HADRON SPECTROSCOPY AND HEAVY FLAVOUR PRODUCTION AT HERA

Boscherini Davide
INFN - Bologna
on behalf of the H1 and ZEUS Collaborations

Abstract

Studies of charm and beauty production in *ep* collisions with a center-of-mass energy of 318 GeV are reported from the two HERA collaborations, H1 and ZEUS. The results are from data collected during the HERA phase I and are compared to the available next-to-leading order QCD calculations. Results on the search for pentaquark states are also shown for the same data taking period.

1 Heavy Flavour Production

The study of heavy flavour processes in *ep* collisions at HERA is a powerful tool for exploring the dynamics of the strong interactions described by the Quantum Chromodynamics (QCD) and for testing the proton structure function.

The production of heavy quarks in *ep* collisions at HERA mainly occurs via the process of boson-gluon fusion. The kinematic region covers photoproduction, in which the exchanged photon is quasi-real ($Q^2 \sim 0$), to the region of deep inelastic scattering (DIS), with photon virtualities much larger than the $c-$ or $b-$quark mass. The large value of the heavy quark mass provides a scale for perturbative calculations which are therefore expected to give reliable results. Two schemes are available for next-to-leading order (NLO) QCD calculations:

- *massive scheme* [1], where u, d and s are the only active flavours in the proton and the photon, and charm and beauty are produced dynamically in the hard scattering
- *massless scheme* [2] where charm and beauty are treated as active flavours in both the proton and the photon, in addition to u, d and s. In this scheme, so-called *excitation processes* occur in which the beauty quark is a constituent of the resolved photon or of the proton.

The former scheme is expected to give better results for transverse momenta of the b-quark of the order of its own mass, while the latter is more reliable for larger transverse momenta.

1.1 Inclusive Production of D^+, D^0, D_s^+ and D^{*+} Mesons in DIS

The production of charm quarks is expected to be well described by perturbative QCD (pQCD) calculations due to the hard scale provided by the charm mass. However, the hadronization of a charm quark into a cluster of hadrons involves non-perturbative processes. Therefore, a theoretical description of the production of charmed hadrons contains a phenomenological, non-perturbative part, which is expected to be process independent.

The visible cross sections of D^+, D^0, D_s^+ and D^{*+} have been measured by H1 [3] making use of the following decay channels: $D^+ \to K^-\pi^+\pi^+$, $D^0 \to K^-\pi^+$, $D_s^+ \to \phi\pi^+ \to (K^+K^-)\pi^+$ and $D^{*+}(2010) \to D^0\pi^+ \to (K^-\pi^+)\pi^+$. The relatively large life time of the weakly-decaying $D-$mesons makes it possible to reconstruct the displacement of their decay point with respect to the primary vertex, using the central silicon tracker and to apply selection cuts on the reconstructed secondary vertices. The number of signal events is determined for each D-meson individually, by fitting the invariant mass distribution with an appropriate background function and a Gaussian to describe the signal.

The measured cross sections are reported in table 1. The comparison with a LO Monte Carlo is quite satisfactory. Preliminary results [4] have been obtained by ZEUS on the same subject and they show a good agreement with NLO QCD predictions.

Cross section [nb]	D^+	D^0	D_s^+	D^{*+}
$\sigma_{vis}(ep \to eDX)$	2.16	6.53	1.67	2.90
Stat. error	± 0.19	± 0.49	± 0.41	± 0.20
Syst. error	$^{+0.46}_{-0.35}$	$^{+1.06}_{-1.30}$	$^{+0.54}_{-0.54}$	$^{+0.58}_{-0.44}$
AROMA LO prediction σ_{vis}	2.45	5.54	1.15	2.61
Prediction uncertainty	± 0.30	± 0.69	± 0.30	± 0.31
Estimated beauty contribution	10%	9%	17%	7%

Table 1: *Inclusive charmed meson electroproduction cross sections for the four meson states in the visible kinematic range, defined by* $2 \leq Q^2 \leq 100\,\mathrm{GeV}^2$, $0.05 \leq y \leq 0.7$, $p_t(D) \geq 2.5\,\mathrm{GeV}$ *and* $|\eta(D)| \leq 1.5$. *Also given are the predictions for D meson production (including the beauty contribution) based on a LO Monte Carlo simulation.*

The fragmentation fractions $f(c \to D)$ are defined as the ratio of the total cross section of a given charmed meson to the one for a charm quark. Using a Monte Carlo model to extrapolate from the visible to the total cross section for the charmed meson, the fragmentation factors shown in fig.1, together with the LEP results, were obtained.

These results agree well with the measurements performed in e^+e^- and thus support the assumption of a universal fragmentation.

1.2 Measurement of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ at High Q^2

Inclusive c and b cross sections have been measured by H1 for $Q^2 > 150 GeV^2$. Events containing heavy quarks can be distinguished from light quark events exploiting the long lifetimes of c and b flavoured hadrons, which lead to displacements of tracks from the primary vertex. The distance of a track to the primary vertex is reconstructed using precise spatial information from the vertex detector. The measurement of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ has been done in a kinematic region where there is little extrapolation needed to correct to the full phase space; therefore the model dependent uncertainty due to the extrapolation is small. In fig.2 the ratios $F_2^{c\bar{c}}/F_2$ and $F_2^{b\bar{b}}/F_2$ are shown. The measurement of $F_2^{b\bar{b}}$ has been performed by H1 for the first time [12]. The contribution of charm to F_2 can be estimated to be around 10-30% in the kinematic region

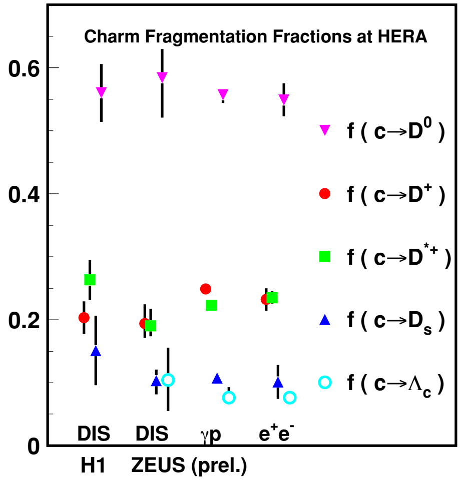

Figure 1: *Fragmentation factors for the different D mesons (and Λ_c). Measurements from H1 and ZEUS are shown together with e^+e^- results.*

considered, while the contribution from beauty is approximately an order of magnitude lower.

1.3 Measurement of Beauty Production Using Events with Muons and Jets

For beauty production, pQCD calculations are expected to give reliable predictions, as the mass of the b quark ($m_b \sim 5$ GeV) provides a hard scale. The first measurements of beauty cross section at HERA [7] were higher than pQCD predictions calculated at next-to-leading order (NLO). Similar observations were made in hadron-hadron collisions [8] and also in two-photon interactions [9].

The cross section for the process $ep \rightarrow eb\bar{b}X \rightarrow ejj\mu X'$ in photoproduction and $ep \rightarrow eb\bar{b}X \rightarrow ej\mu X'$ in deep inelastic scattering have been measured. To discriminate events containing beauty from those with charm or light quarks, H1 [11] has used two distinct features of the B-hadrons simultaneously, for the first time at HERA: the large mass and the long lifetime. The B-hadron mass leads to a broad distribution of the transverse momentum p_t^{rel} of the decay muon relative to the beauty quark jet direction. The B-hadron lifetime is reflected in the large impact parameters $\delta \sim 200\,\mu m$ of the decay muon tracks relative to the primary vertex. Only the first method has been used by ZEUS [10] because of the lack of a precision vertex detector during HERA I. The results obtained by the two experiments are shown in fig.3, together with the NLO predictions in the respective kinematic range of

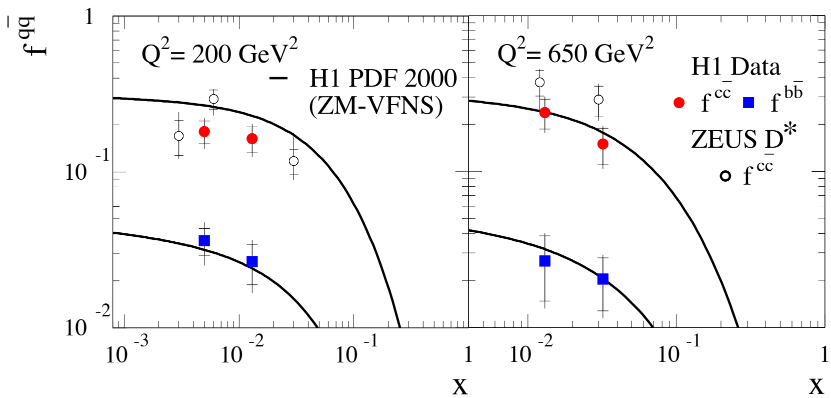

Figure 2: *The contributions to the total cross section $f^{c\bar{c}}$ and $f^{b\bar{b}}$ shown as a function of x for two different Q^2 values. The inner error bars show the statistical error, the outer error bars represent the statistical and systematic errors added in quadrature. The $f^{c\bar{c}}$ from ZEUS obtained from measurements of D^* mesons* [5] *and the prediction of the H1 NLO QCD fit* [6] *are also shown.*

the measurements. The data tends to be above the theory, but the agreement is considerably improved with respect to the previous measurements.

1.4 Summary on Heavy Flavour Production

The results shown on charm DIS cross sections are in good agreement with the NLO QCD predictions. The charm fragmentation factors measured at HERA are compatible with those obtained in e^+e^- collisions. In the beauty sector, the production cross section is in much better agreement with NLO QCD predictions with respect to the previous measurements, but there is still present a tendency for data to be above the theory. The first measurement of $F_2^{b\bar{b}}$ for $Q^2 > 150$ GeV^2 has been performed by H1.

2 Pentaquark Searches

Several experiments have recently reported the observation of a narrow resonance with mass in the region of 1540 MeV, decaying to K^+n or K_s^0p [13]. This state has both baryon number and strangeness +1, such that its minimal composition in the constituent quark model is $uudd\bar{s}$. It has thus been interpreted as a pentaquark, the Θ^+. There is also evidence for two related

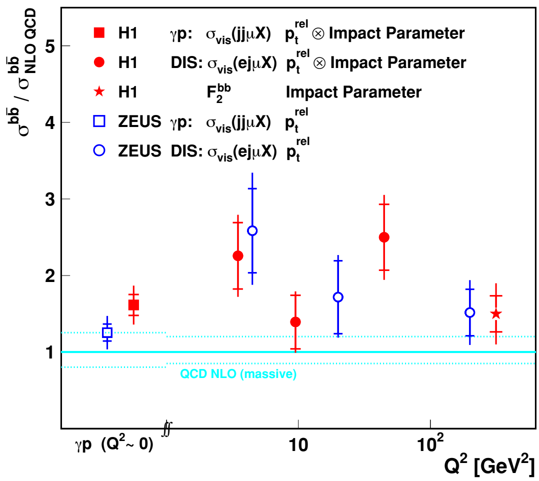

Figure 3: *Cross section ratios (data over theory) as a function of* Q^2 *for the processes* $ep \to eb\bar{b}X \to ejj\mu X'$ *in photoproduction and* $ep \to eb\bar{b}X \to ej\mu X'$ *in DIS, as measured by H1 and ZEUS.*

states with strangeness -2 [16]. Various models have been put forward to explain the nature of these states and the structure of the multiplet that contains them [14]. The possibility of pentaquark states in the charm sector has also been considered [15], following the observation of strange pentaquarks.

2.1 Search for a Narrow Baryonic State Decaying to $K^0_S p$ and $K^0_S \bar{p}$

The luminosity of the data sample used by ZEUS is 121 pb^{-1} [17]. The events are selected in the kinematic range $Q^2 > 1$ GeV^2. K^0_S mesons are reconstructed via the decay mode $K^0_S \to \pi^+\pi^-$. Accepting only K^0_S candidates with transverse momentum $p_t(K^0_S) \geq 0.3$ GeV and pseudorapidity $|\eta(K^0_S)| \leq 1.5$ in the laboratory frame, the number of reconstructed candidates is 866800±1000. Proton (or anti-proton) candidates are selected using the measurement of the ionization loss dE/dx in the central tracker and applying cuts based on the Bethe-Bloch equation. The purity of the proton sample, estimated from MC simulation, is around 60%. The selected K^0_S and proton candidates are combined and the invariant mass is reconstructed fixing the K_S^0 mass to the PDG value. A peak around 1520 MeV in the invariant-mass spectrum is visible for $Q^2 > 20$ GeV^2 as shown in fig.4, while it is less pronounced in different kinematic regions. A Σ bump at 1480 MeV is reported in the PDG, therefore the invariant-mass distribution is fitted with a three-parameter background function and two Gaussians, obtaining a signal peak position of 1521±1.5(stat.) MeV, with a width of 6.1±1.6(stat.)MeV. The fit gives 221±48 events above the background, corresponding to 4.6σ. Fitting with only one Gaussian similar results are obtained.

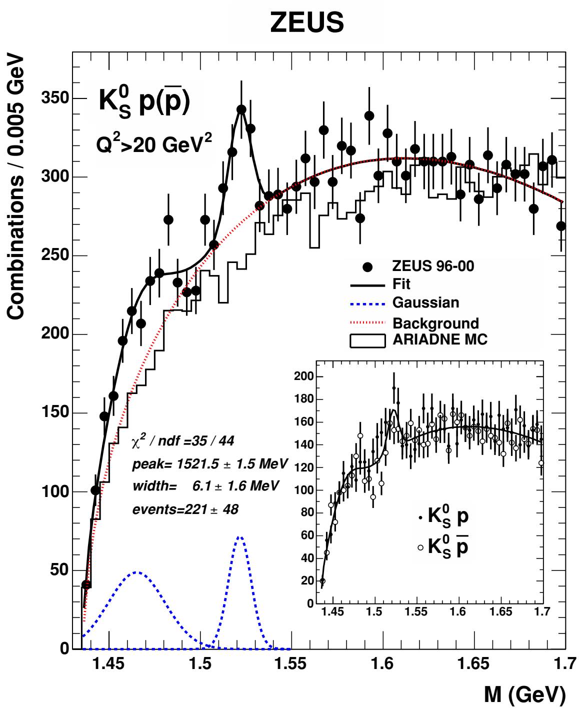

Figure 4: *Invariant-mass spectrum for the $K_S^0 p(\bar{p})$ channel for $Q^2 > 20$ GeV^2, as obtained by ZEUS. The solid line is the result of a fit to the data using a three-parameter background function plus two Gaussians. The dashed line shows the Gaussian components and the dotted line the background according to this fit. The histogram shows the prediction of the ARIADNE MC simulation normalised to the data in the mass region above 1650 MeV. The inset shows the $K_S^0\bar{p}$ (open circles) and the $K_S^0 p$ (black dots) candidates separately, compared to the result of the fit to the combined sample scaled by a factor of 0.5.*

2.2 Search for a Narrow Charmed Baryonic State Decaying to $D^{*+}\bar{p}(D^{*-}p)$

The data analysed by the H1 collaboration correspond to an integrated luminosity of 76 pb−1 [18]. The events are selected in the kinematic range $Q^2 > 1$ GeV^2 and $0.05 < y < 0.7$. The D^* mesons are reconstructed via the decay channel $D^* \to D^0\pi^+ \to (K^-\pi^+)\pi^+$. D^* candidates with $p_t(D^*) > 1.5$ GeV and $-1.5 < \eta(D^*) < 1$ are combined with oppositely charged proton candidates selected according to the proton likelihood based on the particle energy loss dE/dx in the central trackers. A clear peak is visible in the invariant mass distribution $M(D^*p)$, as shown in fig.5, where a fit with a Gaussian distribution added to an appropriate background function is superimposed. The result of the fit for the peak position is $M(D^*p) = 3099 \pm 3(stat.)$ MeV with a root-mean-square width for the Gaussian of 12 ± 3(stat).

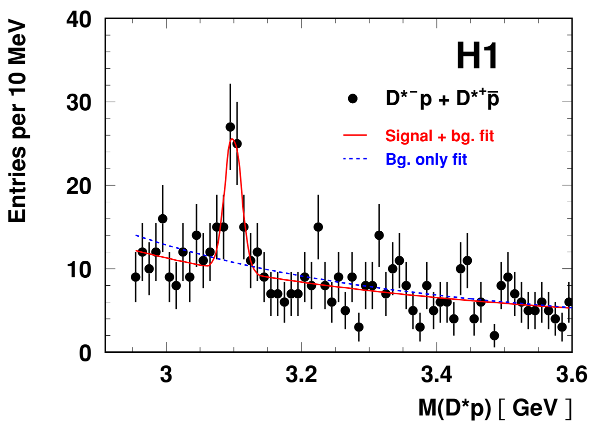

Figure 5: *$M(D^*p)$ distribution from opposite-charge D^*p combinations, as obtained by H1. The data are compared with the result of a fit in which both signal and background components are included (solid line) and with the result of a fit in which only the background component is included (dashed line).*

The signal consists of $N_s = 50.6 \pm 11.2$ events, from which the observed D^*p resonance is estimated to contribute roughly to 1% of the total D^* production rate in the kinematic region studied.

A similar analysis [19] has been performed by ZEUS using an integrated luminosity of 126 pb^{-1}. No resonance structure was observed in the $M(D^{*\pm}p^{\mp})$ spectrum from more than 60 000 reconstructed $D^{*\pm}$ mesons. An upper limit of 0.23% (95% C.L.) has been set on the fraction of D^* mesons originating from Θ_c^0 decays. The upper limit for DIS with $Q^2 > 1$ GeV^2 is 0.35% (95% C.L.), not compatible with the value of around 1% found by H1.

2.3 Search for Pentaquarks Decaying to $\Xi\pi$ in DIS

Recently, the experiment NA49 at the CERN SPS reported the observation of the $\Xi^{--}_{3/2}$ and $\Xi^{0}_{3/2}$ members of the $\Xi_{3/2}$ multiplet [16]. These states would lie at the bottom of the hypothetical antidecuplet of pentaquarks with the Θ^+ at the apex, and, while $\Xi^{0}_{3/2}$ would have an ordinary charge assignment, $\Xi^{--}_{3/2}$ is manifestly exotic with minimal quark content $ddss\bar{u}$. ZEUS used an integrated luminosity of 121 pb^{-1} to search for new baryonic states in the $\Xi^-\pi^\pm$ and $\bar{\Xi}^+\pi^\pm$ invariant-mass spectra [20]. The $\Xi^-(\bar{\Xi}^+)$ states were reconstructed via the $\Lambda\pi^-$ $(\bar{\Lambda}\pi^+)$ decay channel. The Λ baryons were identified by their charged decay mode, $\Lambda \to p\pi^-$, using pairs of tracks from secondary vertices. The resulting $\Xi\pi$ invariant-mass spectrum is shown in fig.6(a) where a clean $\Xi^0(1530)$ state is observed, while no pentaquark signal is found in the region predicted by NA49. In fig.6(b) the invariant-mass spectrum is shown for $Q^2 > 20$ GeV^2, the kinematic region where the Θ^+ signal was best seen by ZEUS. No pentaquark signal is seen in this restricted kinematic region.

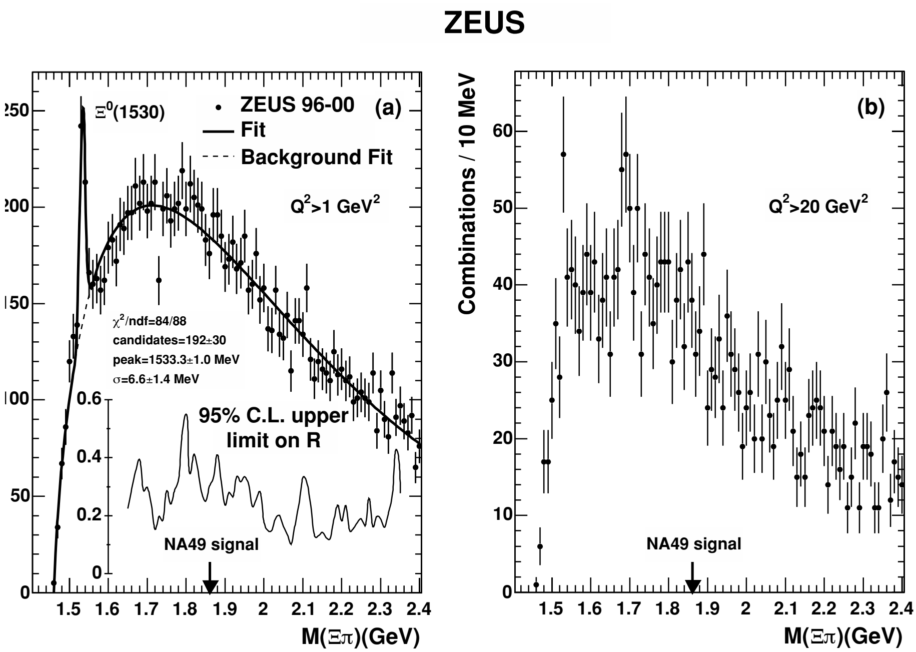

Figure 6: *The $\Xi\pi$ invariant-mass spectrum for: (a) $Q^2 > 1$ GeV^2 and, (b) $Q^2 > 20$ GeV^2, as measured by ZEUS. The solid line in (a) is the result of a fit to the data using a Gaussian plus a three-parameter background function. The dashed line shows the background according to this fit.*

2.4 Summary on Pentaquark Searches

The hypothetical pentaquark state $\Theta^+(1530)$ has been searched for by ZEUS. A signal with a statistical significance of 4.6σ has been observed in the kinematic region of $Q^2 > 20$ GeV^2.

A clear signal has been found by H1 in searching for the charmed pentaquark state $\Theta_c^0(3100)$. This signal has not been confirmed by ZEUS, despite the larger statistical sample available.

ZEUS also has a negative result for searching for the pentaquark state $\Xi^{--}(1860)$ whose observation was recently reported by the NA49 collaboration.

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