Charm production at HERA

Paolo Bellan, on behalf of the ZEUS Collaboration
Padova University and INFN, via Marzolo 8, Padova, Italy.
E-mail: paolo.bellan@pd.infn.it

Abstract. Some recent results on charm physics obtained by the ZEUS experiment at HERA are reviewed. \(D\)-meson cross-section measurements are shown in the deep inelastic scattering (DIS) regime, in photoproduction \((\gamma p)\) and in the intermediate region. Measurements of charm fragmentation ratios and fractions, and analysis of charmed and charmed-strange mesons are also presented.

1. Introduction
Several reasons make heavy quark production very interesting, and in this context charm physics plays a central role, e.g. to test QCD, to measure the charm contribution to the proton structure function \(F_2\) or to provide information on quark production and fragmentation.

The ZEUS Collaboration is extensively studying these topics at the HERA electron-proton collider. At HERA, charm production in DIS proceeds mainly via boson-gluon fusion (BGF), which is directly sensitive to the gluon content of the proton. For lower photon virtualities, also resolved photon processes become important, including charm excitation, in which charm is extracted directly from the photon. Charm quarks are tagged via the reconstruction of different charmed mesons.

2. Charmed mesons at HERA

2.1. \(D^0, D^\pm, D_s^\pm\) in DIS

The differential cross sections as a function of \(Q^2, x, p_T(D),\) and \(\eta(D)\) have been measured\(^1\) using 82 pb\(^{-1}\) of 1998-2000 data, in the kinematic range \(1.5 < Q^2 < 1000\) GeV\(^2\), \(0.02 < y < 0.7, p_T(D) > 3\) GeV and \(|\eta(D)| < 1.6,\) reconstructing the decay channels \(D^0 \rightarrow K^-\pi^+, D^+ \rightarrow K^-\pi^+\pi^+\) and \(D_s^+ \rightarrow \phi\pi^+\) (+ c.c.).

The measurements are compared with the theoretical predictions from the HVQDIS program\(^1\); the overall agreement between the data and the NLO predictions is good. The differential cross sections have been used to extract charm fragmentation ratios and fractions\(^2\) (Fig. 1).

The measured ratio of neutral to charged \(D\) meson production rates, \(R_{u/d}\), agrees with unity, as expected from the isospin invariance. The strangeness suppression factor has been measured to be around 26%. The fraction of charged \(D\) mesons produced in a vector state, \(P_V\), has been extracted using the measured cross sections; the measured value, 0.566 ± 0.025\(^3\) is as expected

1 a next-to-leading order (NLO) calculation for the \(c\bar{c}\) production based on the BGF mechanism; a ZEUS NLO fit to \(F_2\) is used for the proton PDF.
2 and to extract \(F_2^c\) [3].
3 only statistical contribution quoted here; the systematic one is smaller. The largest contribution comes from the branching ratios.
below the naïve spin-counting prediction.

The fragmentation fractions have also been measured for each analysed channel. These, as well as the other aforementioned measurements, are consistent with those obtained in charm photoproduction, in DIS by the H1 Collaboration, and in $e^+e^-$ annihilations, supporting the hypothesis that the fragmentation processes is independent on the hard subprocess.

The $D^+$ and $D^0$ cross sections have been measured also using the HERA II data. The $D^*$ mesons have been studied also in $\gamma p$, i.e. at $Q^2 \approx 0$, reconstructing the decay channel $D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+ (+c.c.)$ [2]; in this context an extensive study on the fragmentation process for the charm quark has been performed, testing different models of fragmentation functions by comparing their predictions to the data.

![Figure 1](image-url)  
*Figure 1.* (a) Ratio of neutral to charged $D$ meson production rates, $R_{ud}$, strangeness-suppression factor in charm fragmentation, $\gamma_s$, and fraction of charged $D$ mesons produced in a vector state, $P_d^V$, (a). (b) Fractions of $c$ quarks hadronising as $D^+$, $D^0$ and $D^+$ charm ground-state mesons. The inner error bars show the statistical uncertainties, the outer bars are the statistical and systematic uncertainties added in quadrature. The ZEUS measurements are shown together with the H1 and the $e^+e^-$ results.

2.2. Extending the $Q^2$ range down to lower values

A particular component of the ZEUS detector suite, the Beam Pipe Calorimeter\(^4\), enables charm production to be measured in the transition region, $0.05 < Q^2 < 0.7$ GeV\(^2\), between $\gamma p$ and DIS. The ZEUS Collaboration performed the measurement of $D^*$ production in the region $0.05 < Q^2 < 0.7$ GeV\(^2\) [4], i.e. a region of transition between the DIS and the photoproduction regime. The measured differential cross sections have been compared with the NLO QCD calculations implemented with two different programs: FMNR, designed to describe $\gamma p$ processes, and HVQDIS, suitable for DIS events. Agreement is found with both predictions.

Converting the $D^*$ cross-section into the $\gamma p$ cross-section, it is possible to show the measurements for processes at low, intermediate and high $Q^2$ values in a single plot, as in Fig. 2. The ZEUS data, spreading over five orders of magnitude in $Q^2$, have been fitted with a function where the

\(^4\) this small tungsten scintillator calorimeter is located very close to the beam pipe, in order to detect leptons scattered at very low angles.
Figure 2. The $\gamma p$ cross section for $D^*$ production as a function of $Q^2$ is shown here for a wide range in $Q^2$: measurement performed in the DIS regime (open circles), in $\gamma p$ (open square) and in the intermediate region at $0.05 < Q^2 < 0.7 \text{ GeV}^2$ (filled circles) are collected here. The inner error bars are the statistical errors, the outer error bars are the statistical and systematic uncertainties added in quadrature. The photoproduction point is drawn at $Q^2=0.003$ for convenience. The curve fitting the data is described in the text.

free parameters are the $\gamma p$ cross section and the energy value in which the transition between the $\gamma p$ and the DIS behaviour takes place. The latter has been found to be around $4m_c^2$, significantly higher than in the inclusive measurements.

3. Excited charmed and strange-charmed $D$ mesons.

New members of the $D$ meson family have recently enlarged the heavy quark mesons spectroscopy. The production of excited charmed and strange-charmed $D$ mesons in $ep$ collisions is significant and hence measurements can be made by ZEUS. Yields, masses and charm fragmentation fractions have been measured for the orbital excited $D^0_0$, $D^0_2$ and $D^+_s1$ mesons; the resulting mass values are in fair agreement with the world average. The spin-parity quantity $J^P$ of the mesons has been also measured. For the $D^0_0$, the results are compatible with the Heavy Quark Eectiv Theory predictions; for $J^P(D^+_s1)$ the outcome is compatible with $1^-, 2^+$ and with the result of the Belle Collaboration [5], whereas the PDG06 value is $1^+$.

4. Conclusions

Charm production is intensively studied with the ZEUS experiment at HERA. Cross sections are measured, together with fragmentation functions, and fragmentation models are tested. Rare states are also seen and their properties are measured. Further achievements are expected with the full-statistics analysis and with the better tracking performances of the ZEUS detector available for the HERA II data sample.

References

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