CHARM PRODUCTION IN DEEP INELASTIC SCATTERING AND DIFFRACTION AT HERA

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$D^{*\pm}$ production in deep inelastic scattering at HERA has been measured by H1 and ZEUS using 19 pb^{-1} of e^+p data. Total and differential cross sections are compared to QCD calculations. A first measurement of semi-leptonically decaying charm at HERA is presented. ZEUS has preliminary results on $D^{*\pm}$ production in 16.7 pb^{-1} of e^-p data and 65.2 pb^{-1} of e^+p data. Charm production in diffractive ep scattering has been observed and results are compared to models of diffractive interactions.

1 Introduction

The importance of charm production in deep inelastic scattering (DIS) is based on its sensitivity to the gluon content of the proton. Charm production can be calculated in QCD using gluon densities derived from the scaling violations of inclusive DIS. The comparison with measured charm cross sections provides an important test for perturbative QCD.

Close to threshold, where the bulk of the charm at HERA is produced, the generation of massive quarks in the boson-gluon-fusion (BGF) process is the appropriate framework for QCD calculations. Well above threshold, a transition should occur to a regime where the mass can be neglected and charm should be included in the parton densities. The sensitivity to the gluon in the proton is obvious in the leading order BGF graph, where a virtual photon radiated from the incoming lepton interacts with a gluon from the proton to form a $c\bar{c}$ pair.

Two calculations in this scheme will be compared to the data. The HVQDIS[1] program implements next-to-leading order (NLO) matrix elements and DGLAP evolution of the parton densities. It can calculate differential cross sections applying relevant experimental cuts. The CASCADE[2] program on the other hand is a Monte Carlo generator based on k_t factorization with leading order matrix elements involving off-shell gluons and CCFM evolution of the un-integrated gluon density. The CCFM evolution includes coherence effects of the gluon emission and is expected to give a better description at very low x.

Major sources of uncertainties in both calculations are the value of the charm quark mass and the hadronization of the charm quarks into the experimentally observable mesons. The hadronization is modeled with the Peterson fragmentation function with parameter ϵ_c. Additional p_t smearing of the meson relative to the quark is applied in HVQDIS. The full hadronic final state is modeled with Lund string fragmentation in CASCADE.

HERA in its present configuration collides 27.5 GeV positrons (or electrons) with 920 GeV protons. However, most of the data presented here was taken before 1998 with a proton beam energy of 820 GeV. As usual, the event kinematics is described using the four-momentum transfer squared $Q^2 = -q^2$, the Bjorken scaling variable $x = Q^2/2p \cdot q$ and the inelasticity $y = p \cdot q/p \cdot \ell$, where p, ℓ and q are the four-momentum of the proton, the incident positron and the virtual photon, respectively. The DIS regime is characterized by large momentum transfers, $Q^2 > 1$ GeV^2, resulting in a scattered positron inside the acceptance of the detector.

2 $D^{*\pm}$ production in DIS

H1 has recently finalized the measurement of $D^{*\pm}$ production using 18.6 pb^{-1} of data taken in 1996-1997[3]. DIS events are selected in the kinematic range 1 GeV$^2 < \mathrm{Q}^2 < 100$ GeV^2 and $0.05 < y < 0.7$, extending the range of previous H1 measurements to lower Q^2.

$D^{*\pm}$ mesons are reconstructed through the well-known decay chain $D^{*+} \to D^0\pi^+_{slow} \to K^-\pi^+\pi_{slow}$ and its charge conjugate. A signal of 973 ± 40 $D^{*\pm}$ mesons is obtained in the visible region $p_t(D^{*\pm}) > 1.5$ GeV and $\eta(D^{*\pm}) < 1.5$. This translates into a visible cross section of

$$8.50 \pm 0.42(stat.)^{+1.02}_{-0.76}(syst.) \pm 0.65(model) \text{ nb}.$$

The dependence of the calculated acceptance on model parameters of the Monte Carlo calculation, the charm quark mass and fragmentation, is quoted as a separate systematic uncertainty.

NLO DGLAP predictions with HVQDIS using GRV98-HO parton densities range from 5.17 nb to 7.02 nb depending on the value of the charm quark mass and the fragmentation parameter ϵ_c. This range is obtained by going from a charm quark mass $m_c = 1.5$ GeV and soft fragmentation, $\epsilon_c = 0.10$, to a lower mass and harder fragmentation, $m_c = 1.3$ GeV$, \epsilon_c = 0.035$, covering the uncertainties in these parameters.

The CASCADE program yields higher predictions ranging from 8.05 nb to 10.77 nb, using an un-integrated gluon density obtained from a fit to H1 inclusive DIS data.

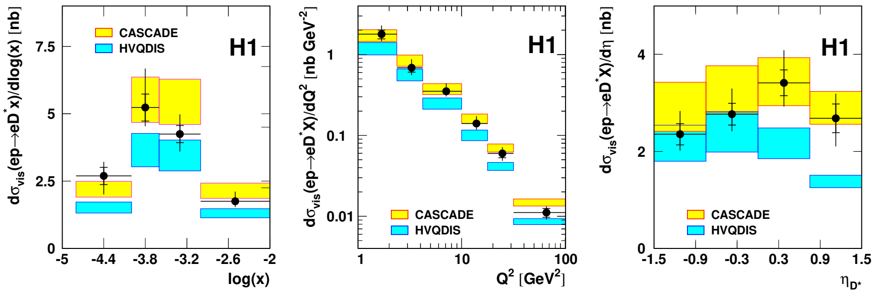

Figure 1. Differential $D^{*\pm}$ cross section from H1 vs x, Q^2 and η. The data are shown as points with error bars. The inner error bar is statistical only. Two QCD calculations are shown as shaded bands. The size of the bands represents the uncertainties due to m_c and fragmentation.

The previously published ZEUS result[4], measured in a similar kinematic region, $1 < Q^2 < 600$ GeV$^2, 0.02 < \mathrm{y} < 0.7$, and visible range, is

$$\sigma_{vis} = 8.31 \pm 0.31(stat.)^{+0.30}_{-0.50}(syst.) \text{ nb.}$$

The H1 measurement is in good agreement with this value.

The shapes of the differential distributions of x and Q^2 are well described by both calculations (fig.1). The largest discrepancy between data and the NLO DGLAP calculation is observed in the region of positive pseudorapidities, $\eta(D^{*\pm})$, where CASCADE gives a better description of the data. Double differential cross sections show that the forward excess over the NLO DGLAP calculation occurs at lowest $p_t(D^{*\pm})$ and at all values of Q^2. It has been verified that the difference between CASCADE and HVQDIS cannot be ascribed to the different treatment of hadronization.

Preliminary results are available from ZEUS using 16.7 pb^{-1} of e^-p data taken during the 1998-1999 running and 65.2 pb^{-1} of e^+p data taken 1999-2000. The higher beam energy is expected to increase the charm cross section by 5%. In the kinematic range $1 < Q^2 < 1000$ GeV^2 and $0.02 < y < 0.8$, the preliminary visible cross sections results are[5]

$$\sigma_{vis}(e^-p \to e^-D^{*\pm}X) = 10.20 \pm 0.48(\text{stat.})^{+0.34}_{-0.54}(\text{syst}) \text{ nb}$$
$$\sigma_{vis}(e^+p \to e^+D^{*\pm}X) = 8.94 \pm 0.24(\text{stat.})^{+0.27}_{-0.51}(\text{syst}) \text{ nb.}$$

No dependence on the lepton charge is expected from the BGF mechanism. The two measured cross sections differ at about the 2σ level. No detector effect was found that would account for the observed difference. However,

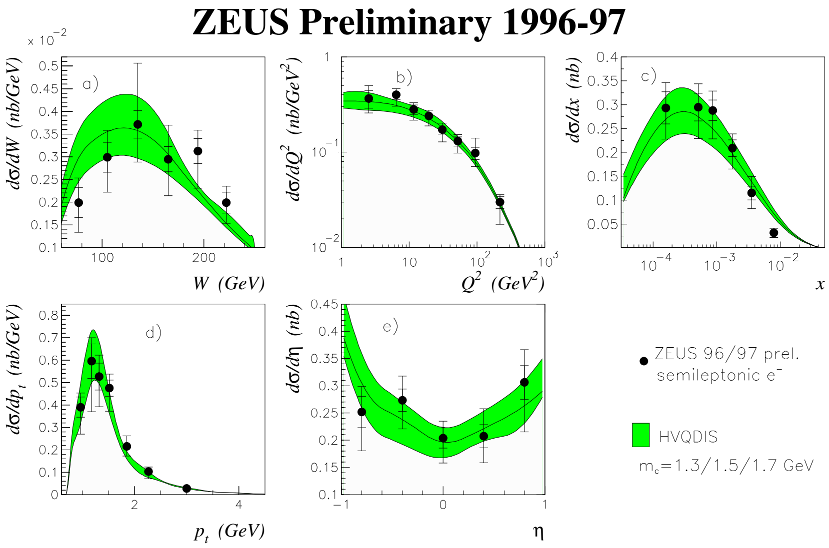

Figure 2. Kinematic properties of events in the semi-leptonic sample. The top row shows distributions of the hadronic energy, Q^2 and Bjorken x, the bottom row shows transverse momentum and pseudorapidity of the electrons. Non-charm background is subtracted. The bands show the result of NLO calculations obtained with GRV94-HO parton densities and charm quark masses between 1.3 and 1.7 GeV.

for both $e^{\pm}p$ interactions, the differential cross sections in x and Q^2 fall into the band of the NLO-DGLAP predictions obtained with different parton densities and values of m_c. The ratio e^-p over e^+p cross section is largest at high values of x, in the forward direction and for $Q^2 > 20$ GeV^2.

3 Semi-leptonic charm decays in DIS

Measurements of charm production at HERA have so far used fully reconstructed mesons. While this allows clean charm tags, it suffers from the small branching fractions. Due to the large branching fraction of semi-leptonic decays, leptons are an attractive signature for heavy quark production. For the first time at HERA, ZEUS has measured charm production using identified decay electrons. The advantage of the larger branching ratio is to some extent diminished by the strict cuts required to select a clean electron sample.

Electrons are selected based on their energy deposition in the electromagnetic calorimeter and the specific energy loss measured in the central tracker.

Reconstructed γ conversions are rejected. The kinematic properties of the selected events are shown in figure 2 after subtraction of residual contributions from hadrons and electrons from unreconstructed γ conversion, Dalitz decays and bottom decays. The remaining distributions agree within errors with NLO DGLAP calculations.

4 $D^{*\pm}$ production in diffraction

Through its sensitivity to gluons, charm production can contribute to the understanding of diffraction. About 10% of the ep events occurring at HERA are diffractive, with no color flowing between the proton and the virtual photon. The signature is a large rapidity gap between the (quasi-) elastically scattered proton, and the recoiling hadronic system seen in the detector.

In the resolved Pomeron model, diffractive events are interpreted as the scattering of the virtual photon on a colorless particle with partonic structure, the Pomeron ($I\!P$), emitted by the proton. This model successfully describes inclusive diffractive scattering where the quark densities of the Pomeron have been extracted. Charm production, like diffractive dijet data, probes the gluon content of the resolved Pomeron, which is almost unconstrained by inclusive diffractive DIS. Other models of diffractive interactions involve the perturbative exchange of a pair of gluons or color neutralization by soft interactions.

H1 has measured $D^{*\pm}$ production in diffractive DIS using 19.1 pb^{-1} collected in 1996-1997 [8]. Diffractive events are selected by requiring no hadronic activity between $\eta_{max} = 3.3$ and the end of the detector acceptance at $\eta = 7.5$. A $D^{*\pm}$ signal of 46 ± 10 events is found in the kinematic range $2 < Q^2 < 100$ GeV^2, $0.05 < \mathrm{y} < 0.7$ and the visible region $p_t(D^{*\pm}) > 2$ GeV, $|\eta(\mathrm{D}^{*\pm})| < 1.5$. This translates into a cross section of

$$\sigma(ep \to e(D^* X')Y) = 246 \pm 54(stat.) \pm 56(syst.) \text{ pb}.$$

The predictions of the resolved Pomeron model lie a factor 1.5–2 above this value for parton densities that are compatible with the diffractive inclusive and dijet data. The model overshoots the data at low values of $x_{I\!P}$, where $x_{I\!P}$ is the momentum fraction of the proton carried by the Pomeron.

An earlier measurement[9] by the ZEUS collaboration finds a preliminary cross section

$$\sigma(ep \to e(D^* X')Y) = 281 \pm 41(stat.)^{+79}_{-73}(syst.) \text{ pb}$$

in the region $4 < Q^2 < 400$ GeV^2, $0.02 < \mathrm{y} < 0.7, 1.5 < \mathrm{p_t(D^{*\pm})} < 8$ GeV, $|\eta(\mathrm{D}^{*\pm})| < 1.5, \mathrm{x_{I\!P}} < 0.016$ and $\beta < 0.8$. Because of the differences in the kinematic region, the experimental results cannot be compared directly.

However, when compared to the resolved Pomeron model using the same Pomeron structure input, the data to theory ratios agree within errors.

Both experiments find that 6% of the total $D^{*\pm}$ production in the given regions of $Q^2, y, p_t(D^{*\pm})$ and $\eta(D^{*\pm})$ is diffractive.

5 Conclusions

$D^{*\pm}$ production in DIS at HERA has been measured with improved precision in a large kinematic range. The experimental results of H1 and ZEUS are consistent and are reasonably well described by the NLO DGLAP calculation. H1 observes a deviation from this calculation in the forward region at very low transverse momenta. The CASCADE program using the CCFM evolution is in good agreement with the H1 data. Preliminary results of a first measurement using electrons to tag semi-leptonic decays of charm from ZEUS are consistent with the $D^{*\pm}$ results. Preliminary $D^{*\pm}$ results from the much larger 1999/2000 dataset were obtained by ZEUS and are in agreement with the NLO-DGLAP expectation. However, the cross section in deep inelastic e^-p scattering shows an unexpected small excess over the e^+p cross section.

Charm production in diffractive scattering can provide additional insight into the nature of the diffractive exchange. It is found to account for 6% of the total charm production in DIS. The measured cross sections are lower than those predicted by the resolved Pomeron model. The data analyzed so far are limited in statistics and cannot discriminate between different models of diffraction.

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