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Heavy Flavour Production at HERA

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Abstract

ZEUS and H1 results on heavy quark production using the HERA data from 1995 to 2000 are summarised with emphasis on unresolved problems. The HERA upgrade and its impact on future heavy flavour measurements is briefly discussed.

1. Introduction

The first phase of HERA operation has yielded extensive results on charm production, both in photoproduction and Deep Inelastic Scattering (DIS)[1]. Recently, both the ZEUS and H1 experiments have also presented results on beauty production[2]. Perturbative QCD calculations have been performed to fixed order in α_s^2 the so-called "massive" scheme for both photoproduction and DIS[3]. It is expected that the masses of the charm and beauty quarks provide a hard scale that should ensure that these calculations give a reasonable description of the hard sub-process. All these calculations rely on Peterson[4] fragmentation functions to provide final, differential hadronic cross-sections. In addition, the standard arsenal of leading-order (LO) Monte Carlo (MC) programs[5] is available to provide hadron-level comparisons to the data.

2. Charm Production

The majority of HERA results on charm are based on D^* tagging using the decay chain $D^{*+} \to D^0\pi^+; D^0 \to K^-\pi^+$ (and c.c.). ZEUS have also used semi-leptonic decays of charm to electrons and D_s

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mesons in their publications[6]. Results on J/ψ mesons are not covered here.

Figure 1 shows a comparison of the NLO QCD predictions of FMNR (using MRS(G)[7] and GRV-G HO[8] for the proton and photon structure functions, respectively) to the measured cross sections. The central predictions (heavy lines) underestimate the data by almost a factor of two, the agreement only being improved by changing the input parameters in the calculations to rather extreme values. There is also a question of the shape of the predictions at low p_t being different to the data. The data lie significantly above the predictions in the forward (positive η) direction which may be a sign of further interactions with the proton beam remnant which are not taken into account using pure Peterson fragmentation.

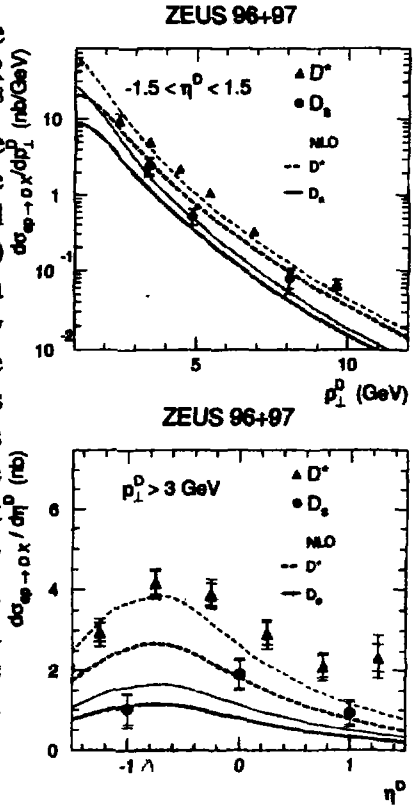

Figure 1: D meson cross-sections in protoproduction as a function of transverse momentum, P_t^D, and pseudorapidity, η^D.

Jets in photoproduction events can provide an additional hard scale that allows an investigation of the heavy quark content of the photon. If there are at least two jets in the event we can define the quantity:

$$x_\gamma^{obs} = \frac{E_t^{jet1} e^{-\eta^{jet1}} + E_t^{jet2} e^{-\eta^{jet2}}}{2yE_e},$$

where *jet1* and *jet2* are the two highest E_t jets in the event, E_e is the lepton beam energy and y is the usual inelasticity variable. x_γ^{obs} can be interpreted as the fraction of the photon's momentum that participates in the hard sub-process. So-called "direct" events have

x_γ^{obs} close to unity, which simply states that the photon behaves like a pointlike object in the interaction. Events with $x_\gamma^{obs} < 0.75$ are known as "resolved" events in which the photon has fluctuated into a hadronic system before interacting. Figure 2a shows a comparison between cross-sections for D^* production with at least two associated jets and LO HERWIG MC. There is clearly a large LO charm excitation component, and the overall shape is well described. However, NLO predictions at parton-level significantly underestimate the data at low x_γ^{obs}, shown in Figure 2b.

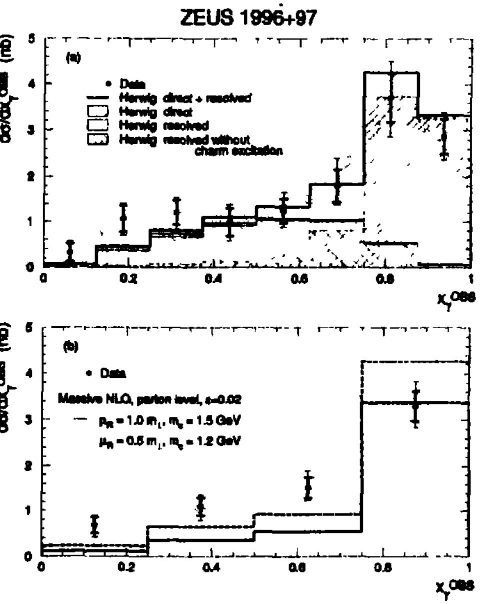

Figure 2: Cross-sections for D^* production with at least two associated jets in photoproduction compared to (a) LO MC and (b) NLO QCD parton-level predictions.

Since there is such a large charm component in the photon structure function, it is instructive to investigate the transition to the DIS regime where it is expected that the resolved charm component is suppressed as we increase Q^2 (Q^2 being the virtuality of the exchanged photon). Inclusive measurements have shown that the resolved component of the cross-section is indeed suppressed[9], but it is now possible to make the same measurement with a heavy quark tag. Figure 3 shows the ratio $\frac{\sigma(x_\gamma^{obs} < 0.75)}{\sigma(x_\gamma^{obs} > 0.75)}$, which should be sensitive to this suppression. Clearly it is hard to draw definite conclusions with the large error bars, but the suppression (if any) seems to be less than that in the inclusive case. It is interesting to note that the CASCADE MC, which uses an unintegrated[10] gluon distribution, agrees with the data without the need for an explicit resolved photon component (not shown here).

Both ZEUS and H1 have measured charm production in DIS and extracted the quantity F_2^c, defined by the double differential cross-section

$$\frac{d^2\sigma}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left(1+(1-y)^2\right)F_2^c.$$

Although this is only an operational definition it can be compared to theoretical predictions based on NLO DGLAP evolution. Figure 4 shows the ZEUS and H1 data compared to such a QCD fit by H1 to their inclusive F_2 measurement. There is impressive agreement between both experiments, different methods of measuring the charm contribution, and the NLO prediction. The charm contribution to the total cross-section is sizeable, rising to ≈40% at low-x and high Q^2.

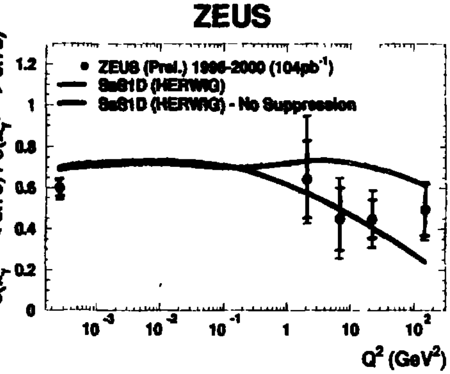

Figure 3: The ratio of resolved to direct charm production with increasing Q^2.

3. Beauty Production

The large data sets from the HERA I (1995-2000) run now permit the first measurements of beauty production. Both ZEUS and H1 have measured beauty production in photoproduction, while H1

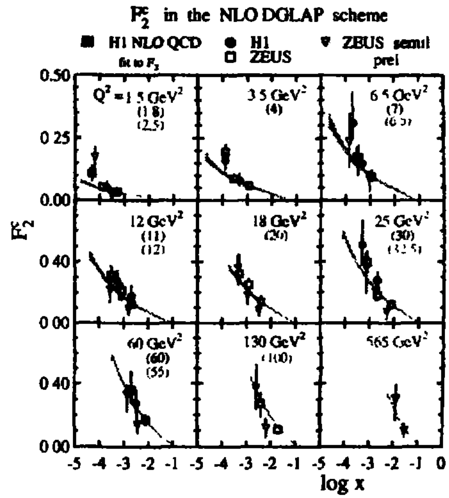

Figure 4: Combined ZEUS and H1 measurements of F_2^c compared to a NLO DGLAP prediction based on a fit to inclusive F_2.

have recently shown first results on beauty production in DIS[2].

The new H1 photoproduction results use data from their silicon microvertex detector to measure charged track impact parameters and complement the previous p_t^{rel} based analyses. Figure 5 shows the H1 results for both the impact parameter and p_t^{rel} measurement. There is a significant beauty component in the data, and the measured cross section is

$$\sigma_{Vis}\left(ep \rightarrow b\bar{b}X \rightarrow \mu^{\pm}X\right) = 170 \pm 25\text{pb}.$$

The NLO prediction by FMNR[3] of 54±9 pb, and LO MC predictions, are significantly below the measurement. ZEUS have recently released measurements of differential cross-sections for beauty production including the very forward region. Figure 6 shows these cross-sections as functions of the muon p_t and pseudorapidity η, the data are reasonably well described by LO MC simulations including beauty excitation, but again the MC underestimates the data in the very forward region. There are no NLO QCD predictions available at present for comparison.

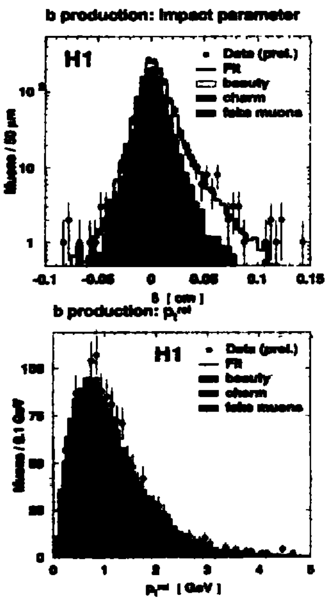

Figure 5: H1 measurements of beauty in photoproduction using both p_t^{rel} and impact parameter information.

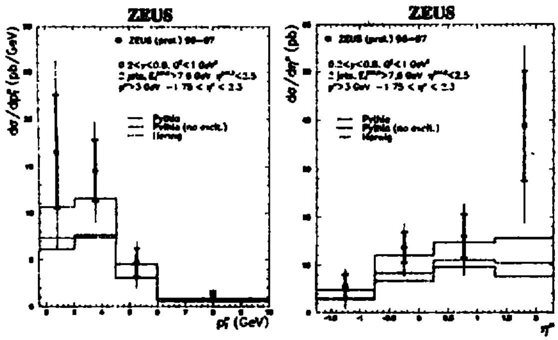

Figure 6: New ZEUS results on beauty production, extending the measure region into the forward direction.

The first measurement

of beauty in DIS by H1 uses the same impact parameter technique as the photoproduction analysis. The measured cross section is:

$\sigma_{Vis}^{ep\to b\bar{b}X\to\mu X}=39\pm8(\text{stat})\pm10(\text{sys})$ pb, a factor of three higher than the NLO prediction of 11±2 pb. Figure 7 shows a summary of the HERA beauty production measurements. The general trend is clear – the measurements are consistent with one another and lie a factor of 2-3 above the theoretical predictions.

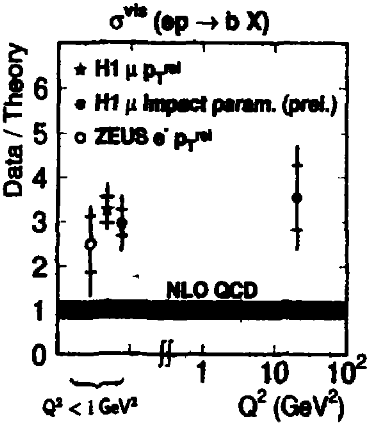

Figure 7: Summary of HERA beauty measurements in DIS and photoproduction compared to NLO QCD.

4. The HERA Upgrade

In 2000 HERA shut down for a major upgrade. The primary goal of this work is to deliver 1 fb^{-1} to both ZEUS and H1 by 2006. In addition, spin rotators will be installed for both the experiments to enable a program of study using longitudinally polarised lepton beams. ZEUS and H1 both have major upgrade programs, including improvements to their tracking detectors and triggers. These improvements, combined with the increase in delivered luminosity, will place heavy quark physics at the forefront of the coming HERA program. New areas of study include charm in charged-current DIS with the associated direct measurement of the strangeness content of the proton and the first measurement of F_2^b.

5. Summary and Conclusions

ZEUS and H1 results on heavy quark production at HERA have been covered. Overall, charm production is reasonably well described by NLO calculations. However, beauty production is significantly underestimated by current predictions and would clearly benefit from more theoretical insight.

The HERA upgrade will clarify the situation with high-precision measurements of heavy quark production; however, in conjunction with the improvement in statistical precision of the measurements, it is clear that improved theoretical tools will be necessary. It is already clear that, whilst the NLO calculations that are available are sufficient to describe the data, detailed comparisons are not possible due to the lack of hadron-level NLO MC event generators. In particular, these will be crucial to understand the excesses observed in the forward production cross-sections. The apparent disagreement between the measured beauty cross sections and NLO predictions may be resolved by a detailed treatment using an unintegrated gluon distribution, but there are, as yet, no NLO calculations available for the HERA environment. There has been progress in the formal treatment of heavy quark production, and new variable flavour number schemes[11] that interpolate between the fixed order schemes and the resummed prescriptions (valid for hard scales >> quark mass) are available. First comparisons with the data are encouraging; their availability in the "mainstream" is eagerly anticipated.

Diffractive production of charm has not been covered here. There is much theoretical interest in this subject. H1 have recently released results[12], but the limited statistical precision again prevents drawing any firm conclusions on the nature of the diffractive exchange. Diffractive heavy quark production will be another major focus of the post-upgrade HERA program.

The next years of HERA operation will produce a wealth of heavy quark data that will elucidate the structure of the proton with unprecedented accuracy – a cornerstone of the global particle physics agenda before the start up of the LHC.

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