Heavy quark production at HERA and the LHC

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Abstract
Measurements of heavy quark production, particularly from HERA, their theoretical understanding and their relevance for the LHC are reviewed[1]. The status of beauty and charm production is discussed in the context of the different components of the production process: the parton density function of the colliding hadrons; the hard scatter; and the fragmentation of the quarks into hadrons. The theory of QCD at next-to-leading order generally describes well the hadronic structure and the production of heavy quarks although sometimes fails in details which are highlighted. The fragmentation of heavy quarks measured at HERA is consistent with that at LEP and hence supports the notion of universality.

1 Why study heavy quark production?

The measurement of heavy quarks can give insights into many physical phenomena such as: new particles which are expected to decay predominantly to beauty (and charm); precise measurements of electroweak parameters; and, the subject of this paper, a deeper understanding of the strong force of nature. The strong force as described within perturbative Quantum Chromodynamics (QCD) should be able to give a precise description of heavy quark production. This postulate is described and tested here. The measurement of heavy quark production also yields valuable information on the structure of colliding hadrons. The production of a pair of heavy quarks in a generic hadron collision is shown in Fig. 1 where it can be seen that the process is directly sensitive to the gluon content of the hadron. Most information on the structure of a hadron comes from inclusive deep inelastic scattering where the gluon content is determined in the evolution of the QCD equations. Therefore measurement of such a process in Fig. 1 provides complimentary information to that from inclusive measurements.

As well as understanding for its own sake, knowledge of the structure of hadrons will be important at future colliders such as the LHC and International Linear Collider where hadronic photons will have large cross section in both e^+e^- and $\gamma\gamma$ modes. Heavy quarks will be copiously produced at future colliders as a background to the more exotic processes expected. Therefore a precise description of their production properties within QCD will aid in the discovery of physics beyond the Standard Model. An example of this was studied by the ATLAS collaboration using Monte Carlo to simulate the production at the LHC of a $b\bar{b}$ pair along with a supersymmetric Higgs particle (H/A) which subsequently decays to a $b\bar{b}$ pair [1]. For an assumed mass $m_A = 500$ GeV, even requiring four beauty jets, a signal-to-background ratio of only a few percent would be achieved. The irreducible background arises from QCD processes where the dominant processes are gg and gb with a gluon splitting to a $b\bar{b}$ pair. A discovery in this channel would therefore only be possible with precise knowledge these QCD background processes.

2 Theoretical and phenomenological overview

For a generic collision between two hadrons, H_a and H_b, in which a heavy quark pair is produced (see Fig. 1),

$$H_a + H_b \to Q\bar{Q} + X,$$

[1] Since the presentation, some results have been updated; these are used in what follows.

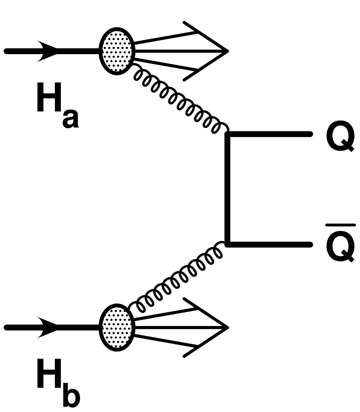

Fig. 1: Example of the production of a heavy quark pair in the collision of two hadrons.

the production cross section, $\sigma(S)$, for such a reaction at a centre-of-mass energy, S, can be written as:

$$\sigma(S) = \sum_{i,j} \int dx_1 \int dx_2 \, \hat{\sigma}_{ij}(x_1 x_2 S, m^2, \mu^2) f_i^{H_a}(x_1, \mu) f_j^{H_b}(x_2, \mu),$$

where the right-hand side is a convolution of the parton densities in the colliding hadrons, $f_i^{H_a}$ and $f_j^{H_b}$, and the short-distance cross section, $\hat{\sigma}_{ij}$. These are evaluated at a renormalisation and factorisation scale, μ, and momentum fractions of the colliding partons, x_1 and x_2. The parton densities are extracted from QCD fits to inclusive deep inelastic scattering and other data. The short-distance cross section is calculable in QCD and is a perturbative expansion in the mass of the heavy quark, m:

$$\hat{\sigma}_{ij}(s, m^2, \mu^2) = \frac{\alpha_s^2(\mu^2)}{m^2} \left[f_{ij}^{(0)}(\rho) + 4\pi\alpha_s(\mu^2) \left[f_{ij}^{(1)}(\rho) + \bar{f}_{ij}^{(1)}(\rho) \log(\mu^2/m^2) \right] + \mathcal{O}(\alpha_s^2) \right], \quad \rho = 4m^2/s.$$

The expansion demonstrates that the larger the mass the faster the convergence. Hence predictions for beauty production should be more accurate than those for charm.

The treatment of the mass of the heavy quark is an important consideration for the implementation of the perturbative formalism in calculations. There are three schemes used: the fixed-order (FO) or "massive" scheme, the resummed to next-to-leading logarithms (NLL), or "massless" scheme and more recently a scheme matching the two, known as FONLL [2]. In the FO scheme, the predictions should be valid for transverse momenta of the order of the mass of the heavy quark. In this scheme, the heavy quarks are not active flavours in the parton distributions of the incoming hadron(s); they are produced in the hard scatter through processes such as $gg \to Q\bar{Q}$ shown in Fig. 1. The resummed scheme is valid for transverse momenta much larger than the heavy quark mass. The heavy quarks are active flavours in the parton distributions of the incoming hadron(s), so can be produced by reactions such as $gQ \to gQ$. The FONLL calculations match the two schemes and are valid for all transverse momenta. The validity of the different calculations is investigated in comparison with data, particularly as a function the energy scale.

The fixed-order calculations used are from Frixione et al. (FMNR) [3] for photoproduction processes and HVQDIS from Harris and Smith [4] for deep inelastic scattering. Resummed calculations are only available for photoproduction at HERA from two groups of authors, Cacciari et al. [5] and Kniehl et al. [6]. The FONLL calculation is also only available in photoproduction. A calculation which is already available for some processes in pp collisions, MC@NLO [7], combines a fixed-order calculation with the parton showering and hadronisation from the HERWIG Monte Carlo generator [8]. Processes at HERA are not yet included, but it is hoped they will be done in the future and thereby provide a new level of detail in comparison with experimental data.

The advantages of a programme such as MC@NLO are its simulation of higher orders and also its sophisticated approach to hadronisation which attempts to describe the whole of the final state. The other programmes produce partons in the final state and fragment the outgoing quark to a hadron usually via the Peterson function [9]. Therefore these calculations may not be able to describe the full hadronic final state of an event. The validity of the fragmentation functions used also needs to be tested; they are usually extracted from fits to e^+e^- data and their applicability to ep or pp needs to be demonstrated. Therefore the fragmentation function should be measured at HERA, and is discussed later, or measurements need to be made at high transverse energy or using jets where the effects of fragmentation are reduced.

Hadron-hadron collisions producing heavy quarks pairs can be simplified to and provide information on: the parton densities and in particular the gluon and heavy quark content of the hadron; the hard scatter and the dynamics of QCD as implemented into programmes; fragmentation or description of the parton to hadron transition. All of these aspects are discussed in this write-up.

3 Information needed by the LHC experiments

The information needed by the LHC which can be provided by the HERA experiments is the following:

- the state of the description of heavy quark production data by theoretical predictions. The production of heavy quarks in the hard scattering process is discussed here in detail. Information on heavy quarks produced in the splitting of a gluon outgoing from the hard sub-process is also important for the LHC, but the information from HERA is currently limited;
- the gluon and heavy quark content of the proton parton density functions;
- details of fragmentation in a hadronic environment;
- the effect of the underlying event in heavy quark processes. This information is limited at HERA but may be studied in the future;
- HERA results can provide general information on event and jet topologies which will be useful for designing algorithms or triggers at the LHC experiments.

The designing of effective triggers for b physics is particularly acute for the LHCb experiment [10]. Large backgrounds are expected although event topologies should be different to the signal b physics. For example minimum bias events will have a smaller track multiplicity and a lower transverse momentum for the highest p_T track. Therefore using Monte Carlo simulation, cuts can be found to be able to reduce the rate of minimum bias whilst triggering efficiently on b events. Such simulations require reliable Monte Carlo simulation of the event topologies of both classes of events.

Measurements of the proton structure function at HERA will constrain the parton densities in a large region of the kinematic plane where B mesons will be produced within the acceptance of the LHCb detector. According to Monte Carlo simulations, these events are produced predominantly with a b quark in the proton. However, this is just a model (PYTHIA [11]) and at NLO some of the events will be summed into the gluon distribution of the proton. Nevertheless, measuring all flavours in the proton at HERA is one of the goals of the experiments and recent results on the beauty contribution to the proton structure function [12] shed some light on the issue.

4 Open beauty production

The production of open beauty and its description by QCD has been of great interest in the last 10–15 years.The difference between the rates observed by the Tevatron experiments [13] and NLO QCD predictions led to a mini crisis with many explanations put forward. Several measurements were performed in different decay channels and then extrapolated to the quark level to facilitate a comparison with QCD and between themselves. The NLO QCD prediction was found to be a factor of 2–3 below the data for all measurements as shown in Fig. 2a. As mentioned, these results were extrapolated to the b-quark level using Monte Carlo models which may or may not give a good estimate of this extrapolation. To facilitate a particular comparison, an extrapolation can be useful, but should always be treated with caution and the procedure clearly stated and values of extrapolation factors given. Initial measurements in terms of measured quantities should also always be given.

The CDF collaboration also published measurements of B meson cross sections. They were also found to be significantly above NLO calculations, but allowed for phenomenological study. Work on the fragmentation function was performed by Cacciari and Nason [14] which in combination with updated parton density functions and the FONLL calculation gave an increased prediction. New measurements at Run II have also been made by the CDF collaboration which probe down to very low transverse momenta. In combination with a measured cross section lower (but consistent) than the Run I data, and the above theoretical improvements, the data and theory now agree very well as shown in Fig. 2b. The programme MC@NLO also gives a good description of the data.

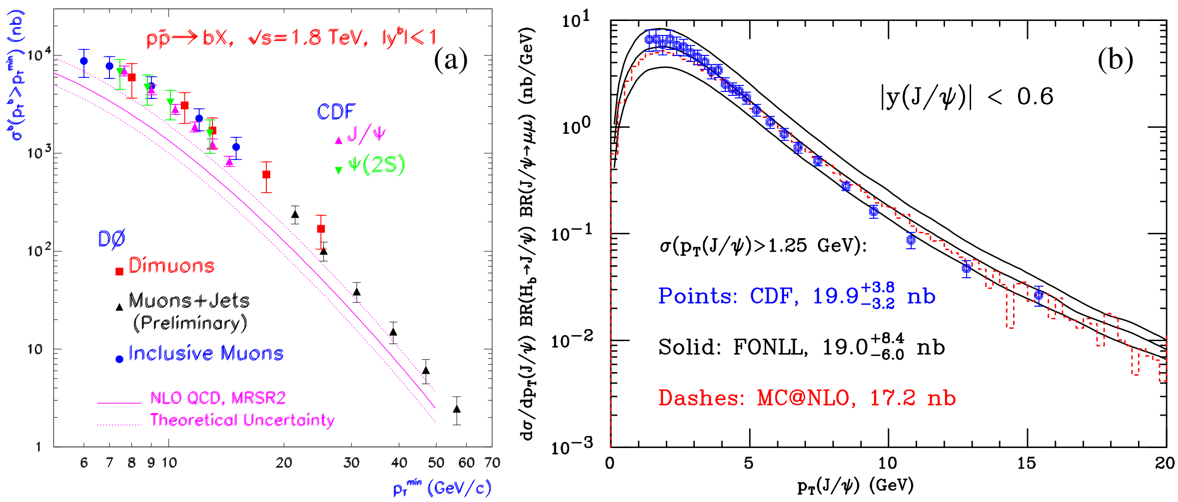

Fig. 2: (a) Tevatron Run I data extrapolated and compared to NLO QCD predictions and (b) Run II data presented in terms of the measured quantities and compared to improved QCD theory.

The first result from HERA [15] also revealed a large discrepancy with NLO QCD predictions. This analysis also presented an extrapolated quantity, whereas later measurements [16–18] also presented measured quantities. The most recent and precise measurements [17] of beauty production with accompanying jets are shown in Fig. 3 compared with predictions from NLO QCD. The measurements in photoproduction (Fig. 3a) are shown to be very well described by the prediction and the data from the two collaborations also agree well. The H1 data is somewhat higher than that from ZEUS; the difference is concentrated at low p_T^μ where the H1 data is also above the NLO calculation. The measurements in deep inelastic scattering are also generally described by NLO QCD although some differences at forward η^μ and low p_T^μ are observed by both collaborations. However, inclusive measurements which lead to a measurement of the beauty contribution to the proton structure function [12] are well described by QCD (see next Section).

The situation for the QCD description of b production has recently changed significantly. In general, QCD provides a good description of the data with some hints at differences in specific regions. Certainly, there is no longer a difference of a factor of 2–3 independent of p_T. The HERA experiments will produce several new measurements in the next few years of higher precision and covering a larger kinematic region at both low and high p_T and forward η. Allied with expected calculational and phenomenological improvements, a deep understanding of beauty production should be achieved by the turn-on of the LHC.

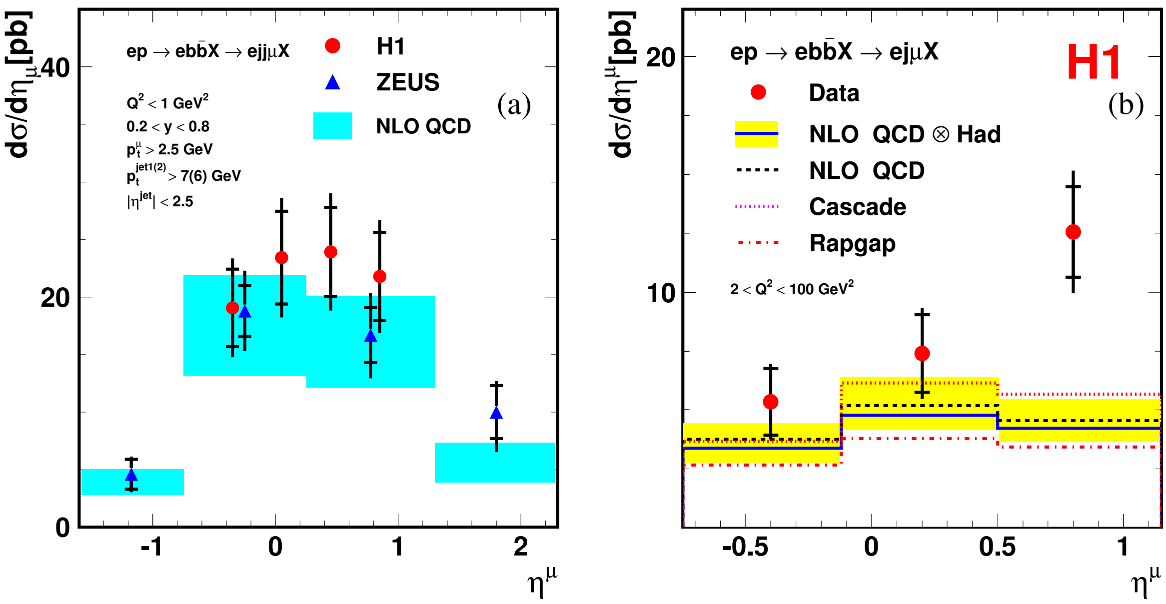

Fig. 3: Measurement of open beauty production as a function of the pseudorapidity of the decay muon for (a) dijet photoproduction from the H1 and ZEUS experiments and (b) inclusive jet deep inelastic scattering from the H1 experiment. (The measurement from ZEUS experiment for (b) is in a different kinematic region but reveals the same physics message and so for brevity, is not shown)

5 Open charm production

Due to its smaller mass, predictions for charm production are less accurate than for beauty. However large data samples allow detailed comparisons with theory. An example of a measured D^* cross section in deep inelastic scattering is shown in Fig. 4a; data from the two experiments agree with each other and are well described by the prediction of QCD. Similar measurements have been made in photoproduction in which the data is less well described. Due to the larger cross section, the photoproduction data could prove valuable in constraining the photon as well as the proton structure. However, as can be seen from Fig. 4b, the theoretical precision is lagging well behind that of the data. Therefore more exclusive quantities and regions, with smaller theoretical uncertainties, are measured.

Measurements of charm photoproduction accompanied with jets pose a challenge for theory due the extra scale of the jet transverse energy. Such complicated final states will be copious at the LHC, so the verification of theory to HERA data will aid in the understanding of these high-rate QCD events. Dijet correlations in photoproduction have recently been measured [19] and compared with available calculations. Events were selected in two regions: one enriched in direct photon events where the photon acts as a pointlike object and one enriched in resolved photon events where the photon acts as a source of partons. The cross section of the difference in the azimuthal angle, $\Delta\phi^{\rm jj}$, of the two highest E_T jets has been measured. For the LO $2 \to 2$ process, the two jets are back-to-back. The data exhibit a significant cross section at low $\Delta\phi^{\rm jj}$ and for the direct photon events are reasonably well described by NLO QCD (not shown). However, the description for resolved photon events is poor as shown in Fig. 5a. This region is particularly sensitive to higher orders not present in the QCD calculation. Monte Carlo models are compared to the data in Fig. 5b; although the normalisation is poor, the shape of the distribution is very well described by the HERWIG simulation. This indicates that for the precise description of such processes, higher-order calculations or the implementation of additional parton showers in current NLO calculations are needed.

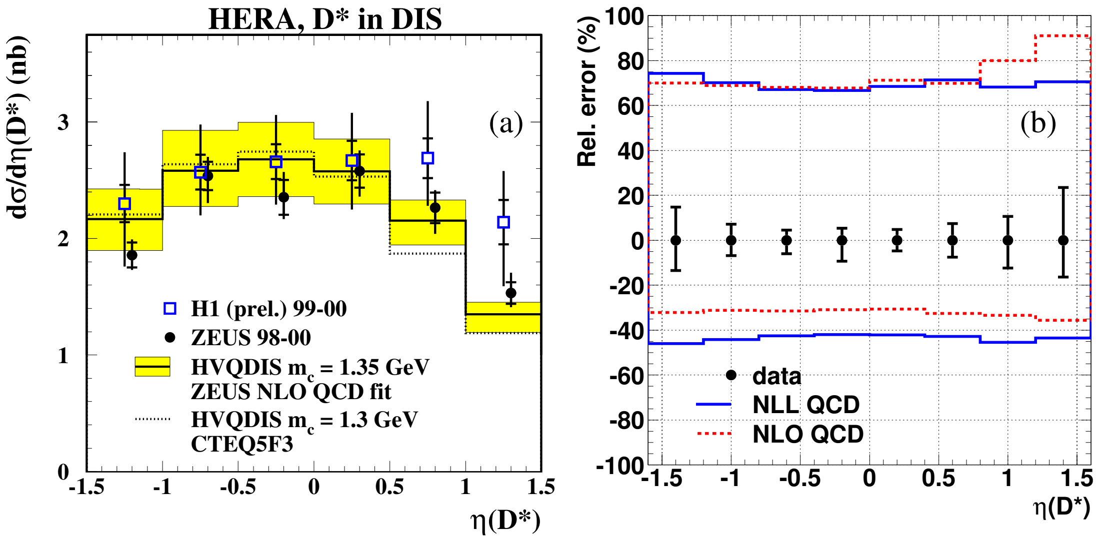

Fig. 4: Measurement of D^* production compared with NLO QCD predictions: (a) the differential cross section in deep inelastic scattering and (b) the relative uncertainty in data and theory in photoproduction.

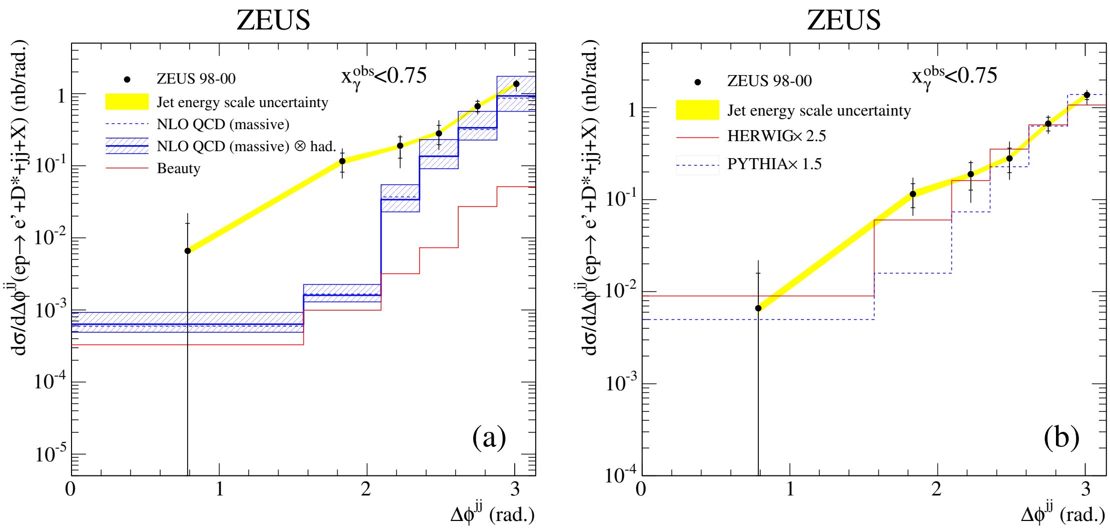

Fig. 5: Difference in the azimuthal angle of the two highest E_T jets in charm photoproduction for a sample enriched in resolved photon events compared to (a) a NLO QCD calculation and (b) Monte Carlo models.

6 The structure of the proton

Open charm (and more recently beauty) production in deep inelastic scattering acts as a powerful probe of the structure of the proton, particularly the gluon and heavy quark densities. Such a direct measurement of the gluon density complements its extraction in QCD fits to inclusive data. The cross section for the production of a heavy quark pair can be written in terms of the heavy quark contribution to the proton structure functions:

$$\frac{d^2\sigma^{Q\bar{Q}}\left(x,Q^2\right)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left\{\left[1+(1-y)^2\right]F_2^{Q\bar{Q}}\left(x,Q^2\right) - y^2 F_L^{Q\bar{Q}}\left(x,Q^2\right)\right\}$$

The value of the charm contribution, $F_2^{c\bar{c}}$, has traditionally been extracted by measuring D^* mesons within the acceptance of the detector and extrapolating to the full phase space.

The values of $F_2^{c\bar{c}}$ extracted from the measured D^* cross sections [20–22] are shown in Fig. 6a compared with NLO QCD. New measurements of $F_2^{c\bar{c}}$ have been recently performed using an inclusive sample of high p_T tracks [12]. This data is more inclusive than the D^* measurements probing much lower p_T and thereby having much reduced extrapolation factors (a factor of 1.2 rather than 2–3 as for the D^* measurements). These results confirm the previous data and add extra information on $F_2^{c\bar{c}}$. The results on $F_2^{c\bar{c}}$ demonstrate a large gluon density in the proton as exhibited by the scaling violations versus Q^2 and are well described by such a parton density function. At high Q^2, charm contributes up to about 30% of the inclusive cross section. It is hoped with higher statistics and a better control over the systematics that the charm cross section data can be used in QCD fits to constrain the gluon (or heavy quark) density in the proton.

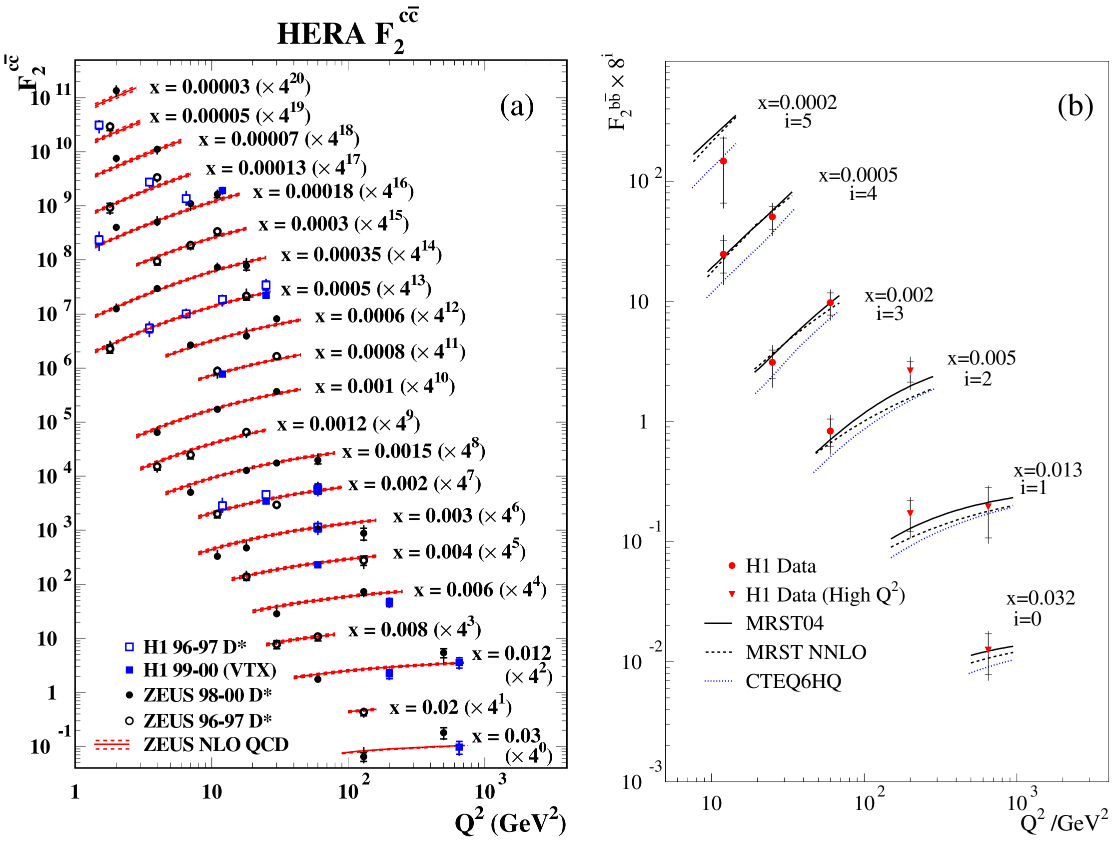

Fig. 6: (a) Charm contribution, $F_2^{c\bar{c}}$, and (b) beauty contribution, $F_2^{b\bar{b}}$, to the proton structure function, F_2, versus Q^2 for fixed x.

Applying the same technique of using high p_T tracks, the H1 collaboration have made measurements of $F_2^{b\bar{b}}$ which are shown in Fig. 6. The results are consistent with scaling violations and are well described by new parton density functions. The differences between the different parametrisations are not insignificant and future measurements should be able to discriminate between them. For the Q^2 range measured, beauty production contributes up to 3% of the inclusive cross section.

7 Universality of charm fragmentation

Heavy quark fragmentation has been extensively studied in e^+e^- collisions. The clean environment, control over the centre-of-mass energy and back-to-back dijet system provide an ideal laboratory for accurate measurement of fragmentation parameters. The measured parameters, e.g. fragmentation function and fraction of charm quarks hadronising to a particular meson, are used as inputs to models and NLO QCD calculations of ep collisions. Therefore, the validity of using fragmentation parameters extracted from e^+e^- data in ep data needs to be verified. The strangeness suppression factor, γ_s, the ratio of neutral and charged D-meson production rates, $R_{u/d}$, the fraction of charged D mesons produced in a vector state, P_v^d and the fragmentation fractions, $f(c \to D, \Lambda)$, have been measured in deep inelastic scattering [23] and in photoproduction [24]. The results are shown in Fig. 7 compared with values obtained in e^+e^- collisions. The data obtained in different processes are consistent with each other and thereby consistent with the concept of universal fragmentation. The measurements in photoproduction also have precision competitive with the combined e^+e^- data. The data therefore provide extra constraints and demonstrate that the fragmentation at a hadron collider in the central part of the detector looks like that in an e^+e^- collision. This will provide useful input for future models to be used at the LHC.

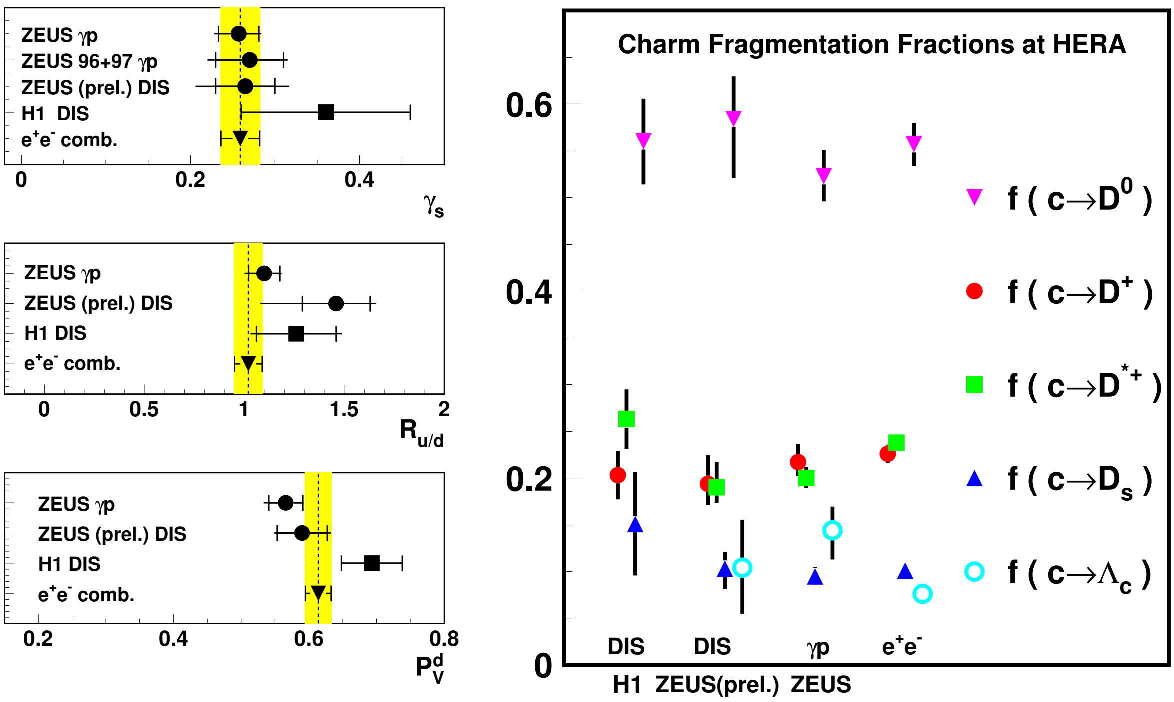

Fig. 7: Comparisons of fragmentation parameters, γ_s, $R_{u/d}$ and P_v^d and $f(c \to D, \Lambda)$ in photoproduction, deep inelastic scattering and e^+e^- collisions.

The charm fragmentation function to D^* mesons has been measured by both the H1 and ZEUS collaborations [25] and compared to e^+e^- data. Although the definitions of the fragmentation function and the energies are different, the general trends are the same. However, a consistent fit to all data within a given Monte Carlo or NLO calculation is needed to clarify this situation. Measurements at the Tevatron would also contribute significantly to this area.

8 Conclusions

An increasing number of high precision measurements of heavy quark production from HERA have recently become available. They are providing valuable information on the parton densities, the overall production rates and the concept of the universality of fragmentation. Precise and well-defined measurements have allowed phenomenological improvements to be made. Generally QCD describes the production of heavy quarks; in particular, due in part to the advances made in the HERA measurements, the prediction for the production of beauty quarks is no longer well below the data. There are some details still lacking which await to be confronted with higher order calculations or NLO calculations interfaced with parton showers and hadronisation. There is also ongoing work in tuning Monte Carlo predictions to all known data which demonstrates the need to have global calculations which can predict all processes under study. In the next few years in the run up to the LHC, HERA will produce a lot more data and more will be known about heavy quark production.

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