Recent results on charm fragmentation and hadron spectroscopy in $e^+/e^- p$ collisions at HERA with the ZEUS and H1 detectors are presented. The measured fragmentation ratios and fragmentation fractions are in agreement with those measured in $e^+e^-$, thus supporting the assumption of universality. Measurements of the inclusive photoproduction of the neutral mesons $\eta, \rho^0, f_0(980)$ and $f_2(1270)$ are also presented. At the same time results on production of pentaquarks are shown. Cross sections of observed states and upper limits on the production cross section of unobserved states are extracted in order to enable comparison between experiments.

1 Introduction

Understanding the process whereby quarks and gluons convert to colour-less hadrons is one of the outstanding problems in particle physics.

In perturbative QCD (pQCD), the cross section for inclusive production of a heavy hadron $H$ can be expressed as a convolution of two terms:

$$\sigma(p_H) = \sum_{\text{part}} \int dz dp_{\text{part}} \sigma(p_{\text{part}}) D_{H}^{\text{part}}(z) \delta(p_H - zp_{\text{part}}) \tag{1}$$

where $\sigma(p_{\text{part}})$ is the perturbative part of the cross section for the production of the parton and $D_{H}^{\text{part}}(z)$ is the corresponding fragmentation function. The latter contains a non-perturbative, calculable part. The factorisation theorem, if applicable, predicts that $D_{H}^{\text{part}}(z)$ is universal, i.e. both its shape and normalisation are independent of the hard subprocess and the scale at which the parton was produced. This assumption needs to be verified experimentally.

The measurements of the inclusive photoproduction of charmed mesons, baryons and of the neutral mesons $\eta, \rho^0, f_0(980), f_2(1270)$ could also contribute to resolving the problem of the hadronisation.
Recently, some experiments have reported narrow signals in the vicinity of 1530 MeV in the $nK^+$ and $pK^0_S$ invariant mass spectra which are consistent with the exotic pentaquark baryon state $\Theta^+$ with quark content $uudds$, while other experiments have searched for this state with negative results. The possible existence of a charm pentaquark has also been discussed, with renewed theoretical interest in calculating their expected properties following the observation of strange pentaquarks.

## 2 Charm fragmentation

In order to study the probabilities of a heavy quark to hadronise into various heavy hadrons, two types of observables are used. The fragmentation fraction for a given charmed hadron is defined as the ratio of the total production cross section for that given hadron to that for the charm quark. Fragmentation ratios are used to highlight certain aspects of the hadronisation process. Their exact definitions can be found in the references.

The ZEUS collaboration has measured the fragmentation fractions and ratios of $D^+, D^0, D_s^+, D^{*+}$ and $\Lambda_c$ states both in deep-inelastic scattering (DIS) and photoproduction. These states were measured by reconstructing the invariant mass and the number of events was determined, after subtraction of reflections, in a fit to signal and background. The measured cross sections are given for the visible phase space, defined for DIS as $1.5 < Q^2 < 1000 \text{ GeV}^2$, $0.02 < y < 0.7$, $p_t(D,\Lambda) > 3 \text{ GeV}$ and $|\eta(D,\Lambda)| < 1.6$ and for photoproduction as $Q^2 < 1 \text{ GeV}^2$, $130 < W < 300 \text{ GeV}$, $p_t(D,\Lambda) > 3.8 \text{ GeV}$ and $|\eta(D,\Lambda)| < 1.6$. The charm quark production cross section in the visible range, needed to calculate the fragmentation fractions, was calculated from the measured cross sections of $D$’s and $\Lambda_c$.

The H1 collaboration has used a different experimental procedure to measure fragmentation ratios and fractions of $D^+, D^0, D_s^+, D^{*+}$ in DIS, profiting from its central silicon tracker. In order to improve the signal/background ratio, cuts on the secondary vertex parameters were used. The number of visible charmed meson states was then determined from a fit to the invariant mass distribution. The measurement was done in the kinematic region $2 < Q^2 < 100 \text{ GeV}^2$, $0.05 < y < 0.7$, $p_t(D) > 2.5 \text{ GeV}$ and $|\eta(D)| < 1.5$. A QCD-based model was used to extrapolate the measured cross sections to the full phase space and to predict the total cross section.

*Together with their charge conjugate states
charm quark cross section. The fragmentation ratios were then calculated from the measured fragmentation fractions.

The results of H1 and ZEUS (see Fig. 1(left)), although obtained with different experimental procedures, are compatible with each other and with the results from \( e^+e^- \) experiments (with comparative errors) and thus support the assumption of universality.

### 3 Light Mesons \((\eta, \rho^0, f_0(980), f_2(1270))\) Photoproduction

Besides charmed states and production of well-known hadrons such as \( \pi, K^0_S, \Lambda \), protons, and charmed mesons, \( J/\psi \), etc. that have been measured by ZEUS and H1; a recent result is the cross section measurement of inclusive photoproduction of \( \eta, \rho^0, f_0(980) \) and \( f_2(1270) \) mesons at H1 in the central rapidity region. In this analysis a photoproduction data sample taken in the year 2000, corresponding to an average energy of the photon proton centre of mass \( \sqrt{s_{\gamma p}} = 210 \text{ GeV} \), was used. The \( \rho^0, f_0(980) \) and \( f_2(1270) \) mesons were reconstructed through \( \pi^+\pi^- \) decay, the \( \eta \) meson through \( \gamma\gamma \) decay.

In Fig. 1(right), the measured differential cross section \( 1/(2j+1)d^2\sigma/dydp_T \) of the resonances as function of \( m + p_T \), where \( j \) is the spin and \( m \) is the mass of the measured particle, was compared with the cross section of charged pions. The resonances have a similar behaviour as observed for long-lived hadrons [4].

### 4 Pentaquarks

A strange pentaquark \( \Theta^+ \) candidate was seen by the ZEUS collaboration. In this analysis deep inelastic scattering (DIS) events were selected by requiring an exchanged photon virtuality \( Q^2 > 1 \text{ GeV}^2 \). The \( \Theta^+ \) was reconstructed in the decay channel \( pK^0_S \). The invariant mass spectrum of proton and \( K^0 \) for events where \( Q^2 > 20 \text{ GeV}^2 \) was fitted with a polynomial background and two Gaussians. The signal peak (see Fig. 4(left)) is observed with a mass of \( 1521.5 \pm 1.5^{+2.8}_{-1.7} \text{ MeV} \) and a width \( 6.1 \pm 1.6^{+2.0}_{-1.4} \text{ MeV} \) consistent with the detector resolution.

The invariant-mass spectrum was investigated for the \( pK^0_S \) and \( \bar{p}K^0_S \) separately. The measured
Invariant mass spectrum for the $K_{S}^{0}p(\bar{p})$ channel for $Q^{2} > 20 \text{ GeV}^2$ (left). $M(D^*p)$ distribution from opposite charge $D^*p$ combinations in DIS. (right).

total cross section for the $\Theta^+$ in the kinematic range $Q^{2} > 20 \text{ GeV}^2$, $p_T > 0.5 \text{ GeV}$, $|\eta| < 1.5$ and $0.04 < y_e < 0.95$ is $125 \pm 27_{-28}^{+37}$ pb.

A similar analysis was done by the H1 collaboration and no peak is visible near 1520 MeV. The resulting upper limit on the $\Theta^+$ production cross section was found to be within 40 and 120 pb over the mass range of 1.48 to 1.7 GeV and does not exclude the previously measured cross section at ZEUS.

A search for a double strange pentaquark $\Xi_{-3/2}$ as found by the NA49 collaboration has been carried by the ZEUS collaboration and given a negative result (see Fig. 2).

A search for a charm pentaquark $\Theta_c$ candidate was carried out by H1 using DIS data. The $\Theta_c$ was reconstructed via its decay to $D^*p$, where $D^* \to D^0\pi \to K\pi\pi$. A clear and narrow resonance (see Fig. 3(right)) is observed for both $D^*-p$ and $D^{*+}\bar{p}$ with a mass of $3099 \pm 3 \pm 5$ MeV with a width compatible with the experimental resolution. An acceptance corrected ratio, the fraction of $D^*$ coming from the decay of the $\Theta_c$ candidate, $R_{\text{corr}}(D^*p(3100))/D^* = 1.59 \pm 0.33^{+0.33}_{-0.45}$. A similar analysis was done by ZEUS using higher statistics and reconstructing $D^*$ mesons both in the $K\pi\pi$ and $K\pi\pi\pi\pi$ channels. No signal near 3100 MeV is observed. ZEUS estimated the upper limit on the acceptance corrected ratio and it is equal 0.59% (0.51% for both $D^*$ decay channels) in DIS that would contradict the measurement of H1.

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