QCD ANALYSES OF HERA CROSS SECTION DATA

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The H1 and ZEUS Collaborations have performed new next-to-leading order QCD analyses to determine the parton density functions of the proton. QCD fits are performed using inclusive neutral and charged current deep inelastic scattering cross sections from HERA-I. The fits include a full treatment of experimental systematic uncertainties, taking into account point-to-point correlations. The extracted parton densities are in agreement with those from global fits. Since HERA inclusive data provide no direct information on the high-\(x\) gluon, an independent fit has been performed by the ZEUS Collaboration in which the inclusive DIS cross sections are supplemented by jet data from deep inelastic scattering and photoproduction. The determination of the gluon distribution is significantly improved in such fits, allowing a competitive extraction of the strong coupling, \(\alpha_s(M_Z^2)\).

1 Introduction

The kinematics of lepton-proton scattering are described in terms of the Bjorken scaling variable, \(x\), the negative invariant mass squared of the exchanged vector boson, \(Q^2\), and the fraction of energy transferred from the lepton to the hadronic system, \(y\).

At Leading Order (LO), in the electroweak interaction, the double differential cross section for Neutral Current (NC) Deep Inelastic Scattering (DIS) can be written in terms of structure functions,

\[
\frac{d^2\sigma_{\pm}^{NC}}{dx dQ^2} \sim [Y_+ F_2 - y^2 F_L + Y_- x F_3]
\]

where \(Y_{\pm} = 1 \pm (1 - y)^2\). Similarly, for the Charged Current (CC) process,

\[
\frac{d^2\sigma_{\pm}^{CC}}{dx dQ^2} \sim [Y_+ F_2^{CC\pm} - y^2 F_L^{CC\pm} + Y_- x F_3^{CC\pm}]
\]

where the CC structure functions depend on the charge of the incoming lepton. The structure functions are directly related to the parton density functions (PDFs) and the \(Q^2\) dependence, or scaling violation, is predicted in perturbative QCD.

Conventionally, QCD analyses use the formalism of the next-to-leading order (NLO) DGLAP evolution equations. These equations yield the PDFs at all values of \(Q^2\), provided they are input as functions of \(x\) at some starting scale \(Q_0^2\). The \(x\) parameterisation at \(Q_0^2\) is usually chosen to be of the general form,

\[
x f(x) = A x^b (1 - x)^c P(x)
\]

where \(P(x)\) is a polynominal function. While \(A\) controls the normalisation, the parameters \(b\) and \(c\) are sensitive to the low and high-\(x\) regions, respectively.

2 HERA-Only QCD Analysis

The PDFs of the proton are usually determined in global fits to both colliding beam data from HERA, as well as to DIS data from fixed target machines. In such analyses, the high precision NC cross sections from HERA are crucial in determining the low-\(x\) sea and gluon distributions, while the fixed target data provide most of the information on the high-\(x\) sea and gluon, as well as on the valence quark distributions. In the global fits, the most important inputs for the determination of the valence PDFs have been the \(\nu F e\) and the \(\mu D\) fixed target data. However, these can suffer from large uncertainties due to heavy target corrections.

In the present analyses, the H1 and ZEUS Collaborations have performed QCD fits to only HERA data, thus eliminating any uncertainties due to heavy target corrections. The full set of inclusive DIS data
from HERA-I has been used, which covers a large range in \((x, Q^2)\). Since NC and CC DIS data provide no information on the high-\(x\) gluon, an independent fit has been performed by ZEUS in which the inclusive data are supplemented by jet cross sections in DIS \((Q^2 > 1 \text{ GeV}^2)\) and photoproduction \((Q^2 \sim 0 \text{ GeV}^2)\).

The PDFs from the H1 and ZEUS analyses are presented with full accounting for uncertainties from correlated systematic uncertainties, as well as from statistical and uncorrelated sources.

2.1 The H1 PDF 2000 Analysis

A full description of the H1 PDF 2000 analysis is given elsewhere. Here, only a summary is presented. The inclusive DIS data used in the analysis, span the kinematic range \(8 \times 10^{-5} < x < 0.65\) and \(1.5 < Q^2 < 30000 \text{ GeV}^2\). To ensure the applicability of perturbative QCD, an additional cut of \(Q^2 > 3.5 \text{ GeV}^2\) is imposed on the data included in the fit. The parameterisation of the PDFs, at the starting scale of \(Q_0^2 = 4 \text{ GeV}^2\), is of the general form,

\[
x f(x) = A x^b (1 - x)^c (1 + e x + f x^2 + g x^3).
\]

The PDFs that are parameterised are the \(U = u + c\) (total up-type), \(D = d + s\) (total down-type), \(\bar{U}\), \(\bar{D}\) and \(g\) and the number of terms in the polynomial is chosen separately for each PDF by searching for \(\chi^2\) saturation. The fit has a total of 10 free parameters and the analysis is performed in the Zero Mass Scheme, which is appropriate for high \(Q^2\).

The resulting parton densities, at a scale of \(Q_0^2 = 4 \text{ GeV}^2\), are shown in Fig. 1. The \(u\)- and \(d\)-valence distributions are constructed from \(u_v = U - \bar{U}\) and \(d_v = D - \bar{D}\) respectively. The dark shaded band shows the total experimental uncertainty, while the light shaded band shows the model uncertainty, which includes contributions from a variation of the input scale \(Q_0^2\), the minimum \(Q^2\) cut on the data, the charm and strange fractions, the quark masses and the value of \(\alpha_s\). The latter results in the largest contribution to the uncertainty on the gluon. The fit provides a tight constraint on the total up-type and down-type quark densities at low-\(x\).

A cross-check to the H1 PDF 2000 fit has also been performed, in which the H1 inclusive NC and CC data are supplemented with precise fixed target data from BCDMS. The resulting PDFs are shown by the solid line in Fig. 1. The H1+BCDMS fit is consistent with the results of H1 PDF 2000. The H1 PDFs are also found to be compatible with those from the global fits of MRST and CTEQ (see Fig. 3).

2.2 The ZEUS-Only PDF Fit

Full details of the ZEUS analysis are given elsewhere. Here, the main features are briefly described. The inclusive DIS data used in the fit, span the kinematic range \(6.3 \times 10^{-5} < x < 0.65\) and \(2.7 < Q^2 < \)}
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30000 GeV$^2$. To reduce higher twist effects, an additional cut of $W^2 > 20$ GeV$^2$ is imposed. The form of the parameterisation is,

$$xf(x) = A x^b (1 - x)^c (1 + ex)$$

at $Q_0^2 = 7$ GeV$^2$. No advantage in the $\chi^2$ is found to result from using more complex polynomial forms. The PDFs that are parameterised are the $u_v$ (u-valence), $d_v$ (d-valence), $S$ (total sea), $g$ and $\Delta = (\bar{d} - \bar{u})^a$.

Since the data from HERA-I are less precise than fixed target data in the high-$x$ regime, the high-$x$ sea and gluon are not well constrained in fits using only HERA data. In the ZEUS-Only fit, the high-$x$ sea and gluon parameters, $c_S$ and $c_g$, are fixed to the values extracted from the previously published ZEUS-S global fit\textsuperscript{12}. The constraints imposed lead to a total of 10 free parameters. The fit is performed in the Roberts-Thorne\textsuperscript{13} variable flavour number scheme.

The ZEUS-Only PDFs are summarised in Fig. 2 and are compared to those of the ZEUS-S global fit. The central values of MRST and CTEQ are also shown. The experimental uncertainties represent the most significant source of uncertainty on these distributions. Variation of analysis choice, such as the value of $Q_0^2$, the minimum $Q^2$ of data entering the fit and changing the form of the parameterisation at $Q_0^2$, do not produce a large model uncertainty.

2.3 The ZEUS-Jets PDF

In QCD fits incorporating only inclusive NC and CC DIS data, the high-$x$ gluon is constrained by the momentum sum rule only.

The ZEUS Collaboration have performed a new fit, in which the inclusive DIS data are supplemented by cross sections from inclusive jet DIS\textsuperscript{14} and two-jet photoproduction\textsuperscript{15}. Both sets of jet data are directly sensitive to the gluon in the range $0.01 < x < 0.1$.

A full NLO calculation for jet cross sections is very time-consuming. Therefore, NLO programs\textsuperscript{b} have been used only initially.

\textsuperscript{a}Since there is no information on the shape of the $\bar{d} - \bar{u}$ distribution in fits to HERA data alone, this distribution has its shape fixed consistent with the Drell-Yan data\textsuperscript{12}, and its normalisation consistent with the size of the Gottfried sum-rule violation\textsuperscript{11}.

\textsuperscript{b}For the inclusive DIS jets, the program DISENT\textsuperscript{16} was used, while for the two-jet photoproduction, the program of Frixione and Ridolfi\textsuperscript{17} was used.
to produce grids of weights, giving the perturbatively calculable part of the cross section. The predictions for the jet cross sections can then be reconstructed using,

\[ \sigma = \sum_{a=g,q,\bar{q}} \int dx \alpha^a_s(\mu_R) f_a(\xi, \mu_F) c_{a,n}(\mu_F, \mu_R) \]

where \( f_a \) is the PDF for parton \( a \) as a function of momentum fraction \( \xi \) and scale \( \mu_F \), and the \( c_{a,n} \) are the perturbatively calculable kernels. The cross sections calculated according to this equation reproduce the real NLO predictions to better than 1%.

Recall that for the ZEUS-Only fit (Sec. 2.2), the high-\( x \) gluon parameter, \( c_g \), is constrained to be consistent with the ZEUS-S global fit. However, the extra information from the jet data allows this parameter to be freed, giving 11 free parameters in total.

The PDF distributions extracted from the ZEUS-Jets fit are compared in Fig. 3 to those of H1 PDF 2000. The central values of MRST and CTEQ are also shown. All fits are compatible within uncertainties.

The jet data are expected to have most impact on the gluon distribution. Figure 4 shows the gluon PDFs for fits without\(^5\) (left) and with (right) jet data. The inclusion of jet data provides a significant improvement to the constraint on the gluon at medium-to-high-\( x \), which persists to high scales.

### Extraction of \( \alpha_s(M_Z^2) \)

The value of \( \alpha_s(M_Z^2) \) has been determined from the ZEUS-JETS fit by treating it as an additional free parameter. The value extracted is,

\[ \alpha_s(M_Z^2) = 0.1183 \pm 0.0027 \text{ (experimental)} \]
\[ + 0.0008 \text{ (model)} \pm 0.0050 \text{ (scale)} \]

where the experimental uncertainty arises from both uncorrelated and correlated sources and the model uncertainty includes contributions from varying the value of \( Q_0^2 \), changing the form of the input parameterisation and varying the cuts on the data included in the fit. The uncertainty in \( \alpha_s(M_Z^2) \), which usually comes from the correlation to the PDF shapes, is automatically included in the experimental uncertainties. The largest uncertainty comes from varying the scale \( \mu_R \), suggesting that NNLO QCD analyses could provide very precise extractions of \( \alpha_s \) in the future.

### Summary

The H1 and ZEUS Collaborations have performed NLO QCD DGLAP analyses of the HERA-I data to extract the parton density functions of the proton. Since HERA is a proton-only target machine, these analyses avoid any uncertainties due to heavy target corrections, which have led to large systematic uncertainties in global fits. In addition, since the data used in the fits are from only one experiment, uncertainties which can arise from combining systematics from differ-

\(^5\)This fit is labelled “ZEUS-O” since it includes the same data as the ZEUS-Only fit described in Sec. 2.2. However the parameter constraints are the same as for the ZEUS-JETS fit i.e. free \( c_g \).
Figure 4. The gluon distribution for fits without (left) and with (right) jet data included. The cross-hatched band show the uncorrelated uncertainty while the shaded band shows the total uncertainty.

ent experiments are also reduced. Jet data have been added in an independent fit, giving a significant improvement in the knowledge of the gluon PDF at medium-to-high-x which persists to high scales. The extra constraint on the gluon has led to a competitive extraction of $\alpha_s(M_Z^2)$ from only HERA data.

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