Charm and Beauty Photoproduction at HERA

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After the completion of data taking at HERA-2, a large data set is at hand to study the photoproduction of charm and beauty quarks in ep collisions. New measurements of charm production based on D^* meson tagging and beauty production based on muon and electron reconstruction test perturbative QCD calculations with improved accuracy. In general, QCD calculations at NLO describe the data well. The scale uncertainties are, however, large and dominate over the experimental uncertainties, calling for more precise calculations.

1. INTRODUCTION

The study of charm and beauty production is a central topic of research at HERA. In ep collisions, charm and beauty quarks are predominantly produced by the photon gluon fusion process, which makes the production rates directly sensitive to the gluon density in the proton. The mass of these heavy quarks provides a hard scale so that calculations in perturbative QCD are expected to be reliable.

However, this seemingly simple picture of photon gluon fusion with a hard scale given by the quark mass is considerably complicated by two issues: on one hand by the presence of additional hard scales such as the quark's transverse momentum, which means that heavy flavour production at HERA is inherently a multi-scale problem; on the other hand by the hadronic structure of the photon that leads to additional contributions such as flavour excitation, which pose additional challenges to theoretical calculations.

While it is possible to take the stance that the theoretical issues are sufficiently well under control that one can infer from the measured charm and beauty production rates the gluon density of the proton, a complementary approach is to use the gluon density as determined from other processes, i.e. fits to inclusive structure function data, in particular from HERA, and investigate the extent to which the formation of heavy quarks is theoretically understood in a régime where multiple scales and QCD dynamics play an important rôle.

In the following, new measurements of charm and beauty production in photoproduction at HERA will be presented. Photoproduction is characterized by a near zero virtuality[1] $Q^2 \approx 0\,\mathrm{GeV}^2$ of the exchanged photon, which essentially behaves like a real photon.

2. THEORETICAL MODELS

To correct experimental data for detector effects, Monte Carlo generators based on leading order ($\mathcal{O}(\alpha_\mathrm{s})$) matrix elements and matched parton showers are used. The Pythia program [1] is based on collinear factorization and DGLAP evolution of parton densities. In contrast, Cascade [2] is based on the k_T factorization ansatz, which uses a k_T unintegrated gluon density that is evolved according to the CCFM evolution.

For calculations at next to leading order, the FMNR program [3], based on the calculation by Nason, Dawson and Ellis [4], is available. In this program, which does not include parton showers, the fragmentation to hadrons is usually modelled using an independent fragmentation approach; a new development is the FMNR $\otimes$ PYTHIA program [5], which augments FMNR with full Lund string fragmentation.

[1]The experimental definition is usually $Q^2 < 1\,\mathrm{GeV}^2$ and is driven by the detector acceptance for scattered electrons.

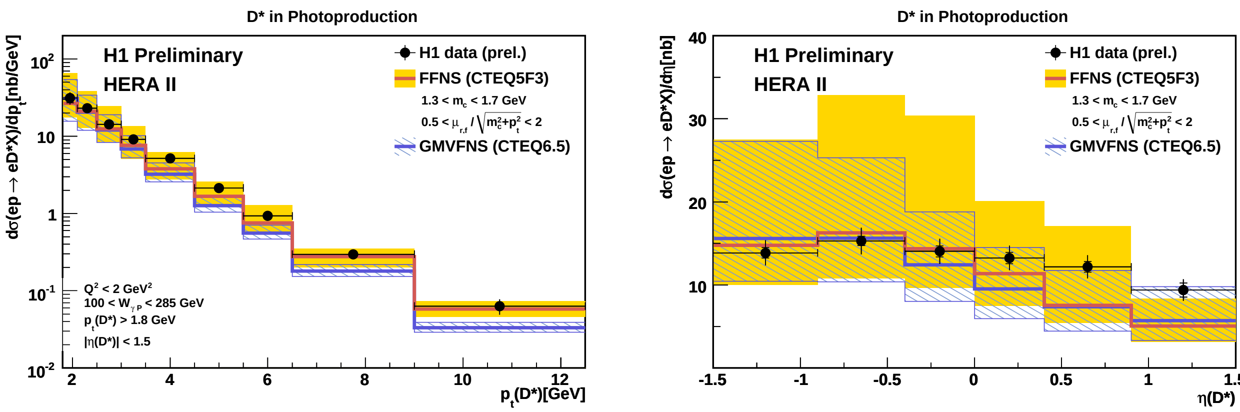

Figure 1: The H1 measurement of D^* photoproduction, compared to two QCD models at NLO: The FMNR program in the FFNS (shaded area) and a new calculation in the GM-VFNS (hatched).

3. CHARM PRODUCTION

The H1 collaboration has recently released a new measurement [6] of charm photoproduction based on an integrated luminosity of $93\,\mathrm{pb}^{-1}$ of data taken at HERA-2. Charm events were tagged by the presence of a D^* meson decaying in the golden decay channel $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ (and charge conjugates). The data were taken using a new trigger [7] that allows a full mass reconstruction of the D^* candidates at the third trigger level within $100\,\mu$s. The data covers a kinematic range defined by photon virtualities of $Q^2 < 2\,\mathrm{GeV}^2$ and photon-proton centre of mass energies of $100 < W_{\gamma\mathrm{p}} < 285\,\mathrm{GeV}$. The D^* meson is measured for transverse momenta $p_\mathrm{T}\,(D^*) > 1.8\,\mathrm{GeV}$ and pseudorapidities $|\eta\,(D^*)| < 1.5$. Differential distributions in $p_\mathrm{T}\,(D^*)$, $\eta\,(D^*)$ and $W_{\gamma\mathrm{p}}$ as well as double differential cross sections in $p_\mathrm{T}\,(D^*)$ and $\eta\,(D^*)$ have been measured and compared to various QCD models. In particular, two models at NLO QCD are available, namely FMNR and a recent calculation in the GM-VFNS [8]. Both models show similar behaviour (Fig. 1): The $p_\mathrm{T}\,(D^*)$ spectrum is well described, with a slight deficiency at high p_T in the case of the GM-VFNS model, with sizeable uncertainties from scale variations, in particular at low p_T. When the $\eta\,(D^*)$ spectrum is considered, the theoretical uncertainties are several times larger than the experimental ones; nevertheless, both models show a tendency to fall below the data at large values of pseudorapidity. A similar behaviour is found in the deep-inelastic regime [9].

4. BEAUTY PRODUCTION

The measurement of beauty photoproduction at HERA is difficult due to the fact that beauty production corresponds only to about $0.03\,\%$ of the total photoproduction cross section. Two basic techniques have been used to enrich beauty production events: The measurement of track impact parameters or secondary vertices, using a silicon vertex detector, which enrich beauty production due to the relatively large lifetime of beauty hadrons, and measurements based on leptons (muons and/or electrons), which are based on the large semileptonic branching fraction of beauty hadrons.

The H1 and ZEUS collaborations have recently released results from several analyses based on lepton tags. Two analyses, one from H1 [10] and one from ZEUS [11], are based on samples with at least one muon and two jets in the final state; in both cases, jet transverse momenta above $p_\mathrm{T}^{\mathrm{jet1(2)}} > 7(6)\,\mathrm{GeV}$ are required. The resulting samples are enriched to about $30\,\%$ of beauty events by the requirement of two high-p_T jets in conjunction with a highly energetic muon. The actual fraction of beauty events is then determined from fits to the distribution of the impact parameter δ of the muon track and the relative transverse momentum $p_\mathrm{T}^{\mathrm{rel}}$ of the muon with respect to the nearest jet axis. In these measurements, the $p_\mathrm{T}^{\mathrm{rel}}$ distribution allows the separation of beauty induced events from those of light (uds) and charm quarks with good precision; the impact parameter distribution on the other hand allows in addition the separation of light and charm quark induced events and thus serves not only as a cross check of the $p_{\rm T}^{\rm rel}$ based measurement, but also helps to reduce the systematic uncertainty which would otherwise be incurred by the uncertainty of the charm quark contribution to the $p_{\rm T}^{\rm rel}$ spectrum. Both measurements cover a range of $0.2 < y < 0.8$ in inelasticity, momentum transfer $Q^2 < 1\,{\rm GeV}^2$, muon transverse momentum $p_{\rm T}^{\mu} > 2.5\,{\rm GeV}$ and jet pseudorapidity $|\eta^{\rm jet1(2)}| < 2.5$; however, the ZEUS data cover a range $-1.6 < \eta^{\mu} < 2.3$ of muon pseudorapidities, while the H1 analysis is restricted to $-0.55 < \eta^{\mu} < 1.1$. The ZEUS analysis is based on $124\,{\rm pb}^{-1}$ of data taken in 2004 and 2005, while the H1 result uses $171\,{\rm pb}^{-1}$ of data from the years 2006 and 2007.

Both analyses show good agreement with perturbative QCD calculations performed with the FMNR program, after corrections for hadronisation effects have been applied to the FMNR predictions, which are available only at parton level. The excess of data over NLO predictions at low values of jet and muon transverse momenta that was reported in an earlier H1 analysis of HERA-1 data [12] and was in disagreement with ZEUS data [13], is not confirmed by the new H1 analysis.

ZEUS has also published a new measurement based on events with semileptonic decays to electrons [14]. In this analysis, events with two jets of $E_{\rm T}^{\rm jet1(2)} > 7(6)\,{\rm GeV}$ and at least one electron are selected from $120\,{\rm pb}^{-1}$ of data taken at HERA-1. The beauty contribution was determined from a fit to a likelihood variable based on quantities that are sensitive to the quality of electron identification, such as the specific ionisation ${\rm d}E/{\rm d}x$, as well as quantities that allow the separation between electrons from light quark or charm induced processes from bottom production. These quantities are again $p_{\rm T}^{\rm rel}$, and $\Delta\phi$, the azimuthal angle difference between the electron flight direction and the direction of the total missing transverse momentum. Again, reasonable agreement with the NLO QCD calculation FMNR is observed, for the total cross section as well as differential distributions.

An upcoming publication by ZEUS [15] is based on $114\,{\rm pb}^{-1}$ of data taken at HERA-1 and utilizes events with two muons in the final state. Contrary to other work discussed here, no jet requirement is imposed in the selection, which is possible due to the high beauty fraction of a dilepton sample, and the analysis is performed down to muon transverse momenta of $p_{\rm T}^{\mu} > 1.5\,{\rm GeV}$, or even $p_{\rm T}^{\mu} > 0.75\,{\rm GeV}$ for high-quality muon candidates. The analysis is thus sensitive down to to the threshold of beauty production, where the transverse momentum of the beauty quarks is close to zero. Therefore a measurement of the total beauty production cross section is possible with relatively small extrapolation errors. The total cross section for the process $ep \to b\bar{b}X$ at $\sqrt{s} = 318\,{\rm GeV}$ has been determined to be $\sigma_{\rm tot}(ep \to b\bar{b}X) = 13.9 \pm 1.5\,({\rm stat.})^{+4.0}_{-4.3}\,({\rm syst.})\,{\rm nb}$, to be compared to the NLO QCD prediction of $\sigma_{\rm tot}^{\rm NLO}(ep \to b\bar{b}X) = 7.5\ \pm^{+4.5}_{-2.1}$ nb. Within the large uncertainties, in particular of the NLO calculation, the NLO prediction is consistent with the data.

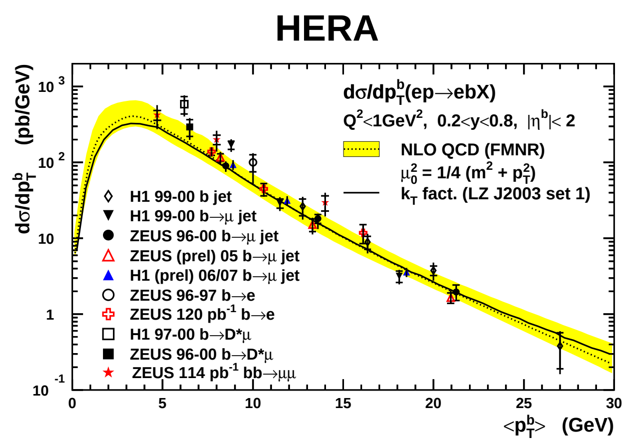

Figure 2: A compilation of beauty photoproduction cross section measurements as a function of the mean transverse momentum of the beauty quarks, compared to QCD calculations at NLO.

Fig. 2 summarizes all currently available beauty photoproduction measurements at HERA, in comparison to the QCD prediction at NLO. It can be seen that NLO QCD describes the data well in shape and normalization, albeit with rather large uncertainties, which are dominated by the choice of scale. Note that for this plot the central value of the QCD prediction is derived for a choice of $\mu_{\rm r,f} = \mu_0 = 1/2\sqrt{m_{\rm b}^2 + p_{\rm T}^2}$ for the renormalization and factorization scales [16], while the individual measurements sometimes use twice this value, i.e. $\mu_0 = \sqrt{m_{\rm b}^2 + p_{\rm T}^2}$ for the central value.

5. CONCLUSIONS

The study of the photoproduction of charm and beauty quarks at HERA remains a challenging testing ground for perturbative QCD. With the increased statistical precision provided by the HERA-2 data set, and improved detector understanding that results in more precise measurements from HERA-1, measurements of charm and beauty production are now available with experimental uncertainties that are significantly smaller than the theoretical uncertainties of QCD calculations, even at next to leading order. Using gluon densities based on fits to inclusive structure function measurements, these calculations in general describe the data reasonably well in shape and normalization, which is a great success of perturbative QCD. However, differential distributions such as the η distribution of D^* mesons indicate deficiencies in the calculations which may need further work to resolve.

Acknowledgments

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