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REVIEW OF HEAVY FLAVOUR PRODUCTION IN *ep* COLLISIONS *

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Measurements of open heavy flavour production in *ep* collisions at a center of mass energy of 318 GeV are reviewed in both photoproduction and deep inelastic scattering.

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1. Introduction

The production of heavy quarks in electron proton collisions predominantly occurs via the photon gluon fusion mechanism, where a photon emitted by the incoming electron interacts with a gluon in the proton, forming a quark–antiquark pair. The dominant contribution is due to the exchange of almost real photons corresponding to a photon virtuality $Q^2 \sim 0$ (photoproduction, γp). In deep inelastic scattering (DIS) Q^2 is large, often defined experimentally by $Q^2 > 2$ GeV^2.

Heavy quark production can be described by a factorization ansatz consisting of four parts: perturbatively calculable hard cross section, proton structure, photon structure, fragmentation. The hard cross section is calculated at a scale μ which may be chosen to be the heavy quark mass m_Q if other scales such as Q^2 are small. The transverse momentum $p_{\rm T}$ of a heavy flavour hadron, the transverse energy $E_{\rm T}$ of a heavy flavour jet or the virtuality Q^2 are also possible scales leading to a multi scale problem. The investigation of the proton structure leads to determine the structure function F_c^2 and the parton densities, especially the gluon density. Further, different evolution models for the parton densities like DGLAP, CCFM and BFKL can be tested. At low Q^2 the photon exhibits a hadronic behaviour. The photon can directly interact with a gluon in the proton (direct processes), or first fluctuate into a $c\bar{c}$ pair before the hard interaction (resolved

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processes). The fragmentation describes the transition of coloured quarks into colourless hadrons. Here the question of the fragmentation universality is important.

The theoretical calculations which are used for modeling open heavy flavour production can be classified into two categories: calculations in NLO perturbative QCD and LO Monte Carlo models in which higher orders are approximated by parton showers. Three different schemes are distinguished for the NLO pQCD calculations. The fixed order massive scheme [1, 2] is valid at low p_{T} and Q^2. The four flavour massless scheme [3] holds at large scales. The matched calculations [4] are an unification of both previous schemes and should provide a good description in the whole kinematic range. The MC generators AROMA [5], RAPGAP [6] and PYTHIA [7] use the DGLAP evolution, while CASCADE [8] is based on the CCFM evolution[1, 2].

At HERA electrons (or positrons) of energy 27.5 GeV are collided with 920 GeV protons providing a center of mass energy $\sqrt{s}$ of 318 GeV. In the following we present recent heavy flavour results obtained by the H1 and ZEUS experiments with an integrated luminosity of about 110 pb^{-1} accumulated from 1997 to 2000 during the HERA-I data taking period.

2. Charm production

2.1. Fragmentation ratios and fractions

At HERA the inclusive production cross sections of the weakly decaying charm ground states D^0, $D^\pm$, $D_s^\pm$, $\Lambda_c^\pm$ baryons and charmed vector meson $D^{*\pm}$ have been measured in the γp and in DIS regimes [9, 10].

The $R_{u/d} = c\bar{u}/c\bar{d}$ ratio measures the rate of neutral to charged D mesons production. A value close to unity is expected in a simple picture of the QCD vacuum due to the small bare u and d quark masses compared to their dressed masses. The measurements of $R_{u/d}$ in γp, DIS, and e^+e^- data are shown in Fig. 1(a). They are all in good agreement with this naive expectation. A weighted average value $R_{u/d} = 1.011 \pm 0.047$ is obtained.

$D_s^\pm$ mesons are expected to be less frequently produced than D^0 and $D^\pm$ mesons due to the higher bare s quark mass. This is quantified by the strangeness suppression factor $\gamma_s = 2c\bar{s}/(c\bar{u} + c\bar{d})$ for which the results are summarized in Fig. 1(b). Irrespectively of the hard subprocess of charm quark production, a significant strangeness suppression of $\sim 1/4$ is observed, which averages to $\gamma_s = 0.266 \pm 0.018$.

[1] AROMA and CASCADE only simulate the direct photon contribution, while CASCADE implicitly contains some contributions from resolved photon processes.

[2] In contrast to the DGLAP evolution model, CCFM requires no ordering of the transverse gluon momentum k_{T} along the gluon ladder. This leads to k_{T} dependent gluon density and hard scattering matrix elements.

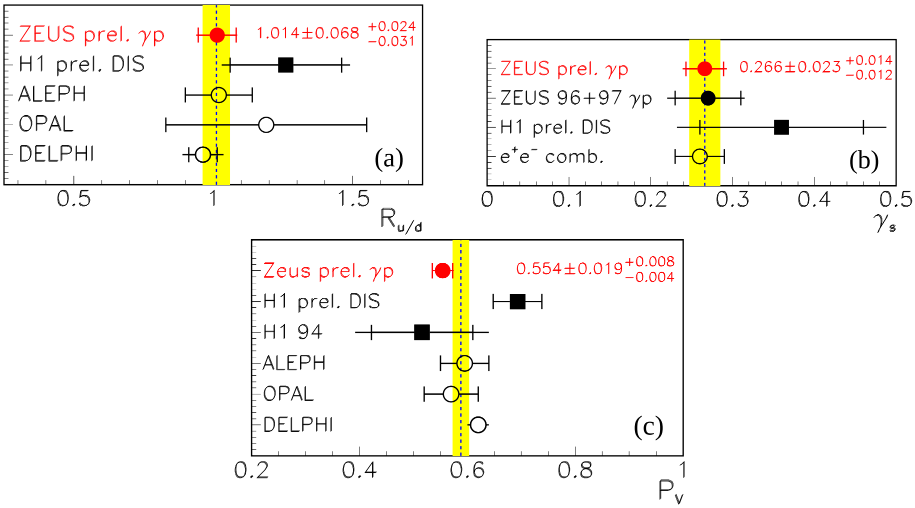

Fig. 1. Neutral to charged D meson production ratio $R_{u/d}$ (a), strangeness suppression factor γ_s (b), and vector D meson production fraction P_V (c) measured in ep collisions in comparison with the e^+e^- results from LEP.

The ratio $P_V = V/(V + P)$ of the fraction of D mesons produced in a vector state is given in Fig. 1(c). From naive spin counting a value $P_V = 3/4$ is expected, while the thermodynamic and string fragmentation approaches [11] both predict 2/3. Independent of the production mechanism the experiments yield consistent results, which are averaged to $P_V = 0.588 \pm 0.014$, significantly below the expectations.

Finally the cross section measurements can be converted to fractions of c quarks hadronizing into particular charmed hadrons, $f(c \to D, \Lambda_c)$ [3]. Fig. 2(a) summarizes the branching fractions measured in γp, DIS, and e^+e^- data [12, 13]. The good agreement observed shows that the QCD vacuum seen during the hadronization of charm quarks is independent of their production mechanism. In this sense charm fragmentation appears universal.

2.2. Differential D^* cross sections

Differential D^* cross sections in γp are measured and compared to the three different schemes of the NLO calculations. The $p_{\rm T}(D^*)$ differential cross section obtained by H1 is presented in Fig. 2(b) [14]. The massive NLO calculations are below the data especially at low $p_{\rm T}(D^*)$, while the

[3] Currently there is no measurement at HERA of the strange-charmed baryons $\Xi_c^{\pm}$, Ξ_c^0 and Ω_c^0, as their contributions are small due to the strangeness suppression.

massless calculations give a reasonable agreement. To investigate the photon structure ZEUS has studied D^* mesons associated with two jets [15] and separated the direct and resolved photon contributions. While NLO DGLAP prediction and CASCADE reproduce well the direct contribution, they cannot reproduce the resolved contribution which is found to be significant in the data ($\sim 40\%$).

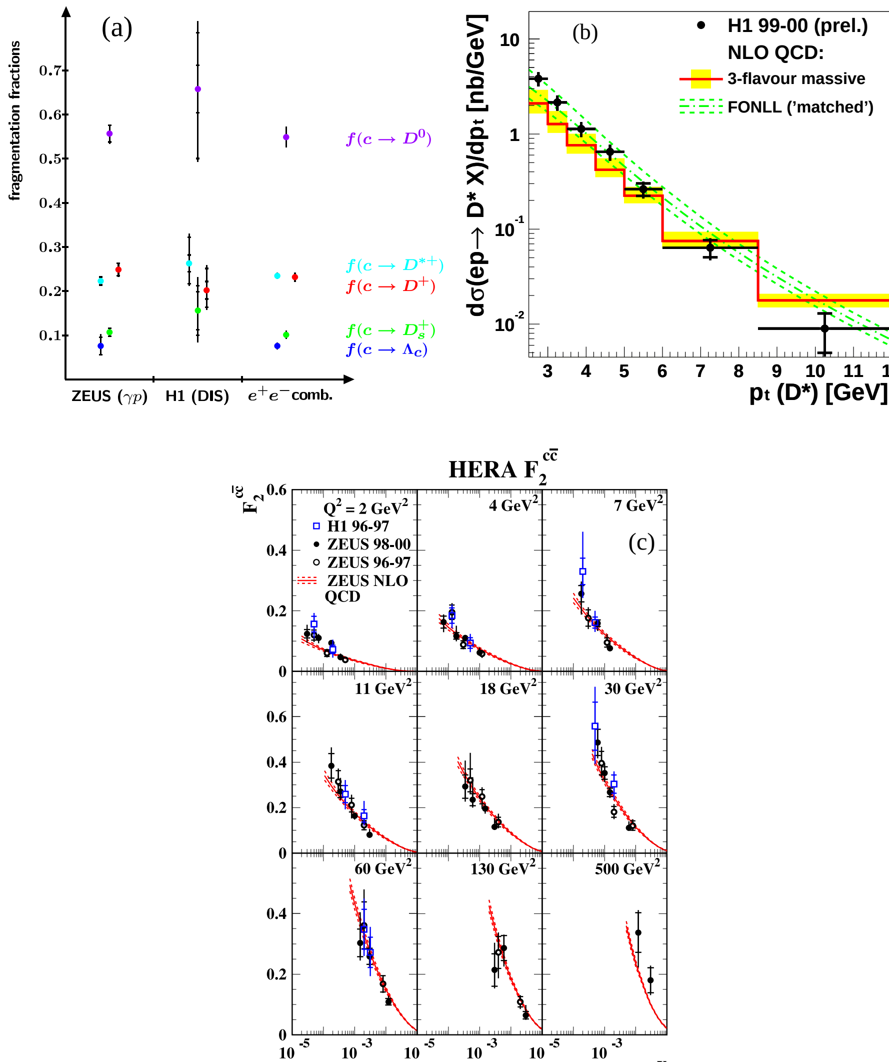

Fig. 2. (a) Fragmentation ratios in γp, DIS and e^+e^- collisions. (b) Differential D^* cross sections in γp measured by H1 as a function of the transverse momentum $p_{\mathrm{T}}(D^*)$. (c) Charm contribution F_2^c to the structure function F_2 compared to a NLO QCD fit.

Differential D^* cross section in DIS have been measured by H1 and ZEUS [16, 17]. The data of the two experiments are consistent, even if small differences of the theoretical interpretation appear. From these measurements has been extracted the charm contribution F_c^2 to the structure function F_2 of the proton (*cf.* Fig. 2(c)). A good agreement between ZEUS, H1, and a NLO QCD fit is obtained over a wide range of x and Q^2 values, meaning that the prediction of the charm contribution to F_2 from scaling violations is consistent with the F_2^c measurement. The strong rise of F_c^2 observed at low x and high Q^2 is driven by the gluon density in the proton.

3. Beauty production

The total $b\bar{b}$ cross section at HERA is about two orders of magnitude smaller than the $c\bar{c}$ cross section. Nevertheless the theoretical prediction should be more reliable for beauty due to the large scale m_b involved in the calculations. The b quarks are experimentally tagged using the semileptonic decays of beauty hadrons into muons or the impact parameter technique.

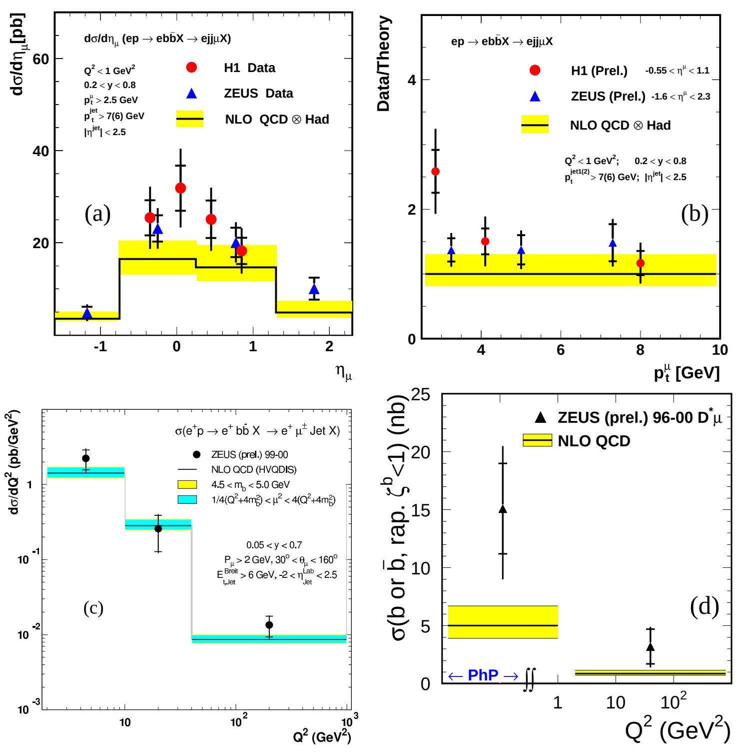

Fig. 3. Visible cross section $\sigma(ep \to eb\bar{b}X \to e\mu jjX)$ measured in γp (a), (b) and in DIS (c). Comparison between ZEUS b or $\bar{b}$ cross section and NLO QCD prediction (d).

Measurements have been performed in γp and DIS [18–20]. Fig. 3(a),(b) show the pseudorapidity and transverse momentum of the muon from semileptonic decays of beauty hadrons in photoproduction. The results from both experiments are consistent. All data points are above the NLO QCD prediction, but in agreement within errors. At low muon transverse momentum the H1 data are above the expectation; this effect is not observed by ZEUS. In DIS, the Q^2 differential cross section measured by ZEUS (*cf.* Fig. 3(c)) is reproduced by NLO QCD within the errors.

If in addition to a semileptonically tagged b quark, a D^* is reconstructed, it is possible to separate charm and beauty via the charge and angle correlations between these two particles [21]. In Fig. 3(d) [22] a comparison between the ZEUS b or $\bar{b}$ cross section and the NLO QCD prediction is presented. The data points are above the NLO QCD calculations but the experimental errors obtained from the HERA-I statistics are still large.

4. Conclusions

Open charm production at HERA has been extensively studied. The LO and NLO QCD calculations provide an overall good description of the data, even if some observed aspects are still not reproduced.

New differential beauty measurements have been shown both in photoproduction and DIS. These new results are quite close to the NLO QCD prediction, but still too high.

Both H1 and ZEUS experiments are in the process of finalizing their analyses using the full HERA-I dataset, while the new HERA-II data taking period with a polarized electron beam is currently ongoing. The new silicon vertex detectors, forward trackers and triggering systems of the upgraded HERA-II experiments will let to investigate larger phase space, especially in the forward region. With the aim of accumulating by the end of 2006 an integrated luminosity as close as possible to the design value of 1 fb^{-1} per experiment, new measurements such as double b quark tagging and F_2^b will become possible.

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