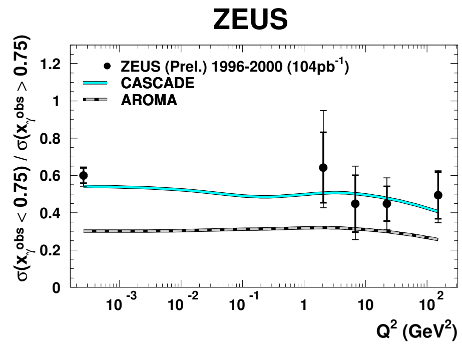

Figure 3: Ratio of low x_γ to high x_γ cross section, compared with predictions.

A possibility to include higher order processes in the modeling of heavy quark production is to use the concept of photon structure also at non-zero virtuality. One can classify events as "direct" or "resolved" according to the measured value of $x_\gamma^{OBS} = (E - p_z)_{2\,jets}/(E - p_z)_{all\ hadrons}$ in di-jet events. Keeping the LO photoproduction language, this corresponds to the momentum fraction of the incoming parton in the photon, but more generally, x_γ^{OBS} is sensitive to any kind of non-collinear radiation in the event. The ratio of resolved *vs.* direct cross sections has been determined in this approach by ZEUS [11] and is displayed as a function of virtuality in Figure 3. In contrast to the situation for light quarks, the ratio in the DIS regime is very similar to that at $Q^2 \approx 0$; as expected, using e.g. the virtual photon structure function set SaS1D [12] implemented in the HERWIG program [13]. The CASCADE model, with gluon emissions ordered in angle rather than in k_T, effectively incorporates the perturbative, anomalous part of the photon structure and reproduces the data well at all Q^2, but not the AROMA Monte Carlo program [14], which does not include such contributions.

Charm production has also been measured separately in e^-p and e^+p DIS by ZEUS [15]. The data are shown in Figure 4 as a function of Q^2. The e^-p and e^+p results are only barely consistent with each other; for $Q^2 > 20$ GeV^2, the discrepancy amounts to 3 standard deviations. However, both measurements are compatible with the theoretical expectation, in which no mechanism exists to generate an asymmetry with respect to the lepton beam charge at such low four-momentum transfers.

In summary, the BGF concept at NLO works well for charm in DIS, up to high Q^2. The HERA data reach the precision to identify regions (e.g. at low x), where refinements are becoming necessary.

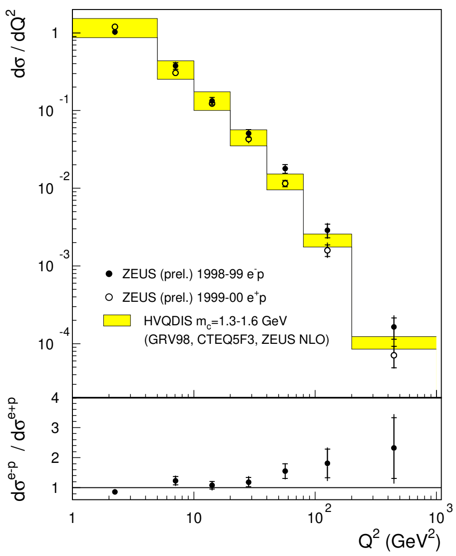

Figure 4: $D^{*\pm}$ cross section in e^-p and e^+p DIS compared with NLO QCD.

3. Beauty

Beauty production at HERA is suppressed by two orders of magnitude with respect to charm. All HERA measurements of b production so far rely on inclusive semi-leptonic decays, using identified muons or electrons in dijet events. Two observables have been used to discriminate the b signal from background sources. The high mass of the b quark gives rise to large transverse momenta p_T^{rel} of the lepton relative to the direction of the associated jet. Using this method, both collaborations have published photoproduction cross section measurements [16, 17], which are higher than NLO QCD expectations.

More recently, with the precision offered by the H1 vertex detector [18], it has become possible to observe tracks from secondary b vertices and to exploit the long lifetime as a b tag, using e.g. the impact parameter δ. This improves the photoproduction result [19] and provides a first measurement in DIS [20], where resolved contributions involving the non-perturbative hadronic structure of the photon are expected to be suppressed [21]. The DIS case is therefore complementary and theoretically simpler. The sensitivity to determine the beauty component is maximized by combining both variables in a likelihood fit to the two-dimensional distribution in δ and p_T^{rel}. The consistency of the two observables has been established with the larger statistics available in the photoproduction regime The δ distribution for muons in dijet DIS events selected from a dataset corresponding to 10.5 pb^{-1}, is shown in Figure 5 together with the decomposition from the two-dimensional fit, which yields a $b\bar{b}$ fraction of $f_b = (43 \pm 8)\,\%$.

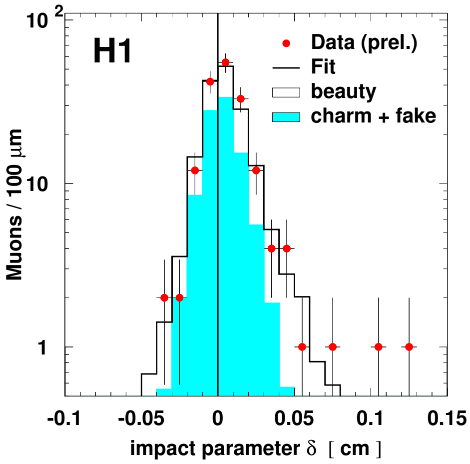

Figure 5: Muon impact parameter distribution, with decomposition from the likelihood fit.

A DIS cross section of $\sigma^{vis}_{ep\to b\bar{b}X\to\mu X} = 39 \pm 8 \pm 10$ pb is extracted in the kinematic range given by $2 < Q^2 < 100$ GeV^2, $0.05 < y < 0.7$, $p_T(\mu) > 2$ GeV and $35° < \theta(\mu) < 130°$. This can be directly compared to NLO QCD calculations implemented in the HVQDIS [3] program, after folding the predicted b hadron distributions with a decay lepton spectrum. The result, 11 ± 2 pb, is much lower than the H1 measurements. The data have also been compared with the CASCADE Monte Carlo simulation; the result of 15 pb also falls considerably below the measurements.

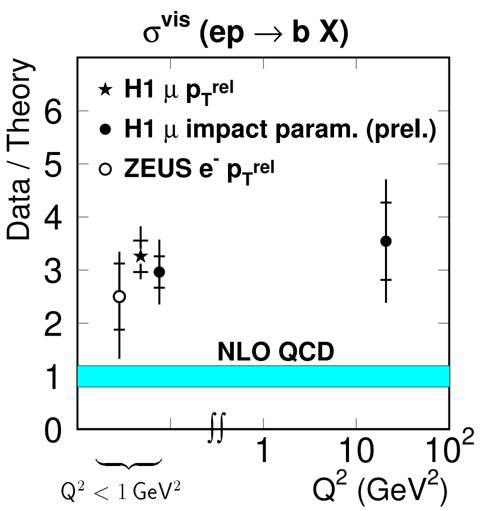

Figure 6: Ratio of measured b production cross sections at HERA to theoretical expectation, as a function of Q^2.

We summarize the HERA b results [16, 17, 19, 20] as a function of Q^2 in Figure 6, where the ratio of the measured cross sections to theoretical expectations based on the NLO QCD calculations [3, 22] is displayed. It is consistent with being independent of Q^2. The discrepancy between data and theory is similar to the situation observed in $\bar{p}p$ and, more recently, $\gamma\gamma$ interactions [23]. The first measurement in DIS indicates that in *ep* collisions this is not a feature of hadron-hadron like scattering alone.

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