HEAVY FLAVOURS AT HERA

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Received 30 November 2004, in final form 5 January 2005, accepted 11 January 2005

Measurements of charm and beauty production in ep collisions at a center of mass energy of $\sqrt{s} = 318$ GeV performed by the ZEUS and H1 experiments at HERA are presented. Final states containing D mesons are used to identify charm production while events containing muons and jets are used to select beauty enriched data samples. Furthermore, new measurements are presented for charm and beauty, which are based on inclusive lifetime tagging methods. Measurements cover both the photoproduction ($Q^2 \sim 0$) and deep inelastic scattering (large Q^2) kinematic regimes. Experimental results are compared to QCD predictions.

PACS: 13.60.Hb

1 Introduction

The production of heavy flavours in ep collisions is dominated at leading order (LO) by the *boson gluon fusion* (BGF) process, $\gamma g \to c\bar{c}$ or $b\bar{b}$, where a vitual photon emitted by the electron interacts with a gluon in the proton producing a heavy quark pair $q\bar{q}$.

At a given value of the ep center of mass energy $\sqrt{s}$, the kinematics of the interaction is specified by a number of (Lorentz invariant) variables, the four-momentum transfer squared of the photon $q^2 = -Q^2$, the Bjorken scaling $x = Q^2/(2P \cdot q)$ representing the momentum fraction of the proton constituent, the inelasticity $y = (P \cdot q)/(P \cdot k)$ representing the energy fraction of the electron taken by the photon and the square center of mass energy of the system proton-photon $W^2_{\gamma p}$. Here P and k are the four-momentum of the proton and scattered electron, respectively. When the exchanged photon is *quasi-real* ($Q^2 \sim 0$) the kinematic regime is called *photoproduction* (γp) whereas large values of Q^2 corresponds to *deep inelastic scattering* (DIS).

Heavy flavour production is dominated by photoproduction : the total cross section for heavy quark production behaves like $\sigma(ep \to eq\bar{q}X) \sim 1/Q^2$, which means that a large fraction of the statistics is found at low values of Q^2. The production of heavy quarks is also dominated by charm production. Due to the large mass m_b and the charge of the b quark, the cross section $\sigma(ep \to eb\bar{b}X)$ is expected to be roughly two orders of magnitude smaller than $\sigma(ep \to ec\bar{c}X)$.

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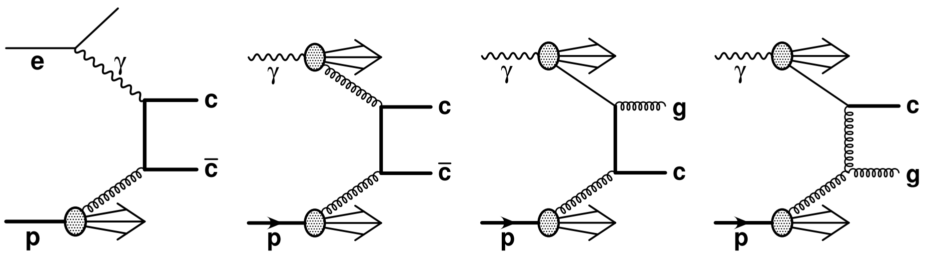

Fig. 1. LO diagrams for heavy flavour production in ep collisions: direct BGF, resolved BGF, two diagrams with flavour excitation from the photon.

However, the large scale m_b should, in principle, make the QCD predictions for beauty production more reliable than the predictions for charm.

In these pages we will try to give an overview of heavy flavour physics at HERA presenting measurements done by the ZEUS and H1 experiments.

2 Heavy Flavour Production

In leading order perturbative QCD (pQCD), heavy flavour production is dominated by *direct processes*, $\gamma g \rightarrow q\bar{q}$, in which the photon couples to the gluon as a point-like particle to produce the pair $c\bar{c}$ or $b\bar{b}$. In γp, *resolved processes* where the photon exhibit a partonic structure, are expected to play a significant role. Heavy quarks can then be produced by the coupling of one parton arising from a fluctuation of the photon to a gluon in the proton, i.e. $g^{\gamma}g^{p} \rightarrow q\bar{q}$ and $q^{\gamma}g^{p} \rightarrow gq$ (Fig 1).

2.1 NLO Calculations for Heavy Flavour Production

NLO calculations are performed in several schemes. All of them assume the existence of a scale sufficiently hard to apply pQCD and the validity of the factorisation theorem.

The *massive approach* is a fixed order calculation in α_s which takes into account the non-zero mass of the heavy quark when calculating matrix elements. Therefore only three active light flavours are needed in the description of the proton, so the heavy quark is nor considered as a part of the structure functions. Within this approach, heavy quarks can, in leading order, only be produced dynamically [1, 2] via BGF proccess. Calculations are expected to be more reliable in the kinematic regime of p_T not much larger than the mass of the heavy quark m_q, when logarithmic terms $\log(p_T^2/m_q^2)$ in the perturbative series become small. Numerical implementations of these calculations are the Monte Carlo programs HVQDIS [3] and FMNR [4], which provide the four-momenta of the outgoing partons in the DIS and γp regime, respectively. Visible differential cross sections of heavy mesons production are calculated after fragmentation of the heavy quarks via the Peterson model [5]

The *massless approach* [6,7] is a calculation that neglects the mass of the heavy quark and resums the leading logaritms in p_T/m_q using perturbative fragmentation functions. Heavy quarks are treated as active flavours in the proton and in the photon, i.e. part of the structure functions.

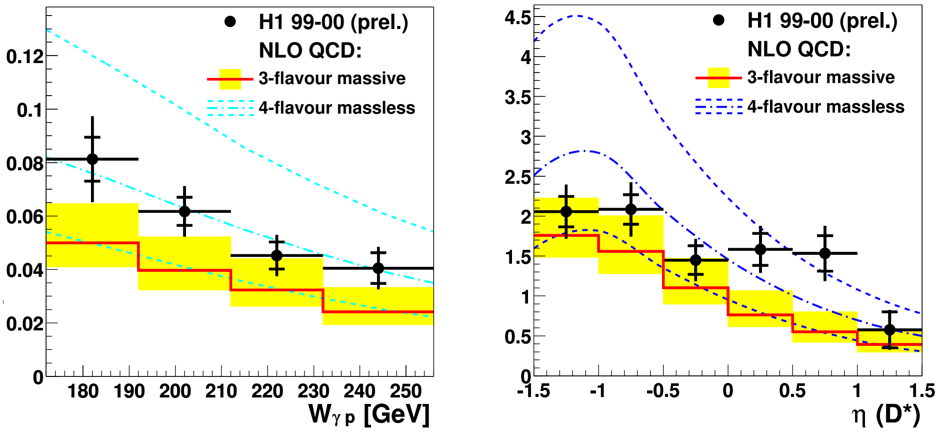

Fig. 2. Differential cross sections $d\sigma(ep \to eD^{*\pm}X)/dW$ (left) and $d\sigma(ep \to eD^{*\pm}X)/d\eta$ (right) compared to NLO QCD massive and massles calculations.

The process of *flavour excitation* (Fig. 1) give rise to new mechanisms of heavy quark production. Calculations performed in this scheme are supposed to be more reliable for $p_T \gg m_q$.

3 Inclusive $D^{*\pm}$ Meson Production in γp

Two different ways are used to select γp events at HERA. The ZEUS experiment selects events where the outgoing electron is not detected [8]. The H1 experiment selects events in which the outgoing electron is detected in the electron tagger located 33 meter down stream from the interaction point. In the analysis from the H1 experiment [9] $D^{*\pm}$ mesons are identified by the decay chain $D^{*\pm} \to D^0\pi^\pm$, $D^0 \to K^\mp\pi^\pm$. Photoproduction events are selected by detecting the scattered electron at small angles. The cross sections are determined in the kinematic region $171 < W < 256$ GeV, $Q^2 < 0.01$ GeV^2, $p_T(D^*) > 2.5$ GeV and $\eta(D^*) < 1.5$ as a function of $p_T(D^*)$, $\eta(D^*)$ and W. They have been compared to NLO QCD calculation in the "3-flavour massive" and in the "4-flavour massles" schemes. None of the calculations is able to predict the shape of the $d\sigma/d\eta$, but the shape of $d\sigma/dW$ is described by all, as shown in Fig. 2

4 $D^{*\pm}$ γp Inclusive Jet Cross Sections

The study of jet events in $D^{*\pm}$ photoproduction is an efficient tool for the investigation of the details of the charm production mechanism. [10] Inclusive jet cross sections with a D^* in the final state have been measured by ZEUS [11] as a function of E_T^{jet} and η^{jet} in the kinematic region $Q^2 < 1$ GeV^2, $130 < W < 280$ GeV, $p_T(D^*) > 3$ GeV, $\eta(D^*) < 1.5$, $E_T^{jet} > 6$ GeV and $-1.5 < \eta^{jet} < 2.4$. The use of jets as an approximation to a parton is expected to reduce the dependence of the cross section on uncertainties due to hadronisation effects. The cross sections

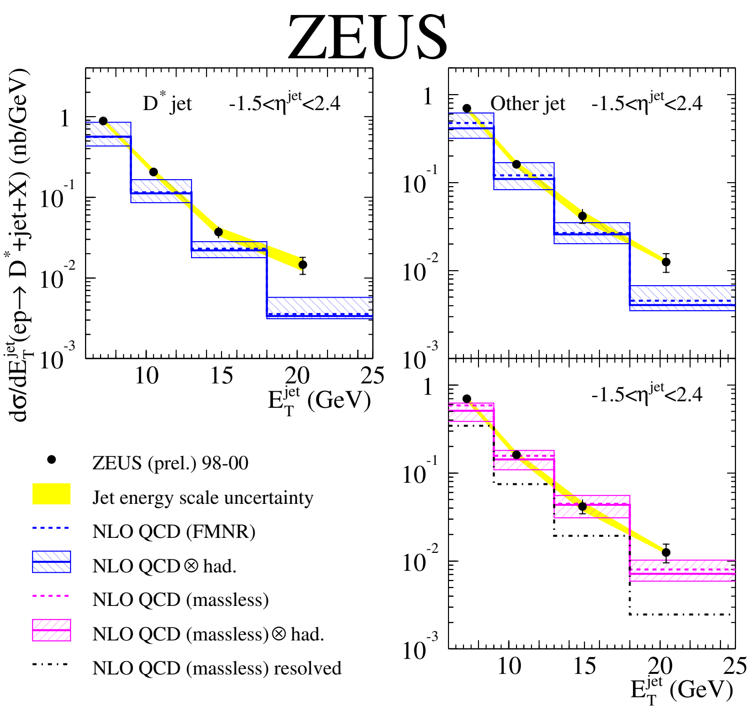

Fig. 3. Differential cross sections $d\sigma(ep \to eD^{*\pm} + jet + X)/dE_T^{jet}$ for the jet associated to the D^* and for other jets. Comparison to pQCD predictions both in the "massive" and "massless" schemes is also shown.

for the jet associated to the D^* are compared to the "massive" pQCD predictions. The cross sections for other jets (not associated to the D^*) are compared to both "massive" and "massless" calculations (Fig. 3) The pQCD predictions generally reproduce the shape of all distributions. However, the central pQCD predictions underestimate the data over the whole range in E_T^{jet} and η^{jet}. In Fig. 3 we see how at high values of E_T^{jet} predictions from the "massless" scheme are closer to the data, as expected.

5 Inclusive $D^{*\pm}$ Meson Production in DIS

The production of D^* mesons has been measured in DIS at HERA in the kinematic region $1.5 < Q^2 < 1000$ GeV^2, $0.02 < y < 0.7$, $1.5 < p_T(D^*) < 15$ GeV and $|\eta(D^*)| < 1.5$ [12]. Predictions from NLO QCD are in reasonable agreement with the measured differential distributions, which show sensitivity to the choice of the PDF and hence to the gluon distribution in the proton. The ZEUS NLO PDF [13], which was fit to the recent inclusive DIS data, gives the best description of the D^* data. In particular, this is seen in $d\sigma/d\eta(D^*)$, as shown in Fig. 4. The double differential cross section in y and Q^2 has been measured to extract the open-charm contri-

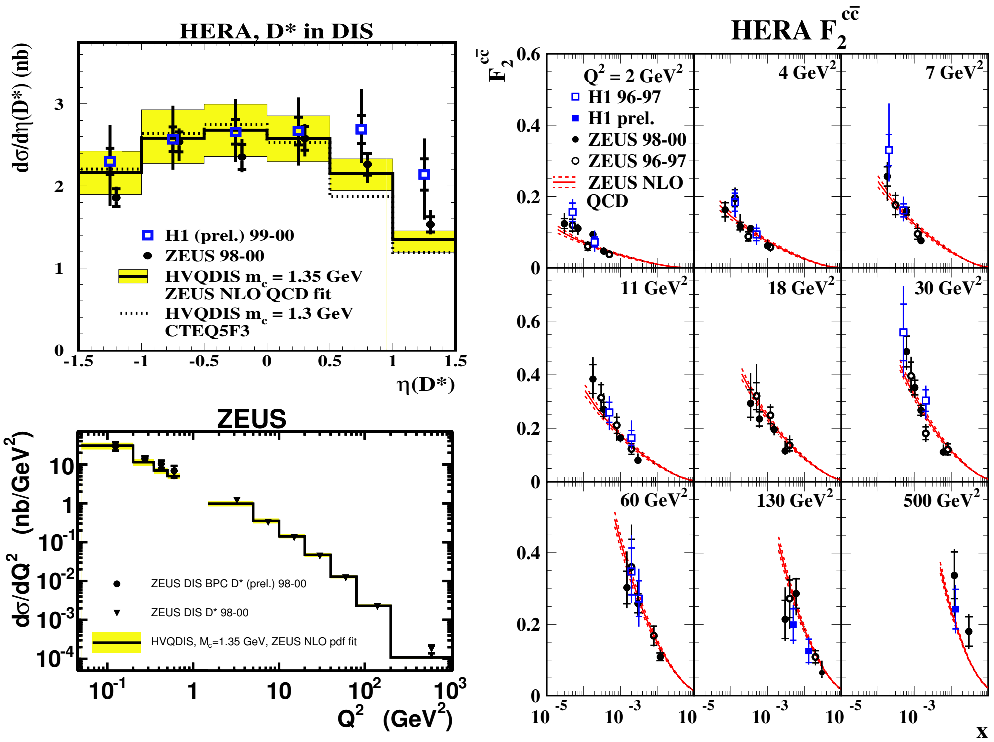

Fig. 4. Differential cross section $d\sigma/d\eta(D^*)$ for $Q^2 > 1$ GeV^2 and $d\sigma/dQ^2$ down to low Q^2 (left). The charm contribution $F_2^{c\bar{c}}$ to the proton structure function F_2 is also shown (right).

bution to F_2, by using the NLO QCD calculation to extrapolate outside the measured $p_T(D^*)$ and $\eta(D^*)$ region (Fig. 4). The production of D^* in DIS has been reacently measured with the ZEUS detector at low values of Q^2 using the special beam pipe calorimeter (BPC), in the kinematic region $0.05 < Q^2 < 0.7$ GeV^2, probing the transition region to γp regime [14]. The theoretical NLO QCD calculation of BGF charm production is consistent with the measured cross sections at low Q^2, as can be seen in Fig. 4.

6 Fragmentation of Charm Quark

Experimentally heavy quarks are not observed directly, but heavy flavoured hadrons are measured instead. This fragmentation process is non-perturbative and can only be described by phenomenological models. These models are implemented into theoretical cross sections assuming fragmentation to be independent of the production mechanism of the heavy quark. This universality can be tested by measuring the charm fragmentation properties in ep collisions and comparing to e^+e^- data.

At HERA the inclusive production cross sections of the charm ground states D^0, $D^\pm$, D_s,

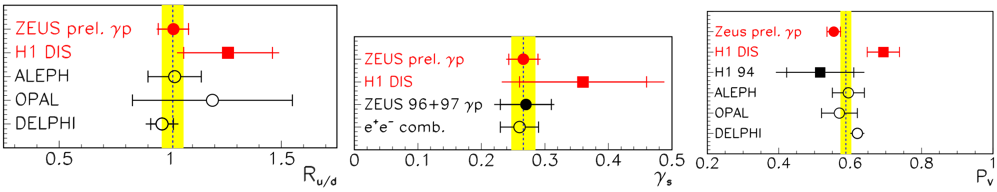

Fig. 5. The fragmentation parameters $R_{u/d}$, γ_s and P_V measured at HERA compared to e^+e^- annihilation results.

D^* and Λ_c have been measured in the γp [15] and in the DIS [14, 16] regime. The analysis of H1 includes new tagging methods for D mesons identification based on the reconstruction of secondary vertex, as well as measurements of differential distributions for the charm spectrum [16].

The ratio $R_{u/d} = c\bar{u}/c\bar{d}$ measures the rate of the neutral to charged D meson production. Due to the smallness of the u and d quark masses compared to their dressed masses, a value close to 1 is expected. The measurements of $R_{u/d}$ are shown in Fig. 5 for γp, DIS and e^+e^- annihilation data. They agree well with the naive expectation.

Due to the higher s quark mass, D_s mesons are expected to be less frequently produced than D^0 and $D^\pm$ mesons. This is quantified by the strangeness supression factor $\gamma_s = 2 \cdot c\bar{s}/(c\bar{u}+c\bar{d})$. Results from γp, DIS and e^+e^- data are summarised in Fig. 5, where a significant strangeness supression is observed.

The ratio $P_V = V/(V+P)$ of the fraction of D mesons produced in a vector state is also shown in Fig. 5, where average value is significant below the expected value, $3/4$, from naive spin counting.

The fragmentation fractions of the c quarks hadronizing as particular charmed hadrons, $f(c \to D, \Lambda_c)$, can be calculated as the ratio of the production cross section of a specific charmed hadron to the sum of all charmed ground state hadrons. No measurement of the strange-charmed baryons $\Xi_c^\pm, \Xi_c^0$ and Ω_c^0 exists at HERA, but their contribution is expected to be small. Tab.1 summarizes the branching fractions as observed in γp and DIS at HERA in comparison with combined values from e^+e^- data [17]. The comparison of the results show that the process of hadronisation is independent of the quark production mechanism.

	H1 DIS	ZEUS prel. PHP	combined e^+e^-
$f(c \to D^+)$	0.203 ± 0.026	$0.249 \pm 0.014^{+0.004}_{-0.008}$	0.232 ± 0.018
$f(c \to D^0)$	0.560 ± 0.046	$0.557 \pm 0.019^{+0.005}_{-0.013}$	0.549 ± 0.026
$f(c \to D_s)$	0.151 ± 0.055	$0.107 \pm 0.009^{+0.003}_{-0.005}$	0.101 ± 0.027
$f(c \to D^*)$	0.263 ± 0.032	$0.223 \pm 0.009^{+0.003}_{-0.005}$	0.235 ± 0.010
$f(c \to \Lambda_c)$		$0.076 \pm 0.020^{+0.017}_{-0.001}$	0.076 ± 0.007

Tab. 1. Ratios of measured cross sections and comparison to corresponding charm fragmentation fractions from e^+e^- data and photoproduction $e^\pm p$ collisions.

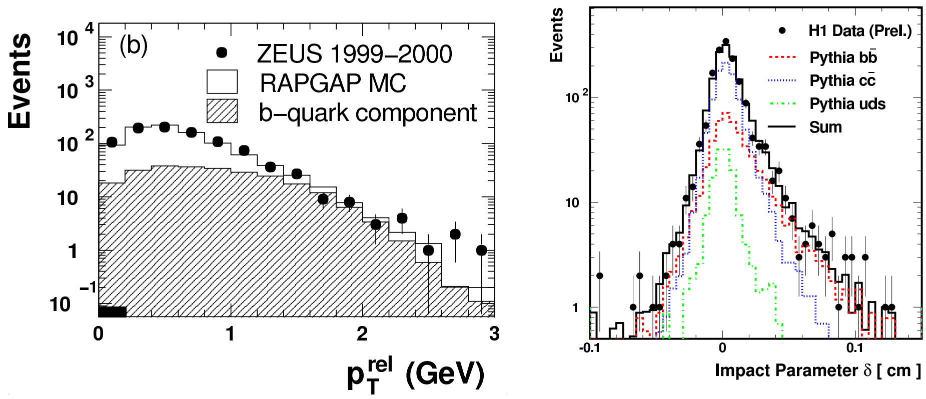

Fig. 6. Estimation of beauty component using the p_T^{rel} (left) and impact parameter (right) methods.

7 Beauty Tagging Methods

The standard method of selecting a beauty enriched sample is based on semi-leptonic decays of b-hadrons. The observation of muons is used to tag beauty events. As a consequence of the large mass m_b, the decay products from b-hadrons, in particular the muon candidate, are expected to have large opening angles with respect the jet direction. Distributions of the transverse momentum of the muon relative to the jet axis, p_T^{rel}, are then used to estimate the b fraction in the sample by fitting to the p_T^{rel} shape of b and background component. At high values of p_T^{rel}, the sample is dominated by beauty. Typical b fractions are found to be of the order of 30% in a jet plus muon sample.

Another approach is also used for selecting beauty samples. The *impact parameter*, δ, is defined as the minimum distance in the transverse plane from the muon candidate track to the primary vertex position. The sign of δ is taken as positive if the muon track intercepts the jet associated to the muon downstream of the primary vertex, and negative otherwise. According to the definition, muons coming from b hadrons decays are expected to have positive and large values of δ, due to the large lifetime of the b hadron. Muons coming from c hadrons should exhibit the same behaviour, but typically with smaller values of δ. Finally, contributions from light flavours should have values $\delta \sim 0$, due to the short lifetime of the hadron. The beauty component of a given sample is obtained by fitting MC to the measured δ distribution.

Examples of beauty extraction using both methods are shown in Fig. 6. With the p_T^{rel} method (left, taken from [20]) the dominance of the b component is clearly seen at high values of p_T^{rel}. With the impact parameter method (right, taken from [19]), the symmetry features of each of the component is also clear.

8 Beauty in Photoproduction and DIS

The production of beauty in γp has been measured at HERA [18,19] in the region $Q^2 < 1$ GeV^2 with inelasticity $0.2 < y < 0.8$. The events are selected by requiring one muon candidate and

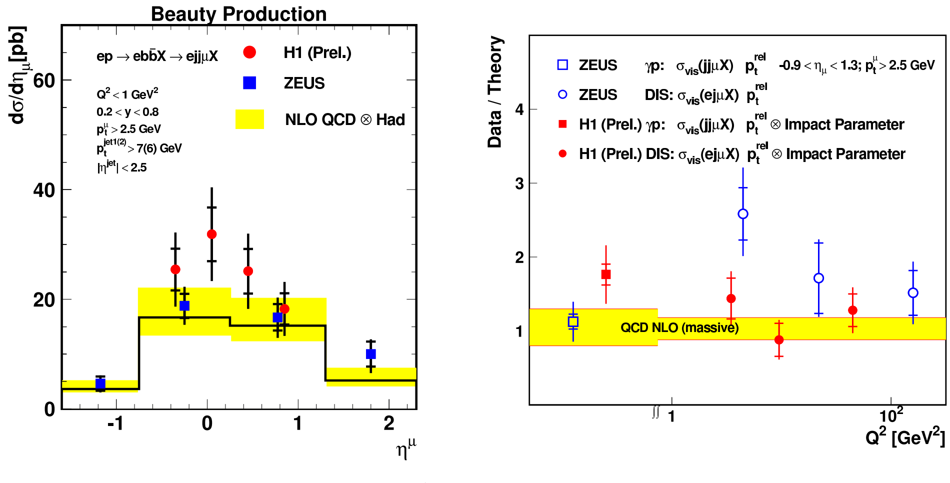

Fig. 7. Differential cross sections $d\sigma/d\eta^{\mu}$ in photoproduction and overview of beauty cross sections.

at least two jets with $p_T^{jet\ 1(2)} > 7(6)$ GeV. The data is compared to the QCD NLO predictions given by FMNR, with hadronisation corrections. Fig. 7 (left) shows the differential cross sections $d\sigma(ep \rightarrow b\bar{b} \rightarrow e\mu JJX)/d\eta^{\mu}$. The central values of the calculations are in agreement with the data when accounting for the errors and theoretical uncertainties.

The production of beauty in DIS regime has been also measured at HERA [20, 21]. Final states are selected by requiring one candidate to muon and the presence of least one hard jet in the Breit frame. The cross section $\sigma(ep \rightarrow eJ\mu X)$ is measured for photon virtualities $Q^2 > 2$ GeV^2. The differential cross sections are in general consistent with the NLO QCD predictions. However, at low values of Q^2, Bjorken x and muon transverse momentum, and high values of jet transverse energy and muon pseudorapidity, the prediction is about two standard deviations below the data, as measured by the ZEUS experiment.

Fig. 7 (right) shows the ratio of the measured to NLO cross sections for photoproduction and DIS as a function of Q^2.

9 Extraction of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ at high Q^2

For the first time at HERA, the production of c and b quarks have been studied using an inclusive method exploiting the precise tracking information from the H1 vertex detector [22]. The inclusive c and b cross sections have been measured using a technique based on the lifetime of the heavy quark hadrons. The *significance* (impact parameter over its error) is calculated for all the tracks in a given event, without muon tagging. The sample is divided in two subsamples, one with only one track and the other with at least two tracks. In the latter subsample, the second highest significance track is used. Simultaneous fit of the Monte Carlo simulation to both distributions allows the extraction of the c and b components. Extrapolation to the full phase space is used to get $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ for the first time. Fig. 8 shows the results of the measurements and

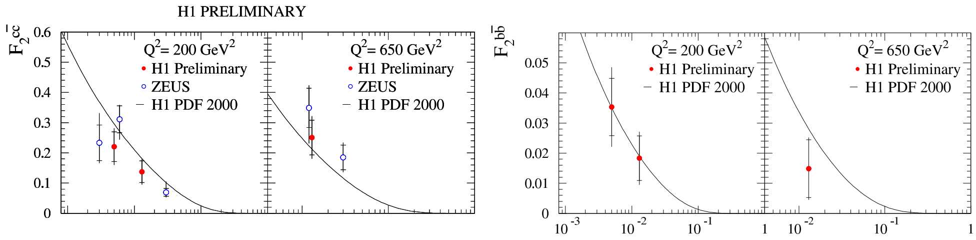

Fig. 8. Extraction of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ at different values of Q^2

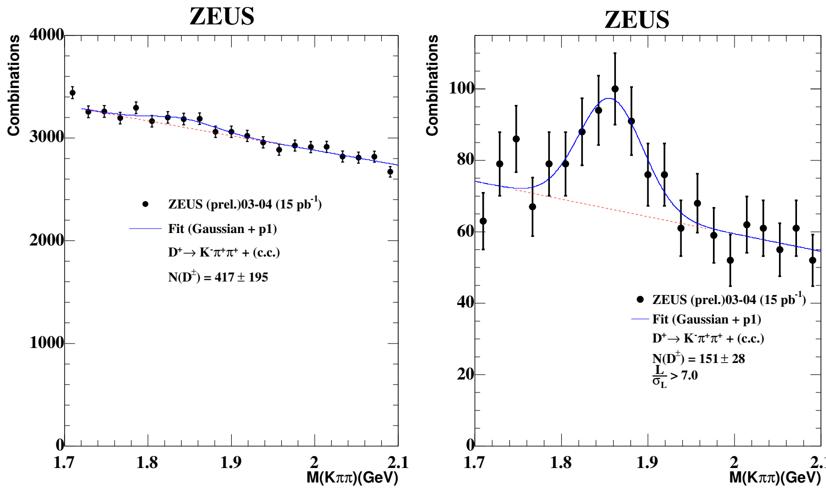

Fig. 9. Dramatic improvement in reconstruction of $D^{\pm}$ signal by secondary vertex techniques

the comparison to the theoretical predictions. In the case of $F_2^{c\bar{c}}$, results from the H1 experiment agree with those of the ZEUS experiment, based on D^* meson tagging. In general, data agree with expectation. At high values of Q^2 extrapolation factors are small, which makes the measurement in this region to be model independent.

10 Summary

Measured charm cross sections at HERA are generally well described by NLO QCD calculations. New measurements extend the kinematic range in Q^2 and p_T or require the presence of jets. In particular, measurements of charm photoproduction with jets in the final state show the need for improvements of theoretical calculations. Studies of charm fragmentation have shown the universal character of the fragmentation process after comparison of the measurements at HERA in ep collisions with those of e^+e^- annihilations.

Regarding beauty physics, measurements are found to be in agreement with the QCD NLO calculations, except in some particular cases, where the data exceed the prediction. New methods and techniques are being used in b physics, giving, for the first time at HERA, a measurement of $F_2^{b\bar{b}}$.

11 Outlook: HERA II

The upgrade of the HERA accelerator, which provides an increased luminosity, together with the use of an improved instrumentation in the detectors makes attractive the study of heavy flavour physics and will provide much more precise measurements in the near future. As an example, Fig. 9 shows the dramatic improvement in the reconstruction of the $D^{\pm}$ signal when secondary vertex techniques are used to select candidates [23].

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