A QCD analysis of ZEUS data including DIS inclusive cross sections with longitudinally polarised leptons and data run at lower proton beam energies.

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New ZEUS data are added into the NLO QCD analysis of the ZEUS-JETS PDF fit. The addition of high-$Q^2$ NC and CC $e^−p$ inclusive cross-section data improves the determination of the $u$-valence quark at high $x$. The addition of high-$Q^2$ CC $e^+p$ inclusive cross-section data improves the determination of the $d$-valence quark at high $x$. The addition of lower-$Q^2$ NC $e^+p$ inclusive cross-section data, run at three different proton beam energies, improves the determination of the sea and gluon PDFs at small $x$. The new PDF fit is called the ZEUS09 PDF fit.

1 Introduction
The kinematics of deep inelastic lepton hadron scattering (DIS) is described in terms of the variables $Q^2$, the negative invariant mass of the exchanged vector boson, Bjorken $x$, the fraction of the momentum of the incoming nucleon taken by the struck quark (in the quark-parton model), and $y$ which measures the energy transfer between the lepton and hadron systems. The double differential cross-sections for the neutral current (NC) process with lepton polarization $P$ are given by,

\[ \frac{d^2 \sigma(e^\pm p)}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \left[ H_0^+ + PH_0^P \right], \quad H_0^+ = Y_+ F_2^{0,P} - y^2 F_L^{0,P} \mp Y_- x F_3^{0,P} \] (1)

where, $Y_\pm = 1 \pm (1 - y)^2$, and, at LO in QCD, the structure functions $F_2^{0,P}$ and $x F_3^{0,P}$ are directly related to quark distributions by

\[ F_2^{0,P} = \sum_i x(q_i + \bar{q}_i) A_i^{0,P}, \quad x F_3^{0,P} = \sum_i x(q_i - \bar{q}_i) B_i^{0,P} \] (2)

The coefficients $A_i^0, B_i^0$ for unpolarised beams are given by

\[ A_i^0(Q^2) = e_i^2 - 2e_i v_i v_c P_Z + (v_i^2 + a_i^2)(v_c^2 + a_c^2) P_Z^2 \] (3)

\[ B_i^0(Q^2) = -2e_i a_i a_c P_Z + 4a_i v_i v_c a_c P_Z^2 \] (4)

The coefficients for the polarisation terms are given by

\[ A_i^P = 2e_i a_i v_i P_Z - 2a_i v_c (v_i^2 + a_i^2) P_Z^2, \quad (5) \]

\[ B_i^P = 2e_i a_i v_c P_Z - 2a_i v_i (v_c^2 + a_c^2) P_Z^2. \] (6)

*On behalf of the ZEUS Collaboration [1]

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The term in $P_Z$ arises from $\gamma Z^0$ interference and the term in $P_Z^2$ arises purely from $Z^0$ exchange, where $P_Z$ accounts for the effect of the $Z^0$ propagator relative to that of the virtual photon, and is given by

$$P_Z = \frac{Q^2}{Q^2 + M_Z^2} \frac{1}{\sin^2 2\theta_W}. \quad (7)$$

The other factors in the expression for $A$ and $B$ are the charge, $e_i$, NC electroweak vector, $v_i$, and axial-vector, $a_i$, couplings of quark $i$ and the corresponding NC electroweak couplings of the electron, $v_e, a_e$. Equations 5, 6 show that polarization effects are only important at high $Q^2$.

Unpolarized HERA data have been used in fits to determine Parton Distribution Functions (PDFs). For low $x$, $x \leq 10^{-2}$, $F_2^0$ is sea quark dominated and its $Q^2$ evolution, as predicted by QCD, is controlled by the gluon contribution, such that HERA data provide crucial information on low-$x$ sea-quark and gluon distributions. At high $Q^2$, the structure function $xF_2^0$ becomes increasingly important, and gives information on valence quark distributions. The charged current (CC) interactions also enable separation of the flavour of the valence distributions at high-$x$, since their (LO) cross-sections are given by

$$d^2\sigma(e^+p) \frac{dx dQ^2}{dxdQ^2} = (1 + P) \frac{G_F^2 M_W^4}{(Q^2 + M_W^2)^2} 2\pi x \left[(\bar{u} + \bar{c}) + (1 - y)^2(d + s)\right],$$

$$d^2\sigma(e^-p) \frac{dx dQ^2}{dxdQ^2} = (1 - P) \frac{G_F^2 M_W^4}{(Q^2 + M_W^2)^2} 2\pi x \left[(u + c) + (1 - y)^2(\bar{d} + \bar{s})\right].$$

Parton Density Function (PDF) determinations are usually global fits \cite{2,3,4}, which use fixed target DIS data as well as HERA data. In such analyses, the high statistics HERA NC $e^+p$ data have determined the low-$x$ sea and gluon distributions, whereas the fixed target data have determined the valence distributions. Now that high-$Q^2$ HERA data on NC and CC $e^+p$ and $e^-p$ inclusive double differential cross-sections are available, PDF fits can be made to HERA data alone, since the HERA high $Q^2$ cross-section data can be used to determine the valence distributions. This has the advantage that it eliminates the need for heavy target corrections, which must be applied to the $\nu$-Fe and $\mu D$ fixed target data. Furthermore there is no need to assume isospin symmetry, i.e. $d$ in the proton is the same as $u$ in the neutron, since the $d$ distribution can be obtained directly from CC $e^+p$ data.

The ZEUS-JETS PDF fit \cite{5} was an NLO QCD fit in the DGLAP formalism to ZEUS inclusive cross-section data and jet production data from HERA-I. The PDFs were parametrized at $Q_0^2 = 7$GeV$^2$ by the form $xf(x) = p_1 x^{p_2}(1 - x)^{p_3}(1 + p_4 x)$, using 11 free parameters. Predictions for the cross-sections were made by evolving the PDFs to the $Q^2$ values of the measurements and convoluting them with coefficient functions, calculated in the general mass variable flavour-number scheme of Thorne and Roberts \cite{13}, to produce structure function predictions. Predictions for jet cross-sections were made using NLO programmes \cite{6,7}. In evaluating the uncertainty on the PDF parameters and the cross-section predictions which derive from them full account is taken of correlated experimental uncertainties using the Offset method. However the determinations of the valence PDFs from HERA-I data are not as accurate as those from global fits because of poor statistics at high-$x$. The addition of data from HERA-II changes this situation. In order to assess the impact of this new data the

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fit formalism has not been changed. This paper describes the improvement to the valence PDFs from adding ZEUS $e^-p$ NC [8] from the 2005-6 running period, $e^-p$ CC [9] data from the 2004-6 running period, and $e^+p$ CC data [10] from the 2006-7 running period, into the ZEUS-JETS fit.

The polarization of the HERA-II data can also be exploited to measure electroweak couplings. The CC cross-sections give information on the propagator mass and the weak coupling. The NC cross-sections give information on the quark couplings to $Z^0$. A preliminary model independent extraction of these parameters was given in Ref [11] and will be updated when the full HERA-II data set is available. In the present paper we compare our data to the electro-weak predictions of the Standard Model.

Most of the data collected at HERA were for collisions between $e^\pm$ of 27.5GeV with protons of 920GeV beam energies. During the final running period, HERA provided lower $Q^2$ data ($24 < Q^2 < 110 \text{ GeV}^2$), with modified trigger conditions, collected at three different proton beam energies (920, 575, 460GeV). These data access high-$y$ and have been used to measure the longitudinal structure function $F_L$ [12]. At low-$x$, NLO QCD in the DGLAP formalism predicts that this structure function is strongly related to the gluon PDF. The reduced cross-section data from these runs have also been added into the ZEUS-JETS PDF fit and this provides an improved determination of the sea and gluon PDFs at small-$x$. The new fit including all these new data is called the ZEUS09 PDF fit.

## 2 Results

Fig 1 (left-hand side) shows ZEUS data on NC $e^-p$ double differential cross-sections from the 2005-2006 running period. There are $99pb^{-1}$ of negatively polarised data ($P_e = -0.27$) and $71pb^{-1}$ of positively polarised data ($P_e = +0.29$). This figure (right-hand side) also shows ZEUS data on CC $e^-p$ double differential cross-sections from the 2004-2006 running period. There are $104pb^{-1}$ of negatively polarised data ($P_e = -0.27$) and $71pb^{-1}$ of positively polarised data ($P_e = +0.30$). Fig 2 (left-hand side) shows ZEUS data on CC $e^+p$ double differential cross-sections from the 2006-2007 running period. There are $56pb^{-1}$ of negatively polarised data ($P_e = -0.36$) and $76pb^{-1}$ of positively polarised data ($P_e = +0.33$).

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The predictions of the ZEUS09 fit are superimposed on the data in all these figures. The $\chi^2$ per degree of freedom of this fit is 0.97. The agreement of all of the polarised data with the fit is a confirmation not only of the validity of the NLO QCD in the DGLAP formalism but also of the electroweak predictions of the Standard Model in a space-like process.

Fig. 3 (right-hand side) illustrates the further impact of adding these new data by comparing the fractional uncertainties of the PDFs extracted from a fit including these data with those extracted from the ZEUS-JETS PDF. The improvement in the $u$-valence quark at high $x$ comes from the addition of the NC and CC $e^-p$ data from the 2004-2006 running. Both these processes are $u$ quark dominated at large $x$. The $d$-valence quark uncertainty is also reduced significantly at large $x$. This improvement derives from the CC $e^+p$ data which are $d$ quark dominated at large $x$. Finally the improvement in the low-$x$ gluon and sea PDFs come from the addition of the NC $e^+p$ lower $Q^2$ data run at three different beam energies. This final addition of data completes the ZEUS09 PDF fit. The low-$x$ scale of the figure is extended to illustrate the improvement which is expected from adding these high-$y$ data. The PDFs extracted from the ZEUS09 fit are also compared to those of the ZEUS-JETS fit in Fig. 3 (right-hand side). The central values of the fit are very compatible with the ZEUS-JETS fit, but the gluon PDF is a little steeper indicating the impact of the low-$Q^2$ data on the gluon PDF.

### 3 Summary

The inclusion of high-$Q^2$ NC and CC $e^-p$ data into the ZEUS-JETS PDF fit results in an improved determination of the $u$-valence PDF. The further inclusion of high-$Q^2$ CC $e^+p$ data results in an improved determination of the $d$-valence PDF. These data were run with...
polarised lepton beams and the cross-section data for the different polarisations provides a spectacular confirmation of the Standard Model electroweak predictions in a space-like process. Finally the inclusion of lower-$Q^2$ data run at three different proton beam energies yields an improved determination of the low-$x$ sea and gluon PDFs. The new fit including all these data is called the ZEUS09 PDF fit [1].

4 Bibliography

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