Extraction of the proton parton density functions using a NLO-QCD fit of the combined H1 and ZEUS inclusive DIS cross sections

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The combined HERA-I data set, of neutral and charged current inclusive cross-sections for e^+p and e^-p scattering, is used as the sole input for a next-to-leading order (NLO) QCD parton distribution function (PDF) fit. The consistent treatment of systematic uncertainties in the joint data set ensures that experimental uncertainties on the PDFs can be calculated without need for an increased χ^2 tolerance. This results in PDFs with greatly reduced experimental uncertainties compared to the separate analyses of the ZEUS and H1 experiments. Model uncertainties, including those arising from parametrization dependence, are also carefully considered. The resulting HERAPDFs have impressive precision compared to the global fits.

1 Introduction

The kinematics of lepton hadron scattering is described in terms of the variables Q^2, the 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 differential cross-section for the neutral current (NC) process is given in terms of the structure functions by

$$\frac{d^2\sigma(e^\pm p)}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4 x}\left[Y_+\, F_2(x,Q^2) - y^2\, F_L(x,Q^2) \mp Y_-\, xF_3(x,Q^2)\right],$$

where $Y_\pm = 1 \pm (1-y)^2$. The structure functions F_2 and xF_3 are directly related to quark distributions, and their Q^2 dependence, or scaling violation, is predicted by perturbative QCD. For low x, $x \leq 10^{-2}$, F_2 is sea quark dominated, but its Q^2 evolution 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_3 becomes increasingly important, and gives information on valence quark distributions. The charged current (CC) interactions also enable us to separate the flavour of the valence distributions at high-x, since their (LO) cross-sections are given by,

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

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

Parton Density Function (PDF) determinations are usually obtained from global NLO QCD fits [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 ν-Fe and μD fixed target data. Furthermore there is no need to assume isospin symmetry, i.e. that 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 H1 and ZEUS collaborations have both used their data to make PDF fits [5], [6]. Both of these data sets have very small statistical uncertainties, so that the contribution of systematic uncertainties becomes dominant and consideration of point to point correlations between systematic uncertainties is essential. The ZEUS analysis takes account of correlated experimental systematic errors by the Offset Method, whereas H1 uses the Hessian method [7]. Whereas the resulting ZEUS and H1 PDFs are compatible, the gluon PDFs do have rather different shapes, see Fig. 1, and the uncertainty bands spanned by these analyses are comparable to those of the global fits.

It is possible to improve on this situation since ZEUS and H1 are measuring the same physics in the same kinematic region. These data have been combined them using a 'theory-free' Hessian fit in which the only assumption is that there is a true value of the cross-section, for each process, at each x, Q^2 point [8], [9]. The resulting systematic uncertainties on each of the combined data points are significantly smaller than the statistical errors. In the present paper this combined data set is used as the input to a NLO QCD PDF fit. The consistency of the input data set and its small systematic uncertainties enable us to calculate the experimental uncertainties on the PDFs using the χ^2 tolerance, $\Delta\chi^2 = 1$. This represents a further advantage compared to those global fit analyses where increased tolerances of $\Delta\chi^2 = 50 - 100$ are used to account for data inconsistencies.

For the present HERAPDF0.1 fit, the role of correlated systematic uncertainties is no longer crucial since these uncertainties are relatively small. This ensures that similar results are obtained using either Offset or Hessian methods, or by simply combining statistical and systematic uncertainties in quadrature. For our central fit we have chosen to combine the 43 systematic uncertainties which result from the separate ZEUS and H1 data sets in quadrature, and to Offset the 4 sources of uncertainty which result from the combination procedure. This results in the most conservative uncertainty estimates on the resulting PDFs.

Despite our conservative procedure the experimental uncertainties on the resulting PDFs are impressively small and a thorough consideration of further uncertainties due to model assumptions is necessary. In section 2 we describe the NLO QCD analysis and model assumptions. In section 3 we give results and in section 4 we give a summary.

2 Analysis

The QCD predictions for the structure functions are obtained by solving the DGLAP evolution equations at NLO in the MSbar scheme with the renormalisation and factorization scales chosen to be Q^2. The DGLAP equations yield the PDFs at all values of Q^2 provided they are input as functions of x at some input scale Q_0^2. This scale has been chosen to be $Q_0^2 = 4\text{GeV}^2$ and variation of this choice is considered as one of the model uncertainties. The resulting PDFs are then convoluted with NLO coefficient functions to give the structure functions which enter into the expressions for the cross-sections. The choice of the heavy quark masses is, $m_c = 1.4, m_b = 4.75$GeV, and variation of these choices is included in the model uncertainties. For this preliminary analysis, the heavy quark coefficient functions have been caluclated in the zero-mass variable flavour number scheme. The strong coupling constant was fixed to $\alpha_s(M_Z) = 0.1176$ [10], and variations in this value of ± 0.002 have also been considered.

The fit is made at leading twist. The HERA data have of the invariant mass of the hadronic system,W^2, of $W^2_{min} = 300\text{GeV}^2$ and maximum x, $x_{max} = 0.65$, such that they are in a kinematic region where there is no sensitivity to target mass and large-x higher twist contributions. However a minimum Q^2 cut is imposed to remain in the kinematic region where perturbative QCD should be applicable. This has been chosen such that $Q^2_{min} = 3.5$ GeV^2. Variation of this cut is included as one of the model uncertainties.

A further model uncertainty is the choice of the initial parametrization at Q^2_0. The PDFs are parametrized by the generic form

$$xf(x) = Ax^B(1-x)^C(1 + Dx + Ex^2 + Fx^3), \tag{1}$$

and the number of parameters is chosen by 'saturation of the χ^2', such that parameters D, E, F are only varied if this brings significant improvement to the χ^2. Otherwise they are set to zero.

For our central fit, the PDFs which are parametrized are xu_v, xd_v, xg and $x\bar{U}$, $x\bar{D}$. The normalisation parameters, A, for the d and u valence are constrained to impose the number sum-rules and the normalisation parameter A for the gluon is constrained to impose the momentum sum-rule. The B parameters which constrain the low-x behaviour of the u and d valence distributions are set equal, and the B parameters are also set equal for $x\bar{U}$ and $x\bar{D}$, such that there is a single B parameter for the valence and another different single B parameter for the sea distributions. Assuming that the strange and charm quark distributions can be expressed as x independent fractions, $f_s = 0.33$ and $f_c = 0.15$, of the d and u type sea, gives the further constraint $A(\bar{U}) = A(\bar{D})(1 - f_s)/(1 - f_c)$. The value of $f_s = 0.33$ has been chosen to be consistent with determinations of this fraction using neutrino induced di-muon production. This value has been varied to evaluate model uncertainties. The charm fraction has been set to be consistent with dynamic generation of charm from the start point of $Q^2 = m_c^2$ in a zero-mass-variable-flavour-number scheme. A small variation of the value of f_c is included in the model uncertainties. Saturation of the χ^2 leads us to set the parameters $D, E, F = 0$, for all partons except xu_v for which only $F = 0$.

The results are presented using this parametrization, including six sources of model uncertainty due to variation of: $m_c, m_b, f_s, f_c, Q^2_0, Q^2_{min}$. Comparison is made to three other classes of parametrization, one based on the ZEUS-JETs parametrization [5], one based on the H1 parametrization [6] and one based on the current parametrization but allowing $D \neq 0$ for the gluon. Comparison is also made to results obtained by varying $\alpha_s(M_Z)$, see reference [1] for details. Our central choice has less model dependence than the ZEUS-Style parametrization because it has fewer asumptions concerning $\bar{d} - \bar{u}$, and it has less model dependence than the H1-style parametrization in that it does not assume equality of all B parameters. Furthermore, although all types of parametrization give acceptable χ^2 values, the central parametrization has the best χ^2 and it gives the most conservative experimental errors.

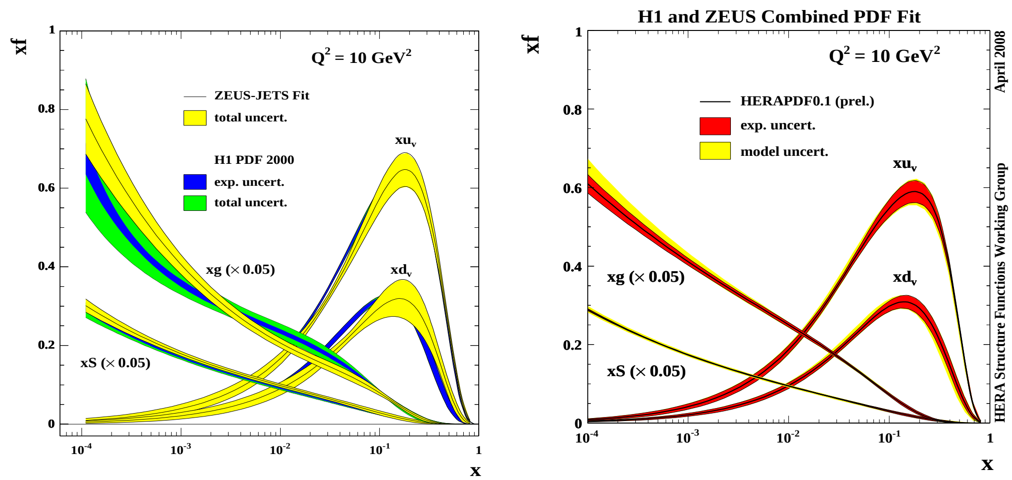

Figure 1: Left: PDFs from the ZEUS-JETS and H1PDF2000 PDF separate analyses of ZEUS and H1. Right: HERAPDF0.1 PDFs from the analysis of the combined data set

3 Results

The total uncertainty of the PDFs obtained from the HERA combined data set is much reduced compared to the PDFs extracted from the analyses of the separate H1 and ZEUS data sets, as can be seen from the summary plots in Fig. 1, where these new HERAPDF0.1 PDFs are compared to the ZEUS-JETS and H1PDF2000 PDFs.

In Fig. 2 we show the HERAPDF0.1 PDFs compared to the CTEQ6.1 PDFs, which also use a zero-mass variable flavour number scheme, and to the preliminary MSTW08 PDFs [11], which use a massive variable flavour number scheme. The precision of the HERAPDF0.1 for the low-x sea and gluon is impressive.

4 Summary

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 and HERA low Q^2 cross-section data can be used to determine the Sea and gluon distributions. The combined HERA-I data set, of neutral and charged current inclusive cross-sections for e^+p and e^-p scattering, has been used as the sole input for a NLO QCD PDF fit in the DGLAP formalism. The consistent treatment of systematic uncertainties in the joint data set ensures that experimental uncertainties on the PDFs can be calculated without need for an increased χ^2 tolerance. This results in PDFs with greatly reduced experimental uncertainties compared to the separate analyses of the ZEUS and H1 experiments. Model uncertainties, including those arising from parametrization dependence, have also been carefully considered. The resulting HERAPDFs have impressive precision compared to the global fits.

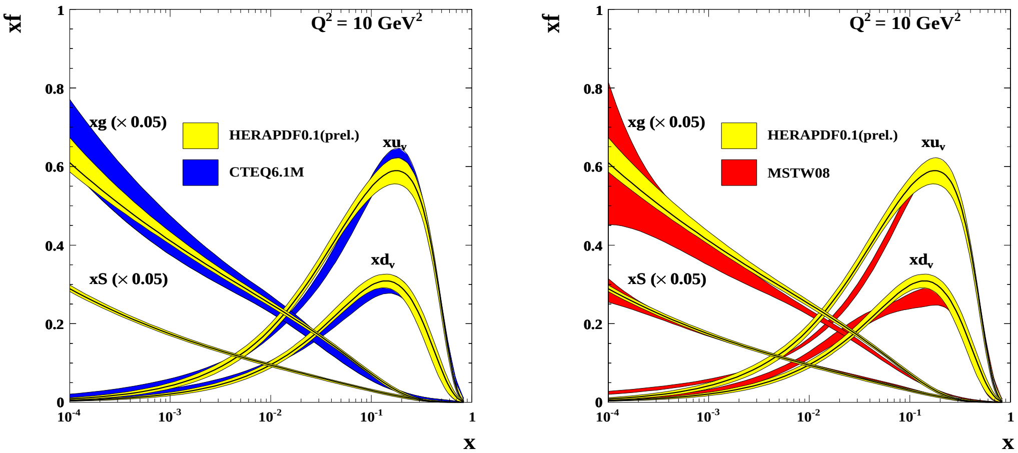

Figure 2: Left: HERAPDF0.1 at $Q^2 = 10\text{GeV}^2$ compared to the CTEQ6.1 PDFs. Right: HERAPDF0.1 at $Q^2 = 10\text{GeV}^2$ compared to the preliminary MSTW08 PDFs.

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