Heavy Flavors in High Energy *ep* Collisions

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Abstract. Most recent measurements of open charm and beauty production in high energy *ep* collisions at HERA are reviewed. The measurements explored the different aspects of quantum chromodynamics involved in the process of heavy flavor production. The results are compared with perturbative theoretical calculations at next-to-leading order.

INTRODUCTION

The masses of heavy quarks, charm and beauty, provide hard scales for perturbative quantum chromodynamics (QCD) calculations. Measurements of heavy flavor production therefore have been and continue to be of great interest as a rich testing ground for the reliability of perturbative QCD predictions.

HERA, which collides electrons or positron of energy 27.5 GeV with protons of energy 920 GeV (or 820 GeV before 1998) resulting in a center-of-mass energy of 318 GeV (or 300 GeV), can test heavy flavor production in a unique way. Two collider experiments, H1 and ZEUS, have accumulated approximately 135 pb^{-1} of integrated luminosity by the end of 2000. After a major upgrade during 2001 and 2002, HERA is running at much higher luminosity with the polarized electron beam and is referred to as HERA II for distinction.

Heavy flavor production at HERA is dominated by boson-gluon-fusion (BGF), as shown in Fig. 1. When the virtuality Q^2 of the exchanged boson, mainly photon, is very small, $Q^2 \ll 1\,\mathrm{GeV}^2$, the virtual photon resembles a real one and the collisions are referred to as γp or photoproduction, in which a certain fraction of the photons can be resolved with parton contents. For large Q^2, the collisions are called deep inelastic scattering (DIS). Only the most recent measurements are presented here.

THEORY AND MODELS

In perturbative QCD (pQCD), single-particle inclusive cross sections in *ep* collisions can be factorized in the form

$$\sigma_{ep\to HX} = \sum_i \phi_{i/p} \otimes \hat{\sigma}_{Vi\to hX} \otimes D_{H/h},$$

where $\otimes$ denotes convolution. The sum is over all relevant partons i, while $\phi_{i/p}$ is a parton density function (PDF) of the initial proton, $\hat{\sigma}_{Vi\to hX}$ is the pQCD calculable cross

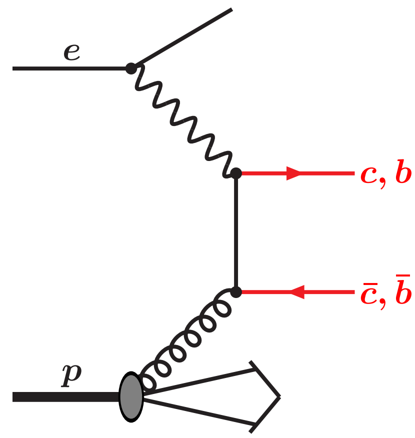

FIGURE 1. Heavy flavor production via Boson-gluon-fusion in the ep collision.

section of hard scatter, and $D_{H/h}$ is the fragmentation function. In resolved photoproduction, an additional PDF of the photon enters the calculation. These terms are evaluated at a renormalization scale μ_R as well as a factorization scale μ_F, which is often taken at the same value as μ_R. The PDFs and the fragmentation functions are non-perturbative and must be determined either experimentally or taken from models, but they are universal. In heavy flavor production, the mass of the heavy quark provides an additional hard scale hence yielding more accurate calculations.

Up to next-to-leading order (NLO), the fixed-flavor-number scheme (FFNS) or "massive" scheme from Frixione et al. [1] for photoproduction and from Harris and Smith [2] for DIS and the zero-mass variable-flavor-number scheme (ZMVFNS) or "massless" scheme from Cacciari and Greco [3] and from Heinrich and Kniehl [4] are compared with the data. They differ in the treatment of mass of heavy quark. In the massive scheme, the heavy quarks are non-active flavors in the proton and are produced through hard scatter such as BGF, while in the massless scheme, the heavy quarks are just the contents of the proton and can enter the reaction directly. The massive scheme works well near the threshold of heavy quark production and the massless scheme works better in the higher kinematic region. A scheme matching the two also exists but is not used for the measurements presented here.

Monte Carlo (MC) models, based on leading order QCD and parton shower approaches, are used for acceptance calculations in all measurements, and sometimes as alternative QCD predictions. They include PYTHIA [5] and HERWIG [6] which differ in the treatment of parton showers and heavy quark fragmentation.

OPEN CHARM PRODUCTION

Inclusive jet cross sections and dijet correlations in D^* photoproduction have been studied by ZEUS [7]. NLO predictions in the massive and massless schemes show reasonable agreement with the data in all inclusive jet cross sections as well as some dijet correlation cross sections, but the massive prediction shows a large deviation at low $\Delta\phi^{jj}$, az-

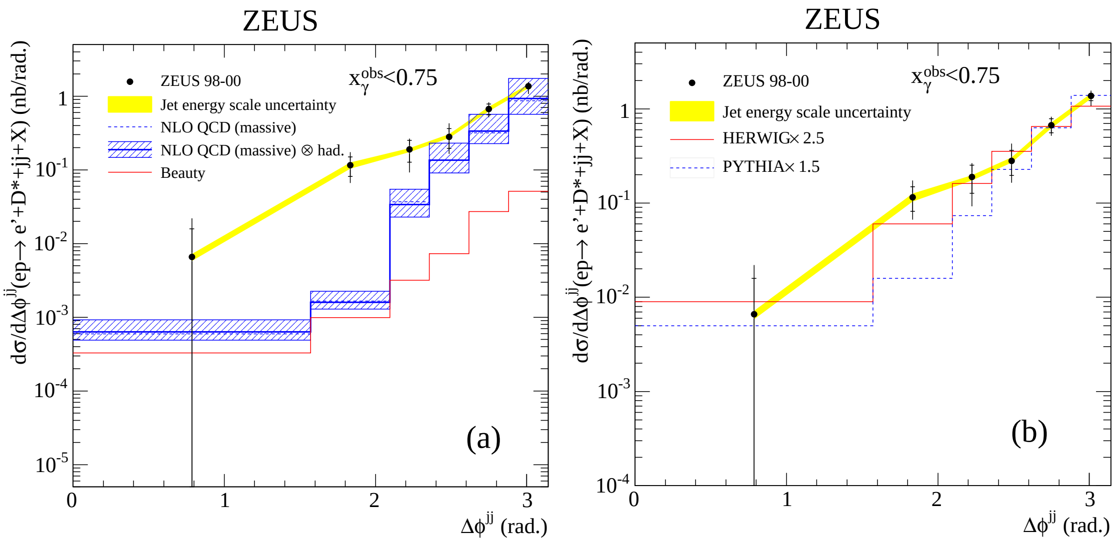

FIGURE 2. Azimuthal angular difference of the two highest E_T jets in D^* photoproduction for the resolved enriched sample, compared to (a) a NLO QCD calculation and (b) Monte Carlo models.

imuthal angular difference of two jets, and high $(p_T^{jj})^2$, squared transverse momentum of dijet system. The discrepancy is enhanced in the resolved-enriched sample, as shown in Fig. 2a. However, the HERWIG MC model describes the shape of the data well, Fig. 2b. This indicates the necessity of higher-order calculations or additional parton showers in current NLO calculations.

Open charm production in DIS is directly sensitive to the gluon contents in the proton. Measurements [8–12] of the charm contribution to the proton structure function, $F_2^{c\bar{c}}$, are shown in Fig. 3a. The results are well described by a QCD prediction based on a QCD fit of the inclusive structure function F_2. A measurement exploring the transition region between DIS and photoproduction has also been reported recently [13] as well as the first charm measurement from HERA II data [14].

Charm fragmentation is traditionally measured at e^+e^- experiments and the results are then adapted into MC simulations or theoretical calculations. Recently, H1 and ZEUS made measurements on charm fragmentation ratios $R_{u/d}$ (the ratio of neutral to charged D-meson rates), γ_s (the strangeness suppression factor) and P_V (the fraction of D-meson in a vector state) as well as fragmentation fractions, $f(c \to D, \Lambda)$ [15–17]. The results are compared to those of e^+e^-, Fig. 3b-d, and confirm the universality of fragmentation. Measurements of the fragmentation function have also been made by H1 [18] and ZEUS [19], and are in agreement with universality. too.

OPEN BEAUTY PRODUCTION

Because of the larger mass, the pQCD calculation for open beauty production should be more reliable than for open charm. Some of the previous measurements [20, 21] have found the prediction to be below the data by up to a factor 3. Recent measurements by H1

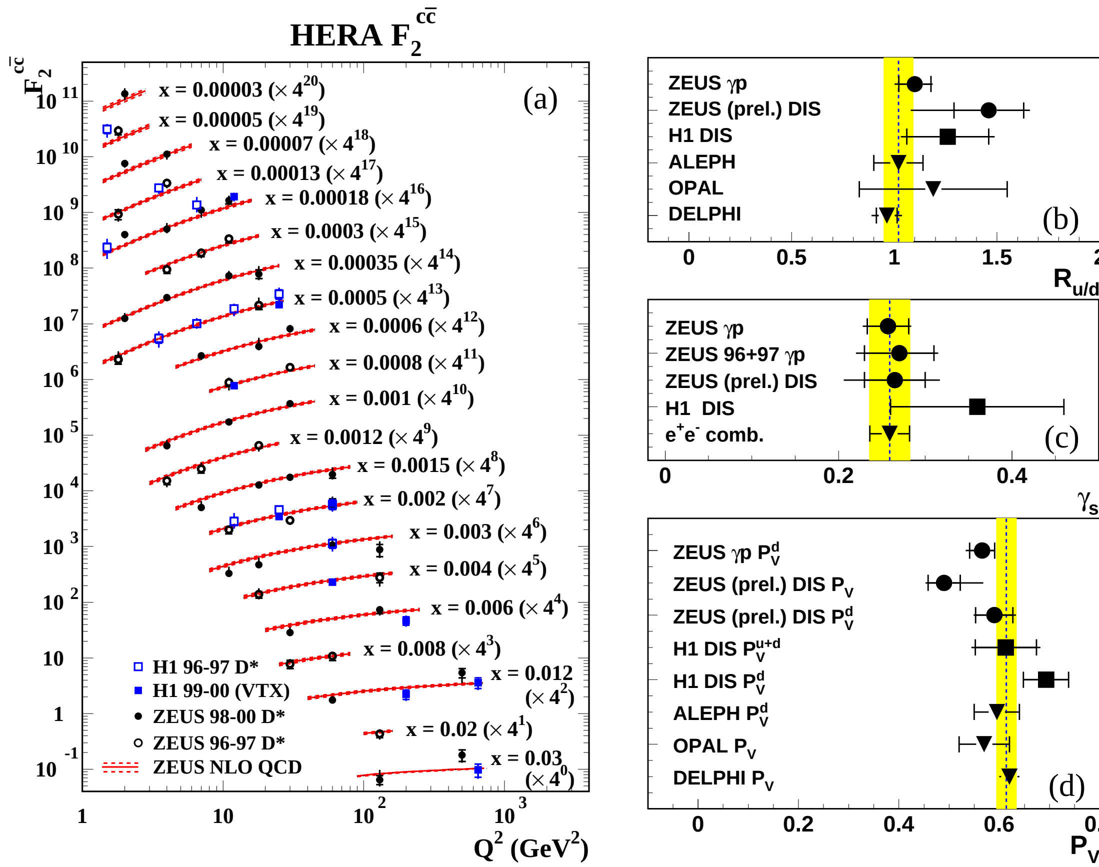

FIGURE 3. (a) $F_2^{c\bar{c}}$ as a function of Q^2 for different values of the Bjorken scaling variable x; (b-d) Comparisons of charm fragmentation ratios $R_{u/d}$, γ_s and P_V. (Comparisons of charm fragmentation fractions, $f(c \to D, \Lambda)$, are not shown for brevity.)

and ZEUS required events containing jets in addition to high p_T muons, which are traditionally used to tag beauty quarks [22–24]. As shown in Fig. 4a, the measurements in photoproduction agree very well between the two collaborations and are well described by the NLO calculations although the H1 data is above the calculation at low p_T^μ. In DIS, similar agreement exists, although discrepancies at low p_T^μ as well as forward η^μ are observed by both collaborations, shown in Fig. 4b as an example.

New measurements using inclusive impact parameters of tracks from decays of long lived charm and beauty hadrons have been performed in DIS by the H1 collaboration [11, 12]. They are the first measurements of $F_2^{b\bar{b}}$, Fig. 5. The data are well described by the NLO predictions and a recent calculation using NNLO structure functions [25]. The values of $F_2^{c\bar{c}}$ also confirm the previous data and have been put in Fig. 3a. Significantly improved further measurements are expected from the increased HERA II statistics and the corresponding detector improvements. First preliminary results on beauty in photoproduction using the new ZEUS micro-vertex detector have already been obtained [26].

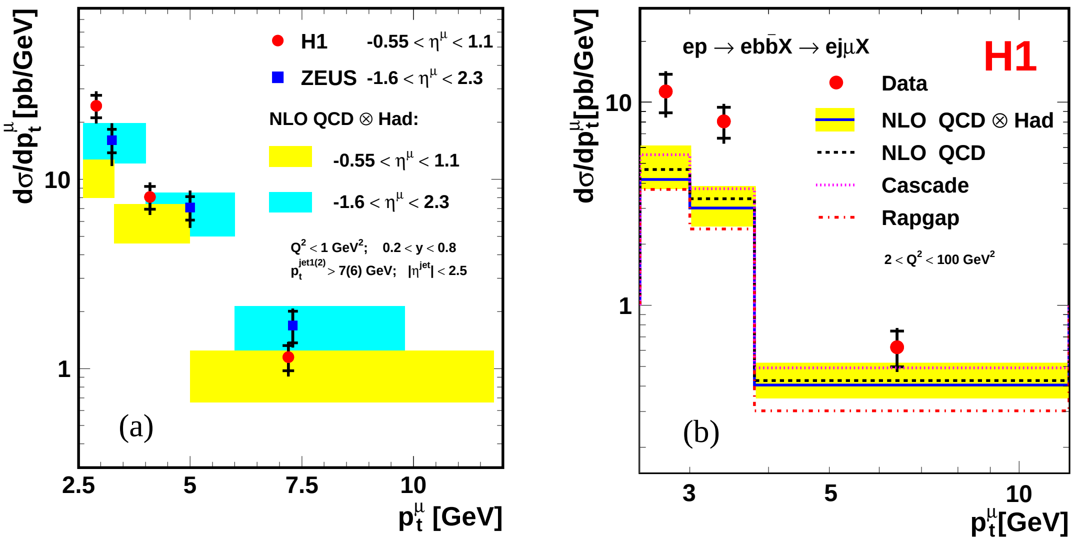

FIGURE 4. Open beauty production as a function of p_T^μ for (a) dijet photoproduction from the H1 and ZEUS experiments and (b) inclusive jet DIS from the H1 experiment. (The measurement from the ZEUS experiment for (b) has the similar result and is not shown for brevity.)

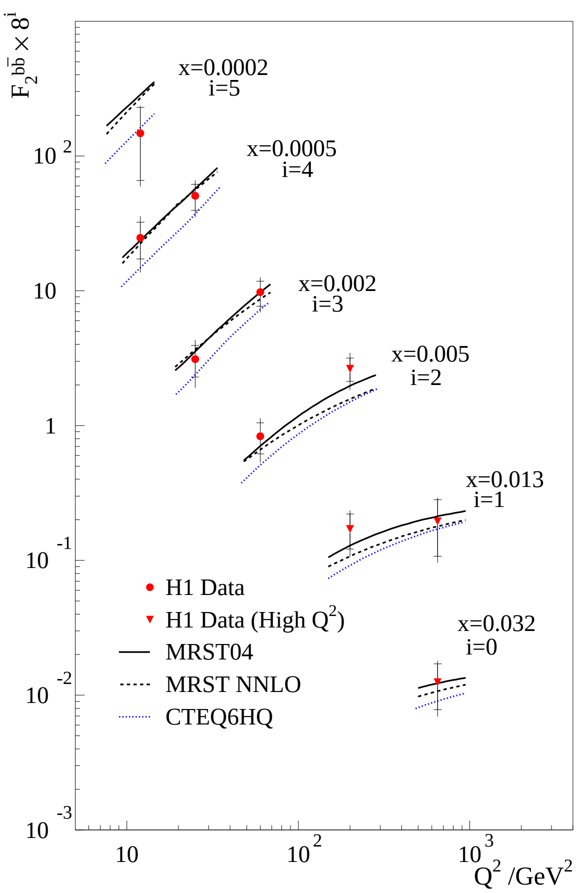

FIGURE 5. $F_2^{b\bar{b}}$ as a function of Q^2 for different x.

CONCLUSIONS

At HERA, measurements on heavy flavor production are getting more extensive and precise. New results improve the understanding of the heavy quark contributions to the proton structure function as well as the hadronic behavior of the photon. The universality of the fragmentation has also been confirmed by the recent measurements. The perturbative QCD calculation generally describes the data at next-to-leading order although discrepancies still exist in some threshold regions. Therefore higher order corrections beyond the existing models and calculations might be needed. More exciting and accurate measurements are definitely expected in the future from HERA II with higher luminosity and improved detector ability of the H1 and ZEUS experiments.

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