HERA Combined Cross Sections and Parton Densities

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Deep inelastic scattering cross section measurements previously published by the H1 and ZEUS collaborations are combined. The procedure takes into account the systematic error correlations in a coherent way, leading to a significantly reduced overall cross section uncertainty. The combined H1 and ZEUS measurements of the inclusive neutral and charged current cross sections are used to perform a common NLO QCD fit. The consistent treatment of systematic uncertainties in the joint data set ensures that the resulting set of parton density functions (PDFs) have a much reduced experimental uncertainty compared to the previous PDF extractions performed separately by the H1 and ZEUS collaborations.

1. Introduction

Deep inelastic scattering (DIS) of leptons off nucleons has been essential for our understanding of the structure of the nucleon. Colliding electrons and positrons with protons, HERA at DESY has played a unique role in revealing details of the proton substructure of quarks and gluons. In June 2007 the operation of HERA was terminated after a period of 15 years of data taking. During this time the H1 and ZEUS collaborations at HERA successfully operated their general purpose detectors which were adapted in 2001 to the luminosity upgrade of the collider interaction regions. Both collaborations have published accurate measurements of $e^{\pm}p$ DIS cross sections based on about 120 pb^{-1} of ep data collected until 2000 [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. These measurements have been crucial in substantially constraining the parton density functions (PDFs) of the proton in global next-to-leading-order (NLO) QCD fits [11, 12, 13], which use fixed target data as well as HERA data. The H1 and ZEUS collaborations have both demonstrated their capability to extract complete sets of PDFs from their data alone [4, 14] achieving a precision competitive to that obtained in the global QCD fits. Aiming for the most accurate determination of PDFs, H1 and ZEUS are now working towards combining their datasets and joining their QCD analyses.

2. Cross Sections, Structure Functions and Parton Distributions

The kinematics of lepton hadron scattering is described in terms of the variables Q^2, the four-momentum transfer squared of the exchanged vector boson, Bjørken x, the fraction of the momentum of the incoming nucleon carried by the struck quark (in the quark-parton-model, QPM), and inelasticity y, which is a measure of the energy transfered between the lepton and the nucleon. The differential cross section for the neutral current (NC) process, $e^{\pm}p \rightarrow e^{\pm}X$, is given in terms of the structure functions by

$$\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}(Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L), \tag{1}$$

where α is the fine structure constant, $Y_{\pm} = 1 \pm (1-y)^2$, and $\tilde{F}_2$, $x\tilde{F}_3$ and $\tilde{F}_L$ denote the generalized NC proton structure functions which include Z boson exchange contributions. The structure functions $\tilde{F}_2$, $x\tilde{F}_3$ are directly related to quark distributions, and their Q^2 dependence is predicted by perturbative QCD. The dominant contribution to the cross section is $\tilde{F}_2$, which in turn is dominated by the electromagnetic structure function F_2. In the QPM, F_2 – below the bottom mass threshold – can be written as

$$F_2 = \frac{4}{9}\left[x(u+c+\overline{u}+\overline{c})\right] + \frac{1}{9}\left[x(d+s+\overline{d}+\overline{s})\right]. \tag{2}$$

For low x, $x \leq 10^{-2}$, F_2 is dominated by the sea quarks, while its Q^2 evolution is controlled by the gluon contribution. Thus HERA data provide crucial information on the low-x sea-quark and gluon distributions. At high Q^2, the structure function $x\tilde{F}_3$ becomes increasingly important, and provides information on the valence quark distributions, $u_v = u - \overline{u}$ and $d_v = d - \overline{d}$.

The charged current (CC) interactions, $e^+(e^-)p \to \overline{\nu}(\nu)X$, provide additional flavor-type specific information to separate quark and anti-quark distributions at high-x, since their (leading-order) cross sections are given by

$$\frac{d^2\sigma^+_{CC}}{dxdQ^2} = \frac{G_F^2}{2\pi x}\left[\frac{M_W^2}{Q^2+M_W^2}\right]^2 x\left[(\overline{u}+\overline{c})+(1-y)^2(d+s)\right], \quad (3)$$

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

with G_F being the Fermi coupling constant and M_W the mass of the exchanged W boson.

The $e^{\pm}p$ NC and CC cross sections can thus be written completely in terms of up-type, $xU = x(u+c)$, down-type, $xD = x(d+s)$, and of anti-quark type, $x\overline{U} = x(\overline{u}+\overline{c})$ and $x\overline{D} = x(\overline{d}+\overline{s})$), distributions. These (anti-)quark type distributions can be determined from HERA data alone. This has the advantage that there is no need for heavy target corrections, which must be applied to the νFe and μD fixed target data used in the global fits. 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 information on the d distribution can be obtained directly from CC e^+p data.

3. Combination of H1 and ZEUS Cross Sections

The H1 and ZEUS collaborations have both used their data to perform PDF fits [4, 14]. Both these data sets have small statistical errors, so that the contributions of systematic uncertainties become increasingly important and their proper treatment is essential. Basically there are two approaches, the Offset method used in the ZEUS analysis and the Hessian method applied by the H1 analysis. The resulting ZEUS and H1 PDFs are compatible, although the gluon PDFs do have somewhat different shapes, as is shown in Fig. 1a.

It is possible to improve on this situation by averaging the H1 and ZEUS datasets in a model-independent way prior to performing a QCD analysis on them. Since both experiments measure the same cross section at a given kinematic point one can minimize the following χ^2 and obtain a common true value at any measured kinematic point together with the correlated systematic shifts

$$\chi^2_{exp}(M^{i,true},\Delta\alpha_j) = \sum_i \frac{\left[M^{i,true} - \left(M^i + \sum_j \frac{\partial M^i}{\partial\alpha_j}\Delta\alpha_j\right)\right]^2}{\delta_i^2} + \sum_j \frac{\Delta\alpha_j^2}{\delta_{\alpha_j}^2}. \quad (5)$$

Here M^i is the measured central value, and δ_i the statistical and uncorrelated systematic uncertainty of the quantity M. The $M^{i,true}$ are the values following from the minimization; $\Delta\alpha_j$ are parameters for the j^{th} source of correlated systematic uncertainty and $\partial M^i/\partial\alpha_j$ denotes the sensitivity of point i to source j. For the cross section measurements the index i labels a particular measurement at a given (x, Q^2). Equation 5 represents the correlated probability distribution function for the quantity $M^{i,true}$ and for the systematic uncertainty $\Delta\alpha_j$.

The χ^2 defined in Eq. 5 is suitable for measurements in which the uncertainties are absolute or *additive*, i.e. do not depend on the central value of the measurement. For the cross section measurement, however, the correlated and uncorrelated systematic errors are proportional to the central values. This proportionality can be approximated by a linear dependence. In this case the combination of the data sets using Eq. 5 has a bias towards lower cross section values since the measurements with small central values have smaller absolute uncertainties. An improved χ^2 can be defined by replacing $\delta_i \to \frac{M^{i,true}}{M^i}\delta_i$ and $\frac{\partial M^i}{\partial\alpha_j}\Delta\alpha \to \frac{\partial M^i}{\partial\alpha_j}\frac{M^{i,true}}{M^i}\Delta\alpha$ which translates the relative or *multiplicative* uncertainties for each measurement to the absolute uncertainty.

The correlated systematic uncertainties are floated coherently such that each experiment calibrates the other one. This allows a significant reduction of the correlated systematic uncertainty for much of the kinematic plane, as is shown in Fig. 1b for three representative x-bins.

A study of the global χ^2/NDF of the average and of the pull distribution provides a model-independent consistency check between the experiments. The H1 and ZEUS data are found to be consistent, thus allowing to calculate the experimental uncertainties of the PDFs using the χ^2 tolerance, $\Delta\chi^2 = 1$. This represents a further advantage compared to those global fits where increased tolerances of $\Delta\chi^2 \gg 1$ had to be introduced to ensure that all input data sets are consistent with the result of the global fit at a 90% confidence level.

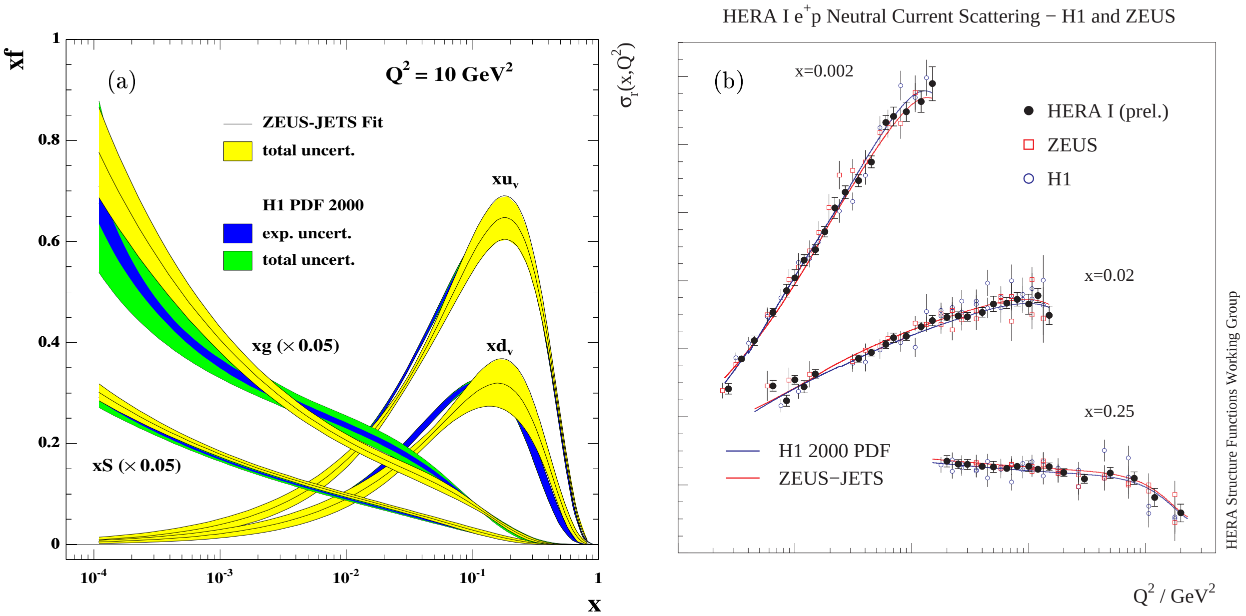

Figure 1: Comparison of the PDFs and their uncertainties from ZEUS and H1 individual QCD analyses at a fixed value of $Q^2 = 10$ GeV^2 (a) and (b) neutral current e^+p cross sections measurements for three selected x bins as function of Q^2. The H1 (open points) and ZEUS data (open squares) are compared to the H1 and ZEUS combined data (full points). Measurements from the individual experiments have been shifted for clarity. The error bars show the total uncertainty. The curves are NLO QCD fits as performed by H1 and ZEUS to their own data.

4. QCD Analysis

QCD predictions for the structure functions are obtained by solving the DGLAP evolution equations at NLO in the $\overline{\text{MS}}$ scheme with the renormalization 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. For our central fit we parameterize the gluon, xg, the valence quarks, xu_v and xd_v, as well as the sea anti-quark type $x\overline{U}$ and $x\overline{D}$ using the generic form

$$xf_i(x) = A_i x^{B_i}(1-x)^{C_i}\left(1 + D_i x + E_i x^2 + F_i x^3\right) \qquad \text{with } i = g, u_v, d_v, \overline{U}, \overline{D} \tag{6}$$

and the number of parameters is chosen by saturation of the χ^2, such that parameters D_i, E_i, F_i are varied, i.e. they are allowed to take values different from 0 during the fit, but are incorporated only if there is a significant improvement of the χ^2. This leads us to set the parameters D_i, E_i, $F_i = 0$, for all partons except xu_v for which only $F_{u_v} = 0$. The normalization parameters A_{u_v} and A_{d_v} are constrained to impose the valence quark number sum-rules and A_g is constrained to impose the momentum sum-rule. The B_i parameters which determine the low-x behavior of the PDFs are constrained such that there is a single B parameter for the valance quark distributions $B_{u_v} = B_{d_v} \equiv B_v$ and another B parameter for the sea anti-quark type distributions, $B_{\overline{U}} = B_{\overline{D}} \equiv B_{\overline{Q}}$. A flavor decomposition of the (anti-) quark type into individual quark flavors can be achieved by assuming that the strange and charm quark at the input scale can be expressed as x independent fractions, f_s and f_c, of $\overline{D}$ and $\overline{U}$ respectively. Imposing that $\overline{d} - \overline{u} \to 0$ as $x \to 0$, a constraint implicit to global fits, further constrains $A_{\overline{U}} = A_{\overline{D}} \cdot (1 - f_s)/(1 - f_c)$. The value of $f_s = 0.33$, has been chosen to be consistent with determinations of the strange fraction using neutrino-induced di-muon production. The charm fraction, $f_c = 0.15$, has been set to be consistent with dynamic generation of the charm from the starting point of $Q^2 = m_c^2$ in a zero-mass-variable-flavor-number scheme. In total 11 parameters of the PDFs at an input scale $Q_0^2 = 4$ GeV^2 are obtained from the fit.

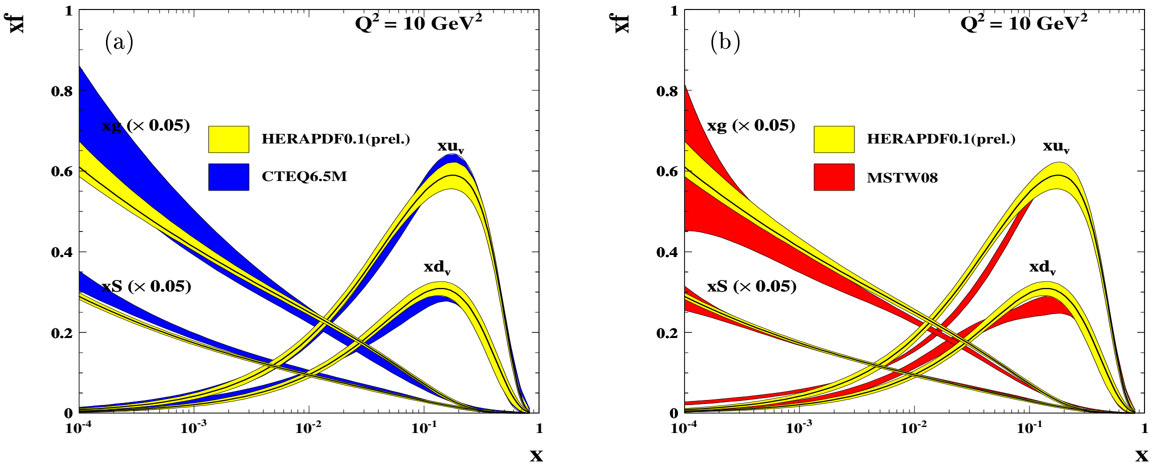

Figure 2: PDFs at $Q^2 = 10$ GeV^2 from the H1 and ZEUS combined data, HERAPDF0.1, compared to recent global PDF analyses, CTEQ6.5M [11] (a) and MSTW08 [15] (b).

5. Results

The set of PDFs obtained from a NLO QCD analysis performed on the combined data set of $e^{\pm}p$ NC and CC cross sections, discussed above, is shown in Fig. 2 (labeled HERAPDF0.1). The much reduced experimental uncertainties of the combined cross sections propagate to the error bands of the PDFs, which also include six sources of model uncertainties due to variation of m_c, m_b, f_s, f_c, Q_0^2, and Q^2_{min}, the minimum Q^2 of the data included in the fit. The central fit, which in addition to all systematic sources of the combined data set, takes into account 4 sources of uncertainties from the combination procedure achieves an excellent χ^2/NDF of 477/562. Figure 2 also compares the HERAPDF0.1 to recent global fits. Note that the HERAPDF0.1 results employs new, still preliminary HERA data of improved accuracy as discussed above. A further difference to the global fits is that these involve data from a much larger variety of experiments and physics processes and thus are forced to use an error definition unlike the $\Delta\chi^2 = 1$ criterion applicable to the HERA data alone.

The preliminary PDF set presented here is obtained from the combined, almost complete set of cross section measurements of the pre-upgrade data taking period. The current PDF set is available at the LHAPDF library and will be published soon, when the HERA I neutral current cross section data are released. The data and QCD analyses thus provide a valuable input for the physics at the Tevatron and the LHC.

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