Measurement of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ using the H1 Vertex Detector and Combination of $F_2^{c\bar{c}}$ with the D^* method

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Recent measurements by the H1 experiment of the inclusive charm and beauty cross sections in e^-p and e^+p neutral current collisions at HERA in the kinematic region of photon virtuality $5 \leq Q^2 \leq 400$ GeV^2 are presented [1]. The data were collected in the years 2006 and 2007 corresponding to an integrated luminosity of 189 pb^{-1}. The numbers of charm and beauty events are determined using variables reconstructed by the H1 vertex detector including the impact parameter of tracks to the primary vertex and the position of the secondary vertex. The measurement of the inclusive charm cross section is combined with the result obtained using the reconstruction of D^* mesons to yield a more precise measurement of the inclusive charm structure function $F_2^{c\bar{c}}$. The measurements are compared with QCD predictions.

1 Introduction

In perturbative QCD calculations, the production of heavy quarks at HERA proceeds dominantly via the direct photon-gluon fusion (PGF) process $\gamma g \to c\bar{c}$ ($\gamma g \to b\bar{b}$), where the photon interacts with a gluon from the proton to produce a pair of heavy quarks in the final state. Therefore, the measurement of processes involving heavy flavour production provides a test of the understanding of the QCD production mechanism and information on the gluon content of the proton. The presence of the heavy quark mass M provides an additional "hard" scale to the momentum transfer of the exchanged boson Q meaning the perturbative series has to be treated in different ways depending on the relative magnitude of M and Q. At small scales ($Q \sim M$) the mass of the heavy quark is taken into account via the "massive" PGF matrix element. This matrix element is implemented within the fixed flavour number scheme (FFNS). At high scales ($Q \gg M$) the quark's mass may be neglected and it is treated as a "massless" parton. The latest sets of global parton density functions (PDFs) from the CTEQ and MSTW fitting groups (CTEQ6.6 [2], MSTW08 [3]) are based on the general mass variable flavour number scheme (GM VFNS) which aims to interpolate between the massive behaviour at low Q^2 and massless behaviour at high Q^2. The measurement of the inclusive contribution of processes involving charm and beauty to the proton structure function $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ allows to directly test the PDFs and the GM VFNS scheme. The understanding of the gluon and heavy quark distributions in the region of low Bjorken x has important implications for the measurement of Standard Model and new physics processes at hadron colliders such as the Tevatron and LHC.

In this paper recent measurements on the inclusive production of beauty(b) and charm(c) quarks in neutral current deep inelastic scattering (DIS) at HERA by the H1 experiment are presented [4]. The analysis uses information based on tracks with hits in the silicon vertex detector to provide precise spatial track reconstruction. The analysis makes use of the full HERA II data sample.

To improve the precision of the data on the inclusive charm cross section the results are combined in section 4 with results obtained from the reconstruction of D^* mesons. The charm structure function $F_2^{c\bar{c}}$ and the beauty structure function $F_2^{b\bar{b}}$ are obtained from the measured charm and beauty cross sections after applying small corrections for the longitudinal structure functions $F_L^{c\bar{c}}$ and $F_L^{b\bar{b}}$.

2 Analysis Techniques

Charm quarks contribute around 20–30% of the inclusive DIS cross section. At H1 charmed hadrons are predominantly detected by reconstructing the decay products of $D^{*\pm}$ mesons in the central tracking detector using the "Golden Decay" chain $D^* \rightarrow K\pi\pi_{\text{slow}}$. Recent measurements using HERA II data have been made at both low [5] and high Q^2 [6].

In contrast to the rather large contribution of charm quarks to the total DIS cross section, beauty quarks contribute only a few %, and an order of magnitude less at low values of Q^2. Therefore, the detection of beauty hadrons is very challenging. In the present analysis events containing heavy quarks are distinguished from those containing only light quarks using variables that are sensitive to the longer lifetimes of heavy flavour hadrons. The most important of these variables are the transverse displacement of tracks from the primary vertex and the reconstructed position of a secondary vertex in the transverse plane. For events with three or more tracks in the vertex detector the reconstructed variables are used as input to an artificial neural network (NN). This method has better discrimination between c and b compared to previous methods [7, 8], which used only the transverse displacement of tracks from the primary vertex. This lifetime based method has the advantage over more exclusive methods, such as using D^* mesons discussed above, in that a higher fraction of heavy flavour events may be used, although the background from light quark events is larger.

The c, b and light quark fractions in the data are extracted using a simultaneous fit of simulated reference distributions, obtained from Monte Carlo simulation, to the measured impact parameter and NN output distributions. The beauty cross sections from HERA II are combined with those from HERA I [7, 8] to obtain the most precise result from the complete HERA dataset. The charm cross sections obtained using this lifetime tagging technique have a much finer binning in HERA II compared with HERA I and the two datasets are not combined. However, the HERA II charm results are combined in section 4 with the results obtained using D^* mesons in HERA II.

3 Heavy Flavour Cross Sections using Lifetime Information

The inclusive "reduced" beauty cross section in DIS $\tilde{\sigma}^{b\bar{b}}$ ($\tilde{\sigma}^{b\bar{b}} \simeq F_2^{b\bar{b}}$) from the combined HERA dataset is shown as a function of x for different values of Q^2 in figure 1(left). The measurements are compared in the figure with the NLO predictions of CTEQ [2] and MSTW [3] and with predictions based on CCFM [9] parton evolution. The data are found to be generally well described by all the models.

The charm structure function $F_2^{c\bar{c}}$ from the HERA II dataset is shown as a function of Q^2 for different values of x in figure 1(right). The data are compared with the GM VFNS QCD predictions from MSTW at NLO[3] and NNLO[10, 3]. The description of the data by

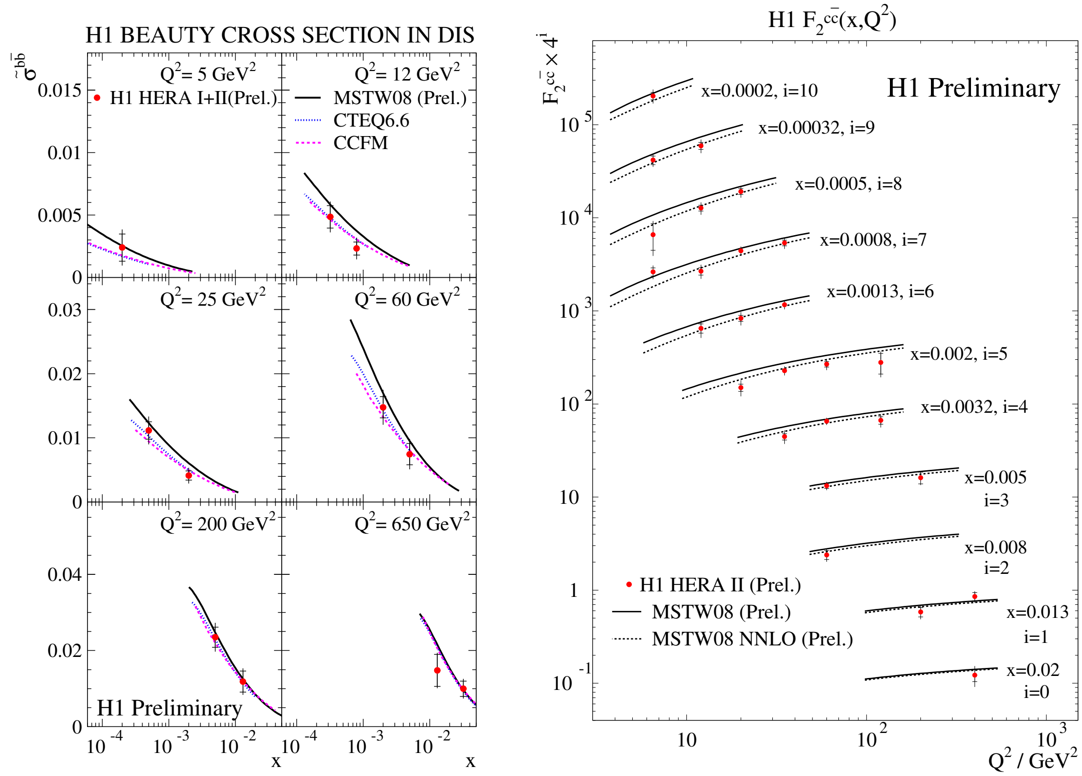

Figure 1: The reduced beauty cross section(left) and $F_2^{c\bar{c}}$(right) obtained using measurements based on lifetime information. The beauty data is a combined HERA I and HERA II dataset, whereas the charm data is from HERA II alone.

the MSTW QCD calculations is reasonable, with the NNLO being somewhat better than NLO.

4 Combination of Results with those from the D^* Method

The charm structure function $F_2^{c\bar{c}}$ obtained using information from the H1 vertex detector (lifetime tag) from the HERA II data set is combined with that extracted from D^* meson cross sections measured at H1. In the combination procedure [11] the bin-to-bin correlations of systematic uncertainties of the single measurements as well as the cross-correlations of the systematic uncertainties of the different measurement methods are taken into account. The advantage of the combination of $F_2^{c\bar{c}}$ obtained by the different tagging methods is the cross-calibration of the measurements due to the different sources of experimental and theoretical systematic uncertainties.

Only three systematic uncertainty sources are common between the D^* and the lifetime tag measurements: the track finding efficiency in the central jet chambers, the hadronic energy scale and the treatment of the fragmentation of c-quark. These are treated as cross-correlated in the combination procedure.

The D^* analysis [5, 6] uses data from the full HERA-II running period, yielding an integrated luminosity of 340 pb^{-1}. The visible phase space accessible by the H1 detector via reconstruction of D^* mesons covers only about 30% of the full phase space of charm production. Therefore the determination of $F_2^{c\bar{c}}$ strongly depends on the model used for the extrapolation. Two models, HVQDIS [12] and CASCADE [13], are used for the extraction of the charm structure function from the D^* measurements, for details see [14]. Overall small differences of the extrapolation factors, as estimated by using the two models, are observed except for 5 high x points in the $5 < Q^2 < 100$ GeV^2 region, where they differ almost by a factor of 2. The five highest x points are excluded from the combination. Otherwise the average value of $F_2^{c\bar{c}}$ obtained using the HVQDIS and CASCADE models is taken and half the difference is assigned as a systematic uncertainty.

The charm structure functions obtained from the lifetime tag method and D^* cross section measurements are derived at different central values of x and Q^2. For the combination, a common (x, Q^2)-grid which is a compromise from the grids of both measurements is used. The $F_2^{c\bar{c}}(x, Q^2)$ values are interpolated to the common grid using the NLO calculation of [15]. The interpolation factors vary between 1% and 13%.

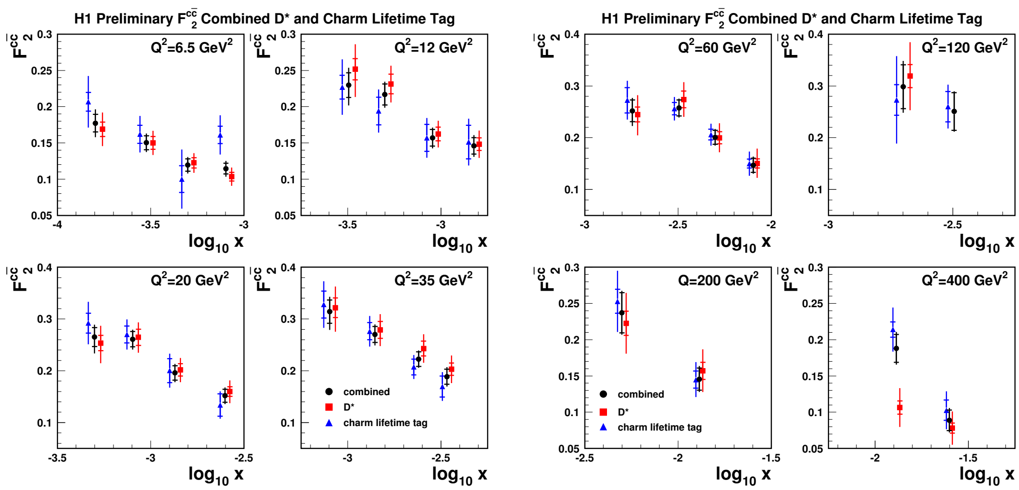

Figure 2: The combined values of $F_2^{c\bar{c}}$ (black circles) compared with the D^* measurement (red squares) and the lifetime tag measurement (blue triangles). The inner (full) error bars represent the uncorrelated (total) uncertainty of the measurements.

The precision of the combined values of $F_2^{c\bar{c}}(x, Q^2)$ compared with the original measurements is shown in figure 2. In the kinematic regions where both measurements have similar precision, the uncertainty of the combined $F_2^{c\bar{c}}$ is reduced by approximately a factor of 2 with respect to a single measurement.

The combined values of $F_2^{c\bar{c}}(x, Q^2)$ are compared with the theoretical predictions in figure 3. The massive FFNS NLO calculation [15] obtained using the CTEQ5F3 PDFs describes the data well. The prediction using the matched FFNS-GM VFNS NLO approach for the global fit by the MRST group [16] lies below the data at low values of Q^2. The MSTW VFNS prediction at NLO [3] lies above the data at low Q^2, whereas the NNLO

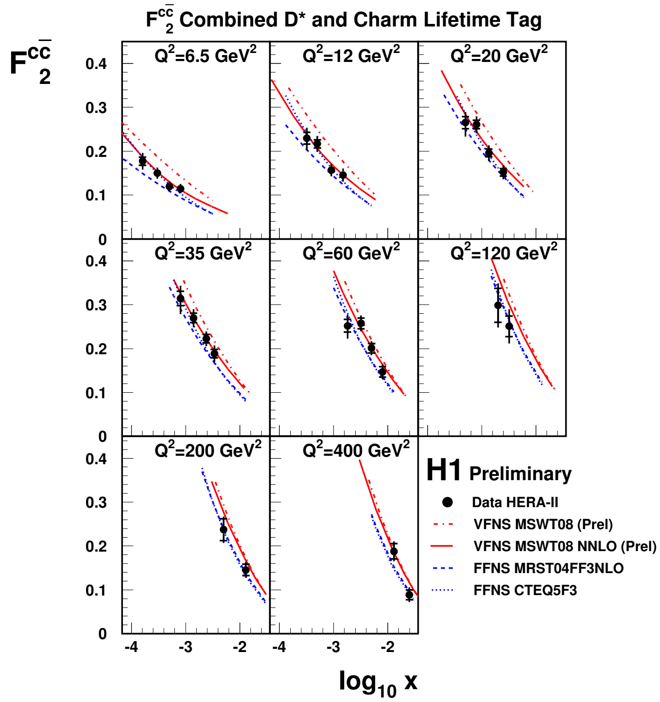

Figure 3: The combined $F_2^{c\bar{c}}$(black symbols) compared with: GM VFNS MSTW08 predictions at NLO(red dash-dotted line), and NNLO (red solid line); FFNS calculations using the MRST04NLO PDFs(blue dashed line) and the CTEQ5F3 PDFs(blue dotted line). The inner error bars represent the statistical uncertainty, the full error bars show the total uncertainty.

prediction [10, 3] describes the data reasonably well over the whole kinematic range.

5 Conclusion

Measurements of the heavy flavour content of the proton in DIS at HERA have been presented. The extraction of the inclusive cross sections $F_2^{b\bar{b}}$ and $F_2^{c\bar{c}}$ is made using information from the H1 vertex detector (lifetime tag). The cross sections are found to be well described by the predictions of perturbative QCD at NLO and NNLO. The averaged $F_2^{c\bar{c}}\left(x, Q^2\right)$ obtained combining the the results of the lifetime tag analysis with those obtained from D^* measurements provides the most precise $F_2^{c\bar{c}}\left(x, Q^2\right)$ measurement at HERA. Hence, more precise tests of perturbative QCD (pQCD) become possible. The NLO calculation in the fixed flavour number scheme describes the data well. The prediction from the PDF fit at NLO in the variable flavour number scheme at NLO overestimates the charm contribution to the proton structure function at low Q^2, which is improved in the NNLO prediction.

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