Recent measurements of beauty production in ep collisions at HERA are presented. The results were obtained using data from the experiments H1 and ZEUS from the years 1996 to 2000 (HERA I). An outlook is given for analysis on data from HERA II. Differential measurements using muons and jets in deep inelastic scattering and photoproduction are compared to NLO QCD predictions. The beauty contribution to the proton structure function $F_2$ was determined at large $Q^2$ ($Q^2 > 150$ GeV$^2$) and is compared with predictions.

1 Introduction

At HERA (DESY, Hamburg) electrons (positrons) are brought into collision with protons at a centre-of-mass energy of 318 GeV (300 GeV up to 1997). From 1996 to 2000 the two experiments H1 and ZEUS collected about 100 pb$^{-1}$, on which the results presented here are based. The measurement of beauty production still is a rich testing ground for QCD, as several hard scales can be chosen, depending on the process to be described. The beauty mass always provides one hard scale, but due to the presence of additional scales, calculations are not straightforward. In HERA ep collisions, beauty quarks are predominantly produced in boson gluon fusion; a photon from the lepton and a gluon from the proton collide to produce a b\bar{b} pair. This process introduces several scales relevant for the calculation of the cross sections:

- mass of the b quark $m_b \sim 5$ GeV
- transverse momentum of the b quark $p_T^b \sim$ typically a few GeV
- virtuality of the exchanged photon $Q^2 \lesssim 1$ GeV$^2 \equiv$ Photoproduction ($\gamma p$)
  $Q^2 \gtrsim 1$ GeV$^2 \equiv$ Deep Inelastic Scattering (DIS)

The optimal scheme for Next to Leading Order (NLO) QCD predictions depends on the dominant scale. If the virtuality, $Q^2$, and the transverse momentum of the b quark squared, $(p_T^b)^2$, are of the order of the b mass squared, $m_b^2$, threshold effects due to the b mass need to be considered and the so called massive scheme (used in the Fixed Flavour Number Scheme - FFNS) is used.
Once $Q^2$ or $(p_T^b)^2$ are much larger than $m_b^2$, massless schemes (used in the Zero-Mass Variable Flavour Scheme - ZM-VFNS) can be used. Here the $b$ quark is treated as a massless parton in the hard scatter. In the Variable Flavour Number Scheme (VFNS) the massive and massless approaches are combined. Differential cross sections are compared to massive NLO predictions by FMNR for $\gamma p$ and HVQDIS for DIS. For references to all schemes, NLO predictions and MC generators please refer to ref. 1 2 3 4.

2 Measurements in $\mu+\text{jet}(s)$

In events with a jet and a muon, two properties of the $b$ hadrons were exploited to tag beauty events: the large $b$ mass and the long lifetime. The $b$ mass leads to a relatively large transverse momentum of the muon relative to the closest jet, $p_T^{\text{rel}}$. The long lifetime of the $b$ was used by measuring the distance of closest approach in the transverse plane, $\delta$, of the muon track to the beam spot or main vertex. A sign was added to $\delta$, which was set positive if the muon track crosses the jet axis downstream of the beam spot, else it was set negative.

2.1 Beauty in $\gamma p$ in $\mu+\text{jets}$

H1 has measured differential cross sections in events with a muon and 2 jets in the photo-production regime for $Q^2 < 1 \text{ GeV}^2$ using an integrated luminosity of 50 pb$^{-1}$. To tag beauty events a simultaneous fit to both the $p_T^{\text{rel}}$ and the signed $\delta$ distribution was performed. The cross sections obtained are given in fig. H1. ZEUS performed a similar measurement relying on $p_T^{\text{rel}}$ only in a wider muon eta range of $|\eta^\mu| < 2.5$.

Differential cross sections in $p_T^\mu$ and $\eta^\mu$ are shown in fig. H1 together with the massive NLO QCD prediction (FMNR) which has been corrected, using LO+PS MC simulations, to describe the measured hadron level properties. Reasonable agreement of the NLO prediction with data is observed. The data are a bit steeper in $p_T^\mu$ in the H1 measurement, see fig. H1. H1 and ZEUS agree within errors, as shown in fig. H1a and b.

Figure 1: Differential cross sections in $p_T^\mu$ and $\eta^\mu$ of muons from beauty events in $\gamma p$ with NLO predictions as measured by H1 and ZEUS.

2.2 Beauty in DIS in $\mu+\text{jet}$

Beauty cross sections were also measured for $Q^2 > 1 \text{ GeV}^2$ using the same techniques as described above. H1 has used a $Q^2$ range of $2 < Q^2 < 100 \text{ GeV}^2$. The H1 cross sections were obtained for events with $p_T^\mu > 2.5 \text{ GeV}$, $-0.75 < \eta^\mu < 1.15$, $0.1 < y < 0.7$, $p_T^{\text{Breit}} > 6 \text{ GeV}$ and $|\eta^{\text{jet}}| < 2.5$.
where the index 'Breit' refers to the Breit frame. The $\eta^\mu$ cross section is shown in fig. 2a.

ZEUS has performed a similar measurement in DIS (fig. 2b) using data in the $Q^2$ range of $1 < Q^2 < 1000$ GeV$^2$ and defining the kinematic range as $p_T^\mu > 2.0$ GeV, $-1.6 < \eta^\mu < 1.3$, $0.05 < y < 0.7$, $E_T^{Breit jet} > 6$ GeV and $-2.0 < \eta_{lab}^{jet} < 2.5$. The $p_T^\mu$ spectrum from both H1 and ZEUS is slightly steeper than the prediction (not shown). An interesting feature is seen in the $\eta^\mu$ distribution in fig. 2: for both H1 and ZEUS (kinematic ranges differ) the cross section rises towards higher $\eta^\mu$, a trend that is not well reproduced by the NLO predictions.

![Figure 2: The $\eta^\mu$ cross section of muons from beauty events in DIS as measured by H1 (a) and ZEUS (b).](image)

### 3 Inclusive measurements using impact parameters

Events with heavy flavour mesons can contain several tracks with large impact parameters. To inclusively determine the beauty contribution, events were selected in H1 by inclusive lifetime tagging, using all $p_T > 0.5$ GeV tracks with reasonable precision vertex tracker information. For these tracks the impact parameter significance $S_{1(2)} = \delta_{1(2)}/\sigma_{\delta_{1(2)}}$ was calculated for the track with the largest (second largest) impact parameter $\delta$ (with $|\delta| < 0.1$ cm). The sign of the impact parameter was chosen relative to the direction of the closest jet if present or from the hadronic final state, also requiring $sign(S_1) = sign(S_2)$. This method yields high statistics and a good separation of beauty from charm and light flavour processes.

#### 3.1 Beauty contribution to $F_2$

To determine the beauty contribution to the proton structure function, double differential beauty cross sections in bins of $x$ and $Q^2$ were measured using inclusive lifetime tagging. The resulting $F_2^{bb}$ is shown in fig. 3. Good agreement with both the H1 PDF 2000 fit [5] and MRST03 [6] was found. The integrated beauty cross section for $Q^2 > 150$ GeV$^2$ and $0.1 < y < 0.7$ has been determined to be $\sigma^{bb} = 55.4 \pm 8.7 \pm 12$ pb. This is compatible with several predictions: H1 PDF 2000 (massless, ZM-VFNS) $\sigma^{bb} = 52$ pb, NLO (massive massless, VFNS) $\sigma^{bb} = 47$ pb, and NLO (massive, FFNS) $\sigma^{bb} = 37$ pb.

### 4 Conclusion and Outlook

NLO QCD predictions generally agree with the data, though they are somewhat below the data in some kinematic regions. H1 and ZEUS measurements with muons + jet(s) in $\gamma p$ and DIS agree. The measurement of the beauty contribution to $F_2$ at high $Q^2$ using inclusive lifetime tagging is in good agreement with NLO.
The upgraded HERA II detectors are giving promising results. ZEUS presented a study of beauty in photoproduction based on the first 20 pb$^{-1}$ taken in 2003/4 using the new ZEUS vertex detector. The impact parameter distribution, as shown in fig. 4a, has been validated by comparing the difference of the positive and negative parts of the impact parameter distribution with MC which in turn has been normalised using the $p_T^{rel}$ method, as shown in fig. 4b.

The displayed MC prediction has been normalised using the $p_T^{rel}$ method.

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