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Recent results from the ZEUS experiment

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A summary of the most recent results by the ZEUS collaboration is presented. The emphasis is put on the understanding of the proton structure and of QCD. The combination of the H1 and ZEUS inclusive cross sections and the PDF set HERAPDF1.0 determined using these data will be described. The new ZEUS results on jet production and on the determination of the strong coupling constant, α_s, will be illustrated as well as the measurements of charm and beauty production and their impact on the PDF fits. The latest results on diffraction, namely the extraction of diffractive PDFs from the ZEUS data, will be presented.

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1. Introduction

After the end of the HERA data taking in June 2007, the two collaborations H1 and ZEUS are finalising their analyses using the full available data statistics. The main goal of the analyses is a deeper understanding of QCD and in particular of the proton parton distribution functions (PDFs). The best possible determination of the proton PDFs is a hot topic at the moment due to their impact on the predictions of cross sections at the LHC. The HERA data cover a kinematic region in Bjorken x corresponding to the rapidity plateau for the LHC processes. Therefore a precise measurement of the proton PDFs in the HERA region provides through DGLAP evolution accurate PDFs for the LHC regimes.

The cross sections of inclusive neutral- (NC) and charged-current (CC) deep inelastic scattering (DIS) interactions provide an accurate determination of the valence- and the sea-quark content of the proton, as well as of the gluon. A further improvement of the understanding of the proton PDFs comes from other more exclusive QCD processes, like jet and heavy flavour production. The study of such processes allows on one hand to test theoretical predictions based on fits from inclusive data only. On the other hand, as also those measurements are reaching a very high precision, they can provide important input to the QCD fits.

For this reason, the H1 and ZEUS collaborations are combining their results in order to achieve the best possible precision of the measurements. In this report [1] a selection of the most recent results from ZEUS and from the H1 and ZEUS data combination are briefly discussed, with the main focus on inclusive NC and CC DIS cross sections, jet and heavy flavour production. For a more detailed description, the individual contributions are available in these proceedings.

2. Inclusive measurements

2.1 Combined H1 and ZEUS inclusive HERA I cross sections and PDFs

Inclusive NC and CC DIS cross sections are measured at HERA in order to investigate the proton structure and determine the proton PDFs. The H1 and ZEUS collaborations have published [2] the combination of the cross sections extracted from the HERA I data (collected between 1994 and 2000). The kinematic range of the NC data extends from $6 \cdot 10^{-7}$ to 0.65 in Bjorken x in the negative four-momentum squared range $0.045 \leq Q^2 \leq 30000$ GeV^2 and inelasticity values y between 0.005 and 0.95. The CC data cover the range $0.013 \leq x \leq 0.4$ and $300 \leq Q^2 \leq 30000$ GeV^2 for y between 0.037 and 0.76.

The combination of the data sets was done using a χ^2 minimisation method [2]. The χ^2 function takes into account the correlated systematic uncertainties for cross-section measurements thus achieving a reduction of the systematic uncertainties in addition to the statistical. In total 1402 data points are combined to 741 cross-section measurements. The data show good consistency, with $\chi^2/n_{\rm dof} = 636.5/656$ and the distribution of pulls shows no tension for all processes in the whole kinematic plane. In total 110 sources of correlated systematic uncertainties, including global normalisation, characterise the separate data sets.

The combined cross sections are everywhere significantly more precise that the individual measurements. The total uncertainty of the combined measurements is typically smaller than 2% for $3 < Q^2 < 500$ GeV^2 and reaches 1% for $20 < Q^2 < 100$ GeV^2.

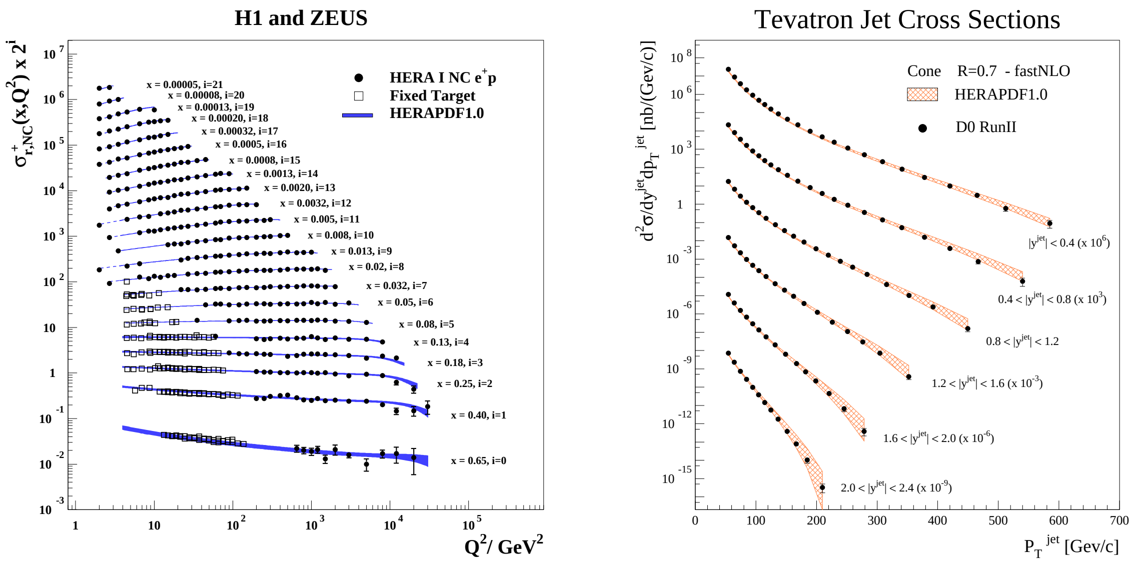

Figure 1: Left: HERA combined NC e^+p reduced cross section and fixed-target data as a function of Q^2 compared with SM predictions based on the HERAPDF1.0. Right: jet production at D0 compared with theoretical predictions obtained using the HERAPDF1.0.

In Fig. 1 the e^+p NC reduced cross section, for $Q^2 > 1$ GeV^2, is shown as a function of Q^2 for the HERA combined e^+p data and for fixed-target data across the whole of the measured kinematic plane. The figure shows the very good precision of the data in the region mentioned before. The data are compared with Standard Model (SM) predictions based on the HERAPDF1.0 PDF set (described below) which describe the data well.

The HERA data have been used as the sole input to extract the HERAPDF1.0 PDF set [2]. The fit was performed using the general-mass variable-flavour-number scheme of Thorne and Roberts (RT-VFNS) [3]. A minimum Q^2 cut of 3.5 GeV^2 was imposed to remain in the kinematic region where perturbative QCD is expected to be applicable. The data at low x determine the sea quark and the gluon distribution while the combination of NC and CC data at large x constrains the up and down valence quark distributions. The consistent input data allow the PDFs to be determined with an experimental uncertainty corresponding to an increase in χ^2 of 1.

Due to the accuracy of the input data, the HERAPDF1.0 PDFs have a precision of the order of a percent in the medium-x region, corresponding to the rapidity plateau region for the LHC measurements. To test the goodness of these PDFs in a kinematic region not covered by the data used to extract them, theoretical predictions for jet production at the Tevatron have been produced. The description of the data obtained for i.e. jet production at D0 [4] is good, as shown in Fig. 1.

Figure 1 also illustrates where the inclusion of the HERA II data (collected between 2003 and 2007 and corresponding to an increase in statistics of a factor three) can improve the picture. In the regions at high Q^2 and high x the uncertainty is dominated by the available statistics, and therefore the inclusion of the HERA II NC and CC cross sections represents valuable input for the better determination of the proton structure in this region.

2.2 New HERA II results

The analyses of NC and CC DIS processes based on the full HERA II data sample by the ZEUS collaboration are ongoing. The CC DIS cross sections have been determined using the full HERA statistics, the latest result being the publication [5] of the measurement based on the e^+p data sample collected in 2006–07, corresponding to a luminosity of $\mathscr{L} = 132$ pb^{-1}. The kinematic region of the measurement is $200 < Q^2 < 60000$ GeV^2, $0.006 < x < 0.562$. Differential and reduced cross sections were measured: the CC DIS reduced cross section plotted as a function of x in different Q^2 bins is shown in Fig. 2. The data are well described by SM predictions based on the HERAPDF1.0 and on other PDF sets. The charged current reduced cross sections are sensitive to the different quark types in the proton: Fig. 2 shows also the contributions to the cross sections coming from u- and d-type quarks. These data will provide useful input at high Q^2 and x once included in the PDF fits, in particular for the d-quark valence distribution.

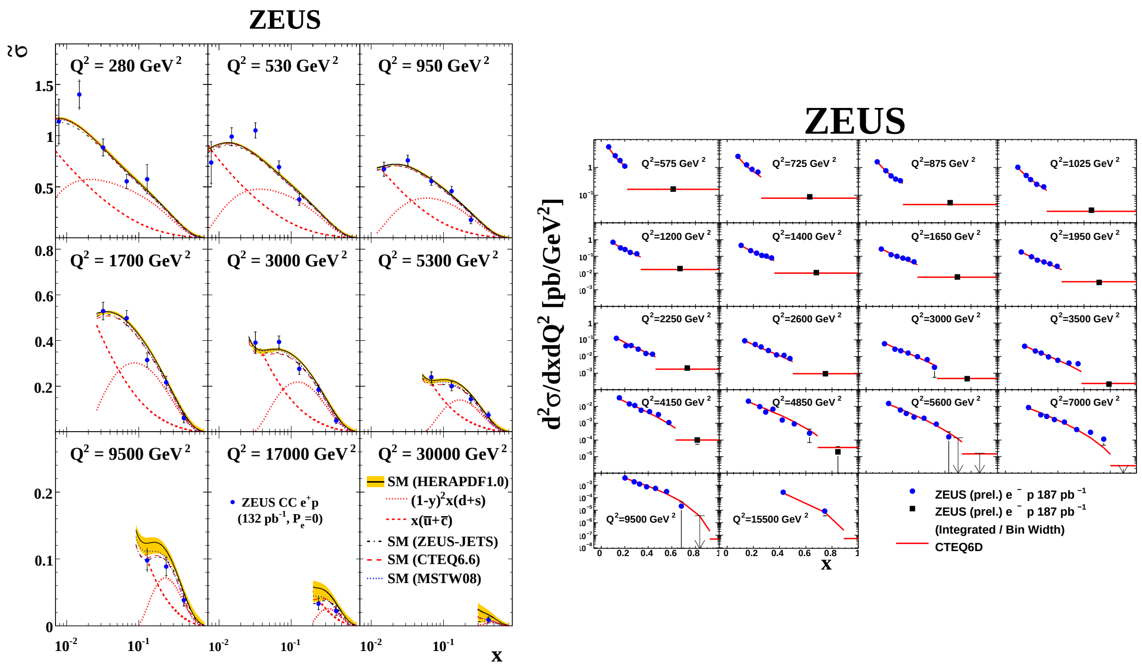

Figure 2: Left: the CC DIS reduced cross sections plotted as a function of x in different Q^2 bins compared to SM predictions based on different PDFs. Right: the double differential cross sections for NC e^-p scattering compared to SM expectations evaluated using the CTEQ6D PDFs.

The NC DIS cross sections at high Q^2 are also sensitive to the proton structure in the high-x region. New preliminary results were presented [6] using the full HERA II e^-p data sample, corresponding to an integrated luminosity of $\mathscr{L} = 187$ pb^{-1}. The analysis relies on the presence of jets expected in high-Q^2 events and a new method is used to reconstruct x with improved resolution. The kinematic region investigated is $Q^2 > 400$ GeV^2 and extends up to $x \sim 1$. The double differential cross sections as a function of x in different Q^2 bins are shown in Fig. 2. The measurements are well described by the SM predictions and have the potential to constrain the PDFs at high x.

The measurement of the NC DIS cross sections in the low-Q^2 and high-y region is also very interesting in order to test QCD predictions, since in this region the effect of the longitudinal structure function, F_L, is most relevant. The ZEUS collaboration has presented new preliminary results [7] in which the NC cross section at high y has been measured down to a lower Q^2 with respect to the previous publication [8]. Neutral current DIS cross sections were measured at three different centre-of-mass energies, $\sqrt{s} = 318,\ 251,\ 225$ GeV. The use of events in which the vertex was shifted in the proton beam direction allowed to measure cross sections for NC DIS down to $Q^2 > 4.5$ GeV^2 for $\sqrt{s} = 318$ GeV. The data, which are well described by SM predictions [7], will provide valuable input once used in the PDF fits.

3. Jet production

The measurements of jet cross sections have been proven to be a very powerful tool to test QCD and to provide a better insight into the proton structure, in particular into the gluon distribution in the medium- to high-x region [9]. Moreover, jet measurements allow the determination of the strong coupling constant, α_s, and the test of its running behaviour. The effort of the ZEUS collaboration is to publish jet cross sections using the full available HERA data sample, both in the DIS and photoproduction ($Q^2 \sim 0$) regimes.

Three new results have been presented at DIS 2010 for jet production in DIS and in the photoproduction regime. In the DIS regime, preliminary results on inclusive jet production [10] and final results on inclusive dijet production [11] in the region $Q^2 > 125$ GeV^2 have been shown. The preliminary measurement uses the full HERA II data sample ($\mathscr{L} = 300$ pb^{-1}), while the published dijet data use the full data sample collected at $\sqrt{s} = 318$ GeV ($\mathscr{L} = 374$ pb^{-1}). Figure 3 shows the differential cross sections for inclusive jets and dijets production in NC DIS as a function of Q^2. The data are compared with next-to-leading order (NLO) QCD predictions. The data, which have very good precision, are well described by NLO QCD, which is also affected by small uncertainties, dominated by the terms beyond NLO. These measurements have the potential to constrain further the proton PDFs.

In the photoproduction regime, a new preliminary result on inclusive jet production [12] has been presented based on an integrated luminosity of $\mathscr{L} = 189$ pb^{-1}. Jets were reconstructed having transverse energy $E_T^{\rm jet} > 17$ GeV in the pseudorapidity region $-1 < \eta^{\rm jet} < 2.5$. Cross sections were determined and compared to NLO QCD predictions. In general, the data description by the theory was good for high enough jet energy (namely $E_T^{\rm jet} > 21$ GeV). At lower jet energy the data description by the theory was less satisfactory. A possible interpretation of the effect in terms of non-perturbative contribution has been proposed [12] but the problem remains open for discussion and is relevant also in the context of the measurements that will be performed at the LHC.

All the measurements discussed above were performed using the k_T algorithm [13] for jet reconstruction. In ep collisions this algorithm, which is infrared and collinear safe, has been proven to have a good performance providing small theoretical uncertainties and hadronisation corrections. As the definition of a jet depends on the algorithm used to reconstruct it, an interesting question is how much the measurements of the jet cross sections and of α_s do actually depend on the particular jet algorithm used. The problem is very relevant also for the LHC, as recently some work has been performed on the theory side in order to provide the experiments with collinear and infrared safe jet algorithms.

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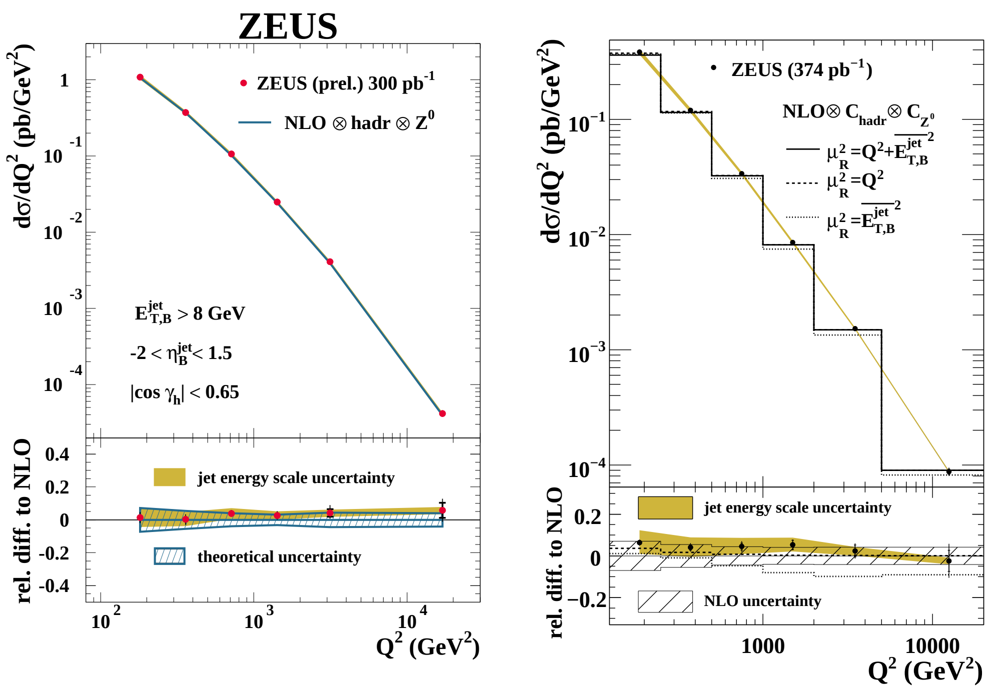

Figure 3: Differential cross section as a function of Q^2 for inclusive jets (left) and dijets (right) production in NC DIS, compared with theoretical predictions from NLO QCD.

Two of these new algorithms, anti-k_T [14] and SIScone [15] were tested at ZEUS [16]. The performance of the algorithms was tested in the well-understood hadron-induced NC DIS process by comparing measurements based on the new algorithms with those based on the k_T and by comparing the data and the QCD predictions. The performances of the three algorithms were found to be very similar. The ratios of the cross sections measured using different algorithms were evaluated in order to study the algorithms performances. Inclusive-jet cross sections can be calculated only up to $\mathcal{O}(\alpha_s^2)$ using the currently available programs. However, differences between cross sections using different algorithms can be calculated up to $\mathcal{O}(\alpha_s^3)$ using NLOJET++ [17], and this allowed to evaluate the ratios of cross sections using different algorithms up to $\mathcal{O}(\alpha_s^3)$ in NLO QCD. The measured ratios were very close to 1 and were well described by QCD up to $\mathcal{O}(\alpha_s^3)$. The results demonstrated the ability of the QCD calculations to account adequately for the differences between the jet algorithms in this particular regime. This is the first test on real data of the performances of these new jet algorithms.

3.1 Measurement of α_s

The new inclusive-jet measurements in NC DIS [10] and photoproduction [12] were used to extract the value of the strong coupling constant α_s and to test its running behaviour [10]. In the DIS regime the NLO QCD fit included the data with $Q^2 > 500$ GeV^2 in order to reduce the theoretical uncertainty, while in photoproduction only the events with $E_T^{\rm jet} > 21$ GeV were used for the reasons indicated above. In the fit for the extraction of $\alpha_s(M_Z)$, the running of α_s as predicted by QCD was assumed. Both in DIS and photoproduction the experimental uncertainty is dominated by the jet energy scale while the theoretical uncertainties are dominated by the terms beyond NLO. Very precise values of the strong coupling were obtained [10].

The scale dependence of α_s was determined by a NLO QCD fit to the same data: a α_s value was extracted at each mean value of $E_T^{\rm jet}$ measured without assuming the running of α_s. Figure 4 shows the dependence of α_s on the scale as extracted from the DIS and the photoproduction data. In the figure the inner shaded area represents the correlated systematic uncertainties and the outer shaded area represents the correlated and theoretical uncertainties added in quadrature. The solid line indicates the renormalisation-group prediction at two loops obtained from the $\alpha_s(M_Z)$ value determined in the analyses. The measurements are consistent with the predicted running of α_s over a wide range of the scale.

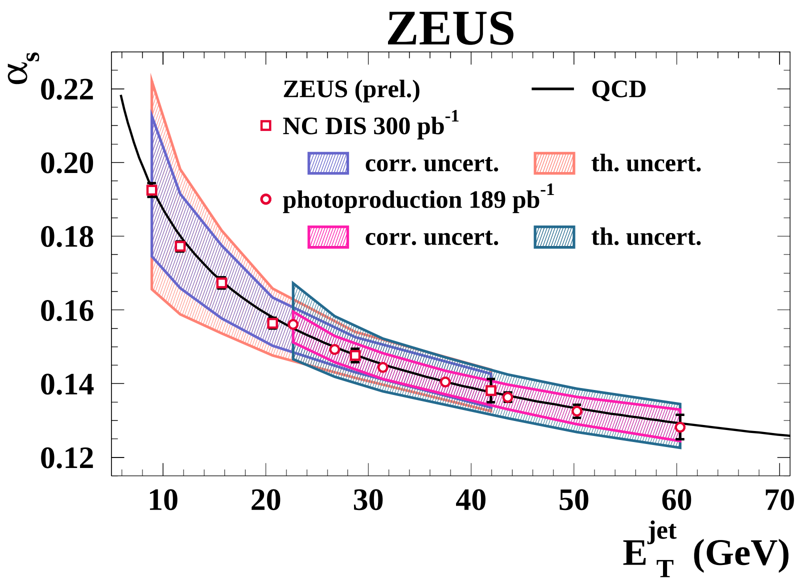

Figure 4: Summary of the running α_s values extracted from the ZEUS jets data in DIS and photoproduction.

4. Heavy flavour production

The measurement of charm and beauty production at HERA is a stringent test of perturbative QCD and can provide information on the structure of the proton. Heavy flavour production in *ep* collisions, in fact, proceeds mainly through the boson-gluon fusion process, $\gamma g \to Q\bar{Q}$ and can therefore provide insights into the gluon content of the proton. Moreover, the appropriate treatment of heavy flavours is an important ingredient of the PDF fits. The study of heavy flavour production at HERA is therefore also a testing ground for the different fit schemes and for the PDF dependence on theoretical parameters such as the heavy-quark masses.

The goal of the HERA experiments is to provide results based on the full available statistics in order to extract the charm and beauty contributions to the proton structure function F_2, $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$, and to perform the most possible stringent tests of QCD for heavy flavour production. At ZEUS the analysis of the HERA II data is mostly important, since the use of the vertex detector, installed in 2000, allows a more efficient heavy-flavour tagging and therefore a much improved precision of the results.

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4.1 Charm production

New preliminary results [18] on D^+ production in DIS based on a data sample of $\mathscr{L} = 323$ pb^{-1} were presented. The measurement improves significantly the previously published D^+ result [19] due to a three-fold increase in statistics and to the improved data reconstruction. The investigated kinematic region was $1.5 < p_T(D^+) < 15$ GeV, $|\eta(D^+)| < 1.6$, $5 < Q^2 < 1000$ GeV^2 and $0.02 < y < 0.7$. The number of D^+ mesons available in the analysis was ~ 7200. Differential cross sections were determined and compared to perturbative QCD predictions based on the HVQDIS [20] program, which performs calculations in the fixed-flavour-number scheme (FFNS) [21]. Figure 5 shows the differential cross section as a function of the transverse momentum of the D^+ meson, compared with NLO QCD predictions and with the previously published ZEUS result. The reduction of the statistical and also of the systematic uncertainties is clearly visible in the figure. Moreover, the data points have better precision than the NLO QCD predictions.

These new measurements were used to extract $F_2^{c\bar{c}}$, the charm contribution to the proton structure function F_2. The extraction was performed using the NLO calculations in the FFNS. The new points are shown in Fig. 5, compared with the combined H1 and ZEUS $F_2^{c\bar{c}}$ [22].

The H1 and ZEUS $F_2^{c\bar{c}}$ was obtained by combining several different measurements performed at H1 and ZEUS using D meson production, semi-muonic decays of charm as well as charm tagging based on inclusive track measurements with lifetime information. Also for the combined result the extraction of $F_2^{c\bar{c}}$ from the cross sections was performed using NLO calculations in the FFNS. The data used cover the kinematic range $2 < Q^2 < 1000$ GeV^2 and $10^{-5} < x < 10^{-1}$. The combination method is the same used for the combination of the inclusive cross sections (see Sect.2.1) and, by taking into account the correlations of the systematic uncertainties, provides an improved accuracy. A precision of $5-10\%$ is reached for the combined results.

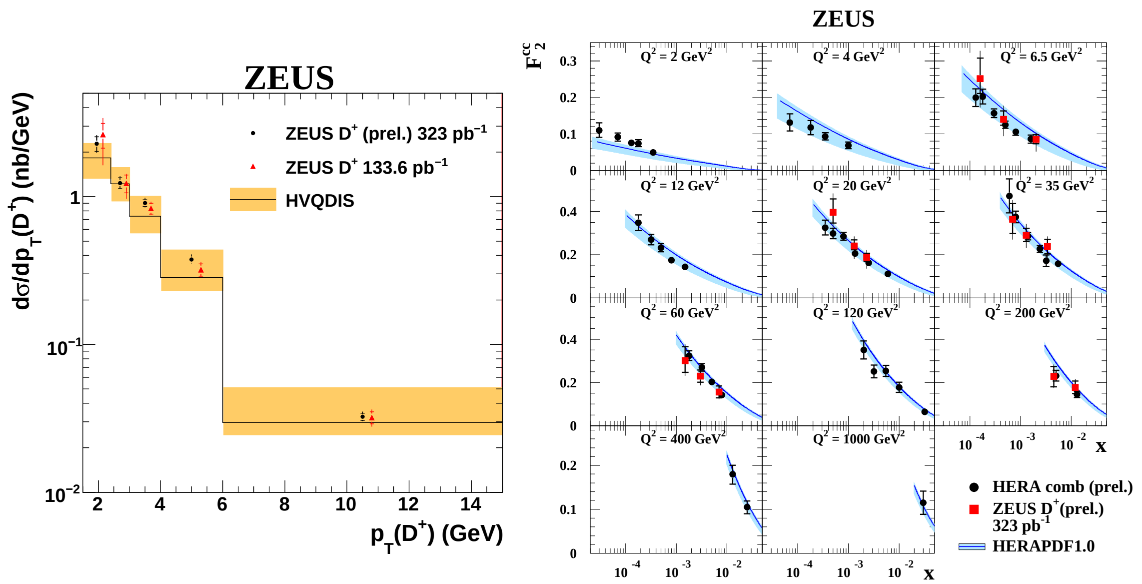

Figure 5: Left: differential cross section for D^+ production in DIS as a function of the transverse momentum of the D^+ meson. Right: combined H1 and ZEUS $F_2^{c\bar{c}}$ (black dots) and $F_2^{c\bar{c}}$ extracted from the new ZEUS D^+ measurement (red squares) compared with the predictions from NLO QCD (band) using the HERAPDF1.0.

This good accuracy can still be improved by including the new HERA II results from ZEUS, as i.e. those from D^+ production, which are not yet in the combination. Figure 5 shows the combined $F_2^{c\bar{c}}$ compared with the NLO QCD predictions obtained using the HERAPDF1.0 PDFs, which do not include the charm data. The data description by the theory is reasonably good. By comparing the combined $F_2^{c\bar{c}}$ with different predictions based on recent QCD fits to global scattering data it can be noticed that in most of the (x, Q^2) plane the data are more precise than the spread observed in the theoretical predictions [22].

The $F_2^{c\bar{c}}$ data represent therefore valuable constraints on the theory of heavy flavour production in DIS, and they have indeed been included in the QCD fits [23]. A modified version of the HERAPDF1.0 was obtained by including in the fit the combined H1 and ZEUS $F_2^{c\bar{c}}$ described above. However, the HERAPDF1.0 used a specific heavy-quark mass scheme – the RT-VFNS (see Sect. 2.1). The new fit including the charm data was performed using various different heavy-quark mass schemes and various values of the charm-quark mass. The results showed that the charm data are sensitive to the value of the charm mass and the choice of heavy-quark mass scheme. This has consequences for predictions of the W and Z cross sections at the LHC. A larger charm mass, with respect to that used in the HERAPDF1.0 fit (1.65 instead of 1.4 GeV), means suppressed charm at threshold and thus the lighter quarks are enhanced to compensate. This results in a 2.5% higher W, Z cross section for $m_c = 1.65$ GeV as compared to $m_c = 1.40$ GeV [23]. This indicates the importance of the charm data to test the heavy quark schemes and masses in the PDF fit and will be subject of further studies.

Another measurement which is interesting also in the context of the $F_2^{c\bar{c}}$ extraction has been recently published [24] by the ZEUS collaboration. The production of D^+ hadrons in DIS has been studied using a data sample of $\mathscr{L} = 120$ pb^{-1}. Events were selected where the charmed hadrons decayed into a neutral strange particle. This allowed the suppression of the combinatorial background and thus the exploration of the very low $p_T(D^+)$ region for the first time at HERA. The kinematic region of the measurement is $0 < p_T(D^+) < 10$ GeV, $|\eta(D^+)| < 1.6$, $1.5 < Q^2 < 1000$ GeV^2 and $0.02 < y < 0.7$ and therefore extends down to very low transverse momentum of the produced charm quark. The total visible and differential cross sections were measured and compared to NLO QCD predictions evaluated using HVQDIS.

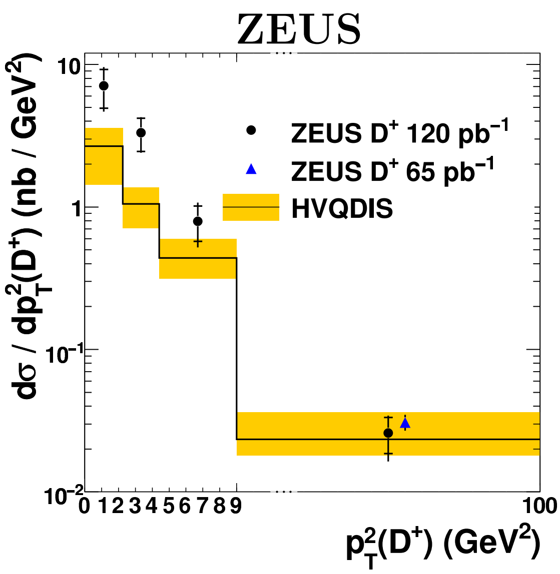

Figure 6: Differential D^+ cross section as a function of $p_T^2(D^+)$ (dots) compared to a previous ZEUS result [25] (triangle) and to NLO QCD predictions from HVQDIS.

The differential cross section as a function of $p_T^2(D^+)$ is shown in Fig. 6 and compared to a previous ZEUS result [25] and to NLO QCD predictions, which describe the data reasonably well within the experimental and theoretical uncertainties.

This kind of measurement is important since the extraction of $F_2^{c\bar{c}}$ from differential cross sections always implies an extrapolation to the full transverse momentum region of the charm quarks, which is usually not fully covered by the measurement. As the extrapolation is done using NLO QCD, it is important to check that the calculations are able to reproduce the data down to very low p_T of the charm quark.

4.2 Beauty production

A new result on beauty production in DIS was presented [26]. The analysis is based on a data sample of $\mathscr{L} = 354$ pb^{-1}. Events were selected with a jet in the final state and beauty production was tagged on a statistical basis, by looking at the significance of the secondary vertex associated to the jet. This inclusive method, in which no semi-leptonic decay is needed in order to identify beauty production, allowed to select a very large beauty sample. The investigated kinematic region was $5 < Q^2 < 1000$ GeV^2, $0.02 < y < 0.7$, $E_T^{\rm jet} > 5$ GeV and $-1.6 < \eta^{\rm jet} < 2.2$. Differential cross sections were measured and compared to the predictions of NLO QCD evaluated in the FFNS with the HVQDIS program. The differential cross section as a function of $E_T^{\rm jet}$ is shown in Fig. 7. The data have reached a very good precision, better than that of the QCD predictions at NLO. This data will be used to extract the beauty contribution to the proton structure function F_2, $F_2^{b\bar{b}}$.

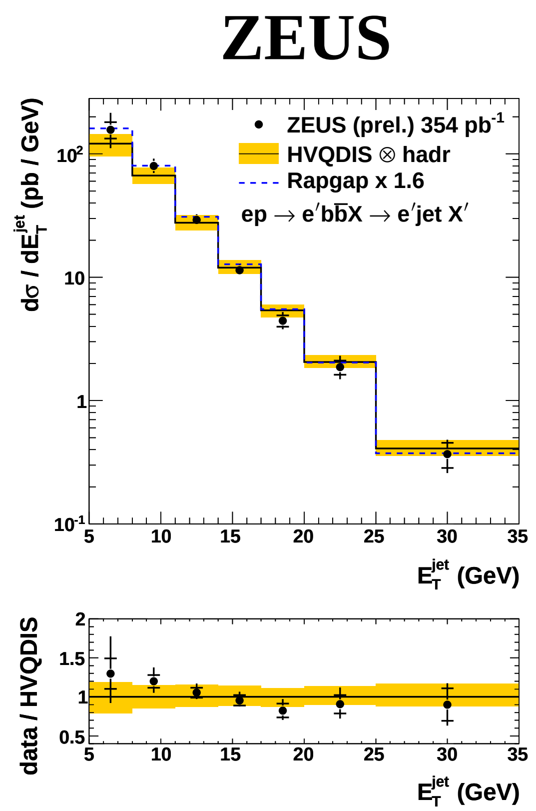

Figure 7: Differential cross section for beauty production in DIS as a function of the transverse momentum of the beauty jet, $E_T^{\rm jet}$, compared with NLO QCD predictions.

5. Diffraction

A NLO QCD analysis [27] was performed on ZEUS diffractive inclusive cross sections and diffractive dijet production in DIS in order to determine the diffractive parton distribution functions. The inclusive data were first fitted alone and then in combination with the jet data. Only the region $Q^2 > 5$ GeV^2 could be fitted within the combined framework of DGLAP evolution and proton-vertex factorisation.

The NLO QCD predictions based on the diffractive PDFs extracted from the inclusive data give a good description of the inclusive and dijet data, but the sensitivity to the gluon density is enhanced when the dijet data are included in the fit. The use of both data sets allows the extraction of the quark and gluon densities with good accuracy.

The quality of the extracted parton densities was tested by using them in producing theoretical predictions for data not included in the fit. These predictions were able to describe fairly well diffractive charm production. The description of jet production in photoproduction was also good over the full kinematic region. Therefore, no hint for suppression of the resolved component was observed.

6. Conclusions

A summary of some of the most recent results of the ZEUS collaboration has been presented. The emphasis has been put on the recent progresses on the understanding of the proton structure and of QCD in general.

The combined H1 and ZEUS inclusive cross sections provide a very precise input to the QCD fits over a large phase-space region. The HERAPDF1.0 PDF set was determined using as sole input the HERA data. Theoretical predictions based on these PDFs have been proven to be able to reproduce data over a larger kinematic range, like for example jet production at the Tevatron. Possible improvements in the regions of the phase space that are now less well covered have been discussed, in terms of inclusive, jet and heavy flavour measurements.

The HERA II data provide a larger statistics which will allow to improve the precision of the inclusive measurements at large Q^2 and x, and at high y. The jet data could help in further constraining the gluon density. Moreover, the jet measurements allow the extraction of α_s with very good precision. The heavy flavour data can give indications on the gluon in the proton and are a very powerful test to check the goodness of the fit formalism and its dependence on theoretical parameters such as the heavy quark masses.

Regarding diffraction, the parton distribution functions extracted from the ZEUS data turned out to be able to describe well a variety of diffractive cross sections measured at ZEUS.

Acknowledgments

It is a great pleasure to thank the organisers of the conference, especially in this particular case in which the attendance was massively reduced due to the volcano ashes and the consequent cancellation of many flights. For us it was also very difficult to reach Florence, we had to take a train from Hamburg and it took us 16 hours to get there! That was really a challenge as I was seven and a half months pregnant at that point. But everything went well. The conference was excellently organised and it was really a pity that many people could not come. I would like to thank the organisers also for the way they promptly reacted to these completely unforeseeable circumstances, organising talks on EVO and so on, allowing the workshop to be successful and stimulating despite the very difficult conditions.

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